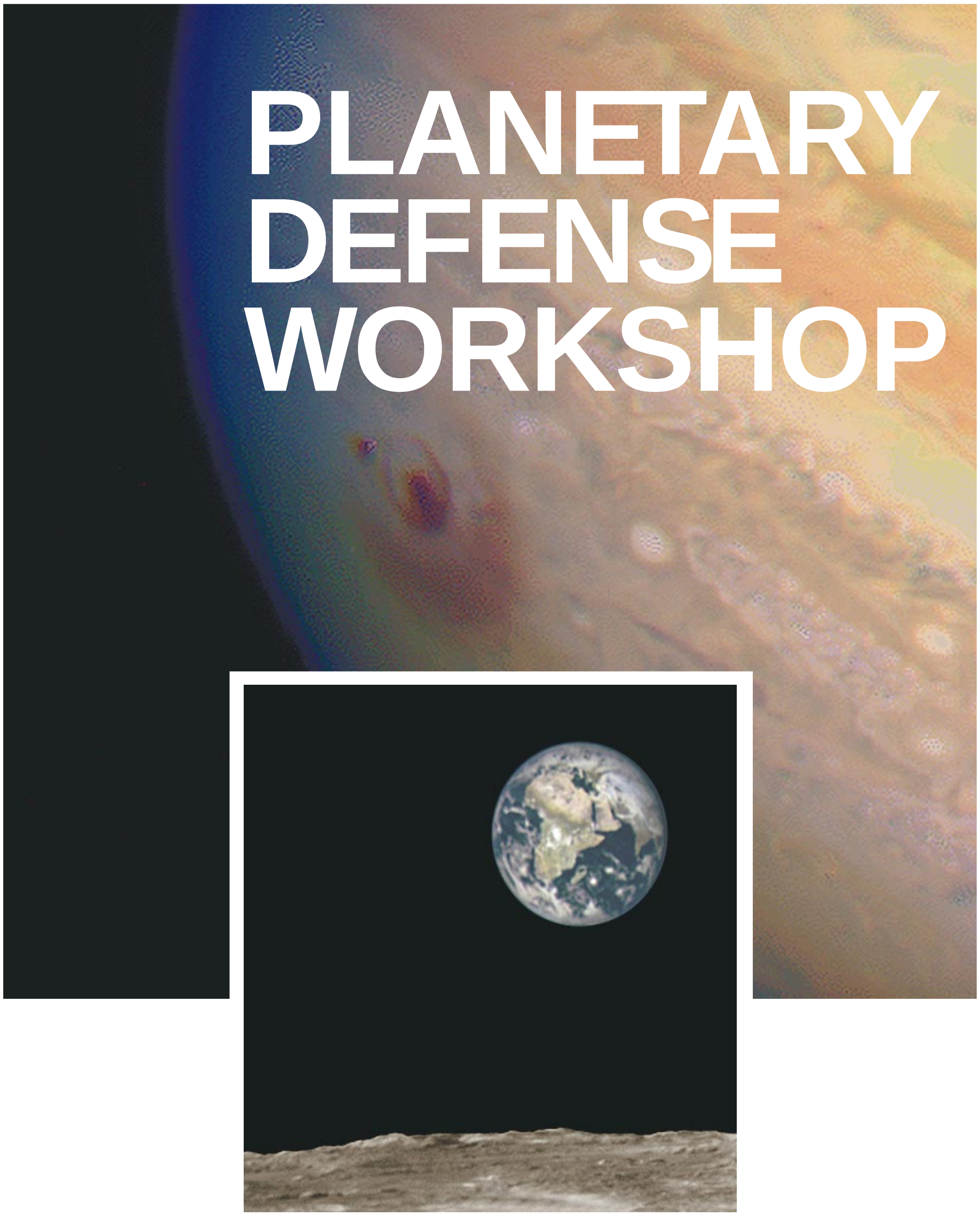

Proceedings of the Planetary Defense Workshop
Lawrence Livermore National Laboratory
Livermore, California
May 22–26, 1995

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Cover: *The impacts of comet Shoemaker-Levy 9 fragments with Jupiter in July 1994 provided an opportunity to observe and to advance our understanding of hypervelocity collisions on a planet. This improved understanding can now be used to develop better models to assess the threat of such impacts to the earth.*

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Executive Summary

INTRODUCTION

John H. Nuckolls
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A Planetary Defense Workshop (PDW) on the detection and mitigation of hazardous asteroids and comets was held at Lawrence Livermore National Laboratory, May 22-26, 1995. More than 100 scientists and engineers participated. This was one of several recent conferences on this subject.*

The PDW Organizing Committee included Dr. Gregory Canavan, Los Alamos National Laboratory; Dr. Eugene Shoemaker, U.S. Geological Survey; Dr. John E. Mansfield, NASA Associate Administrator for Space Access and Technology; Mr. John H. Darrah, Chief Scientist, HQ AFSPC/CN; Dr. Stewart Nozette, BMDO/USAF; Prof. Vadim A. Simonenko, Deputy Scientific Leader, Russian Federal Nuclear Center - VNIITF, Chelyabinsk-70; and Dr. Robert B. Barker, Assistant to the Director, LLNL. These members assisted me in organizing the workshop, and chaired the five major topical sections: Threat (chaired by Dr. Shoemaker), Detection (Mr. Darrah), Experiments (co-chaired by Drs. Mansfield and Nozette) Interdiction (Prof. Simonenko and Dr. Barker), and Integration (Dr. Canavan). Mrs. Shirley Petty, LLNL, was PDW Administrator.

Dr. Canavan proposed an integrated program for detecting and mitigating hazardous near-Earth objects. Proposed USG funding is substantially less than current expenditures to mitigate and respond to natural disasters involving comparable life-loss on the time - average (e.g., that due to hurricanes, large floods, and earthquakes, etc.). There is strong support in the scientific communities represented at the PDW for increased effort to detect hazardous comets and asteroids. There is agreement that a significant threat exists, detection is feasible, and mitigation is often possible.

Major issues are: Will governments principally focused on obvious and pressing problems initiate and sustain a long-term commitment to search for threats from space and prepare for their mitigation? Will detection of a specific comet or

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* Earlier conferences included: April/May '91, at San Juan Capistrano (organized by NASA Ames); Jan. '92, at Los Alamos (organized by LANL/NASA); Jan. '93, at Tucson (organized by University of Arizona); Sept. '94, at Chelyabinsk, Russia (organized by VNIITF, Russian Federal Nuclear Center); and April '95, at the United Nations.

asteroid on a collision course with Earth be required to catalyze rational government actions?

One or more of the thousands of Earth orbit crossing objects carrying ≥ gigaton energies may pass within several diameters of Earth in the lifetimes of our children. Millions of casualties would result in the unlucky event that one of these gigaton objects crashed into Earth's oceans, creating multi-continent-impacting super tsunamis, or exploded near major population centers. Governments may decide to begin near term deflection of hazardous objects predicted to pass near Earth in the distant future because there are significant uncertainties in long-term orbit calculations, and mitigation is less costly and more likely to succeed if performed as far in advance as possible (ideally many decades before close approach to Earth). A near-term goal should be to identify potentially hazardous asteroids and comets which will pass within several diameters of Earth in the 21st Century. This is technically feasible and relatively inexpensive.

Edward Teller participated in the Planetary Defense Workshop (as well as in the earlier conferences at Chelyabinsk and Los Alamos). He provided a broad perspective on detection and mitigation of the threat, and emphasized the need for experiments to determine the composition and structure of comets and asteroids. He also discussed a strategy for mitigating hazardous objects so large as to be beyond the capabilities of nuclear explosive-based means.

Summaries by Organizing Committee members of the five major topical sections comprise the core of this Executive Summary. Opinions and conclusions are those of the authors.

More than 50 papers presented at the PDW provide the main body of this Proceedings. They are organized into five topical sections, including papers presented in the plenary sessions which opened the PDW.

The LLNL PDW Proceedings is available on the net: http://www.llnl.gov/planetary. For further information, contact PDW Administrator, Mrs. Shirley Petty, at petty2@llnl.gov.

The Need for Experiments on Comets and Asteroids

Dr. Edward Teller
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First of all, I would like to thank Academician Khariton for his kind words to all of us and to me especially. We are really sorry that he is not with us. I am glad to see all the people who are here from China, Japan, Italy, and very particularly from Russia.

Now, I would like to say a few things in a straightforward and very serious manner. I believe we are here—in fact, we all know we are here—to look into a situation that is unique in the *size* of the trouble we are looking at and in the *improbability* of these big troubles. For mathematicians, it is easy to multiply the two and to say that this trouble is like other troubles because the product is the same. For politicians who are trained to look carefully at what happens during their terms of office and less carefully at everything beyond, the same does not hold as for the mathematicians. And we, in turn, depend on the politicians to make it possible for us—in the form of dollars, or rubles, or anything else—to do what is needed to be done.

I think it is extremely important that we present a credible case so we can go ahead. I would like to suggest a few points of view on how to present the case that we are talking about—presenting it very truthfully but emphasizing the things that ought to be emphasized.

Here is the situation that, to my mind, is a scandal, and I think people can understand that it is a scandal: There is a probability of a few percent in the next century of the arrival of a stony asteroid—not the biggest possible but a fairly big one, approximately a hundred meters in diameter. It delivers on impact maybe 100 megatons. It is a practical certainty that, when and if such an object should bump into us, it will come *completely* unannounced. We won't have *any* indication of it. Yet such an object is apt, with a fairly high probability, to do a lot of damage—for instance, cause a tsunami if it falls into the ocean. Damage would be concentrated on the shores region, where people like to aggregate. So the effect of the asteroid and the people are attracted to the same meeting point—hence, a lot of damage. Just in dollars it could be billions, and in lives it might reach millions. Yet, no warning whatsoever.

What we need to rectify this situation is half a dozen arrays of charge-coupled devices and appropriate (not very big) telescopes, amounting to probably not much more than ten million dollars altogether. If such a catastrophe should occur, afterwards we'll be able to point out on existing pictures where the asteroid has approached, but we wouldn't know it ahead of time because nobody would have looked at those pictures. I shouldn't have said nobody; I should have said *hardly* anybody. And actually, to find them would be extremely difficult. The CCDs can be systematically trained to scream when there is something suspicious, and in this way we could have information a week ahead of time. To my mind, such action would correct a very large incompleteness in our safety system. And I think that should be a very salable item.

So, we know ahead of time that something is coming. What do we do about it? We would know ahead of time with sufficient accuracy, for instance, what shorelines have to be evacuated. A week is not plenty of time, but it is very considerably more than nothing.

I was interviewed today and the question was asked: Is the international situation ripe for such action? I'm answering with every confidence: It is. I have no doubt that if there is such a danger from outside, if we know that people in certain spots will have to move to save their lives and can't move to save their property, then it will be psychologically not only a necessary thing but an *easy* thing to get help from all over the world to whoever has to evacuate. I hope that the same thing holds for all the other measures that we might be willing and able to take in order to improve the situation, because I certainly don't want to stop at the point of just saying "evacuate."

The next point that I feel is a real necessity is to know what more to do. We have the power to reach out into space and to deliver what is needed. But we don't know how the objects behave that will arrive. Very particularly, we will know rather little about the actual object that has been a mere spot on the best photographic plate and that has grown for the last couple of days a little more to not very much more than a bigger spot.

What do we do about it? I claim that the next thing we ought to do is to gather knowledge about what can be done. What is the variety of things that can be done? Such knowledge can be obtained in a number of different ways. The one I prefer (and that all of us will not necessarily prefer) is to make experiments—one or two or three per year—on objects that are getting close to the Earth, to the approximate distance of the Moon, more or less one light-second away from the Earth. Whatever we do can be observed from the Earth very easily. And to get out there is not very difficult.

And what do we do there? Well, we can do a number of things. I would recommend that, to begin with, we do the very simplest thing on which we can agree: Put up sharp tungsten knives for the purpose of cutting up the incoming object if it's of an appropriate size—something like 300 feet or 100 meters in diameter. Of such objects, approximately a few approach in a year. We make experiments on them. Can every one of them be sliced up sufficiently so that if the fragments fall on the Earth, they will be burned up in the high atmosphere in a completely harmless manner? This certainly can be found out by experiments on objects that have already passed the Earth. I think such experiments will contribute, to a considerable extent, to safety in the one-percent-per-century case that such a danger might actually occur.

Now, if we find that the biggest or toughest of these objects will not be completely sliced up, then, after we have become familiar with the slicing up, we should take the big step—using a nuclear explosive. If, for instance (which I think is a plausible situation), on a 300-meter-diameter object, we have succeeded in slicing up 20 meters of the surface, we can then put a nuclear explosive close to the surface, which will irradiate the rubble that we have already created. This tends to homogenize this rubble and push it one way, while, by reaction, the remaining ninety percent of the material is pushed the other way. The reaction on the main body will be very powerful, and there can be no doubt that appropriate deflections can be arranged.

Objects a kilometer or more in diameter are apt to create worldwide disaster. On the average, they are expected once in a million years. We hope to discover them several months in advance. The use of nuclear explosives as outlined might or might not suffice to deflect them. A more radical method of using several nuclear explosives may be needed. We might use them to create the rubble, and this may be followed by one big blast as mentioned above. Or we might attempt to bore a hundred-meter-deep hole by successive nuclear explosives and then blow up the object by one big, deeply located explosion. Such methods cannot be relied upon without experimentation on objects that have safely passed the Earth.

One final possibility should be considered. Of the hundred-meter-diameter objects, there are approximately a million. They could be discovered, catalogued, and their orbits computed. If a huge, hundred-kilometer object approaches and is apt to hit the Earth within a year, then one of the hundred-meter objects is almost certain to approach it to within approximately one light-second before this can happen. Careful deflection of this smaller object could steer it into the path of the bigger one. The expected result would be to prevent a collision with the Earth, which would be the ultimate catastrophe. One must add that collision of a hundred-kilometer object with Earth is not apt to be predicted even in a billion years.

I would like to conclude with emphasizing one obvious principle: We scientists are *not* responsible and *should* not be responsible for making decisions. But we scientists are uniquely and absolutely responsible for giving information. We must provide the decision-makers with the data. On the basis of this, they will have the best chance to make the right decisions. That is the main reason why I say that we must pursue and must be given the means to pursue the knowledge as to when and how objects will arrive and the knowledge as to possible ways to deal with them. The choice of how to deal with them can be and should be delayed. If need be, it can be done and probably will be done in the last moment. But knowledge—the firm knowledge, not merely guesses on how asteroids will react but knowledge based on experiments—should become available. That is our responsibility. And I believe we should argue, in a carefully considered manner, so that we can acquire, in the most efficient manner, as much of the relevant knowledge as is possible.

I can add only two words: Good luck!

Integration Summary Report

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Recent progress in threat definition, detection and search strategies, intercept concepts, experiment definition, and integration studies have produced a preliminary integrated program for detection and defense against the most threatening objects from space. It addresses objects of all sizes and warning times, and could negate the most frequent and damaging impactors with existing, non-threatening, non-nuclear technologies. The appropriate components could be developed and deployed in a few decades for expenditures of a few tens of millions of dollars per year. The program could benefit from interagency and international cooperation in both detection and defense. There are no technological or classification barriers to thus sharing of the burden of planetary defense.

Introduction

Integration is a new panel, whose definition was both necessitated and made possible by the successes of the other panels at the previous meetings. Further progress at this meeting made it possible to achieve the preliminary integration insights discussed below. This section documents the main areas of progress and those in which further work would be useful.

Threat Panel

The Threat Panel estimated that about 2,000 near-Earth objects (NEOs) larger than one km—of which only about 7% have been discovered—revolve around the sun on short-period orbits that can intersect the orbit of the Earth. There is about one chance in a thousand that one of these objects will collide with Earth during an average person's life span. Such a collision could inject sufficient material into the atmosphere to cause a major loss of global crop production and consequent loss of human life. Expected losses in the absence of defenses are incalculable. Even the average expected losses justify expenditures of ≈ $B/yr on defenses and defenses against both NEOs and comets—independent of the current uncertainties in their relative fluxes.

The Threat Panel also refined the estimates of potential losses from the more numerous intermediate sized NEOs with diameters larger than about 0.1 km, which have a chance of about 10 percent per century of colliding with Earth. Their impact in oceans cause tsunami, which can cause great destruction to distances of tens of kilometers inland all around the oceans into which they fall. While the effects from these intermediate few 100 m NEOs are not global, they could be regionally devastating due to the increasing concentration of value in coastal regions. While the losses from still smaller NEOs is not completely characterized, they are apparently of lesser magnitude. Thus, the primary challenge is to design defenses that can address intermediate and large NEOs and comets.

Detection Panel

The Detection Panel adopted a goal of identifying, characterizing, and cataloguing potentially threatening comets and asteroids. For objects larger than 1 km that could be done with a few dedicated 1 to 2 meter telescopes with advanced CCD detector focal planes. Through about 10 years of rapid, wide-area search, they should discover 50-70% of short period NEOs—or about 90%, given strong Air Force and international participation. Additional objects also need study, including long-period comets (LPCs) seen only on their single pass, low albedo "stealth" comets, and intermediate objects that can cause tsunami and enhanced regional damage. The intermediate size objects could require more advanced technology, including space-based sensors, which appear necessary to address their short timelines.

Interdiction Panel

The Interdiction Panel outlined a set of options for each threat object size and warning time. Of particular interest is the conclusion that kinetic energy interception is adequate for a larger class of object than previously thought, including the intermediate size objects causing the most frequent tsunami. Thus, it should be possible to develop the detection, interdiction, sensor, and control technologies needed to address these intermediate objects without invoking threatening technologies while preserving the option to switch to higher specific energy sources later, if needed. Validating these options will require more theory, laboratory experiments, and interaction experiments with space objects.

Experiments Panel

The Experiments Panel outlined a set of steps leading from theory and laboratory experiments to space flyby and probe experiments, which would establish the basis for a mitigation options matrix. They propose a set of carefully diagnosed interaction experiments in space using technology consistent with that required for subsequent applications, which would leave a residual prototype intercept capability. A key element of this program is the international execution of experiments, interpretation of data, and integration with data from other sources—such as that from small objects that impact the Earth's atmosphere. These experiments would culminate in full-scale kinetic energy impact probe experiments, including precise measurements of orbit change with ground- and space-based sensors, which would both study the impulse transferred by kinetic energy impact and simulate the interaction of higher energy sources.

Warning time

In integrating outputs from the Threat, Detection, Interdiction, and Experiments Panels it is useful to subdivide the threat according to the amount of warning time the defense would have. The paragraphs below use the terms Long Warning to indicate the times of decades to centuries that might be available for the negation of NEOs detected many orbits prior to impact, Short Warning to indicate the months to years that might be available for comets or undetected NEOs, and Very Short Warning to denote the days to weeks of warning that might be available for intermediate objects.

Long Warning times result from the detection times of decades to centuries that might be available for the negation of short-period (4-10 years) NEOs detected many orbits prior to impact. For example, detection of a 10 year period NEO 10 orbits prior to impact would give about 100 years for reaction, which would allow considerable development of defensive measures prior to their deployment. Long Warning permits efficient search with conventional telescopes with large CCD arrays. Current and planned ground-based telescopes should be able to provide the search rates required to survey 90% of large NEOs in one to two decades. Space-based sensors should be available for their augmentation, and even more advanced technology should become available for upgrade during the few decade search interval, if needed. Long Warning also makes it possible to take full advantage of efficient interception tools such as optimal trajectories, deflection at perigee, and low-thrust, high specific energy engines and provide enough leverage to take advantage of efficient deflection concepts such as ion thrusters, solar energy, mass drivers, kinetic energy, etc. The highly efficient performance of each of these interception and deflection approaches with Long warning has been made plausible through analytic studies, although they need more detailed systems and engineering studies.

The distinguishing feature of Long Warning is that the most important element of an effective response to this class of NEOs is the prompt initiation of search, which can be performed by modest and inexpensive telescopic searches. If that search found most of the currently unknown short-period NEOs in a few decades and did not find any that represented an immediate threat to the Earth, it might not be necessary to develop means for interception at all. Thus, there appears to be the potential for eliminating risks amounting to a few tens of $B by performing a search which would cost a few $10M. This roughly 100-fold leverage is so great that it would appear cost effective to develop the means for interception even if they were never needed for NEOs in this class. That is particularly so in if they were so constructed that they were applicable to the other classes of objects, which do require defenses.

Short Warning such as the ≈ 4 months that would result from the detection of a LPC or undetected NEO at 2 AU on final approach admit of far fewer search and intercept concepts. Adequate warning against large LPCs requires search to magnitudes of 23 to 24, which requires either massive ground-based telescopes or space-based sensors, either of which could cost ≈ $100M. Reducing the adverse leverage from the object's high velocity would require the high specific impulse and thrust of nuclear fuels, which would be difficult and expensive to develop. Reducing the penalty from the object's great mass would require payloads with very high specific energy, although that would not require expense or development; current versions could suffice. Short Warning requires that defenses be in place when the threat is detected; there would not be time to develop them later. However, if defenses were developed for Short Warning, which appears justified on the basis of the losses from comets alone, they would also be available to Long Warning threats, although the converse is not true.

Very short warning also requires ready defenses. It needs very fast, wide area search, independent of solar viewing and weather restrictions, for which space basing provides further leverage. For intermediate-size objects, the sensor requirements are not excessive. A ≈ 1 m sensor, which could detect a 1 km object at ≈ 1 AU, could also detect a ≈ 0.1 km object at ≈ 0.1 AU, which would give a warning of about a week. It would not be possible to deflect such an object totally away from the Earth with that little warning, but it should be possible to put a kinetic energy payload in its path that could disrupt it sufficiently such that the Earth's atmosphere could deal with the residue. For intermediate objects, this kinetic energy defense could be developed through a modest number of experiments, whose most stressing elements would be the development of quick-response rockets, homing technology, and control technologies. Should an target require more energy than kinetic energy could provide, it should be possible to substitute more energetic means into the interceptor without invalidating these experimental results or requiring revalidation of the defenses.

Future activities

Future activities include studies, interaction experiments, integration experiments, and operations. Studies should cover the detailed search, interception, and deflection technologies discussed above and define their integrated performance at the level required to estimate their performance and cost. To support this, there is an immediate need for systems concept definition, mission analyses, system engineering, and technology studies to guide the follow on phases. Given adequate definition of the candidate defensive system, various professional societies could make important contributions and add credibility to these assessments. An important part of this activity would be the proper assessment and documentation of expected losses, e.g., a handbook of the likely effects of and expected losses from tsunami in various basins. These studies could be an important measure in maintaining communication among active workers and in initiate educational efforts in the field of NEO defenses. This study phase should cover a few years and could be executed at a funding level of a few $M/yr.

The experiments phase should involve both laboratory and then space experiments. The laboratory experiments should be as thorough as possible, and should test the micro- and macro-mechanical properties of a wide range of candidate objects. These experiments could profitably overlap the study phase somewhat, as they would thereby provide useful focus and guidance. The space activities, which should progress through flyby, probe, and deflection experiments supported and diagnosed by ground-based sensors, could build on the successful Clementine technology, approach, and cost structure. If so, the experimental programs could probably be executed for a few $10M/yr. These space experiments should be thorough, as any defenses should be based on knowledge of the NEO's characteristics.

To that end, international contributions could be very useful in adding unique diagnostic techniques and in integrating U.S. strength in search, homing, and impact technologies with complementary international strengths in rockets, timely response systems, and space science. These space capabilities, although pivotal, are now fragile and possibly transient. However, it might be possible to augment them through the use of deactivated strategic missiles for experiments, if the value of that option could be agreed to quickly. These experiments would also provide a mechanism for practicing through joint field activities the coordination of command and control procedures that could later be useful for actual defenses. The value of these activities would be enhanced if the data could be transferred to an international center for data analysis, which could in time evolve into a joint warning center for NEO hazards.

Integration experiments could overlap the space interaction experiments somewhat, as they would be intended to test the integrated performance of the search, interaction, and command elements, all of which would be needed for precise, properly diagnosed interaction experiments. If this synergism was exploited properly, the integration experiments could be performed for an amount comparable to that for the interaction experiments. Subsequent to these development programs, the residual intercept capability could be maintained for about $100M/yr, with the greater amount resulting from continuous operations and higher reliability, whose timelines and costs would be paced accordingly.

Strawman programs

To provide interim answers to frequent questions as to when it might be possible to develop actual defenses against various space object threats it is useful to sketch out strawman programs that would meet the timelines for the various objects discussed above. The strawman program for Long Warning is shown below:

Long	95	00	05	10	15
search			50%	90%	
intercept	current	maintain			
improved	study	develop			

The three main elements of the program are search, intercept, and improved technology. Adequate search could apparently be performed by one to two, few meter ground-based telescopes with upgraded CCD focal planes. They should achieve 50% completeness against short-period NEOs in about a decade and over 90% in two. The completion of this search is the pacing item for defenses against objects in this class, and the pacing item for completing the search is getting it started quickly with modest telescopes with good focal planes. The interceptors that would be used in the near term are slight modifications of current deep-space missiles. The improved technology development indicated would involve modified boosters, efficient upper stages, improved deflection means, and more accurate control technologies. After the initial study, key concepts and components could be developed further, although it would not be necessary to integrate them before the results of the telescopic search was known, which is why the intercept programs are paced to the search program.

For Short Warning, a few additional program elements must be added to address the much deeper and faster search needed and the need for ready defenses and the experiments required to support them. The resulting strawman program is:

Short	95	00	05	10	15
search	study	develop		operate	
" space	study	develop			deploy
interact exp.	plan	execute		complete	
intercept tech	plan	test		residual	

The key elements are the need to develop much more powerful ground- or space-based sensors. The former would build on, but represent a major extension of, the technology envisioned for near-term, decades long telescopic searches. The latter would involve the development of new search technologies with performance significantly beyond that currently available for observation from space. For that reason, the space-based sensors could take longer to develop and be available later somewhat later. The interaction experiments are paced by the space experiments needed on flyby observables, probes, and kinetic energy deflection. Fortunately, they could be performed with existing or surplus assets. The interception technology experiments could largely be performed as the control mechanisms for those interaction experiments, which would speed the execution and lower the cost of each. These interaction experiments with kinetic energy should also adequately simulate the coupling of very high energy explosives as well. The value of both sets of experiments would be enhanced in both their execution and interpretation if they could be performed with international cooperation as full as possible.

For Very Short Warning, the strawman program is similar, although some of the lines have slightly different interpretations:

Very Short	95	00	05	10	15
search ground	plan		modify		
" space	plan		modify		
interact exp.	plan		complete		
intercept tech	plan		residual		

The distinction is that this program addresses intermediate size NEOs; hence, it can use components that can work with less response time because complete deflection or fragmentation is not required. The Earth's atmosphere can provide some of the defense. The requirement is that the object be broken up and dispersed enough so that the fragments would not survive in enough size and number to coherently produce a tsunami. For such a system ground-based sensors derived from those for Long warning search (e.g., more 1 m telescopes with focal planes that would support an order of magnitude greater search rates) could provide adequate warning, although modest space-based sensors could be developed rapidly to extend search closer to the sun and as a backup to terrestrial weather interruption of ground-based search. These simplifications should enable these modest sensors to be developed significantly more quickly and with less expense than those for Short Warning. The interaction experiments would be similar to those for Short Warning, they would just be done faster, which should not involve technological issues, just modest augmentation of resources. Similarly, the intercept technology could easily be accelerated to complete all of the required experiments required to reach the desired residual intercept capability sooner. The net effect is about a five year acceleration of the strawman program for Very Short Warning compared to that for Long or Short

Warning, which largely stems from the reduced levels of performance required from search sensors, the simplicity of the negation concepts, and the direct applicability of existing missile and intercept technology.

Strawman resource requirements

The strawman programs above appear technically reasonable, but it is appropriate to provide some indication of the resources assumed in constructing them. This section provides a strawman estimate of the resources required for each program and a rough cross comparison of them.

For *Long Warning*, the three main elements of the program would be started in parallel. The search program would involve the several, few-meter telescope program outlined above. Achieving the 50 and 90% completeness levels shown is estimated to cost about $5M/yr, although the times for reaching the latter could be accelerated about a factor of two by funding of about twice that amount. The intercept program is a modest one of studying and modifying current rockets for more accurate deep-space rendezvous, which would also cost about $5M/yr. The element for the development of improved technology for boosters, deflection, and control would shift at the five year point from studies to technology demonstrations and experiments, which would cost somewhat over $5M/yr. It would not be useful to accelerate the intercept and technology programs without accelerating the search program as well. Together the three elements as shown would require about $15M/yr, or a total of ≈ $225M over the 15 year development program shown. The $15M/yr would be about 3% of the expected annual losses from NEOs in this class. Accelerating the program to $30M/yr would not improve its cost-effectiveness during the development phase, but would speed the date at which actual defenses would be provided.

For *Short Warning*, there is an essential requirement to develop much more powerful sensors. Since it is not clear whether ground- or space-based sensors would be required, it would be appropriate to start their development in parallel. For ground-based sensors, that could probably be done as an extension of current telescopic approaches for an additional ≈ $5M/yr, for a total of ≈ $10M/yr for ground-based sensors. The conventional wisdom is that space-based sensors would cost an additional ≈ $20M/yr and take another 5 to 10 years for development. Although current concepts challenge that wisdom, those numbers are used below. The series of progressive space interaction experiments needed could be performed in about 15 years for about $30M/yr by building on the technology demonstrated in Clementine, which would make their results available at about the same time as the sensor developments and the integration experiments that would use them. Those interaction experiments could also be used to test interception technology for an additional ≈ $20M/yr. That would give a total requirement for the Short Warning program of ≈ $80M/yr, or $1.2B over 15 years, which is $1.2B/ ($0.5B/yr x 15 yr) = 16% of the losses expected from objects in this class over that interval. It should be noted that while the Long Warning strawman plan would produce only a survey at the end of 15 years, the Short Warning strawman would produce a significant residual defensive capability. However, because of the long development times for the sensors for Short warning, it is more difficult effectively accelerate its timelines.

For *Very Short Warning*, it is necessary to upgrade and deploy more ground-based telescopes, although they could be modest sensors at the GEODSS level, which are readily available, which would cost about $10M/yr. It would also be appropriate to augment them by deploying modest space telescopes for greater coverage at angles closer to the sun, which might require an additional $20M/yr. Since those two steps would accelerate the completion of the sensor elements to about a decade, it would be appropriate to do the same with the interaction and interception technology experiments, although that should not add appreciably to their costs, which would remain at ≈ $30M/yr and $20M/yr, respectively. This acceleration would produce a defensive capability against intermediate objects about five years earlier than the other programs for an investment of about $80M/yr x 10 years ≈ $800M, which is about half the expected losses from intermediate objects during that interval. Because of the development times for sensors and execution times for interaction and integration experiments, it would be difficult to further accelerate these timelines. However, these defenses, once developed would be available to support the detections from other warning times.

Overall, Long Warning would only lead to an assessment after 15-20 years, not a defense. Since it does not lead to a defense, it can be argued that search only would be about as effective, as has been assumed in earlier studies of objects in this class. A program for Long Warning is the lowest cost option, and does address a significant part of the threat, so it should not be excluded. A program for Short Warning addresses the portion of the threat that cannot be treated by telescopic searches of extended duration. It handles the other global part of the threat, but because of the sensor development required, it does so on a long time scale and at considerable expense. A program for Very Short Warning would lead to both search and defense for regionally threatening intermediate objects. It would also lead to a defensive capability and backup for objects from longer warning searches. The cost for all three of ≈ $175M/yr would be cost effective relative to the threat, but would constitute a significant increment. Thus, it is useful to examine various combinations that could be undertaken at lower annual costs.

In evaluating combinations, it has been conventional to first examine expanding the program for extended search to Long Warning and second to extend it to include Short Warning defenses. Since Very Short Warning defenses against intermediate objects are the newest concern, there is a tendency to treat them as third place. Given the arguments and estimates above, it is not clear that is the appropriate path. Extending to defense with Long Warning is clearly appropriate, because it is a modest extension and that is highly cost effective. But based on the timelines and technology developments outlined above, it would appear that the second step should be defenses against Very Short Warning intermediate sized objects, because that would provide an early capability against the threats that are likely to be encountered first. Executing the Very Short Warning program would start towards the improved ground- and space-based sensors needed for other warning regimes, the limited interaction experiments needed for non-threatening technologies, and adequate demonstration of intercept technology integration. Executing the programs for Long and Very Short Warning defenses together would only cost about $100M/yr, but it would address both the large objects that can be detected by extended search and the intermediate objects that can be negated on final approach. If Short Warning defense was added later, it could build on the technology developments and experiments performed by the two earlier programs to produce defenses using longer ranges and greater specific energies to negate larger objects.

Summary

Integration is a new function made possible by the success of previous meetings in defining the status of the threat, detection, interdiction, and supporting experiments. Further progress at this meeting made it possible to achieve the insights discussed above. The Threat Panel found there was a significant threat from both intermediate and large objects. The Detection Panel indicated means for detecting each of them. The Interdiction Panel outlined options for addressing each as a function of warning time. The Experiments Panel outlined the laboratory and space experiments needed to validate those predictions. The products of those four panels provide an adequate set of tools for negating each class of threat objects, which vary depending whether the object is detected with Long, Short, or Very Short Warning. For Long Warning there are many options for search and negation based on current technology. As warning is reduced, so are the options. However, they remain adequate to span significant and important parts of the threat with non-threatening technologies, which have the capacity for growth to address much larger objects.

These predictions will have to be confirmed through further studies, but if they remain positive, it should be possible to define affordable laboratory and space experiments to demonstrate the effectiveness and affordability of these defenses. These experiments could be performed within one to two decades and could result in a residual capacity for the interception of an important class of intermediate size objects and in the development of interceptor and control capabilities that could support negation technologies of any required energy.

The programs for defensive alternatives depend most strongly on the sizes of threat objects and the warning time they permit. Long Warning programs for objects observed many orbits prior to impact have been studied extensively, but do not lead to actual defenses and address only a portion of the threat. Short Warning programs remedy those deficiencies, but require significant technology development, cost, and delay. Very Short Warning programs could produce early defenses against the most likely threats, which they could address with non threatening technologies with growth potential to objects of all sizes. Executing the Very Short Warning program would move towards the improved ground- and space-based sensors needed for other warning regimes, the limited interaction experiments needed for non-threatening technologies, and adequate demonstration of intercept technology integration. Executing the Long and Very Short Warning programs together would cost about $100M/yr, but would address both the large objects that can be detected by extended search and the intermediate objects that can be negated on final approach with defenses that could build on these technology developments and experiments to produce defenses against larger objects.

It is clear that the threat from both intermediate and large space objects exists. It appears that adequate technology to search for and intercept them exists or can be built on current technology. It also appears that straightforward experiments could be performed to test these technologies and find out the performance and effectiveness of these defenses relative to the expected losses from the impact of these objects. On the basis of preliminary studies, it appears that a combination of search and defenses is more effective than detection alone. A modest combination of studies, laboratory and space experiments, and intercept technology developments, which could be performed openly with scientific and international cooperation, could refine those estimates and objectively assess the ultimate effectiveness and affordability of the full range of defenses needed. There are excellent opportunities for international collaboration in this assessment, and in the testing and deployment of these capabilities, if the formulation and initiation of a responsive program is addressed soon.

Threat/Detection Summary Report

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An estimated 1500 near-Earth objects (NEOs) larger than one km in diameter revolve around the sun on short-period orbits that can occasionally intersect the orbit of the Earth. Only about 7% of this estimated population has been discovered. The number of these objects that currently come close to Earth, on the other hand, is much less than 1000, and observing circumstances are biased in favor of discovery of close-approaching objects. There is about one chance in a thousand that one of the undiscovered ≥ 1 km objects is destined to collide with Earth in the next century. Such a collision has the potential of injecting sufficient dark material into the atmosphere to cause a major loss of global crop production and consequent loss of human life.

Present evidence indicates that the cumulative number of NEOs is approximately inversely proportional to their diameter, in the diameter range between 100 m and 1 km. Hence the probability of collision of a ≥ 100 m body in the next century is of order 10%. Collision of these objects is capable of producing local to regional catastrophic damage.

The discovery of asteroids and comets and the determination of their orbits has been, by long-standing tradition, an international effort. By agreements through the International Astronomical Union, the maintenance and publication of ephemerides of all numbered minor planets has been the responsibility of the Institute for Theoretical Astronomy (ITA) at St. Petersburg, Russia. The ITA has supported a long-range program of astrometry to upgrade the orbits of known asteroids. The center for receiving observations of newly discovered as well as established asteroids and comets has been the Minor Planet Center, now located at the Smithsonian Astrophysical Observatory at Cambridge Massachusetts. This center collates the incoming observations, assigns designations, calculates preliminary and improved orbits, determines when a minor planet becomes numberable, and publishes the results on a monthly basis in the Minor Planet Circulars (MPCs). The work of observers and orbit calculators throughout the world are published in the MPCs. Most of the immediate dissemination of information on NEOs is nowadays via the Minor Planet Center's MPECs (Minor Planet Electronic Circulars), although initial cometary information is communicated via the IAU Central Bureau for Astronomical Telegrams (IAU Circulars), also located at the Smithsonian Astrophysical Observatory. This system has served to coordinate the existing international effort of discovery of asteroids and comets extremely well, including all work to date on NEOs.

There is a continuing high level of international interest in dedicated NEO surveys. One of the strongest on-going efforts is the Anglo-Australian Near-Earth Asteroid Survey (AANEAS). Located at Siding Spring, New South Wales, AANEAS utilizes several telescopes (Steel, 1995). AANEAS not only reports numerous discoveries of NEOs but also provides crucial followup astrometry and recovery of NEOs found elsewhere, particularly when observations are needed in the southern sky. Another important program of followup astrometry is being carried out in Canada.

A new observing system, utilizing an array of CCDs at the focal surface of a 1-m Schmidt telescope is being developed at Côte d'Azure, France. This system, which will be dedicated primarily to NEO search, will substantially improve the coverage of the sky needed in NEO surveys.

In Japan, where amateur observers have made significant contributions to discovery and astrometric observations of NEOs, Syuzo Isobe (1994) of the National Astronomical Observatory of Japan has proposed that a network of telescopes belonging to cities and amateurs be equipped with CCD detectors to provide critical astrometric observations of discovered NEOs and to assist in the NEO search. A suitable CCD system is being tested; as many as 47 telescopes with apertures larger than 50 cm potentially could participate in this network.

A working group of the International Astronomical Union, chaired by Andrea Carusi of Italy, has been established to help formulate an international program of surveying for NEOs. Investigators and observatories in Europe are potential participants, and a plan is being developed for use of a 1-m Schmidt telescope at the European Southern Observatory in Chile in NEO search. In China, funds have been allocated for a 1-m telescope dedicated to an NEO survey.

In the United States, surveys for NEOs are in progress or being developed by four different observing teams. One team, at the University of Arizona, uses a CCD detector on a 0.9-m telescope (the Spacewatch Telescope) and has a 1.8-m telescope under construction for dedicated use in surveying for NEOs. A second team, at Lowell Observatory in northern Arizona, will use an array of CCDs on a 0.6-m Schmidt telescope; observations with this system are expected to begin in early 1996. A third team at the Jet Propulsion Laboratory in Pasadena is developing a CCD camera for use on an Air Force 1-m telescope in Hawaii; this camera may be operational in late 1995. A fourth team, at the University of Arizona, plans to use an array of CCDs on a 0.4-m Schmidt located in southern Arizona.

Advances in the last few years in the development of charge-couple devices (CCDs) as detectors have led to substantial improvement in the projected capability to carry out a systematic ground-based survey of NEOs. Large format, high quantum efficiency, fast readout CCDs have been developed whose performance is now close to the theoretical limit. Use of these detectors on sufficiently large telescopes would enable rapid progress to be made in an international NEO survey.

An international program has been defined that responds immediately to the challenge of discovering potentially threatening NEOs (Shoemaker et al., 1995). It would carry out a census of short-period comets and asteroids larger than 1 km in diameter and seriously address smaller NEOs and long-period comets, as well as develop a broad database of physical observations in order to evaluate the impact hazard.

In order to proceed promptly, maximum use needs to be made of existing telescopes. In particular, collaboration of the U.S. Air Force, using its network of satellite-tracking telescopes, would enhance the undertaking. The Air Force's continued development of large array imaging cameras would also be of value to all participants. The collaboration of the international community, including further development of programs underway in France, Australia, Japan, Canada, China, Russia and for the European Southern Observatory is also encouraged.

The recommended program, based chiefly on further development of existing efforts within the U.S. civilian astronomical community, will accomplish the objective of discovering 60-70% of short-period NEOs larger than 1 km diameter within one decade (by the end of 2006, for funding beginning in FY'96). It will also put into place the assets that will extend completeness above 90% in the following five years, and extend it both further and to smaller objects in subsequent years. Anticipated cooperation from the Air Force and international observing teams could shift the attainment of 90% completeness forward to 2006, and significantly augment capabilities for orbit determination and physical measurements.

The program recommended for the U.S. civilian effort requires investment in search telescopes, detectors, and software to fully utilize current technology. Two dedicated telescopes of about 2-meter aperture are the core of the search system. One of these is already under construction. State-of-the-art CCD focal-plane arrays are required in both telescopes. Acquisition of computers and skilled personnel is required to bring the CCD systems into full operation within three years. One or two existing telescopes near 1-meter aperture, with appropriate advanced focal planes, can round out the survey facilities (capable of both survey work and astrometric follow-up for orbit determiniation). In addition, availability of roughly half time on a 3- to 4-meter class telescope is needed for physical observations of a representative sample of threatening objects. Enhancement of the capability of the Minor Planet Center will be necessary to coordinate the program and handle the enormously increased discovery rates.

The total cost for the first 5 years of the recommended program is $24 million for the U.S. component of the civilian effort. Beyond the first 5 years, the annual costs drop down to operations costs of about $3.5 million per year. Participation of the U.S. Air Force in the survey probably will require a comparable level of funding.

The recommended ground-based NEO survey will discover enormous numbers of Earth-approaching objects down to a few m in diameter. Indeed the vast majority of NEOs found will be less than 100 m in diameter. However, the projected level of completeness of the survey in ten years of operation drops off rapidly at diameters below one km, to about 70% at 0.5 km, about 35% at 250 m, and about 10% at 100 m. Higher levels of completeness could be achieved by investment in an international network of large telescopes and by continuation of the survey beyond the first decade. Even with half a dozen large telescopes, however, about 50 years would be required to achieve 90% completeness to 100 m diameter. Ninety % discovery of 50-m bodies, which can also cause severe local damage, would require a still longer duration survey.

The alternative to ground-based surveys for small NEOs is to monitor near-Earth space for incoming small bodies from space-based sensors (Colella et al., 1991). Such systems would provide only short warning times, typically less than a few weeks, and would need to be maintained indefinitely or until a systematic survey has been completed.

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Interdiction Summary Report

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The problems of interdiction were discussed during the special plenary, panel and discussion sessions. The interdiction subsystem (ISS) is a part of the Planetary Defense System (PDS) against threats from space objects. The problems discussed during the interdiction sessions of the PDW include tasks and demands of the ISS, its demands on other subsystems of the PDS, an outline of the ISS, such as requirements of the choice of interception trajectories and various means of action. The set of interdiction options depends on warning time, size of the object, and object properties: constituent matter properties (rock, stony-iron, iron, comet ices), internal composition, configuration and shape (integrity, multi-body constitution, stone and ice mixture for comet nuclei).

Interdiction objective

The objective of interdiction is to prevent or effectively weaken an imminent impact on the Earth of the NEO which has an intercept course. This can be achieved by deflection, fracturing or pulverization, or evaporation. The choice of one of these possible regimes of impact prevention or mitigation will be defined by optimization of economical and technical opportunities, efficiency and reliability of the application, and the best correspondence to various environmental demands for the Earth and in Space.

ISS structure

The interdiction subsystem will consist of a Means of Action (MoA) to act upon the threatening object and a Means of Delivery (MoD) of the MoA. MoD's include rocket launching systems, space transportation (including space navigational and ground-based control systems), autonomous preparation or manufacturing(?) of the MoA, precise targeting, guidance, and detonation of the MoA. It is possible to create an operational ISS as a part of the global PDS on the basis of existing technologies. Existing technical means, facilities and equipment should be incorporated into the ISS. Additionally, it will demand scientific and technological developments. To validate the ISS and estimate the efficiency of various options, it will be necessary provide a relevant experimentation program, including space experiments with near missing objects. The ISS implementation and subsequent development will demand a specific R&D strategy.

Key parameters for the ISS outline

The lead on the warning times defines the different approaches for research and development, choice of technologies for experimentation, and procedures for implementation of the ISS in the global PDS. Size of the object, duration of warning time, and current technology defines the choice of MoA. Possible choices include kinetic energy, nuclear explosions, nuclear jet propulsion, mass drivers, solar collectors, lasers and others which were discussed at the Workshop. Of significance is the Workshop conclusion that for the sufficiently large warning times, kinetic energy interceptions can be applied for the interdiction of small (less than 100 m) and even intermediate size objects.

The Interdiction Panel proposed the following time scale for the development and application of various interdiction technologies

MoA Technologies

Today	Near Future	Future	Far future
Kinetic projectiles Nuclear explosions	Nuclear jet propulsion	Mass drivers Solar collectors	Laser drivers & other

(((((
1995 2000 2005 2020

Existing technologies are the principal technologies for the near-term needs of PDS. However, a special R&D program must be performed to adjust these technologies to the ISS environment. It includes additional studies of efficiency for specific types of MoA (kinetic or nuclear), technologies for delivery specific MoA and fielding it in space before the hitting the target, and careful study of the results of the MoA. The program needs to include experimentation in the space and the development of basic research and technologies for prospective MoA.

A parallel R&D program needs to be conducted for the MoD. It will include improvement of existed chemical propulsion methods, and development and implementation of chemical cryogenic and electro-nuclear propulsion systems.

The material properties of threating objects, their composition, integrity, shape, and others properties define specific choice of MoA and regimes application. The NEO's trajectory, its velocity of approach, and technical capabilities of the MoD will define the technology for application of MoA.

Reliability demands, space environmental demands, decreasing of negative consequences of MoA application for the Earth and space environment will determine the final choice of MoA.

Interaction with other subsystems

Various kinds of activities must be performed to provided reliable interdiction:
ground-based observation for large (greater than 1 km) asteroids and comets, space- and ground-based observations for intermediate size (100 m - 1 km), a deeper understanding NEO impact, integration of subsystems in the consequences of PDS, adjustment of existing technologies to the PDS needs, experimental research in the laboratories in space.

The ISS needs

For the subsequent development of the ISS, it is necessary to provide validated standard models for various threats to the Earth from NEOs that account for their properties, warning times, trajectories, velocities of approach, and standard MoDs and MoAs.

The ISS R&D results

The results of R&D on interdiction will describe action phenomena for specified MoAs and different regimes of their application, accounting for energy transfer, impulse, fragmentation, spallation etc. Th e results for MoDs shall account for external parameters MoAs, requirements for the delivery, targeting, fielding in space, etc. The R&D shall also produce validated scenarios of the results of application of interdiction, including impact on the space and Earth environments; standard scenarios of interdiction missions for standard threat models, delivery, and recommendations for various threat scenarios.

Conclusion

The interdiction subsystem consists of two co-equal parts: a means of action and means of delivery. There exists today the technology and basic equipment to meet the most probable demands of the Planetary Defense System. However, a modest R&D program needs to be performed to adjust existing technologies and techniques to specific scenarios. It is important to provide experimental validation of various aspects of the ISS including interdiction mission construction and performance of different components of MoD and MoA. All the activity on the Planetary Defense issues should be planned and carried out in an international forum.

Experiments Summary Report
John Mansfield, NASA Headquarters
Stuart Nozette, Phillips Laboratory, USAF

Defense against impacts by comets and asteroids is unlikely to be successfully implemented without comprehensive experimental projects to greatly expand and enhance our present state of knowledge. The census of objects that potentially threaten the Earth is currently very incomplete in terms of population energetics, distribution in phase space, and knowledge of inherent physical characteristics. In addition to a robust survey effort to discover and determine the orbital characteristics of a (hopefully!) nearly complete sample of the largest threatening objects, many other types of observations and experiments must be carried out if a true defensive capability is to evolve.

Some of the needed experiments could take the form of comprehensive *remote* probing, for example, by using sophisticated radar imaging to establish the shape and probably composition of many objects as they pass near the Earth. Other useful physical experiments on strength of materials and response characteristics to energy inputs of various forms can be performed on Earth by utilizing recovered meteorites, surrogate metallic or stony objects composed of earth materials, and/or detailed computer models. Ultimately, however, there must be space experiments that sample, probe, and perturb objects *in situ* to fully establish the responses of real objects of all major classifications. This will lead eventually to demonstrations of the ability to actually alter orbits or completely disrupt sample objects. The latter class of mature experiments will necessarily be performed in ways that will pose no possible threat to the Earth.

Not only will such experiments yield the knowledge base required for true impact mitigation, they will also provide a wealth of new data on the origin and history of the solar system. Each class* of objects will retain different thermal, isotopic, molecular, and geometrical epochal records of origin and evolution that will yield orders of magnitude more accurate scientific detail than previously available. In this regard, it is important to remember that the Apollo and Lunakhod lunar samples are the only virgin extraterrestrial materials yet in captivity; but the Moon was clearly subjected to profound and unique transformations early in its evolution that make its historical record also uniquely biased. In a sense, meteorites collected on the Earth - be they from parent asteroids, comets, Mars, or the Moon - provide a more encyclopedic record of the history of the solar system than the lunar samples, although there remain many uncertainties concerning the times and places of origin of most meteorites and the environmental modifications that they have experienced before, during and after their arrival on the Earth. So there are exciting troves of scientific wealth awaiting discovery in the future when detailed and comprehensive *in situ* sampling of Near Earth Objects becomes feasible.

For these reasons, the organizers of the Lawrence Livermore National Laboratory workshop on Planetary Defense deemed it important to have a panel study devoted to the topic of NEO Experiments. The panel members who participated are shown in Table 1. To guide their deliberations, they formulated the statement of goals and consensus reproduced in Table 2. It can be seen that these goals closely reflect the motives described above.

The Experiments Panel generated an outline of a set of steps leading from theory and laboratory experiments to space flyby and probe experiments. These efforts would

* Classification Definition: (0) comet-like, (1) carbonaceous chondrite-like, (2) stony, (3) iron-nickel, (4) breccia or rubbish pile

Table 1: Panel Members (Experiments)

J. Mansfield, NASA Headquarters (Co-Chair)

S. Nozette, Phillips Laboratory, USAF (Co-Chair)

J. Remo, Quantametrics Inc.

D. Chriswell, University of Houston

J. Degnan, Phillips Laboratory, USAF

P. Hammerling, Quantametrics Inc.

W. Huebner, NASA Headquarters

A. Ledebuhr, Lawrence Livermore National Laboratory

J. Lewis, Lunar and Planetary Laboratory, University of Arizona

E. Tagliaferri, ET Space Systems

W. Tedeschi, Sandia National Laboratory

W. Wattenberg, CSU

Table 2: Experiments Panel Goals and Consensus

I. Gain knowledge of the physical properties and response characteristics of NEOs. Such knowledge can be utilized for :

- Understanding the origin and evolution of the solar system.
- Identification and tracking of NEO families.
- Providing data to predict behavior of NEOs in response to deflection techniques.
- Systematically establishing data on NEO material properties.
- Providing a basis for physical understanding of mitigation options.
- Facilitating effective resource uses.

II. Articulate issues

III. Develop an experiments strategy

IV. Reach a consensus of the experts

establish the basis for a mitigation options matrix. A set of carefully diagnosed interaction experiments in space was proposed, employing technologies potentially useful for subsequent applications in a prototype interception capability. These experiments would culminate in full-scale kinetic impacts on selected NEOs, including precise measurements of orbital alterations. The diagnostic data gleaned from both ground-based and space based measurements would then provide full understanding of the energy transfer mechanisms. This would, in turn, provide a basis for simulating the expected behavior of intercept interactions with higher energy NEOs.

Principal topics of the panel work were defined by three major experimental categories, namely (1) laboratory (i.e. ground-based) experiments and associated computational modeling, (2) satellite observations of the Earth using existing or improved new surveillance satellites to detect and diagnose atmospheric impacting objects and guide sampling missions to debris clouds and meteorite finds, and (3) spacecraft probes to NEOs to yield (a) fly-by imaging, (b) hard impact diagnostics, (c) detailed rendezvous remote sensing to determine composition and mass distribution, and (d) *in situ* surface experiments.

Panelists also considered the types of instrumentation required to maximize data collection for specific missions. Examples include all types of spectrometers (i.e. optical, particle, gamma ray, x-ray, and mass), radiometers, magnetometers, gravitometers, seismometers, and impactors.

The sessions on laboratory experiments focused generally upon how to improve upon current understanding of the fundamental material properties and response characteristics of asteroids and comets. Such experiments include (a) constitutive models, (b) equation of state models, (c) radiation opacities and particle transport properties, (d) electromagnetic properties, (e) large scale mechanical and thermal properties, (f) mechanical and thermodynamic response to various energy fluences, and (g) global momentum deposition and body fragmentation characteristics. Some of these experiments would utilize actual meteorites, while others would use surrogates made from appropriate earth-derived materials. Other "experiments" will be strictly theoretical, analytical, or computational.

Computer simulations will be utilized in many ways, especially in extending understanding of effects and phenomenologies beyond what may be feasible in actual physical experiments at any given stage of development of mitigation capabilities. Complex hydrodynamic codes and radiative hydro codes are of fundamental importance in modeling impacts and disruptions. Radiation opacity codes are useful, for example, in determining blow-off effects of a hypothetical proximal nuclear explosion. Equation of state calculations, together with constitutive models, will enable realistic calculations of the response of simulated NEOs to nuclear and non-nuclear disruption attempts. Models of thermal, gaseous, or plasma diffusion pertain to the evolution and effects of the reaction mass in a blow-off-generating perturbation event. Activation and ionization models will yield synthetic spectra of gases and plasmas that may serve useful diagnostic purposes. Taken together, the ensemble of computer generated experiments and models will go far toward establishment of overall criteria for empirical validation of perturbation and disruption mitigation attempts.

The ultimate goal of experimentation building toward true mitigation capabilities is to perform *in-situ* space missions. Such missions will intimately explore the nature of NEOs and their response to perturbations. The New Millennium and Discovery class small spacecraft missions now being planned will lead to sophisticated diagnostic instrumentation and eventually to the return of material samples to the Earth. Transponders and other *in-situ* diagnostic tools deposited on or beneath the surface of NEOs will permit computed tomography of the internal mass distribution and structure of selected objects. A large suite of diagnostic instruments will observe and measure the effects of impactors.

The panel noted that some significant work applicable to ultimate *in situ* experimental missions is already in progress or in planning stages. The Near Earth Asteroid Rendezvous (NEAR) spacecraft is now nearing completion and will be launched in less than two years. The NEREUS near Earth asteroid sample return mission is aiming for a launch in 2003. The European Space Agency's Rosetta mission intends to fly-by two asteroids and place an orbiter around a comet nucleus with two landers on the comet surface in the 2003 - 2012 time frame. The on-going Clementine II USAF effort and NASA's micro-sat programs will also contribute importantly to the required technology development.

In summarizing its recommendations, the Experiments Panel urged that all experiments be carried out in an interactive manner to coordinate progress among all key players. A committee of experts is proposed to assess, validate, and prioritize the experimental and simulation programs. It is felt that much of this work can be maintained with minimal incremental resources, provided that the existing laboratory facilities which are relevant to the programs are maintained.

Threat

Plenary Session

The NEO Flux, Present and Past

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Interplanetary bodies which strike the Earth can be broadly classified into three main groups: 1) Earth-crossing asteroids, 2) long-period comets, and 3) periodic comets. Earth-crossing asteroids (ECAs), of which about 250 have been discovered, are now becoming fairly well explored. There are an estimated ~1500+/-500 ECAs larger than 1km in diameter. The population of ECAs smaller than 100m diameter is still a matter of debate.

About 700 long-period comets (LPCs) have been discovered, the majority of which were Earth-crossing. The population of LPCs and their collision rate with Earth, as a function of absolute magnitude, is fairly well understood. However, the relationship between absolute magnitude and the size of the nucleus is uncertain.

Periodic comets (PCs) (periods < 200 years) are the "stealth bombers" of the solar system. An estimated 95% of the periodic comets are "extinct" or asteroidal in appearance, and they are especially difficult to discover. A total of 26 active Earth-crossing periodic comets have been found; the active PCs represent only about 2% of the impact hazard. On the other hand, the population of extinct Earth-crossing PCs larger than 1km diameter is estimated to be of order 1500, about the same as that of the ECAs. To date only 25 extinct PCs have been discovered, however, and, of these, only a few are Earth-crossing. The large difference in discovery rate between extinct PCs and ECAs is due to the much longer periods of revolution of PCs and to the larger dispersion of their inclinations.

The contribution of the diverse NEOs to production of craters larger than 10km is estimated as follows:

Earth-crossing asteroids (av. P = 2 years)	60%
Periodic comets (P = 4 to 200 years) (95% extinct)	20%
Long period comets (P > 200 years)	20%

Large uncertainties attend the estimates for crater production by comet impact. On average, a 1km or larger NEO strikes the Earth about once per 100,000 years. The estimated rate of cratering is consistent with the geologic record of impact structures. Judging from the size distribution of small craters on the Moon, the cumulative number of impactors is approximately proportional to the inverse square of projectile diameter in the range from 100m to 1km. Below 100m, the frequency rises more steeply.

Historical Evidence of Recent Impacts on the Earth

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ET Space Systems, California

Global Planetary or Regional Defense Systems using any method to disrupt or (and) deflect small asteroids and comets needs information on their characteristics to predict the result. If the cosmic body is disrupted into small fragments, a new question arises: will these chunks reach the Earth's surface or explode at some altitude above the ground? Observations of current impacts of large meteoroids into the atmosphere both by ground based and satellite based networks give information on characteristics of impacting bodies (e.g. mass, energy, strength, structure, shape, density, composition) and on atmospheric interaction processes (ablation, luminosity, fragmentation, dispersion of fragments etc.). Such information has already been obtained for rather large meteoroids (up to several meters in size and energies up to 10-40 kt TNT). Space based infrared and optical sensors have detected over 200 meteoroid impacts since 1972. 16 light curves in visible have been obtained by optical sensors, mainly the last year. Special theoretical techniques have been developed for the analysis of these data.

Our definition of recent impacts is not very strict. We shall speak about the events that happened as long ago as 10 to 50 thousand years, or this century (after the Tunguska event of 1908), or last 25 years, when satellite observations have begun, and even last year, when systematic survey of satellite observations has started and a large number of events has been registered.

As the duration of the observations is not very long and large impactors are rather rare, our analysis is restricted to cosmic bodies with sizes from 30-100 m down to about 0. 1-1 m.

Sometimes these bodies are named "large meteoroids" or "small asteroids". Such bodies are studied using Spacewatch system (Scotti et al. , 1991; Rabinowitz et al., 1993; Carusi et al., 1994). These observations give us information on the current population of the near Earth objects, mainly on the objects with sizes of about 100 m and larger, though very small asteroids have been detected at small distances from the Earth. But using only telescopes we cannot obtain such important characteristics of these objects as their strength and composition.

Investigation of small lunar craters on the airless Earth's Moon (Neukum and Ivanov, 1994), with the diameters 10 m and larger, allows us to determine the size-frequency distribution of small objects, but only averaged over a very large period of time.

There are other clear signatures of such impacts, i.e., small craters on the Earth and atmospheric effects during the meteoroid's entry. Let us explain why we are interested in the observations of rather small objects, while the main goal of the Workshop is hazards and mitigation of hazards.

First, impacts of bodies with sizes close to the upper limit of the investigated range (30-100 m) may cause local and even regional catastrophes (Adushkin and Nemtchinov, 1994). Our analysis may give important information on structure, composition, strength of the bodies with the sizes only one or two orders of magnitude less than those which may cause catastrophes. Extrapolating the size-frequency distribution, we can obtain probabilities of such dangerous impacts. This information is important for prediction local and regional catastrophes and for investigation ways of mitigation.

Second, trying to defend the Earth from the impacts of these or even larger objects, i.e. 1 km in size or bigger, we may disrupt them into a cloud of fragments with smaller sizes. At least some of the fragments may hit the Earth, and we should know what will be the consequences.

Third, large meteoroids or small asteroids are probably least investigated bodies in the Solar System and their investigation is important from purely scientific reasons. There are other reasons, but these three are enough to justify our analysis.

In Table 1 (data are mainly from Grieve and Shoemaker, 1994) are given sizes of the craters, energy of the impactors hitting the Earth, and the approximate age. The largest (1 km in diameter) is the famous Meteor crater in Arizona. Recently (in 1992) another one has been discovered (1×3 km). It has been created about 10,000 years ago near Rio Cuarto, Argentina, and the impactor energy estimates are 350 Mt TNT (Schultz and Lianza, 1992).

Table 1.

	Time of formation, years	N	d, (m)	E, (kt TNT)
Meteor Crater, Arizona	~ 25000	1	1200	15000
Wolf-Creek, Australia	< 300,000	1	853	5000
Winkler, Kansas, USA		1	750	800
El Mreiti, Mauritania		1	700	650
Monturaqui, Chile	~ 1,000,000	1	455	110
Aouelloul, Mauritania	3, 100,000	1	390	20
Macha, Russia	<7, 000	1	300	15
Herault, France		7	217	10
Labrador, Canada		1	210	10
Gourmac, Mali		1	200	10
Boxhole, Australia	30,000	1	175	5
Henbury, Australia	4, 200±1, 900	14	220*110	4-5
Odessa, Texas, USA	~ 25,000	5	168	4
Kaalijärv, Estonia	~ 5,000	9	110	1.5
Wabar, Saudi Arabia	6, 400±2, 500	4	91	0.8
Campo Del Cielo, Argentina	< 4, 000	20	90	0.8
Ilumetsa, Estonia	> 2, 000	1	80	0.6
Veevers, Australia	< 1,000,000	1	80	0.6
Morasko, Poland	10,000	8	60	0.3
Sobolev, Russia	< 1,000	1	53	0.18
Sikhote-Alin, Russia	12 Feb. 1947	23	26	0.014
Dalgaranga, Australia	27,000	1	21	0.012
Haviland, Kansas	< 1, 000	1	15	0.010
Sterlitamak, Russia	17 May 1990	1	9	0.001

The smallest one is the Sterlitamak crater. The Sterlitamak event happened only 5 years ago, confirming that the Earth is still being bombarded and cratered. A very significant Sikhote-Alin event happened on 12 February 1947, almost 50 years ago. We have estimated that the preatmospheric energy of the iron body was 10 kt TNT, mass was 500 tons. About 99% of the energy have been released in the atmosphere, but 20% of mass have reached the ground, about 100 tons is in the strewn field. 27 tons have been really found as meteorites. Biggest fragments created rather large craters (up to 26 m in diameter). Large trees have been fallen around these craters. Geologists who have observed the strewn crater field (many of them have just returned from the World war II) said that the region of large craters resembled typical battlefield after the heavy military bombardment. The size of this heavily damaged region is 300×300 m (Krinov, 1981).

Counting craters discovered on the Earth we may severely underestimate the number of impacts and hazards which may be caused by these impacts. First, a large part of the surface of the Earth is covered by water of seas and oceans. In that case the impacting body creates unstable crater in the water which soon collapses and disappears. But impacts into oceans and seas may be very dangerous as they cause tsunami (Hills and Goda, 1993; Hills et al., 1994; Nemtchinov et al., 1994). Second, analyzing Table 1, one can see that craters are rather young and a large number of them is found in deserts or semideserts. This is due to the fact that scars on the Earth's surface are healed rather quickly, especially in the regions with wet climate. For instance, Sikhote-Alin crater field was created in the region with rough terrain, but it had been easily found from the airplane three days after the impact. Now even the largest craters are screened by trees in the taiga.

Third, we have already mentioned that energy which was released by fragments of the Sikhote-Alin iron meteoroid on the Earth's surface is only about 1% of the preatmospheric kinetic energy. In the case of the iron Arizona meteoroid it is almost 100%, but Tunguska meteoroid (there is still a controversy was it a comet or a stony body) with approximately the same initial energy has not created any crater at all. The Tunguska airblast might have caused demolishion of a big city, but happily it occurred in an almost inhabitant region.

Do cosmic bodies continue to fall? Yes, they do. A daylight bolide, 1972, grazing incidence, flew over the US and Canada and finally left the Earth with almost the same velocity of about 15 km/sec (Ceplecha, 1994). A minimum distance from the Earth was about 58 km. Another meteoroid of 1990 also left the Earth with only a slightly diminished velocity (42 km/sec) (Borovička and Ceplecha, 1992). But if the trajectory is steep, a meteoroid release all its energy in the atmosphere or even hit the ground.

As an example, a powerful bolide has detonated recently in 1993 over Italy (Korlevic, 1994; Cevolani, 1994).

A small fragment of Peekskill meteoroid hit a car (Brown et al., 1994). But these fragments may be much larger in mass. Several meteorites recently have been found near Montreal with the total mass of about 25 kg (Brown et al., 1995). They were the remnants of a meteoroid which has been detected in flight by a large number of eyewitnesses in USA and Canada and by a satellite.

Space based infrared and optical sensors operated by the United States Department of Defense have detected over 200 bright flashes in the atmosphere since 1972. These intense light impulses were caused by impacts of large meteoroids. The bright flash arises from energy released upon explosive disintegration due to action of aerodynamic forces. Usually meteoroids deposite their energy at high altitudes above the Earth's surface, mainly at altitudes of 30 to 45 km. But some of them penetrate the atmosphere to altitudes of about 20 km.

A relatively small number of satellites at high altitude orbits (20,000 km or higher) provide coverage of most of the Earth's surface. It is possible to have essentially continuous, day and night, all weather detection of meteoroids over the entire surface of the Earth (Tagliaferri et al., 1994).

Meteoroid fireballs detected by infrared radiation sensors, as it would be expected, are rather randomly distributed worldwide. Average number per year is about 30.

In addition, visible radiation sensors have recorded light curves for a subset of these events (Jacobs and Spalding, 1993; Tagliaferri et al., 1994).

Several techniques for the assessment of the meteoroid characteristics from the light curves have been developed (Nemtchinov et al., 1994, 1995; Golub' et al., 1995).

Radiation-hydrodynamic 1D, 2D and even 3D numerical simulations of the flight in the atmosphere of meteoroids with different sizes, velocities, heights of flight have been conducted. They were based on detailed tables of spectral opacities for hot air and ablated material of meteoroids (iron, H-chondrites, cometary material) which have been calculated by us for a wide range of temperatures, densities and wavelengths. As an example, in Fig. 1 spectral absorption coefficients for H-hondrite are given.

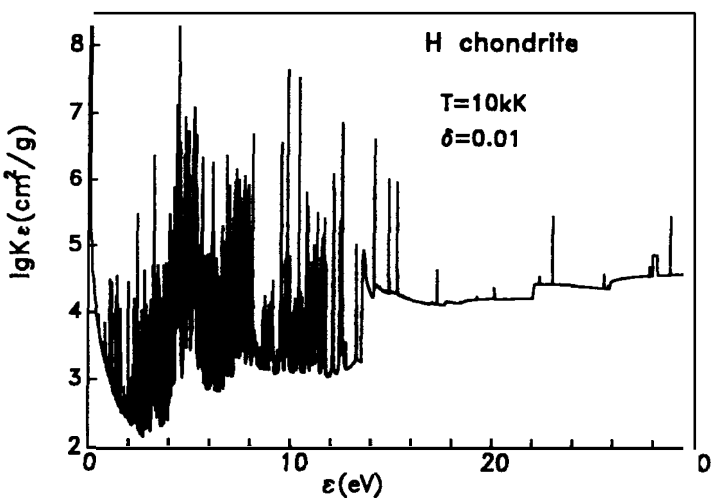

Figure 1. Absorption coefficient K_ε versus photon energy ε.

Equations of radiative transfer have been solved for as much as 10,000 wavelengths (or photon energies) both in air and in the vapor of meteoroid. An amount of meteoroid's energy released in the atmosphere, radiation emitted, and spectrum of radiation have been obtained. This is important because the visible sensors are spectrally selective while a spectrum substantially differs from that of a blackbody, and changes with size, velocity and altitude of flight.

The results of a large number of numerical simulations are the tables of ablation coefficients and luminous efficiencies for different velocities, sizes, altitudes of flight, and composition. They are given for an iron body in Golub' et al. (1995).

Velocity versus time and altitude can be determined from the usual equations of meteoroid's motion, deceleration and ablation. Companion burst-locating sensors can detect an altitude of peak intensity of large events. For some fraction of small events infrared sensors can provide the location of cloud of debris (Tagliaferri et al., 1994).

Intensity of light is proportional to the cross-sectional area and luminous efficiency. Comparing the observed intensity of light with theoretical values for different sizes of the body, we can estimate the effective instantaneous size of the body and can follow an increase of the size of the cloud of fragments after the meteoroid's breakup and rotation of the body which causes the variations of cross-section.

The results of simulations for the 4 October 1991 event are given in Fig. 2. Here the effective radius of the body is the solid curve (1), and a radius calculated by two different models (Hills and Goba, 1993; Chyba et al., 1993) is the dashed and dotted curves (2,3). At high altitudes the radius does not change in time. At an altitude of 40 km the radius begins to grow, and the stagnation pressure at the blunt nose of the meteoroid at the moment of the breakup gives an apparent strength of the body. In this case the meteoroid was a chondritic or stony body, its strength was 10 to 20 Mdyn/cm^2. In the theoretical models we have used empirical values of the body's strength and height of breakup. At an altitude of 35 km radius increases 3 times and at an altitudes of about 30 km increases several times. After the breakup meteoroid was heavily fragmented due to aerodynamic loads but a single-body model of the cloud of fragments and vapor has still been used.

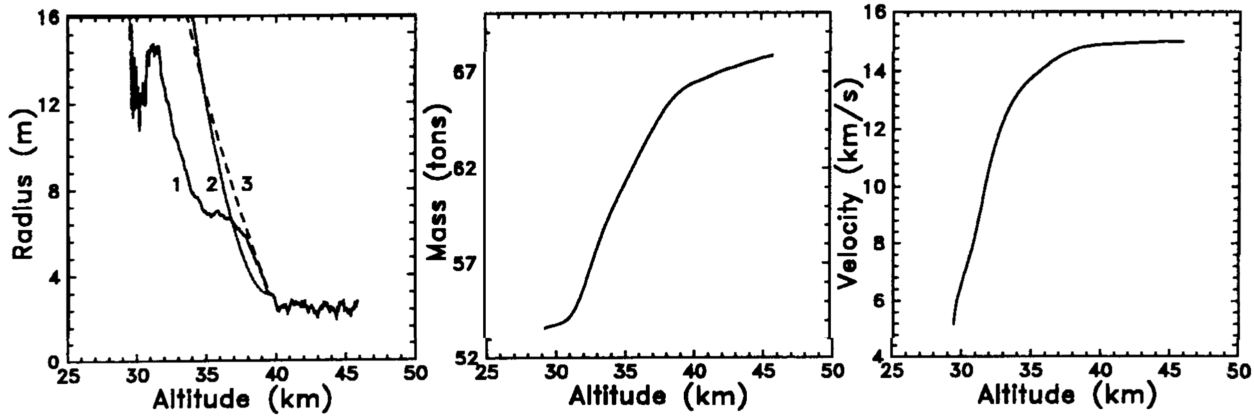

Figure 2. The 4 February 1994 event. Altitude dependence of radius, mass, and velocity resulted from numerical simulations. Initial mass 25 to 75 tons, initial velocity 15 to 20 km/sec, initial energy 1.2 to 2 kt TNT. Breakup at the altitude of 40 km. Substantial (about 6 to 7 times) increase in the radius leads to drastic deceleration of the meteoroid, while mass losses are rather small.

Meteoroid which caused 4 October 1991 event had a radius of about 2 m, initial mass 25 to 75 t, and kinetic energy of 1 to 2 kt, velocity 15 to 20 km/sec.

In Fig.3 the results of numerical simulations of 1 February 1994 even are presented. We have used data on the initial velocity (24 km/sec), and angle of trajectory inclination (45^0) which have been determined by McCord et al. (1995). We have also used a single-body model and obtained initial radius R = 1.7 m, and mass M = 400 tons, and energy E = 30 kt TNT, the obtained initial density is 13 g/cm^3 which is almost twice higher than the density of iron. This is due to rather low precision of determination of this particular parameter and due to usage of a single-body model.

Calculated radius exhibits two distinct maxima, due to the two-stage disintegration. Two patches of debris have been detected, i.e. one at an altitude of 34 km and another at an altitude of 21 km. In 15 sec, the high altitude debris cloud falls to about 33 km due to gravity. The low altitude object stabilizes at an altitude of 19 km.

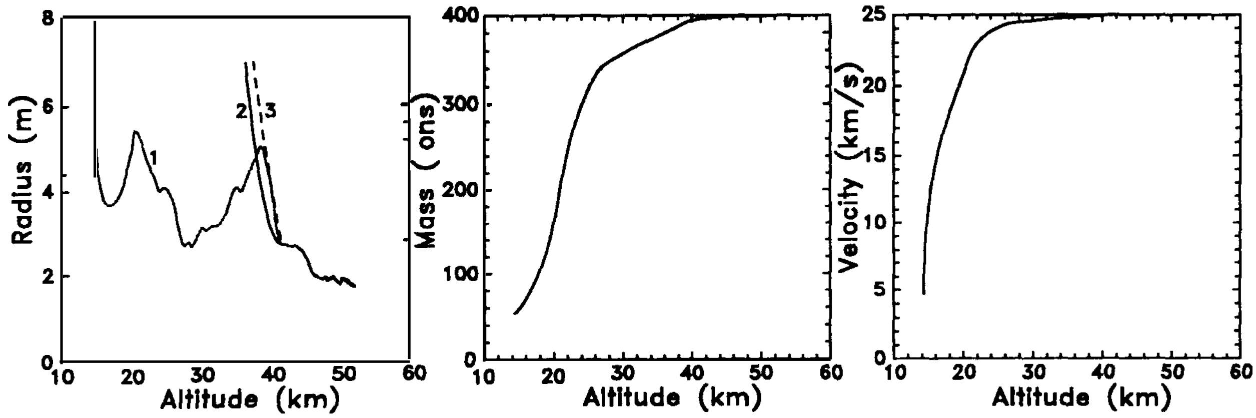

Figure 3. The 1 February 1994 event. Altitude dependence of radius, mass, and velocity. The calculated dependence of radius (1) is compared with analytical models (2, 3) in the left hand side of the figure.
Preset parameters: initial velocity V = 25 km/sec, angle of trajectory inclination θ = 45°, height of peak intensity h_m = 21 km, ablation energy Q = 6.3 kJ/g.
Obtained parameters: initial radius R = 1.7 m, mass M = 400 tons, kinetic energy E = 30 kt TNT, density ρ_b = 13 g/cm^2.

In Fig.4 a light curve for the 1 February 1994 event is given (in the right panel in a logarithmic scale). Assuming two-stage disintegration, we have numerically reproduced the light curve during all the flight. The initial kinetic energy was about 40 kt TNT, mass of about 520 tons, strength of the second fragment of about 100 Mdyn/cm^2, its mass and energy are 430 t and 32 kt TNT correspondingly. The first fragment had very low apparent strength of about 5 Mdyn/cm^2, and probably this iron meteoroid was a binary object. The 1 February 1994 event is an analogue of the Sikhote-Aline iron shower - we have approximately the same mass and initial radius. But initial velocity was twice higher, and this leads to more intense fragmentation process, though we can not exclude that some fragments may have fallen into the Pacific Ocean, causing hydroacoustic signals.

If we do not use data on the initial velocity and trajectory inclination, the range of the energy and mass is wider: 40 to 70 kt TNT and 1,200-2,000 t. Our estimates of the initial velocity are 15 to 20 km/sec.

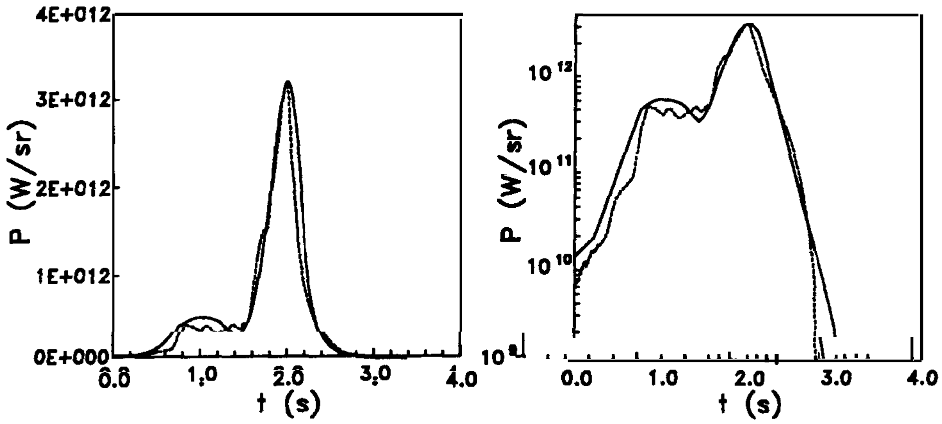

Figure 4. The observed light curve of the 1 February 1994 event (dashed curve) and the light curve obtained in numerical simulations for two fragments with the initial velocity of 25 km/sec (mass and energy of the first fragment M_1 = 84 t, E_1 = 6.2 kt TNT and mass and energy of the main body M_2 = 436 t, E_2 = 32.5 kt TNT). A peak intensity is reached at a height of 21 km. The first breakup occurred at an altitude of 52 km (an apparent strength is 5 Mdyn/cm^2) and a major breakup occurred at an altitude of 31 km (an apparent strength is 100 Mdyn/cm^2).

Increase in the initial velocity (up to 34 km/sec) leads to substantial decrease in mass but not very large decrease in the initial energy. This gives additional foundation to the estimates of kinetic energy for those events for which we do not know initial velocity. On the other hand, it clearly demonstrates that velocity/trajectory tracking substantially increases the precision of the assessment of meteoroid's characteristics.

In both events mentioned above luminous efficiency was in the range 7-1 1%. What is the reason for this big difference between luminous efficiency for nuclear detonation (30%) (Glass tone and Dolan, 1977) and that for the meteoroids explosive disintegration?

The shape of the fireball for the meteoroid impact is quite different from the quasi-spherical shape of the nuclear detonation fireball. It is an elongated quasi-cylindrical luminous plasma column. It is more like a pencil or a slightly diverging cone, not a sphere with the characteristic size much less than for the nuclear detonation of the same yield, as the energy release is gradual.

In some cases a situation when a single body model is not valid may be even much more complicated. In Fig.5 the flow pattern is presented for a case when two fragments of similar size move in the same direction, one after another, and a distance D between them is not very large.

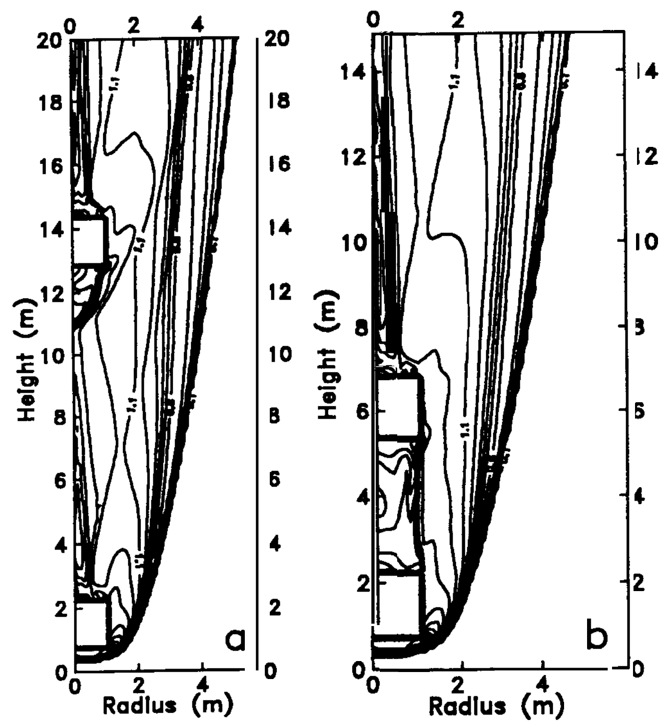

Figure 5. Temperature contours for the flow around two identical fragments moving along the same trajectory one after the other at distance D = 12R (a) and D = 4R (b)

Temperature contours for cylindrical fragments with radius R = 1 m and length L = 1.5 m moving with velocity V = 20 km/sec at a height of flight h = 40 km are shown. Temperature is in eV, distances between fragments are 12R (a) and 4R (b).

Usually aerodynamic interaction between the fragments leads to dispersion of the cloud of fragments with a lateral velocity which is about the velocity along the trajectory multiplied by the square root of the ratio of the air density to the density of the meteoroid (Passey and Melosh, 1980; Melosh, 1989). But in the analyzed case the second fragment moves in the rarefied wake of the first one. It is almost invisible as the radiation is mainly emitted from the shock wave front created by the first fragment. When the second fragment experiencing less drag than the first one leaves the wake and encounters the dense air, a sudden flash occurs which is not associated with fragmentation at this moment of time. For this complicated situations another techniques based on the energy balance considerations have been used.

We have calculated motion, luminosity and mass losses of meteoroids with various initial radii and velocity using a single-body model and assuming that a breakup occurred when the stagnation pressure at the blunt nose reached a definite critical value. As an example, the results of the simulation are given in Tables 2-4 for impact of iron bodies with a strength of 100 $Mdyn/cm^2$ and with an angle of trajectory inclination of 45°.

In Table 2 a fragmentation height is given for various radii and various velocities, in Table 3 heights of maximum intensity are given. For the assumed strength no fragmentation occurs at all for a body with radius 10 cm. A height of maximum intensity for a 10 cm radius is larger than that for radius 30 cm. It is due to substantial deceleration and ablation of such rather small meteoroid. For radii 0.3 m and larger, a height of maximum intensity is usually 2-3 km lower than the height of the breakup, and a peak intensity is associated with the rapid expansion of the cloud of fragmentes. A ratio of the radiated energy absorbed by the Sandia sensor to the initial kinetic energy is given in Table 4.

Table 2. Fragmentation height h_b (km).

Velocity (km/s)	Radius 10 (cm)	Radius 30 (cm)	Radius 100 (cm)	Radius 300 (cm)	Radius 1000 (cm)
12	0	21.0	21.6	21.5	21.5
15	0	24.4	24.3	24.2	24.3
20	0	28.1	27.9	27.9	27.8
25	0	30.9	30.8	30.8	30.8
30	0	33.1	33.1	33.0	33.0

Table 3. Height of maximum intensity h_m (km).

Velocity (km/s)	Radius 10 (cm)	Radius 30 (cm)	Radius 100 (cm)	Radius 300 (cm)	Radius 1000 (cm)
12	33.3	18.4	20.2	18.8	14.5
15	32.5	22.4	22.8	21.1	15.3
20	33.4	26.8	26.3	22.9	14.5
25	36.8	29.8	28.9	23.1	14.5
30	38.8	32.2	31.0	23.5	13.2

Table 4. Ratio of radiated energy to initial kinetic energy (%)

Velocity (km/s)	Radius 10 (cm)	Radius 30 (cm)	Radius 100 (cm)	Radius 300 (cm)	Radius 1000 (cm)
12	0.5	1.4	4.3	8.0	8.7
15	1.4	4.0	7.3	10.8	11.9
20	2.5	7.9	10.8	13.6	15.6
25	2.8	10.0	12.2	14.5	17.1
30	3.0	11.1	12.7	14.6	17.3

A luminous efficiency (taking into account the radiation emitted during the whole flight and taking into account fragmentation and expansion of the cloud of fragments) depends on the initial velocity and radius, but for radii more than 0.3 m and velocities higher than 15 km/sec values of luminous efficiencies are in the range of 4 to 17%, they differ from the average values of 7-11 % no more than 2 times.

An individual analysis of the light curves for several events(15 April 1988, 4 October 1990, 1 October 1991 and 1 February 1994), taking into account real altitudes of breakup (h_b) and of maximum intensity (h_m), has confirmed this conclusion. And for crude estimates here we shall use a constant value of luminous efficiency, i.e. 10%.

We have calculated number of events with kinetic energy in discrete intervals i with the lower limit E_i and upper limit $2E_i$. This energy - frequency distribution is given in Fig.6. Continuation of observations and their analysis for one or several years will increase statistical significance of such distribution, and extrapolation of this distribution will give us probability of impacts with higher energies. A crude estimate gives us prediction that for a 1 Mt impact an average interval between impacts is about 10-15 years. This is in correlation with the analysis by ReVelle (1995) of atmospheric effects caused by large bolides (acoustic gravity waves).

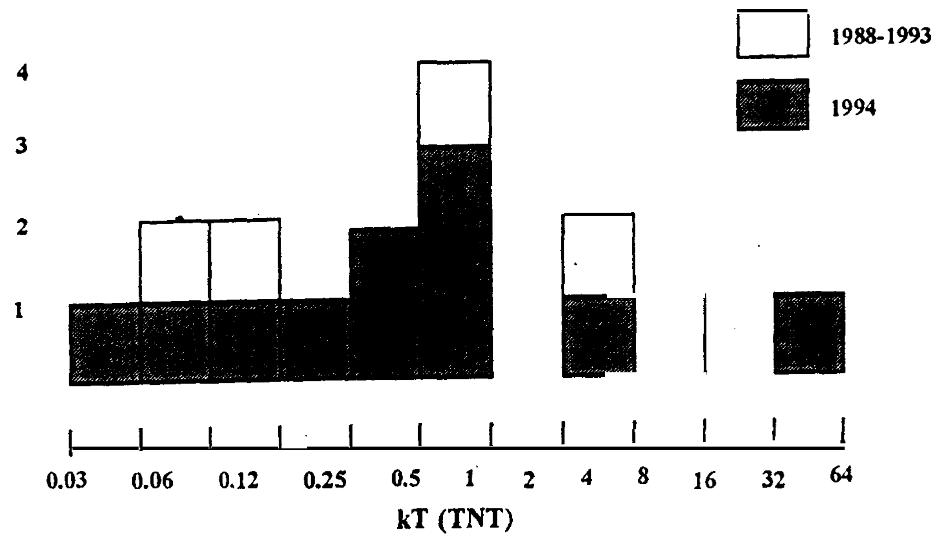

Figure 6. Frequency versus energy of the impactors. Energy derived by the Sandia optical sensors light curves with the assumption of 10% luminous efficiency.

During a period from 1960 to 1972 the US Air Forces have registered 10 events with sufficiently large energies. Taking into account percentage area coverage for each station and each event, ReVelle (1995) has obtained cumulative number N of bodies with a source energy more than E, kt TNT, per year over the entire Earth:

$$N = 7.2\ E^{-0.73}$$

We should underline that during this period of 12 years one event with an energy of about 1 Mt has been registered.

So it seems reasonable to be prepared for observation and analysis of the event with rather large energy. While the fireball caused by the explosive desintegration of a meteoroid exhibits many features of the nuclear detonations with the same yield, there are specific differences. We have already mentioned some of them, let us describe another.

We carried out numerical simulations assuming that an impactor with an energy of 1 Mt broke up at an altitude of 21 km. At an altitude of 5.5 km it has a shape of a cylinder with a radius of 50 m and the same height. This body falls vertically at 15 km/s. We also assume that at the chosen altitude the body has a low density, implying that the body is a mixture of debris and vapor due to action of aerodynamic pressure and ablation. It is adopted that in this stage of flight the body material behaves as compressible gas.

Computations of the fall and gasdynamic motion in the atmosphere were made using a free-Lagrangion method of Hazins and Svetsov (1993). The results of simulation are shown in Fig. 7. The body is pulverized during the fall in the atmosphere, and a maximum radius of a swarm of fragments grows. The body is decelerated and loses its kinetic energy. A maximum of energy deposition is at an altitude of about 4.5 km. But the swarm of debris and the air have significant momentum and persist in moving down till the ground despite their average velocity and kinetic energy become small. The stream of vapor and entrained and compressed air acts like a piston.

After reflection from the ground, the shock wave travels along the Earth surface. At time t = 1.5 sec (measured from the starting moment of the computations) we changed a method of computation for Eulerian one because the particles of the body are entirely pulverized (the process of the fragmentation is over), and we could take finer mesh at the late stage of the fall using Eulerian hydrocode.

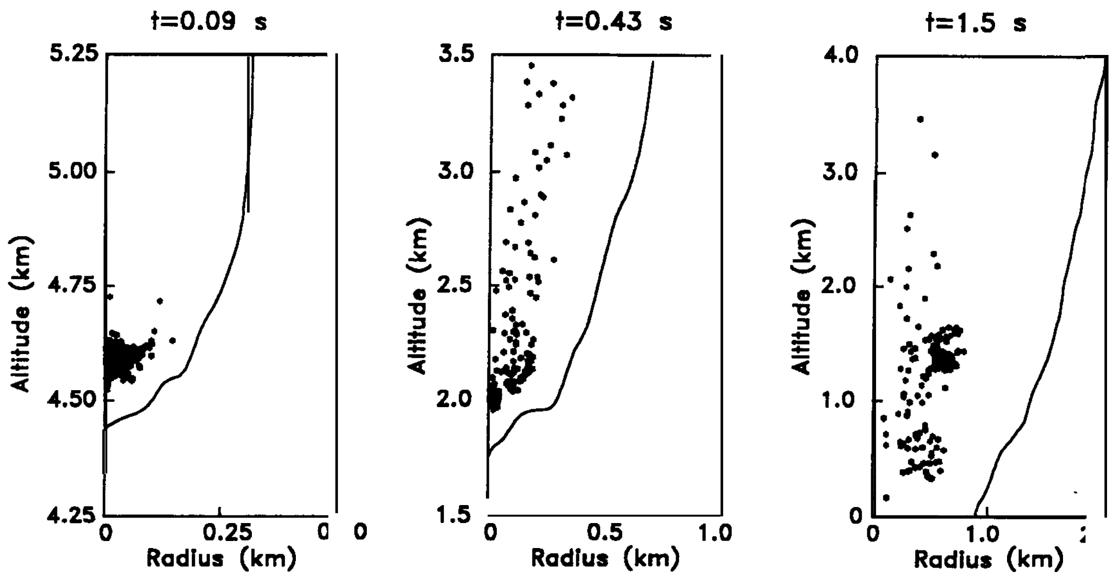

Figure 7. A simulation of a vertical fall of a heavily pulverized impactor. Computations have started at an altitude of 5500 m where a low density body (0.1 g/cm^3) has a radius of 50 m and velocity of 15 km/s. A shock wave is plotted by a solid line. Solid circles are particles of the body material.

A maximum pressure as a function of a distance along the Earth surface is shown in Fig. 8. We have also calculated two idealized variants of instantaneous explosions assuming that the total energy of impactor is released at an altitude of 5 km and at the ground. The results are compared in Fig. 8.

Pressure at the ground for an explosion at an altitude of 5 km is lower than obtained in the simulations of a pulverized impactor all over the surface. An explosion at the ground produces higher pressure at distances smaller than 4 km. But at large distances, to 20 km, the pressure in the surface explosion with equivalent energy is lower. Thus, an airblast caused by the meteoroid creates shock waves with larger amplitudes than the instantaneous explosion with the same energy.

Continuation of satellite based observations and their analysis will give us statistically significant information on the size-frequency distribution of impacts and probability of large (including the Tunguska-class) airblasts. This can also elucidate the scientific problem of meteoroid origin and their relation to the near - Earth asteroid belt discovered by the ground based Spacewatch system (Scotti etal., 1991; Rabinowitz et al., 1993; Carusi et al., 1994).

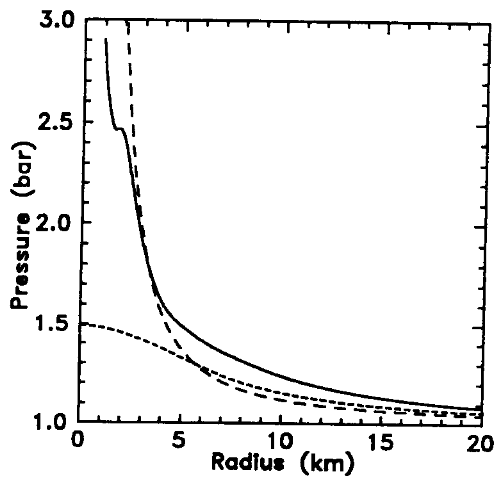

Figure 8. Pressure caused by a shock wave at the Earth surface as a function of a distance from the fall epicenter. Three variants have been computed: a fragmented and pulverized impactor falling vertically at V = 15 km/s (solid line), an equivalent explosion at the ground (dashed line), and an explosion at an altitude of 5 km (dotted line).

The precision of determination of meteoroid characteristics may be increased not only by usage of more sophisticated codes, which are now being developed, but by a larger amount of observational data, e.g. on the angle of trajectory inclination and the velocity of the meteoroid body along the trajectory. Spectral instruments being installed in upgraded satellite systems may also give very important information on chemical composition of the impacting cosmic bodies.

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Impacts and mass extinctions

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The Alvarez Hypotheses of 1980, that the earth was hit by a large asteroid or comet 65 million years ago, and that the environmental effects stemming from that impact event brought about the K/T mass extinction, are now accepted by a majority of earth scientists. The questions is, then, what next for paleontological extinction research? The following topics seem fruitful: 1) Better research on actual killing mechanisms. 2) Calibrating the "kill curve" of Raup (1990; 1991) relating impact (or crater) size and degree of mass extinction. 3) Understanding selectivity. 4) Improving sampling methodology, and using some of the lessons in sampling developed for K/T (The Signor-Lipps effect, confidence intervals and sampling precision perfected for K/T) on other extinction boundaries.

Introduction

Mass extinctions have traditionally been defied as relatively short periods (usually on the order of one to five million years in length) of greatly elevated extinction. There have been many such episodes during the Phanerozoic Era (the last 530 million years, the time of skeletonized life) although only five can be classified as having been "major", in the sense that more than 50% of all species died out (Figure 1).

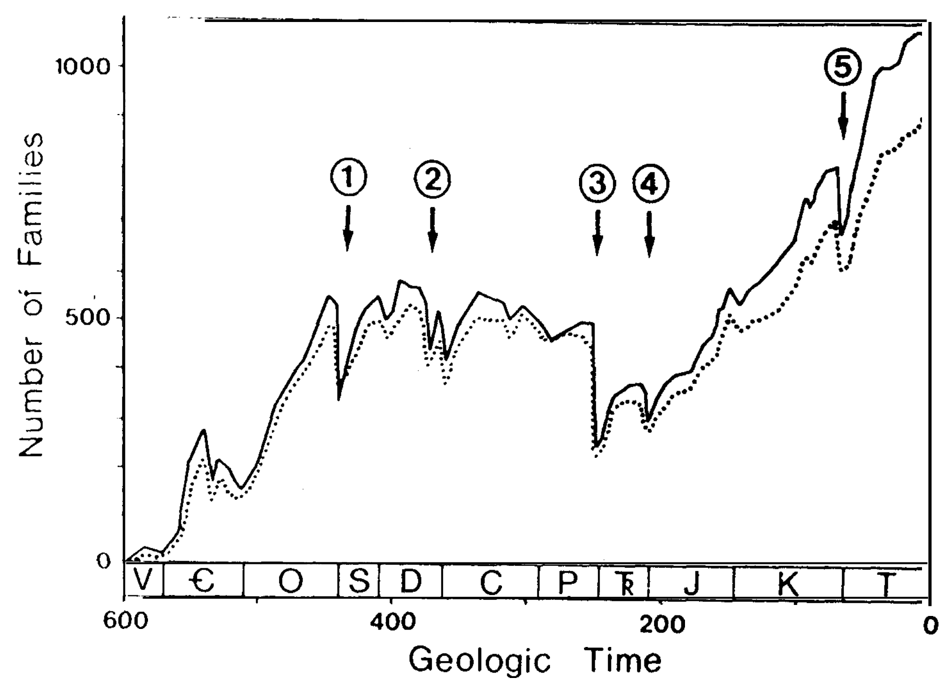

Figure 1. Diversity of marine families through Phanerozoic time, including the five largest mass extinctions. After Sepkoski, 1993

In the last 15 years, there has been a major shift in how we view biological extinctions, particularly with regard to rapid (catastrophic) events of a global extent, and to their potential causes. Sixty percent of all extinctions during the Phanerozoic occurred in short-lived events (termed "pulsed extinctions" by Raup, 1991). Raup concluded that pulsed events resulted in the extinction of more than 5% of all species worldwide living at those times, and took place in time intervals of less than 5 million years.

The causes of mass extinction have been widely debated, with sudden sea level change, climatic cooling or heating, and periods of oceanic being the most widely cited. Recently, however, meteor or comet impact as a cause for mass extinction has been seriously explored, propelled by the hypothesis that the end of the Mesozoic Era was caused by the impact of a large meteor or comet on the earth. (Alvarez et al, 1980).

This suggestion, now known as the Alvarez Impact Hypothesis, was originally controversial, but mineralogical, chemical, and paleontological data gathered over the past decade have confirmed that a large comet impacted the earth approximately 65 million years ago, and that, at the same time, more than half of the species then on earth became extinct rather suddenly. The recent discovery of a large impact crater in the Yucatan region of Mexico (the Chicxulub Crater), now suspected to be multi-ring impact basin as large as 300km in diameter (Sharpton et al, 1994) has virtually swept away remaining opposition to the hypothesis that the end of the Mesozoic Era was brought about by the impact of one of the largest extraterrestrial bodies to crash into the earth since lithosphere formation. Yet this body was by no means the only such large object to have ever hit the earth or perhaps cause mass extinction; many astronomers and earth scientists suspect that other large body impacts may have caused mass extinctions at other times in the past, including the middle Devonian, end-Triassic, and end-Eocene extinctions (Raup, 1990).

There is still some paleontological opposition to the contention that the K/T mass extinction was caused exclusively, or even mainly by an impact, particularly among vertebrate paleontologists (see Rigby et al, 1994), but also among a few invertebrate paleontologists (Zinsmeister and Feldmann, 1994; Keller, 1994). Yet among paleontologists, opposition to Alvarez Part 1 (there was an impact) is now virtually nonexistent, while opposition to Part 2, (it caused an extinction) has been stronger, but now seems to be centering on the concept that the extinction was limited to the tropics (Keller, 1994; Zinsmeister and Feldmann, 1994). Others dispute this, however, and believe that the end Cretaceous mass extinction was equally disastrous throughout the world (Raup and Jablonski, 1994; Marshall, 1994).

There is still much to learn about the timing, details, and mechanisms involved in the K/T catastrophe; there are probably decades of research necessary to flesh out the picture (the possibility of latitudinal gradients in the extinction, selectivity among victims and survivors, and perhaps the presence of high latitude refuges may be the most poorly known aspects). Nevertheless, like plate tectonic theory in the late 1960's, we are early in the era of a new paradigm: a new, grand picture has emerged, but many details remain unknown.

Some of the major lessons from the K/T debate are as follows: 1) Models or mechanisms of lethality are still in their infancy, and are, as yet, inadequate to explain patterns of selective survival and extinction. 2) Impacts can cause extinction. 3) Usually there is more than one killing mechanism going on in any mass extinction - even the K/T event 4) The fossil record literally interpreted at extinction boundaries can be very misleading. 5) All extinctions should be considered as rapid unless proven otherwise. 6) Breakthroughs will be the result of multidisciplinary efforts, often involving paleontology, sedimentology, geochemistry, and atmospheric science.

There are, of course, numerous directions that research into mass extinctions can and will take in the post K/T era. Four that I consider important are described below.

Killing mechanisms

One of the most frustrating aspects of paleontological research on mass extinctions is that models about the actual killing mechanisms are so poorly constrained. Only paleontology can arrive at an accurate list of victims. But rarely can the actual killing mechanism be deduced from literal interpretation of the fossil record. This scenario is at its most exasperating in trying to explain the most consequential extinction of all, the-Permian catastrophe. The accepted mechanisms are climate change following the formation of Gondwanaland, and marine regression as the northern and southern continents came together, approximately 250 million years ago. These are surely related - somehow - to the catastrophic, end-Permian mass extinction. But can they account for extinction of 90% of all species, according to Raup (1979)? And not just in the sea, but on land as well?

One of the most perceptive comments about causes of extinction came not from a paleontologist, but from a petrologist. At a recent meeting, V. Sharpton (personal communication, 1994) said: "Mass extinctions are caused by changes in the global atmosphere inventory". The cause of the atmospheric gas changes (which may be changes in volume or relative constituents of the atmosphere), of course, can be caused by many things: asteroid or comet impact, degassing during flood basalt extrusion, sea level change, etc. But the actual *killing* is brought about through changes in the makeup and behavior of the atmosphere (such as temperature and circulation patterns) that are dictated by properties of the atmosphere. At least for K/T, those few scientists worrying about kill mechanisms tend to agree. The Chicxulub comet, after all, *directly* killed very little. Its effect on the composition of the atmosphere, however, was probably far more lethal. The studies of Pope et al, 1994, on temperature change, Sigurdsson et al, 1992, 1994; and Dhondt et al, 1994, on the effects of sulfur, and Covey et al, 1994, who looked at the global climatic effects of atmospheric dust produced by the impact of a large (10 km) asteroid or comet, all suggest that killing mechanisms were atmospherically forced. The latter study may be particularly important: the Covey et al study suggested that fine dust generated by impact, into *either* an oceanic or continental target area would produce long-term (on the order of months) cooling of land areas, and wholesale changes in the hydrological cycle. The latter effect - the rapid change of rainfall precipitation patterns - may have been particularly lethal to plant ecosystems.

Clearly, we are just beginning to understand killing mechanism. The fine synthetic work of Toon et al (this conference), examining the additive effects of various mechanisms, seems a fruitful new approach.

Calibrating the kill curve: impact size and mass extinction

The killing potential of an impact event must be related to many variables. Clearly, however, the size of the incoming body is among the most important in determining extinction rate. Raup (1990) has followed this line of argument, and proposed a "Kill curve", relating impactor body size (and crater diameter) to percentage of biota expected to be eliminated. This leads to the following questions:

1. Are any other mass or pulsed extinctions (in addition to K/T) caused by impact?
2. Besides size, what determines the killing potential of an impact event?.
3. Can the "kill curves" as proposed by Raup be validated from newly acquired data? Specifically, are the curves monatomic, (as postulated by Rap, 1990), in that increasing crater size and hence impactor body size leads to increased rates of extinctions, or is there some threshold (in size of crater or impacting body involved), such that some critical size leads to extinction, but below that size no, or minimal extinction takes place?.
4. Do impacting bodies kill in the same way regardless of size, or is killing mechanism related to body size? In other words, does size alone alter the kill mechanism, or is killing effect always the same, but increases or decreases in some regularly scaled manner?

In the heady days following the Alvarez hypothesis, some investigators thought that a general synthetic model linking most or all mass extinctions to impact would emerge. The hypothesis that mass extinctions show a 26 million year periodicity (Raup and Sepkoski, 1984) is inherently based on this assumption. By the latter part of the 1980s, however , it became clear that rather than being a typical mass extinction (all caused by an impact), the K/T catastrophe appeared to have been a unique event. Gradually, as boundary after non-K/T boundary did *not* yield evidence similar to that routinely found at K/T boundary sections around the globe, it was argued that K/T was perhaps the *only* one of the big five mass extinctions (Ordovician, Devonian, end-Permian, end-Triassic, end-Cretaceous) to have been caused by impact. Even periodicity lost its luster, since no single cause that could produce periodic extinctions could be discerned.

By the early to mid-1990's, the pendulum began to swing back once again, and continues to do so. Rampino and Haggerty (1995) have recently summarized major extinction boundaries yielding evidence of impact; they report on the findings of elevated iridium from two Precambrian/Cambrian boundaries, three Ordovician/Silurian, three Frasnian/Famennian, one Mississippian/Pennsylvanian, thirteen Permian/Triassic, one Triassic/Jurassic, one Callovian/Oxfordian, one Jurassic/Cretaceous, one Cenomanian/Turonian, more than 100 K/T, "widespread" (their term) late Eocene, one Middle Miocene, and one Pliocene locality. They argue that numerous extinction boundaries *do* indeed yield geologic and geochemical evidence of impact. It is clear, however, that the K/T impact is in a class by itself due to its extremely elevated iridium values, shocked quartz, spherules, and ubiquity of sections showing these traits. It may have been caused by the most energetic impact event certainly of the Phanerozoic, and perhaps for much of earth history (Sharpton et al, 1994).

One of the most obvious, yet powerful generalities to emerge from this period was Raup's concept that impact events would fall on a kill curve; the bigger the impact event, the greater the percentage of global fauna going extinct (Raup, 1990, 1991). As with much of Raup's work, this idea is both simple and powerful (Figure 2). Unfortunately, the curve itself is entirely theoretical, as very few large craters have been sufficiently well-dated or studied to be confidently tied to mass extinction events. Virtually the *only* crater known with any degree of confidence to be associated with mass extinction is Chicxulub. Rampino and Haggerty (1995) attempted to test the validity of Raup's curve by adding in information about three additional craters: Puzech-Katunki, 80 km, Triassic; Popigai, 100km; Tertiary; Manicouagan, 100km; end-Triassic. These additional points seemed to fall within the envelope of error as hypothesized by Raup (Figure 2).

The kill curve concept is one of the most powerful to emerge from the entire extinction debate; one of the prime goals of future extinction research should be tests of its validity. The kill curve concept is probably valid, but one single curve may be insufficient to model the effect of impact and extinction. Many variables must come into play, including factors associated with the incoming body (its size, composition, angle of impact and velocity; Schultz, 1994), as well as the nature of the impact area (the target area). The geology of the target region may have profound implications on the degree of kill. Moreover, not only the *geology* of the impact site, but its *geography* as well may play an important part: an impact in a low latitude site will surely have entirely different consequences from a similar body hitting with similar angle and speed at a high latitude site, since the distribution of lethality across the globe may be produced by atmospheric circulation patterns. Finally, the nature of both the biota and the atmosphere at the time of impact are surely important: An impact in a highly diverse world of specialists will surely have different effects than one impacting a low diversity world of generalists, just as impact into a Greenhouse world may have different effects than one where greenhouse gas inventory, or, say, oxygen content, is lower than that today.

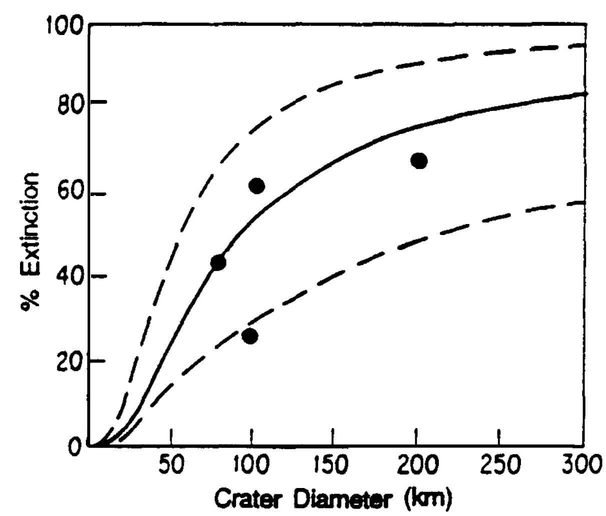

Figure 2. The Kill Curve of Raup, 1990, with data points for Puzech-Katunki, Popigai, Manicouagan, and Chicxulub placed on the curve by Rampino and Haggerty (1995). It should be stressed that at this time the extinction percentages for all but Chicxulub are speculative.

The way which impacts have been linked to mass extinction has proceeded in a less than ideal fashion. In the past, mass extinction horizons have been identified in the stratigraphic record based on paleontological data, and then evidence for impact (iridium, spherules, shocked quartz, etc.) has been searched for *at that horizon*. If physical evidence for impact is found, the last step in the process is identifying a suitable crater. This was the methodology in K/T, essentially. It would be more reasonable *start* with the crater. This, of course, requires that the crater be precisely dated, a major flaw in the past. But when large impact craters are dated with precision, stratigraphic horizons of those ages can be searched for extinctions and physical evidence of impact. This methodology is exactly opposite of that employed to date (Ward and Sharpton, 1994).

Selectivity

Faunal selectivity is surely one of the most powerful clues about mass extinction. Which species survived, and which perished, is partly related to pure chance, surely, but must also be ascribed to effects and killing mechanisms as well. This rich source of information has only begun to be tapped for the K/T catastrophe, and even less so for other extinction boundaries. Nevertheless the information to date is fascinating (see Jablonski, in press, for a review). Among more recent work, Kaiho's (1992) study showing relative rates of planktonic and benthonic foraminiferal extinctions during K/T, as well as Markwick's (1994) use of biological data on selectivity are novel. The former gives us a rough bathymeter of lethality, while the latter shows that the terminal Cretaceous extinctions were not primarily caused by climate change. Further analysis of selectivity is surely one of the most fruitful avenues for future research.

Breakthroughs from K/T should be exported to other mass extinction boundaries

The K/T controversy has made paleontology far more rigorous. A whole new way of looking at extinction boundaries has not only improved the proximal research, but has greatly benefited biostratigraphy as a whole (Ward, 1990). The most notable breakthroughs have been the recognition of the Signor-Lipps effect (sudden extinctions will usually look gradual; Signor and Lipps, 1982), the realization that stratigraphic hiatus can obscure true stratigraphic pattern (gradual extinction can look sudden), and the use of confidence intervals (Marshall, 1990) in studying boundaries.

The case perhaps most in need of applications learned from K/T (and certainly where we stand to learn the greatest information), is the Permo-Triassic extinction. Being much older than K/T, and having a marine regression right in its midst (which at best, reduces information, and could certainly be involved in the mechanisms of the extinction itself), it is clear that we are still looking for a reasonable model. Erwin (1993) has proposed his "Murder on the Orient Express" hypothesis (multiple causes); Hallam (1994) invokes anoxia, while Rampino and Haggerty, (in press) suggest impact. The main problem is the paucity of sections. The best place to study the P/T extinction may be in the Karoo region of South Africa. The P/T boundary there is exposed over hundreds to thousands of miles, and vertebrate material is quite common. I had the opportunity to study these sections (Ward, 1994), and came to the conclusion that the extinction, at least among land vertebrates, was very rapid. In fact, the situation in the Karoo beds is similar to, and should be studied in ways analogous to the Hell Creek dinosaur beds (Sheehan, et al, 1991). By making carefully documented stratigraphic collections of plant and vertebrate fossils from these sections, and then looking at the possibility of Signor-Lipps effect as well as establishing confidence intervals, a straightforward field program could glean, in short order, a great deal of powerful insight into the rapidity, and perhaps, the cause, of the Permo-Triassic extinction.

Post script: Are we currently in a mass extinction?

Most definitions of mass extinction suggest that a typical episode involved the extinction of around half the species on earth in a million years or less. Has the current day biota entered such a phase?

I recently wrote a book (Ward, 1994) suggesting that such is the case. Yet proving this contention is exceedingly difficult. The real problem, of course, is the fact that we only have the *faintest* idea about how many species currently are extant on earth, and thus cannot tell what percentage of total species biodiversity is actually disappearing per year. Approximately 1.6 million species have been defined to date, but most taxonomists agree that there are far more, especially among tropical insects. Peter Raven of the Missouri

Botanical Garden estimates that there are a *minimum* of ten million species, while E. O. Wilson (1993) suggested that there may be a many as *30 million* species. Yet, if we have such a poor handle on how many there are, how can we arrive at reasonable estimate about how may are going extinct? It is my contention that the current mass extinction is already well underway. This hypothesis can only be tested by paleontology.

There is probably no more politically charged arena than trying to discuss whether we are, or are not in the midst of a current mass extinction. Certain facts are inescapable. Barring some unforeseen population collapse, nuclear Armageddon, or large body impact, human population will double to more than 11 billion people by the end the next century; humans are large animals and co-opt resources; humans cause extinctions. At what point (if ever) will enough species be killed off to qualify us as having the dubious distinction of being in a recognized mass extinction event? Certainly, a significant proportion of large mammals have already gone extinct in all continents save Africa in the last 40,000 years (over 50 genera in North America alone in the last 15,000 years). And certainly the rampant reduction of forest cover in the world, especially in the tropical rain forests, is leading to species extinction at some currently unknown rate. The most extreme estimate I have heard comes from Peter Raven: he suggested (oral. comm., the University of Washington, 1995) that 60% of all species on earth will be extinct by 2300 AD. As current world biodiversity seems to be far higher than anytime in the past, this will, if it comes to pass, make the current crisis the most devastating (in absolute numbers of species going extinct) mass extinction of all time.

The current crisis in biodiversity (if it exists) thus competes with mitigation efforts for asteroid or comet defense. How much should we spend on detection and mitigation of the comet threat, versus saving rain forests by increasing biological reserves? If a finite amount of money is available, must we choose between asteroid defense or species endangered by earth-bound causes? What are the relative risks to *our* species of dwindling biodiversity? Is it more important to save human infrastructure than non-human biodiversity? And in a far more barren world, a millennium hence, will we even care about saving ourselves from a newly detected, incoming comet? We are in need of a thoughtful, global debate over these questions.

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Environmental Perturbations Caused by the Impacts of Asteroids and Comets

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We review the major mechanisms proposed to cause extinctions at the Cretaceous-Tertiary geological boundary following an asteroid impact. We then discuss how the proposed extinction mechanisms may relate to the impact of asteroids or comets in general. We discuss the limitations of these mechanisms in terms of the spatial scale that may be affected, and the time scale over which the effects may last. Our goal is to provide relatively simple prescriptions for evaluating the importance of colliding objects having a range of energies, and compositions. We also identify the many uncertainties concerning the environmental effects of impacts. We conclude that, for impact energies below about 10^4 Mts (i.e. impact frequencies less than one in 6×10^4 years, corresponding to comets and asteroids with diameters smaller than about 400 m and 650 m respectively), blast damage, earthquakes and fires should be important on a scale of 10^4 or 10^5 km^2, which corresponds to the area damaged in many natural disasters of recent history. However, tsunami could be more damaging, flooding a kilometer of coastal plain over entire ocean basins. In the energy range of 10^4 to 10^5 Mts (intervals up to 3×10^5 yrs; comets and asteroids with sizes up to 800 m and 1.5 km respectively) water vapor injections and ozone loss become significant on the global scale. If the submicrometer dust injection fraction from the pulverized target material is much higher than is presently thought to be most likely, then dust injections could also be important in this energy range. This energy range is a conservative lower limit where damage might occur beyond the experience of human history. The energy range from 10^5 to 10^6 Mts (intervals up to 2×10^6 years; comets and asteroid up to 1.8 and 3 km diameter) is transitional between regional and global effects. The dust lifted in this energy range, the sulfur released from within impacting asteroids, and the soot from fires started by comets can produce climatologically significant global optical depths on the order of 10. Moreover, the ejecta plumes of these impacts may produce enough NO to destroy the ozone shield. Between 10^6 and 10^7 Mts (intervals up to 1.5×10^7 years; comet and asteroid diameters up to 4 and 6.5 km respectively) dust and sulfate levels would be high enough to reduce light levels below those necessary for photosynthesis. Ballistic ejecta reentering the atmosphere as shooting stars would set fires over regions exceeding 10^7 km^2, and the resulting smoke will reduce light levels even further. At energies beyond 10^7 Mts, blast and earthquake damage reach the regional scale (10^6 km^2). Tsunami cresting to 100 m and flooding 20 km could sweep the coastal zones of

one of the world's ocean basins. Fires would be set globally. Light levels may drop so low from the smoke, dust and sulfate that vision is not possible. At energies approaching 10^9 Mts the ocean surface waters may be acidified globally by sulfur from the interiors of comets and asteroids. The Cretaceous-Tertiary impact in particular involved evaporite substrates that very likely generated a dense widespread sulfate aerosol layer with consequent climate effects. The combination of all of these physical effects would surely represent a devastating stress on the global biosphere.

The Biospheric Hazard of Large Impacts

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This brief overview of the impact hazard characterizes the hazard of impacts as a function of meteoroid energy. As reported previously, for impacts below ten megatons energy there is virtually no risk since few meteoroids penetrate the atmosphere. Between ten megatons and the threshold for global catastrophe, impacts are a moderate source of risk, but substantially less so than more common natural disasters such as earthquakes, severe storms, or volcanic eruptions. The greatest hazard is associated with impacts at or a little above a threshold for global catastrophe, where we have defined a global catastrophe to be one that leads to the death of >25% of the Earth's human population. Following the analysis of environmental effects of impacts by Toon et al. (paper given at this conference), we estimate that this threshold lies near one million megatons, corresponding to an average interval between events of about one million years. Above this threshold the entire world population is at risk from impacts, which are the only known natural disasters capable of killing a substantial fraction of the population or, at still larger energies, of threatening the survival of the species. Simple arguments suggest that expenditure of up to several hundred million dollars per year might be appropriate in dealing with such disasters. Arguments for the cost-effectiveness of programs that address the smaller objects (hundred-meter class) impactors are more problematic. Largely independent of proposed mitigation philosophy, however, there is consensus that the first step should be to carry out a comprehensive census of near Earth asteroids such as the proposed Spaceguard Survey to identify any potential impactors.

Introduction

The present conference is a reflection of widespread current interest in the role of impacts in planetary history, and in particular their continuing threat today. The effect of impacts upon the biosphere is most dramatically demonstrated by the discovery (Alvarez *et al.* 1980) that the K/T mass extinction resulted from the impact of one or more comets or asteroids with a mass (derived from the quantity of extraterrestrial material identified in the K/T boundary layer) of 10^{15} - 10^{16} kg. In this instance a relatively modest cratering event (produced by an object roughly the size of Comet Halley) led to global collapse of ecosystems and the extinction of most terrestrial species, including the dinosaurs.

It is clear that, far short of a mass extinction, a smaller impact could lead to a lesser ecological catastrophe that might nevertheless kill large numbers of people and threaten the stability of society. Such a global catastrophe is qualitatively different from any other natural disaster and can be compared in its consequences only with the result of nuclear war. Interest in all of these impact phenomena was further stimulated by the collision of Comet Shoemaker Levy 9 with Jupiter in July 1994, an event that captured the attention of scientists, the media, and the public at large.

The evaluation of the contemporary impact hazard has developed in tandem with our understanding of the environmental effects of impacts, and particularly their effects on the terrestrial biosphere. The discussion we present here is derived in large part from a series of technical analyses, including the *NASA Spaceguard*

Survey Report (Morrison 1992). Other relevant publications include discussions by Morrison (1993), Chapman and Morrison (1994), and Morrison, Chapman and Slovic (1994). This paper can be considered a status report updating the conclusions of these previous papers in accord with current research on the biospheric effects of impacts (*e.g.,* Toon *et al.* 1994, 1995).

Nature of the Hazard

The flux of meteoroids striking the Earth is composed of near-Earth asteroids and short-period comets (collectively called Near-Earth Objects or NEOs), and of long-period comets. The asteroids and short-period comets have dynamical similarities; both reside in the inner solar system and generally impact the Earth with speeds of order 20 km/s. Physically, however, they span a wide range of properties, from metal (like the iron meteorites) through various types of rock (like the chondritic and achondritic meteorites) to the low-density, volatile-rich assemblages associated with the comets (Chapman *et al.* 1994). Less is known about the rarer long-period comets, but they are probably also composed of low-density, volatile-rich material. Long-period comets strike with higher velocities, sometimes greater than 50 km/s. Although the physical properties of the impactors can influence their environmental effects, it is clear that for the larger impacts the primary effects are related simply to the kinetic energy of the objects (expressed in megatons (MT), where 1 MT = 4.2×10^{15} joules). The impact flux was discussed in detail at this conference by Shoemaker.

Based on the average flux of comets and asteroids striking the Earth, we can evaluate the danger posed by impacts of different magnitudes. We have found (Chapman and Morrison 1994; Morrison, Chapman and Slovic 1994) that the concept of energy thresholds is useful for differentiating the qualitatively different effects of impacts, which span a range of 100 million (from 10 MT to 10^9 MT). The concept of a threshold does not necessarily imply a sharp transition from one scale of risk to another, however. The transitions between local blast effects and global catastrophes, for example, may be quite gradual. However, a threshold is useful for discussing the impact energies at which one class of physical effects gives way to another.

The atmosphere protects us from small impacts. An impact with the energy of the Hiroshima nuclear bomb occurs roughly annually, while a one-megaton event is expected at least once per century. Obviously, such relatively common events have not been destroying cities or killing people. Even at megaton energies, most meteoroids break up and are consumed before they reach the lower atmosphere. This is because objects up to tens of meters in diameter are subject to aerodynamic stresses that cause fragmentation and transverse dispersal at high altitude. Only if the object disperses below an altitude of about 20 km is the airburst highly destructive. Numerical models of atmospheric fragmentation and dispersal show that only rocky objects > 50 m diameter (10 MT energy) and cometary objects > 100 m (100 MT energy) penetrate deep enough to pose significant hazards (Chyba *et al.* 1993; Hills and Goda 1993; Chyba 1993).

The area of the surface that is damaged or destroyed by an airburst or a cratering event can be derived in a straightforward way from the known properties of large explosions (*e.g.,* Toon *et al.* 1995). The area of destruction is larger for impacts into oceans than for land impacts as a consequence of the great travel distances of impact-induced tsunamis (Hills *et al.* 1994, Toon *et al.* 1994, 1995). For yields greater than about 10^3 MT, tsunamis associated with oceanic impacts contribute more to the hazard than the direct blast damage of impacts on land or in the continental margins. The detailed nature of the tsunami hazard is a subject for current investigation (see other discussions in these proceedings), but even at our current level of understanding it is clear that objects as small as a few hundred meters in diameter can pose a substantial hazard by this mechanism.

At sufficiently great energies, an impact has global consequences. An obvious if extreme example is the K/T event 65 million years ago. This impact released > 10^8 MT of energy and excavated a crater (Chicxulub in Mexico) at least 200 km in diameter. Among the environmental consequences were devastating wildfires and changes in atmospheric and oceanic chemistry as well as a dramatic short-term perturbation in climate produced by some 10^{16} g of submicrometer dust injected into the stratosphere (Chapman and Morrison 1994, Toon *et al.* 1994, 1995). The K/T impact darkened the entire planet for many months and precipitated a general destruction of terrestrial ecosystems. However, projectiles much smaller than the K/T impactor can still generate a global environmental shock that could severely curtail human agricultural production around the world. Such an agricultural disaster might result in collapse of global economic, social, and political structures. However, we do not know the degree of coupling of these effects, and it is very difficult to estimate the resilience of society to such massive environmental insults. In our previous papers (Chapman and Morrison 1994, Morrison, Chapman and Slovic 1994) we defined a globally catastrophic impact as one that results in the deaths of more than a quarter of the world's population, due primarily to widespread loss of agricultural production and resulting mass starvation.

In Morrison, Chapman and Slovic (1994), we identified a nominal threshold for a global catastrophe at an impact yield of 3 x 10^5 megatons, based largely on the work of Toon *et al.* (1994). In this model, the energy threshold for a globally catastrophic impact is determined by the explosive yield required to loft sufficient submicrometer dust into the stratosphere to induce crop failures on at least a hemispheric scale. The more recent analysis (Toon *et al.* 1995 and presentation at this meeting) suggests that a slightly larger impact may be required to produce a climatic effect of this magnitude, with a nominal threshold for global catastrophe of 10^6 MT. The total uncertainty in this threshold value might be as high as an order of magnitude, leading to average frequencies of global catastrophe (as we have defined it) of between 200,000 and 2,000,000 years.

Hazard Analysis

In our previous papers we have addressed the scale of destruction expected for impacts and the numerical hazard associated with impacts of various magnitudes. By numerical hazard we mean the probability of death for an individual due to this event. We will now examine how these estimates might be changed if the threshold size for global catastrophe is at 10^6 MT, and we also consider the effects of the (currently poorly known) tsunamis that can be induced by impacts below this global threshold.

For yields above the threshold energy for global catastrophe (10^6 MT), the number of fatalities is (by definition) >1.5 billion. If the nominal interval between such impacts is 10^6 yr, the equivalent deaths per year for all impacts above the threshold is about 2000, corresponding to an annual risk of death by impact for an individual of about 1 in 3 million.

The smaller, frequent events larger than the 10-MT atmospheric cut-off (what we may call Tunguska-class impacts) yield equivalent annual fatality rates of only a few tens of deaths/yr for the current world population (Morrison, Chapman and Slovic 1994). The low risk of such impacts is apparent when we realize they take place on land only about once per millennium. This corresponds to a strike in a heavily populated urban region only about once in 10,000 years at current population levels, and considerable longer at historical levels. Thus it is no surprise that we have no record taht such impacts have destroyed cities or produced significant casualties over the course of human history. Indeed, aside from two fatalities probably associated with the 1908 Tunguska impact, there are no reliable historical records of any deaths caused by impacts of any size. The average annual risk from such impacts appears to be less than 1 part in 100 million.

Of greater concern is the risk associated with tsunamis, as discussed at this conference by Hills and others. Modeling of impact-induced tsunamis and, even more, of their effects on coasts and coastal populations is an important topic for future work. At present it is possible to conclude with confidence only that the risk is somewhere between that of Tunguska-like land impacts and the global catastrophe associated with yields above one million megatons. Consider, for example, a person living on the Atlantic coast within a few meters of sea level. There are millions of such people on both sides of the Atlantic. Since an impact of a few thousand megatons may be sufficient to generate an Atlantic tsunami, and such an impact might be expected in the North Atlantic about once in 10^5 yrs, these people run an annual risk of a large tsunami of about 1 in 100,000. The equivalent risk of death from the tsunami is obviously much less, depending on warning systems and opportunities for evacuation, but it is possible that for this person the "local" tsunami risk is as much as an order of magnitude greater than the risk from "global" impacts above 10^6 MT. However, only a small fraction of the people on Earth live close to sea level, so the average risk distributed over the entire population falls well below that associated with the global catastrophe (1 part in 3 million).

The most robust conclusion from this hazard analysis is that the average global risk increases monotonically with yield from very low values (annual risk of roughly 1 in 100 million) near the ten-megaton atmospheric penetration threshold up to the million-megaton global catastrophe threshold (annual risk of roughly 1 in 3 million). The shape of this curve is not yet well defined, but total risk summed over all size impactors is probably near 1 in a million. Expressed in terms of equivalent annual monetary value of an effective defense program (Morrison, Chapman and Slovic 1994), the total such value for a United States population near 250 million is of order a few hundred million dollars per year, most of which is associated with the larger projectiles. According to the very rough estimates given here, the tsunami danger itself might justify U.S. defense expenditures of as much as 10^8 dollars/yr.

Comparison with other Hazards

In a rational world, society's response to the threat of impact by an asteroid or comet should be evaluated against other hazards that people face. In a typical year, nearly 1,000 people in the United States alone are killed as a result of being struck by a falling object. None of these objects, at least so far, has been a meteorite, comet, or asteroid.

In the United States, motor vehicle accidents lead the list of hazards, followed by falls, poisoning by solids or liquids, drowning, fires and burns, suffocation, firearms, and poisoning by gas. Still other dangers are widely feared even though fewer than 100 people die per year in the U.S. (*e.g.*, dog bites, lightning, poisonous snakes and spiders). All accidental deaths combined account for approximately 10^5 deaths/yr in the United States (Morrison, Chapman and Slovic 1994).

More useful may be a comparison of the impact hazard with other *natural* hazards. In the United States, the risk of death from natural hazards (earthquakes, hurricanes, tornados, floods, volcanic eruptions) is very low, currently amounting to fewer than 100 deaths/yr, although the occurrence of one major disaster such as a large earthquake in the Los Angeles Basin or a violent eruption of Mt. Ranier near Seattle might dramatically alter these statistics. Even making reasonable allowances for such very rare catastrophes, however, it appears that the average annual risk of death from natural disasters for someone living in the United States or Canada is less than 1 in 10 million (<0.1 parts per million).

The situation is much different in other parts of the world, especially in a few locations that are frequently subject to natural disasters that dwarf anything experienced in North America or Europe. Averaged over the 20th century, the annual risk of death from floods for a person living in Bangladesh has been roughly 1 in 20,000, or 50 parts per million. In China, Japan, and Turkey, the annual risk of death from earthquakes has exceeded 10 parts per million during this century. These values are all more than two orders of magnitude greater than the level of risk from natural hazards experienced in North America and Europe.

Where do impact hazards fit on this scale of natural hazards? In the U.S. and Europe, these risks appear to be of the same (low) order of magnitude as those from the worst other natural disasters, such as earthquakes. However, we have not taken into account the fact that the U.S. and Europe are surely more robust than the global average against impact hazards as well as other natural hazards, so it is likely that here also the impact risk is substantially less than that of other hazards such as earthquakes. This analysis simply has not been done. On a global scale, however, the answer is clear; in many parts of the planet, the impact risk is orders of magnitude lower than that associated with other natural hazards, and only as these other risks are reduced by current and future mitigation programs will the impact hazard seem to be significant.

There is, however, a critical qualitative distinction between impacts and other natural disasters, at least for the case of the global catastrophe associated with impacts above a million megatons. Independent of the maximum energy or destructive power of different modes of natural disasters, they all -- with the possible exception of explosive volcanism -- differ from the globally catastrophic impact hazard in one important respect: they are localized. Even tsunamis, which can extend their reach around the world along ocean coastlines, cannot touch continental interiors. No matter how large the non-impact natural catastrophe, many nations would be unscathed by earthquakes, floods, or storms of the most exaggerated possible scale. Impacts above the million-megaton threshold are unique in producing global consequences at a scale that could threaten the entire world's population simultaneously. That fact alone justifies our continuing concern about these phenomena.

This qualitative distinction also naturally focuses our interest on the larger asteroids and comets, those with impact energies above one million megatons (diameter roughly 2 km for asteroids, 1 km for comets). Any program to mitigate the impact hazard should begin with a comprehensive survey of the larger Earth-crossing asteroids (such as the proposed Spaceguard Survey). Such a survey would provide decades of warning for asteroidal impacts and permit us to develop effective defensive systems, should such an impact threat be identified.

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Tsunami Produced by the Impacts of Small Asteroids

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The fragmentation of a small asteroid in the atmosphere greatly increases its cross section for aerodynamic braking, so ground impact damage (craters, earthquakes, and tsunami) from a stone asteroid is nearly negligible if it is less than 200 meters in diameter. A larger ones impacts the ground at nearly its velocity at the top of the atmosphere producing considerable impact damage. The protection offered by Earth's atmosphere is insidious in that smaller, more frequent impactors such as Tunguska only produce air blast damage and leave no long-term scars on the Earth's surface while objects 2.5 times larger than it, which hit every few thousand years, cause coherent destruction over many thousands of kilometers of coast. Smaller impactors give no qualitative warning of the enormous destruction wrought when an asteroid larger than the threshold diameter of 200 meters hits an ocean. A water wave generated by an impactor has a long range because it is two-dimensional, so its height falls off inversely with distance from the impact. When the wave strikes a continental shelf its speed decreases and its height increases to produce tsunami. The average runup in height between a deep water wave and its tsunami is more than an order of magnitude. Tsunami produce most of the damage from asteroids with diameters between 200 meters and 1 km. An impact anywhere in the Atlantic by an asteroid 400 meters in diameter would devastate the coasts on both sides of the ocean by tsunami over 40 meters high. An asteroid 5 km in diameter hitting in mid Atlantic would produce tsunami that would inundate the entire upper East Coast of the United States to the Appalachian Mountains. Studies of ocean sediments may be used to determine when coastal areas have been hit by tsunamis in the past. Tsunami debris has been found to be associated with the Cretaceous - Tertiary impact and should be detectable for smaller impacts.

Introduction

Tsunami may be the most serious consequence of asteroid impacts unless the asteroid is massive enough to produce global, catastrophic changes in the atmosphere, as apparently occurred after the impact responsible for the Cretaceous-Tertiary extinction. Just as on land, much of the kinetic energy of an asteroid that impacts the ocean goes into the formation of a crater, but the crater is not stable. The outward propagation of its rim and its refilling produces a series of waves that propagate outward away from the impact (Gault and Sonett 1982).

In this paper we are primarily concerned with the impacts of small (compared to the depth of the ocean) asteroids that produce waves with amplitudes less than the depth of the ocean. Such deepwater waves do not dampen significantly until they run into shallows where they steepen into breakers and increase in height to form tsunami (Mader 1988). The average tsunami runup, the height of the tsunami in units of the deepwater wave that produced it, is about an order of magnitude.

The height of a deepwater wave only decreases inversely with the distance from its origin, so it can cause serious problems far from the impact. This results from the wave being inherently two-dimensional. The intensity of a three-dimensional disturbance such as an airburst or an earthquake falls off as the inverse square of the distance, so such a disturbance is far more localized than water waves.

There are many anecdotal illustrations of the long-range nature of tsunami; e.g., the earthquake in Chile in 1960 produced deepwater waves that traveled 150 degrees (over 17,000 km) around the Earth to produce tsunami in Japan that were from 1-5 meters high (average about 2 meters) and killed at least 114 people with another 90 people missing (Takahasi 1961). [It is estimated that the full amplitude of the deepwater wave before hitting Japan was 40 cm, so the maximum height above normal sea level was 20 cm, and it had a period of 60 minutes (Iida and Ohita 1961)]. This imply an average tsunami runup of

10 fold and a maximum of 25 fold). In the Hawaiian Islands, at 10,600 km from the epicenter, the maximum runup was 15 meters. The major damage was in Hilo harbor where the maximum tsunami height was over 10 meters and 61 people were killed (Cox 1961). The average tsunami runup in Hawaii is about 40 fold. We shall see that asteroid impacts can produce tsunami vastly larger than the 1960 tsunami and in regions, such as the Atlantic, where coastal areas are poorly prepared for them.

Impacts into Deep Oceans

To determine heights of tsunami produced by an asteroid or comet, we first determine its kinetic energy at its impact with the ocean. Figure 1 (from the work of Hills and Goda 1993) shows the height in the atmosphere at which half the kinetic energy of a stony meteoroid is dissipated. We note that asteroids with radii exceeding 100 meters hit the ground with most of their original kinetic energy. The straight-line portion on the left side of the figure is for asteroids that do not fragment. Fragmentation can enormously increase the effective radius of smaller meteoroids and their rate of energy dissipation in the atmosphere. If we extend the straight line portion of the figure to sea level, we note that if it were not for fragmentation, asteroids with radii larger than 10 meters would be able to penetrate to sea level with most of their kinetic energy. The increased energy-dissipation cross section due to fragmentation causes stony asteroids with radii between 10 and 100 meters to dissipate most of their energy in the atmosphere rather than on impact with the ground.

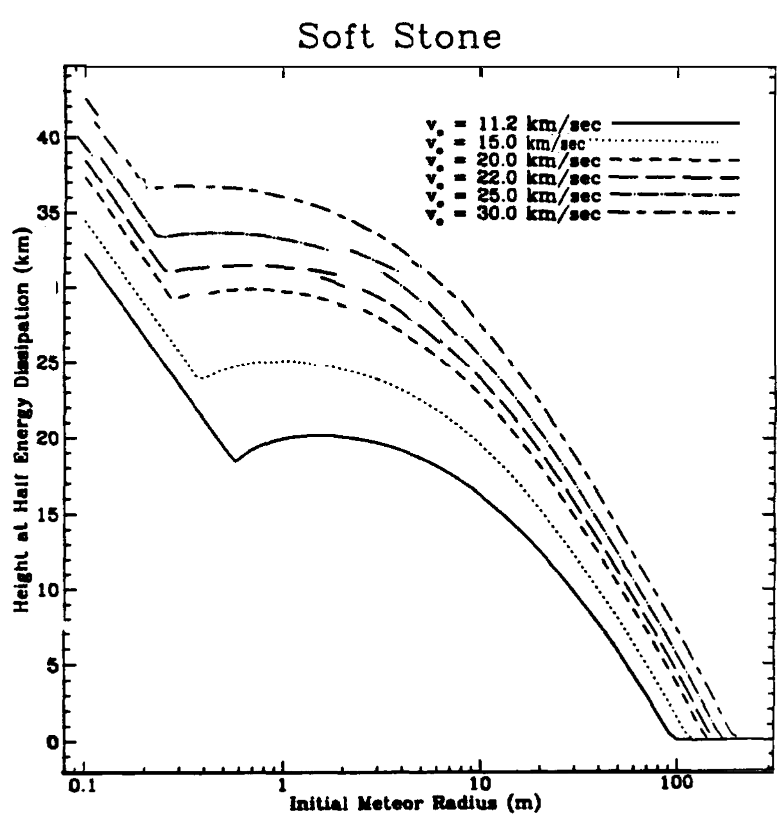

Figure 1. The height (in km) in the atmosphere at which half the initial energy of the impactor has been absorbed. This is for soft (common) stony asteroids. It is given as a function of the radius of the impactor for various impact velocities (in km/s).

We use the impact energy at sea level to find the height of the deepwater wave. An empirical analysis of experiments with underwater nuclear explosives shows that the full height of a deep-water wave at a distance r from the underwater detonation of energy Y is given by

$$h_W = 40,500\ ft\ \frac{(Y/kton)^{0.54}}{r/ft} = 6.5\ meters \left(\frac{Y}{gigaton}\right)^{0.54} \left(\frac{1000\ km}{r}\right) \qquad (1)$$

(Glasstone and Dolan 1977). This result is not sensitive to the depth at which the explosion occurs. The height, h, of the water wave above the ocean is half the full height of the wave, so h = 3.3 meters at 1000 km from a 1 gigaton = 4.2 x 10^{25} ergs explosion.

A more recent analysis of Pacific test explosions in deep water with yields between 1 kiloton and 5 megatons and of modeled nuclear explosions of up to 100 megatons, shows a similar equation for the h above the ocean level. One of us (Mader) finds that

$$h = \frac{1}{2}h_W = 4.5\ meters \left(\frac{Y}{gigaton}\right)^{1/2} \left(\frac{1000\ km}{r}\right) \qquad (2)$$

The values given by this Equation for R > 100 meters are in satisfactory agreement with those given by Equation (1), considering the large extrapolation beyond the experimental points.

Hills and Goda (1993) found the ground impact energies of comets, stony asteroids, and iron asteroids as a function of size and impact velocity taking into account the increase in their aerodynamic cross sections due to fragmentation. Figures 2 and 3 show the full height, H_W, (twice the height h above sea level) of a deep water wave 1000 km from the impact point for nickel-iron and stony meteorites, respectively, as a function of impactor radius for various impact velocities. The heights were gotten by putting the ground impact energies Y found by Hills and Goda (1993) into Equation (1).

We note that the wave heights for stony asteroids less than 100 meters in radius are significantly less than they would be without aerodynamic dissipation. This is also true of iron asteroids with radii less than 40 meters. The smaller cutoff radius for irons is due to their greater strength, which causes them to fragment less easily than stones.

For stones with radii R> 100 meters, which suffer no significant energy dissipation in the atmosphere, the deep-water wave height (h = $h_w/2$) above mean sea level at distance r [based on the heights determined by Equation (1)] is given by

$$h = 7.8\ meters \left[\left(\frac{R}{203\ meters}\right)^3 \left(\frac{V}{20\ km}\right)^2 \left(\frac{\rho_M}{3\ g/cm^3}\right)\right]^{0.54} \left(\frac{1000\ km}{r}\right) \qquad (3)$$

Here a stony asteroid with a radius of 203 meters and a velocity of 20 km/s has an impact energy of 5 gigatons. An asteroid of this size or larger impacts Earth about every 10^4 years.

Asteroids of sufficient size produce craters that exceed the ocean depth. In these cases, Equations (1)-(3) and Figures 2-3 are no longer valid. We shall discuss such impacts in the next section.

Impacts into Shallow Seas

The average ocean depth is 4-5 km. If the depth of the impact crater exceeds the local ocean depth d, we can no longer use Equation (1) to compute the height of the deepwater wave far from impact. It is known from nuclear weapon tests that an explosion in shallow water (e.g., Pacific test Bikini Baker) deposits less mechanical energy into the water than one in deep water (Glasstone and Dolan 1977). Glasstone and Dolan find that the full height of the deepwater wave at distance r from the explosion is given by

$$h_w = 1450\ meters \left(\frac{d}{r}\right) \left(\frac{Y}{gigatons}\right)^{0.25} \qquad (4)$$

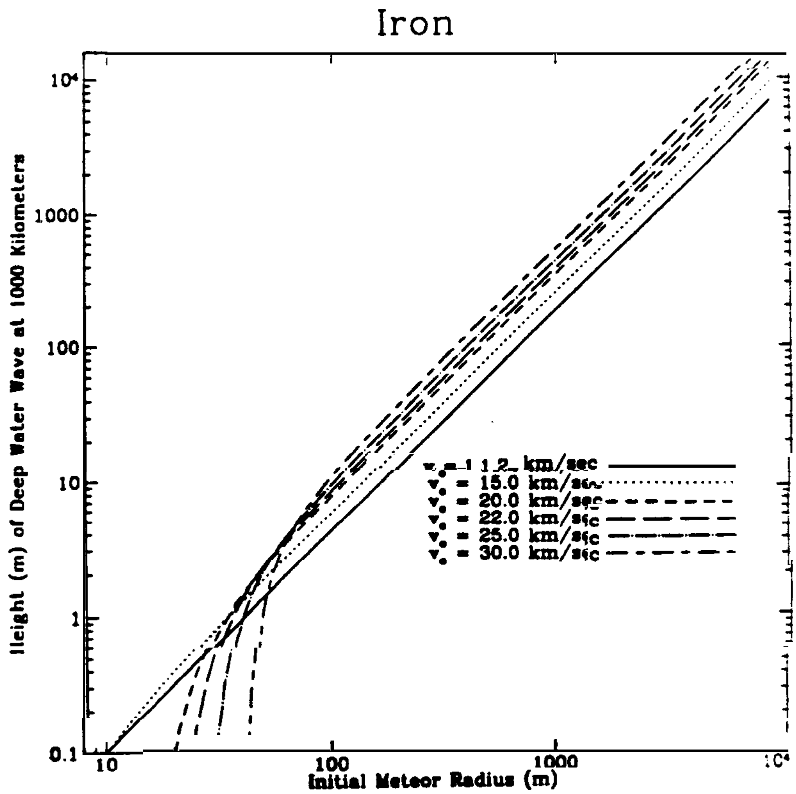

Figure 2. The full height (meters) of a deep-water wave 1000 km from the impact of a nickel-iron asteroid. The height is given as a function of impactor radius for various impact velocities. The height of the wave above mean ocean level is half the full height shown. This wave increases in height by over an order of magnitude to produce tsunami when it runs into a continental shelf.

where d is the depth of the water and Y is the yield. We note that the wave height increases less rapidly with yield than it does for waves generated in deep water, but there remains an inverse relationship between height and distance from the source. If we let d = 5 km, the average depth of the ocean, we find that Equations (1) and (4) give the same full height of $h_w = 8.1$ m at r = 1000 km for a yield of Y = 1.5 gigaton, which corresponds to a stony asteroid with a diameter of 272 meters and an impact velocity of 20 km/s.

Schmidt and Holsapple (1982) found that the depth of a crater in water is about 12 times the impactor diameter. This suggests that where the impactor diameter significantly exceeds 8% of the depth, it is better to use Equation (4) than Equation (1) to determine the terminal height of the deepwater wave far from the impact. In the ocean, where d = 5 km, we should use Equation (4) if the impactor diameter much exceeds 400 meters.

Hydrodynamic simulations by Nemchinov and associates [as given in Hills, et.al. (1994)] of craters produced by asteroids with diameters comparable to the ocean depth suggest that the wave height falls between the values given by Equations (1) and (4), as expected. The fine structure that develops in these hydrodynamic simulations does not allow them to be run to times when the crater has collapsed into a series of outward propagating waves. The calculations must be stopped while the crater is still forming.

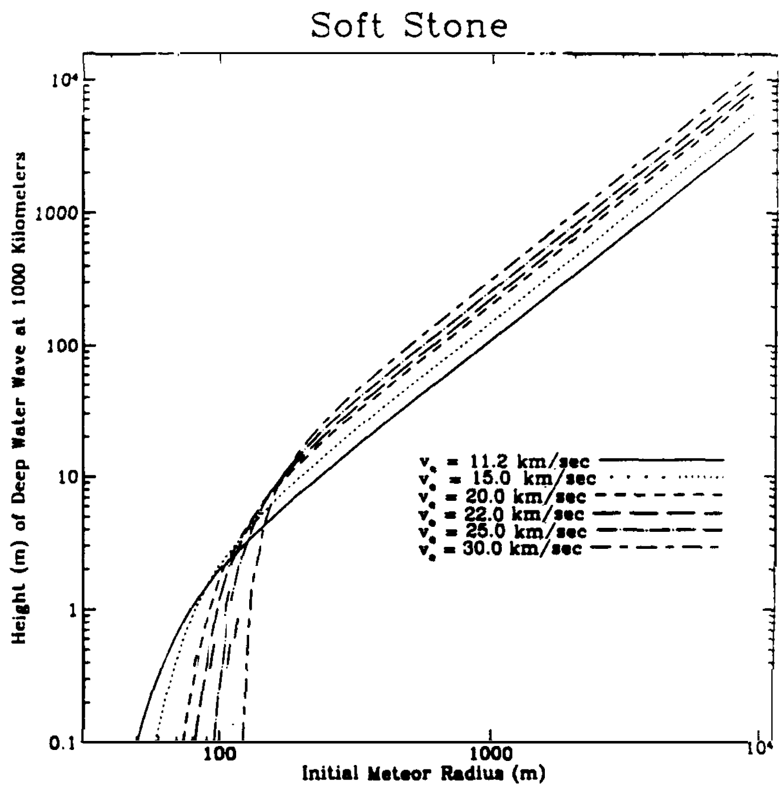

Figure 3. The full height (meters) of a deep-water wave 1000 km from the impact point of a stony asteroid. This height is given as a function of impactor radius for various impact velocities.

From energy considerations, the present authors (Hills and Mader) estimate that the diameter of the water crater when it stops growing is typically about 25 to 30 times that of the asteroid that produced it.

Tsunami

As the deep-water wave goes into a shoal, its speed decreases and its front increases in sharpness and amplitude until it breaks. This wave travels inland from the coast with decreasing speed and height above sea level. We shall first use analytic models to estimate the effect of the tsunami along a typical coast line. We shall emphasize the U.S. East coast. We shall then use a full numerical model to determine the damage from the impact of a large asteroid into the mid Atlantic.

Analytic Model

We noted earlier that the 1960 Chile tsunami produced coastal runups in Japan that averaged 10 fold but reached about 25 fold in the Northern Islands. These values are fairly typical. On Hawaii the average runup is about 40, but it can be less in areas with gradual continental shelves, such as off Florida. As an example, a stony asteroid with a radius of 200 meters (diameter 400 meters) that drops anywhere in the mid Atlantic will produce deep water waves that are at least $h = 4$ meters high when they reach both the European and North American coasts. When it encounters land, this wave steepens into a tsunami with an average height of 40 meters (if it follows the Japanese runups) that hits both sides of the Atlantic nearly simultaneously.

Tsunami Flood Plane. When the tsunami impacts the shore, the maximum distance, X_{max}, to which it surges inland depends on the maximum depth of the water at the shoreline, the runup height h_o, the slope of the shore away from the coast, and the roughness of the ground that the water moves across (cf, Mader 1991). If there is a flat coastal plane on which the flood depth h has a maximum value h_0, the depth at a distance X inland is given by

$$\frac{h}{h_o} = \left[1 + \left(\frac{X}{X_{max}}\right)\right]^{4/3} \tag{5}$$

where the maximum inward distance to which the water flows scales as

$$X_{max} = \frac{h_0^{4/3}}{n^2} A = B h_0^{4/3} \tag{6}$$

where n is the Manning roughness number of the terrain over which the water surges and A is a constant (Bretschneider and Wybro 1977). Here n varies from about 0.015 for very smooth terrain (e.g. mud flats and ice) to 0.070 for very rough coast areas (dense brush and trees and coarse lava formations). Developed areas typically have n = 0.030-0.035. For n = 0.03 and h_0 = 15 meters (50 feet), X_{max} = 2.5 km (8000 feet) (Bretschneider and Wybro 1977). Putting this scaling factor into Equation (5), we find that

$$X_{max} = 1.4\ km \left(\frac{h_0}{10\ meters}\right)^{4/3} \tag{7}$$

We note that in a developed area with a Manning roughness number of n = 0.03, a 40-meter tsunami would travel inland about 9 km, a 100-meter one would travel about 30 km, and a 200-meter ones would go 76 km. For croplands or grazing land with a Manning number approaching 0.015, the corresponding figures are 4 times larger. While there may be some difficulties in extrapolating Equation (7) to these large values, it is clear that tsunami of these magnitudes would cause unprecedented damage to low-lying areas in North America such as Long Island.

The damage caused by tsunami results principally from the impact of the debris carried by the moving water. There is much debris in developed areas. This debris acts as a battering ram that effectively scours away the area impacted by the tsunami flood; e.g., in the 1960 Hilo, Hawaii inundation caused by the earthquake in Chile, the steel pipes supporting some of the parking meters in the city were bent to the ground by the ramming of debris carried by the flood. The higher the tsunami flood, the larger its mean flow velocity, and the more effective the ramming.

Because a disproportionate fraction of human resources are close to the coasts, tsunami are probably the most deadly manifestations of asteroid impacts apart from the very large Cretaceous-Tertiary type superkillers.

Numerical Model

While analytic models can approximate the general effect of a tsunami, detailed numerical models are needed to determine the runup and inundation along any particular coast. The height and direction of the deepwater wave along the coast may depend on reflections from nearby land masses as well as on the magnitude, distance, and direction of the impact. The runup depends on the height and direction of the wave and on the topology of the coast.

We did a numerical simulation of a tsunami along the East Coast of the United States produced by an asteroid falling into the mid Atlantic. It was modeled with the 2-dimensional Swan hydrodynamic code with 1-km spatial resolution. Figure 4 shows the position of the impact. We considered an initial perturbation in which the (square) crater was 150 km across with a depth equal to that of the ocean. We estimate that the formation of this crater requires an asteroid about 5 km in diameter, so this impactor is a little larger than the parent object of Comet Shoemaker-Levy 9 that impacted Jupiter in 1994 but an order of magnitude less massive than the impactor responsible for the Cretaceous-Tertiary extinction.

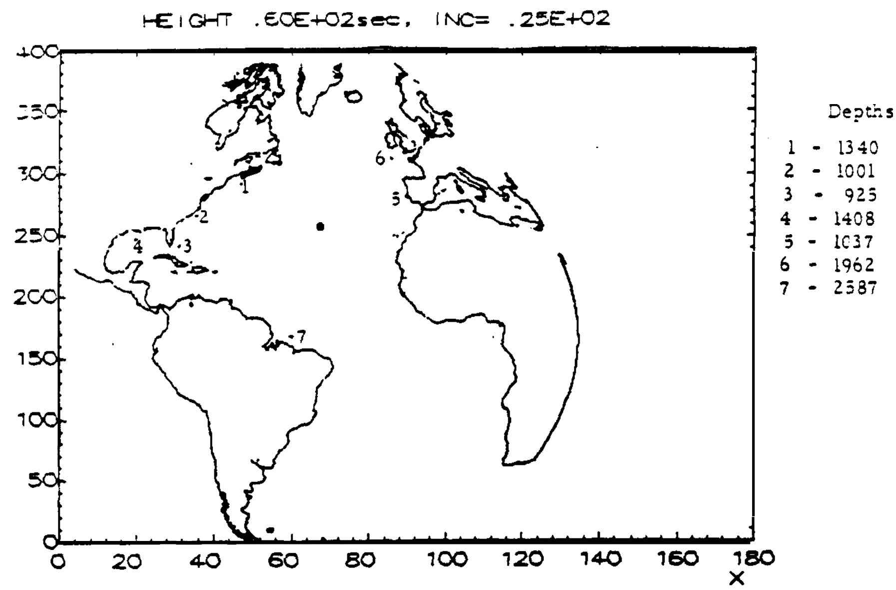

Figure 4. The position in the Atlantic of the 150 km diameter crater produced by an impactor. Also shown are seven locations off the continental shelves at which we determined the heights of the deep water waves in the computer simulation.

Figure 4 shows seven representative locations just outside the continental shelf where the heights of the deepwater wave were determined. The table to the right of the figure shows the depth of the water (in meters) at these points. Table 1 shows characteristics of the series of deepwater waves that passed through each of these seven positions. The second column gives the maximum drop (in meters) in the level of the ocean as the deepwater waves passed by while the next column gives the maximum increase (in meters) in the level of the ocean. We see that off the central East Coast of the United States (Position 2) the maximum wave height and fall off are each 100 meters before the continental runup. Figure 5 shows the height

Table 1. Deepwater wave characteristics from Atlantic impactor.

Location	Min	Max	Period
East Coast (Location 1)	-100	95	1000
East Coast (Location 2)	-100	100	1000
Florida (Location 3)	-95	30	1000
Gulf of Mexico (Location 4)	-5		
Portugal (Location 5)	-85	50	1200
England (Location 6)	-36	100	1500
Brazil (Location 7)	-100	50	1500

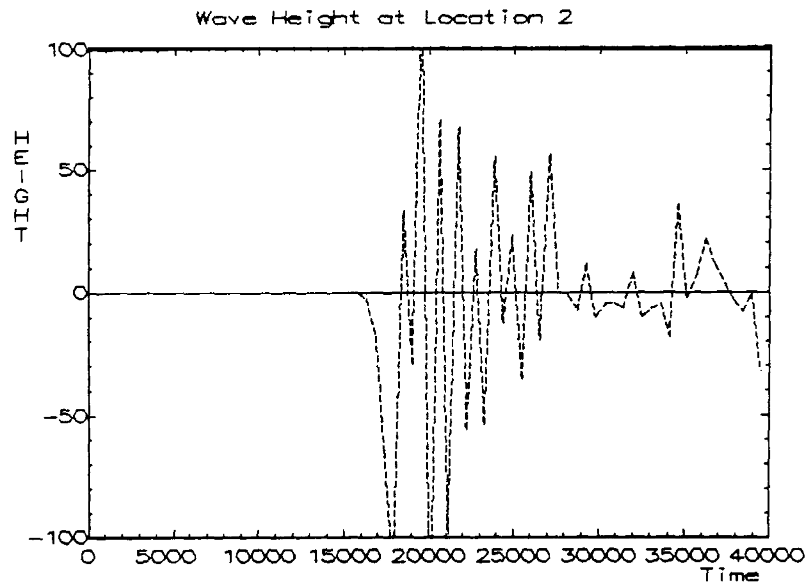

Figure 5. The wave height (meters) as a function of time (seconds) at Location 2 off the East Coast of the United States. This is still in deepwater before any significant tsunami enhancement. We note the large number of separate waves that hit the coast over a period more than 6 hours.

of the wave as a function of time at Location 2. We note the large number of waves that will inundate the shore over a time of over six hours. The final column gives the period of the wave in seconds. These periods are similar to those measured in the 1960 Chilean tsunami. Shorter period deepwater waves disperse without energy dissipation, due to differences in their velocity with period, until their periods lengthen to these values.

The East Coast of the United States is hit very hard by the surge. The wave travels inwards to the foothills of the Appalachian mountains in the upper two-thirds of the United States including surges of more than 200 km across Delaware-Maryland and Virginia. Delaware, Long Island, and all of Maryland below the Piedmont Plateau are completely inundated as are all coastal cities in this area. The damage would be unprecedented in human history.

There are surprises. The Florida coast is largely protected except for the Miami-West Palm Beach area by a gradual continental shelf that reflects most of the tsunami energy back into the Atlantic. Inland areas of Florida are safe despite its low elevation. The enhanced damage in the Miami area compared to rest of Florida points to the particular danger to seaports from tsunami. Seaports are particularly valued if they have a deep offshore channel in otherwise shallow coastal waters. This channel can support a much more energetic tsunami than can the rest of the coast.

The tsunami causes much less damage to Europe than it does to North America because of a large continental shelf off most of the European coast. An exception is the Portugal-Spain peninsula which has almost no continental shelf. The tsunami wraps itself around the peninsula up to the foothills of the mountains. The particular vulnerability of this region may have been forewarned by the tsunami produced by the Lisbon earthquake of two centuries ago. The lost city of Atlantis was allegedly along this section of the Atlantic coast before it was swallowed suddenly by the sea, although there is no archaeological evidence for its existence. Evidence for a strong tsunami along this coast at the same time as one along the upper East Coast of the United States would provide strong support for a major event in the Atlantic of the type expected from an asteroid impact.

Observational Evidence for Tsunami from Impactors

Very large tsunami have occurred. Deposits of unconsolidated corals hundreds of meters above sea level on the Hawaiian Islands of Lanai, Hawaii, Oahu, Molokai, and Maui provide evidence of giant tsunami (Johnson and Kin 1993). On Lanai they are found as high as 326 meters above sea level. A tsunami of similar height occurred in a fiord in Alaska in historical times. These occurrences show that there is no physics limiting large-scale tsunami at least 300 meters high. A tsunami at least 50-100 meters high appeared along the Texas coast after the Cretaceous-Tertiary impact (Bourgois, et. al. 1989).

Most searches for tsunami in the geological record have been done in the past few years, so it is likely that new evidence for them will appear at an increasingly rapid rate. It may be especially profitable to search for tsunami produced by impacts along the Atlantic coast which is less prone to earthquake-induced tsunami than is the Pacific. Geological (and perhaps archaeological) evidence for large tsunamis along the coasts of the major oceans (due to their large impact cross sections) may be the best counters for impacts of moderately large (R = 100-1000 m) asteroids.

Conclusions

The atmosphere is ineffective in preventing impact damage to the ground when the diameter of a stony asteroid exceeds 200 meters. For iron meteorites that impact at greater than 20 km/s, the critical diameter is about 40-60 meters. These properties cause a threshold effect whereby stony asteroids less than 200 meters in diameter produce no significant ground (ocean) damage [but those larger than 60 meters in diameter can cause significant damage from airbursts (Hills and Goda 1993)], while those larger than this value can cause catastrophic tsunami.

The growth of the height of the deepwater wave with increasing impact energy slows considerably when the crater depth becomes comparable to the depth of the ocean. This occurs at an impact energy of a few gigatons at a typical ocean depth. The probability is a few times 10^{-4} per year that an asteroid of sufficient size will impact an ocean on the Earth to produce tsunami with average heights exceeding 100 meters along the entire coast of the ocean.

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Panel Papers

Magnetic Effects of Meteor Impacts

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I shall talk about a possibility which, as far as I can find out, has not been given the kind of approach that I will describe. It is known that the Earth's magnetic field changes sign in a rather random manner about once every hundred thousand years. This is a fact, and it is the only fact that I will mention. The rest is speculation.

The question is: Is there a correlation between meteor impacts on Earth and the flips of the Earth's magnetic field? If there is a correlation, it would be very interesting because it would give us an additional way to find out when meteors have hit the Earth. Some people have looked for such a correlation, but so far there is no evidence for it.

First, let us consider the Earth's magnetic field. The Earth's magnetic field is caused by a disorderly motion in the Earth's core, in the electrically conducting molten iron. According to Alfven, this motion intensifies the magnetic fields in a disorderly manner. A little order is introduced into this disorderly arrangement of magnetic fields by the Earth's rotation and the resulting Coriolis force. There are two stable arrangements of the magnetic field, one with a general lineup for the magnetic pole at the Earth's north pole and the other at the Earth's south pole.

An incoming asteroid carrying 10^{30} ergs, more or less, can have major effects. One might expect that there would be a direct effect on the currents in the Earth's core, but I don't believe this for the following reason. By the time the shock from the asteroid impact reaches the Earth's core, it is essentially sonic. And in a sonic vibration, the forward and backward motion is very similar, so whatever current changes are left behind are small and will result in no overall changes. However, in the atmosphere and outside the Earth's surface (out to a distance of two Earth radii), about one percent of the energy of the dipole field is contained, and this field can be readily altered by the incoming object.

The flips of the Earth's magnetic field have left their records in lava flows. The magnetic field has oriented magnetic dipoles in the lava while it was liquid. As the lava solidified, it preserved the record of the orientation of the magnetic field. This evidence shows that the Earth's magnetic field has changed every few hundred thousand years, and that the changes have taken a few thousand years.

There is one exception. A lava flow in Oregon shows evidence of a change that apparently occurred in a few days. Now, if the magnetic field comes from the core, it has to go through the Earth's mantle. The conductivity of the mantle results in a time delay of about ten thousand years, and nothing can change much faster. In five thousand years, yes. In a week, no!

Such a sudden change must come from an asteroid. The impact changes the magnetic field in an hour. Then, the magnetic field gets into the conducting ocean, and it gets into the top few miles of the Earth's mantle. A strongly changed field is frozen into a region of the Earth's mantle, and this can have the effect of favoring a different order in the magnetization of the Earth's core as a consequence of the impact. According to this picture, an impact need not be accompanied by a change in the magnetic field. But a change in the magnetic field will *always be introduced* by an impact. The impact will not cause the change to happen, but it will give it a chance to occur.

A very obvious question is: Will not nuclear explosions give similar effects? The answer is "No" because, given the density of the atmosphere, the effect of a nuclear explosion will be limited in volume. At a very high altitude, where the atmosphere is one-thousandth as dense as at sea level, the volume affected can be hundreds of kilometers in linear dimension or more.

How do we gather evidence for such magnetic field changes? The Air Force is looking at incoming objects that don't reach the surface. Whenever such an event occurs, there could be a mechanism to notify scientists who can look for a magnetic storm. The big objects—those that arrive once in a hundred thousand years—carry enough energy to affect the whole atmosphere, ionize much of it, move it. On the surface of the Earth, at one atmosphere, 10^{3} ergs per cubic centimeter of air is a few million times as much as the magnetic energy density. And if we go up a hundred kilometers, the magnetic energy density of the air is down to one part in a million, but the magnetic field has not changed much. Now the two energy densities are comparable. As the atmosphere is moved, it will be ionized, the magnetic lines will move with the atmosphere, and there will be large regions where the magnetic energy density is multiplied severalfold.

But is this a permanent change? It is not, but a part of it is. The regions of the atmosphere where the energy density has increased will expand again. The atmosphere can expand perpendicular to the magnetic field or parallel to the magnetic field. If it moves perpendicularly, it takes the magnetic field along with it, which is apt to undo the change that has been made. But if the atmosphere expands parallel to the magnetic field, then the magnetic field will not change, and the intensification of the magnetic field will be permanent.

As the shock of the asteroid impact reaches the Earth's surface, it finds bodies that are conductors, like the ocean and the mantle. The resulting hydrodynamic changes will run their course in a few hours. The waters of the ocean will have moved quite a bit, and their motion will have occurred along whatever magnetic field exists in the ocean. In a few hours, the magnetic field will penetrate the Earth's surface to a few tens of kilometers. The penetration depth goes with the square root of the time. The resulting changes will be undone, in part, in a few hours, but some will diffuse to greater depths.

Following this line of reasoning, it may be plausible that there occur, on rare occasions for short times, violent changes followed by much slower changes. Eventually, these changes may lead to a stabilization of the Earth's magnetic fields in the opposite direction, an orientation that is as stable as the original one.

So, what are the consequences of such a happening? If the Earth's magnetic field flips between the two extremes, the magnetic field is apt to be *less* intensive for a few thousand years. This has been observed. A smaller magnetic field will allow more cosmic rays to penetrate the atmosphere. Cosmic rays can cause mutations. I do not know what percentage of mutations is caused by cosmic rays, but increasing the amount of cosmic radiation might conceivably increase the mutation rate by as much as tenfold. That is entirely unimportant. Whatever a horse would otherwise do in evolving in ten thousand years, it will now do it in a thousand years.

But there may be changes—in fact, there must be changes—that require multiple mutations. Assume that a new kind of organ will not originate if too few mutations occur. Assume that six mutations are needed to establish a new kind of an eye. A tenfold increase in the rate of single mutations will, in this case, be a millionfold increase for six mutations. Therefore, for a few thousand years, while the magnetic field is low, very extraordinary developments might go from being impossible to something that is barely possible. And if this is so, then the mass extinctions caused by asteroid impacts may be accompanied by a period of increased mutations, an increased rate that is important in the case of radical changes although unimportant in the case of gradual changes.

Audience Questions and Comments

Audience: Dr. Teller, thank you for the presentation. At the risk of never being invited back to one of these conferences, may I ask one question?

Dr. Teller: Any question—not only a question, even a statement if you wish.

Audience: I've spent my career studying the Cretaceous, and one of the curious aspects is that the middle of the Cretaceous has the longest interval, with no reversals, of the last 600 million years.

Dr. Teller: No?

Audience: A period 40 million years long and no reversals.

Dr. Teller: 40 million years—no reversals. And in the last 5 million years, I'm told there have been 23 reversals.

Audience: 40 million years and no reversals.

Dr. Teller: Do we have any evidence of asteroid strikes during this period?

Audience: Yes.

Dr. Teller: How many?

Audience: Of the strikes that are well dated, a few are certainly in this long normal period.

Audience: This is the oddest thing—no one can explain it at all why we have this one, unique, long normal period.

Dr. Teller: Well, look, the reversals *certainly* are not explained. And I think they may have more reasons than one.

Audience: Based on minor mass extinctions and the formation of new species, more often than not, stage boundaries coincide with reversals.

Dr. Teller: How long do these changes take and in how long a period do they occur?

Audience: The stages themselves are about 5 million years in length, but you find the species forming extremely rapidly, in a hundred thousand years or less.

Dr. Teller: A hit could cause a low magnetic field that could last for a few thousand years—difficult to have it last more.

Audience: But the species transitions may take longer. Once you start the ball rolling, then biology takes over and goes its own stately pace.

Audience: It's been observed in hypervelocity impact experiments that impacts do, indeed, give off magnetic pulses. I think you've identified another impact consequence—the magnetic pulse given off by the impact in the atmosphere could couple its energies into our existing flow of electrons in our society (long lines, power lines, radios, etc.). It's something that it ought to be looked at.

Audience: According to Billy Glass, who studied the problem, there are two cases in which there appears to be a very close correlation with a layer of impacts glass spherules and the reversal. One case is the last major reversal at 780,000 years ago. It's also very close to the time of emplacement of the Austro-Asian tektite shelf. And so that has been one of the reasons for suspecting there is a connection between impact and a reversal. The other case is a reversal that occurred about a million years ago. And this, too, is very close to a layer of microtektite that we know comes from a crater in Gant. The problem is that, in very careful recent studies, while the timing is close, it's not close enough. In fact, in each case, the reversal has preceded the tektite shower by a small amount.

Dr. Teller: By how much?

Audience: Well, typically by tens of centimeters of sediment, so it may be times on the order of tens or a few tens of thousands of years.

Dr. Teller: More questions?

Audience: Another point you might be interested in is that there was a well-observed magnetic pulse from a regular magnetic observatory associated with the Tunguska event.

Dr. Teller: The what?

Audience: The Tunguska fireball produced a known magnetic excursion.

Dr. Teller: *Very* good. Very good. You know, I have a proprietary interest in Tunguska. It occurred when I was half a year old.

The Shoemaker-Levy 9 Impact Plumes on Jupiter: Implications for Threat to Satellites in Low-Earth Orbit

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Computational simulations of the impacts of comet Shoemaker-Levy 9 (SL9) fragments on Jupiter have provided a frame work for interpreting the observations. A reasonably consistent picture has emerged, along with a more detailed understanding of atmospheric collisional processes. Several aspects of Earth-impact hazards can be re-evaluated with knowledge gained from observations and from simulations of SL9. In particular, the threat of impact-generated plumes to satellites in low-Earth orbit (LEO) should be recognized. Preliminary 2-D computational simulations suggest that impacts of a size that recur about once per century generate plumes that rise to nearly 1000 kilometers over an area thousands of kilometers in diameter. Detailed modeling of such plumes should be carried out to quantify this threat to satellites in the near-Earth environment. Careful observations of high-energy atmospheric entry events should be made using both satellite and ground-based instruments to provide validation for these computational models.

Introduction

The multiple impacts of comet SL9 fragments with Jupiter in July 1994 provided an historic opportunity to directly observe the phenomena resulting from hypervelocity collisions on a planet. Detailed analysis of this event has advanced our understanding of comets, of Jupiter, and of the collisional processes that shaped the solar system. This improved understanding can now be used develop better models for the assessment of the impact threat to Earth.

The principal reason we performed computational simulations of the SL9 impacts was to take advantage of a "natural experiment" to validate Sandia's shock physics codes, CTH and PCTH (McGlaun et al., 1990), for an impact involving velocities, masses, and kinetic energies many orders of magnitude higher than had ever before been witnessed. By simulating a natural astronomical event, the validation could be based on observational, rather than on experimental data. Additional reasons for our work were to 1) provide predictions to help guide astronomical observations of the event, and 2) assist astronomers in interpreting the observational data.

Prior to impact, the computational effort was focused primarily on making predictions. In the period between the recognition (in mid-1993) that SL9 would strike Jupiter, and the availability (in early 1994) of new astrometric data, the estimated point of impact was far on Jupiter's back side, and there was little hope for a direct view from Earth. After better orbital data put the impact point about six degrees over the Jovian limb, more attention was focused on the fireball/plume phenomena that had the greatest potential for being observable. By the time the comet arrived at Jupiter, there was general agreement among the impact modeling groups that, for sufficiently large impactors, debris ejected by the collisions would rise into line of sight of Earth (Zahnle and Mac Low, 1994; Stellingwerf et al., 1994; Ahrens et al., 1994; Boslough et al., 1994a,b; Shoemaker et al., 1995).

The fireballs and plumes predicted by the models were indeed observed, but the actual event produced a much richer array of consequences than anyone anticipated. Because of a massive international effort, an overwhelming amount of high-quality observational data was collected during impact week. Some of the new phenomena have already been explained and are fully consistent with the models. Interpretation of other observations will require further analysis and synthesis of the data. We expect that computational modeling will continue to provide guidance and contribute to our understanding of this event. Moreover, the simulations--coupled with observational results of the SL9 impact--will enhance our ability to predict the consequences of an comet or asteroid impact on Earth, leading to improved threat assessments. The purpose of this paper is to summarize a "big picture" interpretation that is consistent with much of the observational data that has become available to date (see: *Science, 267,* March 3, 1995, *Geophys. Res. Lett. 22(12),* June 15, 1995, *Science 268,* June 30, 1995, and *Geophys. Res. Lett. 22(13),* July 1, 1995), and to point out implications for impact hazard assessment on Earth.

SL9 observations

The geometry and timing of the series of impacts could hardly have been better for making useful observations from Earth (Figure 1). With the impact location only a few degrees beyond Jupiter's limb, the hot debris ejected by each collision had to rise only a few hundred kilometers to become visible. It could then be seen in profile, making it possible to observe its shape and size. The vantage point from Earth was close to perpendicular to the trajectory of the fragments, so that the effect of impact obliquity could be seen. Because the impact point was beyond the limb (horizon), the time of arrival of debris above the line-of-sight altitude could be measured. Combining this information with the time of impact extracted from direct measurements from Galileo (and in some cases from Earth), the fireball trajectory can be determined. The position of Jupiter (near quadrature) put the luminous debris in shadow when it first

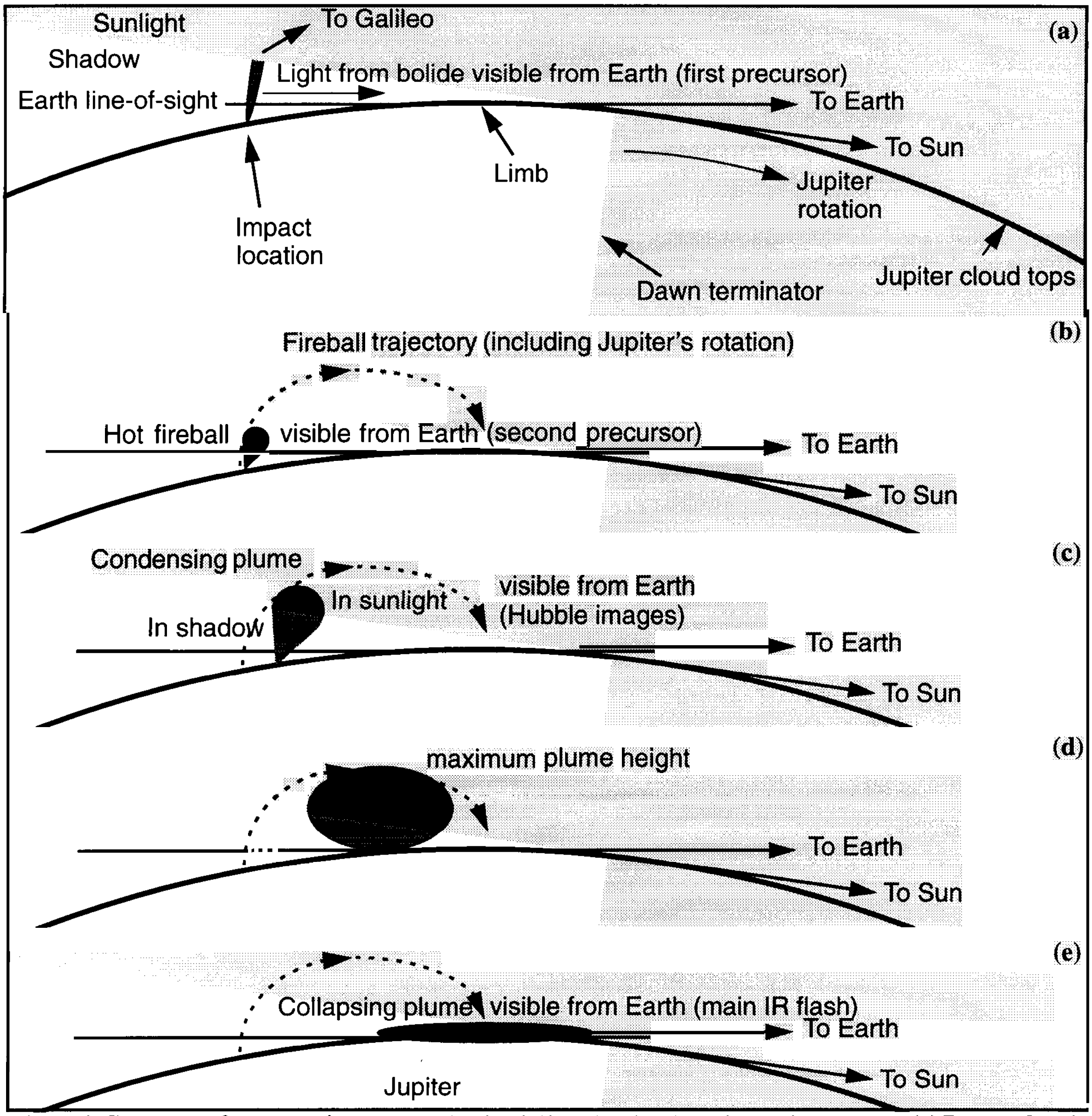


Figure 1. Geometry of impacts, just beyond Jupiter's limb (horizon) as viewed from Earth; (a) Dust and main fragment enter Jupiter's atmosphere, generating entry flash, (b) Incandescent fireball rises into view from Earth, (c) condensing plume ballistically rises into sunlight, (d) Plume reaches maximum altitude of about 3300 km above clouds, (e) Plume collapses and rotates into view (modified from Boslough et al., 1994b)

rose into view, making it possible to determine its brightness. This configuration also means that additional trajectory information can, in principle, come from the time of arrival of the fireball into sunlight. Morphology information can be extracted from the shadow-line on the plume. Furthermore, each impact site was on the side of Jupiter (near local dawn) that immediately rotated into view from Earth, giving the fireball a velocity component toward the limb, and making it possible to observe the pattern of debris and wave phenomena immediately after impact. This best-case impact configuration allows many direct comparisons to be made between simulations and observations.

The event took place at a time that was extremely fortuitous in terms of the instruments that could be used to make observations of the impact sites. The Hubble Space Telescope (HST) and the Galileo spacecraft were both available to complement Earth-based observations. HST happened to be in position to directly image the plumes from four impacts, and Galileo had a direct line of sight for all the impacts. HST images have provided information about the size, shape, evolution, and optical properties of the fireballs and plumes, and about the structure and evolution of the impact sites after plume collapse (Hammel et al., 1995). HST and Earth-based spectroscopy yielded evidence for water, ammonia, iron, silicon, magnesium, sodium, calcium, lithium, potassium, diatomic sulfur other sulfur compounds, carbon monoxide, and hydrogen cyanide at the impact sites (Noll et al., 1995, Bjoraker et al., 1994; Yelle et al., 1994; Maillard et al., 1995; Marten et al., 1995; Roos-Serote et al., 1995). Galileo has provided precise timing for the entry of many of the fragments into the atmosphere, as well as information about the expansion rates and cooling histories of the incandescent fireballs (Martin et al., 1995; Carlson et al., 1995; Chapman et al., 1995, Hord et al., 1995). The event timing as determined by Galileo measurements has provided a strong basis for interpreting the multiple flashes observed from Earth in a way that is consistent with the computational models (Figure 2)

We use the term "fireball" to refer to the mass of hot gases consisting of a mixture of Jovian atmosphere and cometary material that is ballistically shot upward by the impact. In the first moments after impact it is very hot, incandescent, and radiating in the visible and near infrared. The fireball is preceded by the "entry flash" or "bolide" phase, during which time the comet fragment (and associated debris) deposits its energy in Jupiter's atmosphere. The entry flash as seen from Earth may be dominated by the deposition of energy at very high altitude (above the limb) by small particles in the coma surrounding the main fragment, and for that reason its use as a timing fiducial may not be straightforward. The main fragment mass does not begin to deposit a large amount of energy until it has passed beyond the limb, after which it begins to heat an entry column of atmosphere as it loses its kinetic energy. It is that column of gas that explosively expands and becomes the fireball. We use the word "plume" to describe the debris cloud after it has expanded, cooled adiabatically, and begun to condense. Clearly, there are no precise temporal demarcations separating bolide, fireball, and plume phases.

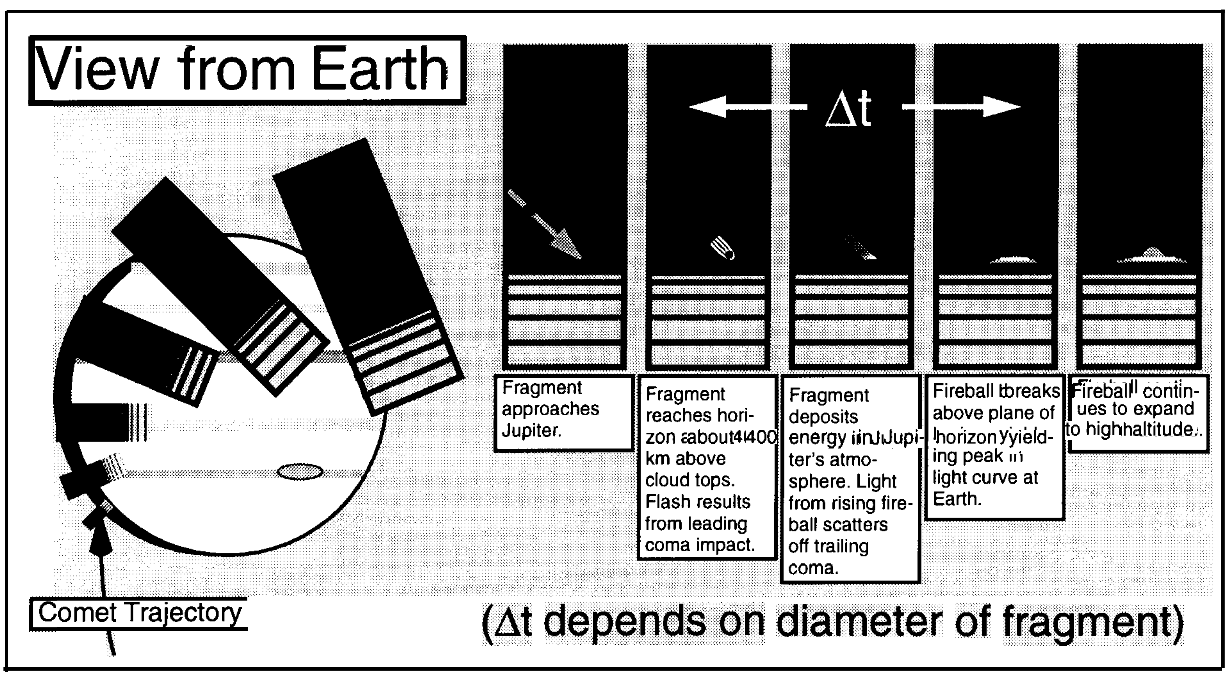


Figure 2 Cartoon representation of early part of impact/fireball sequence as seen from Earth, with method of constraining initial fireball trajectory. In reality, entry flash and fireball arrival times are blurred by dust and indirect light scattering.

SL9 interpretations

Figures 3 and 4 depict idealized schematic representations of the sequence of events inferred from Earth-based photometry data, Galileo light curves, and HST imagery. Figure 3 is a plan view of the impact site from a stationary (non-rotating) vantage point, with snapshots of a map projection of the evolving impact sites at various time steps after impact. As the point of impact rotates from west to east, it moves from left to right in the stationary field of view of the illustration. Jovian north is up; the approximately vertical lines represent the minimum line-of-sight altitudes to the Earth and sun. The figure is not intended to depict the exact geometry, nor is it supposed to represent a particular impact, but is a composite of features observed from various events. Figure 4 shows a simplified side view of the fireball/plume evolution. In reality, the ejecta cloud is not a discrete packet but a continuum with widely varying temperatures, densities, and pressures. In addition, the impacts were not necessarily the "clean experiments" described here, but probably involved closely-spaced multiple impactors embedded within a dusty, light-scattering cloud of smaller particles (coma), which also had a hypervelocity, light-producing interaction with Jupiter's atmosphere.

In the Figure 3 inset are some idealized examples of Galileo and Earth-based light curves. The Galileo Photopolarimeter Radiometer (PPR) curve is based on the measurements of several impacts at 945 nm (Martin et al., 1995). The upper Earth-based light curve resembles data at 3.5 μm collected at the Palomar Observatory by Nicholson et al. (1994) for the R impact; a similar curve was obtained by Graham et al. (1994) at 2.3 μm with the Keck Telescope, and for the K impact at 2.35 μm at the Okayama Astrophysical Observatory by Takeuchi et al. (1995). The lower curve is based on 10 μm data collected at the European Southern Observatory by Livengood et al. (1994).

The following is a description of the sequence of events, with letters corresponding to those in Figures 3 and 4. The various phases are defined primarily for conceptual purposes; there are not distinct demarcations between them, and in many cases they overlap. Approximate times relative to initial entry are listed for each phase.

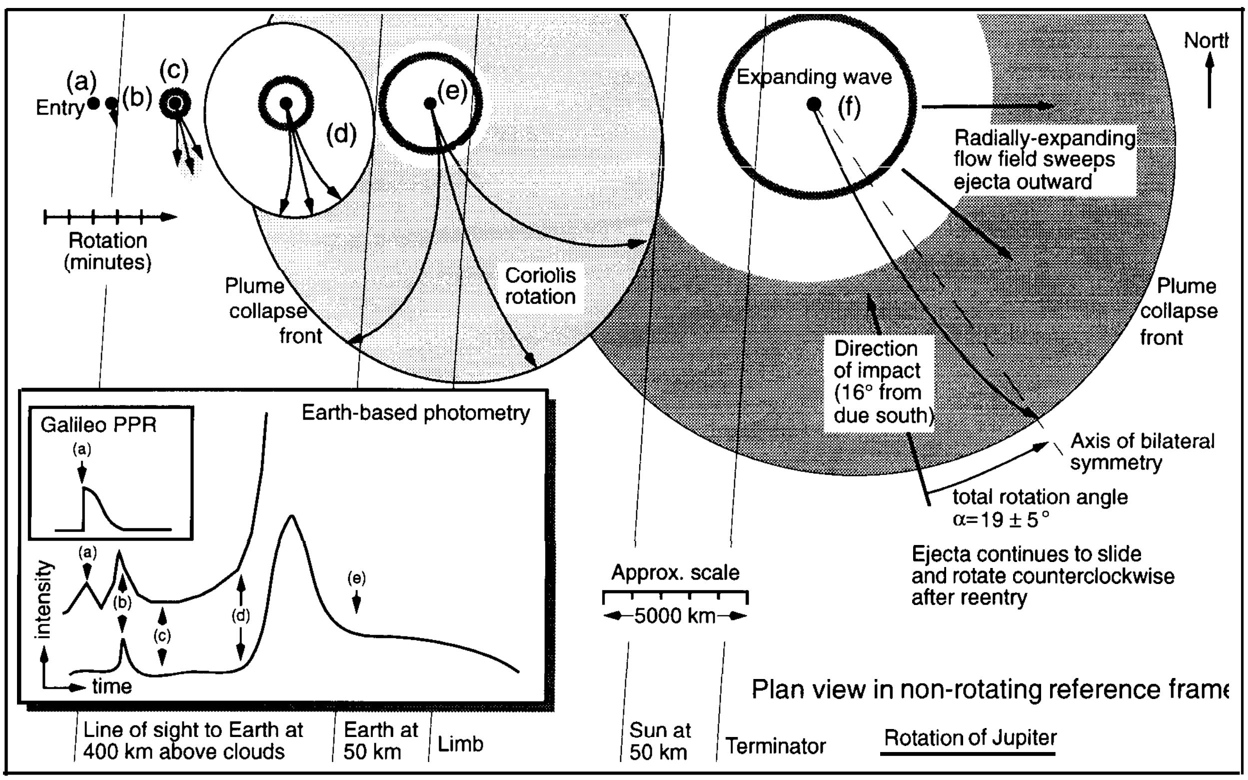


Figure 3 Plan view (map projection) of idealized impact site from a stationary (non-rotating) vantage point, with snapshots of a planar projection of its evolution, interpreted using the conceptual framework provided by computational simulations. This figure schematically represents features that were seen after several of the larger impacts. See text for detailed explanation (from Boslough et al., 1995).

(a) Entry phase (zero to 10 or 15 seconds)

A fragment (or cluster) enters Jupiter's atmosphere, depositing energy and leaving a debris column that consists of a mixture of Jovian atmosphere and cometary vapor at high temperatures and pressures. Thermal radiation from this column is seen directly by Galileo's instruments, and, for some impacts, via scattered light (or directly in the earliest stages) from Earth. This appears as the first precursor in some of the Earth-based light curves. The long risetime associated with this precursor is probably due to the direct view from Earth of the hypervelocity collision of the leading part of the coma into Jupiter's upper atmosphere.

(b) Fireball phase (5 or 10 seconds to 3 or 4 minutes)

The column explosively expands upward and outward along the atmospheric density gradient, cooling isentropically as it rises. The expansion begins instantaneously, before the entry phase is complete. This is seen by Galileo as a decrease in radiative intensity, and a shift toward longer wavelengths in thermal emission. Within one minute, the incandescent fireball rises to a few hundred kilometers and becomes visible from Earth, appearing as another precursor in photometry data. The exact timing depends on both fragment size and the point of impact, as summarized by Crawford et al. (1995). The fireball is preceded by several seconds by a shock wave. Earth-based detection of this shock would provide strong validation of the computational models, but it may be too weak to have been seen as an independent precursor. The arrival time of hot material above the Jovian limb, as viewed from Earth, is probably blurred by fireball light scattered from trailing coma material.

(c) Plume phase (3 or 4 minutes to 10 or 15 minutes)

The debris continues to rise ballistically. It expands and cools, and begins to condense. When it reaches an altitude greater that one or two thousand kilometers (depending on the point of impact), it enters sunlight. Careful analysis of time-resolved photometry might provide the timing for this event, which would be useful for reconstructing the ballistic trajectory.

(d) Maximum height (between about 6 and 9 minutes)

The lower part of the debris cloud begins to collapse and heat Jupiter's stratosphere. As the front of this heated region propagates and rotates over the limb, the strongest peak in the Earth-based light intensity curves begins to appear.

(e) Plume collapse phase (about 5 to 15 minutes)

As the still-expanding debris cloud begins to fall back, it compresses and heats a large area of the Jovian stratosphere. The heated region grows rapidly. The peak in Earth-based photometry curves is determined by a combination of competing effects, including increasing area, radiative and decompressional cooling, and viewing geometry.

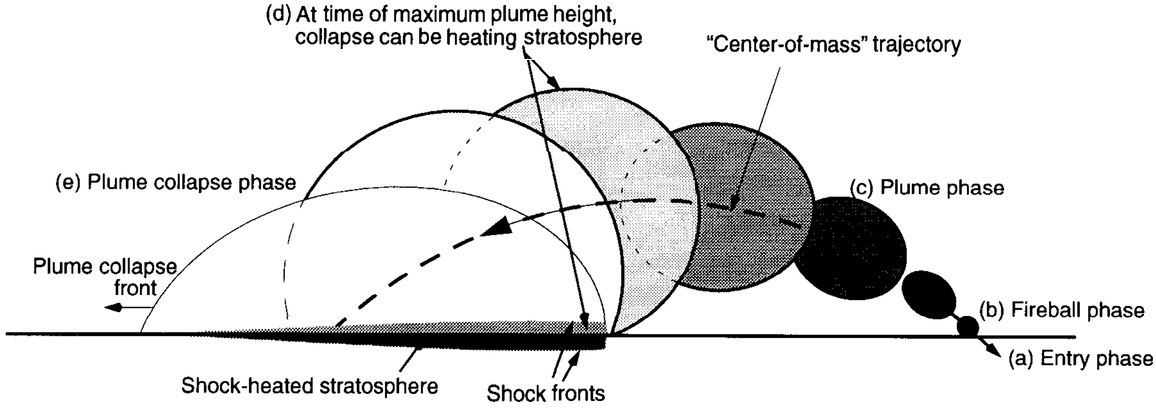


Figure 4. Side view of highly idealized fireball/plume evolution which leads to a "hypervelocity splat" when the plume collapses, heating Jupiter's upper atmosphere over a very large area. This schematic shows the ejecta cloud as a discrete packet, rather than the continuum it really is (modified from Boslough et al., 1995).

Recently-downloaded data on the R impact from Galileo's Near Infrared Mapping Spectrometer (NIMS) has now provided direct evidence for stratospheric heating from the collapse of the plume, and timing information for that event (Carlson et al., 1995). The expanding debris cloud rotates counterclockwise due to the Coriolis Effect, so the ejecta footprint's symmetry axis does not line up with the fragment trajectory. The outwardly-directed velocity component sets up a radially-expanding flow field that sweeps condensed matter outward.

(f) Post-collapse "splat" phase (about 15 to 45 minutes)

The plume collapse goes to completion. The fully-collapsed ejecta blanket continues to expand radially and rotate counter-clockwise until stopped by viscous and other dissipative forces. The final angle between the impact trajectory and axis of bilateral symmetry depends on how much rotation takes place after the plume collapses. The post-collapse rotation is evidence that ejected material flows horizontally over very long distances after reentry, and indicates that the ejecta blanket also expanded radially. A linear, radially expanding wave is made visible by an unknown mechanism, possibly condensation in the rarefaction part of the wave.

(g) Upwelling phase (minutes to hours)

The computational models indicate that there is also an upwelling phase. Careful examination of the 3-D simulations of Crawford et al. (1995) reveals that for massive, deeply-penetrating impactors, a bubble (or several bubbles) of hot Jovian atmosphere mixed with cometary vapor rises buoyantly from the depth of maximum energy deposition. This is between 200 and 300 km beneath the 1 bar level for 2-3 km diameter fragments. At 82 seconds after impact for a 1-km impactor there are three or four instabilities developing between about 50 and 200 km below the 1 bar level. At this time, they are 20-30 km in diameter, and have risen by about that distance from their starting point. These bubbles are analogous to buoyant nuclear explosion fireballs. Extrapolation of their upward motion suggests that they will begin arriving at the ammonia cloud layer within minutes, after having adiabatically expanded to many times their size. The resulting massive displacement of atmosphere is a likely source for the expanding wave. The upwelling might also manifest itself as thermal brightening or appearance of new spectroscopic signatures at the impact sites. It may be possible to extract information about the penetration depth (and therefore fragment mass) from the timing, temperature, and composition of any buoyantly -upwelling material. High-resolution 3-D simulations of this buoyancy phase are clearly needed.

SL9 computational simulations

Crawford et al. (1995) used the CTH Eulerian shock-physics code to simulate two- and three-dimensional representations of the impact events. The 2-D computations were of the penetration phase, simulating the entry, deformation and breakup of the impacting comet fragments. The calculations were performed in a "reverse ballistic" sense using a Jovian atmosphere moving upward at 60 km/s impinging upon an initially stationary fragment. The Eulerian mesh extended 100 km radially and 1000 km above and below the comet. The fragment was maintained in a high resolution portion of the mesh (equivalent to 25 computational zones across the projectile radius and extending 10 km vertically and 5 km radially) by Galilean transformations of the entire mesh every 0.1 seconds of simulation time. Zone size gradually increased away from the high resolution portion of the mesh to preserve all the materials of the calculation yet maintain computational efficiency.

The comet fragments in the simulations were composed of water ice with initial density and temperature of 0.95 g/cm^3 and 100 K, respectively, using tabularized version of the ANEOS equation-of-state which allows melting and vaporization (Thompson, 1989). The atmospheric stratigraphy in the calculations matched Voyager data for Jupiter at high altitudes (Orton, unpublished data) and extended adiabatically to lower altitudes. The atmosphere consisted of 89% hydrogen and 11% helium at all altitudes and was modeled with a tabular equation-of-state allowing dissociation and ionization (Kerley, 1991). It was scaled vertically by a factor of 1.41 (to account for the approximate 45° entry angle) and inserted into the lower portion of the computational mesh. The atmosphere propagated into the upper portion of the mesh as the comet deformed and broke up in the higher-pressure regions of the lower atmosphere.

During entry into the low density outermost reaches of the atmosphere, the projectile forms a clean bow shock. Atmospheric temperatures at the leading edge of the projectile reach values as great as 35,000 K. During deformation, the projectile thins and the leading edge flattens. Acceleration instabilities develop (Swegle and Robinson, 1989). Eventually, projectile thinning meets with the growing instabilities and breakup occurs. During penetration, the projectile continuously gives up kinetic energy to heating and deflection of the Jovian atmosphere (a relatively small amount goes towards internal heating of the cometary constituents). Crawford et al. (1995) determined the total energy deposited by hypothetical 1-, 2- and 3-km diameter cometary fragments during their penetration of the Jovian atmosphere. An important result for fragments between 1 and 3 km in diameter was that most their kinetic energy and mass was deposited beneath Jupiter's outermost visible cloud layer, which is about 10-15 km above the reference altitude at 1-bar. Because most of the fragment's mass is deposited at depth, less than 1% is entrained in the upwardly growing fireball. Crawford et al.(1995) also investigated the influence of fragment body shape on the energy deposition profile, and tested for sensitivity to numerics by performing the same calculations with different resolutions.

The final results of the Crawford et al. (1995) fireball simulations are shown in Figure 5 for the impact of a 3-km diameter fragment. For this calculation, the results from the two-dimensional entry, deformation and breakup studies were inclined at 45° and mapped into a three-dimensional representation. Three-dimensional, bilaterally symmetric simulations most accurately rendered fireball evolution beginning about 10-15 seconds after first contact of the fragment with Jupiter's atmosphere. Density, temperature, fluid velocity and pressure of the cometary debris and shocked Jovian atmospheric constituents were preserved in a spatially average sense while total energy is conserved. The calculation was allowed to evolve for up to 120 seconds. Generally, the simulation results indicated that early-time fireball growth is predominantly directed outward along the incoming bolide trajectory but is redirected, at later time, towards growth dominated by the vertical gradient of the Jovian atmosphere. In order to attain adequate resolution for these large fireball simulations, the calculations were performed on the 1840-processor Intel Paragon massively par-

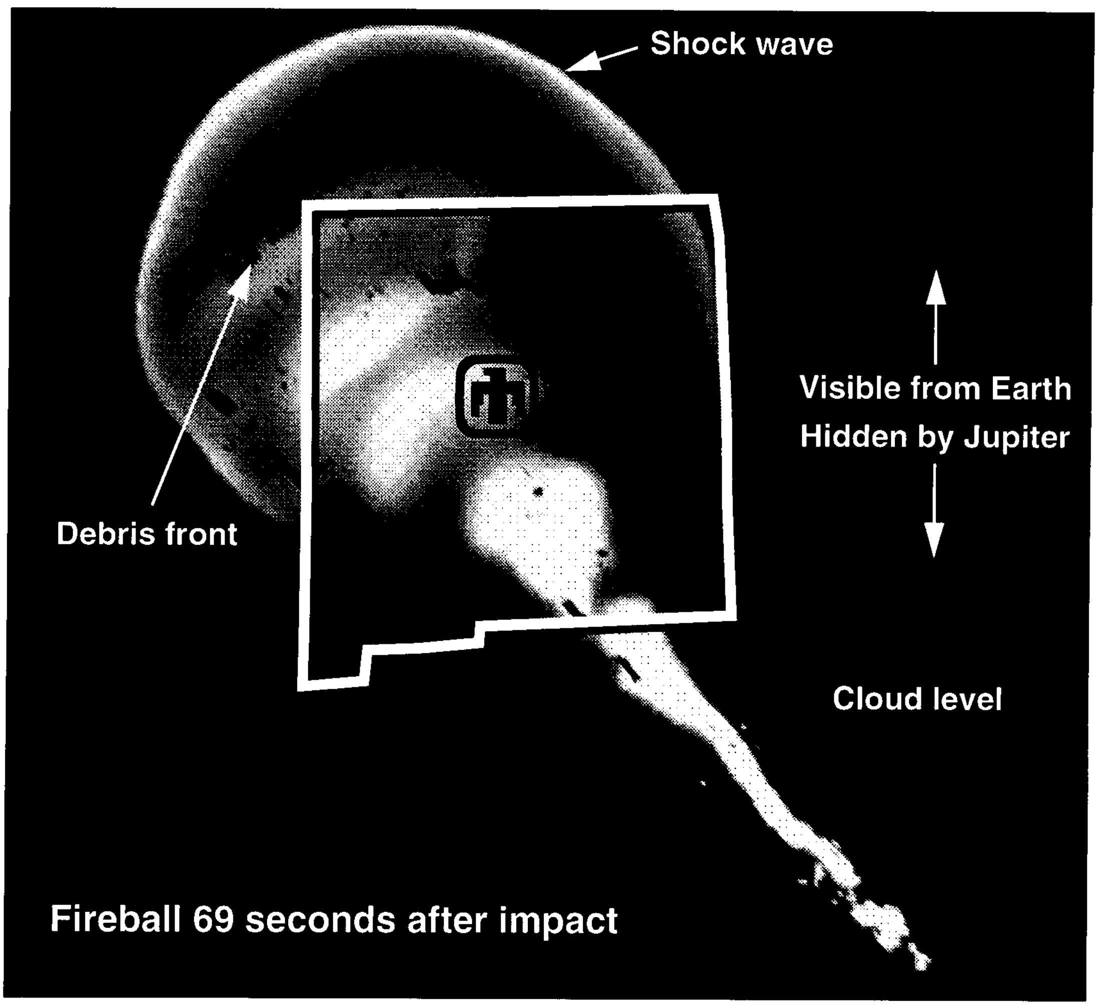
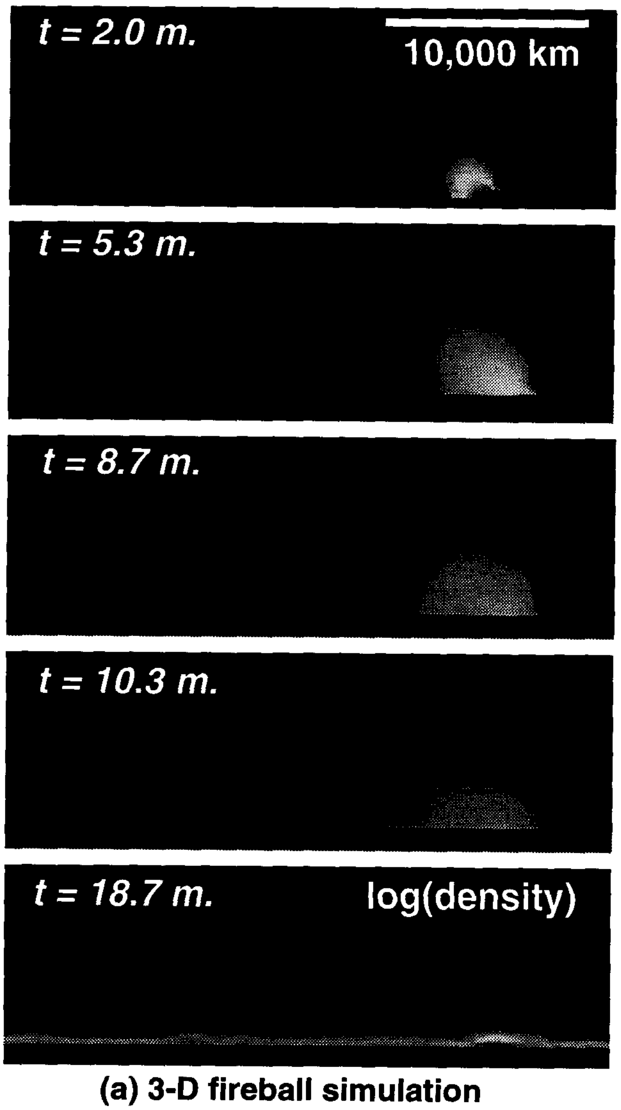


Figure 5 Cross-section of simulated fireball from the impact of a 3 km-diameter fragment of ice into Jupiter at 60 km/s, using state of New Mexico for scale. Temperature is represented by grayscale, with highest temperatures at this time step of about 2200 K (modified from Crawford et al., 1995).

allel supercomputer at Sandia National Laboratories. The simulation of the fireball formed by the impact of a 3-km comet fragment consisted of 8 million 5-km cubical zones. Lower energy events, formed by the impact of 1- or 2-km fragments, were modeled with more finely resolved, but less spatially extensive, simulations.

The fragment deposited (as internal energy of H_2, He and H_2O vapor) more than 95% of its kinetic energy (6 million megatons) during its penetration of the Jovian atmosphere (a comparatively small amount remained as kinetic energy of cometary water vapor). The fireball and surrounding shock wave resulting from a 3 km impactor is shown about 69 seconds after impact. The spherical shock wave is advancing upward at a velocity of 25 km/s. It has reached a diameter of 700 km and an altitude of 900 km above the clouds. For reference, the Jovian cloud tops are located at an altitude of 10-20 km and the limb of Jupiter (as seen from Earth) varies as a function of impact location. The limb position for impacts occurring 4 and 6 degrees beyond the limb were at 200 and 400 km altitude, respectively.

The fireball itself is a rapidly rising cloud of cometary debris and Jovian atmosphere at high temperature. Sixty-nine seconds after the impact of a 3-km cometary fragment, the fireball is still at 1700 K, and the shock wave temperature is 2300 K. An optically-thick fireball would have had an apparent bolometric magnitude (as viewed from Earth) of about 2 at this time. The observed fireballs were significantly dimmer, implying they were not optically thick.



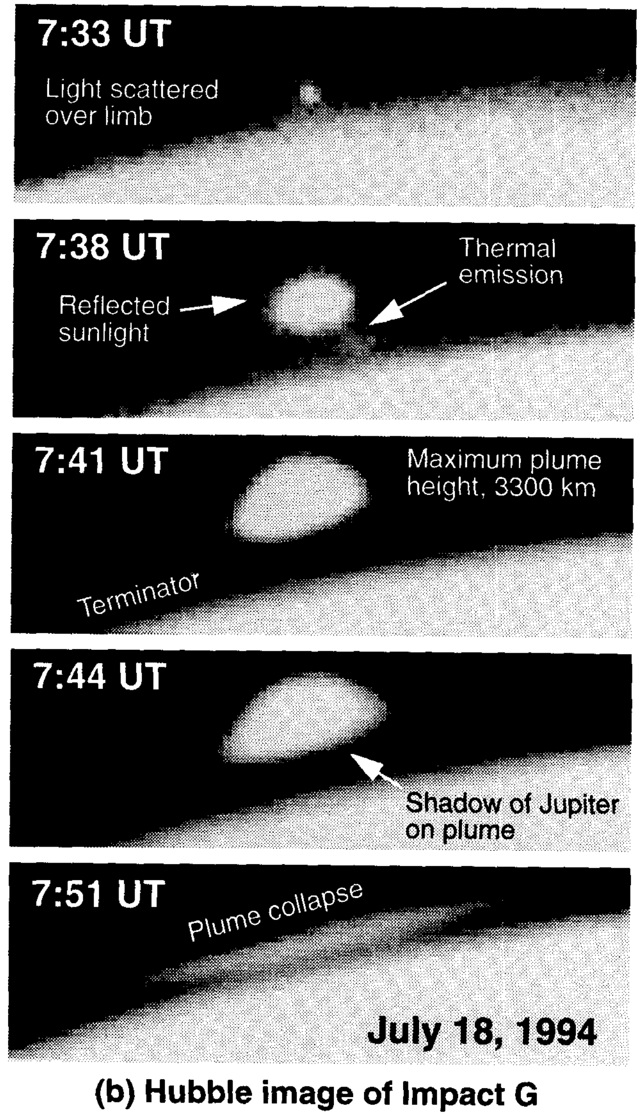


Figure 6. (a) Simulation of 3-D fireball/plume evolution after the impact of a 3-km diameter fragment. Shading indicates log(density) with a cutoff at 10^{-12} g/cm3; times are in minutes after impact (from Crawford et al., 1995) (b) Sequence of G plume images collected by Hubble Space Telescope (from Hammel et al., 1995).

We have been calling this hot debris cloud a fireball, but the differences between it and other closely-related phenomena should be outlined. Analogies to the fireball associated with the detonation of a nuclear device are limited. The development of a nuclear fireball is dominated by interior radiative transport at temperatures of tens of millions of degrees. Some fraction of this energy forms a shock wave in the atmosphere, which separates from the fireball but can still be luminous if strong enough. The shock wave generated by the impact fireball is similar to the outer, mechanically-driven nuclear blast wave, but the temperature of the impact-generated shock wave is higher at a given propagation distance because the energy source is about six orders of magnitude greater than a megaton-scale nuclear device. The fireball itself is a ballistically-rising mixture of shocked atmosphere and vaporized cometary material. A nuclear fireball that is small compared to the scale height of the atmosphere will be driven upwards by buoyant forces because it is less dense than the surrounding atmosphere. A large impact fireball can be much greater than the scale height of the Jovian atmosphere. Because the atmospheric pressure is much greater at the bottom than at the top, it is contained at depth and relatively uncontained at altitude. It, therefore, accelerates upwards as if shot from a gun. Even though its density is much greater than the surrounding atmosphere at the top, its inertia will carry it on a ballistic trajectory which rises as much as several thousand kilometers above the clouds.

Preliminary 3-D simulations of plume evolution following the impact of a 3-km diameter ice fragment provide support for many of the interpretations presented in the previous section. Figure 6 shows that, over a period of about twenty minutes, the plume rises to its maximum height and collapses over a large area, shock-heating the upper atmosphere to temperatures on the order of 1000 K. In this simulation, the plume reaches an altitude nearly twice that observed for several plumes (including the G plume) by HST. When comparing the simulated with the observed plumes one must consider the fact that the observed plume height partially depends on the minimum density at which the debris cloud begins to condense and scatter sunlight. The diameter of the high temperature fallback region is about 30% larger than the dimensions of the G impact site. This suggests that the G fragment (or swarm of fragments) had a diameter of somewhat less than 3 km at the time of entry.

Implications for Earth-impact hazard assessment

Figure 7 suggests that the physics of atmospheric entry and plume generation is similar over many orders of

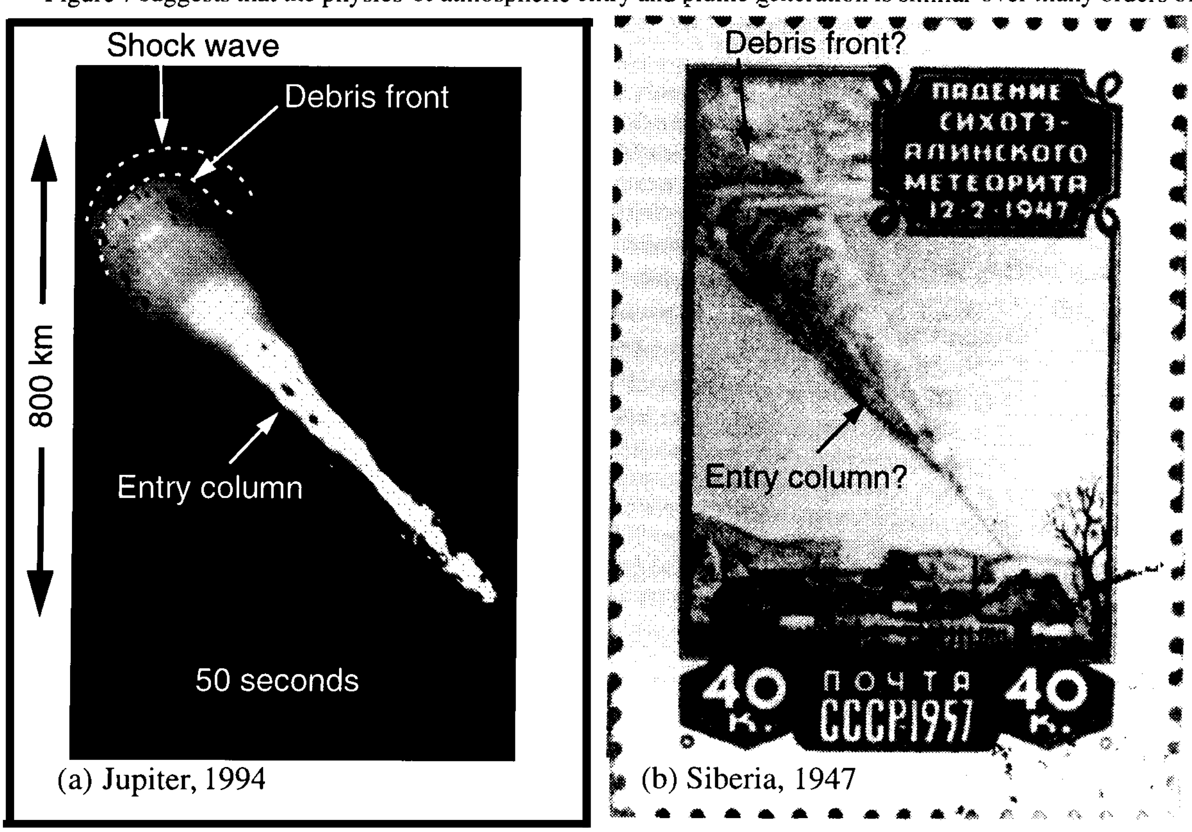


Figure 7 Comparison of (a) 3-D simulation of impact of 3-km diameter fragment on Jupiter, 50 seconds after entry (from Crawford et al., 1995) with (b) artist's depiction of 1947 Sikhote-Alin impact.

magnitude in the scale of impactor kinetic energy and physical size. The figure makes a direct comparison between the Crawford et al. (1995) 3-D fireball simulation and an eyewitness artist's depiction of the February 12, 1947 Sikhote-Alin fireball in Siberia. The Sikhote-Alin impact energy was 10-20 kilotons (Nemtchinov, 1995), whereas the simulated fireball is from a 6 million megaton impact event, nearly a billion times as energetic. The simulation image shows the explosion 50 s after the impact of a 3-km diameter fragment on Jupiter, and the illustration of the Siberian event, commemorated on a tenth-anniversary Soviet postage stamp, was recorded on canvas by artist Medvedev immediately after the fall. If the feature depicted by Medvedev represents the debris in the entry column and rising incipient plume, then its resemblance to the Jovian event implies that atmospheric impact explosions behave similarly over many orders of magnitude.

The simulations and observations of the impact of SL9 raise some issues that relate to the impact threat to Earth. In addition to demonstrating that large objects do indeed collide with planets, the series of impacts has shown that ballistic impact fireballs and plumes are ejected to very high altitudes, and that explosive expansion of shocked atmosphere along the entry column is highly directional and poorly modeled by point explosions. These observations lead to the suggestion that satellites in low-Earth orbit (LEO) may be vulnerable to ejection of material into their environment by an impact into the atmosphere. Because of the high orbital velocities of these satellites (about 7 km/s), even a very low-density plume ejected into their path would be catastrophic. For a vapor plume, a satellite/plume interaction would be similar to an atmospheric reentry. At best, an interaction with a very low-density plume would cause a change in the attitude and orbit of the satellite. A worse outcome would result from a higher-density plume, which could cause premature reentry or otherwise destroy the satellite. For a plume containing particles of condensation, like those generated by SL9, the interaction would involve numerous hypervelocity impacts similar to those occasionally experienced with space debris and micrometeorites. This would most likely end the life of the satellite.

Computational modeling of Earth-impact plumes

To test this idea, we have performed preliminary 2-D simulations of the plume generated by a 34-m diameter stone (density=3 g/cm^3) impacting at 20 km/s with vertical incidence. The kinetic energy of the impactor is equivalent to an explosive yield of 3 Megatons of TNT, and the expected frequency of such an event is about once per century (Morrison et al., 1995). The simulation was performed using the CTH shock physics code (McGlaun et al., 1990) by inserting an appropriate impact energy deposition curve into a gravitationally -stabilized, stratified Earth atmosphere, using the 1976 U.S. Standard Atmosphere (NOAA, NASA, USAF, Washington D. C., 1976) density profile. The energy deposition curve was calculated using the model of Crawford (1995) which assumes negligible radiative ablation for 10+ m objects in Earth's atmosphere (as required by momentum conservation) and hydrodynamic deformation governed by long-wavelength Kelvin-Helmholtz instability. This model has been calibrated with results of entry simulations using CTH.

The energy was inserted as 100 discrete energy sources with appropriate magnitudes along the axis of symmetry from 120 km to the surface. The individual "point charges" were set off sequentially, beginning at the top, and initiating downward with the velocity of the projectile, accounting for its deceleration as it descends into the atmosphere. This method of energy insertion effectively simulates the entry column as a line charge of varying energy density.

A time sequence showing the results of the simulation is given in Fig. 8(a). The shading indicates material velocity magnitudes, ranging from 100 m/s to 3 km/s. Immediately after entry, the meteoroid has deposited its energy in a long column, with a sharp peak in the energy deposition curve at an altitude of 7 km. The column begins to expand explosively the instant that energy is deposited in the column, so by the time the object reaches the bottom, the top of the column has had time to expand and accelerate upwards. When the main fireball begins to develop lower down, it expands most easily up along the low-density, high-sound-speed column that is already moving upward. In this way, much of it's mass is accelerated and launched into space as a "ballistic fireball". At about 100 seconds after atmospheric entry, the top of the plume (as defined by the 120 km density contour) has reached an altitude of nearly 300 km, and is still moving upward at a velocity of about 3 km/s (the "fingers" protruding from the top of the plume are an artifact of numerical instabilities resulting from the relatively low resolution used for this simulation). Ballistic extrapolation indicates a peak plume height at about 800 km, putting it across the path of many satellites in LEO. The plume will have a "hang time" greater than 10 minutes; during this interval it will obstruct any satellite passing overhead. Furthermore, it will continue to expand radially during this time to cover a region thousands of kilometers in diameter. Observations and simulations of the plume collapse on Jupiter imply that the atmospheric density contours in the region of collapse will remain elevated for a much longer period of time, posing a further risk to satellites entering the area.

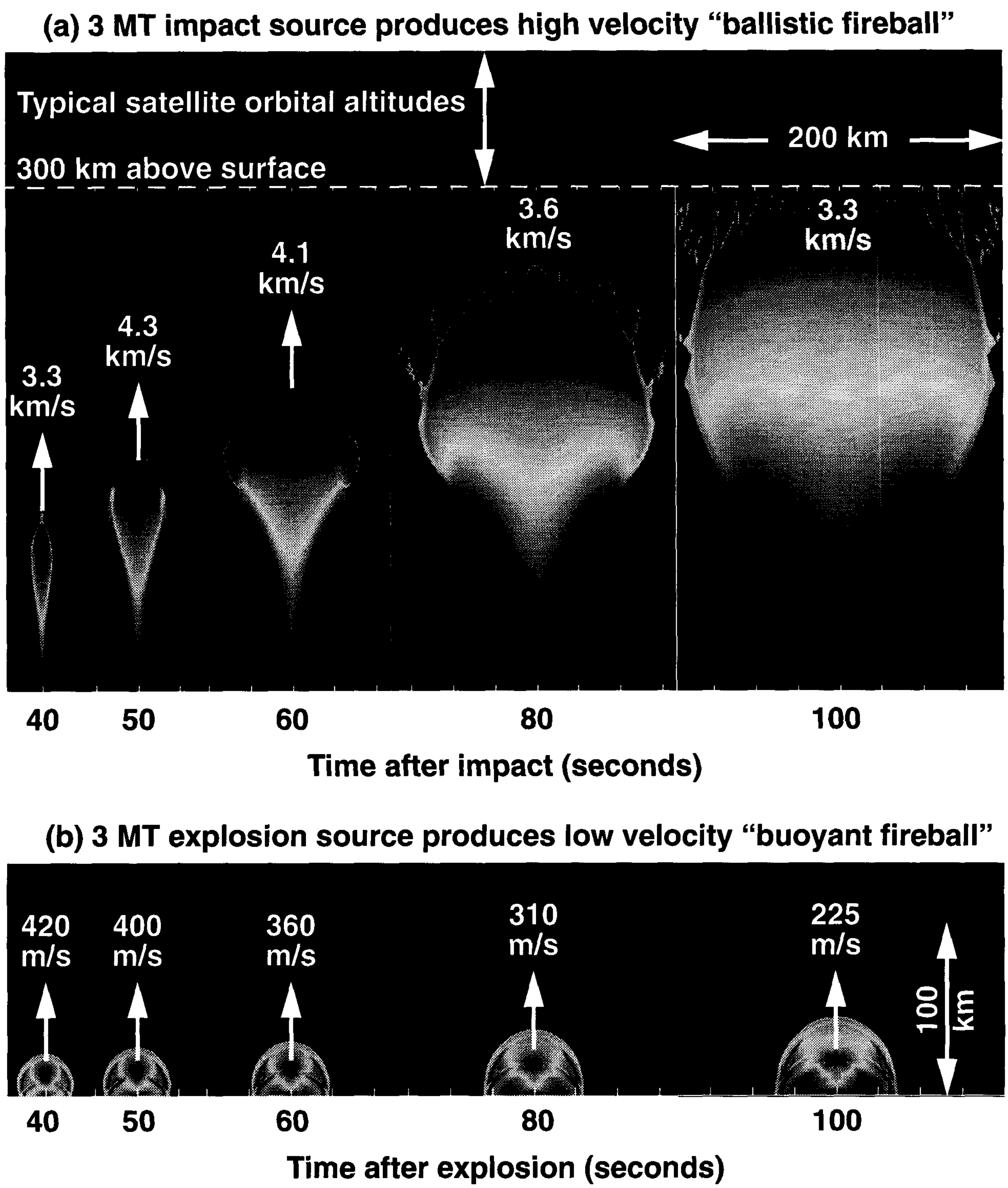


Figure 8. Comparison on the same scale of evolution of (a) ballistic fireball generated by 3 megaton impact to (b) buoyant fireball generated by a 3 megaton explosion at same altitude of maximum energy deposition (7 km). Shading indicates velocity magnitude of the air as indicated in the text.

For comparison, we simulated a point source explosion of 3 MT in the same Earth atmosphere. We kept all other conditions identical and inserted a single energy source at an altitude of 7 km, the point of maximum energy deposition for the entry calculation. Figure 8(b) shows that no plume has formed by 100 s after the start of the calculation, suggesting that the point explosion is well-tamped by the overlying atmosphere, and more realistic linear energy sources are much more efficient at generating plumes. The upward velocity of the fireball is lower by an order of magnitude, and it was necessary to redefine the velocity shading scale in order to see it in these plots (shading ranges logarithmically from 0.5 to 400 m/s). The mass motion in this case is dominated by density, and results in a "buoyant fireball" typical of free-air burst nuclear explosions.

Observational validation

The impact of SL9 underscores the importance of observational validation of impact modeling. It is probably not realistic to expect another opportunity to watch a comet collide with Jupiter, an event that probably only happens once in a period ranging from 200 to 10,000 years (Shoemaker, 1995). A more reasonable plan would be to attempt to gather as much information as possible about the smaller atmospheric impacts that are continuously taking place on Earth. If the physics of atmospheric entry and plume formation is indeed similar at scales that are different by more than 9 orders of magnitude, then careful, quantitative measurements of impacts that take place at intervals of a year or less would give entry and impact models the degree of validity necessary to allow their use as a basis for hazard assessment. To accomplish this task, we recommend a coordinated campaign based on a combination of satellite sensors and Earth-based observations. Infrared and visible-light sensors on satellites operated by the U.S. Department of Defense have already detected over a hundred events (Tagliaferri et al., 1995), including the February 1, 1994 bolide over the South Pacific with an estimated energy of 40-70 kilotons (Nemchinov, 1994). Microbarograph records are particularly useful in characterizing the explosive yield of large impact events, and have recorded an explosion as large as 1.1 megatons for the October 3, 1963 bolide over the ocean south of Africa (Revelle, 1995). Other sources of data that can be used to validate the simulations are photographic and video images (e.g. Ceplecha, 1994; Brown et al., 1994), and seismic data.

There is one major drawback in all the above methods as they have been used to date: the events they observed were not predicted in advance. Therefore, the instrumentation was operated in "open shutter" mode, or set to trigger off of the event, or relied on serendipity. By contrast, the impact of SL9 was predicted a year in advance, and observing plans were carefully assembled well in advance of the event, resulting in the collection of vast amounts of high-quality data. We suggest a similar strategy would be most useful for validation of Earth impact models. A ground-based search system capable of providing short notice of an impact in the 100 kiloton range would mean that the approaching object could be characterized before impact. Moreover, arrays of sensors, cameras, and satellite observing plans to be quickly put in place so that data from the event could be captured and used to provide quantitative validation.

Conclusions

Preliminary computational analysis suggests that satellites at low altitude are at significant risk from plumes due to impacts as small as a few megatons. This conclusion is based on the insight, physical understanding, and model validation gained from observations of the impact of comet Shoemaker-Levy 9. This newly-recognized threat should be examined by further modeling and by extensive observational validation by gathering data on the continuous impact flux of smaller objects.

Acknowledgments

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Comet Shoemaker-Levy 9, A New Class of Object

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The Comet SL9 has high abundance of sulfur and low abundance of H_2O, CO and nitrogen, but most of the fragments were embedded in circularly symmetric inner comae from July 1993 until late June 1994, implying that there was continuous and weak outgassing activity. It indicates that the comet SL9 is a new class of object which is different from those known comets and asteroids. The main features of SL9 are: 1) low abundance of H_2O, CO and nitrogen; 2) high abundance of sulfur; 3) existence of central coherent body, not swarm of debris; 4) fragile nature; 5) low albedo; 6) containing carbonaceous and silicate material; 7) low-volatile object and 8) inhomogeneous distribution of volatile material in the parent body. The existence of this new class of object - SL9 indicates the variety of the objects in the solar system.

The comet SL9 was obviously a complex body. No gas was ever observed in the comet, despite extreme efforts to detect the usually strong cometary CN line with the ESONTT (West, 1994). Most of the fragments were embedded in circularly symmetric inner comae from July 1993 until June 1994, implying there was continuous and weak outgassirg activity. Here are some points favourable and unfavourable for the viewpoint that the SL9 was a comet.

The evidence that is favourable for that SL9 was a comet is as follows:

- Some of the fragments continued to break up after the tidal disruption of the parent body of SL9, this fragile nature is consistent with other observations of cometary nuclei.
- The existence of persistent, symmetric coma around each fragment, possibly indicating continuous and weak outgassing activity (Weaver et al, 1995).

The evidence that is unfavourable for that SL9 was a comet is as follows:

- There are high abundance of sulfur (S) and low abundance of nitrogen (N), CO and H_2O. After the collision of comet SL9, the UV spectra obtained with the HST by (Noll et al,1995) identified that the most remarkable result is the large abundance of S-containing molecules, particularly S_2 and CS. The mass of S_2 in their small aperture alone approches the total mass of S they would expect from a 10^{15}g cometary impactor. They expect slightly more S from an asteroid impactor, but the enhancement is by no more a factor of 2. The S/N ratio in the observed debris after impact of SL9 apparently exceeds 100, whereas in any location on Jupiter the most likely value for the S/N ratio is < 0.16 and in a comet the S/N ratio is about 2. Before the collision of comet SL9, no gas ever observed in the comet, despite extreme efforts to detect the usually strong cometary CN lives with the ESONTT (West, 1994). Spectra of the SL9'S fragments from the 3.6meter CFHT and 10meter Keck telescope were obtained to search for gas (OH, CN, N_2^+, CO^+) in the 3000 Å to 4500Å wavelength region by Jun Chen et al, but no evidence for emisson was found (Chen, 1994). The above facts indicate that there were large abundance of S and low abundance of N, CO and H_2O. Oxygen containing molecules (CO, H_2O, SiO and others) were conspicuous by their absence (Noll et al, 1995).
- In addition, according to Chodas and Yeomas (published at DPS meeting on October 31, 1994), SL9 most likely came from the inside, i.e. via the asteroidal belt and
- According to (Rettig et al, 1995), they estimate the characteristic dust grain size of order of 10 to 100 μm and its outflow velocity of 3meters/sec. In cometary outflows measured in other comets, the emitted dust grains leaving the SL9 fragment are unusually large with considerably lower velocities.

From the diversity of the impacts and their observed effects, there were obvious differences between the individual fragment of SL9. Generally, the off-train fragments produced less obvious ejecta patterns than their brightness would expect. It implys the off -train fragments contained more volatile material and were more fragile that the on-train fragments. More volatile material in the off -train fragments could release relatively more dust and increase their observed brightness. It might indicates the inhomogeneous distribution of volatile material in the parent body of SL9.

It indicates the SL9 was different from the known comets which have high abundance of volatile material H_2O, CO, NH_3 and others. The existence of the SL9's comae, implying the continous and weak outgassing activity, was also different from the features of the known asteroids. It has been suggested that the SL9 was an object of a new class (Wang, 1994). The existence of this new class of object indicates the variety of objects in the solar system.

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Colliding Asteroids with very Short Warning Time

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There are many collision asteroids approaching the Earth with very short warning time, and especially, when the asteroids approch the Earth from a blind celestial area surrounding the Sun (here, we tentatively define the area within 30° from the Sun), they can not be detected at all by ground-based observations because of bright sky-background brightness. Our estimation show that a percentage of the asteroids approaching from the blind area in the total asteroids approaching the Earth with the closest distance less than 0.01 AU is larger than 30% which is very dengerous situation.

Introduction

In July, 1994, many fragments of the comet Schoemaker-Levy 9 (SL-9) collided one by one with the Jupiter. Because of these big events, public people are given a deep understanding in possible comet and asteroid collisions with planets including our own Earth. There is an estimate that a collision probability of objects with a size of SL-9 with the Jupiter is onece a thausand year. Since a mass of the Earth is only one thausandth, its probability with the Earth is much smaller. However, there are certain evidences that collisions of asteroids with the Earth happened and there is a certain probability of the collisions in future. When an asteroid with a diameter larger than 1 km will collide with the Earth, a global catastrophie will follow.

When an asteroid is discovered at only a few weeks prior to its collision (we call it as a warning time), we have no way to escape a global catastrophie except bombing atomic bombs thrown by misiles on its surface. However, to proceed this certainly, we have to keep always misiles and atomic bombs at a stand-by condition. A big budget has to be uselessly payed during a period without its collision.

We discovered a large fraction of collision asteroids with very short warning time of a few days. These will be shown in this paper.

Asteroids approaching the Earth from Blind Drections

The space-guard project is a project to set up a network of 5 ground-based telescopes with an aperture of 2.4m. Because of ground-based telescopes there is a blind celestial area which is directions surrounding the Sun (here, we tentatively define the area within 30° from the Sun). We have to observe an asteroid approaching the Earth from the area only during a day-time and therefore can not detect it because of bright sky background. We found that a percentage of the asteroids approaching from the blind area in the total asteroids approching the Earth with the closest distance less than 0.01 AU is larger than 30 %.

Since 1988 when a detection observation of near-earth-asteroids (NEA) was started, using the space-watch telescope of the University of Arizona, a number of detected NEAs is a few tens per year and over 200 at the end of 1993. Most of them have relatively large values of an eccentricity different with those of asteroids distributing within the asteroid belt. Therefore, they cross an orbit of the Earth not only from the outer part but also from the inner part.

One of authors (MY) calculated orbital motions of many asteroids and analysed close encounters between asteroids and planets (Yoshikawa and Nakamura 1994, Yoshikawa 1994). Yoshikawa (1994) calculated positions of 188 NEAs detected till 1993 during a period from 1994 to 4600. In our study, we analyse close encounters between asteroids and the Earth using the results of Yoshikawa (1994).

Figure 1 shows motions of three typical asteroids relative to the Earth where X axis and Y axis are a direction of Sun-Earth line and its perpendicular direction, respectively. It is shown by dashed and dot-dashed lines for cases when the asteroids overtake the Earth. For both the cases, relative velocities between each asteroid and the Earth are small. For case shown by solid line when e is large, an orbit of the asteroid crosses that of the Earth, and it comes from a direction near the Sun.

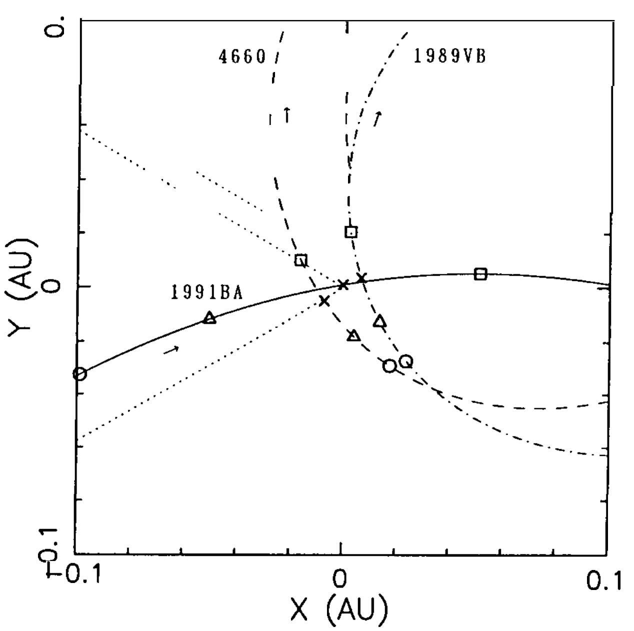

Figure 1. Motions of three asteroids near their closest approach relative to the Earth. X and Y axis are a directions of Sun-Earth line and its perpendicular direction. The Earth is at (X,Y)=(0,0). Positive values of X and Y are an anti-solar direction and an orbital direction of the Earth, respectively. Dotted lines are at 30° from the solar direction. Solid line is a case at the closest approach with a distance of 0.0011 AU on July 6, 2843, for the asteroid 1991BA with a semi-major axis, a, of 2.267 AU, an eccentricity, e, of 0.683, and an inclination, i, of 2.116°. Dashed and dot-dashed lines are cases at that of 0.0089AU on January 13, 3269, for the asteroid 4660 with a=1.520, e=0.370, and i=1.171° and at that of 0.0093AU on November 1, 4096, for the asteroid 1989 VB with a=1.856, e=0.460, and i=1.981, repectively. Circles, triangles, crosses, and squares show points at 10 days before the closest approach, at 5 days, at the closest approach and at 5 days after that, respectively.

It is clear that a ground-based observation can not detect asteroids at a direction of the sun and also surrounding the sun because of bright sky background. Considering that the asteroids near the sun are at low elevation at a time with dark sky background after sun-set and before sun-rise, we define a blind area for asteroid detection within 30° from the solar direction as a working condition.

Number of asteroids approaches the Earth during the given period from 1994 to 4600 depends on distances of the closest approaches. It is 6694 times for that of 0.1 AU, and 5689, 4702, 3799, 2918, 2146, 1469, 864, 378, 94 for that of 0.09 AU, 0.08 AU, 0.07 AU, 0.06 AU, 0.05 AU, 0.04 AU, 0.03 AU, 0.02 AU, and 0.01 AU, respectively. The number obtained by extrapolating this relation to 0.000043AU which is a radius (6400km) of the earth is onece 1.3×10^6 years which is a collision probability of 188 NEAs in the period. One should remind that this is for the detected 188 NEAs including asteroids with small radii about 10m.

Some NEAs cross the blind zone at their closest approaches to the Earth and stay there for only a few days. In those cases there is a possibility to detect the NEAs several days before their closest approaches. However, if an asteroid approaches the Earth directly from the blind zone, it stays in the zone more than 10 days prior to the the closest approach. Figure 2 shows two examples when each asteroid runs out from the zone. One can see that, for the case of asteroid No.1991BA, it will run out from the zone on the day at the closest approach. This leads to a conclusion that there is a possibility of asteroid collisions without a warning time.

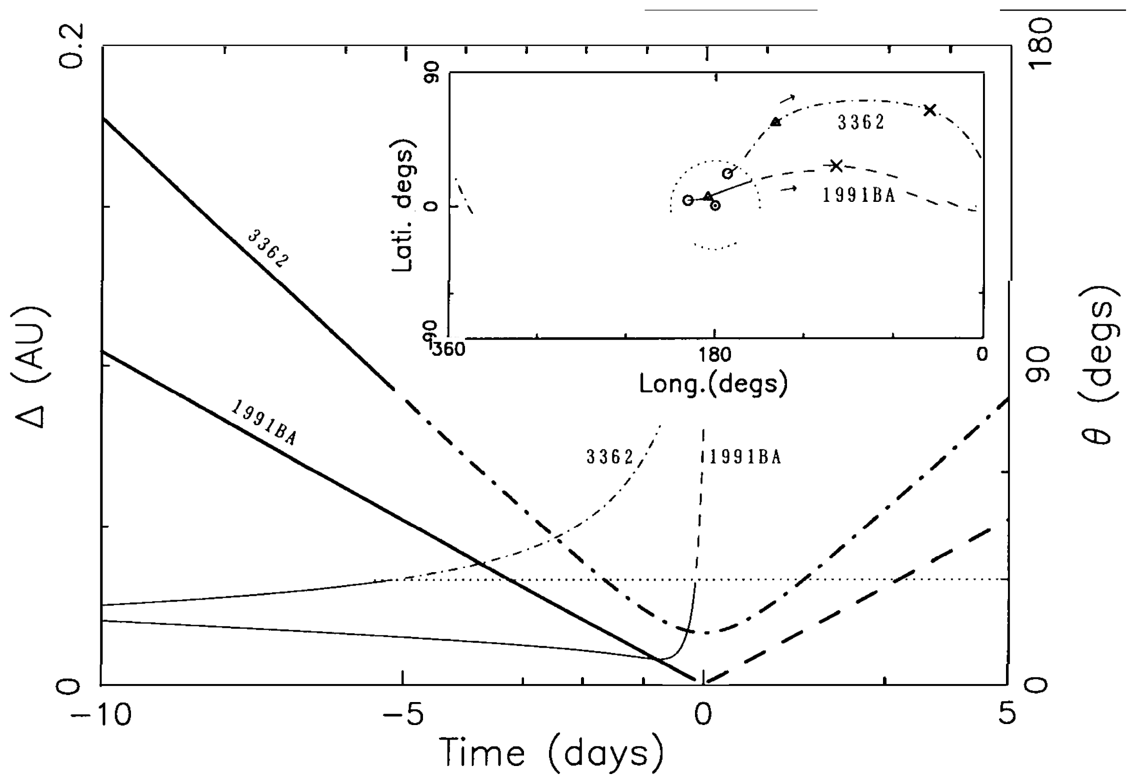

Figure 2. Distance variation of two asteroids depending on time where positive and negative values are after and before the closest approach, respectively. Left (corresponding to thick lines) and right (corresponding to thin lines) ordinates show a linear distance of asteroids from the Earth and an angular distance of asteroids from the Sun, respectively. Dotted line is given at the angular distance of 30°. Curves with dashed and dot-dashed lines are for asteroids of 1991BA and 3362, respectively. Each asteroid is inside the blind zone at a part of solid line on each curve. Superposed figure shows motions of two asteroids on a longitude and latitude plane relative to the Sun. The Sun is at 0° latitude and 180° longitude. Circles, triangles, and crosses are points at those days 10 days, 1 days, and 0 day before the closest approach, respectively.

A brightness of asteroids depends on those radius and albedo and also those distances from the Earth. Therefore, it is very difficult to detect the asteroids more than 10 days prior to those collisions or the closest approaches because of their faint magnitude. Although those detectability depends on their radius, here we define asteroids running out from the blind zone at a few days prior to the closest approaches as a dangerous one.

Numbers of asteroids running out from the zone at each day proior to the closest approaches ralative to the total number of close approch asteroids are shown in figure 3. A fraction of the dangerous asteroids is less than 3 % for the case of 0.1 AU, but is over 30 % for 0.01 AU. This means that a large fraction of colliding asteroids is a dangerous one. It is clear that even if powerful misiles and atomic bombs are kept to be at a stand-by condition we have no possibility to reject a collision of the dangerous asteroids.

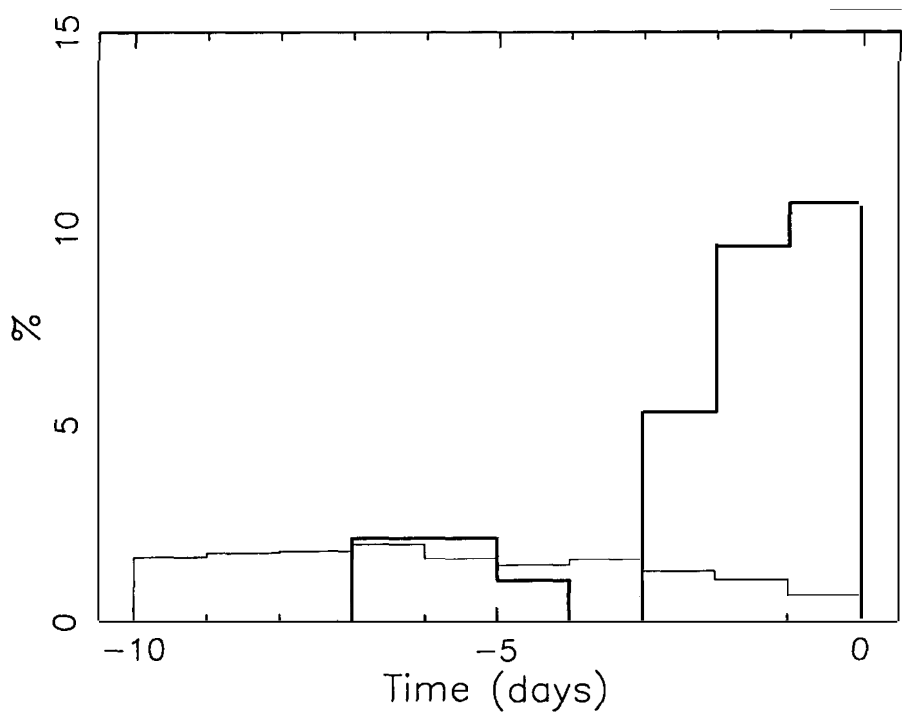

Figure 3. Number ratio of asteoids running out from the blind zone at each day prior to the closest approach out of the all asteroids approaching the Earth with the shortest distances less than 0.1 AU (thin line) and 0.01 AU (thick line), respectively.

The most effective way to escape the collision is to find all the NEAs and determine those orbits. The US spaceguard project is the one to aim this but only for asteroids with a radius larger than 1 km which certainly cause a global catastrophie and an extinction of human-beings. If an orbit of the dangerous asteroid is well determined many years prior to the collision, we can easily escape from the collision by giving only small additional velocity, for example, 1 cm/s, to the asteroid at a time of several ten revolution around the sun prior to the collision. This velocity change is produced by usual TNT bomb explosion on a surface of the asteroid and we are able to reserve enough to prepare launching a satellite carring the bomb.

Nessecity of Space-borne observations

The space-guard project is not a perfect one, because only 99 % of NEAs with a diameter larger than 1 km are planed to be detected and about 1 % will escape from a detection. Most of the NEAs with a diameter between 100 m and 1 km which will cause a catastrophie in a continental scale can not be detected.

Only one way to reject a collision of asteroids escaping from the detection by the space-guard project is an observation by telescopes located at places without terrestrial atmosphere where sky brightness is very dark only except to a direction of the sun. There are discussions to build a lunar-based station till a middle of 21st century under an international collaboration. If its project will be in reality, one should put the first priority to build there telescopes for a detection of the dangerous asteroids. To keep a warning time as long as we can do, one should develop a telescope watching an area of 1 steradian.

There is an estimate that a death probability of a human-being by asteroid collisions is nearly equal to that by air accidents in the total accidental death. We dare to say that an air accident makes only a fraction of those whole human-beings in the world but the human are able to live without any interuption. However, a collision of an asteroid with a diameter larger than a few hundred meter has a posibility to brings an extinction of the human as dinosaurs were extincted 65 million years ago.

Although it is not nessesary for us to be hurry to build the proposed lunar based telescopes for a detection of dangerous asteroids because of a low collision probability, the catastrophic asteroid collision will certainly happen with a certain collision probability. Therefore, considering the serious problems, human-beings should start to set up a system to escape the collison.

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The Observations and Studies on NEOs and SL9 Impact at PMO, China

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Since 1964, a systematic asteroid search and study in China have been led by Y. C. Zhang, the former director of the PMO (the Purple Mountain Ob servatory), and Jiaxiang Zhang. Using a 40-cm double astrograph, over one hundred numbered asteroids and three comets have been found. Two of those asteroids are Mars-crossers ([2077] Kiangsu and [2078] Nanking), discovered by Jiaxiang Zhang, Jiexing Yang, Qi Wang and their colleagues.

In 1987, a systematic program for NEO's search and study was proposed by Sichao Wang. Thereafter, Qi Wang, Yongliang Ge and other astronomers of the PMO went to use the 60cm Schmidt telescope at the Xinglong Station of the Beijing Observatory several times. The field of the telescope is 4.8°. Since the stereo pair technique on plate and the star plate comparator were used, the comet Ge-Wang and the fast moving object 1991 BH have been found by Yongliang Ge and Qi Wang, both of who joined the International Near-Earth Asteroid (INAS) in 1988. Meanwhile they have been studying the survey strategy. Now the difficulty is that the available observation time is very limited.

In addition to the search of NEOs, using their numerically self-established dynamical model for objects of solar system, exploring method and making software, Jiaxiang Zhang and his colleagues provided the July 7 edition of heliocentric orbital elements and impact prediction of the SL9, as well as the jovicentric positions and velocities of the nuclei before impact. The last astrometric data used in those solutions were up to the date of 1994 July 2. This edition was sent to the mail exploder for observers of SL9 impact and was listed as the latest addition on July 11, 1994. The predictions mainly matched with actuality. Using the 1-m reflector with CCD at the Yunnan Observatory, the accurate position observation of Icarus was made and the orbit research of some unusual NEAs (including Icarus and 1989 FC) was studied by Jiaxiang Zhang and his colleagues.

During the period between July 13 and September 14, 1994, the optimum impact and post-impact period, using the 60cm reflector (f=10m) which is attached by the MTV 1881 EX CCD video camera with R filter and without filter, the observations of Jupiter were made by Sichao Wang et al. Over 800 thousand images of Jupiter have been recorded on the metal tapes of high quality by the M2 video recorder and over 900 images of Jupiter have been sampled by the multimedia computer. During the period between July 18 and September 14, the dark spots induced by the nuclei G, H, K, L, Q1, R, S and W of the comet Shoemaker-Levy 9 were monitored. The characterisics of the size, central nucleus with ring-like structure and low albedo of the dark spots suggest the following interpretation:

- The spots could be produced by a high- altitude cloud in the stratosphere and the cloud is consisting of dark articles and other materials that have condensed from the impact plume.
- The southern dark feature could be caused by splash- back dark articles and other materials of the plume.

Yuehua Ma et al. have carried out computer simulation on the ablation and dissociaion of the comet SL9 when entering the jovian atmosphere. The comet fragments were modeled as 10^{12}, 10^{13}, and 10^{14} kg with density of 3.0, 1.0, 0.8, 0.5 and 0.2g/cm^3, respectively. Their results show that these fragments explode below the ammonia cloud layer, near the 1-bar level, explaining the observation of ammonia without water. Finally, their simplified explosive model estimates that these explosions can lift the material in the atmosphere up to 8000 km high above the top cloud layer of the jovian atmosphere as observed, the angle of the covering area of the ejecta to the Jupiter's center is about 10°.

Recently, the shock effects of the high velocity impacts among solid bodies in the solar system have been studied by Sichao Wang, Pinxin Xu and Jianming Wang and the collision frequencies between 41 Aten-Apollo-Amor objects and the Earth have been calculated by J. H. Lu.

The impact of comet SL9 on Jupiter has resulted in a great attention and public interest in NEOs in China and the PMO has recently proposed a new plan to install an about 1 meter telescope with a 2048*2048 CCD equipment in 2-3 years at the PMO's station, about 400 kms north of Nanjing where it is promising to have fine weather and low light-pollution. We do hope that the station with such a powerful instrument at the indispensable longitude of east 8-hour time zone in Asia can be set up, before long, to make contribution to the international NEO's survey.

Investigation of Cavities and Craters Formed as the Result of Nuclear Explosions for the Purpose of Solving the Problem of the Earth Protection against the Near-Earth-Objects

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The possibility of the Earth collision with the Near-Earth-Objects (NEO) necessitates searching for methods of influencing the NEO which could help to prevent this threat. In the materials of the Conference held in Snezhinsk late in September 1994 and dedicated to this problem we can find different proposals for solution of this problem [1]. From among them there is a proposal on nuclear device delivery to the NEO, and the nuclear explosion at the NEO. This could enable to achieve the following:

— disintegrate the NEO into fragments of dimensions necessary for providing their burning in the Earth's atmosphere;
— disintegrate the NEO into fragments and alter their trajectory in order to miss the Earth;
— alter trajectory of the NEO as a whole by transferring a certain momentum to it.

Selection of a certain method of acting will be the content of a specific project and will depend on specific circumstances, but even now we need to carry out calculations and experimental research to reveal those aspects of the future project that to the largest extent will influence the selection of the specific method. In other words, even now, without waiting for the impending terrible menace we must do research results of which are necessary for implementing the project of preventing this catastrophe. During one of the presentations in Snezhinsk one of the authors of this paper gave rather convincing reasons proving that even now we have sufficient means for implementing the project of the Earth protection against the NEO [2]. But availability of the means is the necessary but not sufficient condition for implementation of such project. The project can't be considered acceptable if it contains a high uncertainty of assessing effectiveness of its implementation which eventually will depend on effectiveness of nuclear explosion interaction with the NEO.

The theory, calculations, and experience of nuclear explosions under terrestrial conditions show that effectiveness of the nuclear explosion influence on a certain object or ground is determined not only by energy release of the nuclear device and position of the nuclear explosion center with respect to the surface, but also by characteristics of the material subject to the nuclear explosion effect: its density, strength, equation of state.

The nuclear explosion acting on the NEO must take place far from the Earth [2], but the process of the explosion energy transfer to the NEO will be the same as on the Earth, i.e. either by the explosion radiations (x-ray and/or neutron), or at direct contact between the nuclear device and the NEO, or with the nuclear device buried in the NEO. In any of these three cases of the NEO interaction with the nuclear explosion we need to know the properties of the NEO matter. Despite of the rather detailed classification of the asteroids and comets by the types of the substances composing them [3], this classification should be considered as a tentative during assessing the effectiveness of a certain method of applying the nuclear explosion (explosion at some altitude, surface explosion, or buried explosion). As we know accuracy of these estimates to the largest extent depends on the pressure range under consideration. Up to 400 kbars the processes of terrestrial ground behavior are well described in calculations, as well as shock propagation in it. The pressure range from 400 down to 100 kbars is characterized by a rather complex behavior of substances, practically different for each substance because of the phase transitions. Therefore, it is difficult to describe it with the calculations. With pressure decrease in the shock wave the strength begins to play larger role. This necessitates to take into account the deviator of stresses and strains which is not the same for material samples and for the same material *in-situ*. Though Academician M. A. Sadovsky and his disciples showed that the process of rock fragmentation follows the same laws regardless of the place where these rocks are located, on the Earth or beyond it, prediction of a specific sample fragmentation (whether it is a too large sample formed during explosion in a rock drill hole or a separate rock that must be withdrawn from a future highway) is always a complicated task that is more often solved practically but not with calculations. Besides that, our experience of nuclear explosions both under the ground and above it is referred to terrestrial conditions when interaction between the nuclear explosion and the ground takes place under conditions of the Earth's atmosphere and the Earth's pull. For the case of asteroid or comet these conditions will be quite different, and this must be taken into account. The above mentioned brings us to the only conclusion: prediction of the NEO behavior after its affecting with nuclear explosion is an extremely complicated and crucial task.

Certainly, many problems could be removed if we could investigate different asteroids using space sondes or bring to the Earth the ground samples from asteroids. At the above mentioned conference in Snezhinsk, Professor Teller proposed as an alternative or complementary to such research to perform a nuclear explosion at some asteroid, and to investigate its effect on the asteroid. But both the space investigation of the asteroids and the nuclear explosion at the asteroid are hardly possible in the nearest future. At the same time there are thousands of horizontal and vertical holes on the Earth in which the underground nuclear explosions were conducted. Most of these explosions were contained, but a small number of them were cratering explosions. Rocks surrounding the cavities of the both types of the explosions still preserve the traces of the nuclear explosions. These effects were investigated in the USA, in the USSR, and France. Some results of this research have been published [4]. Comparison of the results of investigating the explosion cavities and the surrounding rocks with results of numerical calculations showed that these results describe very well behavior of different soils during the nuclear explosion under terrestrial conditions. We believe it is interesting to continue this work since the research which has been carried out has covered a relatively small number of the terrestrial ground types. Continuation of this research could yield calibration of computer methods at large number of different ground types, and by that to improve their validity essentially.

Preliminary study of the experience of investigating the explosion cavities in the mountain-mass Degelen at the former Semipalatinsk nuclear test site shows that the preferable method is excavation of holes towards the place in the adit the investigator is interested in. Despite of the fact that the mountain-mass Degelen is composed of primarily strong (10-12 points by the Protodyakonov's scale) rocks, excavation of the holes in them is not a problem. We might be interested in not only the part of the rocks directly external to the explosion cavity, but also in the zones of fragmentation and fracturing, as well as the zones of collision between the contrary shocks from several explosions carried out in one adit with time interval of several milliseconds. Character of the rock fragmentation in such collision zones may significantly differ from the character of fragmentation in the fragmentation zones which are formed during propagation of one shock.

Direct study of the rock state in various zones around the cavity of a certain explosion can be complemented with various geophysical methods: seismic sounding, gravimetrical and magnetic measurements, study of radionuclide migration.

It is evident that to do this work the efforts of one country won't be enough. We propose to unite in the international project the efforts of scientists and engineers of the five nuclear states and Kazakhstan the territory of which (the mountain-mass Degelen) has several hundreds of adits where in the end boxes the nuclear explosions were conducted. Besides that, there are several craters from the cratering explosions. The cavities of these explosions haven't been opened. Within the framework of the proposed international project we could:

- investigate the cavities of the nuclear explosions;
- investigate the zones of fragmentation and fracturing;
- carry out calculations and compare their results with the results of investigating the cavities, the zones of fragmentation and fracturing;
- on the basis of the work done develop the calculation method for different nuclear explosion effects upon ground at various position of the explosion epicenter with respect to the surface of the asteroid or comet.

We estimate the cost of the full complex of the geophysical research at the Degelen mountain-mass as $4 mln. U.S. Someone may think this sum is too large, but to our mind, this work in a short time could yield creation of method for engineering calculations for future projects of nuclear explosion effect upon the NEO. We don't know how much time we have therefore we mustn't waste it. Just now we need to lay the basis for implementing the project "The Earth against the NEO".

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Detection

Plenary Session

EVALUATION OF SURVEY SYSTEMS

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Introduction

The evaluation of the performance of a given survey system depends primarily on only two parameters: the threshold brightness for detection (limiting magnitude), and the rate of sky coverage. Of much lesser importance are such factors as the geographic location of the observing site(s), the ability to detect rapidly moving objects compared to the sensitivity to stationary targets, and the detailed strategy used to follow up detections to obtain preliminary orbits. For the proposed NEO survey, we will show that the best strategy for maximizing the rate of discovery of NEOs is to cover the entire observable sky each month. An optimum search system should be designed to be capable of fast enough operation to achieve all-sky coverage, sacrificing limiting magnitude as necessary to achieve this goal. Thus we can, within the uncertainties of the models employed, reduce the problem to a single parameter: the limiting magnitude that a given system can deliver in the mode of covering the whole sky each month. The practical achievement of this mode has become possible with the present state of development of CCDs.

In this chapter, we will present the results of a survey simulation to show the level of completeness that can be expected from putative survey systems as a function of time (length of survey), area of sky covered per month (from which we derive the above conclusion for all-sky coverage), and size of NEO. We can then simply relate these results to specific systems through estimates of the limiting magnitude achievable with a given system. In Appendix III we give a more detailed report of the evaluation methods and results for specific systems. In this chapter, we summarize the search strategies and expected capabilities in more general terms.

Survey Systems

For the purpose of a quantitative discussion, we shall evaluate survey completeness for three rather specific systems. However it should be noted that results can easily be scaled to other systems that might be contemplated. The three systems are representative in general terms of systems of 0.5-m, 1-m, and 2-m aperture. Following is a brief description of each system.

1. The Lowell Observatory Near-Earth Object Survey (LONEOS) telescope is a modified Schmidt telescope of 0.58 m aperture, 1.11 m focal length (f/1.91), which is under construction at Lowell Observatory. "First light" is expected during this year. Initially, it will be equipped with a two CCD chips with 2048 x 2048 pixels, 15 microns square, or a field format of 3 cm by 6 cm. Eventually, it is planned to use two butted 2048 x 4096 chips with 15 micron pixels, for a 6 cm square format, which yields an angular field of view 3°.17 on a side, or an area of 10.1 square degrees. It is planned to use front-illuminated, unthinned CCDs with a quantum efficiency of ~25%. We estimate that this system can reach a limiting visual magnitude of 19.4 with 68 second exposures. In our evaluations, we consider the "full-up" system with $(4096)^2$ pixels.

2. The USAF Space Command currently operates a network of 1-m, f/2 wide-field telescopes, the Groundbased Electro-Optical Deep Space Surveillance (GEODSS) system, for tracking Earth satellites. The GEODSS Upgrade Prototype System (GUPS), currently under development, will employ large format CCD detectors, which with only minor modifications and changes to the computer software, might be effectively employed for NEO surveys. The CCD detector under development at Lincoln Laboratory is a single chip of 1960 x 2560 pixels, 24 microns square, or a total format of 4.7 cm by 6.1 cm. In the GEODSS telescope, this yields an angular field of 1°.23 by 1°.61, or 1.98 square degrees. The chip is thinned, back-illuminated, with a quantum efficiency exceeding 75%. We estimate that this system can reach a limiting magnitude of 20.2 with 20 second exposures.

3. The Spacewatch (SW) Telescope on Kitt Peak, Arizona. The present (operating) system is a 0.9 m telescope of 4.6 m focal length (f/5) with a single CCD detector with 2048 x 2048 pixels of 24 microns, or a total format 4.9 cm on a side. The detector is thinned, back-illuminated, with a quantum efficiency of ~75%. SW has a demonstrated limiting visual magnitude of ~21.2 with a 147 second exposure covering a 0.57 square degree field. Since it is the only currently operating system, we have estimated the limiting magnitudes expected for the other systems by scaling from the demonstrated performance of SW.

4. A second telescope (SW-II) of 1.8m aperture and 4.9m focal length (f/2.7) is under construction. Initially, it will be equipped with a similar CCD detector, which will yield a field of view of 0°.57 on a side. In a scanning mode with a 30 second integration time, this system should reach a limiting visual magnitude of 21.5. With this detector and exposure arrangement, SW-II cannot achieve all-sky coverage each month (to be discussed later). It could do so with a mosaic of 4 butted CCD chips, giving a field of view of 1°.14 on a side, and rapid read-out electronics so that it could take individual exposures as short as 10 seconds. The telescope is mechanically and optically capable of accommodating this array and exposure rate. With 10 second exposures, the limiting visual magnitude would be about 20.9.

Survey Simulation

The approach taken was to generate a set of 1000 synthetic NEO orbital elements, matching the distribution statistics of the actual NEO swarm as best we can determine that from the present sample of known NEOs. We imposed one "unnatural" restriction: we included in the sample only orbits which pass within 0.05 astronomical unit of the Earth's orbit. As a general rule, asteroids whose orbits do not pass within 0.05 AU of the Earth's orbit pose no threat of collision on a time scale of a century, as the planetary perturbations necessary to reduce the miss distance to zero require longer than that to make such a change. Thus we have limited our sample to a subset of the actual distribution: the ones that actually pose a potential threat. Our results don't appear to be very much affected by this restriction, but it is reassuring to know that we have prejudiced the distribution in favor of the more hazardous objects.

Having created a set of synthetic orbit elements, we then generated a set of positions for each object, one for each lunation (new moon) for ten years, or 125 positions for each object. For each computed position, we also calculate the rate of motion on the sky and a relative magnitude which takes into account the distances from the Earth and Sun, and the solar phase angle (analogous to the "phase of the moon", which in a like way very much affects the brightness of the object).

To conduct a survey simulation, we "filter" the file of 125,000 positions to tabulate which objects are "discovered" and which are not. The various "filter" elements include limitations on the sky area viewed, either those imposed by the maximum area the putative system can cover or those naturally existing due to horizon limits, Sun or Moon in the sky, too close to the galactic plane, where detections are impossible due to background star confusion, and most important, object size/system limiting magnitude. On this latter point, we note that the system limiting magnitude and the absolute magnitude of objects are 100% correlated parameters. That is, a system capable of detecting objects 4 times fainter than another system will achieve the same level of completeness of NEOs at 1/2 the diameter as the other system. Thus in estimating completeness vs. size of NEOs, we needn't do independent evaluations for different limiting magnitudes. The same "completeness curve" applies for completeness vs. size at a given threshold magnitude as applies for completeness vs. threshold magnitude for a given size of NEO.

Observational Strategy

Even the basic *detection* of an asteroid requires multiple observations. The method used by the only operational system, Spacewatch, is to scan the same area of sky three times, separated by ~1 hour each. The images are compared to reveal any moving object, with the third scan as a confirmation against erroneous or confused images in either of the other two scans. It is anticipated that the systems described above would operate in a similar mode. Some economy could be achieved by storing a catalog of the sky from past (previous months or years) scans of the same area, so that only two new scans, to be compared against the archival catalog, would suffice. Thus the first step, detection and confirmation of a moving NEO, requires taking two or three scans of a given sky area, separated by an interval of time of the order of an hour or two. This results in a measurement of the instantaneous position in the sky and a rate of motion, which is sufficient for finding the object sometime later, for example the next night.

In order to obtain even a preliminary orbit for the object, further observations are needed. Present practice is to identify NEO candidates on the basis of anomalous rate of motion compared to main-belt asteroids, as determined on the first night of observation. For these objects, additional observations are needed, on at least two more nights, and preferably spaced over an interval of about a week. A one week "arc" is usually sufficient to make a preliminary estimate of the "minimum orbit intersection distance" (MOID) from the Earth and determine whether the object presents any potential hazard to the Earth on a timescale less than a century. A longer arc is necessary to consider the object reliably "cataloged", but with only a week arc the number needing further follow-up, on the strict basis of hazard alone, can be reduced to a small enough number to be accomplished with modest resources.

With highly automated systems, recording detections at much higher rates than present systems, it may become more efficient to just cover the sky often enough that the week-arc follow up occurs automatically, for everything. This has the advantage that all objects are followed up to the level of a preliminary orbit determination. Thus the few NEOs which chance to be mimicking main-belt motion at the time of detection are discriminated and become "discovered." To operate in this mode requires covering the search area about 4 times each month, rather than once plus targeted follow up.

In summary, "detection" consists of a sequence of two or three observations on a single night, which are usually sufficient to distinguish a main-belt object from an NEO and to find it again the next night. To "discover" the object, in terms of a preliminary orbit, requires two or three more observations over about a week, and represents about a doubling of resources over detection alone.

Survey Completeness vs. Area of Sky Coverage

For our first simulations, we specified the area of sky covered per month as the radius of a circle on the celestial sphere centered on the opposition point, which is generally the most productive area to search. In this experiment we made no restrictions for horizon or closeness to the galactic plane. For the detection threshold, which is a combination of telescope limiting magnitude and size of object, we chose limiting magnitudes appropriate for a single GEODSS telescope equipped with the Lincoln Laboratory GUPS CCD chip, with exposure times appropriate to allow coverage of the area of sky assumed in each case. For size of object, we took the brightness corresponding to a 1 km diameter object of albedo 0.15 (typical S class albedo), or equivalently, a 2 km object of albedo 0.04 (somewhat darker than average C, D, etc. objects). In Figure 1 we plot the rate of detections of NEOs for three assumed sky areas corresponding to circles of radius 34°, 65°, and 137° out from the opposition point. For the focal plane instrumentation assumed, these sky areas correspond to exposure times per single image of 100 sec, 30 sec, and 10 sec, respectively. With these exposure times, the specified sky areas can be covered three times (the redundancy required for detection and confirmation) in ~100 hours of observing time, which is the typical amount of time available from a given site in a month, allowing for weather and other types of interruptions. The 34° and 65° sky areas are probably achievable from a ground-based site. 137° corresponds to covering the whole celestial sphere down to a solar elongation of only 43°, clearly not possible from anywhere on the ground without serious losses from atmospheric extinction. The point of this figure, which is a very robust result and applies for any system we have evaluated, is that it is better to cover more sky and sacrifice limiting magnitude as necessary, until all available sky is being surveyed.

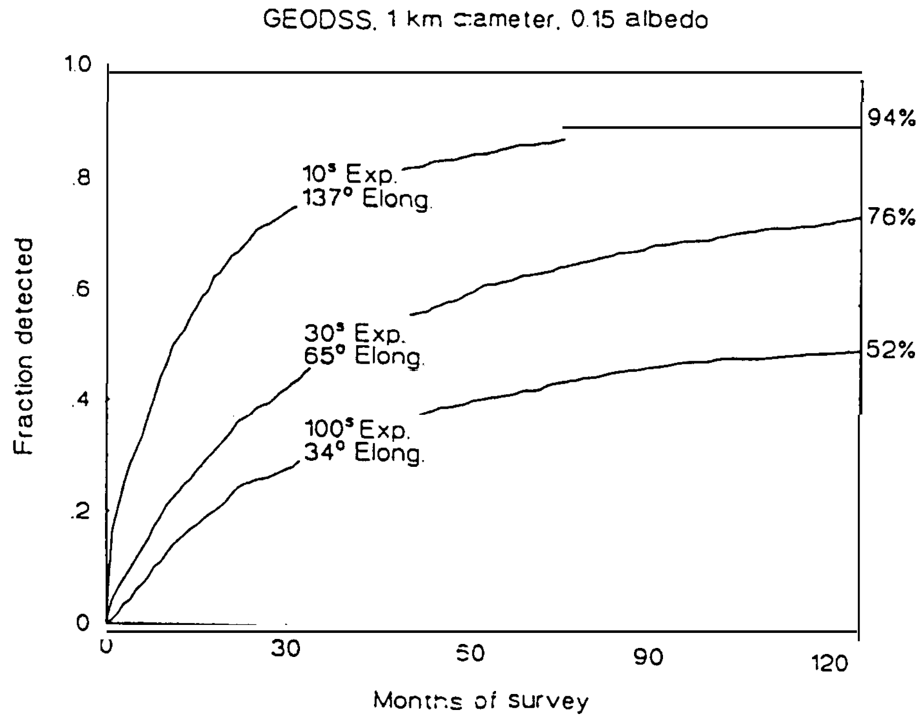

Figure 1. Rate of discovery *vs.* time for one GEODSS telescope. Each curve represents a different choice of exposure time, and consequently limiting magnitude, and results in a different area of sky per month that can be covered. The curves represent the discovery rate for ~1 km diameter objects of moderate albedo (0.15), or ~2 km diameter objects of low albedo (0.04).

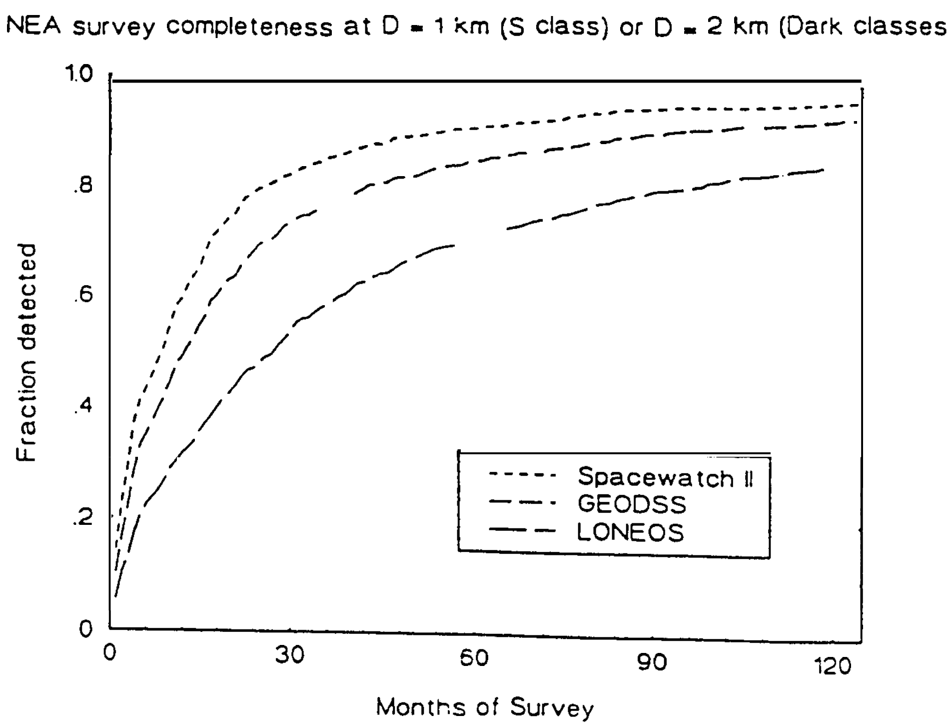

Figure 2. Rate of discovery *vs.* time for each of the three systems evaluated, assuming that the rate of sky coverage is chosen such that all available sky area is covered each month. The curves represent the discovery rate for ~1 km diameter objects of moderate albedo (0.1 5), or ~2 km diameter objects of low albedo (0.04).

All-sky Surveys

Having established that the optimum strategy is always to cover all available sky each month, we concentrated on this mode of operation in the remaining analyses. We first evaluated how much sky is accessible and how many hours are available to cover it for each month of the year. The restrictions applied are:

1. The Sun must be more than 10° below the horizon.
2. The moon must be below the horizon.
3. The target area must be more than 25° above the horizon at some time during the night.
4. The target area must be more than 20° away from the galactic plane.

Subject to these conditions, we determined that, almost independent of station latitude, the maximum rate of sky coverage required is ~135 square degrees per hour in order to cover all of the sky once per month. Allowing for duty cycle losses, cloudy weather, and other down time, the rate of sky coverage should be ~200 square degrees per hour to cover the whole sky once per month. It is important to note here that any system intended to contribute seriously to the survey itself, rather than serve as a "test bed", should be designed to cover sky area at the above rate. Indeed, unless a separate system of astrometric follow-up is contemplated, the survey system needs to be capable of 2 or 3 times that rate to assure enough observations to derive preliminary orbits for the discovered objects.

In Figure 2 we plot the fraction completeness vs. time for each of the three systems described above. For both LONEOS and Spacewatch - II, we have assumed the "full-up" configurations described above which would be capable of all-sky coverage each month. These curves represent the fraction of objects detected, and do not allow for the necessary work of follow-up observations to determine orbits for detected objects, which will be discussed later in this chapter.

Completeness as a Function of Size of NEO or Limiting Magnitude of System

As noted above, the question of whether or not an NEO is detected, given that it passes within the surveyed area, is a function of only one parameter: brightness compared to the detection threshold of the survey system. Thus size and albedo of NEO and threshold limiting magnitude of the detection system all collectively constitute only a single variable. So we can derive a single "completeness curve" which can be used to describe completeness as a function of limiting magnitude of the survey system, for a given size and albedo of object, or equivalently, completeness as a function of size of body, for a system of specified threshold detection magnitude.

Figure 3 is a plot of that function derived from the simulated 10-year survey of 1000 objects. The vertical scale is simply the fraction of the 1000 objects "detected". The horizontal scales are either relative size of object, or threshold detection limit of the system. We have plotted the curve twice (dashed lines), offset by a factor of 2 in diameter (1.5 magnitudes brightness), which correspond the difference of approximately a factor of 4 in albedo between the brighter, "S-Class" asteroids and darker, "C-class" and related types. Among measured NEOs, the ratio of high to low albedo objects is approximately 10:1. However this is strongly affected by the fact that dark objects of a given size are much more difficult to detect. Thus we suspect the bias-corrected ratio is closer to half each, at a given size. The solid line curve in Figure 3 is an equally weighted average of the two dashed curves, and represents the completeness curve for an NEO population consisting of equal numbers of high and low albedo objects. We will use this curve for further analyses.

In Fig. 4, we have plotted the completeness curve to represent completeness vs. diameter of NEO, for various values of system limiting magnitude. In Fig. 5, we present the completeness curve, this time scaled vs. limiting magnitude of the system, for various diameters of NEOs. In addition to the three systems discussed above, we have included curves for the current Palomar 46-cm Schmidt photographic system and for the suggested "Spaceguard Survey" system (see Appendix 1) of 2-3m telescopes capable of surveying to a threshold magnitude of 22. From these plots, it appears that a system reaching limiting magnitude 20 can achieve about 80% completeness of NEOs down to a size of 1 km diameter in a 10-year survey.

Strategies for Preliminary Orbit Determination

One can contemplate two strategies to determine orbits rather than merely detect objects. One way is to do targeted follow-up observations, either by assigning the observations to a second telescope or by taking time from the discovery survey to make these observations. A second mode is to cover the whole sky so often that repeated detections of the same object are sufficient to yield orbit solutions from the regular survey observations. Figure 6 is a comparison of these two follow-up strategies, which we now describe.

Presently, surveys are done in the first mode, of targeted follow-up. To make the problem tractable, it is necessary to discriminate NEOs from the much more abundant main-belt (MB) objects based on motion in the sky, before an orbit is known. Thus there is a "blind spot" of slow sky motion where an NEO can mimic a MB object and thus not be discriminated. As we go to surveys reaching to fainter magnitude, discoveries will be made at greater distances, thus at slower average motion, and the "blind spot" becomes a more significant loss factor. To evaluate this mode of follow-up, we have computed a second completeness curve, this time filtering out objects which, even though they may be in an observable part of the sky at a given time, are exhibiting main-belt-like motion, and thus would not be "noticed". From past experience (e.g. Spacewatch, Palomar photographic), the "overhead" of follow-up of past discoveries appears to be a task of the same magnitude as the survey itself. Thus a survey telescope may be occupied about half time taking follow-up observations and half surveying new sky. Or if two telescopes are available, one could scan while the other does follow-up. In either case, the "cost" is a factor of two in exposure time that could be devoted to survey -only, which translates to ~0.4 magnitude in threshold detection. So we shift the "targeted follow-up" curve 0.4 magnitudes to the right.

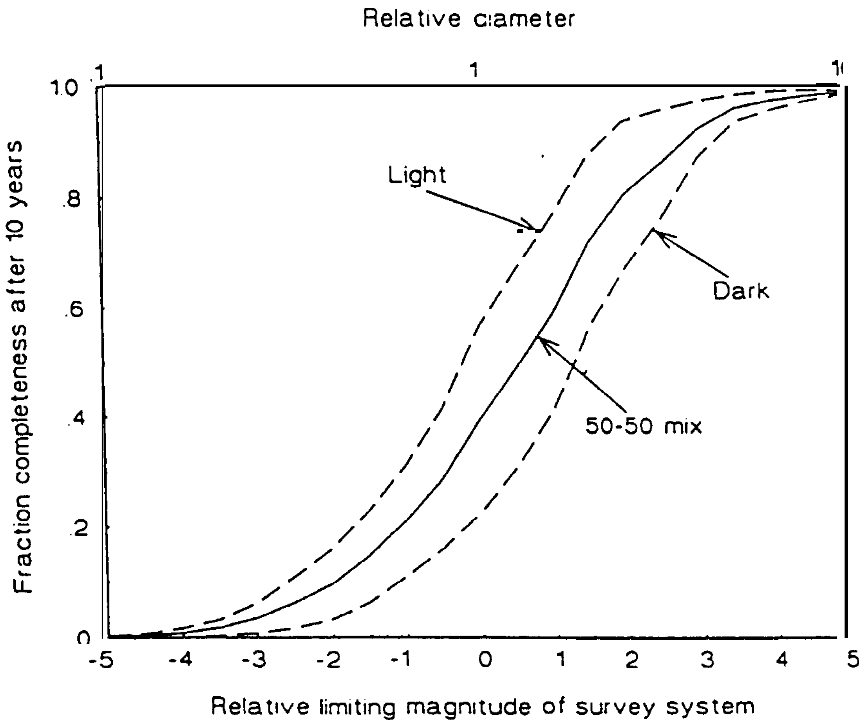

Figure 3. Completeness as a function of limiting magnitude of survey systems. Light refers to a population with albedo equal to average S-type (light) asteroids and dark refers to asteroids with albedo equal to average C-type (dark) asteroids.

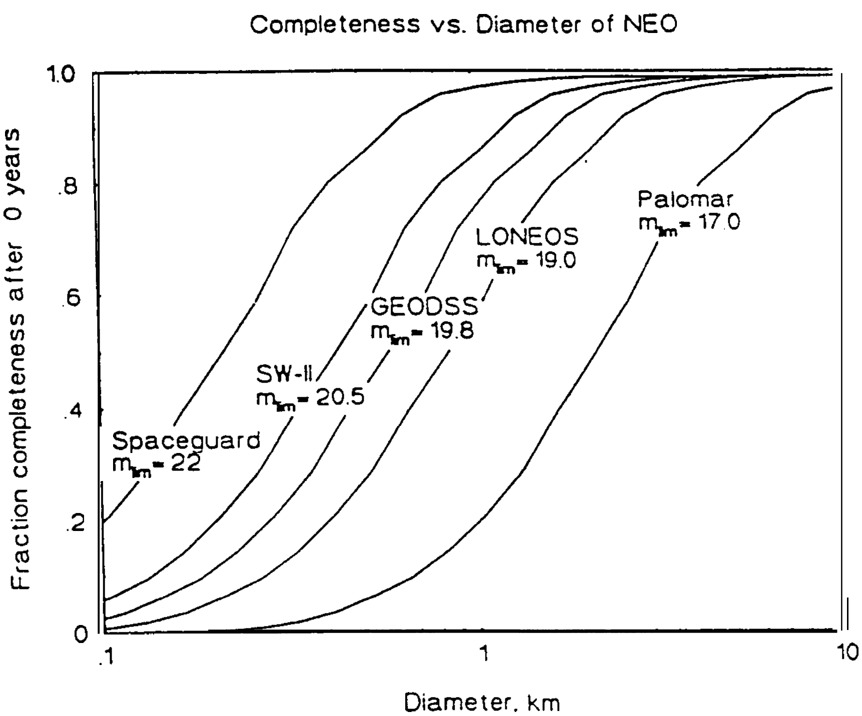

Figure 4. Completeness as a function of asteroid diameter for five survey systems described in text

The second possible follow-up mode consists of simply scanning the sky more often, so that enough positions are obtained of each object to derive a preliminary orbit of every object detected. Thus even those exhibiting normal MB motion are discriminated. For the same threshold magnitude, this technique would obviously discover more objects. However, it is likely that operation in this mode would require covering the sky many times per month, perhaps 4, to assure that at least three observations, each separated by several days, would be obtained of a given object. Thus the "cost" is a factor of 4 in exposure time, or ~0.8 magnitude. So we shift the other curve in Figure 6, 0.8 magnitude to the right.

The result is that the two curves cross one another, so the strategy of targeted follow-up is superior except for the very largest objects. On the other hand, it is the very largest objects which are most important. A pedantic reliance on anomalous motion leads to a worrisome result that no survey, no matter how sensitive, can achieve >90% completeness in 10 years. But the largest objects are also brighter, and very much less numerous, than smaller objects. Furthermore, any large object mimicking main-belt motion will be there the next month for repeat coverage. Thus a hybrid strategy should be possible which could closely approximate the higher level of the two curves over the entire range. In any case, the problem of following up to the point of preliminary orbit determination is roughly a "factor-of-two" complication over bare detection only.

Returning briefly to Figs. 4 and 5, We have associated " LONEOS" with a limiting magnitude of 19, whereas we estimate it is capable of reaching 19.4 in an all-sky survey mode with 68 second exposures. Thus the limiting magnitude of 19.0 is about correct if that telescope is tasked with doing its own targeted follow-up, consuming half its time. The limiting magnitude of 20 associated with GEODSS is about the expected performance of one GEODSS telescope, full time surveying. Thus in truth, this curve represents the capability of two GEODSS telescopes, one surveying and a second one doing follow-up, or some similar combination. The magnitude limit of 21 associated with SW-II is the limit expected for single-coverage of all sky, so again, to achieve this level of performance would require a second 2m telescope, or perhaps a highly automated version of SW-I could keep up with the task. Finally, the limit of 22 associated with "Spaceguard" is in a sense "by definition. " In the Spaceguard Report (see Appendix I) a requirement was defined to achieve nearly all-sky surveying to limiting magnitude 22. That requirement was then estimated to correspond to a system of about five 2-to-3 m telescopes equipped with CCD arrays. We concur with that scale of instrumentation required to achieve all-sky coverage to magnitude 22.

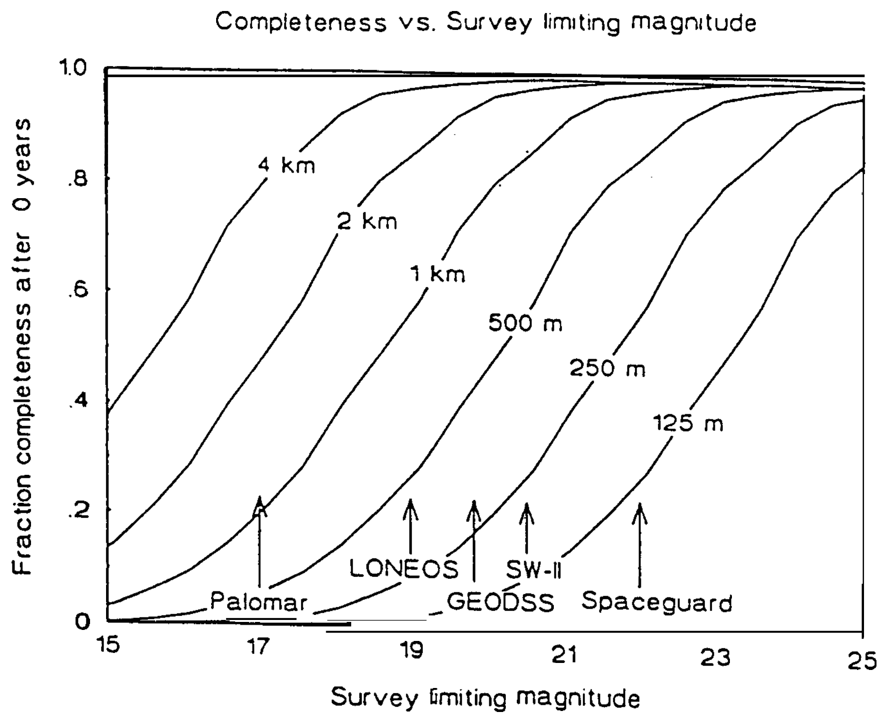

Figure 5. Completeness as a function of limiting magnitude of survey telescopes.

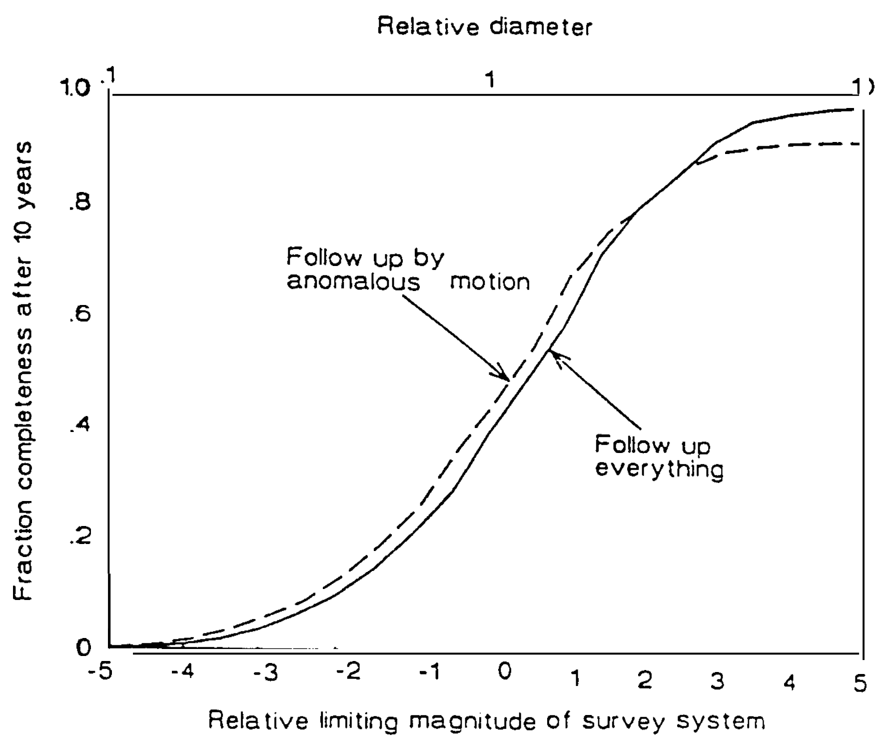

Figure 6. Completeness as a function of limiting magnitude of survey systems with two different strategies for preliminary orbit determination (see text).

Conclusion

If one asks the question, what is the likely largest size of any remaining undetected object (that is, where completeness equals one over the number of objects of that size expected), the answer is about 3 km for the evaluated systems, after 10 years. Pushing this limit down to ~1 km would require a Herculean effort. Thus we must accept some level of incompleteness. The systems evaluated can yield completeness in the range 80-90% or better, especially if all are used in concert. This level of completeness should reduce the threat from collision by an undetected NEA to less than that posed by impacts from long-period comets, so in that context, we can declare these systems capable of achieving the Spaceguard goal of reducing the hazard of asteroid collision by an unknown object to below that from comets.

The most important lesson which emerges from this analysis is that the best survey strategy is to cover the entire accessible sky every month, sacrificing whatever magnitude limit is necessary to accomplish this. A very positive result is that if that strategy is followed, adopting reasonable and even conservative limit on sky observability, it is possible to obtain reasonable completeness in ten years, including objects which never quite reach out to the orbit of the Earth and hence never come to opposition. Thus the ability to observe closer to the sun or to remove horizon limitations is not a sufficient justification in itself to move to a space-based survey system.

Reproduced from the "Report of the Near-Earth Object Survey Working Group," NASA Solar System Exploration Division, June 1995.

CCD Scanning for the Discovery of Comets and Asteroids

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CCD scanning was developed at the 0.9-meter Newtonian telescope of the Steward Observatory of the University of Arizona. Three CCD systems of increasing performance have been in operation since 1981. Presently, about 70,000 observations are made a year which includes astrometry for about 25 near-Earth asteroids. A new altitude-azimuth folded prime focus Spacewatch Telescope of 1.8-meter aperture is being built.

The general goal of our work is to obtain magnitude-frequency relations for various populations of small bodies in the solar system. The work is a sequel to photographic surveying of the solar system at the Yerkes, McDonald, Palomar and Leiden observatories, but it is now done with CCDs, charge-coupled devices (Gehrels 1991, Scotti 1994). The work is presently done at the 0.9-meter Spacewatch Telescope while a new 1.8-meter reflector is being built. During the bright part of each lunation, centered on full moon, the telescope is dedicated to the detection of planets of other stars (McMillan et al., 1994).

Spacewatch CCD Scanning

Before Spacewatch, the discovery of near-Earth asteroids was done with photographic cameras so slowly that it might have taken a century to find the 1,700 largest comets and asteroids that are dangerous to life on a global scale. In 1981 we set out to develop new techniques with electronic detectors and fast computers to increase the discovery rate. The new techniques were first developed on an existing 0.9-m telescope that the Steward Observatory had made available; we now call that the Spacewatch Telescope. The automatic detection required some eight man-years of computer programming. Three consecutive scans are made of the same strip of the sky; the moving objects are identified from comparison of the repeated scans. The instrumental developments have attracted wide attention as have our discoveries. During a clear winter night some 600 moving objects are found, which are mostly asteroids in the main belt between the orbits of Mars and Jupiter. On average, about one in 900 of such discoveries will yield an object that might come close to the Earth. The distance from the Sun is distinguished from the reflex of the Earth's motion, as is shown in Fig. 1, which works well in directions opposite to that of the Sun.

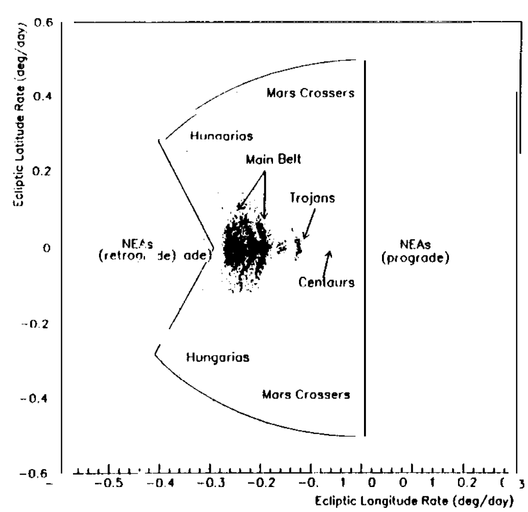

Figure 1. Plot of Ecliptic Latitude and Longitude Rates

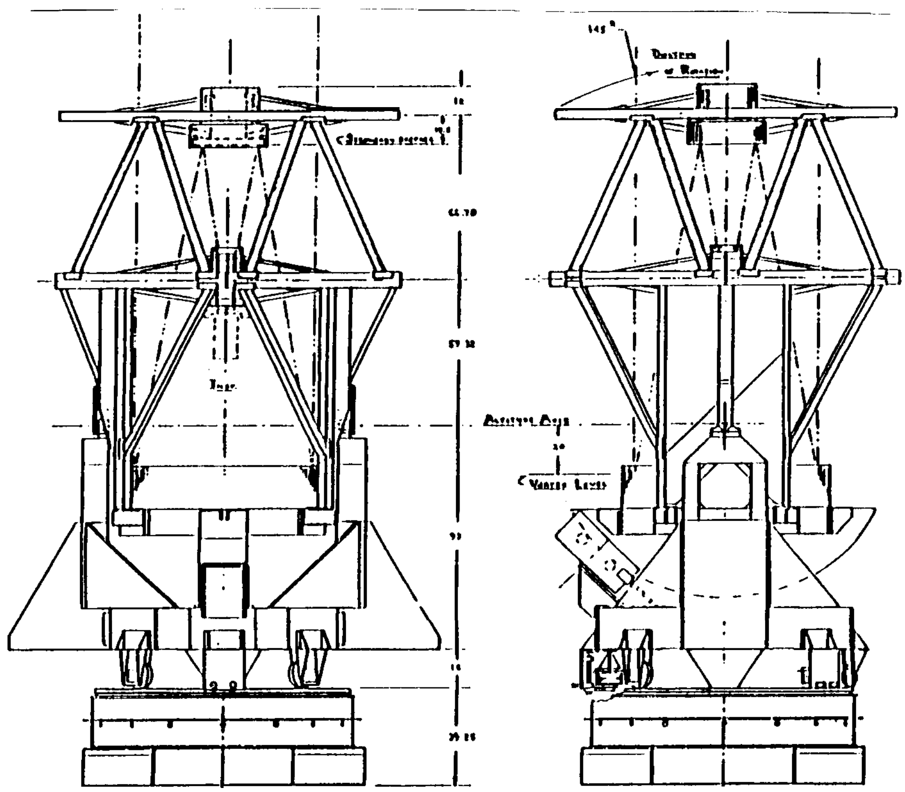

Figure 2. 1. 8-m Folded Prime Focus Spacewatch Telescope

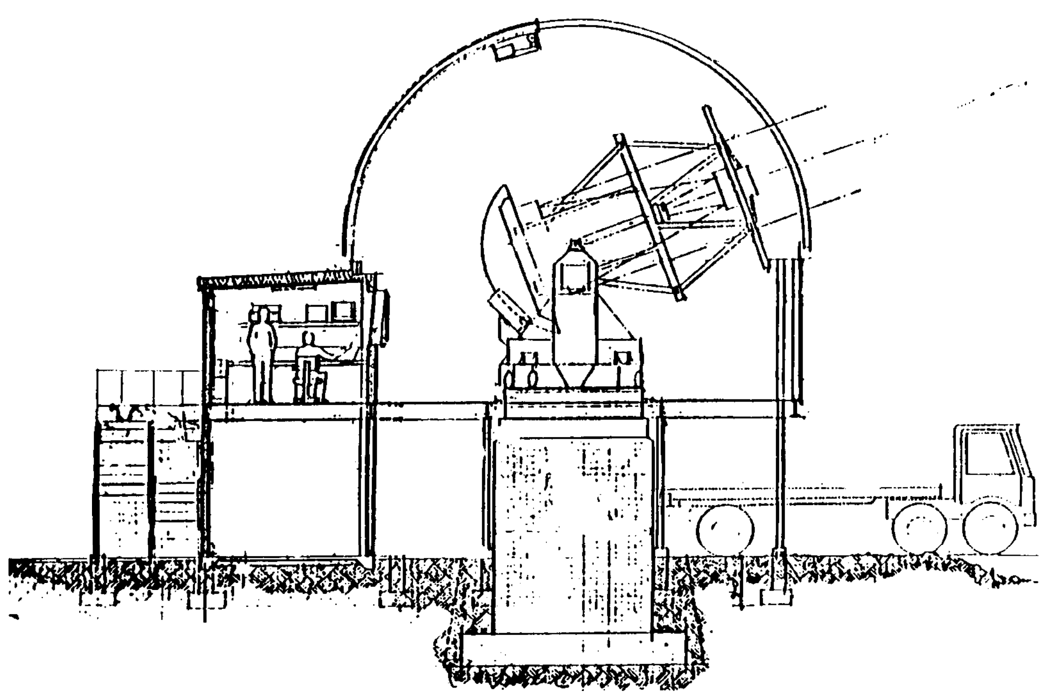

Figure 3. Pier, Dome and Building at Kitt Peak

Summary of Results

Spectacular discoveries have already been made. A grouping or family of small asteroids was found, of about 10-meters' size. The explanation of the phenomenon is keenly debated among colleagues. Another discovery is of large objects, 100 kilometers, in the outer solar system, near the orbits of Saturn, Uranus and Neptune. This population had been predicted, but farther out, near Neptune, as a source for comets and near-Earth objects eventually. A sample of findings is shown in Table 1.

The present rate of discovery of near-Earth asteroids is about 25 per year; it is still being improved. In 1994, about 70,000 astrometric positions were reported to the Minor Planet Center in Cambridge, Massachusetts. Our results have been reported and discussed in some 40 publications to date. The popular interest in this work is also considerable, with international TV reportages and articles by science writers in various journals.

Table 1. Examples of Discovered Objects

Identification	Perihelion distance (AU)	Aphelion distance (AU)	Diameter (km)
1992 AE	1.24	3.20	3.30
1994 XM1	0.90	3.10	0.01
1993 EA	0.53	2.00	2.10
1992 BA	1.25	1.40	0.40
1991 VG	0.97	1.10	0.008
P/Jedicke	3.80	7.80	-
1992 AD	8.70	32.20	140.00

1.8-m Spacewatch Telescope

The new telescope has a lightweight fused-silica mirror 1.8 meters in diameter. The telescope design is made by Larry Barr who has worked on large telescopes at the Kitt Peak, the Lick and Mauna Kea Observatories. The telescope (Figs. 2 and 3) is of a new design that we call a folded prime focus, which yields a short, compact tube, a sturdy instrument even in adverse weather conditions. The telescope is presently being built in the University Instrument Shop. This is an ideal situation in which the people who will have to run and maintain it are close to the fabrication. Students are attracted to this new program of sky surveillance. We are making a special facility, for generations to come.

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Near Earth Object Search With Ground Based Electro-Optical Deep Space Surveillance System (GEODSS)

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Detection of near-Earth objects (NEOs) includes the broad functions of identifying, characterizing, and cataloguing potentially threatening comets and asteroids. These functions can be accomplished for objects larger than 1 km using a few dedicated 1 to 2 meter telescopes. However, the key parameter to enabling such functions for the whole sky with any degree of speed is the search rate of the instruments used to collect and process the data. Search rates of reasonable magnitude to cover the whole sky suggest the use of advanced CCD detector focal planes. The Air Force has developed and is continuing to explore such capabilities in upgrading their Ground Based Electro-Optical Deep Space Surveillance System (GEODSS). Recently the Spacewatch Telescope on Kitt Peak, operated by the Universtity of Arizona with backing from the Air Force Office of Scientific Research, has discovered and begun to exploring a new population of 10 meter to 300 meter asteroids which have a more frequent arrival rate of once in a thousand years and energy equivalent to upwards of a hundred megatons. This changes broadens the potential threat and illustrates the need to also consider a warning system for threats of a size that would incur regional damage.

Development of the Ground Based Electro-Optical Deep Space Surveillance System (GEODSS)

The United States Air Force has a relatively long history of advocacy, funding, technical involvement, and operational experience with the types of systems essential to planetary defense. Front end technological capabilities needed to effectively perform such a mission include wide field of view sensors with rapid search capability, techniques for identifying moving targets in a cluttered background, and a continuously updated data base of positional and other information on all space objects. These are the same capabilities required and used by the Air Force since the beginning of the space age. Initiated in response to Sputnick, the Air Force space surveillance program has maintained a world wide network of sensors tasked to track the location of all manmade space objects. The development of the current, wide field-of-view optical search systems used by the USAF started with the Prairie Network Optics designed by Baker. These optics and technologies were incorporated in the Baker-Nunn telescope which the Smithsonian Astronomical Observatory designed for the tracking of satellites. The Baker-Nunn system was turned over to the Air Force in Colorado Springs to incorporate into their space surveillance system in 1961. In 1970 the Air Force started research and development (R&D) that led to the replacement of the Baker-Nunn optical system with the Ground Based Electro-Optical Deep Space Surveillance System (GEODSS). GEODSS used the Epsicon tube as a detector instead of film.

Large Format Charge Coupled Devices (CCDs)

Epsicon tube technology was and continues to be very successful in space surveillance applications. The current GEODSS, which was designed to have very high search rates, is an interesting design, which differs from most astronomical telescopes, mounts, cameras, and processors. The Air Force has invested nearly $200 million since 1970 in this R&D effort. But the space surveillance task load continues to grow. Today, for example, the Air Force space surveillance system processes approximately 50,000 observations each and every day and maintains orbital parameters for between seven and eight thousand man-made objects in orbit around the earth. In 1972 the Air Force started the development of solid state detectors that led to large format Charge Coupled Devices imaging cameras. These are the same devices used in spacecraft for detectors in the visible, infrared, and x-ray bands. The Air Force developed this technology and is testing it for incorporation in GEODSS as a potential modernization of part of its global space surveillance system.

Efforts to develop commercial CCDs began after a 1981 review in Washington D.C. encouraged the Spacewatch Program to develop new CCD-scanning techniques on an existing 0.9-meter Newtonian telescope contributed by the Steward Observatory of the University of Arizona. Surveying began in 1984 with a RCA 320 X 512 CCD. Though useful for other tasks, it lacked the area coverage required to detect near-Earth asteroids. In 1988, a 2048 X 2048 Tektronix CCD was delivered and near-Earth asteroids could be found.

Near Earth Object (NEO) Search

This large format Charge Coupled Devices technology appears to have significant capabilities in searching the whole sky for detecting and tracking non-man-made objects such as asteroids and comets. The Spacewatch surveying program currently finds about 25,000 asteroids per year generating their astrometric positions good to +/- 0.5 arcseconds. This surveying effort was the first to discover an entirely new population of smaller asteroids in the 10 meter to 300 meter range. The mass of these asteroids could impact with upwards of a hundred megatons of energy. This defines a threat level below the global catastrophe that would occur in the case of sizable long period comet but considerable enough to cause major regional damage particularly through tsunamis if impact occurs in a broad ocean area. The asteroids in this size range are more numerous and calculated to strike the earth with a frequency close to once every thousand years.

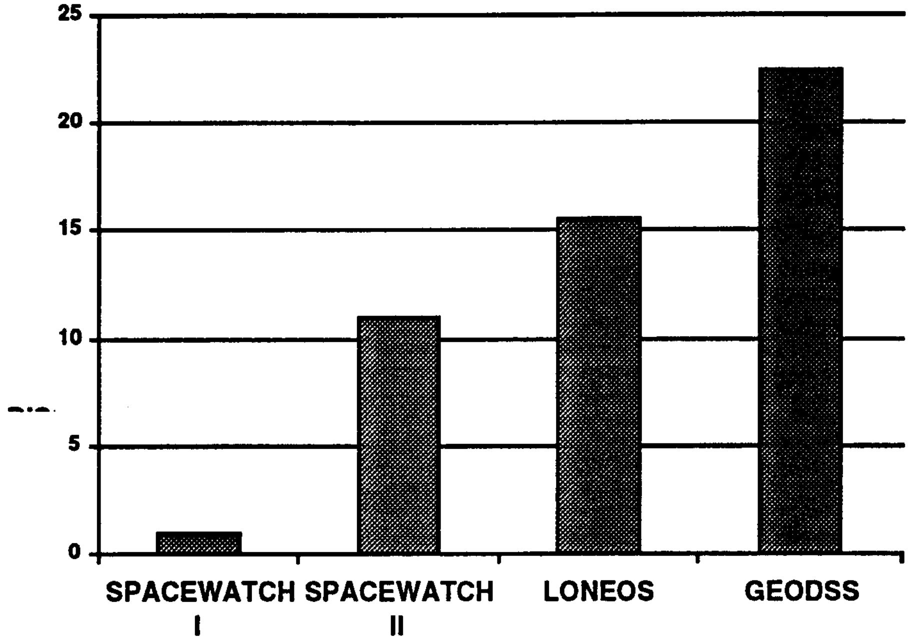

Figure 1. Near Earth object discovery rates for single telescopes in the northern hemisphere relative to Spacewatch I.

Conclusion: Future Possibilities

The resulting advances in these technologies make it possible to envision a more automated, production-oriented cataloguing than past and current efforts might imply. As shown in Figure 1,the projected system capabilities of a single GEODSS telescope upgraded with CCD technology should have more than 20 times the discovery rate of NEO's than the current SPACEWATCH. SPACEWATCH is the largest current contributor to NEO discovery. The Air Force is constructing a new, approximately four meter, very agile telescope (AEOS) on Maui at a cost of approximately $120 million. This and its predecessor (STAR FIRE at Albuquerque) might also have use in the characterization of NEO's.

Space-Based Detection of Earth-Threatening Asteroids: Sensor Design and Performance Analysis

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We consider the prospects for space-based electro-optic detection of Earth-threatening asteroids. Large asteroids with diameter > 0.1 km, which have the potential to cause significant damage to Earth's biosphere, also are sufficiently bright in reflected Sunlight to be detected from space at great distances from Earth. We estimate the asteroid signal of reflected Sunlight, and the visible background clutter in space from other sources distributed over the celestial sphere. Very large asteroids with diameter ≥ 10 km would be clearly detectable from space at distances ≥ 10 AU, by small 0.5 m aperture visible sensors with modern megapixel CCD arrays. A constellation of such sensors that repeatedly scans over 4p steradians could detect, track and classify all large asteroids in nearby interplanetary space and provide early warning of a potential collision with Earth. A conceptual design is presented for the sensor satellite.

DoD Technology of Relevance to Planetary Defense

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The 1994 DoD Clementine mission met or exceeded its planned objectives, except one. Due to a software error it was unable to complete the demanding flyby of the NEO 1620 Geographos. This capability must be demonstrated to allow exploration of a range of NEOs. The knowledge of physical properties gained by such exploration is a prerequisite to understanding any proposed deflection method. The Clementine spacecraft is still operating in interplanetary space, the first DoD spacecraft to do so. This demonstrates that advanced lightweight technology can perform at the distances and mission durations required for NEO exploration. Plans and technology development for a follow-on to Clementine are underway. It now appears feasible to develop a smaller (under 100 kg), cheaper (under $20M), follow-on spacecraft to flight qualify current (late 1990's) technology. The exploration of NEOs remains a challenging test environment for the flight qualification of the next generation of advanced space technology under development by the DoD. To fully understand the detailed properties of a diverse range of NEOs a low cost capable spacecraft capability is needed. The current status of the Clementine spacecraft will be discussed along with a review of on-going technology development and testing programs for the next generation of advanced lightweight DoD space technology. A series of low cost NEO missions have been investigated and will be discussed. These could include NEO flyby and hard impact missions launched as piggyback payloads or as dedicated payloads.

Steps Toward Impact Mitigation: New Approaches for NEO Detection and Characterization

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The end of the cold war has coincided with widespread perception of the reality of the NEO impact threat. There now exists a unique opportunity to greatly advance the capabilities for detecting, characterizing, and interdicting NEOs through the use of previously unavailable technologies and strategies. Some examples of candidate "high-tech" approaches will be described. The desirability of an international effort based upon coordination of ground and space-based assets is evident.

Introduction

Having chaired the NASA/DoE Near Earth Object Interception Workshop at Los Alamos National Laboratory in January, 1992, I'm particularly delighted to see how mutual understandings have progressed in the three years from Los Alamos to Livermore. Scientists from many different countries and disciplines who formally seldom interacted are now working side-by-side on the problem of Planetary Defense. Happily, these new collaborations encompass both civilian and defense communities and also unite our efforts across international borders.

The emergence of some of the remarkable "SDI" technologies into the unclassified world also represents very significant progress. The mostly-successful Clementine mission was vital in showing an easier path to future capabilities. Other capabilities that formally were classified secrets are now becoming available to address the Near Earth Object (NEO) threat. All of this progress is due to the hard work and deft diplomacy of numerous people, many of whom are at this meeting.

In this paper I want to share some perceptions about a potpourri of loosely related topics that are collectively very important and must be attacked in depth in order to achieve a true planetary defense. I will propose some new approaches, both observational and experimental, that can expedite progress. I am motivated by a belief that advanced concepts are readily achievable that go beyond incremental, "business as usual" approaches to detection and mitigation. I believe that innovative concepts and technologies can yield highly effective capabilities that are less expensive, more quickly realizable, and much broader in application than what has been considered to date.

While constraints such as budget limitations and perceived immaturity of present technologies seem to fore-ordain very gradual evolution toward effective mitigation capabilities, the true complexity of the NEO mitigation challenge gets swept under the rug in the process of being prudent. For example, if we are serious about defending the Earth, we have to take seriously the fact that there will always be a need for "short fuse" reaction capabilities -- things that can be done quickly to respond to short-warning threats. This will be particularly true during the next several decades, during which the number of unknown NEOs will greatly exceed the number of known ones, and the technologies for long range detection and mitigation will be immature. In order to develop capabilities to effectively mitigate the threat of NEOs, we must first increase greatly our knowledge of their physical properties and, second, graduate as soon as possible to numerous, systematic non-nuclear experiments to destroy or perturb avariety of objects. With this in mind, I want to try to point the way toward approaches that can accelerate our reaction times and simplify missions while also expanding our knowledge base by orders of magnitude.

At present, most attention is focused upon very large "doomsday" objects, which are rarely encountered in both space and time. Thus, present ideas revolve around searches for large objects covering many years, punctuated by occasional missions to explore and/or perturb well-known large objects. Paradoxically, I believe that the required quick-reaction capabilities will develop from a better approach to detection and experimentation focused upon the very large population of very small, periodic asteroids that are constantly passing near the Earth. They can provide a readily accessible experimental arena that will permit the development of effective mitigation strategies in scaled-down, frequent tests of interception hardware and methods.

I will describe a new strategy based upon a spacecraft called ARGUS which directss grourd-basedl radar and optical astronomy resources with very high efficiency. ARGUS will also discover all of the large objects targeted by other search strategies, but quicker andwiith more comprehenive results. Interestingly, GUS may also make it possible to easily capture small velocitinto Earth orbitsCin the huge stable regions L4 and L5 on the lunar orbit, where detailed experiments and analyses will become feasible.

Difficulties of Interception of Random Large NEOs

In an actual mitigation mission, it would be desirable to rendezvous with the target object far from the Earth so that small perturbations imparted to the object can integrate to large miss-distance at the Earth. To do this, however, requires very precise information about very faint objects whose characteristics must be well known years in advance. (Such information permitted the spectacular fly-by photographs of the main-belt asteroids Gaspara and Ida by NASA's Galileo spacecraft now in route to Jupiter.) The problem of how to intercept randomly occurring objects such as long period comets is very different from the question of how to deal with periodic NEOs whose orbits can be well determined so that we can plan research and interception missions at leisure. I don't feel that adequate attention has been given to the vast difference in technological capabilities needed to address these two types of threats. Comets may comprise more than 25% of the overall threat, particularly when their higher velocities are included in the threat analysis.

For missions to encounter randomly-occurring Earth-threatening objects, the word "rendezvous" is vastly optimistic; it should be "fly-by" or "impact", because generally the energy required to actually match the spacecraft velocity with that of the object would be very large. A low delta-V spacecraft, meaning essentially that it possesses relatively low fuel mass compared with the mass of the payload, will necessarily be confined closely to the plane of the Earth's orbit (see Figure 1). The spacecraft must be launched so that it arrives at the right place and the right time to encounter the NEO as it crosses the ecliptic plane. That will usually result in a high-speed encounter with a very short visit duration. If the mission is merely to gather data on the object, the data must be obtained very quickly. To destroy the NEO or deflect it from its initial orbit, the encounter would have to be executed with great precision.

If a high delta-V spacecraft were available, it might be possible to launch into the orbital plane of the NEO, changing from the plane of the Earth's orbit (Figure 2). Better options would then become possible. If enough time is available, the spacecraft can eventually achieve a true rendezvous. The best place to perturb an NEO to cause it to miss the Earth is at perihelion, where maximum change in its velocity vector will occur per unit of energy delivered to the NEO.

Of course, if unlimited time is available, gravitational deflections from encounters with one or more planets can change the orbit effectively even with modest delta-V (Figure 3). But, it is clear that such leisurely approaches will not apply in the general NEO defense case.

True planetary defense must deal with a very large parameter space. Comets must be included, which may comprise one tenth to one fourth of the overall threat, or even more if the consequences of their higher kinetic energy are included. Comets could be encountered having diameters greater than 10 kilometers, velocities up to about 70 kilometers per second, and warning times that may range from zero up to 1,000 years. -- The great majority of asteroidal Earth-threatening objects are also hard to deal with in a timely way because they are small and faint, and therefore quite hard to find, even though their velocities are considerably lower than some of the comets. The chart shown in Figure 4, adopted from the Spaceguard study, emphasizes the latter fact. This chart shows the expected results from 25 years of observations with that proposed ground-based system: If, indeed, the survey could reach to the twenty-second stellar magnitude, after a few years the catalog would be about 90 percent complete for one-kilometer diameter asteroidal objects having regular, relatively short period orbits. For half-kilometer objects it would be perhaps 70 percent complete. Smaller objects fall precipitously off the bottom of the chart, being undetectable except in small percentages because of their faintness; and there are much vaster numbers of smaller objects.

Therefore, the detailed physical andies oftthettotal population m ass, m cótion, rand orbital distribution of Earth-threatening objects will remain inaccessible and incomplete if based on data exclusively from ground-based surveys of larger, less numerous objects unless the data is accumulated over hundreds of years. Obviously, no data on material reactions will be accumulated without actual in-space experiments; and ,to be meaningful, such experiments must be performed on as large a sample of the population as possible.

Reconsidering the Importance of Small NEOs

I think that this large deficit of information is unacceptable. While we all agree that large objects are the ones to worry about in terms of global extinction events, the key to understanding the large objects may well lie in the vast hidden data of the smaller objects. The steep power law characterizing the size distribution indicates that there are millions of NEOs at the 10 meter diameter level. Very few of these would survive the Earth's atmosphere to produce damage at the surface; but, in space, they can provide a wealth of vital data. A thorough census of the small objects, gathered in the course of seeking the large "Earth Destroyers", can reveal the answers to many questions such as: (1) What are the relative percentages of heavy metal objects, icy comet fragments, hydrated relicts of the solar nebula, carbonaceous chondrites, and dry achondrites in the total population passing near the Earth? (2) What is the total distribution of orbital state vectors? Are there bunching effects in phase space that will change the frequency of impacts over time? Does the pulsating potential well created by the Moon orbiting the Earth drive such bunching? (3) Is there a gaussian "tail" of low velocity NEOs that we can easily reach as they pass through the Earth-Moon system? Are they sometimes quasi-trapped in the Moon's L4 and L5 Lagrange regions?

The consequences for world-wide catastrophe decrease as impacting object sizes fall below the kilometer/half-kilometer diameter range. In spite of lower expected mortality from smaller (but much more frequent events), this does not mean that the potential for locally terrible consequences from smaller objects should be ignored. The people who are paying for our efforts are concerned about massive carnage on any scale, particularly in the near term; and we must be able to give honest assurance that we are working to avoid catastrophes of all magnitudes.

Among the most important pieces of work inspired by our 1992 Los Alamos workshop was the work of Hills and Goda[1] (Figure 5), who calculated the effects of energy dissipation by impacts of objects in the 10 to 500 meter diameter range. They have achieved quantitative understanding of how stony and metallic impactors break up and what the radius of destruction in kilometers is as a function of the size of the object. A stony object 200 or 300 meters in diameter would essentially annihilate an area the size of Connecticut. I do not believe that we could find objects this small with any reliability using the proposed Spaceguard system. Even if we did find them fortuitously in a terminal-orbital phase, I do not believe that we could react quickly enough to evacuate Connecticut in the short warning time that a strictly Earth-based system would provide. Over the centuries, we are involved in a "crap shoot" situation, where it's the roll of the cosmic dice that determines what gets hit. Surely it must be our responsibility to find ways of preventing even these very rare but potentially enormous tragedies from smaller, but much more frequent, impactors.

The Tunguska impact in 1908 did give us quite a real lesson in the effects of a small comet in the 50-100 meter diameter range. The Spaceguard report showed the lethal area of about four pounds per square inch over-pressure: Figure 6 shows the way the trees were laid down from that event compared with the areas of New York City and Washington.

Further work has been reported on tsunamis caused by impacts. These can also be very profound events. On the eastern seaboard of the United States, for example, there is evidence that there was a tsunami within the last 100,000 years that devastated everything from the coast of North Carolina and Virginia all the way to the edge of the Piedmont plateau. If this occurred now, millions of people would die. Air-burst events like Tunguska don't leave any significant geologic signatures and indeed may be washed away within a short time even on the scale of human history. But tsunamis leave much longer lasting signatures that may provide better understanding of "smaller" events.

So, we have to continue to refine the definition of the threat. We have to find out truly what the full significance of these small objects is and where you draw the line between no concern whatsoever and active concern. Basically, I believe that we can easily build a new type of detection system that will be able to garner an essentially complete census of all periodic NEOs down to ten meter diameters. This system will, of course also find all of the large, periodic "extinction-class" objects over several years of operation. The fact that the small objects are so much more numerous suggests that they are, by far, the easiest to use in active experiments to enable us to develop the ability to intercept and mitigate.

Need for Interactive Mitigation Experiments

The past decade has seen the advent of the first images of both comet nuclei and asteroids, which typically turn out to be quite elongated in form. First, the pictures of the nucleus of comet Halley revealed a peanut-shaped object 21 kilometers long and about 8 kilometers in diameter. Then the pictures of the main-belt asteroids Gaspra and Ida taken by the Galileo spacecraft revealed highly elongated, irregular objects. -- Concurrently, radar imaging of smaller, closer NEOs have shown Castalia (see Figure 7), Toutatis, and Geographos also to be very elongated or double.

Consider a hypothetical experiment to perturb Toutatis, shown in Figure 8. Where would you hit it? An impulse near one end would probably cause it to spin like a dumbbell, possibly separating it centrifugally. Hitting it near the middle might break it into two or more objects. Then you'd have to have more payloads available to deal with the fragments. We are in a state of profound ignorance as to having reasonable abilities to predict what the actual reaction would be. There is a strong case for non-nuclear ein pactme pex ents o n small NEOs in the not-distant future. At the very least, we will get data on ewhether ith reaobj as socts ie or bur tsa part as dust To oathis, howeverewill require careful advanced set-up of the interceptors and real-time detection of large numbers of small NEOs in order to find one that we can reach in a timely way.

If we achieve expanding capabilities in space in the next two decades, it is quite possible that some significant experiments can be done. In addition to answering the three classes of questions previously mentioned crning NE O ical/s properties rbitaladynamio we cwill be eabl to fi d some ideal targets for controlled experiments. Existing data suggsts that, at any given time, there aapproxinate ly 100 NEOs larger than 10 meters in diameter passing through a spherical volume centered on the Earth with n usdö of e million kilometers. This motivates me to p ppose a new set of detection technologies that will, a rrelaveiv ldwlccwt, be able to find and characterize 100% of such objects in real time, leading to capabilities for numerous quick-reaction perturbation experiments in the first decade of the new millennium. The proposed system exploits the best of both worlds: space-based detection and ground-based data augmentation.

A New "High-Tech" Detection Strategy

ARGUS Spacecraft

By borrowing from formerly defense-oriented technologies, we can build a versatile, low cost new spacecraft that can be stationed at the L1 point between the Earth and the sun -- about 1 ,5 million kilometers toward the sun (Figure 9). It has been named "ARGUS", for Asteroid Research Global Unbiased Surveyor (Figure 10). It can be built on many of the same technologies that were integrated into Clementine: "smart" visible and infrared focal plane sensors and state-of-the-art onboard computing technologies. The ARGUS spacecraft at solar L1 with a 3 degree field of view and 32 degree field of regard in circular scan mode will detect all 10 meter or larger diameter NEOs passing through the vicinity of the Earth with nearly 100% success probability. At an average speed of 20 kilometers per second, typical NEOs would be tracked for more than half a day -- sufficient to hand them off to any observers on Earth equipped with radar and optical telescopes. They can then do a thorough and complete job of analyzing the detailed properties of essentially all of our visitors..

What characteristics are required for the spacecraft to find these faint objects? Detailed photonic analysis by a team at Marshall Space Flight Center headed by Max Nein has confirmed the capabilities of the proposed suite of technologies. The largest departure from Clementine technology is the need for a low-weight primary reflector 1.5 meters in diameter. This does not need to be a very precise or expensive reflector. Since the resolution will be limited by the pixel size, the primary reflector can be made with composite materials and integrated with the light-weight spacecraft technologies now available. The probable "push-broom mode" CCD sensor observes the distant stars to 21st magnitude. The spacecraft is self-stabilizing because the on-board computer recognizes the star field. It has smart computer technology using a four gigabyte, all solid state processor that reports only moving objects that come into the field of view, leading to very modest data transmission requirements. I believe all of this can be done economically and quickly based upon technology that now exists.

Free Electron Maser Radar for 3 mm Wavelength

Radar, as we have seen, can image NEOs. It can also measure their state vectors to high accuracy, thus pinning down the orbits precisely. Moreover, radar can probably distinguish among metallic, icy, and dry, stony objects. In addition to all of these advantages, it can readily hand off the detected objects to optical and infrared astronomers for detailed studies.

One thing that radar cannot do well is whole-sky searches because there is too much sky for too few radars. This is why the ARGUS spacecraft is needed to hand off each detection to the ground-based radar for refinement. Also, radar is an inverse fourth-power device, which requires very high peak power pulses and/or very narrow beam width to achieve long ranges and high signal-to-noise. Narrow beam width is obtained by having the largest possible antenna in terms of the wavelength of operation. Super high power at short (millimeter) wavelengths has hitherto been restricted by available technology. Both of these requirements (i.e. high peak power and large, fully steerable antenna) can now be met by excellent new technologies that are completely within the state-of-the-art.

Millimeter wavelength astronomy has driven antenna technology to 30 meter diameters with surface accuracy of 100 micrometers (rms) or better. The cost of these antennas is surprisingly low. So it is easy to build an antenna for 3 mm wavelength for about $6 million that has higher gain than the Arecibo system and is fully steerable.

How, then, can we achieve very high peak power pulses? The answer is to use free electron coherent emission technology, which has been undergoing many generations of development in the past 20 years. Basically, you need a compact, modest-cost high-current electron accelerator and a row of alternating magnets known as a "wiggler". (Figure 11) The electromagnetic wave length that emerges from the wiggler is inversely proportional to the square of the relativistic energy of the electrons: 6 Mev electrons will produce copious radiation at 3 mm.

At NASA, in a joint program with the Ballistic Missile Defense Organization, considerable effort has been put into developing reliable ways of building a new type of compact, high current accelerator. (Figure 12) Each of the illustrated modules produces one million electron volts at 500 amperes using all solid-state silicon technology, and they have demonstrated billions of pulses without missing a tick. This is totally new territory in terms of accelerator technology that is both reliable and inexpensive. One module costs $450,000 to build. The entire free electron maser for the asteroid radar would cost under $10 million. (Six accelerator modules are required, plus the cathode and wiggler and a building to house it.). Coupled with the magnetic wiggler technology developed at the Lawrence Livermore National Laboratory, this system will produce peak power pulses on the order of 10 gigawatts with duration of 50 nanoseconds at a rate of 500 pulses per second. One such radar in the northern hemisphere and one in the southern will be sufficient to image and fully determine the orbits of all objects discovered by the ARGUS spacecraft.

Help from Russia

There is yet another tantalizing near-term opportunity for NEO search and diagnostics that presently needs political talent more than technical talent to realize it. Figure 13 is unfortunately a very poor picture which proves that truth is stranger than fiction. Those of you who read Tom Clancy's book, The Cardinal of the Kremlin, back in 1986, remember that the scene of the action was a place in Tadjikistan which was supposed to be a ground-based laser site. After a lot of ruckus about this, Pravda published this picture of this site on top of Mt. Sanglak, which is about 50 kilometers south of Dushanbe. It's an excellent site, 7,000 feet above sea level, with superb weather the year around. There are ten domes, six of them in one cluster and four more in a second group -- probably an arrangement for detailed imaging and ranging of space objects of all sorts. The site was still under construction in 1986 when Figure 12 was taken.

This is clearly a state-of-the-art optical facility in the world, and it is eminently capable of advancing the NEO search. Each dome contains a telescope between 2 and 3 meters aperture, and they could easily be equipped with the latest imaging technology. You could, for example, put a "staring-mode" sensor on each of the telescopes and look in ten different directions at once. It also could have stereo and phased-array capabilities so that objects could be imaged at high resolution. Combined with a pulsed laser capability, active imaging from this site would also be possible.

The unfortunate fact is that there is now a very unstable political situation in Tadjikistan. Perhaps international attention to the significance of this site for NEO research might help to stabilize that unhappy situation. I am told that Russia would very much like to see that happen. Given enough motivation from clearly beneficial activities such as the protection of the world from impacts, perhaps this could become a unifying principle to do something constructive for all people. Maybe NEO researchers could get a foothold there and establish this as an enclave that would be protected and woul de the search to go forward at a much accelerated pace. So, this something that I would propose as a topic for a lot more international discussion. Mount Sanglak and other former Soviet facilities provide very real potential opportunities, and they can certainly play a vital role in achieving our fondest hopes for NEO progress.

No Malicious Use of NEOs

There is one final matter that I want to address. At the 1993 Tucson meeting, the question was raised by Carl Sagan as to whether anyone who developed the means of deflecting an object might not do it with malice aforethought so that they might dump an NEO in the backyard of their enemies. In view of what I've said about the unpredictable occurrences of these objects, the unknown center of mass, the unknown questions about whether they're going to come apart into many pieces if you try to do something, such hostile acts seem extraordinarily unlikely as well as unwise.

Suppose we knew that an object was going to collide at the point indicated in Figure 14. The best estimate of the impact point would be surrounded by a circular error probability. If you undertook to deflect the object, you would try to make it miss the Earth by at least three Earth radii because you can certainly expect an additional large gaussian error probability for any action that you undertake. No matter what you do, unquestionably you will want to do it so that you've allowed for several standard deviations from all potential sources of error. The residuals are always going to be very large.

If you had in mind dumping this NEO in your enemy's backyard, it would just as likely land in your own backyard or in some other even less desirable place. In addition to that, I think it's fairly obvious that it's much easier to send a "nuke" directly to your enemy's backyard than it is to try to go all the way out to an asteroid in order to accomplish the same nasty thing. So, concentration should be on eliminating war rockets and eliminating "nukes" for hostile purposes rather than curtailing development of abilities to deal with NEOs that will surely eventually pose a real threat to innocent people on Earth.

At the same time, we must, of course, reflect on the problem of just how far it is prudent to go with elimination of nuclear devices. In building nuclear weapons, the superpowers have developed over the past 50 years the most sophisticated technology in the history of the world. Sustaining it requires an enormous infrastructure. Let's hope for the best and suppose we will have a peaceful world, a world of nuclear disarmament. Still do we want to keep some of these capabilities against the inevitable impact threat? Do we want to preserve the know-how, the ability to build these things in order to protect against the ultimate cosmic disaster? This is a policy issue of international importance that we all need to think about. It is not a simple issue.

Conclusions

The key initial requirement is for a complete survey of Near-Earth Objects, and I emphasize "complete." The level of that survey should be extended down to 10-50 meter diameter objects so that we have a full sample of population density versus size, orbital dynamics, and physical properties of all short period (i.e. <10 years) objects. We must increase the detection range and time so that we can send diagnostic probes to a variety of different objects. Further, we must continue with precursor activities to expand the knowledge base of comets and other long period objects in any way we can. Test deflections and disruptions using non-nuclear means must be attempted as soon as possible on the small and frequently detectable objects that safely visit the earth in droves and pose no threat. A new detection spacecraft named ARGUS has been proposed that, together with a new type of ground-based radar and ground-based optical facilities, can achieve the required detection capabilities to complete the survey and hand off to interceptor probes with very cost-effective hardware and operations. I think that these things must be done expeditiously if we're really serious about trying to defend the Earth.

Figure 1

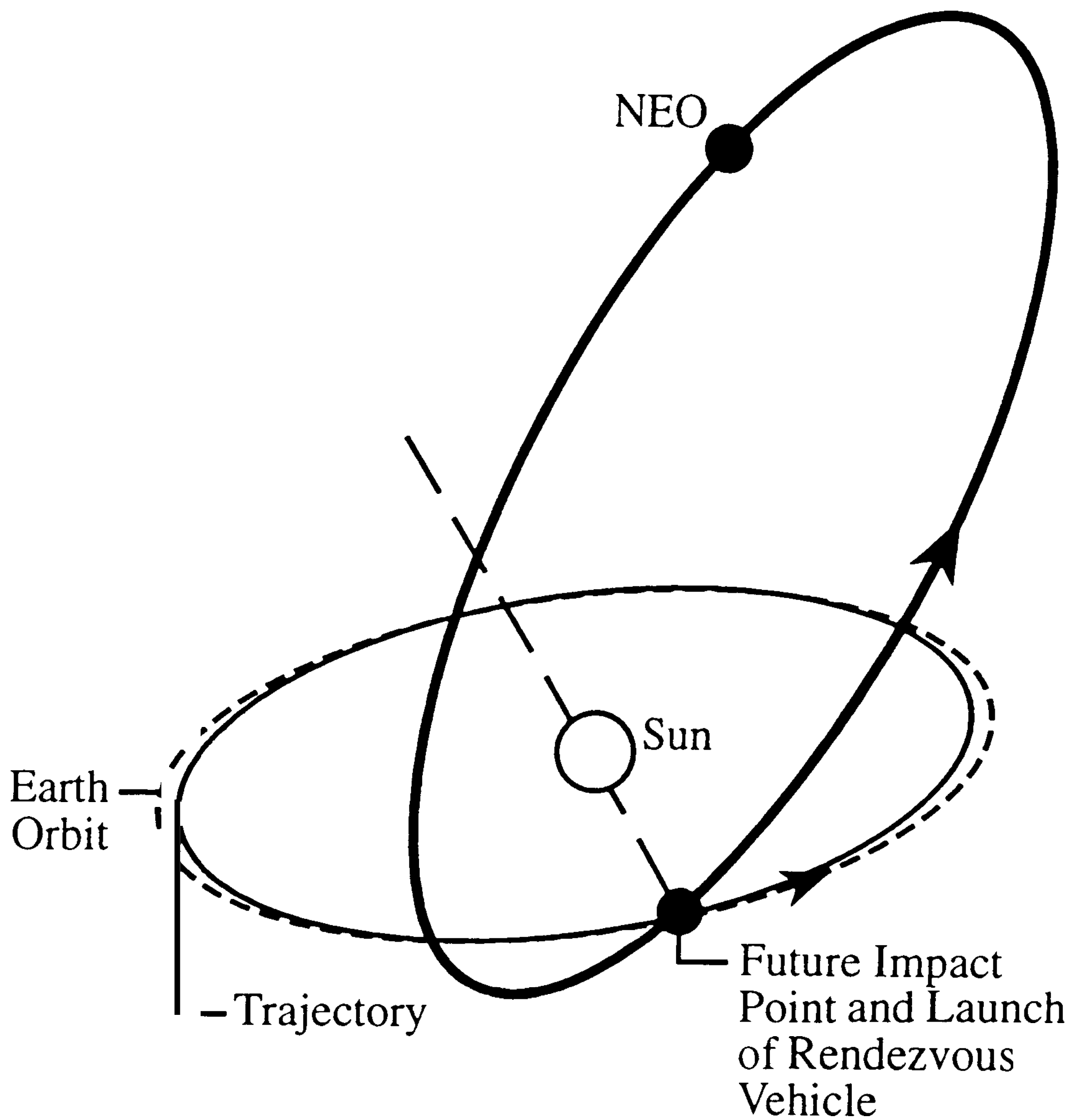


Figure 1: Low-ΔV, high-closing velocity interception. Interceptor orbital period is slightly greater or less than one year in order to achieve phasing needed for interception. Several NEO orbital periods must be available before Earth impact.

Figure 2

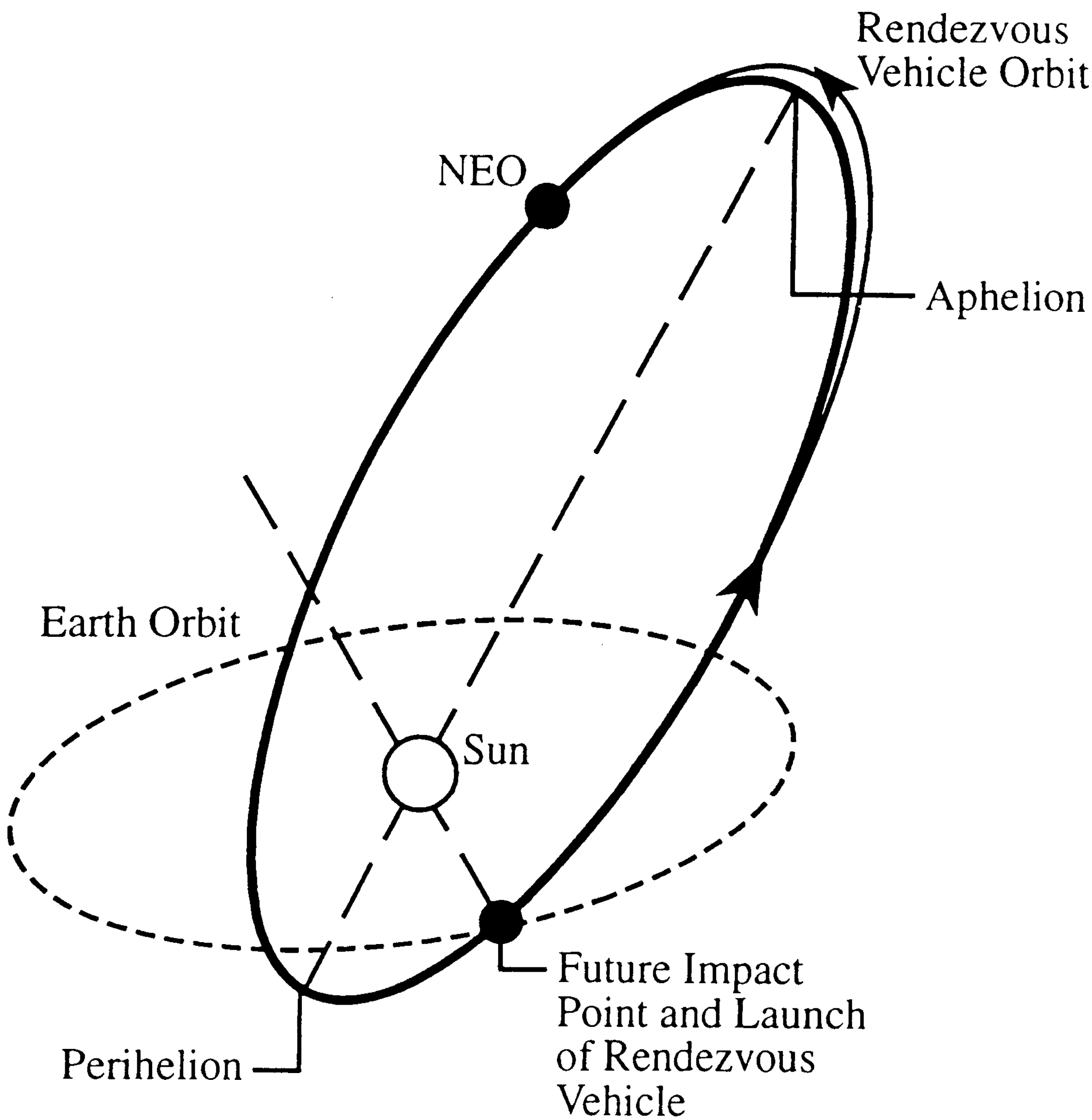


Figure 2: High-ΔV NEO rendezvous mission.

Figure 3

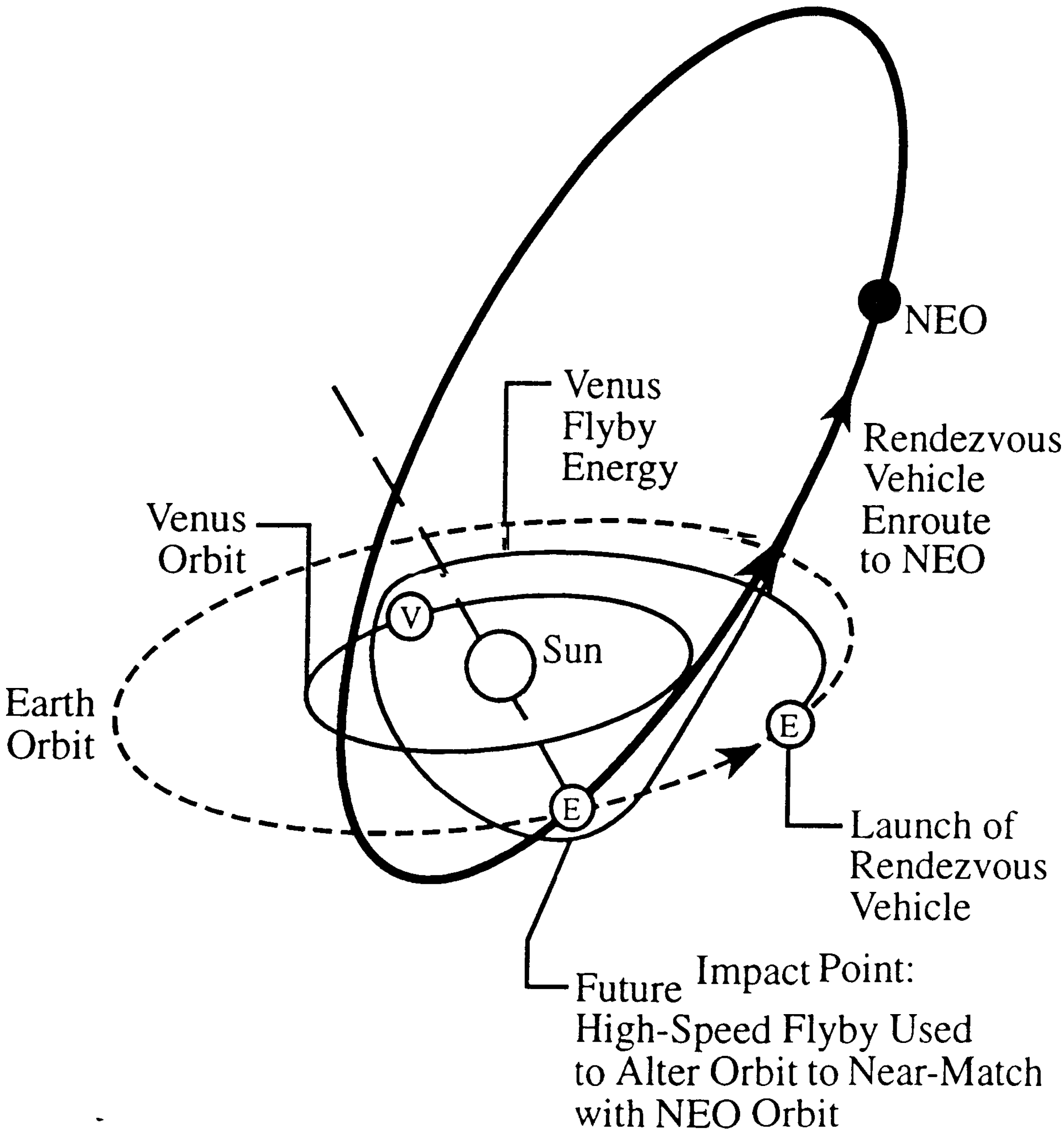


Figure 3: Moderate-ΔV rendezvous mission, using planatary flyby (in this case, Venus first and then Earth).

Figure 4

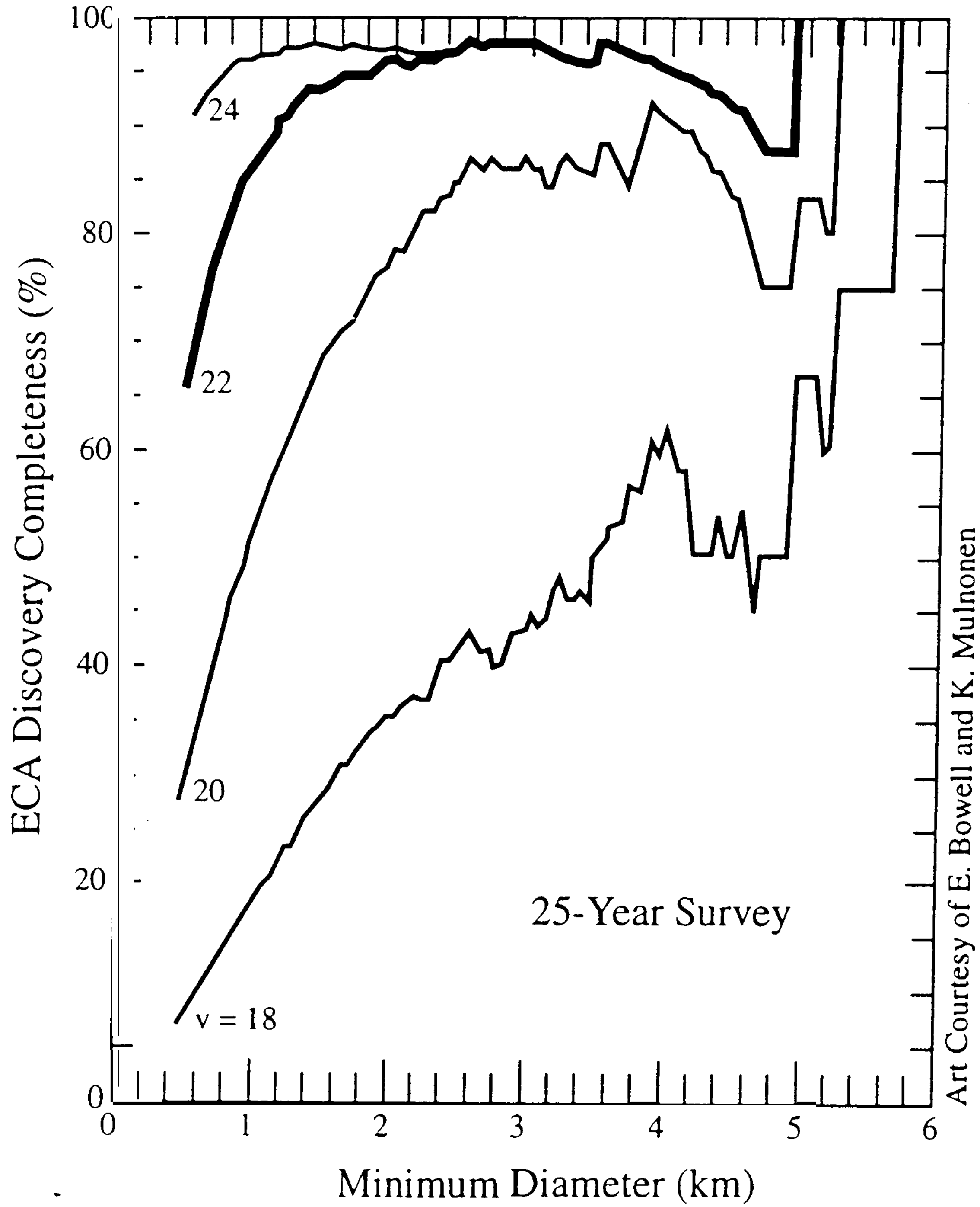


Figure 4: ECA discovery completeness as functions of threshold diameters and limiting magnitude V for the standard survey region (see text). In the bias-corrected model population examined, several large ECAs went undetected throughtout the survey, even at faint V.

Figure 5

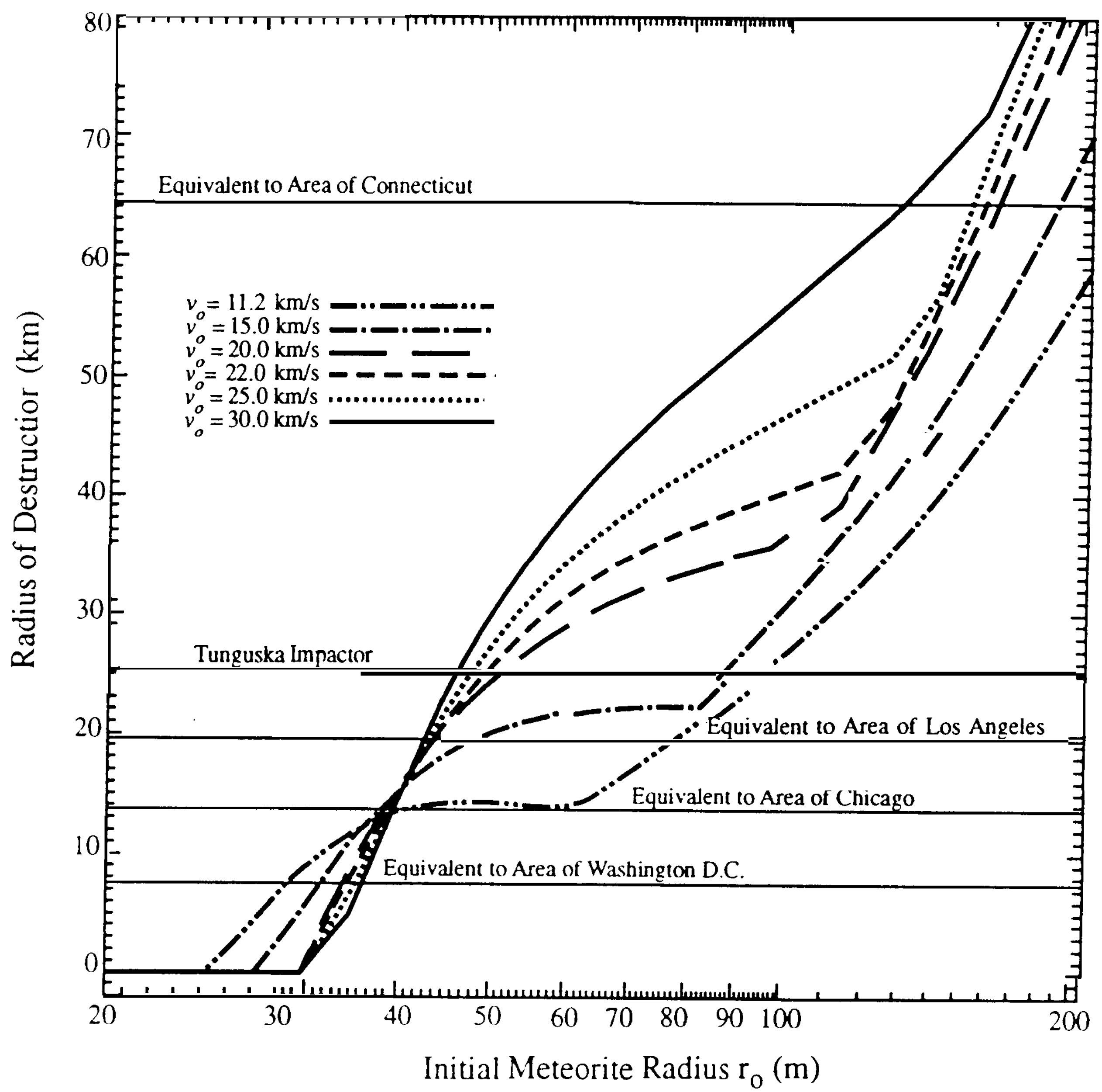
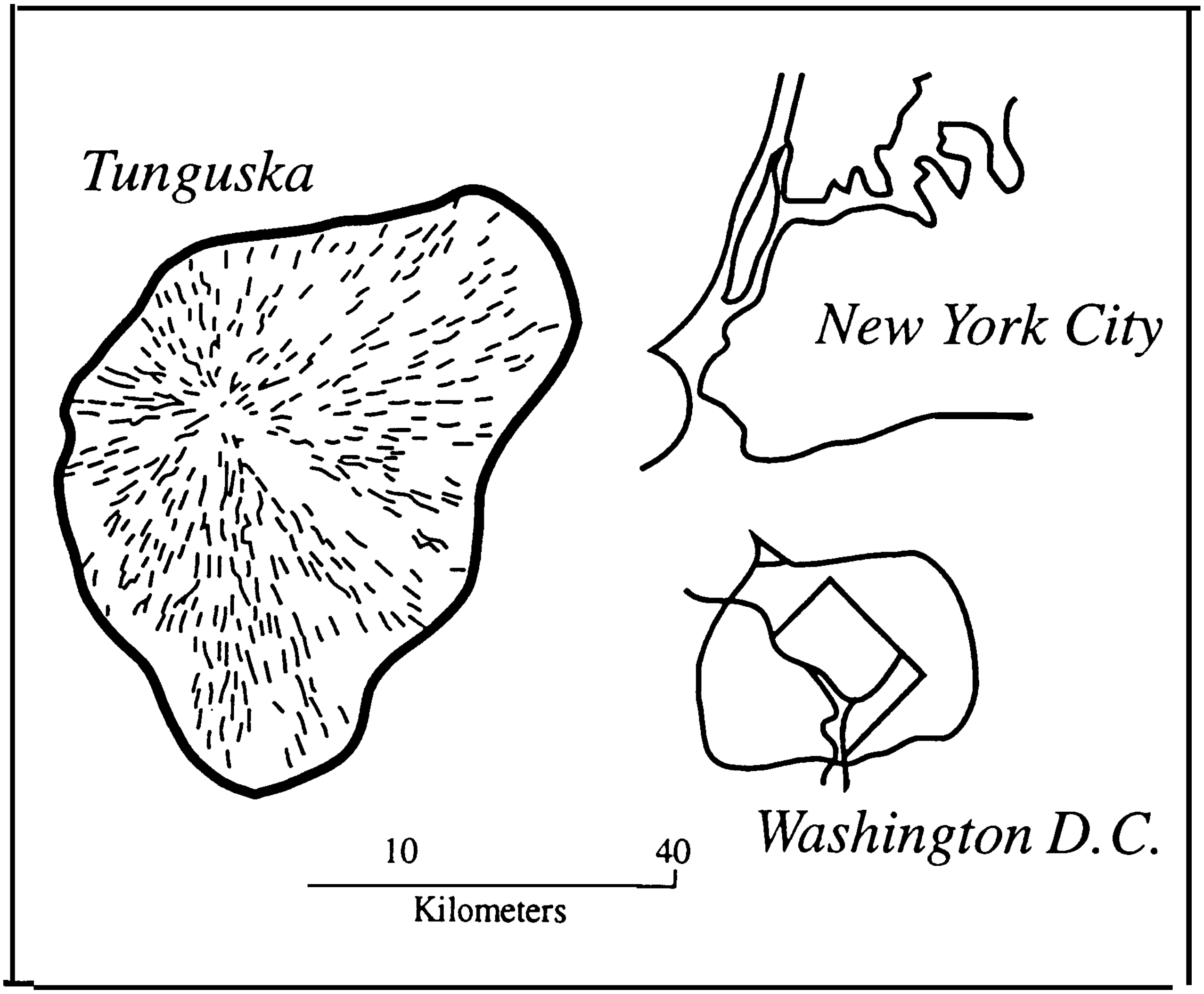


Figure 5: Stony meteriote radius of destruction as function of size and impact velocity.

Figure 6



Art Courtesy of John Pike

Figure 6: Tunguska in Perspective

Figure 7

Asteroid 1989 PB

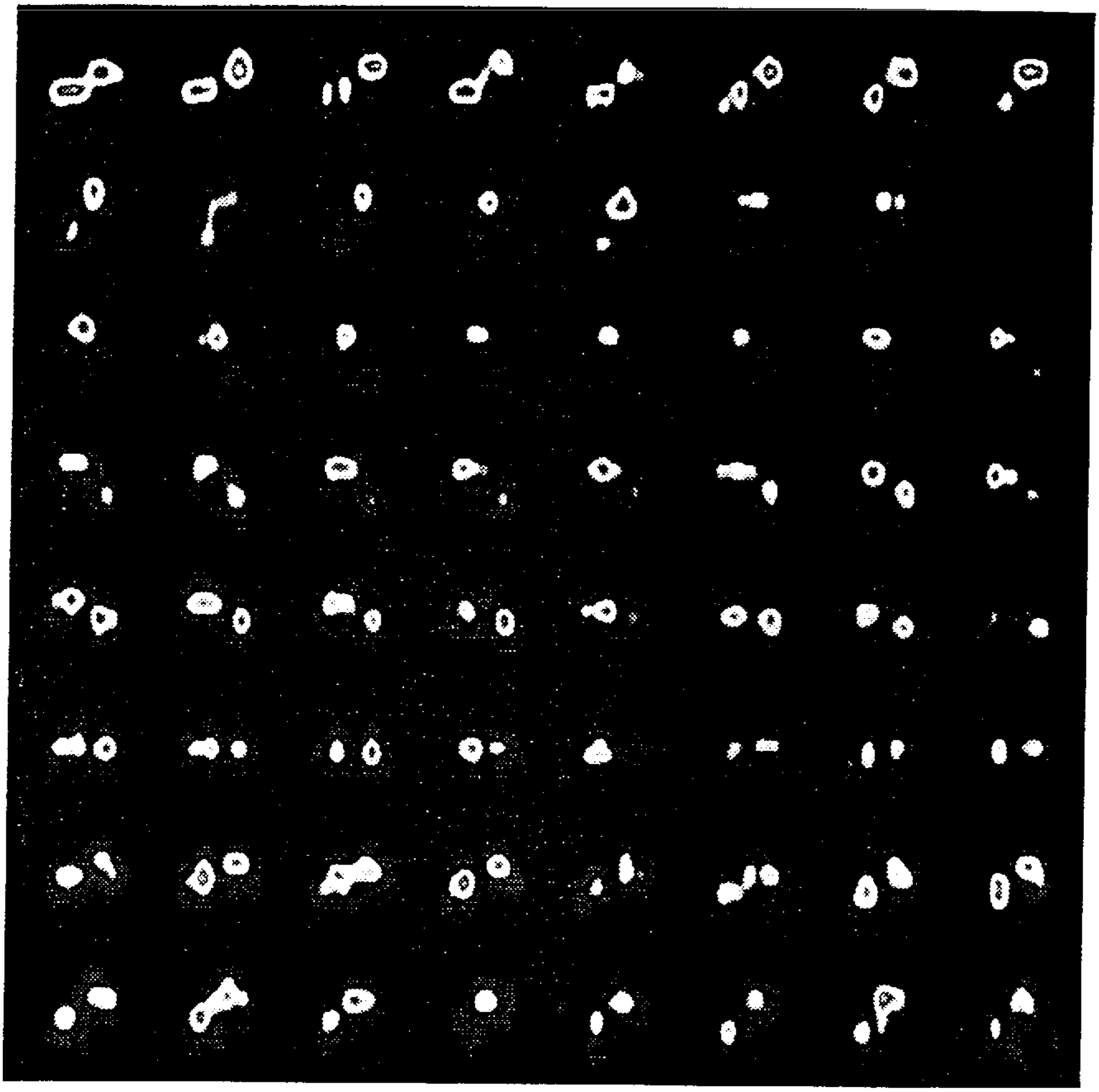
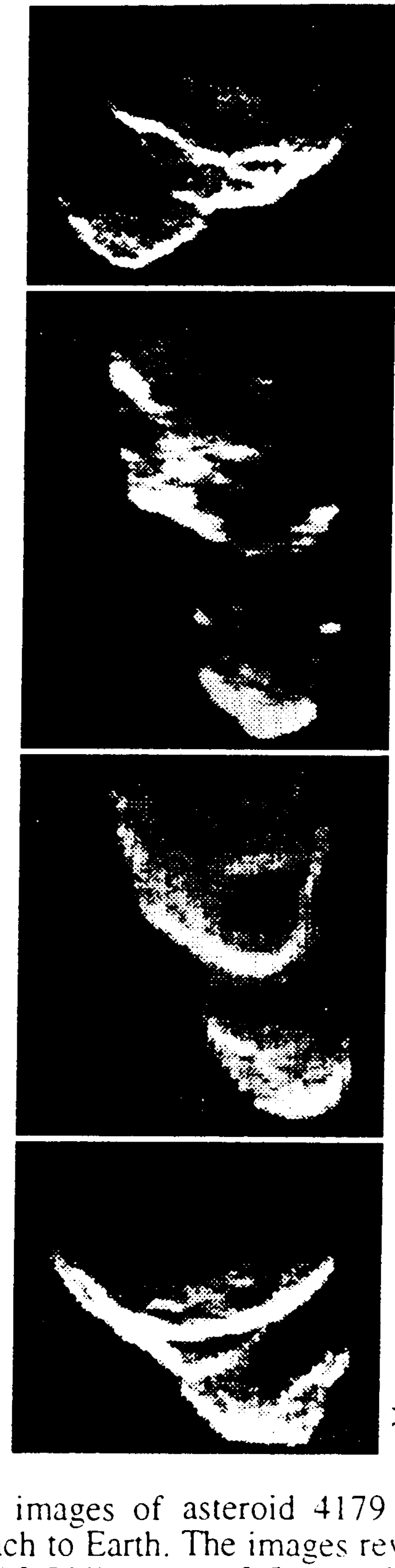


Figure 7: Radar images reveal 1989 PB to consist of two distinct, half-mile-diameter lobes that appear to be in contact. It seems likely that the lobes once were seperate and that they collided gently to produce the current "contact-binary" shape.

Reference: S. J. Osrto, J .F. Chandler, A. A. Hine, I. I. Shapiro, K. D. Rosema, D. K. Yeomans.
Radar Images of Asteroid 1989 PB. *Science* 248, 1523-1528 (June 22, 1990).

Figure 8



January 4, 1993
Toutatis RadarImages

Figure 8: These are radar images of asteroid 4179 Toutatis made during the object's recent close approach to Earth. The images reveal two irregularly shaped, cratered objects about 4 and 2.5 kilometers (2.5 and 1.6 miles) in average diameter which are probably in contact with each other.

TRANSFER TRAJECTORY TO HALO ORBIT AT EARTH/SUN L_1

ISEE-3 / Ice Comet Mission Launched August 12, 1978

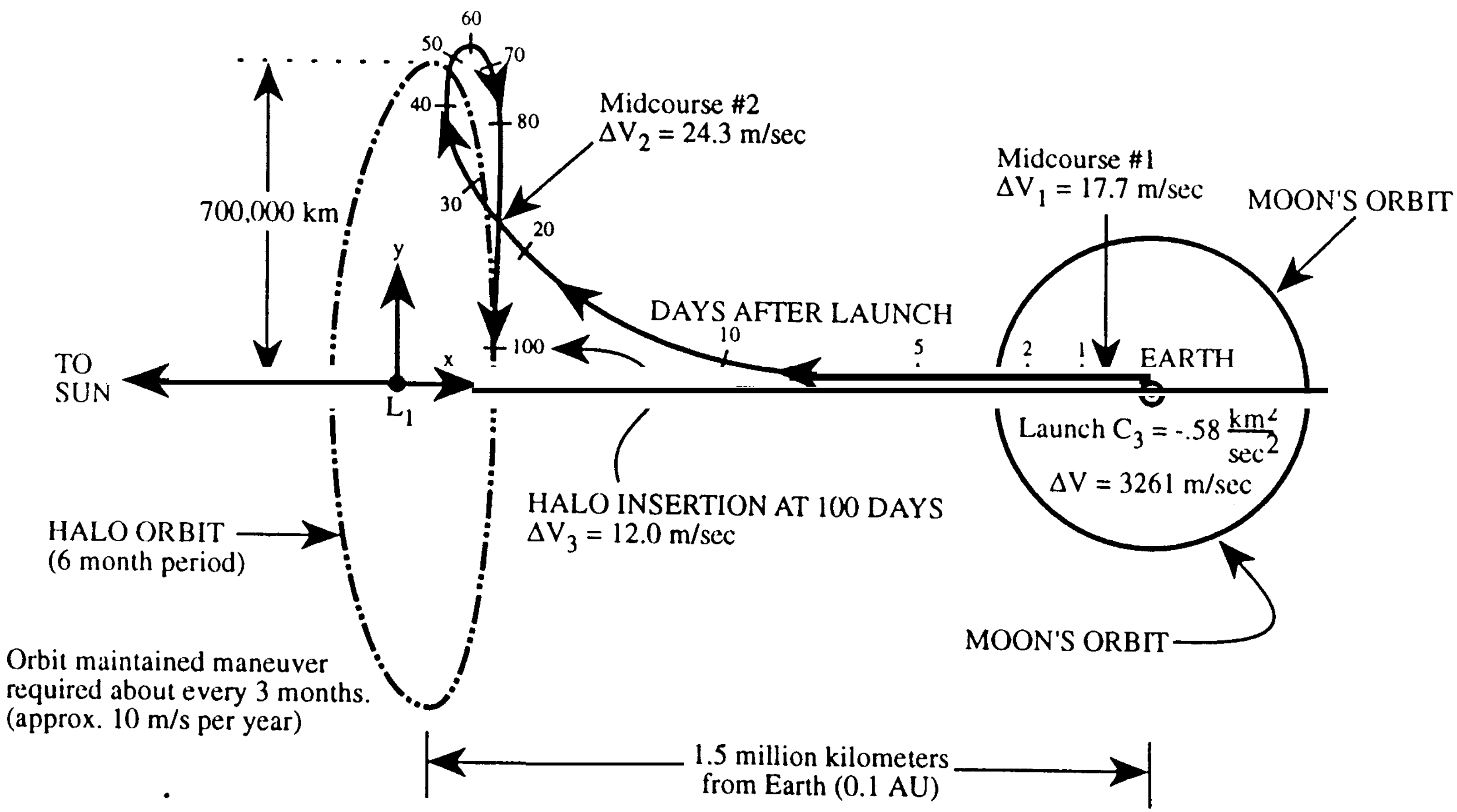


Figure 9 Reference: J. McCarter - NASA Marshall Space Flight Center.

Figure 9

ARGUS
Deployed Configuration

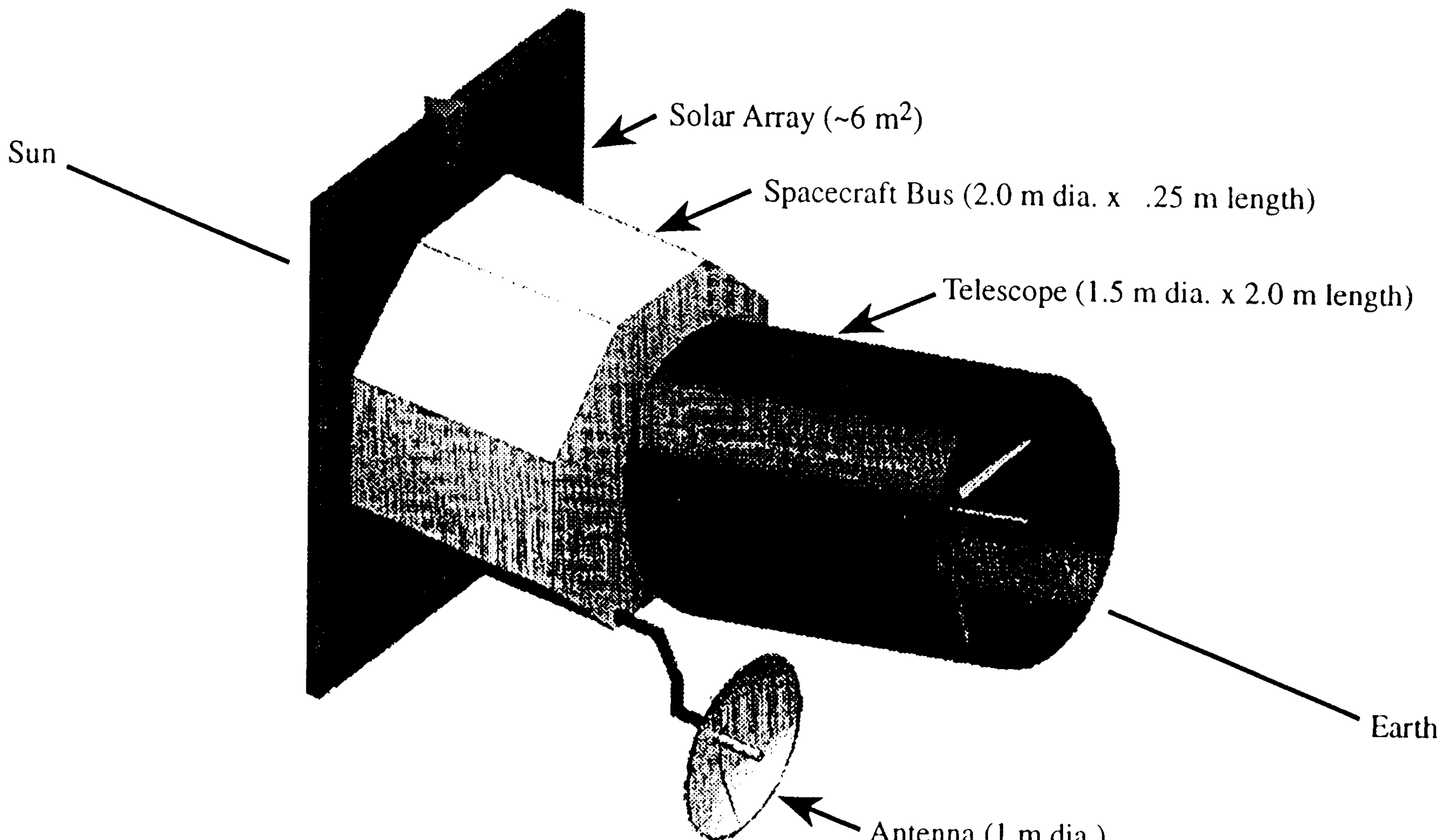


Figure 10: NASA/MSFC, PD23/Sharon S. Fincher, January 19, 1995.

Figure 10

Figure 11

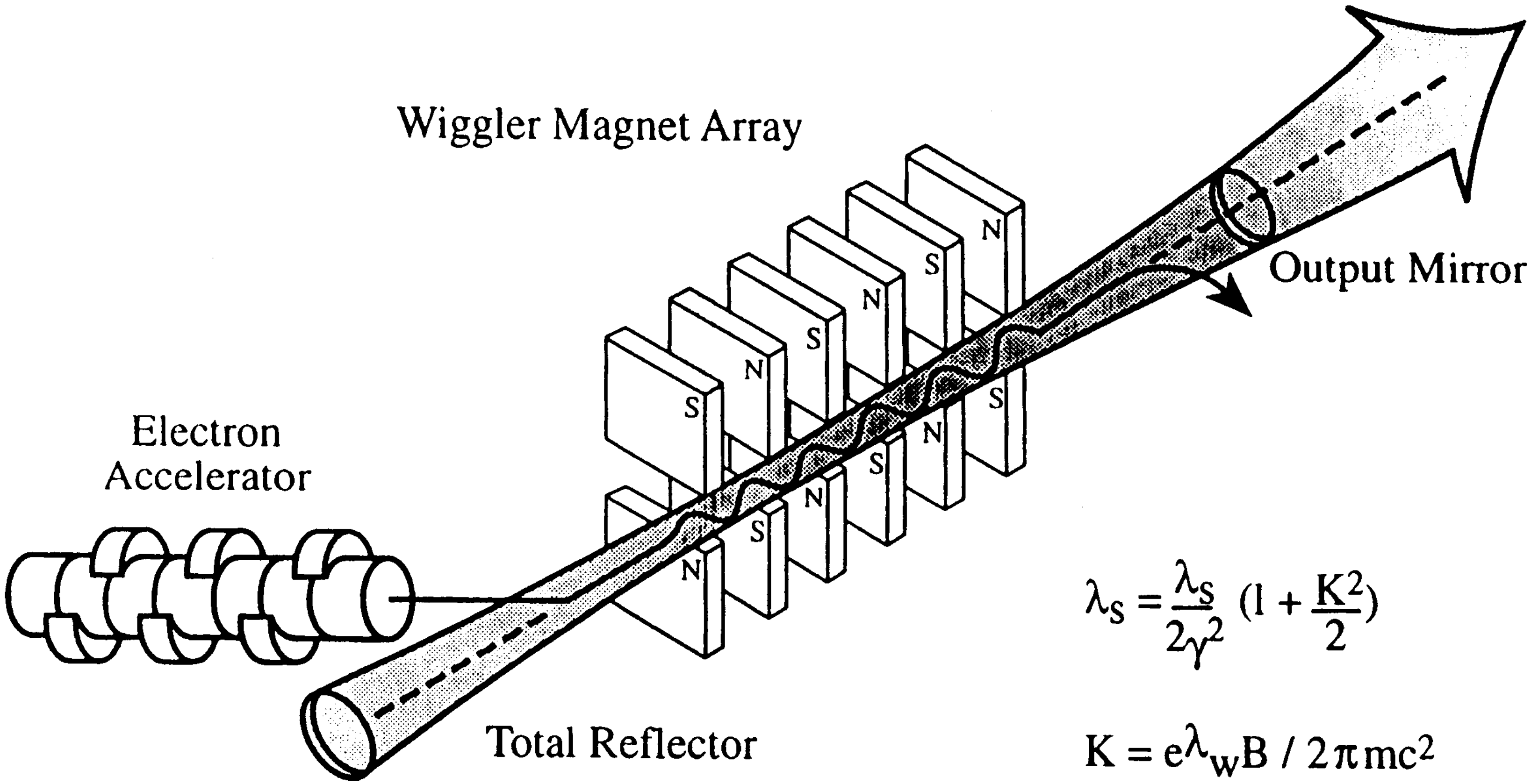


Figure 11: Basic elements of a Free Electron Laser. The accelerator must deliver 500 ampere pulses at 6 Mev to generate 3 mm wavelength for the NEO radar application.

Figure 12

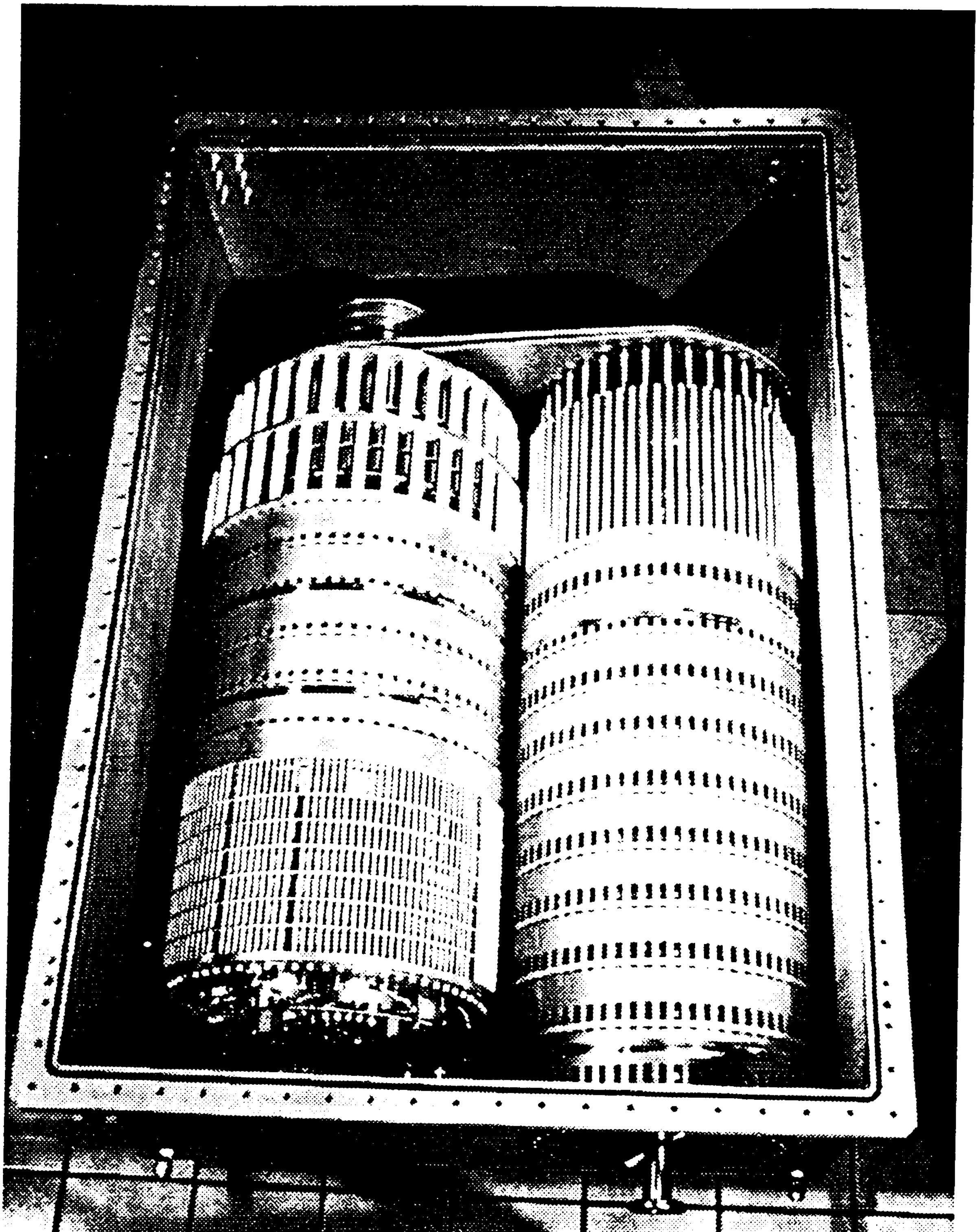
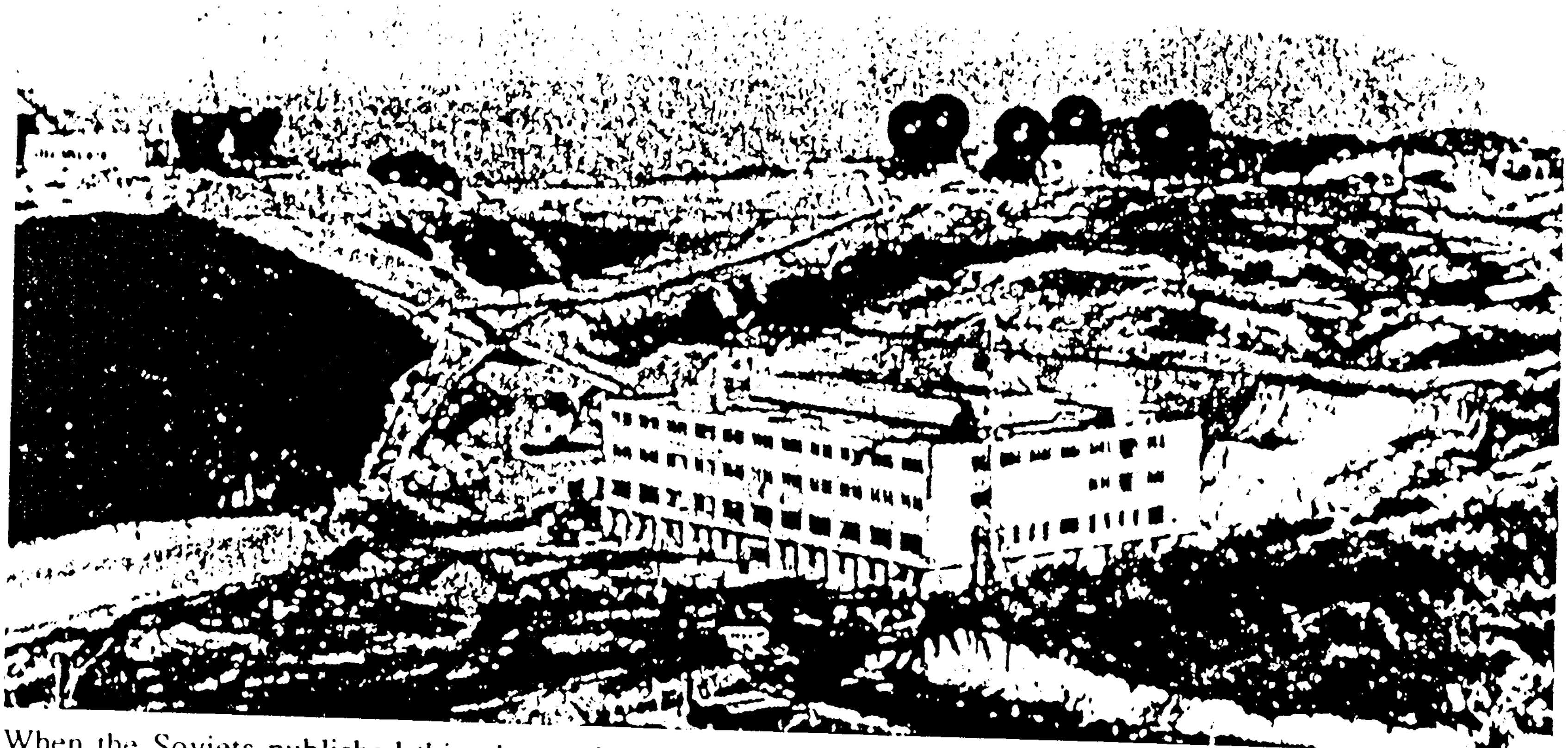


Figure 12: Compact, all solid-state electron accelerator module developed by Science Research Laboratory, Inc. in a joint NASA-SDIO project. Six such modules would power the 3 mm wavelength NEO radar.

Figure 13



When the Soviets published this photo of their space-tracking facility at Dushanbe, they maintained that its purpose is to track satellites. The amount of power supplied by a nearby hydroelectric dam, however, exceeds that needed solely for satellite tracking. It may in fact be used to generate high-energy laser beams for antisatellite missions.

Figure 13: Pravda photo of Russian space tracking station reproduced in U.S. Dept. of Defense annual review, "Soviet Military Power, 1988". Original caption is included.

- Must Achieve Several Standard Deviations
- Residuals Always Will Be Large

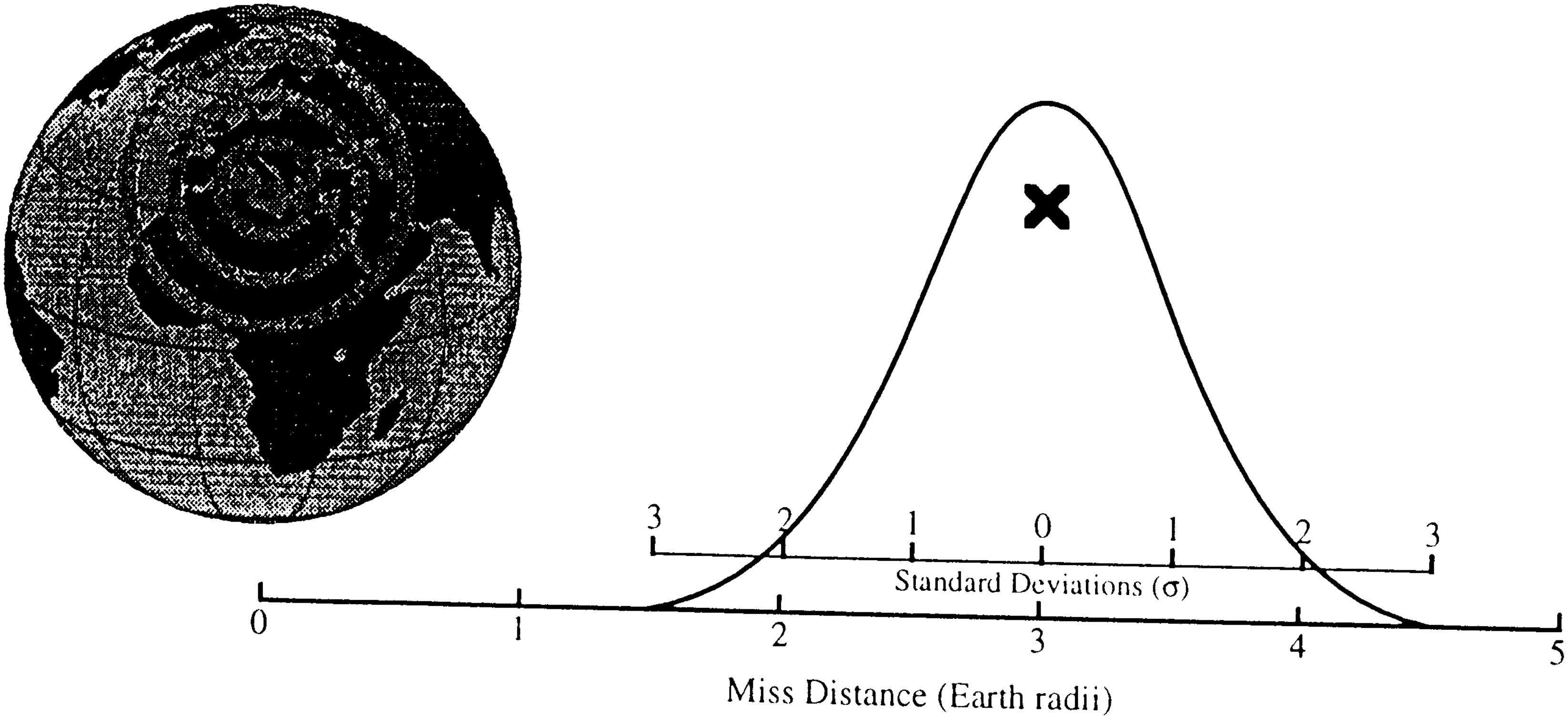


Figure 14: Unpredictable errors will be decisive in NEO deflections. There will be uncertainties in the predicted impact point plus large uncertainties in the reaction of the NEO to perturbation efforts. These errors will render malicious use of NEO impacts highly unlikely.

Figure 14

Panel Papers

Technology for the Detection of Near Earth Objects

Grant H. Stokes
Lincoln Laboratory Massachusetts Institute of Technology

Introduction

Since the launch of Sputnik in 1957, the Department of Defense (DOD) has invested considerable effort developing the technology and operational techniques required to conduct surveillance of earth orbiting objects. One major thrust of the DOD effort has been the development of techniques needed to discover and maintain a catalog of all manmade objects, with sizes above approximately 10 cm., in earth orbit. The technology and techniques that have allowed Space Command to populate and maintain such a catalog for over 30 years are applicable to the current issue of discovering and maintaining a catalog of natural objects that have the potential of impacting the earth. This paper examines the current generation of detector technology being infused into the operational space surveillance network, and predicts the performance of such systems when applied to the detection of natural Near-Earth Objects (N EOs). The predicted performance is then compared with the performance calculated for the proposed Spaceguard Survey system consisting of a network of 6 2.5 meter telescopes (Ref. 1).

Currently the United States maintains a world wide network of ground-based sensors used to develop and update the ephemeridies of all manmade objects in orbit around the earth. These sensors include both radars and passive electro-optic sensors. The sensor system of most interest for the detection of NEOs is the Ground-based Electro-Optical Deep Space Surveillance (GEODSS) system. Each GEODSS site has a complement of 40-inch main telescopes, currently equipped with Ebsicon detector systems. The GEODSS were designed to conduct wide area searches for high altitude satellites and as such have many of the features required to conduct NEO searches. Considerably improved detection performance will be achieved when the detectors are replaced with solid state Charge-Couple Devices (CCDs) under an ongoing upgrade program discussed in the next section.

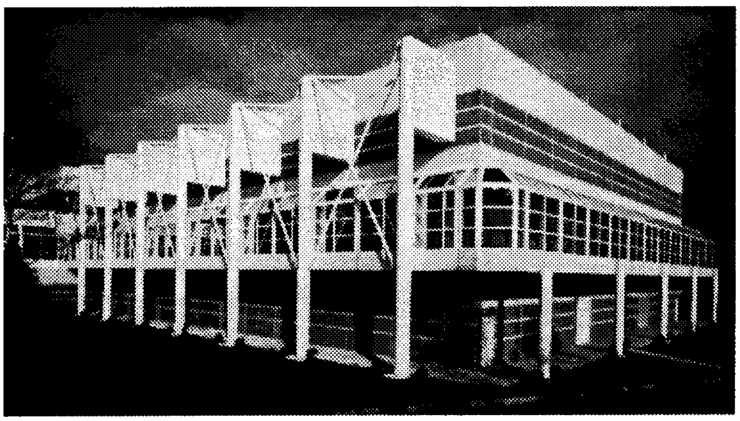
Lincoln Laboratory Focal Plane Technology

In support of the DOD, Lincoln Laboratory has developed a series of progressively more capable visible wavelength CCD focal planes. The CCDs are currently fabricated in the facility shown in Figure 1. The Lincoln Microelectronics Laboratory is a class 10 clean room facility which is capable of fabricating devices with features smaller than .25 microns. As shown in Figure 2, the first CCDs, developed in 1977, had 40,000 elements and readout noise of about 50 electrons at a readout rate of 0.5 Mpixels/sec. In order to support larger fields of view, successive generations of the CCDs were constructed with more pixels and were abuttable to allow large focal plane arrays to be built by constructing a gap free mosaic of several CCDs. As the fabrication process improved, the readout noise of the CCDs declined as well. The current generation, 1960X2560 pixel, CCD has noise performance better than 3 electrons at 1 Mpixel per second readout rates. In addition, the CCDs have been fabricated to be largely blemish free, containing very few bad columns or pixels.

Figure 3 shows the detail of the current generation 1960X2560 pixel CCD. The focal plane is equipped with 8 parallel readout ports to allow the 5 million pixel values to be readout in about 0.3 seconds. In contrast to most large format CCDs now on the market, which read directly out of the image array into the output port, the Lincoln Laboratory CCD is equipped with frame store buffers. These buffers are used to store the image outside of the active area for the duration of the readout. This feature eliminates the need for a mechanical shutter to define the exposure because the image is transferred from the image area into the frame buffer in about a millisecond. As soon as the image is transferred out of the active area a new integration may begin. The frame store locations are identified in Figure 3.

The sensitivity of the Lincoln Laboratory CCDs is enhanced by the very high quantum efficiency achieved over a broad wavelength band. As shown in Figure 4, when the CCD is appropriately anti-reflection coated the quantum efficiency exceeds 90% at peak and is above 20% across the entire interval between 400 nm. and 1000 nm. The optical response uniformity of the CCD is also quite good as shown in Figure 5. In the visible range the uniformity is better than 2% with degradation to about 10% into the near IR band.

LINCOLN MICROELECTRONICS LABORATORY



PROCESS CAPABLITIES

- 0.6 μm, LOW POWER, BULK CMOS
- MEGAPIXEL CCD IMAGERS
- FLAT PANEL DISPLAYS IN SOI CMOS
- 0.25 μm SOI CMOS (Development)
- FUSES AND ANTIFUSES
- 0.25 μm VERTICAL DEVICES
- PROGRAMMABLE MULTICHIP MODULES
- SUPERCONDUCTING CIRCUITS

- 8100 ft^2 CLASS 10
- PRODUCTION-CLASS 0.6 μm CMOS TOOLSET
  - ANGLED ION IMPLANTATION
  - CLUSTER METALLIZATION
  - CHEM-MECHANICAL PLANARIZATION
  - DRY ETCH
- UNIQUE 0.25 μm OPTICAL LITHOGRAPHY

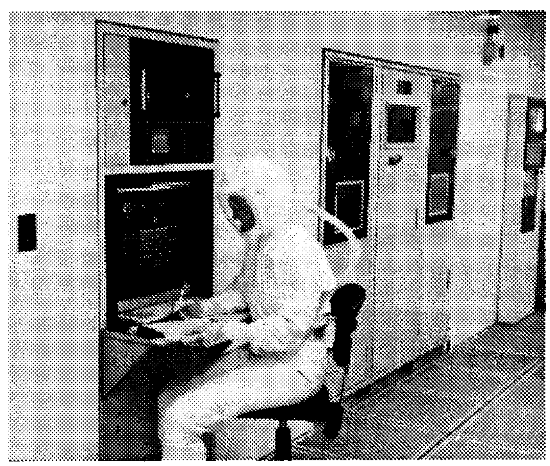
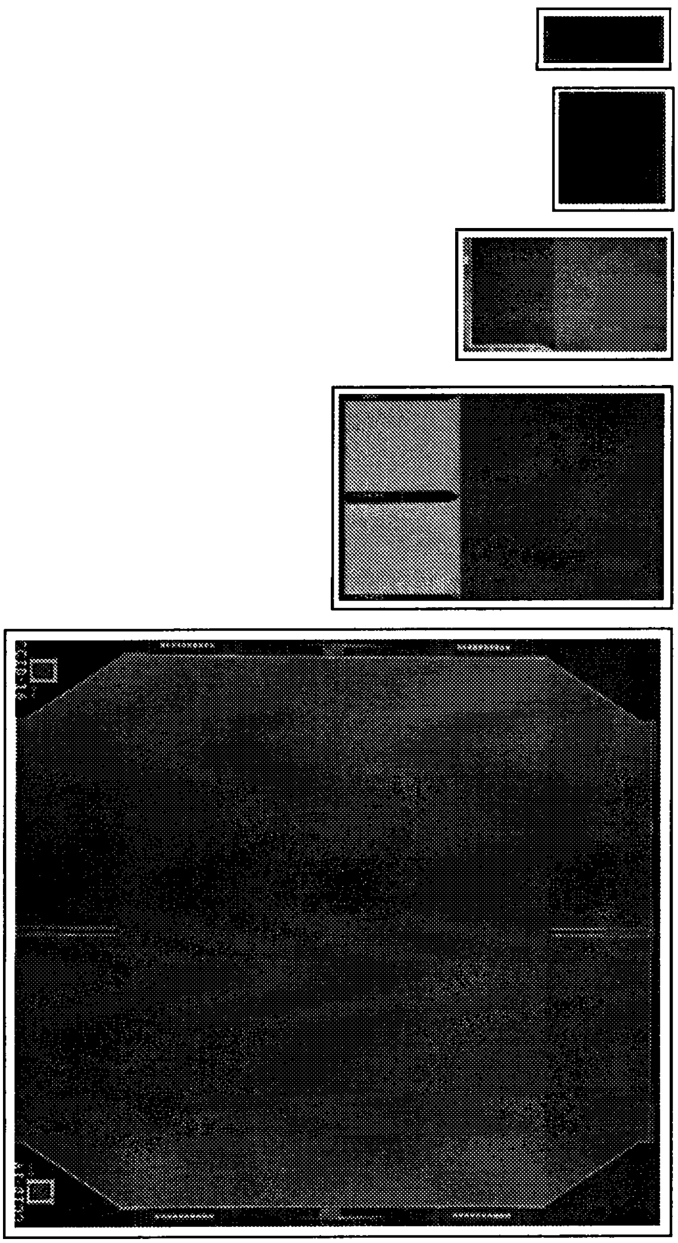


Figure 1. Lincoln Laboratory Microelectronics Laboratory.

CCD IMAGER DEVELOPMENT AT LINCOLN LABORATORY



1977	100 × 400 PIXELS NOISE ~ 50 e^- AT 0.5 MHz
1983	420 × 420 PIXELS TWO-SIDE ABUTTABLE NOISE ~ 20 e^- AT 1.0 MHz
1988	420 × 420 FRAME TRANSFER THREE-SIDE ABUTTABLE NOISE < 6 e^- AT 1.0 MHz
1991	BACK-ILLUMINATED RADIATION HARDENED
1992	1024 × 1024 FRAME TRANSFER THREE-SIDE ABUTTABLE NOISE < 3 e^- AT 1.0 MHz BACK-ILLUMINATED RADIATION HARDENED
1994	WAFER-SCALE IMAGER 1960 × 2560 PIXELS FRAME TRANSFER NOISE < 3 e^- AT 1.0 MHz BACK-ILLUMINATED HIGH-YIELD PROCESS

Figure 2. Five generations of visible CCD devices developed at Lincoln Laboratory for DOD applications.

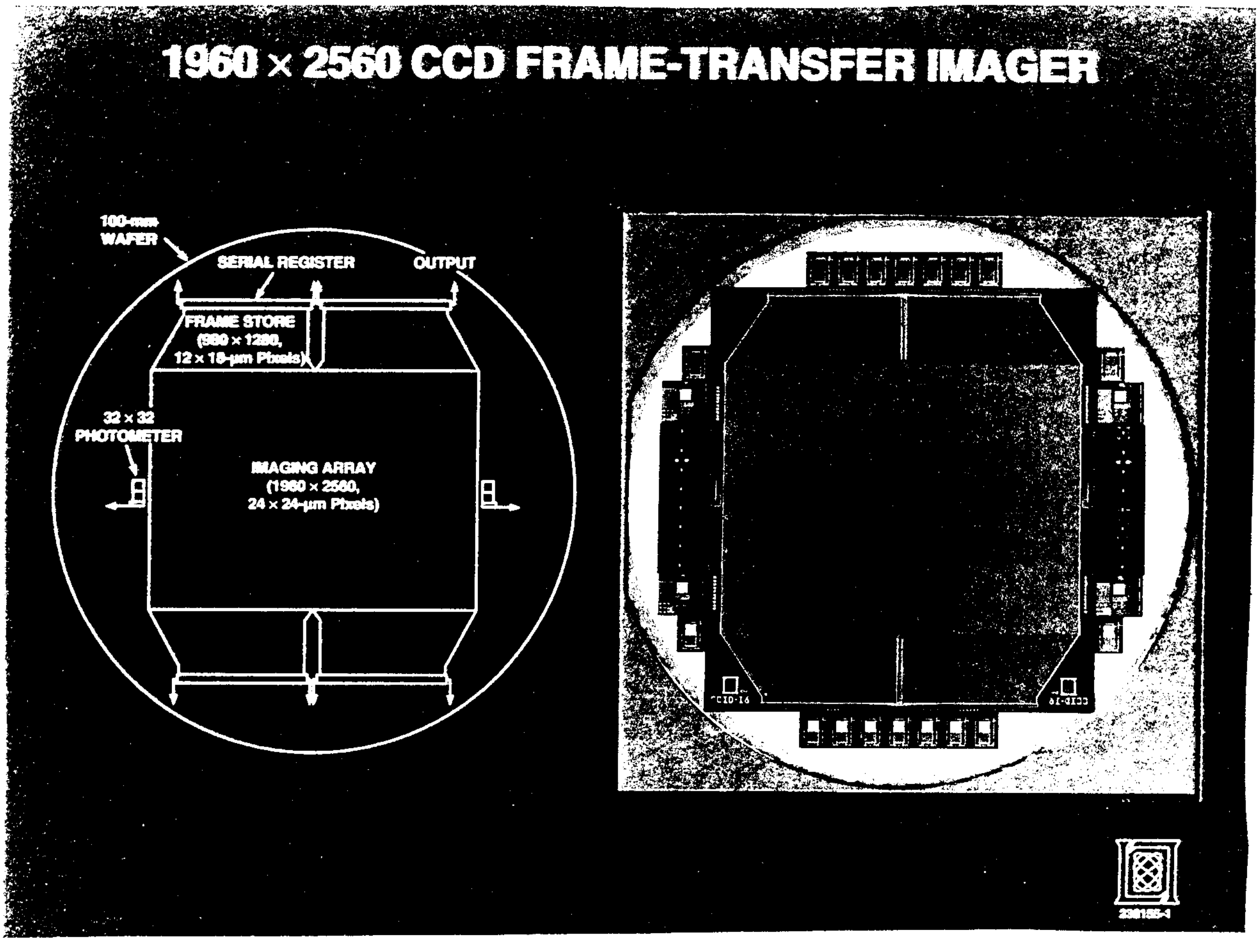


Figure 3. Detail of 1960X2560 pixel CCD showing output ports and frame storage locations.

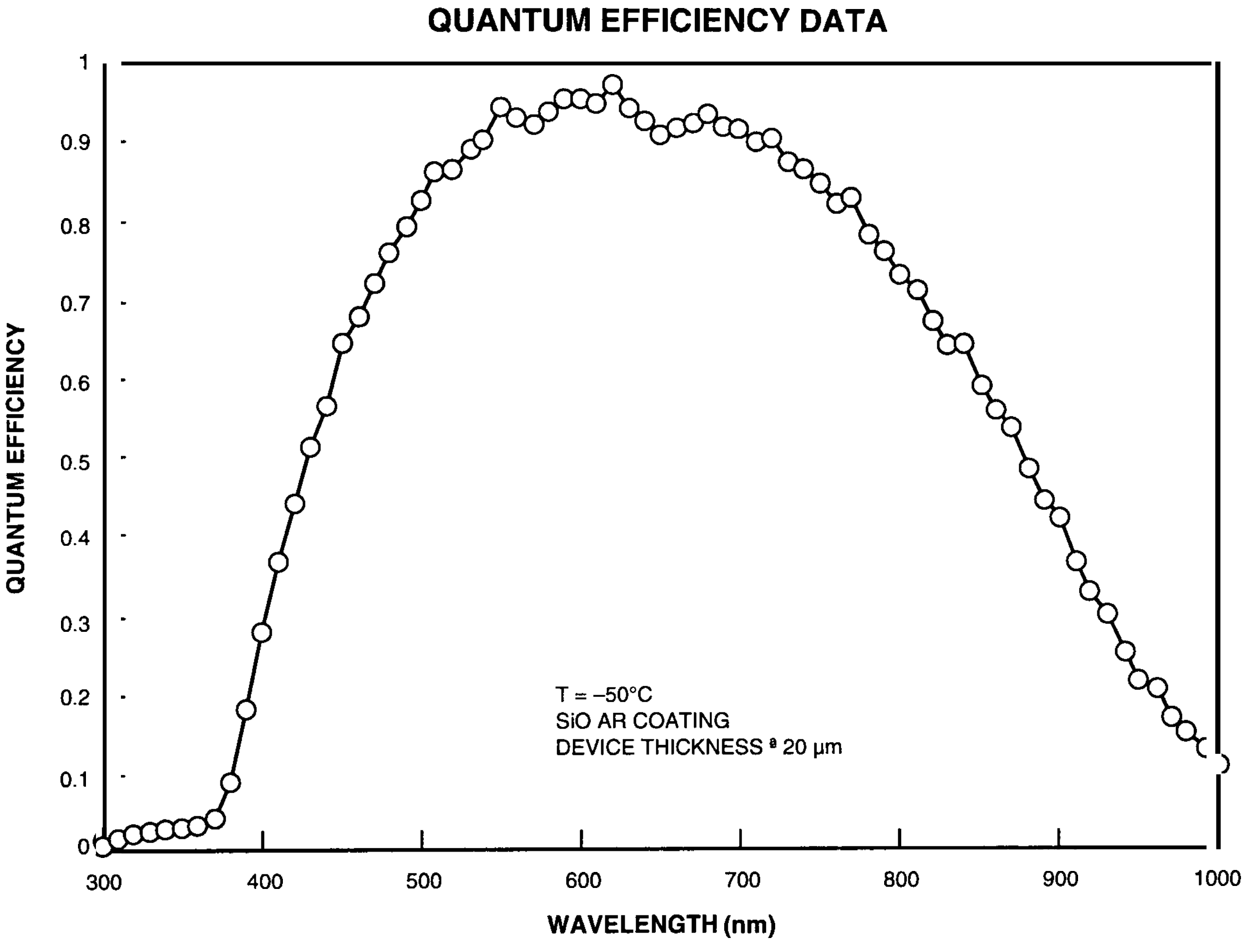


Figure 4. Quantum efficiency and a function of wavelength for anti-reflection coated 1960X2560 pixel Lincoln CCD.

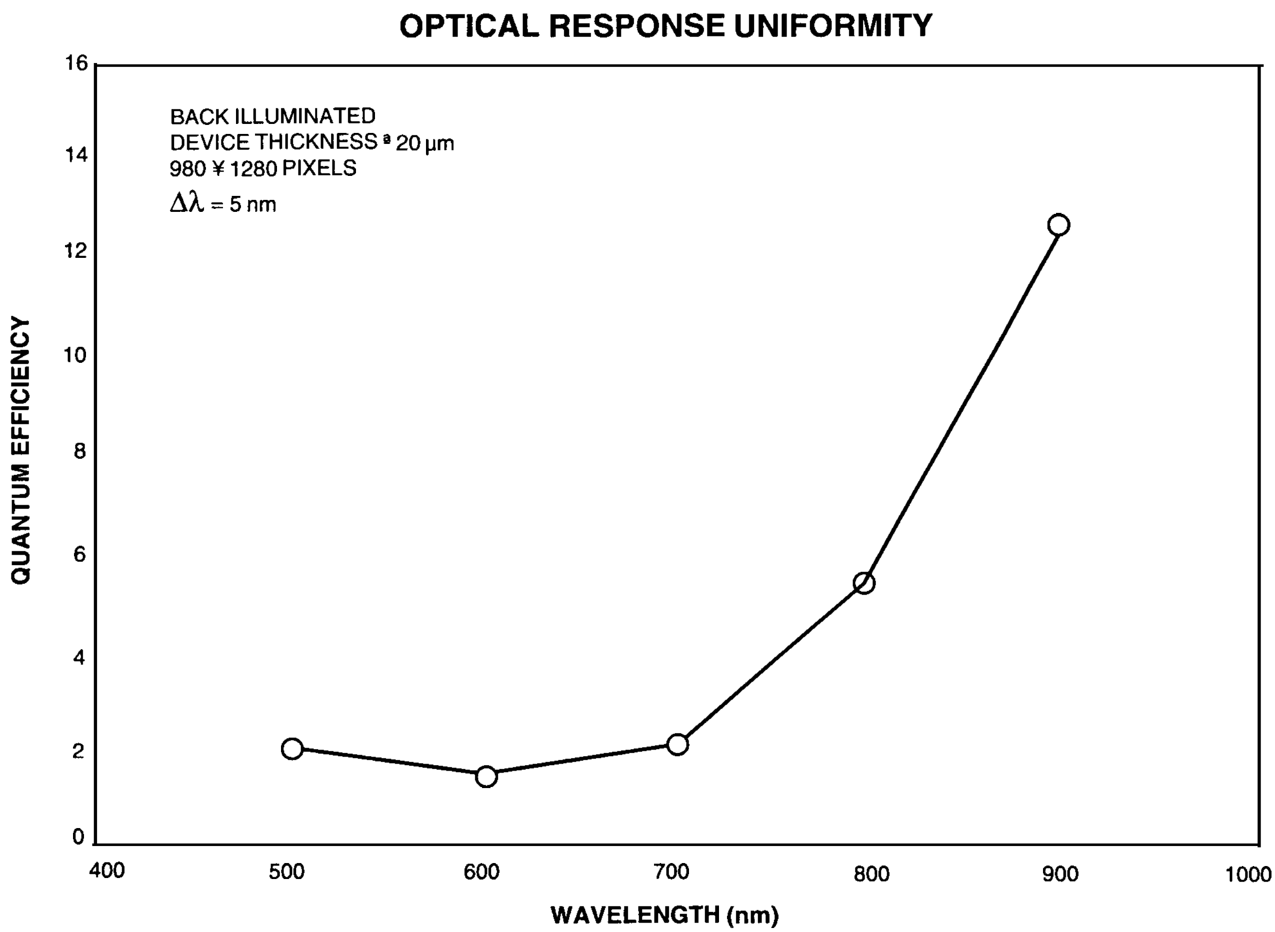


Figure 5. Optical response uniformity of the current generation Lincoln CCDs.

Another feature of interest for the detection of NEO's is the deep well capacity of the CCD. This allows long integrations to be accomplished before the dark current fills the well. The Lincoln Laboratory CCD has a well capacity of 200,000 electrons per pixel. For comparison, when the CCD is cooled to -50 degrees Centigrade, the dark current per pixel is approximately 10.5 electrons per second. That means that the dark current alone will take several hours to fill the well capacity.

The extremely fine angular resolution afforded by the large number of pixels is demonstrated by Figure 6. The picture, taken by the 1960X2560 pixel CCD, shows a house standing on Lexington Green since the Revolutionary War days. There is enough resolution in the picture to enlarge the sign on the front of the house and read the story of a Lexington Minuteman wounded at the Green who dragged himself home to die in the doorway at his wife's feet.

The CCDs described above have been constructed specifically to allow large portions of the sky to be searched to find dim, moving targets. As such, they have the best combination of large format and detection performance of any CCDs that exist today.

GEODSS System

The GEODSS system was deployed in the early 1980s by Space Command to conduct world wide electro-optic surveillance of deep space objects (deep space object in the Space Command parlance refers to any manmade satellite with an orbital period longer than 255 minutes). Reference 2 describes the details of the GEODSS system. The GEODSS were conceived as search sites capable of searching significant fractions of the geosynchronous belt in a night. As such, each site was equipped with three, agile, wide field-of-view telescopes. The main telescopes have 40-inch primary mirrors and a field of view of 2.1 degrees.

Using the current Ebsicon detector, the GEODSS system specifications require it to be capable of detecting satellites with a limiting magnitude of 16 when integrating for 0.6 seconds with a 19.5 magnitude sky background. This capability is not sufficient for productive NEO searches. However, the GEODSS telescopes, when combined with the large format CCD cameras discussed in the preceding section will have considerable NEO search capability as discussed in the next section.

Asteroid Detection Capability

The CCD detector and GEODSS telescopes discussed in the preceding sections have been designed to detect moving objects in space. While they have been specifically developed to detect satellites in earth orbit, they are also well suited to the detection of natural objects in heliocentric orbits. When compared with manmade satellites, asteroids and comets are generally seen moving more slowly, in the range from 0.1 to a few degrees/day, and are several magnitudes less bright. Appropriate modification of the integration times and velocity filters/detection algorithms employed to detect satellites will allow sensors based on these technologies to detect NEOs with quite good performance.

In order to have a basis for evaluating the performance of a GEODSS-based NEO detection system, some standard of comparison must be established. The defacto standard in the NEO community is the proposed Spaceguard system. The Spaceguard Study (Ref. 1), concluded in 1992, proposed the deployment of a system of six 2.5 meter telescopes each fitted with a commercial 2048X2048 CCD detector. Such a system is expected to be able to search 6000 square degrees of sky each month to a limiting magnitude of 22. In addition, the telescopes would conduct follow-up observations to develop and maintain a catalog of NEOs. The proposed system is estimated to achieve detection of 90% of the earth threatening objects, larger than 1 km in diameter, in 25 years of operation. Such a system was estimated to cost \$50M (FY93) to construct and \$ 10M per year to operate.

The specific measures of interest to our analysis of the GEODSS system capability is the Spaceguard goal of searching 6000 square degrees per month to a limiting magnitude of 22. This establishes a convenient basis on which to compare the capabilities of search systems.

The sensitivity of a system consisting of a Lincoln Laboratory CCD mounted on a GEODSS telescope is shown in Figure 7. The graph indicates the limiting magnitude (for SNR=4) achieved as a function of integration time. The top line indicates the performance expected in the absence of the moon, while the lower line indicates the performance for periods of full moon with the sensor looking 45 degrees away from the moon. The parameters used in the estimate of the performance are provided in the figure. As is indicated in Figure 7, on dark nights the system is capable of detecting objects with a visual magnitude of 22 with less than 100 seconds of integration.

HIGH SPATIAL RESOLUTION ACHIEVED BY 1960 × 2560 PIXEL CCD

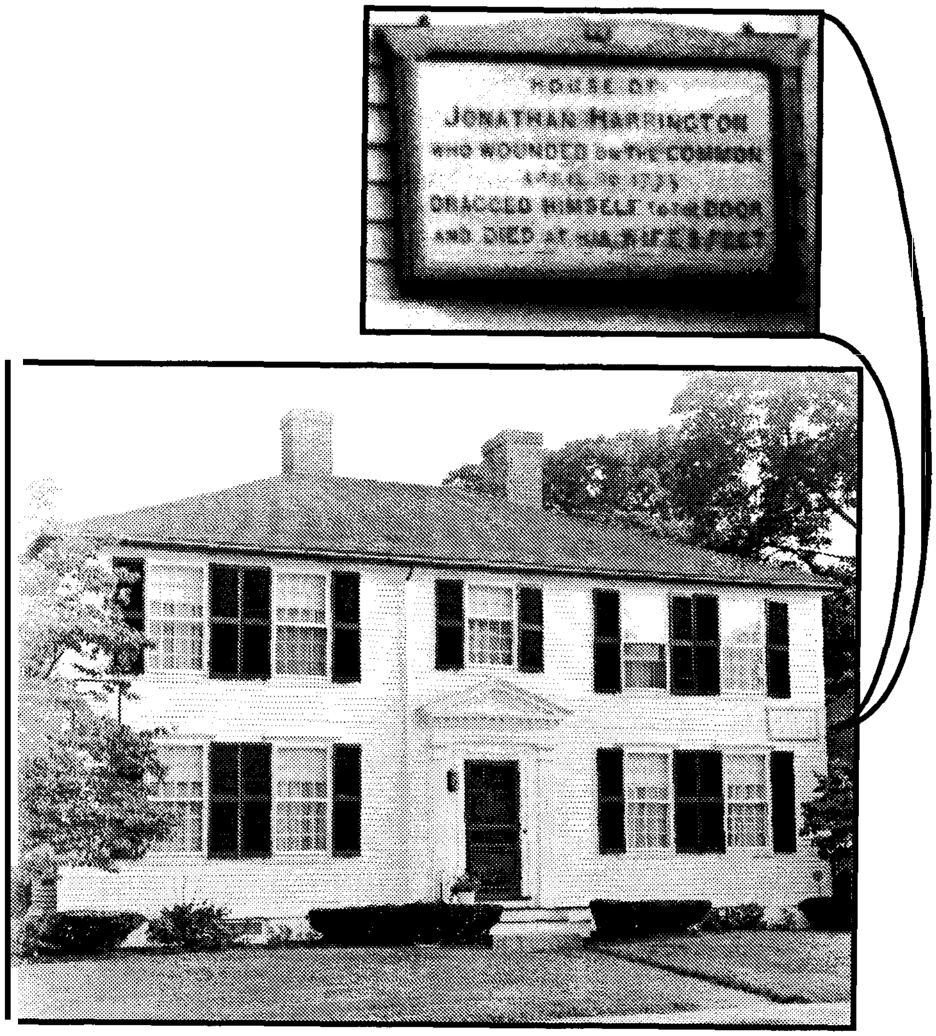


Figure 6 - Image of house on Lexington Green demonstrating the high spatial resolution achieved by the 1960X2560 pixel CCD.

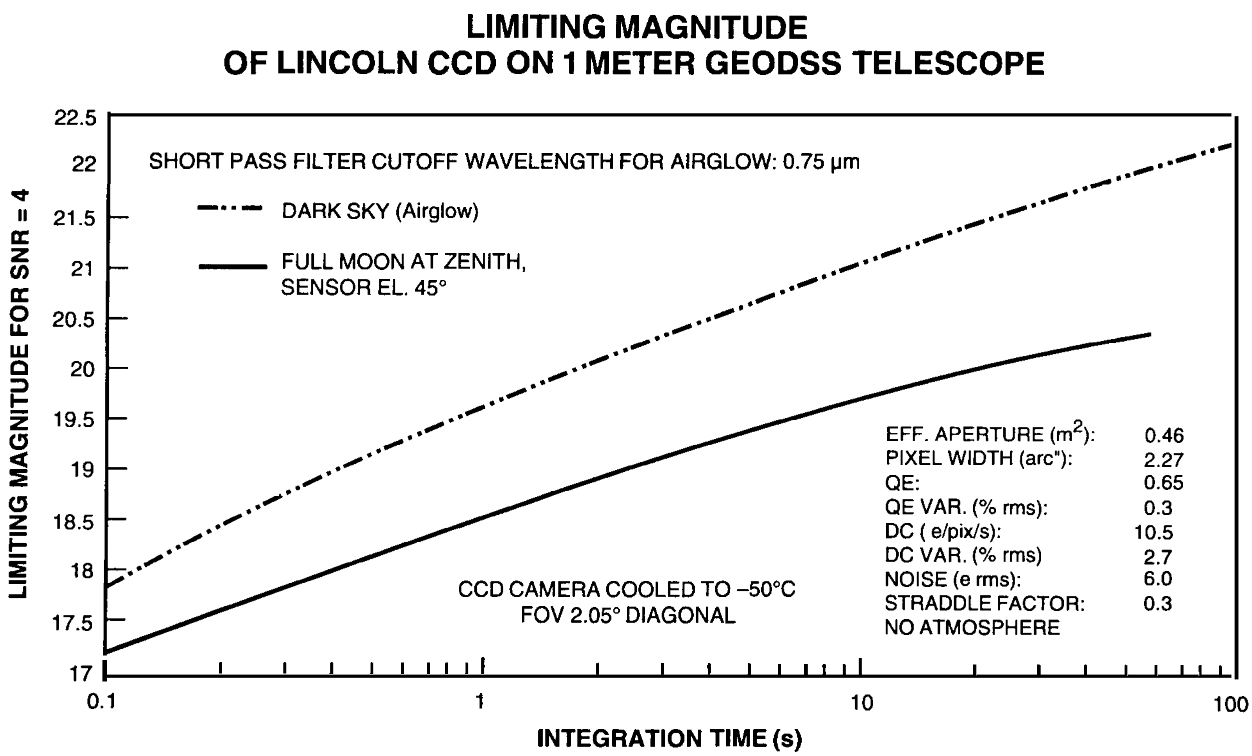


Figure 7. Limiting magnitude achievable using Lincoln CCD detectors on a GEODSS main telescope as a function of integration time.

Figures 8 and 9 give a feeling for what this detection performance means when applied to the detection of asteroids. Figure 8 (derived from Ref 1) provides the spectral characteristics for various classes of asteroids. This combined with the detection performance shown in Figure 7, yields the minimum diameter asteroid that the GEODSS/CCD system can detect at a distance of 1 AU. As shown in Figure 9, the minimum diameter is between about 100 meters and 300 meters depending on the asteroid's spectral class. Figure 9 also shows the effect of changing the short pass cutoff filter wavelength. The short pass cut off filter is used to remove the short wavelength light scattered by the atmosphere.

The limiting magnitude versus integration time, along with the other characteristics of the GEODSS telescopes has been combined in Figure 10 to indicate the search rate which could be accomplished by the GEODSS/CCD system as a function of limiting magnitude. The figure indicates the search rate for a system of either one or two GEODSS main telescopes and assumes three integrations will be needed for each field of view to detect the moving targets. The analysis assumes that the observing site will provide 1000 hours/year of good observing conditions. Under these conditions, a system consisting of a single telescope is capable of searching about 1500 square degrees per month to a limiting magnitude of 22. This analysis would indicate that 4 of the 1 meter GEODSS telescopes equipped with the Lincoln Laboratory CCD detector could search the 6000 square degrees per month as outlined in the Spaceguard Study.

Figure 10 also indicates that a system consisting of two telescopes could search the equivalent of the entire sky each month to a limiting magnitude of greater than 20.5. A search that covered the entire sky each month could be effective at finding smaller nearby objects which move faster and would likely have a higher initial discovery rate than deep searches covering smaller portions of the sky.

Lincoln Laboratory Field Tests

Lincoln Laboratory has conducted a series of field tests to demonstrate and validate the performance of the detector systems for space surveillance applications. These field tests have generally been focused on applications involving manmade satellites but, some data on natural objects has been collected. A discussion of the test series and the results obtained has been published in Ref. 3. This discussion will provide a top level overview of the historical test efforts and will describe an upcoming series which will test the latest large format CCD in a GEODSS telescope.

The historical tests of the CCD detector systems have been conducted using the facilities of the Lincoln Laboratory Experimental Test System (ETS) site located on the White Sands Missile Range near Socorro, New Mexico. The ETS is the prototype for the GEODSS systems. The primary telescopes at the ETS are the 31-inch polar mount Cassegrain telescopes shown in Figure 11. In September 1992 tests were conducted at ETS using a 420X420 pixel focal plane in both front- and back-illuminated configurations. Data were acquired on several known asteroids via a small scale search at opposition as well as via observations directed at known objects. In May 1993 a camera system based on the next generation 1024X1024 front illuminated pixel CCD was tested at the ETS. Several known objects were observed including 114 Kassandra as shown in Figure 12.

The system detection performance during these tests was quite good Figure 13 displays the detection performance for objects (stars) of known magnitude. Data from both front- and back-illuminated CCDs are included in the figure which shows the integrated signal as a function of the magnitude of the observed object for a given integration time. The dimmest catalogued object observed had a visual magnitude exceeding 20. This measurement validates the performance of the detector system for quite dim objects.

During the summer of 1995 the latest generation of CCD camera will be taken to the ETS and installed on a GEODSS 40-inch telescope for a series of tests related to the GEODSS Upgrade Program. These tests will employ a back-illuminated 1960X2560 pixel CCD in a step stare search mode. As an adjunct to the main tests, we plan to conduct a series of observations specifically tuned to determine the system performance for the detection of NEOs. These measurements will include demonstrations of the detection capability of the system as well as the acquisition of multi-frame data sets suitable for detection algorithm development. In addition we hope to conduct rudimentary operations of the system in the NEO search mode to gain experience with any operational issues that are involved.

Conclusions

DOD-developed Space Surveillance technology has been reviewed for its applicability to the detection of NEOs. Detection systems developed for the upgrade to the GEODSS system have been examined and found to

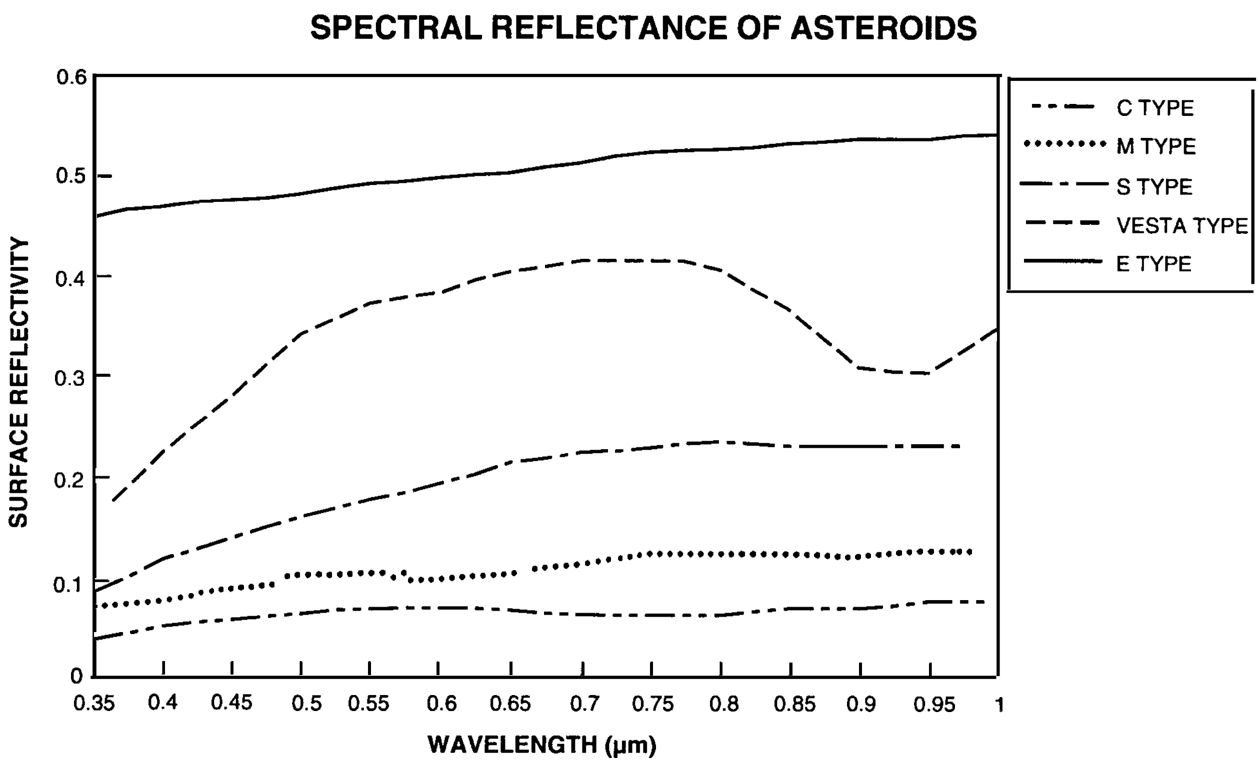


Figure 8. Spectral reflectance of asteroids (after Ref. 1).

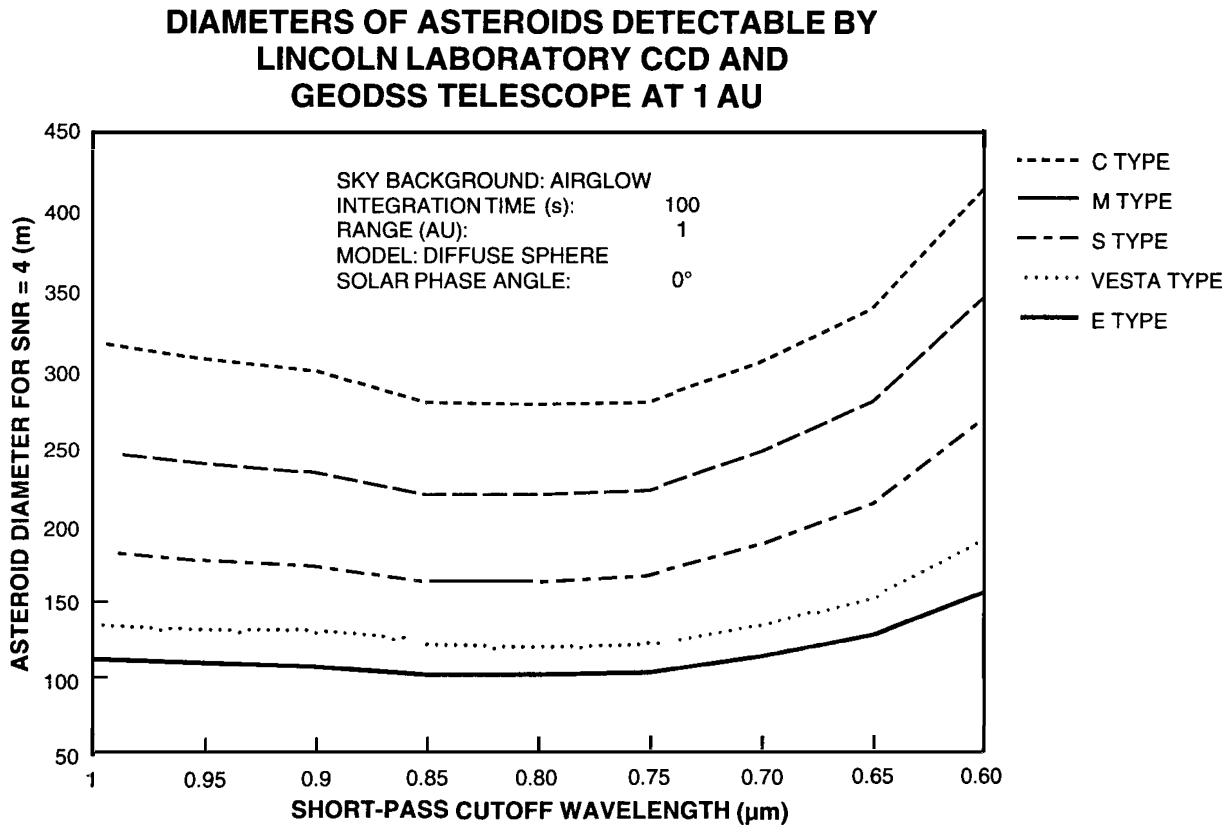


Figure 9. Minimum asteroid diameter detectable by GEODSS/CCD at 1 AU by spectral type of asteroid as a function of short pass cutoff filter wavelength.

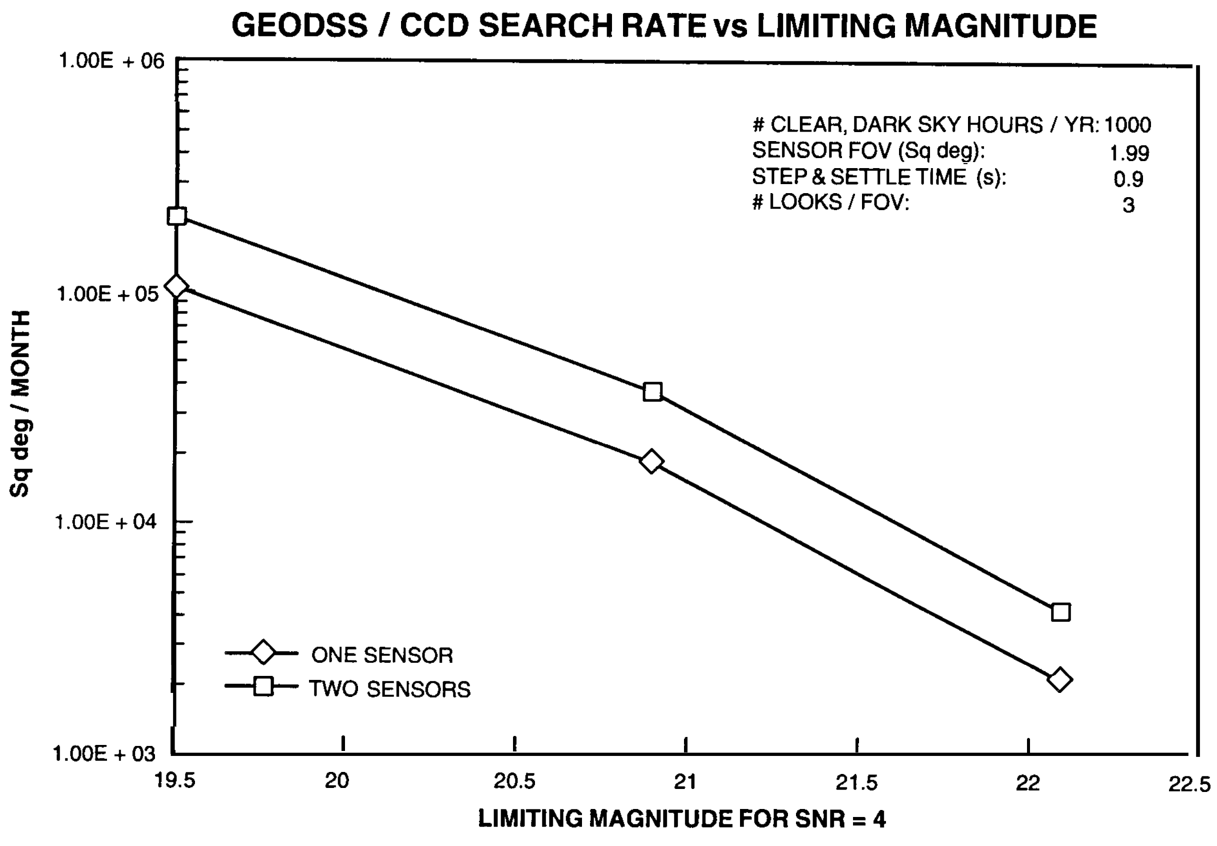
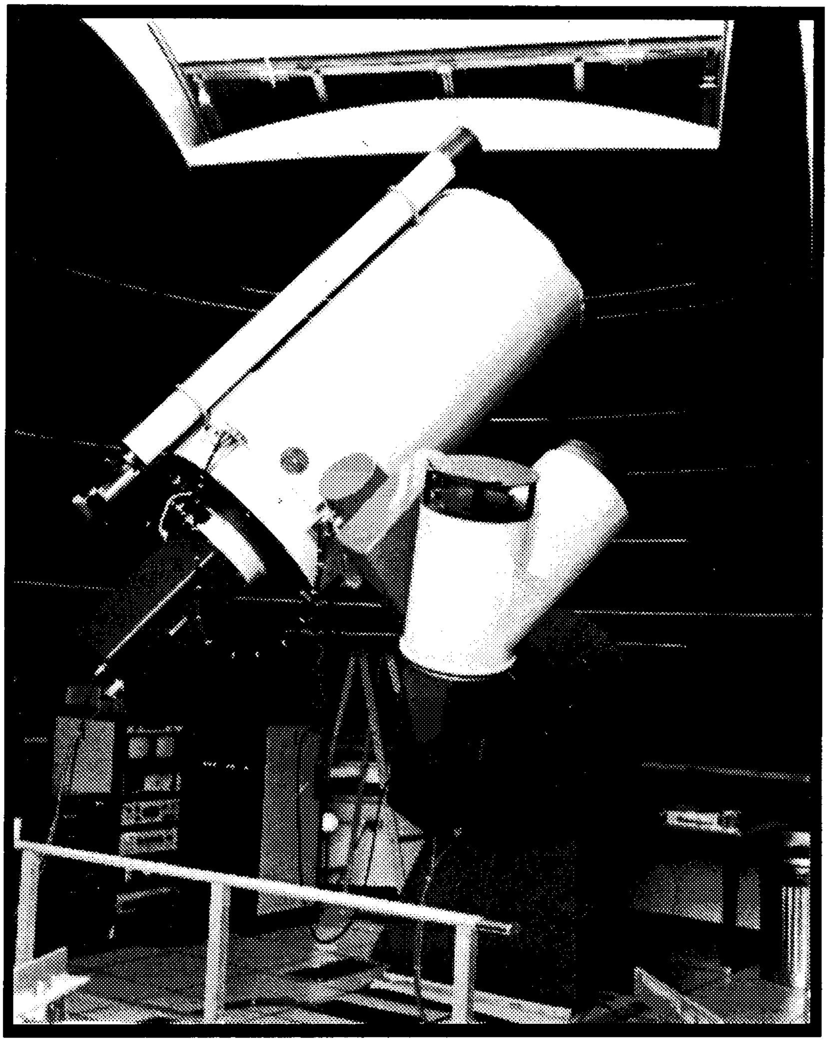


Figure 10. Search rate achievable by one or two GEODSS/CCD telescopes and a function of limiting magnitude.

ASTEROID DETECTION EXPERIMENT



31 INCH
POLAR MOUNT
CASSEGRAIN
TELESCOPE
AT LINCOLN
EXPERIMENTAL
TEST SITE

Figure 11. Experimental Test System telescope used during historical field tests including asteroid detection experiments.

**DETECTION OF ASTEROID 114 KASSANDRA
NEAR OMEGA NEBULA**

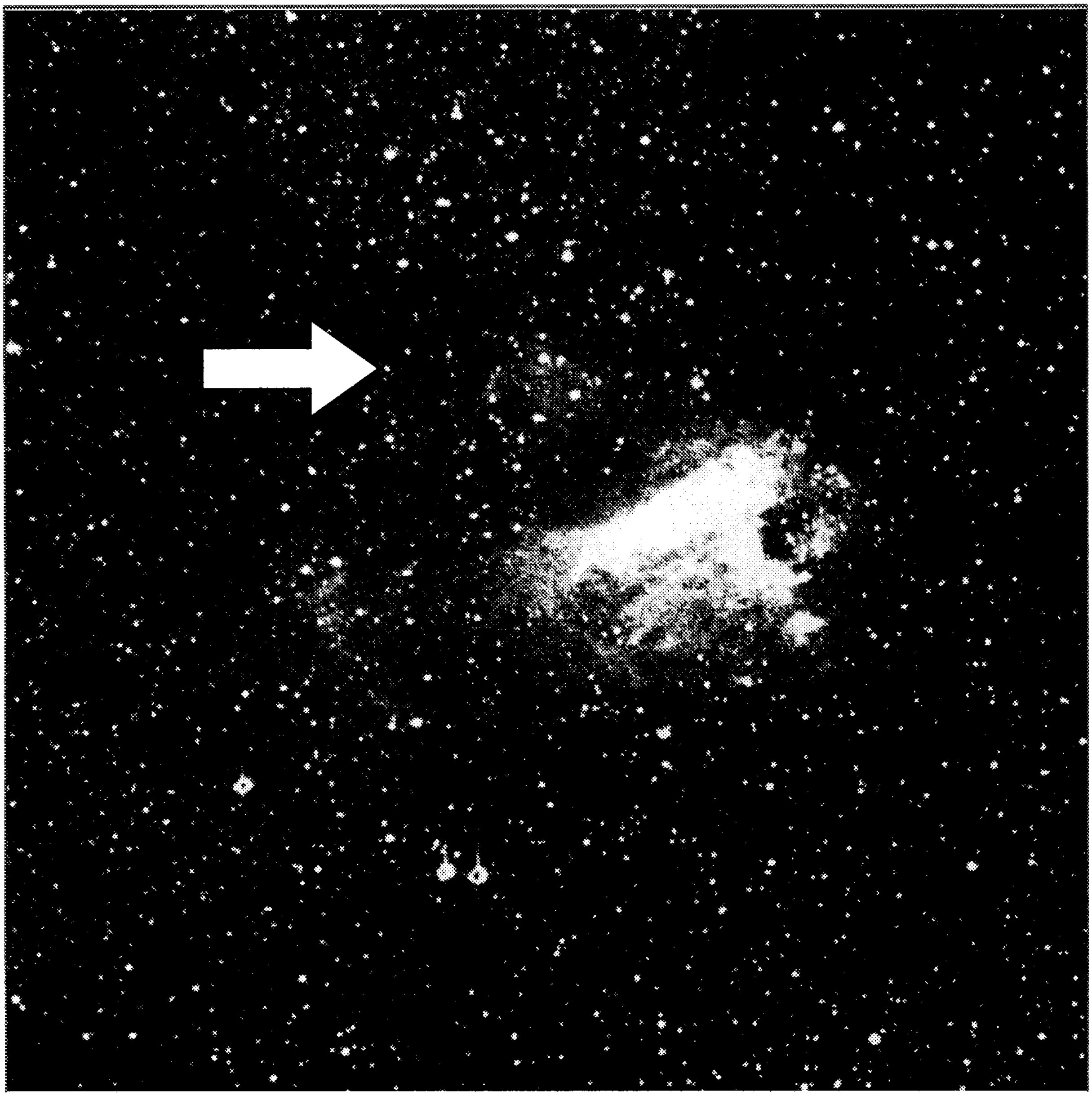


Figure 12. Detection of 114 Kassandra near the Omega Nebula

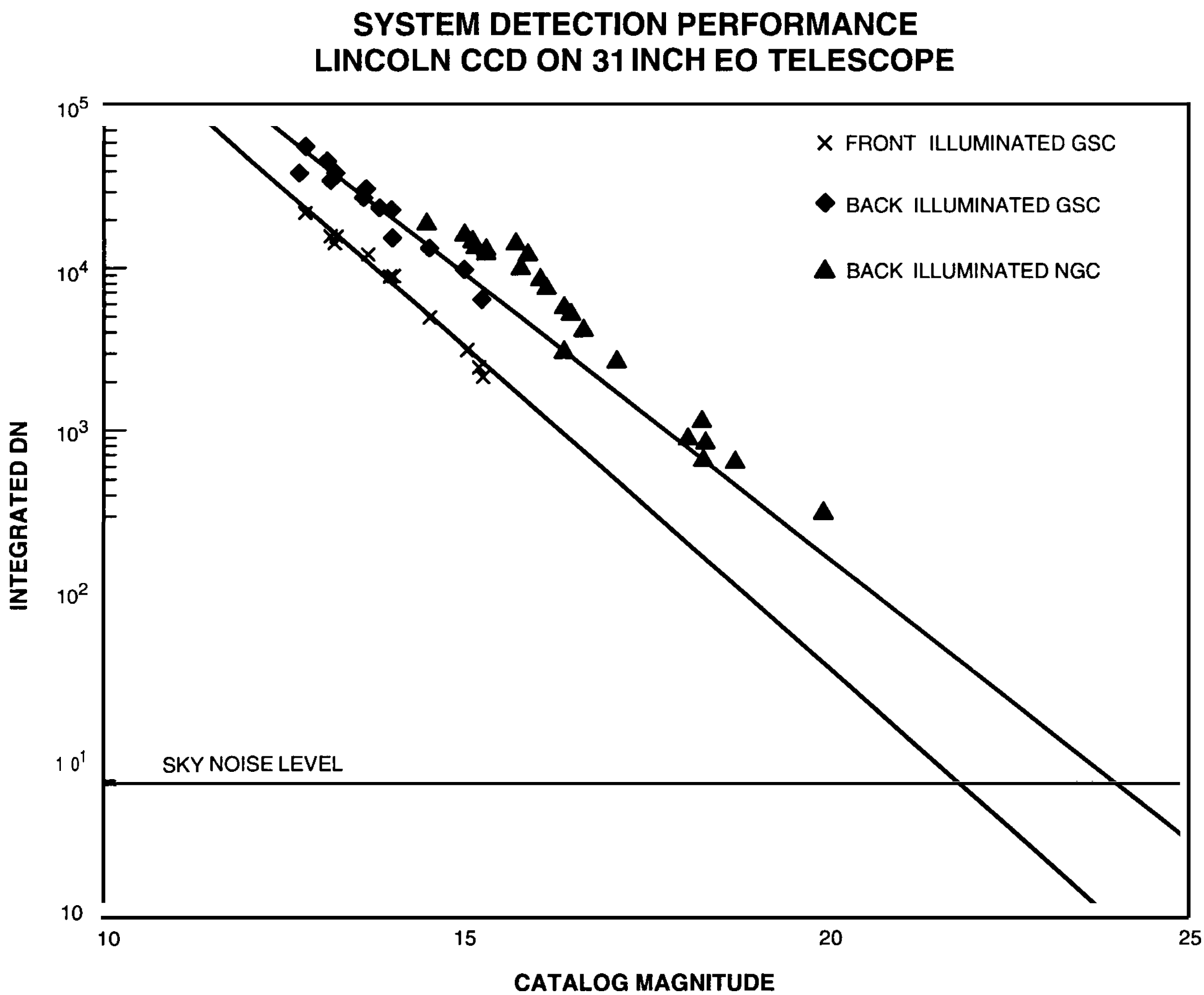


Figure 13. System detection performance achieved during historical field tests using the Lincoln CCD detector on the ETS 31" telescope.

provide detection performance using 1 meter telescopes which rivals the performance expected from the Spaceguard system which proposes using commercial CCD detectors on six 2.5 meter telescopes. A system of four upgraded GEODSS telescopes could search 6000 square degrees per month to a limiting magnitude of 22, which is the Spaceguard goal. Alternately, two upgraded GEODSS telescopes could search the equivalent of the entire sky once per month to a limiting visual magnitude exceeding 20.5.

Field test validating the performance of predecessor versions of the detections system have shown the expected performance on natural objects. A new series of field measurements are planned for the summer of 1995. The goal of the new series is to validate the performance of the system containing the latest version of the Lincoln developed CCD for NEO detection and to develop operational experience conducting NEO searches.

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The Orbits of Asteroids That Impact Earth and Groundbased Detection Strategies

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Searches for Earth-Crossing asteroids (ECAs) have concentrated towards the solar opposition region. This produces selection effects that are evident in a published analysis of the search effectiveness of the proposed Spaceguard system (Morrison 1992), which will also concentrate its search there. This analysis shows that Spaceguard will recover 90% of all known ECAs but fewer than 50% of the Atens (asteroids with semimajor axes less than 1 A. U. that cross the orbit of Earth). This strongly suggests that Atens are under- represented among known ECAs and that Spaceguard may find significantly fewer than 90% of all ECAs. If the orbits of the ECAs were completely therm alized in close encounters with Earth, half the ECAs would be Atens, which is certainly the upper limit. When Atens impact Earth, they approach it from the direction of an angular cone that is centered on the third-quarter moon (the direction of the Earth's revolution around the sun). Among ECAs that will hit Earth within the next 300 years, we find that a sizeable fraction of Atens and Apollos with small semimajor axes would be missed by searches that are confined to the solar opposition region. Any groundbased survey needs to cover as much of the sky as possible. A large fraction of the asteroids that will hit Earth during the next 300 years will make close approaches to Earth before impact. We find that they become bright enough to be detected with small telescopes at these close approaches, but they often appear in directions that are far from solar opposition. One quick fix would be to add a battery of small telescopes to the Spaceguard survey that would cover the entire sky (except near the sun) every night. Such a battery would also be very effective in finding asteroids as small as 100 meters in diameter during the final two weeks to impact.

Introduction

This conference has shown the danger of impacts by Earth-crossing asteroids (ECAs). Asteroids 60 meters in diameter and larger can destroy large cities by airblast, by 200 meters in diameter they produce substantial regional impact damage as well as tsunami that can devastate the shore lines of entire ocean basins, and by 1 km in diameter they may, in addition, perturb the atmosphere enough to produce global mass extinctions (e.g., Hills and Goda 1993).

In this paper we examine strategies for detecting ECAs that may hit Earth within the next few years. We wish to detect asteroids down to 60 meters in diameter in sufficient time to allow them to be deflected or destroyed before Earth impact. A week is sufficient warning to allow a single rocket equipped with a nuclear explosive (using existing rocket boosters and nuclear explosives) to deflect from Earth impact an asteroid with a diameter up to 1-2 km if such a rocket were on standby for this purpose (Canavan 1992, and Canavan & Solem 1992; Arons and Harris 1993). To deflect a larger asteroid requires a lead time of months to years even if rockets to deflect it were on standby.

These lead times suggest that objects less than about 1 km in diameter need only be detected a week or two before impact as part of a terminal defense system. Larger objects need to be detected up to several years before impact. In the next section we shall discuss the orbit characteristics of asteroids that are within a few orbital revolutions of Earth impact. In the section after that we determine the detectability of small asteroids in the final weeks before impact. Next, we discuss the detectability of larger ECAs in the final few years before their impact. This last section is the main thrust of the current paper.

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Orbits of Asteroids that Impact Earth

The orbits of asteroids that impact Earth were determined by Hills and Leonard (1995). We briefly summarize their results.

The orbits of all asteroids that suffer head-on collisions with Earth can be mapped in geocentric coordinates by their impact speeds prior to gravitational acceleration by Earth and by their positions on the sky at a given time prior to impact as seen by a hypothetical observer at the center of Earth. Two angles are needed to specify the position on the sky, so three parameters are required to specify the final trajectory. For an object of a given size and composition, the impact speed determines how much damage it can inflict (Hills & Goda 1993). Its position on the sky determines how readily observable it will be prior to Earth impact.

If we treat Earth's orbit as circular, these three geocentric parameters determine three heliocentric orbital elements: the asteroid semimajor axis, a, eccentricity, e, and inclination to the ecliptic, i. The argument of perihelion, ω, is also known from a and e through the equation of an ellipse,

$$r = \frac{a\left(1-e^2\right)}{1+e\,cos\,(f)}, \tag{1}$$

because at impact with Earth $r = 1$ AU, so the orbital phase or true anomaly $f = \omega$ or $(2\,\pi - \omega)$. A fifth orbital element T, the time of perihelion passage, is determined by the time of impact and the time the asteroid took to go from perihelion to impact, which is known from a, e, and f. The time of year of impact also determines the sixth orbital element Ω, the angle of the ascending node, since Earth crosses the line of nodes at impact. We first specify the orbit of the asteroid in geocentric coordinates and then transform to heliocentric coordinates to determine its position relative to Earth in the days and years before impact.

Asteroid collisions should be equally probable throughout the year if the orbit of Earth were circular, so in a statistical evaluation we may ignore the orbital elements Ω and T. We need only consider the three heliocentric orbital elements a, e, and i (because ω is known from a and e for Earth impactors) or the three geocentric parameters: relative impact speed, V_{rel}, and the two angular coordinates giving the direction of approach of the impactor at some specified time prior to impact. Specifying all permitted values of either set of three parameters provides an equally satisfactory mapping of all possible asteroid impactors.

The true distribution of orbits of Earth-crossing asteroids (ECAs) is not well known; e.g., their observed distribution is consistent with up to half them being burned-out comets (cf, Wetherill 1988), which have initial orbits that differ considerably from that of classical asteroids. The orbit distribution of ECAs detected to date may be highly biased. Asteroid surveys have tended to be confined to near solar opposition, so the cone in which asteroids are discovered tends to be elongated towards opposition.

Using a geocentric coordinate system to map the distribution of impacting asteroids is simpler than using a heliocentric one. It may also provide a more natural way of estimating the frequency of asteroids in various permitted orbits. Most asteroids make several close approaches to Earth before impact; e.g., an impacting asteroid will have passed within $2R_{\oplus}$ of Earth about 3 times before its impact (ignoring gravitational focusing). Such a close encounter tends to rotate the velocity vector of the asteroid without affecting its speed, V_{rel}, relative to Earth, so a succession of close encounters tends to randomize its direction of approach to Earth. If an Aten originated either as a short-period comet or from the asteroid belt, it suffered at least one close encounter with Earth to have had its orbit shrunk below 1 A.U.

If an asteroid has an Earth-approach speed $V_{rel} < V_c \equiv (2^{1/2} - 1)\, V_{\oplus} = 12.3$ km s^{-1}, where $V_{\oplus} = 29.8$ km s^{-1} is the orbital speed of Earth around the sun, then it is in a bound orbit around the sun for all possible directions of approach to Earth impact. Repeated close encounters with Earth would tend to cause such low-impact-speed asteroids to evolve towards a near-isotropic distribution of impact directions with respect to the moving Earth. At approach speeds $V_{rel} > V_c$, there has to be a deficiency of objects that approach Earth from directions where they would be in hyperbolic orbits around the sun. This zone of avoidance is an angular cone that points away from the direction of Earth's orbital motion around the sun. Objects are in this cone if they approach Earth from an angle, θ, that is more than

$$\theta_2 \;=\; cos^{-1}\left[\frac{\left(\frac{V_{rel}}{V_{\oplus}}\right)^2 - 1}{2\left(\frac{V_{rel}}{V_{\oplus}}\right)}\right], \tag{2}$$

away from the direction of Earth revolution. This cone of avoidance increases rapidly with increasing V_{rel}.

For a given approach speed, V_{rel}, the minimum semimajor axis, a, of an impacting ECA occurs at $\theta = 0$ for prograde asteroid orbits ($V_{rel} < V_{\oplus}$). Within some critical $\theta = \theta_1$, $a < a_{\oplus} = 1$ AU, so these ECAs are Atens. We find that

$$\theta_1 = cos^{-1}\left(\frac{1}{2}\frac{V_{rel}}{V_{\oplus}}\right). \tag{3}$$

Objects with $\theta_2 > \theta > \theta_1$ are Apollos, ECA in bound orbits with $a > 1$ A.U.

If the distribution of impacting velocities is isotropic except in the forbidden zone, where the ECAs would be in hyperbolic orbits, then the fraction of impacting ECAs that are Atens is 0.4-0.5 for most impact velocities. While this is undoubtedly an upper limit, it points out that Atens may be under-represented among known ECAs. This may be the result of the tendency of observers to concentrate their searches near solar opposition. Computer simulations of the expected search characteristics of the proposed Spacequard survey (Morrison 1992), which is similar to the search strategies used by most observers today, shows that it would miss a substantially larger fraction of Atens than other NEAs. The degree of under-representation of Atens can only be resolved by observations. We suggest that observers devote some of their telescope time observing near the direction of Earth's revolution around the sun at $\theta = 0$ (approximately the direction of the third-quarter moon).

Detectability of ECAs During Their Final Few Days to Impact

The detectability of asteroids during their final days to Earth impact was considered in Hills and Leonard (1995). We briefly review that work.

Magnitude

The apparent visual magnitude, V, of an asteroid depends on its distances from Earth, d, and sun, r, diameter, D, visual Bond albedo, A, and reflection phase law, $\phi(\alpha)$. Phase angle α is the angle between the sun and Earth on the sky as observed from the asteroid. Here ϕ is the flux density of the asteroid at phase angle α in units of its maximum value at $\alpha = 0$. We assume that the asteroid is spherical and that $\phi_m(\alpha_m)$ obeys the lunar phase law given by Allen (1974). We find that the visual magnitude of the asteroid is given by the equation

$$V = -5.0 \log_{10}\left[\left(\frac{1.0025695}{r\ (\mathrm{AU})}\right) \left(\frac{10^4}{3.476 \times 10^8}\right)\left(\frac{0.0025695}{d\ (\mathrm{AU})}\right)\right]$$

$$-2.5 \log_{10}\left(\frac{0.2}{0.067}\right) + \Delta V(\alpha) - 5.0 \log{(D/10^4\ \mathrm{cm})} - 2.5 \log{(A/0.2)} - 12.73, \tag{4}$$

Figure 1 shows V versus angle from the sun, $\theta_{\odot}$, for model asteroids with $D = 100$ m and $A = 0.2$ that approach Earth at 10 km s^{-1} at 10 days to impact. The reflected light from an asteroid is weak for small $\theta_{\odot}$ due to the phase effect; it would look like a crescent moon if observed with a sufficiently powerful telescope. Objects that approach from the anti-solar direction have $V \lesssim 16$. Asteroids that approach at right angles to the sun have $V \gtrsim 18$ while those within 30° of the sun have $V < 21$, which makes their detection very difficult.

The infrared N-band, as defined by Allen (1974), is centered at 10.2 μm, which is near the peak of the thermal spectrum for asteroids near Earth. We assume that the asteroid is rotating rapidly enough that its surface radiates uniformly in the infrared. The phase effect is not relevant in this case. We also assume that the asteroid radiates as a black body, so its spectrum is determined by its effective temperature, T_{eff}. We adopt our visual Bond albedo, $A = 0.2$, for the bolometric albedo. We use $D = 100$ m for our standard "small" asteroid.

Figure 2 shows the apparent N magnitude versus angle from the sun of 100-m asteroids that approach Earth at 10 km s^{-1} at 10 days to impact. In contrast to visual magnitudes, the asteroids are brightest in the N band if they approach from the solar direction, because they have the highest effective temperatures.

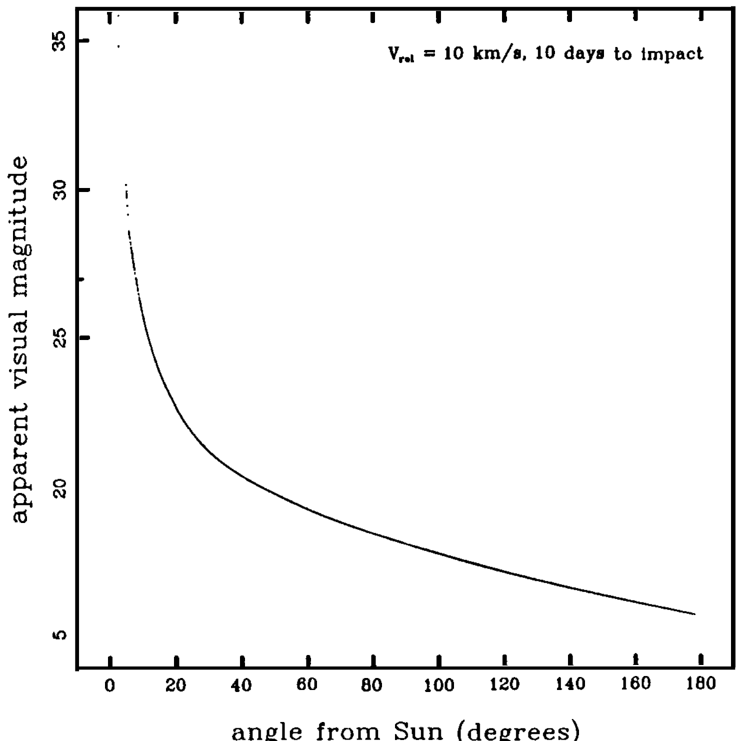

Figure 1. Magnitude V of the intruding asteroid as a function of angle from the sun. The model asteroid has diameter D = 100 m, albedo A = 0.2, and obeys the lunar phase law. It approaches Earth at 10 km s^{-1} and is observed at 10 days to impact.

Therefore, infrared telescopes may be the most effective ground-based means of detecting impactors that approach Earth from within 30° of the sun.

Parallax

The parallax, in radians, of an asteroid at distance, d, from Earth when viewed over a baseline of one Earth radius, $R_\oplus$, is simply

$$\Pi = \frac{R_\oplus}{d}. \tag{5}$$

Unlike the proper motion, the parallax steadily increases in the final weeks prior to impact. An asteroid that is one to two weeks away from Earth impact has a small proper motion, a large parallax, and is becoming brighter.

At a 10 km s^{-1} impact speed and 10 days from impact, the objects are at a distance of about 8.6×10^6 km = 0.058 AU = 22 times the distance to the moon. Their parallax for two observers at a projected separation of 1 $R_\oplus$ is about 150 arcsec = 2.5 arcmin, which is readily resolved with wide angle cameras. If an asteroid 100 m in diameter or larger hits Earth every 300 years (Shoemaker *et al.* 1990, 1991), then about 6000 such objects pass within 0.058 AU of Earth each year.

Geocentric Proper Motion

The geocentric proper motion of an asteroid is found by subtracting from the position vector of the asteroid relative to Earth at the desired time to impact the corresponding vector from a few minutes earlier. The angle between the two vectors divided by the elapsed time yields the proper motion.

Figure 3 shows daily geocentric proper motion μ versus angle from the sun $\theta_\odot$ for asteroids that approach Earth isotropically at 10 km s^{-1} at 10 days to impact. The maximum μ is small. We note the relatively

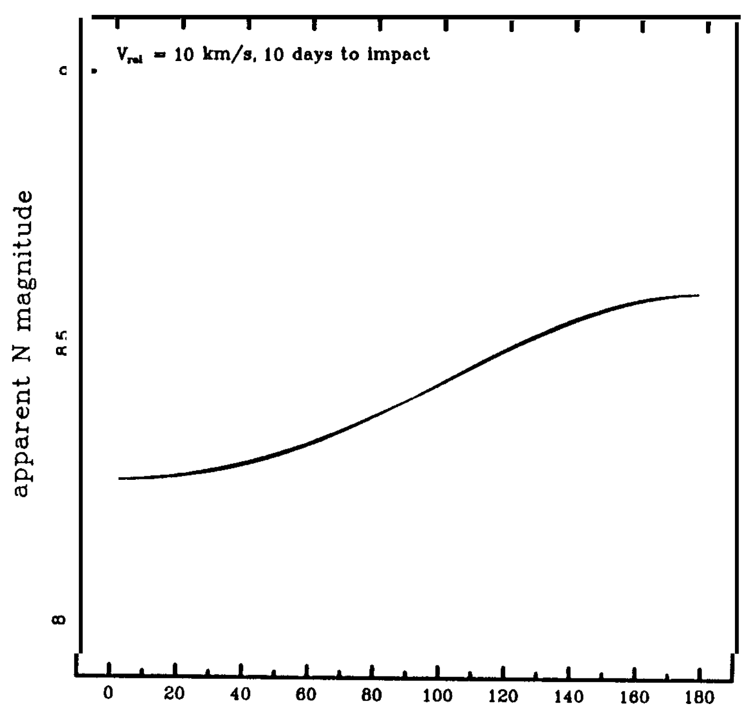

Figure 2. The apparent N magnitude versus angle from the sun of 100-m asteroids that approach Earth at 10 km s^{-1} at 10 days to impact.

narrow range of μ in Fig. 3 at each value of $\theta_{\odot}$. The minimum μs occurs at $\theta_{\odot} = 0°, 90°$ and 180° while the maximum μs of about 300 arcsec day^{-1} occur near $\theta_{\odot} = 45°$ and 135°. The values of μ are sufficiently small that in a typical 2-minute CCD exposure an asteroid moves less than 0.4 arcsec, so its CCD image appears nearly stellar. To detect the proper motions of these asteroids, we need to observe them a few hours to a few days apart.

An observer on the rotating Earth sees an additional proper motion due to his own motion that is superimposed on the geocentric proper motion. The maximum reflex proper motion due to rotation can be comparable to the maximum geocentric proper motion at 10 days from impact. Because of the vector nature of the geocentric and reflex proper motions, there may be portions of the sky where the total proper motion vanishes when these two components are added together. The maximum summed proper motion is low enough at 10 days to impact that the typical movement across the CCD in a 2-minute exposure is less than 1 second of arc, so the image remains stellar. The reflex proper motion resulting from rotation becomes increasingly important as the object approaches Earth. The additional proper motion due to the finite impact parameter of the object also becomes important as it approaches impact.

Search Strategies for Impacting Asteroids

We have seen that the proper motions of asteroids during their final days to Earth impact are small and may even vanish in certain parts of the sky, so they may be missed by conventional surveys that rely on large proper motions to flag promising candidates. However, their parallaxes are easily detected with wide-angle (low-resolution) telescopes observing over a baseline of a few thousand kilometers. The major challenge is to correlate, in near real time, pairs of images from two or more sites to find promising candidates that would then be observed for proper motions. A large parallax and a low proper motion indicates a promising candidate, whose orbit would then be determined by further observations.

Relatively small telescopes are adequate to observe asteroids 100 m or more in diameter during their final days to Earth impact. A 5-inch, f/5 telescope would reach a saturation magnitude of 17.7 in a 2-minute exposure using the Spacewatch CCD array, which would cover a field $\approx 5°$ across. This limiting magnitude

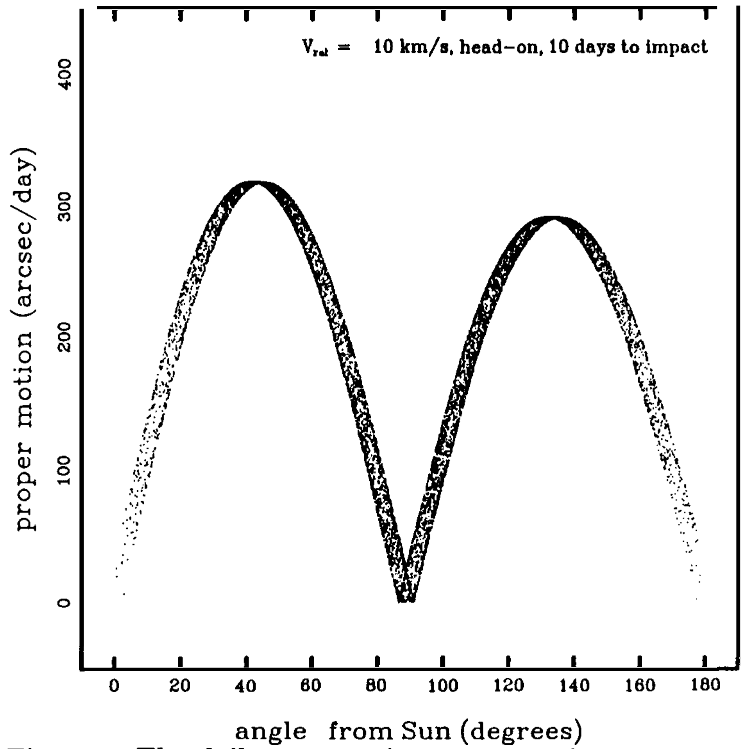

Figure 3. The daily geocentric proper motion μ versus angle from the sun of asteroids that approach Earth isotropically at 10 km s^{-1} at 10 days to impact.

will allow detection of a 100-m diameter asteroid 10 days from impact if it approaches Earth anywhere in the hemisphere centered on solar opposition. A 10-inch, f/5 telescope would reach a limiting magnitude of 19.2, which would allow it to detect these asteroids if they approach farther than 70° from the sun while a 16-inch, f/5 telescope would detect them farther than 40° from the sun. A 36-inch, f/5 telescope with a limiting magnitude of 22 could observe them if they approach no closer than 25° to the sun, which is about as close to the sun as twilight would allow observations under the best of circumstances. Alternatively, to reach the desired limiting magnitudes, we could use larger telescopes, e.g., 1-meter, that are rapidly scanned near opposition and more slowly scanned closer to the sun.

Detectability of ECAs During Their Final Few Years to Impact

Objects larger than 1 km in diameter need to be detected months to years before impact to allow time for deflection away from Earth. Proposed surveys for finding them, such as Spaceguard (Morrison 1992), will attempt to find all ECAs of this size rather than just those that will hit Earth in the next few years. They plan to concentrate their search towards solar opposition, as have most surveys to date. This limitation in sky coverage may produce severe selection effects, as is evident in the preliminary analysis of the detection capabilities of the Spaceguard survey (Morrison 1992). It showed that the survey would find 90% of all Near-Earth asteroids (NEAs) larger than 1 km in diameter after 25 years of searching if undiscovered NEAs have orbits similar to those of known ones. However, the survey would find only about 50% of the Atens, ECAs with semimajor axes less than 1 A.U. Since *existing* surveys such as Spacewatch concentrate their search towards opposition, they are likely to suffer the same selection effect, so Atens are under-represented among known ECAs.

ECAs that will hit Earth in the next few years should be easier to detect than other ECAs because they approach much closer to Earth. Any ECA, which is defined to have its perihelion (closest approach to the sun) within the orbit of Earth and its aphelion (farthest distance from the sun) beyond it, can *eventually* hit Earth. When impact occurs, the distance of the ECA from the sun equals that of Earth at one of the two points where the orbit of the asteroid intersects the orbital plane of Earth (the nodes). For a given

ECA this happens at two different values of the argument of perihelion, the angle at the sun between the ascending node and the perihelion of the asteroid. In a purely two-body problem, this angle is invariant, but perturbations by the planets cause it to precess (rotate) by 2π radians on time scales of about 2×10^4 years. Twice per precession cycle, or about every 10^4 years, the distance from the sun at the node equals 1 A. U., so the ECA can collide with Earth if the orbit phasing permits it. The mean time to a collision is about 2×10^8 years, so the orbit of the asteroid intersects that of Earth about 2×10^4 times before the asteroid collides with Earth. The mean closest approach of the ECA to Earth during each orbit crossing within the precession cycle is about $(2 \times 10^4)^{1/2} R_\oplus = 141 R_\oplus$ = 2.3 times the distance to the moon = 0.006 A.U. If the object is destined to hit Earth, we expect close approaches of this order during the orbit revolutions immediately proceeding the one that leads to impact. The object will be much brighter than average during these close approaches. During the remainder of the precession cycle, the ECA orbit does not pass nearly as close to Earth especially if its perihelion lies well inside the orbit of Earth and its aphelion lies well outside it. ECAs in such non-intersecting orbits are much harder to detect, but they are of no immediate danger to Earth.

These orbit intersections within the precession cycle of the line of apsides are times of crisis for Earth. The close approaches during these times make the ECAs easier to observe, but they also make their orbits much more chaotic. We need to detect all objects that are in near-intersection orbits with Earth and then track them sufficiently well to assure that they will not hit Earth before precession again causes their orbits to diverge from that of Earth. In this paper we examine the observability of objects in near Earth-intersection orbits. If we define an Earth-intersecting asteroid (EIA) as one whose orbit is within +-200 years of intersection with the orbit of Earth due to planetary perturbations, then EIAs constitute about (2*200)/(20,000/2) = 4% of the ECA population. If there are 2000 ECA with diameters exceeding 1 km, then there are about 80 EIAs with such diameters. There should be nearly 10^5 EIAs with diameters exceeding 100 meters.

Orbital precession assures that a representative sample of Earth-crossing objects are now in orbits that pass near Earth. (These EIAs are, fortunately, the easiest ones to explore in detail including with the use of space probes.) There is no hidden ensemble of objects that may eventually hit the Earth, unless they are very rare. An extreme case of such a rare object may be Comet Hale-Bopp. It is reportedly 10 times the size and 1000 times the mass of Comet Halley or of the impactor responsible for the demise of the dinosaurs. This object may be massive enough to sterilize Earth. Fortunately, the chance of such an object hitting Earth is very small. A normal long-period comet hits Earth every 10^8 years (e.g., Hills 1981) with about 5 such comets intersecting the orbit of Earth each year. If this is the comet of the century, it is about 500 times rarer than the average long-period comet, so such an Armageddon comet would hit Earth about every 5×10^{10} years. Since the dawn of life on Earth, there has been about a 10% chance that such a comet would have hit. Except for such masive long-period comets, we should find a representative sample of the various types of Earth-impacting objects among the current-day EIAs.

In this paper we consider the detectability of ECAs that will impact Earth in the next few years. We show that the currently proposed searches will systemmatically under-discover Atens and will not find Apollos as efficiently as they could. We show that these deficiencies can be corrected by changes in observing strategy.

Test Orbits

To study the observability of Earth-Intersection Asteroids (EIAs), we considered an ensemble (usually 10,000) of them having a fixed impact velocity with respect to Earth. We used Monte Carlo sampling to place them isotropically, except for the forbidden zone corresponding to those in hyperbolic orbits, on a shell centered on Earth at 1 day from Earth impact. We found the heliocentric orbit of each and ran it and the orbit of Earth back through time for several years to find the position and magnitude of the EIA with respect to Earth prior to impact. We took our standard asteroid to have a diameter of 1 km, an albedo of A = 0.2, and a lunar phase law. The results are trivially scaled to other albedos and diameters.

To sharpen our intuition, we shall consider the detailed observational properties of a few representative impactors from the ensemble before looking at it statistically. Column 1 of Fig. 4 shows the magnitude and angle from the sun of typical Atens that have impact velocities of 15 km/s prior to gravitational acceleration by Earth while Column 2 shows their position on the sky. Fig. 5 shows representative Apollos. The points in both plots are given at one-day intervals for the final 10^4 days prior to impact. Column 2 of each figure is a Mercator projection in which the vertical axis is the angular distance from the north ecliptic pole. The horizontal axis is the angular distance in the ecliptic plane away from the instantaneous direction of Earth's motion around the sun. The sun is always located at ecliptic longitude 90^o (and polar angle 90^o) while the solar opposition point is at ecliptic latitude 270^o (and polar angle 90^o).

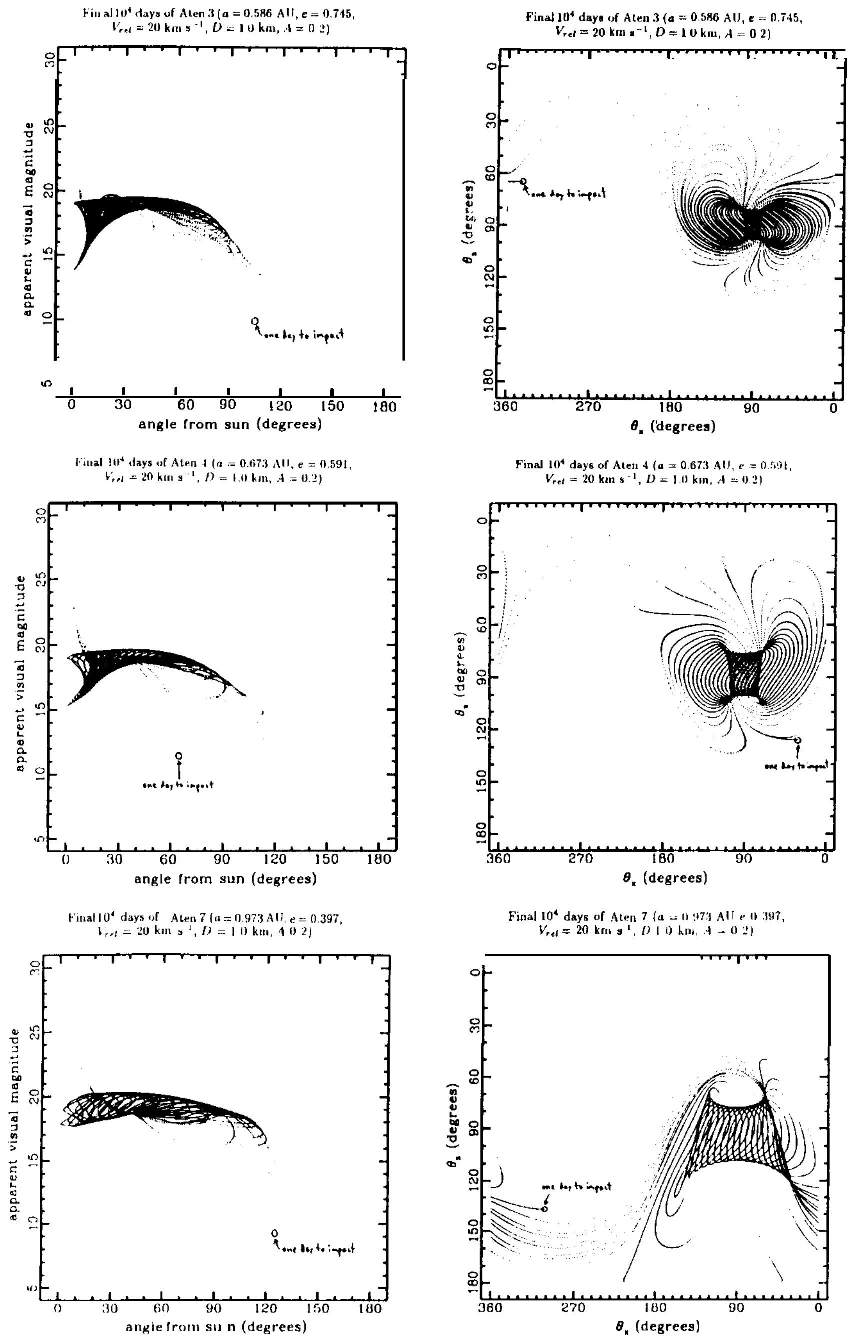

Figure 4. Column 1 shows the apparent V magnitude and angle from the sun of typical Atens that have impact velocities of 15 km/s prior to gravitational acceleration by Earth. Column 2 shows the positions of these objects on the sky. The data points are at one-day intervals during the final 10^4 days to impact.

The loops to brighter magnitudes shown in Fig. 4 and 5 occur during close approaches to Earth. The objects can be very bright during these close approaches especially the Atens, which can reach magnitude 10 during some close approaches as shown in Fig. 4. We see that most Atens do not approach near enough to the solar opposition point to be found by existing and proposed ECA surveys despite their becoming quite bright during these close approaches. When the Atens are 180^o in ecliptic longitude away from the sun, they tend to be near the north or south ecliptic poles. This is due to their being relatively close to Earth at these times, so they tend to have a high ecliptic latitude even if they have a relatively small orbital inclination to the ecliptic. While Apollos can produce loops that dip down to comparably bright magnitudes, they make fewer revolutions around the sun per unit time than the Atens, so there is less probability of catching them when they are exceptionally bright. We note that the loops do not occur when the Apollos are near solar opposition, so to detect them when they are bright requires a survey that scans most of the sky. Apollos, with diameters of 1 km and albedos of 0.2, are generally about magnitude 18 during a typical close approach loop.

The last pair of plots in Fig. 5 is that of an Apollo that hits Earth on the first pass after observations begin rather than making several close approaches before it impacts. It is typical of long-period Apollos and long-period comets. We note that it is very faint until the final few months. It approaches the threshold of detetectability of magnitude 22 (characteristic of the proposed Spacequard system and typical of larger ground-based systems) at an angular distance of about 110^o from the sun or 70^o from opposition and never strays very far from it until impact. This is well outside the observing window centered on opposition proposed for Spaceguard or carried out currently by existing surveys such as Spacewatch. Such surveys would clearly miss the object. It points out the desirability of a survey that covers the entire sky to faint optical magnitudes.

Probability of Detection

Fig. 6a shows the probability of detecting an ensemble of Earth-intersecting Atens with impact velocity 15 km/s during the interval from 10^4 to 10^3 days to impact. It shows the fraction of objects detected by a survey that observes all the sky farther than a certain angle from the sun to a given limiting magnitude. A detection is assumed if the object is visible for 5 or more days in the observing window. The limiting magnitudes of the surveys are 14,16,18,20, and 22. The near superposition of the surveys for all limiting magnitudes onto one curve shows saturation, so that any survey with a magnitude limit of 14 or fainter would equally be able to detect the objects. The main limit is the geometric one. A survey limited to 45^o of opposition would only find about 0.4 of the Atens while one that extends to at least 90 degrees from opposition would find them all. The lack of dependence on magnitude is due to the loops to brighter magnitudes shown in Fig. 4, which occur in close approaches to Earth. The importance of close encounters is evident by the contrast with the discovery probabilities given in Fig. 6b where we have taken the same objects as in Fig. 6a and randomized their arguments of perihelia, so they more closely resemble the general Aten population rather than just those Atens that hit Earth. We note from Fig. 6b that a survey to find all Atens will not be complete unless its limiting magnitude is at least 18 rather than 14. The survey is also not complete unless it extends farther than 90^o from opposition.

Fig. 7a shows the detection probability of Earth-intersecting Apollos with impact velocities of 15 km/s when observed 1000 to 10,000 days to impact. The situation is not as favorable as for the Atens. An all-sky survey would find fewer than 60% of the Apollos if its limiting magnitude is 14 and under 90% if it is 16. At magnitude 18 about 98% would be discovered. Even allowing for albedos much darker than 0.2, it is likely that a survey with a magnitude limit of 20 would find at least 98% of the objects with diameters greater than 1 km. This survey would have to cover the entire sky farther than 90^o from the sun. Fig. 7b shows the detection probabilities if the line of apsides of these objects were rotated by random amounts so that they represent better the general ECA population. Again, a survey would find a smaller fraction of objects than if only Apollos with Earth-intersection orbits were considered, but the differences are not as large as they are for Atens.

Long-period objects, 1 km in diameter, such as the last one shown in Fig. 5 cannot be detected 1000 days before impact at a limiting magnitude of 22. That object does not approach the threshold of magnitude 22 until the last few months to impact, and it only reaches magnitude 14 during the last two weeks to impact. Such objects can only be detected years to impact by going to much fainter than magnitude 22, as is evident from the last plot in Fig. 5. Because of such objects, even the faintest survey does not reach unity in Fig. 7a.

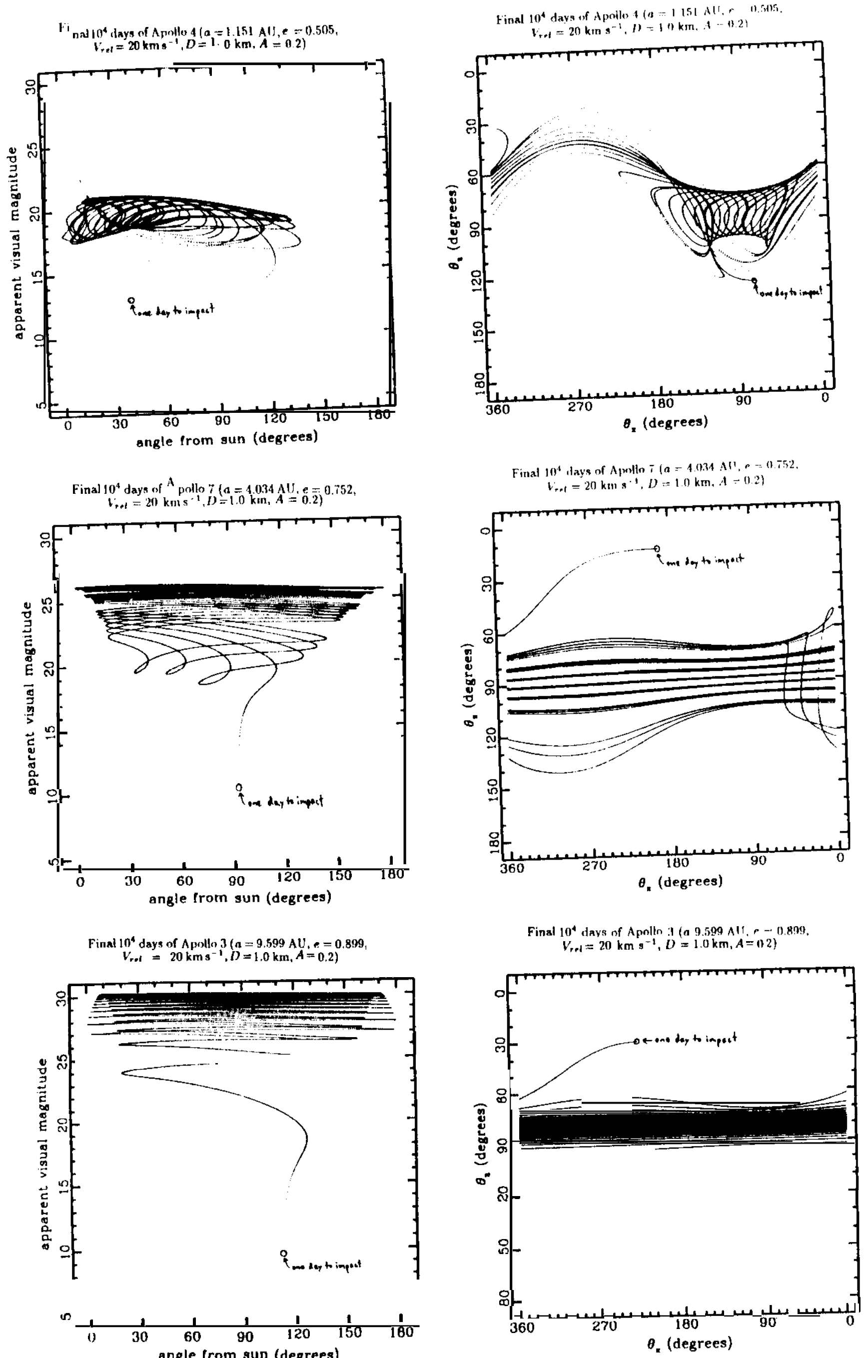

Figure 5. Same as Fig. 4, but for representative Apollos.

Because the sky background is about 22 magnitudes/(arc sec)^2, the only practical way of going to fainter magnitudes is to observe from space where the diffraction limit of even moderate aperture telescopes is less than 1 sec. This suggests a strategic plan where the initial all-sky surveys would only go down to magnitude 18-20, but would cover the entire sky a few times a week. This would find more than 90% of the Earth-crossing asteroids in Earth-Intersection orbits. It does not make much sense to go down much further than this at high marginal cost unless the survey addresses the detection of long-period comets, which, like the last object in Fig. 5, needs to be detected at much fainter than magnitude 22 to be found years to impact. A wide-field 2-meter space telescope would go down to magnitude 27 before sky saturation, which would be adequate to detect these objects a few years to impact. This would require long exposures on each field, so

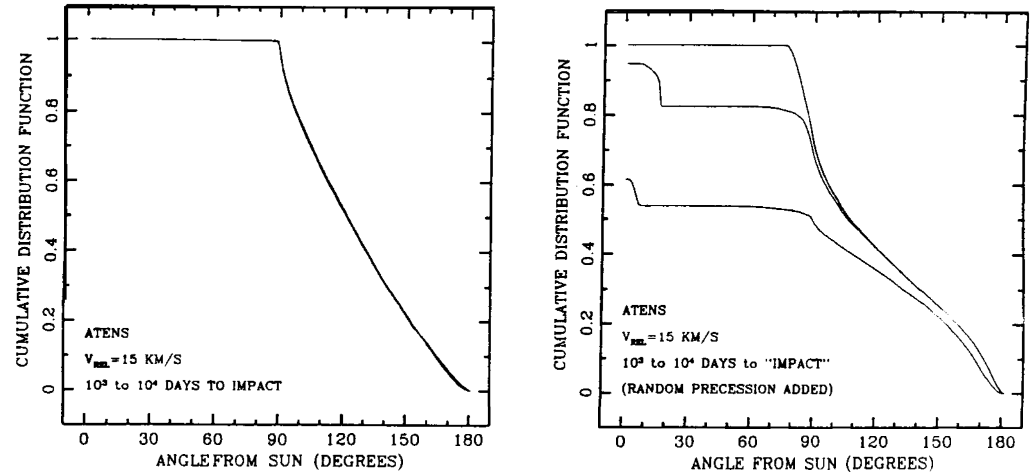

Figure 6. Here 6a gives the probability of detecting an ensemble of Earth-intersecting Atens with impact velocity 15 km/s during the interval from 10^4 to 10^3 days to impact. The probabilty is the fraction of objects detected by a survey that observes all the sky further than a given angle from the sun to a given limiting magnitude. A detection is assumed if the object is visible for 5 or more days in the observing window. The limiting magnitudes of the surveys are 14,16,18,20, and 22. The near superposition of the probabilities onto one curve shows that any survey to limiting magnitude 14 or better would be equally able to detect these objects. Here 6b estimates the probability of detecting the general ECA population of Atens. This was found by randomizing the arguments of perihelia of the objects used in constructing Fig. 6a.

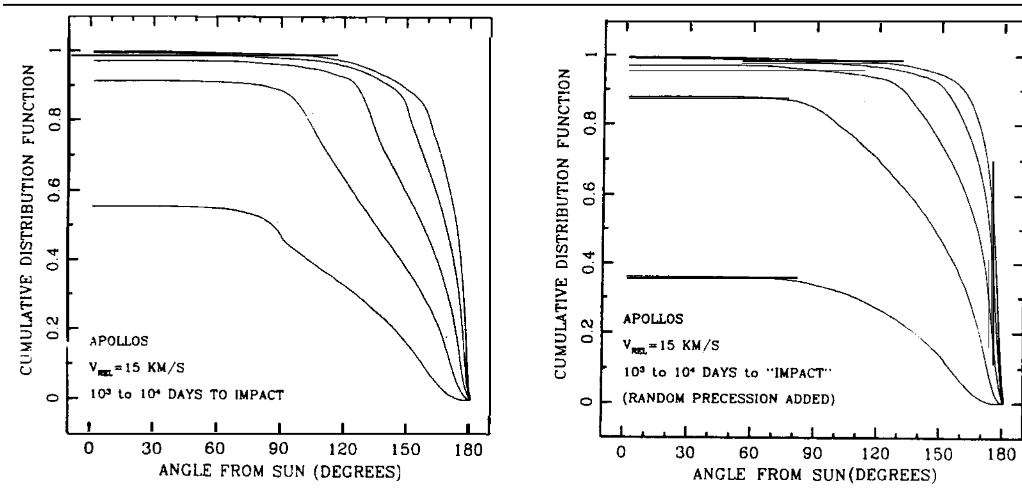

Figure 7. Same as Fig. 6 but for Apollos rather than Atens. The curves are for limiting magnitudes 14, 16, 18, 20, and 22. Unlike Fig. 6, it shows that the surveys are not complete at the brighter limiting magnitudes.

it would only make, say, annual observations of each field. Two or three exposures on each field separated by a few days would be enough to show the proper motion of these distant objects. Likely objects would then have to followed with another space telescope to determine the orbit. The second space telescope would not have to have a wide field, unlike the discovery telescope. It could probably do this follow-up work as part of its other activities.

To discover more Earth-Intersection asteroids, particularly Atens, with present equipment, such as Spacewatch, it may be desirable to use it during the bright moon, when it is not currently used. It can do very rapid scans to magnitude 16-18, which is well above the sky background during the full moon, so the telescope will not be hampered by moonlight. During these times the telescopes should look at the part of the sky far from opposition, which is then occupied by the (near) full moon. The change in procedure would not reduce the current discovery rate of these telescopes at opposition, but it would allow additional EIAs to be detected far from opposition, at some increase in manpower.

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Tracking and Characterization of NEO's

Using AMOS Ground-Based Optical Telescopes

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Both the mass and orbit must be known to assess the threat from a given NEO. The orbit and position define the velocity so the uncertainties in the momentum and energy are dominated by how accurately the mass can be estimated. The mass, in turn, is the product of the volume and density of the NEO. Because NEO reflectivity can vary from about 2 to 50%, simply measuring brightness and assuming reflectivity results in a diameter estimate with a factor of two uncertainty. This leads to a factor of eight uncertainty in the volume. Asteroid densities are believed to vary from about 2 to 7 g/cm^3. Adopting a mean density introduces another factor of two uncertainty into the mass. Thus, the total uncertainty in the momentum and impact energy, due to the individual uncertainties in the diameter and density, can be as large as a factor of sixteen. The taxonomic class of an asteroid can be determined from visual photometry. This constrains the mineralogy of the object and reduces the uncertainty in the density estimate. Size estimates based on visual photometry and infrared radiometry are accurate within 10%. We describe an observational program which uses the demonstrated capability at AMOS to obtain accurate astrometry necessary for orbit determination, photometry for classification, and the ongoing upgrades to the AMOS facility to provide the observations required to determine the physical parameters discussed above. These observations reduce the total mass uncertainty to about 50%.

Introduction

Physical characteristics of NEOs

Risk assessment of threat NEOs is hampered by a lack of knowledge regarding their physical properties, in particular their mass and composition. In order to assess the threat from a given NEO, one must know both its orbit and its mass. For a given velocity, the energy and momentum of an NEO is proportional to its mass, *i.e.*, to the product of its volume and density. In order to choose the appropriate mitigation strategy, knowledge of the NEO's composition (carbonaceous?, iron?), dynamics (spin rate and pole orientation), and structure (shape, cohesiveness) are also required.

We will estimate the mass uncertainties with and without knowledge of the size and taxonomic class of an NEO under the assumption that the NEO's are either asteroids or have surface reflectance and thermal properties similar to those of asteroids. We describe a program using the AMOS facilities to obtain astrometry for orbit determination and multicolor photometry for taxonomic classification. Future upgrade to provide infrared radiometry are explored.

NEO mass and composition

Because the reflectivity of an asteroid can vary from a few percent to as high as fifty percent, simply measuring its brightness and assuming a reflectivity results in a diameter estimate with about a factor of two uncertainty. This leads to a factor of eight uncertainty in its volume.

Asteroid densities are believed to vary from about 2 to 7 g/cm^3. Assuming a density of 3.5 g/cm^3, introduces another factor of two uncertainty into the mass. Thus, the total uncertainty in the impact energy and momentum, due to uncertainties in the diameter and density, can be as large as a factor of sixteen.

As was demonstrated in the Phillips Laboratory (GPOB)-supported IRAS Minor Planet Survey (Tedesco, 1992, 1994), asteroid diameters can be determined to within less than 10% uncertainty if both a visual brightness and a single thermal infrared flux are known. Additionally, if a taxonomic class can be determined, then the density can also be constrained. For example, the density of the "carbonaceous" classes is believed to be about 2.5 ± 0.5, that of the "stony" classes about 3.5 ± 0.5, and that of the "metallic" classes around 7 g/cm^3. Thus, assigning an asteroid to one of these three broad classes reduces the density uncertainty to about 15%. Hence, in cases where both the diameter and taxonomic class are known, the total uncertainty in the mass can be reduced to about 50%, *i.e.*, to about 3% of the uncertainty in the absence of such data.

The Phillips Laboratory program

Background

While many organizations have expressed an interest to participate in the discovery phase of PDI, few have proposed the requisite follow-up observations and no group has the unique combination of facilities and expertise to obtain accurate position measurements and to analyze and classify the objects discovered by means of observations at different wavelengths. The Geophysics (GP) and Lasers and Imaging (LI) Directorates have such facilities, expertise, and interest to do such follow-up observations and analyses.

The Backgrounds Branch (GPOB) in the Optical Environment Division of the Geophysics Directorate, Phillips Laboratory has a mission to determine the general nature and detailed character of the backgrounds against which an Air Force electro-optical system must operate. This is accomplished by conducting field measurements and surveys of the transmission and emission of the atmosphere as well and the radiance from the celestial background. Under the celestial background effort, the branch has long been interested in asteroids as a major component. Because of their low reflectivity and high infrared emissivity, asteroids are a source of infrared clutter and false targets of interest to the midcourse surveillance community. The PL/GP predecessor organization, AFCRL, provided the first realistic predictions of the magnitude of the asteroid problem for a space based infrared sensor (Murdock, 1973). This analysis was concurrent with the first infrared detections and limited survey of asteroids from space by the AFCRL/AFGL rocket borne sky surveys (these are unpublished, reference is given to the later article by LeVan and Price, 1984). PL/GP later sponsored the retrieval of archived asteroid measurements obtained by a NASA survey satellite (IRAS) and had them reanalyzed to produce the currently used database of asteroid sizes. These analyses have been codified into a model which has been incorporated into a Celestial Background Scene descriptor which provides the position and brightness of any of the known, numbered asteroids, for a specified date and predicts the statistical distribution for the fainter, as yet to be discovered, objects. The GP interest in the planetary defense initiative is a natural consequence of previous experience and contribution to the overall objective of understanding the distinguishing factors which separate the asteroids into different populations.

Analysis sponsored by GP has led to the ability to accurately determine the diameter and taxonomic class of an asteroid. As noted above, this is important to planetary defense because one must know both the orbit and size in order to assess the threat from a given NEO.

GP is engaged in or associated with current efforts to detect and classify asteroids. The astronomy experiments on BMDO's Midcourse Space Experiment are the responsibility of the GP principal investigator. There are two of these experiments to measure asteroids: One is to obtain the ultraviolet through infrared multicolor observations necessary to classify and determine the physical parameters of selected known objects; another is a target of opportunity experiment specifically for follow-up characterization of NEOs. Another experiment uses the European Space Agency's Infrared Space Observatory (ISO) to discover faint asteroids. The NEO observations directly support the PDI objectives. Observations of main-belt asteroids indirectly support PDI through analysis of the characteristics of the general population of asteroids with NEOs as a defined sub-class. The GP interest in the Planetary Defense Initiative is a natural consequence of previous experience and contribution to the overall objective of understanding the distinguishing factors which separate the asteroids into different populations.

The mission of Phillips Laboratory's Air Force Maui Optical Station (AMOS), part of the Maui Space Surveillance Site (MSSS), is to conduct research and development of new and evolving electro-optical sensors, as well as to provide support for operational missions defined by US and AF Space Command. In addition, AMOS also provides experiment support to a wide variety of military and civilian organizations in diverse fields. This support has included the Strategic Defense Initiative Organization (SDIO) and its successor, the Ballistic Missile Defense Organization (BMDO), the National Aeronautics and Space Administration (NASA), the Jet Propulsion Laboratory (JPL), and many universities. Typical AMOS visiting experiments include:

- support for tactical and strategic missile launches out of both Vandenberg and Kauai
- detection and tracking of orbital debris
- observations of shuttle and satellite special operations
- atmospheric physics
- space sciences and astronomy

Recent and historical experience in all of the above missions has given PL/LIMM expertise in those areas necessary to support the PDI in general, and to provide PL/GPOB with the data to derive the physical characteristics of NEOs.

AMOS telescopes include a 1.6 meter telescope, an 80 centimeter Beam/Director Tracker, and a 60 centimeter Laser Beam Director. The Maui Optical Tracking and Identification Facility (MOTIF) includes twin 1.2 meter telescopes on a common mount. The JPL CCD camera, currently used in support of NEO observations, is mounted on one of the 1.2 meter telescopes. An automated filter wheel containing Johnson U, B, V, and R filters plus an Eight-Color Asteroid System x filter (*cf.*, Tedesco, *et al.*, 1982) will replace the single-filter holder in the JPL CCD camera in July 1995. GEODSS includes two main 1 meter telescopes and an auxiliary 40 centimeter telescope. A major upgrade to AMOS will be the Advanced Electro-Optical System (AEOS), a 3.67 meter telescope scheduled for first light in 1997. AEOS will have seven coudè rooms for various experiments, as well as bent Cassegrain positions located on the mount itself.

Sensors associated with these telescopes include a wide range of detectors and visible through infrared imaging arrays. The 1.6 meter telescope has a Compensated Imaging System which has been operational since 1982. The new AEOS will also incorporate an adaptive optics system for atmospheric turbulence compensation. Recently completed is the AMOS Daytime Optical Near Infrared Imaging System (ADONIS), capable of extending the AMOS imaging capabilities to 24 hours per day. These adaptive optics systems allow AMOS to take photographs with outstanding clarity, close to the diffraction limit, in spite of the severe problems of dealing with atmospheric turbulence.

GPOB and LIMM contributions to PDI will be along the following lines:

- LIMM will do timely follow-up astrometry and multi-color photometry subsequent to discovery of a Near Earth Object. This capability is the result of the unique environment at the MSSS, which must respond rapidly to short notice tasking by the Air Force. This rapid response is not possible for most civilian observatories using large optical telescopes. LIMM is active in the search for, and follow up of, NEOs, routinely sending astrometric and photometric data to both the Jet Propulsion Laboratory (JPL) as well as to Dr. Brian Marsden of the Minor Planet Center.
- GPOB has the experience and expertise to interpret the photometry and radiometry and accurately derive the physical characteristics of the object.

Orbits

LIMM has used the JPL camera in a single visible spectral band on the 1.2 m telescope for more than a year in support of the JPL visiting experiment. Rapid and efficient procedures have been developed to acquire and track the designated NEOs. LIMM is obtaining positional accuracies of less than 1 arc second, using the Hubble Guide Star Catalog and the astrometry routines with the astronomical software package IRAF. The photometry is calibrated to about 2 percent, allowing reliable determination of light variations with time.

Taxonomy

AMOS will accurately measure the astrometric positions of NEOs discovered in the search programs and obtain multicolor photometry on them. We will analyze the multicolor photometry to ascertain the taxonomic classification, and to improve the accuracy in estimating the size and mass of the object. This will be a collaborative effort between the Air Force Phillips Laboratory's Air Force Maui Optical Site (Directorate LIMM) and the Geophysics Directorate (GPOB).

Taxonomic classes can be determined, to first-order, from multi-color photometry alone. As shown by Tedesco *et al.* (1989), measurements in the U, V, and x filters, plus an albedo determined from radiometric or polarimetric observations, results in a classification into one of a dozen or so broad classes.

Of the approximately 300 NEOs discovered to date about 50 have multi-color photometry and about 40 measured diameters and albedos. The reason for the small fraction of NEOs with physical observations is the difficulty in obtaining the requisite measurements. Unless an observer interested in NEOs and fortuitously at a telescope equipped with the appropriate instrumentation, during, or within a month or so, of the discovery it is not possible to obtain an observation until the NEO once again makes a close approach to the Earth. This very often does not happen for many years. Even if such an observer is ready to make the observation it often happens that, either the orbit is not yet known accurately enough to find the object, or poor weather, result in no observations being obtained. This is true of the astrometric follow-up as well. The AMOS program is designed to overcome these obstacles.

Sizes

Radiometric observations at 10 μm, using the AMOS 1.6 m telescope will, when combined with the visual photometry from the 1.2 m telescope, provide the data necessary to determine the diameter and albedo.

The AMOS NEO program

The AMOS program is unique in that there are multiple co-located telescopes each performing a specialized, coordinated function.

The tasks necessary to fulfill the PDI charter may be summarized as follows:

1) Search and Discovery
2) Astrometric Follow-up
3) Physical Characterization
   a) visual photometry/spectroscopy
   b) infrared photometry and/or polarimetry

The AMOS program is the only one with all of the following coordinated systems:

1) Search and Discovery
   CCD-equipped Maui 1 m GEODSS search instrument
2) Astrometric Follow-up
   MOTIF 1.2 m telescope with CCD camera (orbit refinement)
3) Physical Characterization
   a) visual photometry/spectroscopy
      Multi-color (U, V, x) photometry with the MOTIF 1.2 m (taxonomic classification)
   b) infrared photometry and/or polarimetry
      IR (10 μm) capability with the MOTIF 1.6 m and, eventually, the AEOS 3.67 m (size and albedo)

Phillips Laboratory Development Strategy

Current Capabilities (mid-1995)

1 m Maui GEODSS for detection. (JPL NEAT program.)

MOTIF 1.2 m telescopes for follow-up. (800x800 JPL CCD camera with U, V, and x filters.)

Near-Term Plan (FY 1997)

Replace the JPL CCD camera on the 1.2 m telescope with a three-channel CCD camera for simultaneous U, V, and x photometry.

Acquire a sensitive VLWIR (10 μm) radiometer for the 1.6 m telescope.

Long-Term Goals

Expand follow-up observations by AMOS to other Phillips Laboratory sites at Malabar, Florida and Albuquerque, New Mexico.

Enhance follow-up observations at AMOS through the use of larger aperture telescopes (*e.g.*, 3.67 m AEOS) and new instrumentation (*e. g.*, a polarimeter).

Summary

The program described here has already begun to produce results. LIMM routinely sends astrometric data to Dr. Brian Marsden of the Minor Planet Center, and AMOS was commended in a recent NASA report for the first follow-up of a Near Earth Object by a military telescope.

In the process of obtaining follow-up observations, uncataloged objects are routinely detected in the instrument field of view. Asteroid 1995KB, for example, was discovered at AMOS during routine operations.

The program will enter phase 2 in July 1995 with the addition of a multi-color photometry capability.

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Fast Optical Comet Search Experiment

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Long period comets, particularly at solar elongations less than 90 degrees, can cross the orbit of the Earth and therefore are potentially hazardous to the Earth. However, the number and sizes of these objects are not known. No automated effort has ever been made to carry out a systematic search for these comets. A team at Lawrence Livermore National Laboratory is constructing an array of small wide-field-of-view telescopes in an attempt to search for these faint comets within a year. The system consists of an array of 10 cm aperture refractive lenses each viewed by a 2048 x 2048 CCD camera. Each camera has a 5.3 x 5.3° field of view. A system of 4 such cameras can survey the entire night sky in one night. Based on the performance of a single camera prototype, we expect the system to be sensitive down to Mv ~ 17, which is a full 6 magnitudes deeper sensitivity than achieved by dedicated amateur comet hunters. This paper will describe the performance of this telescope system and plans for implementing this system at Lowell Observatory.

Introduction

The search for earth-crossing objects has become a very active field in the last several years. Earth-crossing objects consist of ~60% asteroids, ~20% long period comets and ~20% extinct comets (Shoemaker, 1995). There are many programs searching for earth-crossing asteroids. These telescopes have 1 ~ 2 meters of apertures but very small fields of view. To maximize the discovery rate for new asteroids these programs concentrate their searches on the region of sky near the ecliptic at opposition. However, this biased scanning strategy prevents discovery of higher inclination comets. Furthermore, the dynamics of Earth-cossing asteroids in the final weeks before their impacts with Earth show that they are bright (Mv < 16) and at very small solar elongation (Hills, 1995). In order to discover high inclination objects and objects at small solar elongation, a systematic survey of the entire available sky has to be performed each night. Such a survey is within the reach of automated, small to modest-sized telescopes with large fields of view.

In the past decade, experiments aimed at detecting near-Earth asteroids have been increasingly adding to the catalog of known comets. The Palomar Planet-Crossing Asteroid Survey (PCAS) and the Spacewatch program are described by Carusi et. al. (Carusi, 1995). PCAS, whose primary aim is the detection of asteroids in near-Earth space, has been in operation for nearly 20 years and uses the 0.46 m Palomar Schmidt telescope. The PCAS observations occur in dedicated campaigns spaced throughout the year. The technique involves taking pairs of photographs, covering 56 square degrees, of selected star fields, spaced 45 minutes apart, then examining them with a custom-designed stereomicroscope for evidence of objects that have moved against the stationary star background. The team can obtain between 50 and 60 images during a good night (representing 25 to 30 star fields.) The use of hyper sensitized Kodak 4415 film and 4 to 6 minute exposures achieves a limiting magnitude of V=17.5. The team also manages to do follow up observations on 30 to 50 objects for improved orbit determination. To maximize their sensitivity to asteroids, the team limits its observations to the 10% of the sky near the ecliptic, which is the most favorable part of the sky to scan for new asteroids. Due to the experience and dedication of the PCAS team the current annual sky coverage amounts to 40,000 to 50,000 square degrees per year. Current plans are to upgrade PCAS by adding a CCD (Charged Coupled Device) camera.

In 1991 a CCD based near-Earth object search became operative at the 0.91 m reflector at Kitt Peak. This was the Spacewatch program. The liquid-nitrogen cooled detector has 2048 x 2048 pixels and achieves a limiting magnitude of 20.5 with a 146.53 second integration time. This search is also limited to regions around the ecliptic in an effort to increase the likelihood of finding Earth-crossing asteroids with limited sky coverage.

More ambitious searches are under construction or consideration. The Spaceguard program plans to develop instrumentation to search the 6000 square degrees centered on the ecliptic at opposition down to magnitude 22, again concentrating on near-Earth asteroids. The Lowell Observatory Near-Earth Object Search (LONEOS) is currently instrumenting a 58 cm Schmidt with a four-chip CCD camera. LONEOS is designed to provide information that can be exported to Spaceguard.

Because of the limited inclination coverage, current and planned surveys are not optimized to find comets (Shoemaker, 1995). Furthermore, it is unlikely that the current and planned surveys will be quickly extended due to the expense of duplicating the large telescope systems in order to survey larger areas.

Optimal sensitivity to comets obviously requires a dedicated system that automatically surveys a large portion of the night sky, and can quickly and automatically recognize new objects. Automated target recognition requires CCD imagers whose digital output is directly compatible with computer processing. The high cost/area of CCDs demands that short focal length optics be used in order to cover a significant fraction of sky each night with a minimal number of CCDs. However, the short focal length requirement conflicts with attempts to increase the effective aperture.

Current and planned search experiments are resorting to very large format custom CCDs to obtain the largest field-of-view per image. This allows them to exploit meter class optics for maximum sensitivity to asteroids near the ecliptic. The resulting compromise emphasizes sensitivity over search area and revisit time.

An alternative approach which emphasizes search area and revisit time over sensitivity uses arrays of moderate aperture telescopes. We have found that modest cameras consisting of good-quality, commercially available telescopes, mounts, and CCDs can achieve sensitivities comparable to the PCAS program. Moreover the use of commercially available components significantly reduces the cost per camera. In this paper we show how a modest, fully-automatic, low-cost instrument can be built that can survey the entire available night sky on a weekly basis down to magnitude 17. We call the system FOCSE for Fast Optical Comet Search Experiment.

We have put together a collaboration from Lawrence Livermore National Laboratory (LLNL), the University of Michigan, and Lowell Observatory to implement and operate the FOCSE system. The collaborators from LLNL and the University of Michigan have previously collaborated on an automated telescope project (called GROCSE (Akerlof, 1993) for Gamma Ray Optical Counterpart Search Experiment) located at LLNL to search for optical counterparts of gamma ray bursts. The collaborators at Lowell bring their experience with the PCAS program to FOCSE.

Fast Optical Comet Search Experiment (FOCSE)

Figure 1 is a schematic of the proposed FOCSE system to be sited at Lowell Observatory. It consists of one or more sets of two 10 cm aperture f/3.3 telescopes mounted on a common mount protected by an automated clam shell. Each telescope is viewed by its own 2048 x 2048 pixel CCD with independent image acquisition and storage systems. A host computer operates the mount and sequences the imagery.

The combination of focal length and image format that we have chosen results in a 28.1 square degree field-of-view. The system requires 120 seconds per image including slewing time, integration time (100 sec), and transferring the image to disk. This results in 240 images centered on 120 star fields (two images per field) per camera per 8 hour night. A single camera, therefore, surveys 3370 square degrees per night. The four camera system proposed in this paper would survey 13,480 square degrees in 8 hours which is about one half of the total available night sky. Thus the system would revisit each star-field every two nights.

FOCSE Hardware

The FOCSE telescopes are manufactured by Tele Vue. The telescopes are a modified version of Tele Vue's commercial 10 cm aperture, f/5.4 Genesis telescopes. The modification consists of adding 3 new optical elements that shorten the focal length to f/3.3 and changing the spacing of the objective to better match the CCD spectral response. With a 2048 x 2048 CCD imaging device having 15 μm x 15 μm pixels the total field of view is 5.3° x 5.3° with each pixel subtending 9 arcsec. This semi-custom lens is commercially available at low cost and its optical quality is sufficiently high for our search, as proven in our prototype system (see the section of FOCSE Prototype System Performance).

The focal plane is a low noise Loral 2048 x 2048 pixel CCD with 15 μm x 15 μm pixels. Using a modified Loral CCD evaluation boards we measured the readout noise level to be < 50 electrons at room temperature. We are constructing new analog and digital camera boards which are much lighter, consume less power, have lower readout noise, and incorporate a thermal electric cooler to allow longer integration times.

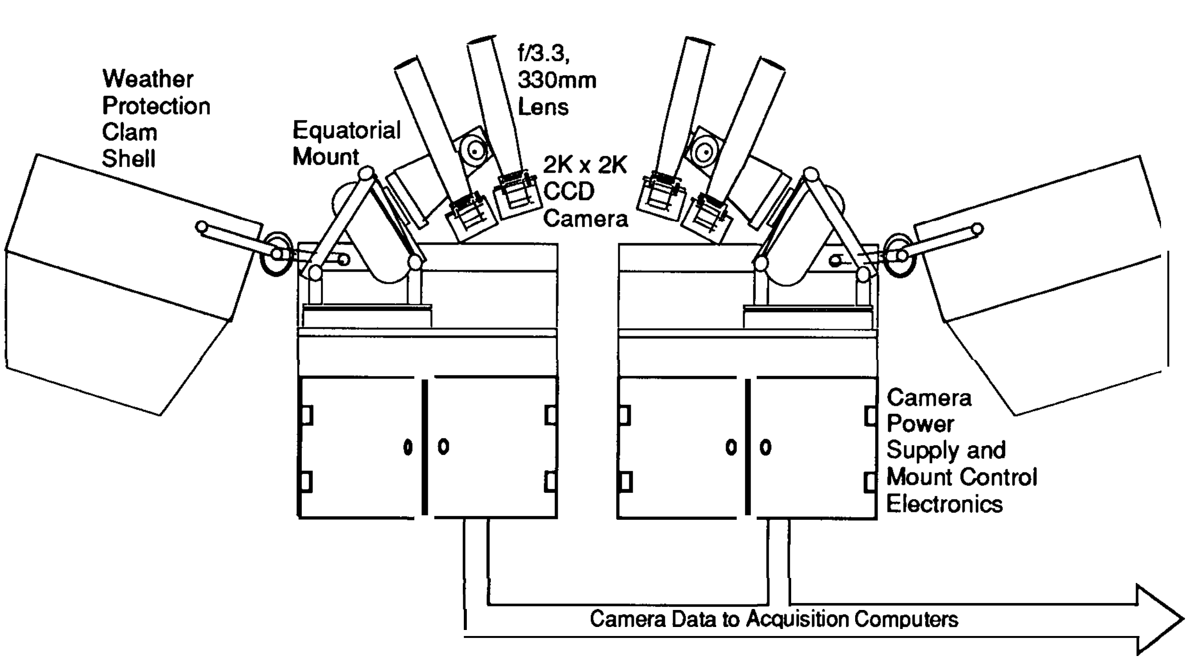


Figure 1. FOCSE Four Camera System and Weather Protection Clam Shell

Extensive laboratory calibration (Park, 1990) will be applied to produce the best processed images for extracting low signal to noise ratio objects. Pixel by pixel sensitivity and dark current calibration will remove the focal plane array (FPA) non-uniformity, fixed pattern noise, dark noise etc. at any integration time settings and any ambient temperature conditions. This pixel by pixel image calibration method gives more precise results than the traditional dark image subtraction and flat-field division at one given setting.

The robotic mount is manufactured by Epoch Instruments. It is of equatorial design and has separate motors for rapid slewing as well as tracking at earth rate. The mount can handle ~50 lbs of load and the tracking accuracy over 100 sec is better than 1 arcsec. The base size of this mount is only 16 " x 16" making it easy and affordable to construct a concrete base at the observatory site.

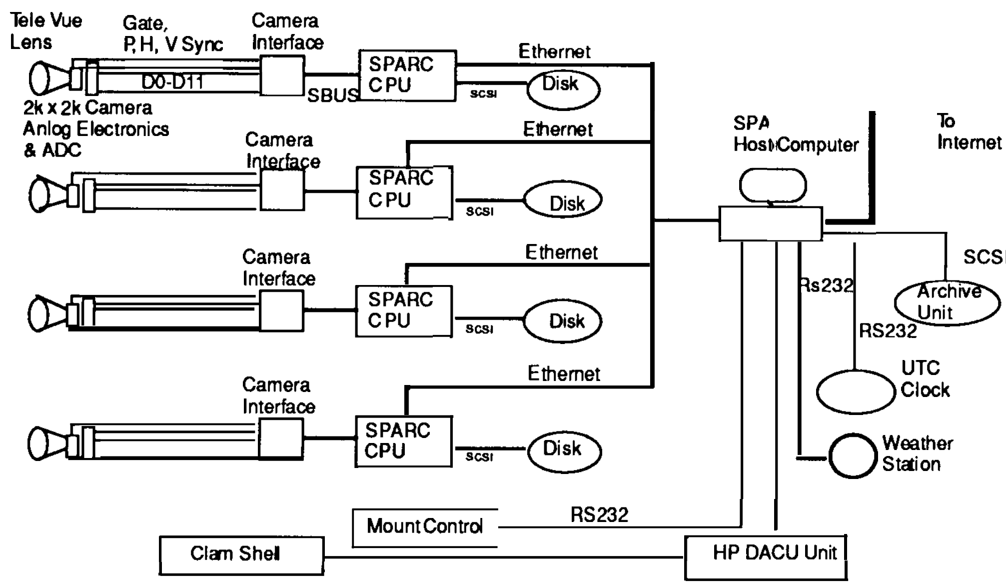
FOCSE Data Acquisition System

The data acquisition system is sketched in Figure 2. The camera digital and analog control electronics, including a 14 bit digitizer, are in the camera back plane. The digitized output, along with pixel, horizontal, and vertical sync signals, are serialized then transmitted to the SPARC image acquisition computer. Our custom frame buffer generates control signals for camera gain and integration time and transfers the images directly to the SPARC DRAM where it is accessed by the program then stored on the harddisk. The individual image acquisition CPUs are linked via ethernet to a main host computer (SPARC 10) which communicates over the internet, reads the UTC clock, controls the Epoch mount through an RS232 interface, archives the images taken at night, controls the clam shell (the telescope housing) and monitors the weather condition.

FOCSE Prototype System Performance

We assembled a prototype camera with an f/3.3 Tele Vue lens and a Loral 2048 x 2048 CCD read out with Loral's readout electronics. This "prototype" system was used to acquire imagery of M44 (Beehive) with 5 second integration time. Figure 3 shows a 0.64 degree portion extracted from the resulting images with identified star magnitudes marked on it. Mv > 14 stars are easily recognized in this image as expected from our radiometric model of the CCD and telescope.

It was not possible to integrate for 100 seconds (the nominal FOCSE integration time) with this prototype because of the design of the readout electronics and the tracking stability of the mount used for the test. Since the radiometric model correctly predicts the performance at 5 second integration time we used it to predict the performance at 100 seconds integration time. The model follows the method outlined in Rieke (Rieke, 1994), including estimates of all noise sources. The source was approximated as a blackbody of temperature 5800 K (reflected sunlight) with visual magnitude, zenith angle, and integration time as input variables. Bolometric correction and wavelength-dependent atmospheric transmission loss values listed in Allen (Allen, 1973) were used. Wavelength-independent instrument transmission losses of 2% per each of the five lens elements and an additional 2% loss due to particulates on the single, exposed objective were assumed. The wavelength-dependent quantum efficiency of the Loral CCD is based on our measured values, which conform closely to specifications. Atmospheric and optics transmission losses were multiplied by the sensor response to yield total atmosphere/instrument throughput efficiency. The input power from the source at the top of Earth's atmosphere was converted to number of photons, then multiplied by the atmosphere/instrument throughput efficiency to yield the total signal, in terms of photons/s, then integrated over all wavelengths to generate the total photon rate. The total signal was divided by the number of pixels for a point source, which was determined from the root-sum-square of the intrinsic spot size (< 1 arcsecond), the pixel size (9 arcseconds), and the seeing (in the model, seeing was fixed to 3 arcseconds). The following per pixel noise sources were included: shot noise, readout noise (measured at 50 e^- rms per pixel per frame), as measured dark current, out-of-wavelength band rejection, fixed pattern noise residual (set to 0.2% of signal), and sky background (set to mVsky = 22.0 for a dark site). The per pixel signal-to-noise ratio (SNR) was multiplied by the square root of the number of pixels subtended by a point source to yield total SNR at zenith, as plotted in Figure 4. The FOCSE instrument thus penetrates to better than 17th magnitude with SNR = 5 at zenith.



Fgure 2. FOCSE data acquisition system.

FOCSE Software

The FOCSE software is comprised of three main parts, the data acquisition and image processing software that runs on the image acquisition computers, the software running on the on-line host computer, and the long term analysis software that runs on computers at LLNL.

The data acquisition and image processing software runs on the image acquisition computers (SPARC 2s). When signaled by the host computer, the image acquisition software clears the CCD then starts the 100 second integration. During integration the software analyses the previous image. First the pixel-by-pixel calibration equation is applied to the image to eliminate the effects of dark current and pixel sensitivity non uniformity. The corrected image is passed to an image processing algorithm that identifies all star-like objects in the image. This algorithm was developed as part of LLNLs work on target recognition for ballistic missile defense. The algorithm computes the image mean and sample deviation then thresholds the image at the level of the mean plus 3 x the sample deviation. A connectivity algorithm is used to associate all pixels above the threshold into connected, star-like objects and compute the centroid, moments, and intensity of each object. The centroids are converted into RA and DEC. The information on all objects found in the image is stored in a table on the hard disk along with the image. If the image is a repeat of a previously imaged star-field, the program compares the absolute positions of the objects with those of the previous image searching for objects that have apparently moved. These objects are flagged and a notification is sent over the network to the host computer for further action such as scheduling follow-up observations that night.

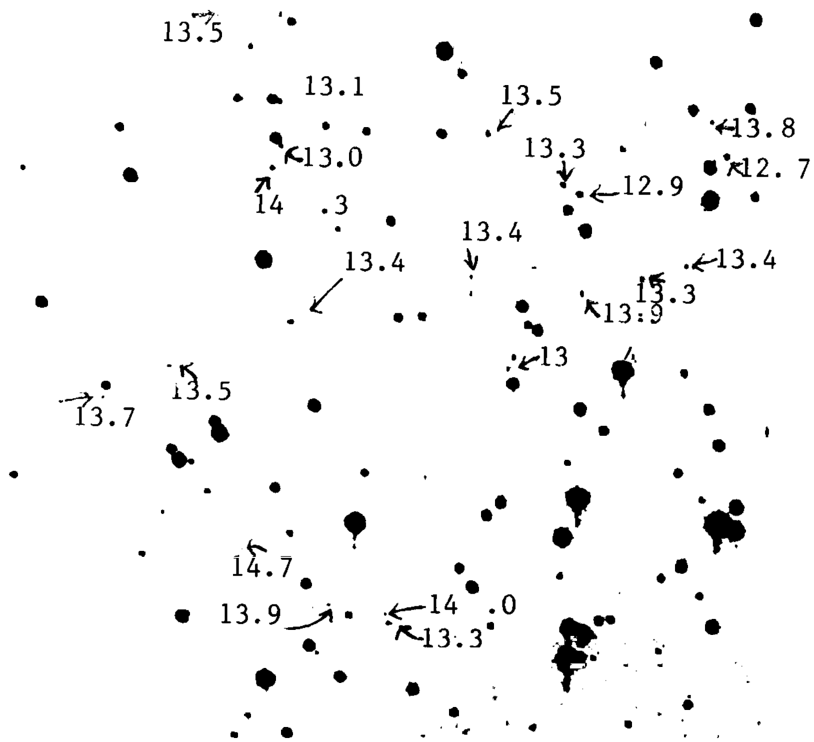


Figure 3. Highly magnified portions of imagery near M44 taken by prototype FOCSE camera utilizing the 330 mm focal length f/3.3 Tele Vue lens and Loral 2048 x 2048 pixel CCD imager. The field of view of the 256 x 256 pixel partial image reproduced here is 0.64 degrees. The magnitudes of stars identified in the Guide Star catalogue are marked.

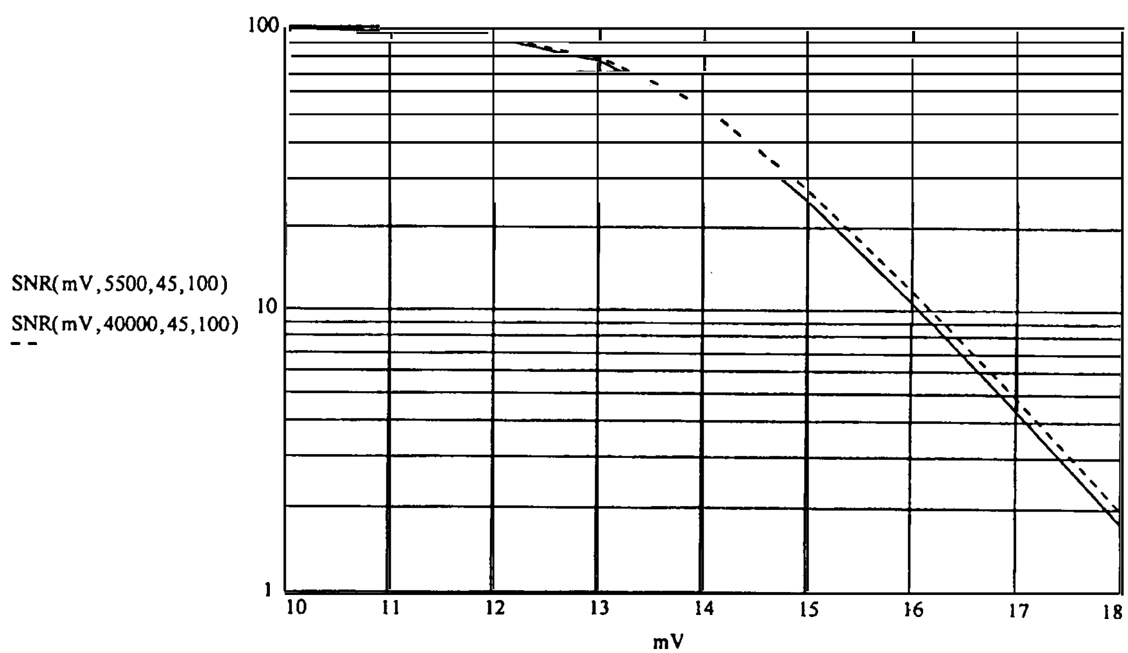


Figure 4. Signal-to-Noise Ratio Versus Visual Magnitude for 100 s Integration of 5,800 K Source.

When the 100 second integration time has passed, the image acquisition computer transfers the image to its memory for subsequent analysis.

The software running on the host computer (SPARC 10) initializes the system, checks the weather, and opens the clam-shell. It positions the Epoch mount for each star-field and signals the image acquisition computers to begin imagery or re-imagery. When the observations are complete for the night, the host computer closes the clam-shell and begins archiving the imagery and tables stored on the image acquisition disks. The tabular and image data are stored on a 17 GByte tape archival system.

The host also maintains a database of all objects found. The database is indexed by the RA and DEC of all objects found by the image acquisition computers. The host takes the entries from the image acquisition computer and associates them with previous entries according to their positions. New objects, or objects that have moved are flagged.

There is a lot of flexibility on how the host responds to moving objects identified by the data acquisition system. We envision that initially, frames containing moving objects will be examined by physicists for identification. Later, as we become more confidant in our system, the host may send coordinates of suspicious objects to other instruments over the internet. The host could also schedule additional observations of suspect star-fields automatically.

Long term analysis at LLNL involves looking through the host object table for interesting objects that have changed their characteristics.

Site

We have chosen the Anderson Mesa complex at Lowell Observatory as the site for the FOCSE system. The site has good seeing, and a large flat field that can accommodate observations down to within 20 degrees of the horizon. The site offers room for future construction of additional FOCSE telescopes to improve throughput.

Summary

We have shown that a dedicated 2x2 array of small telescopes can be used to search for long period comets in high inclination orbits. The systems makes maximum use of low cost commercially available components resulting in a system that can become operational on time scales of one year.

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Infrared Detection and Characterization of Near Earth Objects

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Infrared detection from space offers an invaluable adjunct to the ground based visible searches for the discovery and characterization of Near Earth Objects (NEOs). An infrared NEO survey compensates for the bias of visible searches to preferentially discover high albedo objects. Additionally, visual to infrared spectral signatures of NEOs are markedly different from those of the large majority of stars. This provides the basis for a bulk filter that significantly reduces the onboard signal processing required for target acquisition and track. Infrared observations reduce the uncertainty in estimating the size, and subsequently the mass, of an NEO. A geometric albedo must be assumed in order to calculate a diameter from the single band visual photometry obtained during discovery or follow-up astrometry. The estimated size is thus quite uncertain owing to the factor of 20 range in NEO geometric albedos. The modeling assumptions needed to convert an infrared observation into a diameter are more tightly constrained. An infrared observation combined with visual photometry provides the requisite information to accurately determine both the albedo and size. Since the estimate of the NEO mass depends on volume, the determinations of NEO mass from infrared derived diameters are about an order of magnitude more certain than estimates from visual photometry.

Introduction

Passive thermal emission from objects located in the inner solar system peaks in the mid-infrared (defined to be between 5 and 35 μm). This is the natural consequence of the object being in thermal equilibrium with the incident sunlight. Objects of low reflectivity, or geometric albedo, which makes them difficult to detect in the visible, absorb most of the incident sunlight. The resulting characteristic temperature and the high infrared emissivity of an NEO produces a spectral energy distribution that peaks in the mid-infrared. The three idealized models commonly used to describe the thermal emission from an airless body are discussed below. Each of these models produces the subtle effect that the emission is either independent of phase or the phase function falls off much less steeply than the visual. This means that detecting NEOs at large phase angles in the infrared has inherent advantages over visual surveys.

The apparent magnitude of an NEO is a function of the brightness of the sun, its heliocentric distance, the Earth - NEO distance, the size of the object and its reflectance properties through the albedo and phase. Orbital parameters provide accurate distances and the phase curve can be measured or reasonably assumed. That leaves the geometric albedo coupled with the projected area as the remaining unknowns. The geometric albedo and the size of the object can be accurately uncoupled using visual and infrared observations.

NEO brightness parameters

Near Earth Asteroids (NEAs) and comets have a wide range of physical characteristics, the most important of which (for the present discussion) are the reflectivity and thermal properties. We provide detailed background to support our choice of parameters in estimating the detection thresholds.

Albedo

Veeder and Tedesco (1992) have determined geometric albedos for small (diameter less than 40 km) main belt asteroids from radiometric observations. Based on this albedo distribution and the assumption that the NEAs originate in the main asteroid belt, we infer that the distribution of NEA geometric albedos has a broad peak between 0.04 and 0.2

with a long tail to the high reflectivity and some objects with an albedo as low as 0.02.

Wetherill (1988) calculated that enough asteroidal fragments from collisions in the asteroid belt interior to 2.6 AU "... are perturbed into Earth crossing orbits as a consequence of the 3:1 Jovian commensurability resonance at 2.5 AU and the ν_6 secular resonance in the innermost asteroid belt" to account for the currently estimated number of NEAs. Roughly 20-25% of the NEAs come from the inner asteroid belt near 2 AU with the remainder from the center of the belt. Tedesco and Gradie (1987) point out that NEAs also could originate near the 5:2 commensurability resonance further out at 2.8 AU. Indeed, Shoemaker et al. (1990) identified 7 of the 90 or so Earth crossing objects with Jovian commensurabilities, one at 4:1 (near the ν_6 resonance at 2 AU) 3 each at the 3:1 and 5:2 commensurabilities. Wetherill (1988) also raised the possibility that a significant minority of NEOs could be devolatilized (short period) comets.

Tedesco and Gradie (1987) corrected the visual bias for NEAs with C and S class taxons and concluded that the resulting numerical ratio was more nearly what is found in the asteroid belt near 3:1 and 5:2 commensurabilities than at the inner boundary at the 4:1 commensurability which is dominated by the high albedo E class (Gradie & Tedesco, 1982). Luu and Jewett (1989) modeled the discovery bias of NEA's using Monte Carlo techniques and found that the factor of 5 to 6 bias against discovering low albedo objects was large enough to account for the observed overabundance of bright albedo asteroids. They concluded that the C class asteroids with a mean geometric albedo of ~0.05 should be about as populous among the NEAs as the more reflective S class (mean geometric albedo of 0.2). However, Wetherill (1988) predicts an enhancement of high albedo ($p > 0.3$) E class NEAs originating at the 2 AU resonance. On the other hand, devolatilized comets among NEOs have low albedos ($p \sim 0.05$) and augment the dark population. Following what is universally assumed in the literature, we adopt the mean albedos for the C and S classes to do comparisons.

The energy balance giving rise to the infrared flux requires an estimate of the bolometric Bond albedo. The Bond albedo, A, is the product of the phase integral, q, and the visual geometric albedo, p_v, ($A = qp_v$). q is obtained by integrating over the IAU adopted visual phase function and is given by the simple expression $q = 0.29 + 0.684*G$ (Bowell, et al., 1989). Values of G range from 0 to 0.5 but, in the absence of a measured value, 0.15 is used. Thus, q ranges from .3 to .6 with 0.39 being the default value. More specifically, low albedo asteroids ($p_v \sim 0.05$, C class for example) have a mean value of G of about 0.12, moderate albedo asteroids ($p_v \sim 0.2$, S class for example) have a mean of about 0.25 and high albedo asteroids ($p_v \sim 0.45$, the E class dominant at 2 AU for example) have $\langle G \rangle \sim 0.4$. This corresponds to mean Bond albedos of 0.02, 0.09 and 0.25. In lieu of any information on the matter, the bolometric Bond albedo is assumed to be equal to the Bond albedo herein defined.

Apparent visual magnitude and energy distribution

Jewett and Luu (1989) provide a formula for the apparent visual magnitude of an asteroid:

$$m_v = m_v(sun) - 2.5\log\left(\frac{p[D/2]^2 f}{2.24x10^{16} R^2 \Delta^2}\right) \tag{1}$$

where $m_V(sun) = -26.74$ is the apparent solar visual magnitude, p is the geometric albedo, D is the asteroid diameter and f is the simpler version of the Lumme-Bowell-Harris phase function (Bowell et al., 1989):

$$f = 0.85e^{-3.33\left(\tan\frac{\alpha}{2}\right)^{0.63}} + .15e^{-1.87\left(\tan\frac{\alpha}{2}\right)^{1.22}} \tag{2}$$

Bowell et al. (1989) found that this phase function is valid to at least 120°.

The visual flux is obtained from the zero point flux of $3.72x10^{-12}$ W cm^{-2} μm^{-1}. The solar spectrum is approximated by a 5800 K blackbody.

$$H(\lambda) = \frac{BB(\lambda, 5800K)}{BB(0.55\mu m, 5800K)} * 3.72x10^{-12} 10^{-0.4m_V} \tag{3}$$

Infrared Spectrum

A number of thermal models have been developed to account for the infrared radiometry. The models assume that the object is spherical and, if the body rotates at all, the object's equator is in the Sun-Earth-asteroid plane (unless the pole of rotation is known). The characteristic temperature of the emission is determined by the energy balance that requires the absorbed energy to be equal to that radiated. There are three idealized models that are used to account for the thermal emission of an airless body in space:

1) The "standard" thermal model (Lebofsky and Spencer, 1989) is widely adopted, at least for main belt asteroids. This model assumes that the surface is in instantaneous equilibrium with the solar insolation. The model applies to the situation where the surface temperature equilibrates to changes in a time much shorter than the rotation period. Thus, the object may not be rotating, is rotating very slowly or has a surface of low thermal conductivity. The temperature distribution varies as $T_{SS} \cos^{1/4} \theta$, where T_{SS} is the subsolar temperature and θ is the angle between the subsolar point and the point in question as measured from the center of the body (the temperature is zero for $\theta \geq \pi/2$)

2) The isothermal constant latitude model has been found to be more representative of a few Earth crossing asteroids. (Lebofsky et al.; 1978, 1979). In this model, the surface is assumed either to have high thermal inertia and/or the object is rotating rapidly. The result is a temperature that is constant along a given latitude. The temperature profile is maximum, with T_M, in the equatorial plane and decreases with latitude as $T_M \cos^{1/4}\phi$.

3) A highly conductive body such that the entire surface is at a single temperature. This applies to no known asteroids but is often used to approximate the infrared emission from man made objects orbiting the Earth. This model underestimates the infrared flux from NEO's.

Each model has a characteristic temperature which is given by:

$$T = \left[\frac{(1-A)W}{g\epsilon\sigma R^2}\right]^{1/4} \tag{4}$$

where:

$T = T_{SS}$, the subsolar point temperature for the standard model
$T = T_M$, the maximum (equatorial) temperature for the isothermal latitude model
$T = T_C$, the constant temperature model
A is the Bond albedo (0.019 for C types, 0.09 for S types and 0.25 for highly reflective asteroids)
W/R^2 is the solar flux at the distance of the asteroid (R); W is the solar constant (.1373 W cm^{-2})
σ is the Stefan-Boltzmann constant (5.6698×10^{-12} $Wcm^{-2}K^{-4}$)
g is a geometric parameter which
= η (0.756) the beaming factor in the standard model
= π for the isothermal latitude model
= 4 for the constant temperature model
ϵ = the infrared emissivity (0.9)

The geometry for the standard model requires g be equal to one. However, the radiation from craters is preferentially scattered in the sunward direction (Spencer, 1990) and while the model assumes it is too cold to do so, emission from the dark side of the asteroid contributes to the infrared flux. These effects are accounted for by a beaming factor η which modifies the surface temperatures by $1/\eta^{1/4}$ and an empirical phase function of ~0.01 mag/deg. The infrared emission from an asteroid of diameter, D, heliocentric distance, R, and distance from the Earth, Δ, is given by:

$$H(\lambda, D, \Delta) = \frac{\pi D^2}{4 * 2.24x10^{16} \Delta^2} \epsilon \overline{BB(\lambda)}$$

$$\overline{BB(\lambda)} = \int_0^{\pi/2} BB(\lambda, T_{SS}\cos^{1/4}\theta)\ 2\sin\theta\cos\theta\ d\theta \quad \textit{standard model} \tag{5}$$

$$= \int_0^{\pi/2} BB(\lambda, T_M\cos^{1/4}\phi)\ 2\cos\phi\ d\phi \quad \textit{isothermal constant latitude model}$$

$$= BB(\lambda, T_c) \quad \textit{isothermal model}$$

To a good approximation, the infrared magnitude is given by:

$$m_{ir} \approx -2.5 \log H(\lambda, \Delta, R) - 30.25 - 9.5 \log \lambda \tag{6}$$

The isothermal constant latitude model is phase independent as is the isothermal case. Significantly, the infrared phase function falls off less steeply with phase angle than the visual function given in Equation (2).

Influence of asteroid parameters on flux

It is obvious from Equation (1) that the visual flux is directly proportional to albedo. All other parameters being equal, a C class asteroid is about 4 times (1.5 mag.) fainter than an S class. There is a second order effect in that C class asteroids have neutral optical colors, that is, the reflectivity is independent of wavelength, while S class asteroids have reddish colors. The long recognized consequence is that, if C and S class asteroids are equally numerous, any magnitude limited visual survey of NEOs will be strongly biased against detecting the low reflectivity objects.

Because the characteristic temperature varies as the one-fourth power of the absorptive, emissive and geometric properties of the object in Equation (4), these factors influence the temperature weakly. There is only a 6% difference in the characteristic temperature in a given model between the darkest (C's) and most reflective (E's) classes of asteroids. There is only a 6% difference in T between the isothermal model and the isothermal latitude model arising from the respective values of the geometric parameter, g. The sub-solar temperature for the standard model is some 40-45% higher than the other models. The characteristic model temperature has a somewhat stronger dependence on heliocentric distance, $T \propto R^{-1/2}$.

The infrared flux is given by the nonlinear blackbody function of temperature and wavelength. The flux is very sensitive to temperature on the Wien side of the blackbody peak. Such is the situation in the mid-infrared for objects in the main belt (Apollo and Amors at aphelia). Here, there are significant differences between the fluxes predicted by the standard and isothermal latitude models. Marsden (private communication) proposes that a good NEO survey strategy would be to observe the NEOs at aphelia, when they are moving slowly with small phase angles. Figure 1 shows the spectral energy distributions for C type asteroids 1 km in diameter at opposition 2 and 2.9 AU from the Sun, the region encompassing the Jovian commensurabilities from which the NEOs originate. The upper curve to each energy distribution is from the standard model while the lower is from the isothermal constant latitude model. Also, shown are the 10th and 20th magnitude curves. The infrared flux from the standard thermal model is about the same as the visual flux with the consequent $m_v - m_{ir} > 10$ to 11. The visual flux would be 4 times (1.5 mag.) greater for an S class asteroid but the decrease in infrared flux would be barely distinguishable in the Figure.

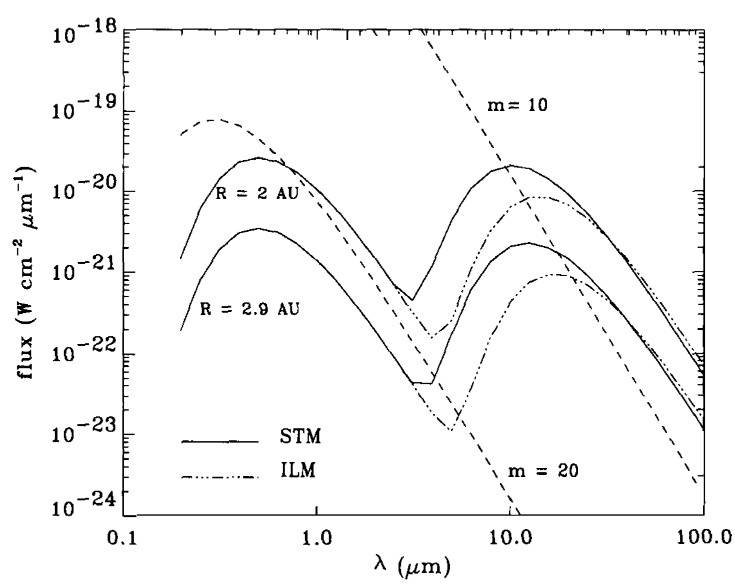

Figure 1 Spectra measured at Earth from 1 km diameter C class asteroids 2 AU and 2.9 AU from the sun. STM refers to the "standard" thermal model of Lebofsky and Spencer (1989). ILM refers to the isothermal constant latitude model. 10th and 20th magnitude curves are plotted for comparison.

If the temperature is high enough and/or the wavelength long enough, the blackbody function approximates the

Rayleigh-Jeans energy distribution which is proportional to temperature. There is not much difference in the fluxes predicted by the different thermal models. This is the situation in the mid-infrared for NEOs interior to the Earth's orbit. Interior to the Earth's orbit the phase function becomes significant. To demonstrate this we examine the scenario posed by Hills and Leonard (1995). Figure 2 shows the apparent brightness of a 100 m object, 10 days from impact with the Earth and traveling at a relative speed of 10 km/sec. Since the stated objective of Hills and Leonard was to detect "most" objects we use a C class geometric albedo of 0.05 for the visual fluxes and the E class bolometric bond albedo of 0.25 for the thermal model. Figure 2 does, indeed, confirm the Hills and Leonard observation that the infrared is better at detecting NEOs at large phase angles (small solar elongations). The fluxes predicted using the standard thermal model and the isothermal constant latitude model are roughly a factor of two higher than that from the isothermal (conductive) model used by Hills and Leonard.

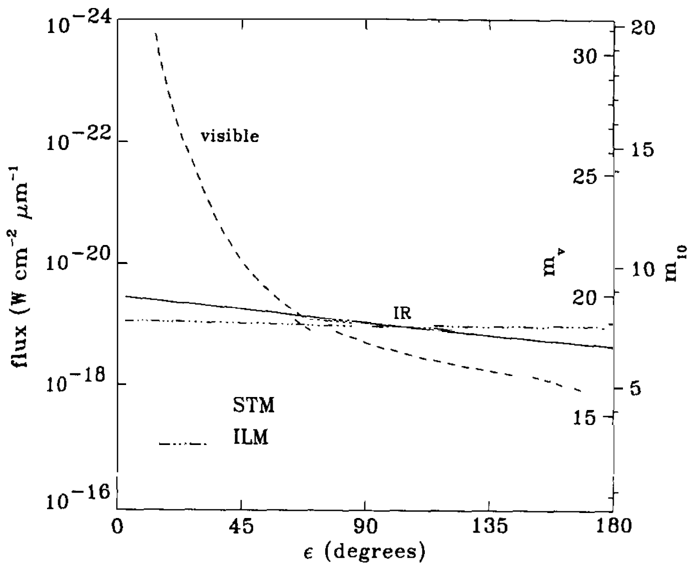

Figure 2 Brightness of a 0.1 km diameter asteroid as a function of solar elongation angle. The visible (0.55 μm) curve assumes C class albedo, while the IR (10.6 μm) curves assume E class. The right hand y-axis is scaled for visual and IR apparent magnitude.

The main points in this section are:

- The majority of Near Earth Objects likely originate in the main asteroid belt. Their taxonomies, reflective and absorptive properties should reflect that of their origins. Therefore, a large number, if not the majority, of objects will be of low reflectivity.
- The large proportion of highly reflective asteroids among the known NEOs is due to a discovery bias that visual surveys have against dark objects. This bias has been estimated at 5:1. One must use a geometric albedo representative of the low reflectivity objects in estimating the visual survey performance required to detect the majority of objects down to a given size.
- The visual phase function is steep for phase angles greater than 90°, making visual searches difficult interior to the Earth's orbit.
- In the infrared, the assumed or adopted parameters have a weak influence on the mid-infrared flux. An infrared survey will be only slightly biased against the minority of objects whose observed mid-infrared flux is consistent more with the isothermal constant latitude model than the standard model. An infrared survey is invaluable in compensating for the low reflectivity bias of ground based visual searches.
- The infrared phase function is nonexistent or weak compared to that in the visual. An infrared survey would be advantageous in discovering objects at large phase angles.

The Infrared Advantage

Background

Infrared observations from the ground must be made through the atmosphere. Atmospheric absorption limits the observations to "window" regions. Emission from both the atmosphere and telescope create a photon noise which is the ultimate limit to the performance of an infrared detection system. Variations in the atmospheric emission and absorption can produce a much larger "sky noise." These sources of noise are reduced by using small instantaneous fields of view and, in some cases, beam switching. Beam switching consists of alternatively viewing two adjacent areas of sky, one containing the field of interest, the other a blank field. Differencing the two fields cancels out the variations in atmospheric emission which is correlated. The closer the two fields the higher the correlation. Small instantaneous fields of view and the current limits to focal plane device format (256x256 pixels) make ground based, large area infrared searches for NEOs impossible.

A space-based system does away with atmospheric problems. Furthermore, the vacuum of space permits the optical system and focal planes to be cooled to a temperature where self emission is no longer a limiting factor. Price (1988) provides a historical review of surveys including the space-based efforts up to and including the Infrared Astronomical Satellite (IRAS). The first space based mid-infrared detections of asteroids were made during the AFGL probe rocket survey; LeVan and Price(1984) published information on the subset of asteroids for which far infrared observations were obtained. By far the largest mid-infrared asteroid survey is "The IRAS Minor Planet Survey' (Tedesco, 1992) which contains measurements on more than 2,000 asteroids. While the IRAS survey strategy provided for revisiting an area of sky within hours after it was surveyed and, therefore, could detect object motion, it did not have the continuous revisits necessary for identification and track. Thus, IRAS requires that the asteroid have a known, reliable orbit in order to identify it by means of a position match. The IRAS Minor Planet Survey has about a 10-15% efficiency in detecting the higher numbered asteroids (Tedesco, et al., 1992). Thus, an additional 300 or so detections lurk in the IRAS data based on the increase in the numbered minor planets since mid-1991 when the known minor planet input catalog was frozen for the IRAS Minor Planet Survey.

Currently, there are three major infrared experiments either manifested for flight or being constructed. The Infrared Space Observatory (ISO) is an observatory class experiment with small (3 arcmin) fields of view designed to obtain spectroscopy, photometry and small area imagery. The optical system has a 0.6 m primary aperture and super-critical helium for an 18-month lifetime. The Wide-field Infrared Experiment (WIRE) is a NASA sponsored "MIDEX" program designed to obtain very sensitive imagery over a few tens of square degrees in two mid-infrared spectral bands during a 4-month mission. WIRE has a 0.3 m optical system with two128x128 arrays with diffraction sized pixels. The SPIRIT III instrument on the Midcourse Space Experiment (MSX) has a one-third meter unobscured optical system cooled with solid hydrogen (Mill et al., 1994). MSX has several experiments planned to survey several hundred square degrees with the line scanned arrays.

Feasibility

The Space Infrared Telescope Facility (SIRTF) is a meter class instrument which is currently supporting technology development in all areas of space based infrared technology (Werner and Bothwell, 1993). Edison (Thronson, private communication) is a design concept for a 1.7 meter instrument which makes full use of passive, or radiative, cooling for an extended lifetime.

Thus, given the technology both demonstrated and in hand, most of the hardware capability for a space based infrared survey for Near Earth Objects is extant. In the near future, more sensitive focal planes will be developed as will sophisticated hybrid (active plus passive) cooling for an extended lifetime. We estimate the following reasonable physical characteristics of such a system.

Sensitivity and spatial resolution drive us to a large optical system. A one meter telescope is well within current technology. Furthermore, we select an unobscured aperture not only for the clear collecting area but for the superior off-axis rejection when operating at relatively small angles to a bright source, the Sun or Moon for example. We propose two mid-infrared spectral bands, 6-14μm and 17-25μm. A third visual CCD provides visual - infrared color discrimination between stars and NEOs. The optics should be diffraction limited at 12 μm with the pixels sized to 2.44*(12 μm)/1 m, i.e., 6".

Focal plane manufacturers list current device capability as < 150 noise electrons at a 10 Hz sampling rate. The noise electrons per second is given by:

$$N_e = \frac{e_n}{t_s} \quad \frac{\textit{noise electrons/sample}}{\textit{seconds/sample}} \tag{7}$$

To get the equivalent photon flux, this expression has to be divided by the quantum yield, the efficiency of the detector in converting photons to electrons. This quantity is usually taken as a constant, 0.9. The efficiency is actually a function of wavelength, $\eta(\lambda)$ [note the η parameter is redefined] and is the factor that causes the relative response curve to depart from the ideal λ/λ_p variation. The number of photons per second equivalent to the noise electrons in Equation (7) is

$$N_{ph} = \frac{e_n}{t_s\eta(\lambda)} \quad \textit{photons/sec.} \tag{8}$$

The equivalent total power in the noise is $N_{ph}h\nu$ and

$$NEP = N_{ph}h\nu = \frac{e_n}{t_s\eta(\lambda)}\frac{hc}{\lambda} \quad \textit{watts} \tag{9}$$

Normalizing to λ_p:

$$NEP = \frac{e_n}{t_s\eta(\lambda_p)}\frac{hc}{\lambda_p}\left[\frac{\eta(\lambda_p)}{\eta(\lambda)}\frac{\lambda_p}{\lambda}\right] \tag{10}$$

The inverse of the quantity in brackets is the relative response of the detector, designated R_D. Note that since R_D is a function of wavelength the NEP is an inverse function of wavelength. A peak wavelength of 23 µm is representative for Si:As BIB detectors. The peak wavelength corresponds to the energy between the valence and conduction bands in this material. Longer wavelength response arises from impurity energy levels lying above the valence band.

Assuming the rather modest device improvement in the near future will produce readout noise of 100 noise electrons for a 10 msec sample interval, the NEP becomes:

$$\begin{aligned} NEP &= \frac{100 \quad 2x10^{-19}}{0.01 \cdot 0.9 \quad 23} R_D^{-1} \quad \textit{watt} \\ &= 10^{-16} \; R_D^{-1} \quad \textit{watts} \end{aligned} \tag{11}$$

The noise equivalent flux density (NEFD) at wavelength, λ, is the NEP given in Equation (11) divided by the effective collecting area:

$$NEFD = \frac{NEP}{A_c\tau_M\tau_f\tau_e} \quad W\ cm^{-2} \tag{12}$$

where:

A_c = 7854 cm^2 and is the collecting area of an unobscured 1 meter optical system.

τ_M = the total reflectivity of the mirrors in the optical system

τ_f = the transmission of the filter and dichroic.

τ_e = the energy from the point response function encompassed by a pixel.

The spectral NEFD is obtained by dividing Equation (12) by the response weighted spectral bandwidth

$$NEFD = \frac{4}{\pi \cdot 10^4} \frac{10^{-16}}{\int_{\lambda_1}^{\lambda_2} \tau_M \tau_f \tau_e R_D \, d\lambda} = \frac{1.3x10^{-20}}{\int_{\lambda_1}^{\lambda_2} \tau_M \tau_f \tau_e R_D \, d\lambda} \; W \; cm^{-2} \; \mu m^{-1} \qquad (13)$$

For nominal values for the τ 's, the response weighted bandwidth (the integral in the denominator) and equal intensity effective wavelength are about 2.2 μm and 10.5 μm, respectively, for the 6-14 μm spectral band and about 5 μm and 21 μm, respectively, for the 17-25 μm band. The single sample sensitivities are, therefore, $6x10^{-21}$ and $2x10^{-21}$ W cm^{-2} μm^{-1} at 10.5 and 21 μm, respectively.

The focal planes baselined for the sensor are line scanned arrays with eight columns in the scan direction, four on either side of a half pixel offset. On board signal processing will use a matched filter tuned to the nominal point response to eliminate low frequency background (*e.g.* zodiacal emission) and increase the signal to noise. With a 4 samples per pixel scan rate the "visibility" of the tuned filter and the time delay and integrate of the 4 in line pixels increases the point source detection sensitivity by a factor of 4.4. We adopt a signal to noise threshold of 6 for detection, a common value used for infrared systems. The detection threshold for our system is, therefore, $8x10^{-21}$ and $3x10^{-21}$ W cm^{-2} μm^{-1} at 10.5 and 21 μm, respectively. (These fluxes correspond to the respective infrared magnitudes of ~10.5 and ~7.)

We see, from Figure 1, that the system can easily detect the 1 km diameter asteroid at 2 AU. At 2.9 AU the system would be limited to detecting objects with diameters greater than 2.5 km. The system would have no problem detecting the 100 m object in the scenario given in Figure 2.

Summary

The known Near Earth Objects are predominately highly reflective. There is a discovery bias inherent in visual surveys against dark objects. For a given size, the dark objects are at least a factor of four fainter in the visual than those with high albedo. Various analyses argue that the population of dark objects among the NEOs should be at least as great as the highly reflective objects. The difference in the infrared fluxes from high and low albedo objects is relatively small, with slightly more flux coming from the dark object. A 1 m class space based infrared NEO surveillance capability is within the current state-of-the-art technology. Such a system would be an invaluable adjunct to the ground based visual survey to compensate for the bias against the smaller, dark objects and to monitor the region at relatively small solar elongations.

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Interdiction

Plenary Session

NEO Dynamical Properties, Orbit Determination, and Impact Prediction

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I will describe the geography of the asteroid and comet regions, together with the flux of near-Earth objects (NEOs) crossing the orbit of the Earth. Because the discovery rate and flux of Earth-crossing asteroids (ECAs) is about an order of magnitude larger than that of Earth-crossing comets (ECCs), it is the former objects that predominate in orbit determination and hazard evaluation. Newtonian or relativistic force models accurately explain the motions of ECAs, but some comets exhibit activity due to vaporizing ices that requires the use of nongravitational forces to model their observed motions.

Orbit determination begins at the moment of discovery, and orbits are refined as the observational arc lengthens. Most NEOs are discovered by virtue of their unusual sky-plane motion. Apparent magnitude and sky-plane motion provide a very rough measure of an ECA's size and distance; then parallax—even on the discovery night—can be used to certify nearby objects. As a rough rule, and when only optical astrometry is available, the accuracy of orbital elements—and hence of positional prediction—increases as the square or cube of the orbital arc length. Radar delay-Doppler measurements, hitherto available only for close Earth approachers, can improve ephemeris prediction by several orders of magnitude. For an orbit that is uncertain on the timescale of a century, a useful measure of an NEO's potential hazard to Earth is the minimum orbital intersection distance (MOID) between the NEO and the Earth and other planets. MOID is thus a measure of the closest possible planetary approach of an NEO that is not in resonant motion. Empirically, I have found that NEOs (excluding long-period and some other comets) having $MOID_{Earth} < 0.05$ AU should be regarded as potentially hazardous because MOID can change, due to planetary perturbations, by a few hundredths of an AU per century. Most NEOs for which $MOID_{Jupiter} < 1$ AU are likewise potentially hazardous. Typically (depending on discovery circumstances), $MOID_{Earth}$ and its evolution over a century can be reasonably well determined for an ECA only 10 days after discovery, thereby providing a powerful filter for discriminating NEOs requiring follow-up on the basis of their potential hazard.

Accurate long-term ephemeris and Earth-approach predictions can only be made when multi-apparition orbits are available. For ECAs and some ECCs observed at several apparitions, one can generally predict Earth approaches several centuries hence. Exceptions are asteroids like (2340) Hathor, that make close planetary approaches (during which they are gravitationally scattered) on timescales of decades, long-period comets and comets exhibiting nongravitational motions, all of which require frequent monitoring. An NEO's Earth-impact probability can be estimated on the basis of the Bayesian *a posteriori* probability density, from the six-dimensional integral of the (stochastic) orbit for the time interval of interest by using, for example, Monte Carlo modeling. The Earth-impact probability, together with the kinetic energy of impact, can then be used to derive a value of the so-called NEO hazard index, an easily understood parametrization that is being designed for public dissemination.

Physical and Chemical Properties of NEOs

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The physical and chemical consequences of comet and asteroid impacts are strongly dependent on the physical state, chemical composition, and entry conditions of the impacting body. Knowledge of the physical properties of asteroidal material is nearly nonexistent, being limited to radar data showing the duplicity of a handful of NEAs, imaging of two Belt asteroids by *Galileo* on its way to Jupiter, and thermal data that generally requires the presence of regolith on large Belt asteroids. The densities, porosities, and crushing strengths of a number of individual meteorites from several different compositional classes have been measured in the laboratory, and crude extrapolations of the crushing strength from measurements made on specimens the scale of a kilogram can be done using a Weibull strength law. Cometary material probably exhibits at least three different strengths, associated with the surface lag deposit of fluffy dust (weak cometary meteors), gravitational bonding of large structural blocks (near-zero physical "welding" strength), and crushing of these massive permafrost blocks (strengths comparable to sedimentary rocks). Our lack of first-hand evidence regarding the structures and strengths of small asteroids and comets is a serious limitation on our ability to model entry or interdiction behavior.

The chemical composition of the impacting body is important in several respects. On Earth, the sulfur content of the impactor is highest for those bodies that fragment most readily at high altitudes, the carbonaceous chondrites. Massive injection of sulfur occurs at high altitudes, where formation of sulfur dioxide and oxidation to sulfuric acid are critically important. Sulfate aerosols generated in the stratosphere may have devastating short-term climatic effects which would be devastating to agriculture for a few weeks, but which would not be capable of producing a global extinction signature that would be discernible in the paleontological record. Massive sulfur injection represents a selective threat to civilization, not to species diversity. Co-injection of water along with sulfur help in the rapid formation of massive sulfuric acid aerosols. Injection of platinum-group metals is already recognized as an important (albeit highly variable and over-rated) marker of large impacts. On other planets, injection of water and other volatiles may be the most important chemical effect, pointing to possible influence of cometary impacts on the early biosphere of Earth.

The interaction of orbital parameters, entry velocity, entry angel, size-dependent crushing strength, and chemical composition governs the deposition profiles of energy, momentum, mass, and sulfur in the terrestrial atmosphere. Monte Carlo simulations are uniquely suited to modeling these multidimensional interactions.

Space Protection of the Earth: Concepts and Approaches to the Development

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A set of general demands to a system for Space Protection of the Earth (SPE) with wide opportunities is presented. It includes categorization of near-Earth objects (NEO) on lead time, type of NEO's orbits, angles and velocities of approach, NEO's shape and overall properties, constituent matter properties etc. The possible structure of the SPE system on the base of existed and near-future technologies is discussed.

Depending on quantitative values of main defining parameters of threatened impact, NEO's orbital movement and internal properties, demands for means of action upon assailant object are discussed. For the most probable methods of action (kinetic projectiles and nuclear explosions, it is presented and analyzed possible regimes of applications. The essential aspects for future studies of these regimes, possible results and their consequences for the Earth and space environment are illuminated.

It is discussed the demands for the launch and ejection subsystems, for delivery, guidance and terminal navigation components. Main attention is devoted to desirable directions for modern and near-future experimental and theoretical research. There are among them overall and matter properties of NEOs, physical and mechanical processes for various regimes of action upon them, more reliable description of consequences of deflecting or shattering actions.

Possible experimental programs for direct study of NEO's properties as a whole is presented. It is advisable to have a conceptual outline of the SPE system, based on the existed technologies, to invest into separate segments of the SPE be near-future technologies development, to correct the SPE subsequently according to this development, and to implement an active space experimental program of NEO's research. This program will provide additional testing of the SPE perspective segments and their interaction.

Essential attention ought to be devoted to social, political and educational aspects to detection and forecast of NEO's threat and to balanced approaches to the SPE system development. It becomes expedient to develop an international coordination of efforts on NEO's threat forecast and the SPE conceptual development. This collaboration will provide more efficient use of limited scientific and technical resources.

Interception and Disruption

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Given sufficient warning we might try to avert a collision with a comet or asteroid by using beamed energy or by using the kinetic energy of an interceptor rocket. If motivated by the opportunity to convert the object into a space asset, perhaps a microgravity mine for construction materials or spacecraft fuels, we might try a rendezvous to implant a propulsion system of some sort. But the most cost-effective means of disruption (deflection or pulverization) is a nuclear explosive. In this paper, I discuss optimal tactics for terminal intercept, which can be extended to remote-interdiction scenarios as well. I show that the optimal mass ratio of an interceptor rocket carrying a nuclear explosive depends mainly on the ratio of the exhaust velocity to the assailant-object closing velocity. I compare the effectiveness of (1) stand-off detonation, (2) surface burst, and (3) penetration, for both deflection and pulverization, concluding that a penetrator has no clear advantage over a surface-burst device for deflection, but is a distinctly more capable pulverizer. The advantage of a stand-off device is to distribute the impulse more evenly over the surface of the object and to prevent fracture, an event which would greatly complicate the intercept problem. Finally, I present some results of a model for gravitationally bound objects and obtain the maximum non-fracturing deflection speed for a variety of object sizes and structures. For a single engagement, I conclude that the non-fracturing deflection speed obtainable with a stand-off device is about four times the speed obtainable with a surface-burst device. Furthermore, the non-fracturing deflection speed is somewhat dependent on the number of competent components of the object, the speed for a 13 component object being about twice that for a 135 component object. Generalizations indicate: (1) asteroids more than 3 km in diameter can be most efficiently deflected with a surface burst; (2) asteroids as small as $\frac{1}{2}$ km can be effectively deflected with a stand-off device; (3) smaller asteroids are best pulverized.

Introduction

Many schemes have been devised to deflect or pulverize comets and asteroids bent on colliding with our fair planet (Canavan and Solem, 1992; Canavan and Solem, 1993; Canavan *et al.*, 1994; Ahrens and Harris, 1994; (Simonenko *et al.*, 1994). Reaction devices have been proposed that require landing on the object quite some time before the impending collision and setting up a rather elaborate propulsion power plant. These include very-low-specific-impulse devices such as mass drivers (O' Neill, 1977), which are essentially electromagnetic bucket brigades that scoop up material from the object and expel it into space with physics reminiscent of a conveyor belt. They also include high-specific-impulse devices such as nuclear-reactor rocket engines that use volatiles from the object as a propellant (Willoughby, 1994). Albeit with exceedingly low thrust, solar sails (Friedman, 1988; Wright, 1992; Melosh *et al.*, 1994) have also been proposed to gently drag the threatening object off its course. Beamed energy has been suggested in the form of high-power laser or microwave sources to heat and blow-off material from the object's surface, thereby providing a high-specific-impulse rocket with a remote power source. Solar collectors have been designed to focus the sun's radiation onto the object and thereby produce a modest vapor blow-off during a protracted encounter (Melosh *et al.*, 1994), producing a gradual acceleration and deflection. Kinetic energy devices seem quite viable for both deflection and pulverization, (Solem, 1993a; Solem, 1993b; Solem, 1993c; Solem, 1994a; Solem, 1994b; Melosh *et al.*, 1994) because of the enormous energies involved in orbital collisions.

Exploration of the myriad alternatives is a wonderful stimulus to the imagination and makes an for an excellent set of exercises for undergraduates. I mean this only in a positive sense. In 1967, remarkably a dozen years before Alvarez's pronouncement on the cause of the Cretacious-Tertiary extinction, and inter-departmental student project at the Massachusetts Institute of Technology was addressed to intercepting a hypothetical collision with a one-kilometer asteroid, *Icarus* (Kleiman, 1968). The students solution, however, was to use nuclear explosives. Specifically, they proposed deploying six *Saturn V* carrying 100-MT warheads.

We would like to find solutions other than nuclear explosives. Clearly, the arms-control, safety, and nonproliferation implications are horrendous. But a practical technology beyond nuclear explosives has yet to emerge. The most nearly competitive technology is the kinetic energy device. The specific energy of an interceptor spacecraft at typical orbital speeds is several hundred times that of high explosive. However, the specific energy of a nuclear explosive is several million times that of high explosive. The kinetic energy device to deflect a kilometer-size object is an unimaginable leviathan (Solem, 1993a; Solem, 1993c). At this time, and probably for decades to come, the only thing we have is a nuclear explosive.

This paper gives a cursory discussion of three subjects related to the deflection or pulverization of NEOs using nuclear explosives. First I discuss the problem of terminal intercept, the tactics that may be used when there is little warning and how those tactics may be optimized. Second, I present some conclusions concerning modes of engagement, the surface burst, the stand-off detonation, and the penetrator. The justification for these conclusions resides mainly in prior publications. Third, I show some limitations on the velocity increment that can be imparted in a single engagement, if the object is modeled as a gravitationally-bound agglomeration (flying rubble pile).

Terminal Intercept, Tactics, Optimization

The final velocity of an interceptor missile relative to the Earth, or the orbit in which it is stationed, is given by,

$$V = v_x \ln \frac{M_i}{M_f}, \tag{1}$$

where M_i and M_f are the initial and final mass of the interceptor and v_x is the rocket exhaust velocity. The time required to reach this relative velocity will be short compared to the total flight time. The time elapsed from launch to intercept is

$$\Delta t = \frac{R_l}{v + V}, \tag{2}$$

where R_l is the range when the interceptor is launched and v is the speed at which the object is closing on the Earth. So the range at intercept is

$$R_i = R_l \left(1 - \frac{v}{v + V}\right). \tag{3}$$

If the nuclear explosion gives the object a transverse velocity component $v_\perp$ then the threatening assailant will miss its target point by a distance

$$\varepsilon = R_l \frac{v_\perp}{v}\left(\frac{V}{v + V}\right), \tag{4}$$

where we have neglected the effect of the Earth's gravitational focussing and used a linear approximation to Keplerian motion. The nuclear explosive will blast a crater on the side of the object. The momentum of the ejecta would be balanced by the transverse momentum imparted to the object. From Glasstone's empirical fits (Glasstone 1962), the mass of material in the crater produced by a large explosion is

$$M_e = \alpha^2 E^\beta, \tag{5}$$

where α and β depend on the location of the explosion, the soil composition and density, gravity, and a myriad of other parameters. Clearly the *crater constant* α and the *crater exponent* β will vary depending on whether we are considering an assailant composed of nickel-iron, stony-nickel-iron, stone, chondrite, ice, or dirty snow. For almost every situation involving a surface explosion, however, we find $\beta \simeq 0.9$. This has now been extensively verified by numerical simulations (Solem and Snell, 1994).

Only a fraction of the nuclear explosive's energy is converted to kinetic energy of the ejected or "blow-off" material. Let this fraction be equal to $\frac{1}{2}\delta^2$ for algebraic convenience. Most of the weight after the rocket fuel is expended would be the nuclear explosive, which produces a yield of

$$E = \varphi M_f\,,. \tag{6}$$

where φ is the yield-to-weight ratio. Again, $\delta^2/2$ of this energy goes into the dirt ejected from the crater, so the transverse velocity imparted to the object is

$$v_\perp = \frac{\delta}{M_a}\sqrt{\varphi M_f M_e} = \frac{\alpha\delta}{M_a}\left(\varphi M_f\right)^{\frac{\beta+1}{2}}\,. \tag{7}$$

Although when the complete orbital mechanics is considered, we will want to impart a transverse velocity only when the object is very close to collision, the magnitudes obtained from this simplified calculation are effective over substantial distances. We can combine Eqs. (4), (5), and (7) to obtain

$$\varepsilon = \frac{\alpha\delta R_l}{M_a v}\frac{V(\varphi M_f)^{\frac{\beta+1}{2}}}{V+v} \tag{8}$$

for the displacement.

To obtain the optimum mass ratio for nuclear explosive deflection, we substitute Eq. (1) into Eq. (8) and solve

$$\frac{d\varepsilon}{d(M_i/M_f)} = 0. \tag{9}$$

The logarithm of the mass ratio that produces the largest value of ε,

$$Q = Q \equiv \ln\frac{M_i}{M_f} = -\frac{v}{2v_x}\left(1 - \sqrt{1 + \frac{2v_x}{(1+\beta)v}}\right)\,. \tag{10}$$

This is an interesting, although not profound, result. Despite the many parameters that come into the problem, the optimal mass ratio depends only on the quotient of the *closing velocity* and the *exhaust velocity*. The *crater exponent* is well established at 0.9. A substantial advantage accrues to a higher-specific-impulse rocket (Solem, 1993b; Solem, 1994a). The maximum displacement of the impact location on Earth is then given by

$$\varepsilon = \frac{\alpha\delta R_l}{M_a v}\frac{v_x Q(\varphi M_i e^{-Q})^{\frac{\beta+1}{2}}}{v_x Q + v} \tag{11}$$

For a surface burst, Glasstone uses $\beta = 0.9$, but takes $\alpha \simeq 1.6\times 10^{-4}\ \mathrm{gm}^{\frac{1}{2}(1-\beta)}\cdot\mathrm{cm}^{-\beta}\ \mathrm{sec}^{\beta}$. He describes the material as dry soil. Medium strength rock would be more consistent with $\alpha \simeq 10^{-4}\ \mathrm{gm}^{\frac{1}{2}(1-\beta)}\cdot\mathrm{cm}^{-\beta}\cdot\mathrm{sec}^{\beta}$, and, in the 20-kt range, would roughly agree with Cooper (1976). If about 5% of the nuclear explosive energy goes into kinetic energy of the blow-off, then $\delta = 1/\sqrt{10} \simeq 0.316$. bigskip Equation (11) can be rearranged to give the required initial mass of the interceptor,

$$M_i = \frac{e^Q}{\varphi}\left[\frac{M_a v\varepsilon}{\alpha\delta R_l}\left(1 + \frac{v}{v_x Q}\right)\right]^{\frac{2}{\beta+1}}\,, \tag{12}$$

where Q is given by Eq. (10). bigskip It is generally known that the yield of nuclear warheads can be a few kilotons per kilogram if they weigh more than about a hundred kilograms. For the purpose of these estimates, we will take a conservative value of $\varphi = 1$ kiloton kilogram^{-1}. Figure 1 shows the initial mass of the interceptor required to deflect an object by 10 Mm, as a function of the assailant's diameter d and its range R_l when the interceptor is launched. Figure 1 assumes an object density of $\rho = 3.4$ gm cm^{-3}, an assailant velocity of $v = 25$ km sec^{-1}. The deflection is conservative for missing the planet entirely ($R_{\odot} = 6.378$ Mm), partially compensating for the neglect of gravitational focusing. From the graph, it is clear that threatening objects as large as a kilometer can be deflected, even if the are only one astronomical unit away when the interceptor is launched. A Russian *Energia* rocket could easily boost the 100-ton interceptor int Earth orbit.

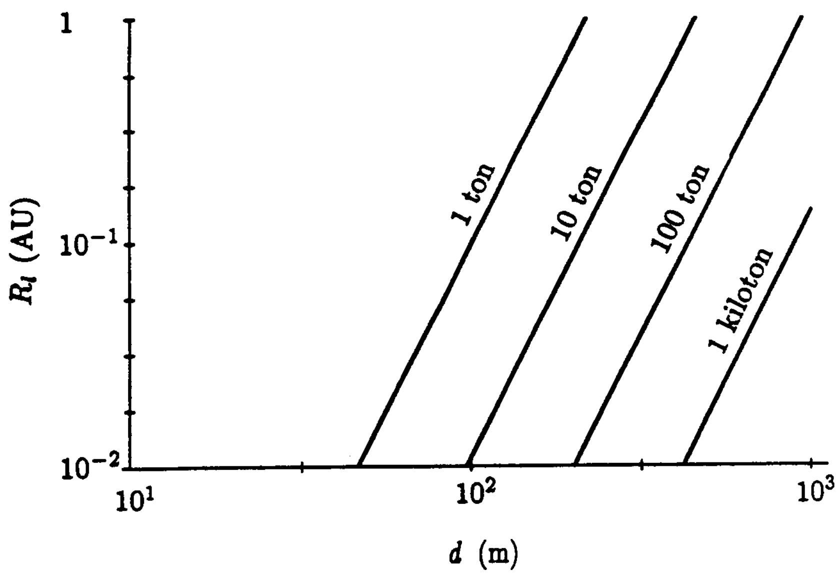

Figure 1. Initial masses of optimally designed interceptor rockets to obtain 10-Mm deflection.

Modes of Engagement

There are three qualitatively different ways in which a nuclear-explosive-carrying interceptor can engage a comet or asteroid, either for the purpose of deflection or pulverization. The engagement can deploy (1) a surface-burst, which is detonated at or very near the surface of the object; (2) a stand-off device, which is detonated at considerable distance from the surface; or (3) a penetrator device, which buries the nuclear explosive at an optimum depth. These modes have been discussed extensively in prior publications, I will present here a brief description of what we believe we have learned.

Surface-Burst Device

The optimization calculations of the previous section, which led to Fig. 1, were based on a surface-burst engagement. The surface burst is highly efficient for transferring momentum to the target object. If the same *opt omization procedure is applied to the kinetic energy device, the nuclear-explosive and interceptor system can be shown to be three orders of magnitude lighter. A problem with the surface burst is that it creates a crater to provide blow-off material. This introduces a great deal of stress and a fairly high probability of fracture. It is also somewhat difficult to time the surface-burst detonation at high rates of closure. If the relative velocity of the interceptor is 50 km $\cdot$ s^{-1} and the acceptable error in altitude of the detonation is 10 cm, as it might be for a typical surface explosion, then the timing jitter must be less than 2 μsec.

Stand-Off Device

The fracture problem can be much mitigated by detonating the nuclear explosive some distance from the astral assailant. Rather than forming a crater, the neutrons, x-rays, γ-rays, and some highly ionized debris from the nuclear explosion will blow-off a thin layer of the object's surface. This will spread the impulse over a larger area and lessen the shear stress to which the object is subjected. Of these four energy transfer mechanisms, by far the most effective (at reasonable heights of burst) is neutron energy deposition, suggesting that primarily-fusion explosives would be most effective (Shafer *et al.*, 1994).

complete description requires computer simulations. However some general statements can be made. At an optimal height of burst, I find about 2 to 8% of the explosive's energy is coupled to the assailant's surface, again depending on the object's actual composition and the neutron spectrum and total neutron energy output of the explosive. Most of the energy is deposited within 10 cm of the surface. The blow-off fraction will be about a factor of 35 times smaller than the surface burst and the initial mass of the interceptor would have to be about 40 times as large.

Penetrator Device

A greater momentum can be imparted for the same yield if the detonation is below the surface. The relative velocity will provide adequate kinetic energy the bury the nuclear explosive at significant depths. In order to penetrate into the assailant, the nuclear explosive must be fitted with a weighty billet: a cylinder of material that will erode during penetration. The billet will add weight to the package that must be delivered. Analytic studies have shown that a penetrator has no value in enhancing deflection, but may be of great value if we choose to pulverize the object (Solem, 1995).

Surface and subsurface detonations make a crater that is small compared to the characteristic dimension of the object. The linear momentum impulse will be imparted along a line connecting that crater and the center of mass — with corrections for local geology and topography. An aspheric object will also receive some angular momentum, depending on the location of the crater and the object's inertial tensor. The size of the impulse will depend on material properties, geology, and topography. bigskip Thus, it will be necessary to characterize the geology and mechanical properties of the object when using the *cratering* deflection techniques. Such characterization might be accomplished by a vanguard spacecraft. Stand-off deflection is much less sensitive to these details. In general, linear momentum will be imparted along the line connecting the detonation point with the center of mass — a large lever arm. Little angular momentum will be imparted, and this will depend on relative projected areas of various topographical features compared with components of the inertial tensor. Thus, besides its inherent fracture-mitigation virtues, the stand-off deflector demands substantially less information about the object it is deflecting.

Multicomponent Gravitationally-Bound Objects

Energetically, it is always preferable to deflect the object, particularly when it can be intercepted early, perhaps several orbital periods before it would impact our planet. More friable objects, however, might be susceptible to fracture, which may make the problem of deflection more difficult as several resulting objects would have to be deflected or pulverized by nuclear explosives, probably delivered by subsequent interception vehicles. bigskip Here, I address the problem of fracture by modeling objects as conglomerates of competent rocks bound together by gravitation and subjecting them to various impulses imparted by nuclear explosives. Simulations can never substitute for the deep understanding provided by analytic formulations, but a series carefully analyzed can supply some insight into this exceedingly complex problem.

Model for Asteroid Fracture

The model of an asteroid as a agglomeration of competent rocks bound together by mutual gravitational attraction is surely a great simplification. We have little knowledge of how asteroids are held together. There are certainly other cohesive forces between components, but the model may be adequate for many objects, particularly the larger ones. bigskip The goal is to ascertain under what conditions the asteroid will: (1) hold together as a single body, but change its trajectory; (2) fracture into dangerous shards, some of which are on nearly the original trajectory; or (3) be pulverized into harmless smithereens that will burn-out in the Earth's atmosphere if their departure from the original trajectory is insufficient to miss the Earth entirely. bigskip For these simulations, I model the rocks or snowballs comprising the asteroid or comet as uniform spheres, which interact gravitationally except when they touch. The touching, or collision, of two rocks is handled a scattering, that is, the velocities are suddenly changed in such a way that momentum is conserved. The scattering approximation, as well as the lack of cohesive strength between the component rocks, favors shattering the asteroid over moving it as a unit. Thus we are bounding the problem from the conservative end. The objects are modeled as more friable than they probably are. bigskip The depiction of comets as "flying rubble piles" has enjoyed increasing support (Solem, 1994b; Asphaug and Benz, 1994; Scotti and Melosh, 1993; Weissman, 1986; Weidenschilling, 1994) and comets with multiple nuclei, probably owing to tidal disruption, are not uncommon (Sekanina and Yeomans, 1985; Sekanina, 1993; Whipple, 1985). Asteroids may well be similar agglomerations.

Sketch of the Simulation Algorithm

During the calculation, the spherical components interact gravitationally except when they touch. The touching, or collision, of two components is handled as a non-adhesive frictionless scattering, that is, the velocities are suddenly changed in such a way that momentum is conserved, but some of the kinetic energy may be converted to heat. Because the components are frictionless, no spin is imparted in a collision. The simulation is a detailed calculation of the gravitational interaction and collisions of the components — it is not a hydrodynamic calculation. bigskip A further simplification, which greatly accelerates computation, is to assume the radius r_0 and density ρ of each component to be the same. Under this assumption, the equation of motion in the vicinity of the comet's center of mass is well approximated by

$$\ddot{\vec{r}}_j = Gm_0 \sum_{i \neq j} \frac{\vec{r}_i - \vec{r}_j}{|\vec{r}_i - \vec{r}_j|^3}, \tag{13}$$

where $G = 6.672 \times 10^{-8}$ dyn cm^2 gm^{-2} is the universal gravitation constant, $m_0 = \frac{4}{3}\pi\rho r_0^3$ is the component mass, $\vec{r}_i$ is the radius vector of the ith component from the comet's center of mass. bigskip As long as all the components remain separated by at least two radii, the motion is found by straightforward integration of Eq. (13). A "collision" occurs whenever $|\vec{r}_i - \vec{r}_j| < 2r_0$ and the emergent velocities are given by

$$\dot{\vec{r}}_i{}' = \dot{\vec{r}}_i - \frac{\delta(\dot{\vec{r}}_i - \dot{\vec{r}}_j) \cdot (\vec{r}_i - \vec{r}_j)}{8r_0^2}(\vec{r}_i - \vec{r}_j). \tag{14}$$

A frictionless collision can only alter the normal component of the relative velocity. If $\delta = 2$, the normal component of the relative velocity simply reverses direction and the collision is perfectly elastic. If $\delta = 1$, the normal component is reduced to zero in the collision. It is easy to see that the only allowed values are $1 \leq \delta \leq 2$. bigskip We have little knowledge of how components of this sort might lose kinetic energy in collisions. For this calculation, the details are not very important. It can be shown that for completely random impact parameters, the selection of $\delta = 1$ causes the average collision between components to lose half its relative kinetic energy to heat. This seems realistic. Because the gravitational orbital dynamics favors grazing collisions over random impact parameters, $\delta = 1$ will result in slightly less than half energy loss on average. bigskip The model embodied in Eqs. (13) and (14) enjoys a remarkable scaling relationship: all distances scale with simple similarity. Locations are described by the dimensionless vector $\vec{r_i}/r_0$. If we increase the diameter of the object by a factor of 2, the geometrical arrangement of all components at any time after disruption will be exactly the same, with the distance scale increased by a factor of 2. The energetics enjoy a similarly simple scaling relation. A factor of 2 increase in component radius increases all energies (kinetic energy, gravitational potential energy, and heat generated in component collisions) by a factor of $2^5 = 32$. As a result of these scaling properties, we can cover objects of all sizes with a single calculation. bigskip For the initial geometrical arrangement, I place one component at the center of mass with either 12 or 134 components packed around it in a face-centered cubic (FCC) array, which results in a model that is close to a gravitational potential minimum. The time step for the dynamical calculation is adjusted so only binary collisions occur, although there may be many binary collisions among separate pairs within that time step. The lattice spacing for the spheres to just touch is $r_0\sqrt{2}$, but this contact packing would cause the binary-collision condition to be violated on the first time step. So I use an initial lattice spacing of $r_0(\sqrt{2} + 0.0001)$ — the spheres are very close together, but not actually touching.

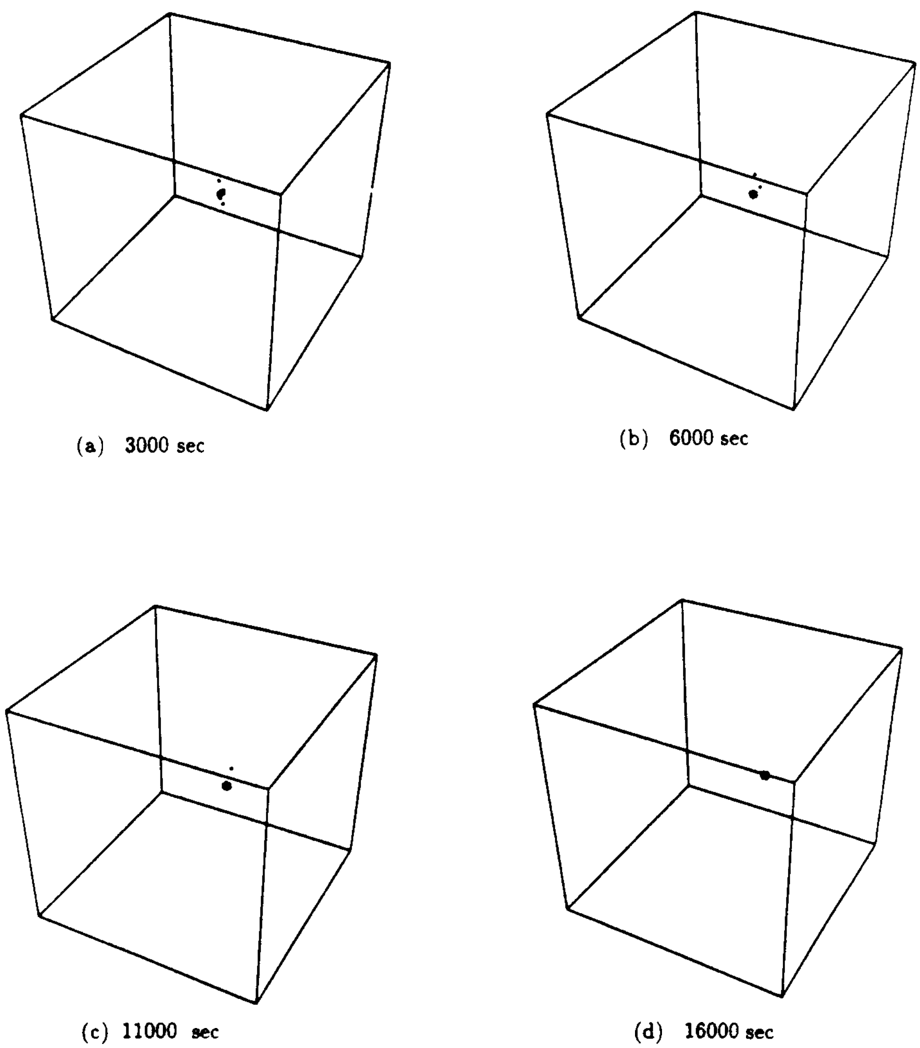

Figure 2. Incipient fragmentation of a gravitationally-bound asteroid consisting of 13 components, when subjected to a surface burst corresponding to a single outer component velocity of 1 m sec^{-1}.

Fragmentation Studies

I have performed a large number of calculations with this model, and it is possible to give only a few to provide some flavor for the behavior of these objects. Figure 2 shows the response of an object consisting of 13 components when one outer component is driven toward the center with a velocity of 1 m sec^{-1}, corresponding to a kinetic energy of 6.28×10^{16} erg, which is somewhat less than the total binding energy of the asteroid. This imparted velocity would result from a nuclear-explosive yield of 10.2 kilotons (4.29×10^{20} ergs). I take the density to be $\rho = 3$ gm cm^{-3}, so the mass of each sphere is $m_0 = \frac{4}{3}\pi\rho r_0^3 = 1.26 \times 10^7$ tons. The box is 15 km on a side, and the component rocks are shown to scale. The total mass of the asteroid is 1.63×10^8 tons and its greatest diameter is 600 m.

It is a case of *incipient fragmentation*. The object comes apart but then coalesces owing to mutual gravitational attraction. Just a little bit more energy will cause the object to remain fragmented.

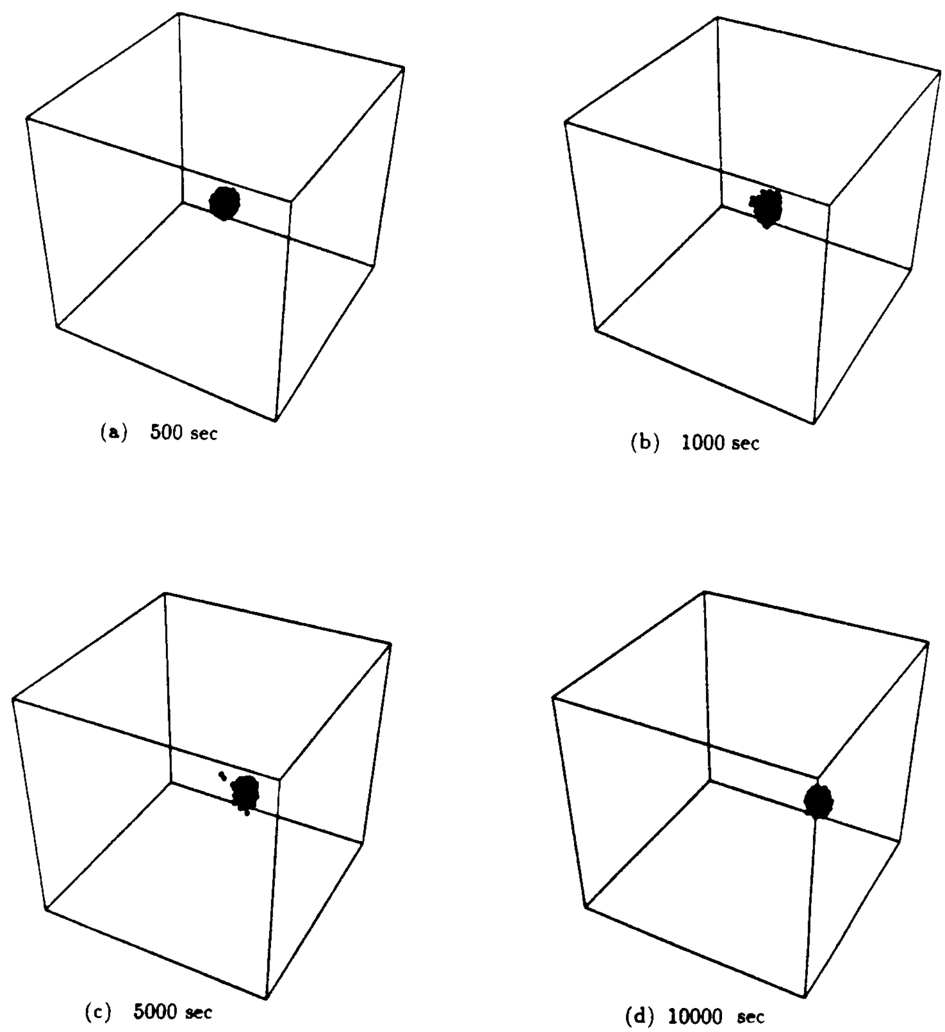

Figure 3. Incipient fragmentation of a gravitationally-bound asteroid consisting of 135 components, when subjected to a stand-off detonation corresponding to an average outer component velocity of 30 cm sec^{-1}.

Figure 3 shows the response of an object consisting of 135 components where the components on one side are driven with the velocity distribution appropriate to a stand-off nuclear explosion. The total mass of the object is 1.70×10^9 tons and its greatest diameter is 1258 m. The total binding energy of the asteroid is 3.86×10^{18} erg. The average velocity given to the outer components is 30 cm sec^{-1} This is another example of *incipient fragmentation*, and a little more energy will leave the object permanently fragmented.

Summary of Results

Table 1 shows the maximum velocity that can be imparted to gravitationally bound asteroids while maintaining their overall integrity. The comparison is for surface detonation and stand-off detonation with 13- and 135-component asteroids. Component density is 3 gm $\cdot$ sec^{-1}. For the stand-off detonation, the nuclear explosive is placed $\sqrt{2}$ $\times$ the asteroid radius from the asteroid surface. For the surface burst, a single component is accelerated into the body of the asteroid. The single component's crater parameters correspond to medium strength rock: $\beta = 0.9$, $\alpha = 10^{-4}$ $gm^{\frac{1}{2}(1-\beta)}$ $cm^{-\beta}$ sec^{β}, and δ=0.316. The stand-off detonation corresponds to $\beta = 0.97$, $\alpha = 1.5 \times 10^{-6}$ $gm^{\frac{1}{2}(1-\beta)} \cdot cm^{-\beta}$ sec^{β}, and δ=0.3.

Table 1. maximum non-fracturing deflection speeds

Asteroid Diameter	13 Components				135 Components			
	Stand-Off		**Surface**		**Stand-Off**		**Surface**	
(km)	(cm/s)	(kilotons)	(cm/s)	(kilotons)	(cm/s)	(kilotons)	(cm/s)	(kilotons)
20.	1000	9×10^8	256.	3×10^7	477.	5×10^8	118.	1×10^7
10.	500.	5×10^7	129.	1×10^6	239.	3×10^7	58.9	7×10^5
6.	300.	6×10^6	76.9	2×10^5	143.	3×10^6	35.3	8×10^4
3.	150.	4×10^5	38.5	9×10^3	71.5	2×10^5	17.7	4×10^3
2.	100.	7×10^4	25.6	2×10^3	47.7	4×10^4	11.8	8×10^2
1.	50.0	4×10^3	12.8	9×10^1	23.9	2×10^3	5.89	4×10^1
0.6	30.0	6×10^2	7.69	1×10^1	14.3	3×10^2	3.53	5×10^0
0.3	15.0	3×10^1	3.85	5×10^{-1}	7.15	2×10^1	1.77	3×10^{-1}

Implications of Table 1

The calculations presented in Table 1 are, of course, for a single engagement. Multiple engagements will impart the vector sum of the velocity increments from each explosion. However, when approaching the level of incipient fracture, the time interval between successive explosions musty be great enough to allow the asteroid to settle down — to convert gravitational kinetic energy from the disturbance into heat energy.

From Table 1 we could conclude that, for a single engagement, the non-fracturing deflection speed obtainable with a stand-off device is about four times the speed obtainable with a surface-burst device. We also see that the non-fracturing deflection speed depends on the number of components, the speed for a 13 component object being about twice that for a 135 component object. The calulations given in the table lead us to the following tentative conclusions: (1) asteroids more than 3 km in diameter can be most efficiently deflected using a surface burst; (2) asteroids as small as $\frac{1}{2}$ km can be effectively deflected using a stand-off device; (3) smaller asteroids are best pulverized.

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COSMIC BOMBARDMENT V: THREAT OBJECT-DISPERSING APPROACHES TO ACTIVE PLANETARY DEFENSE*

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ABSTRACT

Earth-impacting comets and asteroids with diameters ~0.03 – ~10 km pose the greatest threats to the terrestrial biosphere in terms of impact frequency-weighted impact consequences, and thus are of most concern to designers of active planetary defenses. Specific gravitational binding energies of such objects range from ~10^{-7} to 10^{-2} J/gm, and are small compared with the specific energies of ~$1x10^3$ to ~$3x10^3$ J/gm required to vaporize objects of typical composition or the specific energies required to pulverize them, which are ~10^{-1} to ~1 0 J/gm. All of these are small compared to the specific kinetic energy of these objects in the Earth-centered frame, which is ~$2x10^5$ to ~$2x10^6$ J/gm. The prospect naturally arises of negating all such threats by deflecting, pulverizing or vaporizing the objects.

Pulverization- with-dispersal is an attractive option of reasonable defensive robustness, and can be implemented with a mass-multiplication efficiencies of ~10^5 to 10^7, i.e., a unit mass of optimally designed pulverization equipment can pulverize and disperse 10^5 to 10^7 times its own mass of threat object. Examples of such equipments – which employ no explosives of any type – are given. With contemporary technology, these appear adequate to negate threats from cometary objects of diameters ≤0.6 km, stony asteroidal objects of diameters ≤0.125 km and nickel-iron asteroidal objects with diameters ≤0.05 km, using equipment which may be deployed on single Energiya*-class booster. Multi-booster systems using*

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only existing space-launch hardware can negate threat objects of ~3 times greater diameter.

Vaporization is the maximally robust defensive option, and may be invoked to negate threat objects not observed until little time is left until Earth-strike, and pulverization -with-dispersal has proven inadequate. Kinetic energy-based vaporization with non-nuclear equipments based on contemporary technology and use of existing space-launch assets appear adequate to negate cometary threats of diameters $\leq$*0.1 km, stony asteroidal threats of diameters* $\leq$*0.035 km and nickel-iron asteroidal threats with diameters* $\leq$*0.025 km.*

Physically larger threats may be vaporized with nuclear explosives, which with contemporary technology appear adequate in scale to negate 1 km-diameter threat objects, and to pulverize 10 km-scale threat objects. No contemporary technical means of any kind appear capable of directly dispersing the ~100 km diameter scale Charon*-class cometary objects recently observed in the outer solar system, although such objects may be deflected to defensively useful extents. Exploitation of means discussed herein will apparently permit sub-kilometer-diameter near-Earth objects to be steered into the path of such giant threat objects, with dispersive pulverization likely resulting.*

Means of implementing defenses of each of these types are proposed for specificity, and areas for optimization noted. The primary challenges posed to defensive system designers are understanding the basic structure of the threat object, forestalling unwanted interactions when several nuclear explosions are used, and performing moderately high-precision delivery of adequate quantities of engineered mass into the vicinity of distant, rapidly moving objects. Rising to these challenges appears within the present-day capability of the international technical community.

Attention is invited to the prospects for rapid, economical implementation of initial active defenses, employing "Cold War surplus" military space hardware and systems, as well as to the indifference of a well-designed defensive system to highly detailed knowledge of the properties of a threat object. That cosmic threat objects present themselves with speeds greatly in excess of sound-speed is very useful in this respect, as material properties become of reduced interest.

Biospheric impacts of threat object debris are briefly considered, for bounding purposes. Under virtually every threat negation circumstance, these impacts are manageable.

Experiments are suggested on some of the myriad cometary and asteroidal objects of sub-kilometer diameter which pass by or through the Earth-Moon system every year in order to assess each of these defensive prospects, including means for diagnosing their results.

Introduction. The threat posed to the terrestrial biosphere from cosmic bombardment by comets and asteroids is peculiarly large in magnitude and low in frequency, relative to all the other threats known. In the current stage of solar system evolution, impact on Earth of objects sufficiently large to penetrate the atmosphere and crater its surface occurs with typical intervals of millennia. On time scales of several tens of millions of years, however, objects sufficiently large to profoundly impact the ability of the Earth's near-surface regions to support life have occurred in the past, and can be expected to occur in the future. Figure 1 indicates the relative dimensional and energy scales of Earth-impactors of various incident frequencies.

Since there are presently nearly 6 billion people on Earth, the statistical loss-of-life from such exceedingly rare events is nonetheless of the order of 100 lives lost each year, due to the biggest objects alone. The aggregate statistical loss-of-life due to the much more frequent impacts of considerably smaller-scale cosmic bombardments may be estimated to be several times the life-loss at the 'extinction level,' so that several hundred lives may be lost each year, on an actuarial basis. As human life is valued along the economic axis in the First World, this level of life-lost due to the immediate effects of cosmic bombardment has an imputed cost of the order of $1 B per year. (With purchasing power parity-based discounting to account for Second and Third World income scales and noting present populations in the First, Second and Third Worlds, the current value of this imputed cost due to cosmic bombardment is perhaps $0.3 B per year.)

A program of active defense against cosmic bombardment would be economically rational if it were to have a cost less than the time-averaged damage expectancy of cosmic bombardment. Other considerations than merely economic ones, such as insuring the survival of the human race, may justify somewhat higher expenditures. Some of the technical aspects of such a program to create and operate active defenses are outlined in the following.

Character Of The Threat To The Biosphere From Comets And Asteroids. As currently understood, the threat to terrestrial life arises from three aspects of cosmic bombardment: blast, heat and late-time atmospheric effects. Blast and thermal effects arising from the abrupt conversion of the kinetic energy of the incoming object into internal energy are well-understood, at least in principle, from the understanding of explosive phenomena in geophysical contexts which has developed over the past century. Due to the extraordinary physical scales of the larger impacting objects – not small compared to those of the Earth's crust and the scale-height of its atmosphere – the grossly non-spherical character of the blast waves and the comparatively localized nature of the thermal pulse may be somewhat non-intuitive, but nonetheless may be readily and reliably modeled computationally.

Atmospheric effects, in contrast, are significantly less well-understood, due to the complexity of solar-modulated atmospheric physics and chemistry, hydrometeorology and land-ocean interactions. Rather gross changes in atmospheric composition due to both direct and secondary injection of mass by incoming objects (and sets of objects) have been suggested to be important, and large, albeit transient, changes in the radiative transport properties by relatively modest amounts of micron-scale particulate mass have also been implicated in profound biospheric impacts.

Defensive systems must consider appropriately these latter effects. Primary defenses which would allow pulverized threat object mass in >100 megatonne quantities – corresponding to incoming objects initially well under 1 km in diameter – to impact the terrestrial atmosphere (and thus particulate-load the stratosphere) might inadvertently induce several kelvin global-average temperature drops. This would be an order-of-magnitude scale-up of the recent Mt. Pinatubo global cooling phenomenon, which is variously estimated to have injected ~20 megatonnes of largely sulphate particulate into the stratosphere and thereby to have induced a peak temperature drop of 0.4 – 0.6 kelvin. Moreover, fine particulate loading of the stratosphere may persist for a few years. Such temperature decreases may be sufficiently long in duration and large in magnitude to induce large-scale failures of agricultural production, with resulting widespread famine.

Threat Objects. Three major classes of threat objects may be delineated, based on composition. These are the cometary ones, composed predominantly of water and ammonia ices with embedded light-metal-oxide-based particulates, the stony asteroids composed of similar metal oxide particulates with varying degrees of compaction, and the nickel-irons composed predominantly of the metallic forms of the iron-group elements. Some of the properties of these objects pertinent to active defense are summarized in Figure 2.

Viewed from a threat negation perspective, the stony asteroids may actually be grouped into two major sub-classes, one consisting of "flying rubble piles" and likely representing cometary objects from which the volatile ices have been evaporated by long-term residence in the inner solar system, and the other consisting of highly compacted rock-like objects which likely originated by collisional fragmentation from larger "parent" bodies in the Asteroid Belt. These two sub-classes may be expected to vary substantially in the specific energy required to pulverize them (and also in their susceptibility to deflection-based defensive schemes).

Each of these classes of threat objects may also be categorized from a high-level defensive system architectural perspective, depending on their size. For each type of threat object, as will be seen below, there will be a maximum size which can be negated with non-nuclear explosive-based means. Objects of greater size can be negated along the pulverization and vaporization means of present interest only by use of relatively high-energy nuclear explosives.

Threat Negation Prospects In The Next Quarter-Century. The prospects for negating cosmic bombardment threats to the terrestrial biosphere during the next quarter-century necessarily are dependent for their implementing means on contemporary technology. As will be discussed further in the following, these appear to be readily sufficient to deal with 0.1 km-diameter threats by a variety of means, to cope with 1 km-scale threat objects with a much more limited set of tools, and to deal with 10 km-diameter threats only with rather heroic endeavors. These large differences in means of course derive immediately from the factor-of-

1000 in mass which separates each of these three size-classes of threat objects from its nearest neighbor.

At present, it is feasible to contemplate deflection, pulverization-with-dispersion and vaporization of threat objects as the primary defensive means – obviously supplemented by combinations of these. Deflection implies minimal energy expenditure and the longest warning-times. It thus admits of the greatest elegance and the widest variety of technical approaches, for it requires relatively very modest expenditures of energy, as it employs large time intervals as a very long lever on the planetary defense problem. Deflection-based defensive approaches also generally require unusually great knowledge of the threat object, e.g., precision and accuracy of data with respect to its orbit, its composition, its physical state and mechanical strength. Some pertinent energy scales are indicated in Figure 3.

Pulverization represents active defense conducted with an intermediate level of knowledge, and with relatively modest warning-times. In principle, it is very energy-economical, in that it proposes to break only perhaps at most one-billionth of the chemical bonds present in the threat object in the process of reducing it into meter-scale fragments. (In practice, the inefficiencies almost inevitably attendant upon even such coarse-scale pulverization are likely to degrade such excellent theoretical energy efficiencies by several orders of magnitude, particularly when the pulverization is rapidly performed, e.g. by explosive fracturing rather than fracturing in an adiabatically-operated press.) In addition, the resulting fragments generally must be given kinetic energies larger than their gravitational binding energies, in order to disperse the fragmented threat object and to force the fragments to interact with the Earth's atmosphere in an individual, non-collective manner – if they impinge on the atmosphere at all. Finally, if the time-interval before Earth-impact is small and the object is large, minimizing the total threat object mass incident on the Earth's atmosphere – both for peak localized thermal pulse and stratospheric particulate-loading considerations – requires that the fragments be given sufficient speed relative to their center-of-mass to separate them by a substantial multiple of the ~13 megameter Earth-diameter within whatever time-to-go is available.

Vaporization is the maximally robust defensive mode currently feasible to consider, and also is the most energy-intensive. Vaporizing objects of more that ~10^6 tonnes, i.e., of ≥100 meters diameter, by optimal conversion of their kinetic energy to internal forms is a daunting technical challenge to the defense at current technological levels. (Threat objects carry at most three orders of magnitude more specific kinetic energy than their own heat of vaporization, and delivering more than 500 tonnes of equipment to the immediate vicinity of a threat object doesn't appear feasible in the reasonably foreseeable future, as noted below.) For vaporization-based defenses against larger threat objects, nuclear energy sources are seemingly required. As will be discussed below, these means suffice to vaporize the 1 km-diameter objects which are believed to Earth-strike roughly every megayear. They are quite insufficient (with present rocket-based delivery means) to vaporize the ~10 km-diameter objects which strike every ~60 megayears – though they can robustly pulverize them. They cannot even reliably pulverize the *Charon*-class (≥100 km diameter) comets recently observed in the outer solar system.

Threat Pulverization. When pulverizing an incoming object whose kinetic energy is very large compared to the energy required to vaporize it, the quantity to be optimized – i.e., minimized – is the implementing mass; there is energy to spare. Since threat objects will always arrive at the Earth with speeds exceeding the 11 km/sec speed of Earth-escape – and typically with speeds of 20-60 km/sec, the defensive system designer is allowed to focus almost exclusively on minimizing the mass of pulverization equipment which must be transported to the immediate vicinity of the object.

Fragmenting a solid threat object into pieces of pre-specified maximum scale – e.g., 1 meter boulders, in the case of a well-consolidated stony asteroid – necessitates the imposition of a fracturing-level stress-field having the same periodicity. Indeed, in order to maximize the fragmentation benefits of large-scale crack propagation, it is desirable to simultaneously impose such a stress field over as large fraction of the object as may be technically feasible.

The technology-set conventionally employed for trenching and tunneling through high-strength rock seems applicable to this problem. Although emplacing a parallel sheet of periodically-spaced drill-holes, filling them with explosive and detonating the explosive strings synchronously in order to shear off a rock slab obviously is not practical for pulverization of cosmic threat objects, a technically-equivalent analog probably will be practical.

Specifically, a dense, refractory projectile with aspect ratio of 2–5 is capable of penetrating into hard rock to a depth an order-of-magnitude greater than its length, leaving in its wake a right circular cylinder of vaporized rock. The temperature and pressure in this cylindrical volume are comparable to that of detonated chemical high explosive – for whose creation the energy source is of course the kinetic energy of the incident projectile. This projectile is naturally slowly consumed as it traverses the hard rock. Its forward tip shocks the rocky medium into vapor, and ablates preferentially from its forward end and secondarily from its sides as the near-solid-density rock vapor flows over it. It is feasible to arrange its three-dimensional structure so that it "flies" stably through most all of its entire trajectory, i.e. so that the center-of-pressure integrated over its surface lies behind its center-of-mass until virtually all of the mass of the projectile has been ablated.

Linear strings of such penetrating projectiles, tip-to-tail-separated by 2–3 lengths, may be employed to create a "tube" of rock vapor of arbitrary length, and parallel linear penetrator strings may be used to generate sheets of such tubes. Obviously, these sheets may be expected to be functionally identical to sheets of blasting-holes used for deep-trenching through dikes of hard rock on Earth: the sheet-cracks connecting the plane-parallel tubes very soon after the tubes are formed will widen into fracture planes, and an extended slab of rock will then shear-off, either as a unit or as a set of boulders whose size is comparable to the spacing of the blasting-holes. If parallel sheets of penetrators are employed, an entire rock-mass may be rendered into slabs of rock or, more likely, a three-dimensional lattice of rubble. These sheets of dense, refractor hypervelocity penetrators – "tungsten knives" –

thus may be expected to serve to swiftly slice an asteroidal mass of any material into "bite size" chunks. See Figure 4.

As will be justified below, the nearest-neighbor distance of the penetrators in this sheet-lattice will need to be of the order of one meter. The sheets must be spaced so that the rubble from the N^{th} sheet's pulverization action has left the vicinity of the threat object's surface before the $(N+1)^{st}$ sheet arrives. This isn't a significant limitation, as pulverization will generally not be employed as a defensive option unless there is at least one megasecond time-to-go until Earth-strike; the time-spacing between sheets of penetrating-and-pulverizing projectiles can then be $10^2 - 10^3$ seconds, accommodating adequate dispersal between pulverizing events even if the rubble leaves the threat-object's surface at speeds as slow as 10 – 1 meter/sec. The use of as many as 10^3 penetrator-sheets is then reasonable.

Trading off against the inconvenience of needing many projectile-sheets is the ability to orient the sheets – and to maintain this orientation from the time of release to the time of impact – by simply imparting an appropriate vector angular momentum to a canister containing a tightly-packed "net" of hypervelocity penetrators. The projectile-sheet thus will impact the threat object in just the desired orientation. This approach admits of an especially simple – and thus highly reliable – deployment mechanism, one moreover well-adapted to existing ICBM post-boost vehicles. See Figure 5.

Going from two to three dimensions, equi-spaced stacks of such sheets of projectile strings may be erected in space to form a lattice which, when made to collide with a threat object of comparable dimensions, may hypersonically penetrate it through its entire thickness with blasting holes of meter-spacing – and thus render it into a rubble-pile of meter-scale boulders, interpenetrated with tubes of rock vapor of density $\sim 10^{-1} - 10^{-2}$ that of solid density, which will serve to swiftly disperse it. Such extended lattices are of limited utility unless the velocity vector of the lattice is reasonably well-aligned with that of the threat-object at which it is directed; however, the required degree of co-alignment is straightforward to arrange with modern equipment.

In vacuum, no impediment exists to the erection of such projectile assemblies– and, in particular, there is an abundance of time available for reasonably high-precision lattice generation from a stowed-for-transport package.

A complication which must be dealt with in a robust manner during pulverization is the possible premature dispersal of a "flying rubble pile" of moderate (e.g., 1 km diameter) scale. Such a pile may harbor a large number of, e.g., 100 meter-scale consolidated objects easily capable of penetrating to the Earth's surface, and yet may aggregate these objects only very weakly, via gravitational binding. If not pulverized carefully, such a rubble pile may disassemble early in the pulverization process into an awkwardly large family of mini-threat objects, under the influence of the energy inadvertently "leaking" from the pulverization working-site into the remainder of the "parent" threat object, during the early phases of pulverization. Alternatively, a weakly aggregated threat object of very low mechanical strength may spontaneously disassemble as it comes within the terrestrial Roche limit, due to tidal forces – as Shoemaker-Levy 9 did prior to its final plunge into Jupiter –

although the smallness of the terrestrial Roche limit probably obviates such concerns except for near-grazing-incidence rubble-piles.

Pulverization employing a massive three-dimensional penetrator lattice, demonstrated and validated in "practice sessions," may be the preferred approach to such a complication, as it definitively pulverizes a threat object, including a flying rubble-pile, before it can possibly disassemble – or move in any other fashion. An alternative approach applicable to larger threat objects which may be difficult to pulverize with a 3-D lattice of feasible size is to employ a sequence of lattice-sheets of penetrators to disassemble the flying rubble pile and then to pulverize-at-discretion any unacceptably large objects within it which remain on Earth-collision trajectories.

Figure 6 illustrates the use of hypervelocity penetrators for both pulverization and vaporization of threat objects; it presents results from both computational and experimental studies of pertinent hypervelocity penetrators interacting with high-strength plastic, cement and steel targets (which may be taken as surrogates for very strong ice or carbonaceous chrondritic, stony and nickel-iron threat objects, respectively). The computer simulation studies were performed by our able colleague Yu-Li Pan, using sophisticated, first-principles physics design codes which model elastoplastic hydrodynamics and all pertinent types of energy transport; these codes are known to be high-fidelity models of physical reality from detailed comparisons with a wealth of well-diagnosed pertinent experiments.

Figure 6A indicates initial conditions for a set of studies employing a long tungsten hypervelocity penetrator interacting with a steel target, while Figures 6B and 6C show “snapshots” in time of the interaction for an incident penetrator speed of 4.5 km/sec, where the unit compression (i.e., normal density) contours of the tungsten and the steel are shown. Figure 6D displays final bore-hole or cavity contours for identical projectiles of varying incident speed, and notes that energy conservation is expressed by linear cavity volume increase with incident kinetic energy. Figure 6E notes that usage of penetrator mass is optimized by using small (length-to-diameter) aspect-ratio penetrators, a point which is generalized somewhat in Figure 6F; "P/L" expresses the dimensionless ratio of the penetration depth in the material being studied to the initial length of the penetrator. Figure 6G indicates the hypervelocity penetrator system configuration suggested by many such studies: a heel-to-toe sequence of small aspect-ratio penetrators is best for deeply penetrating any solid. Figure 6H indicates how a single such penetrator interacts with concrete as a function of initial penetrator speed; little improvement is seen for incident penetrator speeds above that sufficient to largely vaporize the concrete. Figure 6I indicates how a short string" of 3 such penetrators in a geometry similar to that indicated in Figure 6G interacts with a concrete target, immediately after the third projectile has completely ablated; some late-time target relaxation has yet to occur near the tip of the bore-hole. Figure 6J indicates how a single steel sphere of 1 cm-diameter and incident speed of 5 km/sec penetrates on-axis into a strong plastic cylindrical target, while Figure 6K indicates how an identical target evolves when 3 successive spheres are made to impinge in succession on the same axial location; the penetration depth into the target is seen to be approximately 3 times that of the target struck by only a single penetrator. Finally, Figures 6L and 6M indicate the same phenomena in two concrete targets struck by a single steel sphere and by 3 steel spheres in succession, respectively (these two targets fragmented more severely than did the pair of plastic ones, for well-understood reasons). In these experiments, measured bore-hole total depths and radii-vs.-depth agreed with prior physics code predictions to better than 10% accuracy, as much prior experience had indicated they would.

We therefore are highly confident that our modeling-code based predictions provide a very reliable basis for evaluating active defense concepts on much larger scales, for physics is scale-invariant and predictions of these codes have been extremely extensively examined and validated in very many pertinent experiments.

Threat Vaporization. Vaporization of a threat object of course represents one end of the spectrum of negation robustness, as well as another on the spectrum of energy (and mass) cost-of-negation. Thus, it is the method-of-choice for an ultimate defensive layer, or when large amounts of energy are readily available. Because of the huge mismatch in sound-speeds of a nuclear explosion-generated fireball consisting only of the explosive debris and of ordinary zero-temperature matter, coupling of nuclear explosive energy to essentially any kind of threat object is highly inefficient, if the energy is released on or above the object's surface.

One may optimize this coupling efficiency by embedding the explosive sufficiently deeply in the threat object prior to energy generation so that the ensuing shock emerges nearly simultaneously at virtually all points on the object's surface, i.e., one may generate the explosion's energy in the object's core. If the surface-emergent shock from such a well-placed explosion generates a post-shock temperature above the local critical temperature, this is sufficient to assure that the entire object will be vaporized; if the emergent shock strength is above the Young's modulus of the object material, this is sufficient to guarantee that the entire object will be pulverized. Straightforward arithmetic indicates that of the order of 1 gigaton of energy deposited in the core of a 1 km-diameter object will suffice to vaporize it (after all, its mass is of the order of 1 gigatonne). The same energy pulse placed at the core of a 10 km-diameter object will generate ≥0.1 kilobar stress levels when it reflects from the object's surface, sufficient to pulverize it, except when it is composed predominantly of unfractured nickel-iron (in which case order-of-magnitude higher stress-levels may be required, those which could be attained on the surface of a ~5 km-diameter object).

Detailed computer-based physical simulations, supplemented with pertinent testing of military nuclear explosives systems, suggests that emplacing a large nuclear explosive in the center of a multi-km-diameter consolidated object may be feasible in the circumstances of interest. The same basic approach as was pursued for non-nuclear pulverization is employed, with a string of megaton-scale nuclear explosives substituting for the string of dense, refractory projectiles. (This procedure is in part based on experience with nuclear explosives. The proposed geometry is novel in its spatial extent, and possible interactions are complex and of high energy-density. Nonetheless, we consider the success of the proposed procedure probable but by no means assured. Experimental validation of detailed computer modeling results clearly is required.)

Each nuclear explosive, wrapped in a suitable structure of high-strength thermal insulation, advances kinematically to the current end of the advancing bore-hole, comes to a stop in the manner of an earth-penetrating munition, immediately deposits its energy-pulse, and thereby extends the ≥100 meter diameter bore-hole in the object radially inward by another ~100 meters (after a radial hydrodynamic relaxation interval of ~0.1 second after each pulse. The exceptionally high speeds of the incoming nuclear charges makes it probable that charge emplacement will occur when-and-as expected, even though the final charges must traverse possibly several kilometers of still-rarefying and reasonably hot rock vapor (which long, reasonably dense tube of vapor serves to decouple usefully many of the prompt effects of the leading charge from all of its followers). Ablative insulation with a net transport time-constant as modest as 1 second will suffice to completely decouple the arriving charge from ambient thermal conditions, and an adequately high-strength mechanical support for this thermal decoupling layer may be provided for. Acceleration-switched fusing will automatically generate the nuclear energy pulse when the charge embeds itself in the innermost tip of the bore-hole being drilled, and standard kinematic decoupling approaches, extended to the order-of-magnitude higher speeds of impact of present interest, may be used to provide for proper operation of the charge. None of these techniques are completely novel, and their fundamentals "are known to one ordinarily skilled in the art." (As also noted above, the unusual physical conditions make it highly desirable to validate these approaches experimentally, well before the time of real defensive need.) See Figure 7.

The drilling of a bore-hole of ~0.1 km minimum diameter to the center of even a 10 km-diameter threat object can be performed on a time-scale of the order of 5 seconds, and its character assured in advance by giving the appropriate set of reasonably precise initial positions and velocities to a set of a few dozen identical nuclear charges of types which presently exist in abundance (e.g., the several thousand warheads of the SS-18D ICBM, now commencing decommissioning under START II). The repeatedly demonstrated performance of modern post-boost vehicles in positioning remarkably precisely reentry vehicles in linear coordinate-linear momentum-angular momentum phase space is more-than-adequate for this task.

Immediately after the bore-hole to the center of the threat object is completed, it is appropriate to emplace the main charge, whose function it is to initiate a radially diverging shock of maximum feasible strength. Single space-launches using the largest boosters presently available, i.e., *Energiya*, can emplace gigaton-scale nuclear charges anywhere in the inner solar system between the orbits of Mars and Venus, and the use of such an explosive is contemplated for dispersing the largest threat objects. The relatively high-strength shock which can be engendered by a charge of this scale will overtake the comparatively weak shocks launched by the bore-hole drilling operation well before the cumulative effect of all of them have significantly displaced outward the surface of the object, so that this final strong shock will "see" virtually all of the object in nearly undisturbed condition. Then, as noted above, this shock will heat and stress the object's surface (and, to even greater extents, all of its interior mass) to extents readily estimated from basic mass and energy considerations, i.e., 1 km-scale objects will be completely vaporized, and 10 km-scale objects will be reliably pulverized and then dispersed with ~0.1 km/sec mean speeds, relative to the center-of-mass of the threat object. (Even as soon as ten days later, the diameter of a 10 km-diameter object's debris cloud will be a dozen times that of the Earth.)

Such an approach could also be employed to deflect a giant, *Charon*-class comet, if such an object were detected with sufficient time-to-go in its Earth collision-bound trajectory. The main charge, dynamically emplaced and detonated at a depth of the order of 10 km into the comet's surface, would blast a crater of a few tens of km diameter in its side. The crater ejecta, heaved with a typical speed of ~0.03 km/sec, would mostly escape, since the escape velocity from the surface of a 100 km-diameter comet is ~25 meters/sec. (For this reason, no mass would be lost from elsewhere on the comet, no matter how mechanically weak it might be, when the shock reflected off other portions of its surface, distant from the crater.) The giant comet, having thus lost $\sim 10^{-2}$ of its mass in escaped crater ejecta, would perforce undergo a velocity change of $(\sim 10^{-2})$(0.03 km/sec), or ~0.3 meters/sec. If this maneuver were performed with a time-to-go as small as 1 year, when the comet might be expected to be inside the orbit of Jupiter, it could shift the Earth-comet collision parameter by $\sim 10^4$ km, just sufficient to change a direct hit into a near-miss.

If such giant cometary objects can be detected with significantly greater time-to-go, it might be feasible to steer into its path an asteroid of at least several km diameter from the main Belt. The resulting collision at ≥25 km/sec, occurring as the giant comet crossed the Belt, would certainly pulverize and likely vaporize both asteroid and comet. This conceptually interesting prospect twice-leverages anthropogenic mass, in that a relatively very modest amount of equipment is employed to explosively deflect a carefully selected natural object by perhaps 1% of its orbital velocity, sufficient to steer it into the path of the sunward-falling comet. This steered asteroid mass then acts to convert a sufficiently large fraction of the comet's kinetic energy into internal forms to negate it completely as a threat. The energetics of this approach appear attainable with existing equipment, but its overall feasibility cannot be assessed until a significantly more definitive census of the smaller objects in the Belt is obtained – presumably with space-based observational means.

Less spectulatively in both required implementing mass and Main Belt population statistics is the prospect of employing the "best" of the class of $\sim 10^6$ near-Earth objects with diameters of ~100 meters whose existence has only very recently been discovered. A short sequence of steering-events, each one of which involves ~1 tonne of anthropogenic mass employed to ablate $\leq 10^3$ times greater mass from the $\sim 10^6$ tonne near-Earth object, could readily impart the precise velocity change (of the order of 1 cm/second in magnitude) sufficient to steer the "best of class" into the path of the incoming giant threat object. The center-of-mass kinetic energy would not be greatly in excess of 100 megatons, but the mass ejected from the resulting impact crater on the giant threat object is likely to carry off enough momentum to convert a direct hit on the Earth into a near-miss. Thus, employing twice the high specific kinetic energy (relative to both sound speeds and threat-object escape speeds) of objects in solar orbit makes feasible-in-principle defense of the Earth from impact by even giant threat objects – moreover with means not requiring use of nuclear explosives.

Threat Negation Equipments. Threat negation of all the types considered here involves the placement of mass in the immediate vicinity of the threat object (or set of threat objects). Depending on the particular defensive approach taken to negation, this mass may be in the form of thousands of small hypervelocity projectiles or 1 – 2 dozen nuclear explosives. In either case, precision positioning of the defensive mass relative to the threat object is likely essential to success of the defensive mission. Figure 8 summarizes the approaches to active defense from an energetics standpoint, which in turn motivates defensive system mass budgets.

Fortunately, means are presently available in quantity for these placement tasks, all of which must be executed far from Earth, as noted both above and below. A few examples may serve to illustrate this. The SS-18 ICBMs of the former Soviet Union, of which more than 300 still remain but are scheduled for retirement prior to 2003 under START II, are each capable of sending a payload of roughly 2 tonnes into Earth-escape trajectory (with a modern solid rocket motor replacing their current PBV propulsion). The post-boost vehicles (PBVs) of both Russian and American MIRVed ICBMs are all scheduled for retirement under START II. The best of these are capable of deploying typically 10 objects, each of 0.1-1 tonne mass, into quite distinct trajectories with velocity precisions of the order of 1 part in 10^5 and orientation precisions of the order of 1 part in 10^3 (which orientations are maintained by appropriate angular momentum endowments imparted to the objects as they are deployed). These already-demonstrated precisions are substantially better than are likely to be required to position kinetic energy penetrator-nets and nuclear explosives relative to threat objects, in order to attain optimum defensive results: e.g., they correspond to threat-negation packet placement-precision of <0.1 km across a distance of 10^4 km.

High-precision laser radars and inertial frame-generating units, both stellar and internal, exist which are adequate to support such precision positioning of negation packets in the deep space environment. For example, the imaging laser radar carried on the *Clementine* spacecraft which performed the first high-resolution, three-dimensional mapping of the entire Moon just last year demonstrated a ranging precision of 10 meters across a 0.64 megameter range, limited only by the counting-precision of its 16-bit clock; its demonstrated performance capabilities would have supported ranging to a few meters precision at distances in excess of one megameter. The camera of *Clementine's* imaging laser radar has since been upgraded to a 5 μradian resolution level. Thus, with a few obvious, easily implemented enhancements, the *Clementine* imaging laser radar module could perform 1 part in 10^5 precision range <u>and</u> angular position measurements of threat objects at rates as high as 10 Hz, over multi-megameter distances. Similarly, either of the two independent laser-based inertial measurement units carried by *Clementine*, together with either of its two independent stellar inertial reference units, would be entirely adequate, in bias, noise, drift, dynamic range and bandwidth, to guide the threat negation platform throughout its threat object-negation packet-dispensing program. Some of these *Clementine* technologies are shown in Figures 9A and 9B, in as-flown configuration.

To support vaporization of 1 km-diameter threat objects and definitive dispersion of 10 km-diameter objects, very large amounts of energy will be required, of the order of a billion tonnes of TNT-equivalent (noting that a 1-km comet has a mass of ~0.5

billion tonnes and a heat-of-vaporization of ~0.3 billion tonnes of TNT-equivalent). While the efficiency of the best nuclear explosives is high, it is amusing to note that it amounts only to ~10^{-3} of the rest-mass energy of the explosive. Fortunately, at least one very high-capacity space launch system is presently available, the Russian *Energiya*, which can put ~25 tonnes of payload into an Earth-escape trajectory (topped with a suitable – and presently available – upper stage). Such payload mass is sufficient to deliver a single integrated nuclear explosive of the required energy production capability to vaporize km-scale threat objects and to disruptively pulverize 10 km-diameter ones, via the high-efficiency "from the inside out" technique discussed above.

It is a fortuitous consequence of the end of the Cold War that all of these equipments – created at aggregate costs far in excess of $100 billion – are currently available at essentially zero cost, as "war surplus." They can potentially be employed to comprise the essential hardware infrastructure of a highly capable active defense of the terrestrial biosphere against cosmic bombardment, quickly and inexpensively.

Mass Budgets For Threat Negation. The total quantities of mass required to be emplaced with reasonable precision in the vicinity of incoming threat objects range from the modest to the demanding, depending on the choice of threat negation technology to be employed. Fairly careful reckoning of mass budgets, in turn, indexes the likely cost of active defense systems in the near-term, for space-launch costs seem likely to dominate at least the "hardware" portions of defensive systems budgets. It seems especially important to give the highest priority consideration to systems whose space-launch mass budgets do not exceed those which can be satisfied by the "Cold War surplus" hardware inventories of the U.S. and the former Soviet Republics becoming available under START II – for these are the systems which will be by far the most economically feasible to implement or employ in the foreseeable future.

For nuclear explosive-based defenses, perhaps 50 charges of 1 megaton-scale would be sufficient to drill into the core of even a 10 km-diameter threat object. (Of course, far more modest means would suffice to negate a 1 km-diameter object, and significantly smaller threat objects may be dealt with by entirely non-nuclear means.) Perhaps two such charges and a modest amount of post-boost vehicle, with aggregate mass under 2 tonnes, could be thrown into an Earth-escape trajectory by a SS-18 ICBM topped with a suitable, high-I_{sp} upper stage. A single gigaton-class charge could be similarly launched on a single *Energiya* booster, equipped with a *Centaur*-class upper stage. Approximately two dozen SS-18s and a single *Energiya* would thus suffice to execute the launch portion of the largest presently foreseeable active defensive operation.

In a hybrid defensive scheme, one face of a threat object could be pulverized with a barrage of hypervelocity penetrators and then vaporized, with the use of a nuclear explosive standing off of the order of one radius from the expanding rubble. The resulting shock wave may give the remaining threat object a relatively gentle and sustained acceleration, and thus a reliable deflection from its previously Earth-bound trajectory.

The mass-multiplication efficiency of the most mass-efficient non-nuclear threat dispersion schemes known to us – those involving hypervelocity projectile-based conversion of threat object kinetic energy to internal energy with unit efficiency – depends on the square of a threat object's speed in the Earth reference frame (which is its specific kinetic energy), in units of its zero-temperature adiabatic sound-speed (which squared quantity we use to estimate the object's specific heat-of-vaporization). These efficiencies range from $\sim 10^2$ for vaporization of the lowest-speed nickel-iron asteroids to $\sim 10^6$ for pulverization-and-dispersion of heliocentric retrograde-orbiting ice-rich comets.

For defenses not using nuclear explosives, the size – specifically, the mass – of the threat object which can be successfully negated, either by pulverization or vaporization, scales linearly with amount of mass available to direct upon it as hypervelocity projectiles. The total mass which all launchers becoming available under START II could put into Earth-escape trajectory is between 300 and 500 tonnes. An upper-bound mass-multiplication efficiency of 10^6, corresponding to pulverization of a very high-speed threat object, would thus permit a single half-gigaton object – a comet or a stony asteroid of ≤ 1 km-diameter – to be negated by impact of hypervelocity penetrators, if the entire START II-generated launch capacity were to be expended in transporting arrays of such penetrators.

Figure 10 gives estimates of the size of objects of various compositions and orbital characteristics which can be negated with the various active defensive technologies , both non-nuclear and nuclear, which we have discussed, for two types of approaches to system deployment: single, heavy-lift launch and launch on a fleet-of-100 SS-18s with high I_{sp} upper-stages. The mass efficiency – the mass of the threat-object negated per unit mass of defensive equipments lofted into interplanetary space – is indicated for each of the four major approaches as E_{mass}. It is clear both that non-nuclear active defenses will suffice for the smaller threat objects which Earth-strike relatively frequently, and that only nuclear defensive means are adequate for the sizes of threat objects which threaten life on continental and all-Earth geographical scales and which are apt to strike the Earth no more frequently than once every million years.

Biospheric Consequences Of Threat Negation. In order to minimize the biospheric consequences of threat negation, it is necessary to ensure that mass and energy loadings of the Earth's atmosphere be kept below reasonably well-understood damage thresholds, in the worst case contingency, and that possible atmospheric composition changes and particulate loadings be managed very conservatively (because of greater present-day uncertainties regarding the consequences of such changes).

Mass and energy loadings of the atmosphere and the underlying surface of the Earth are of course related principally through the speed, composition and mechanical state of the residual debris of the post-negation threat object. It is required that thermal and acoustic loadings on the ground be below tolerable limits at the most threatened location(s), under the worst contingency. The corresponding energy releases in the atmosphere as a function of height and thus of debris size, composition and mechanical state, are very well-understood in principle at the present time, due to the extensive studies of the past several decades on military applications of nuclear explosives, in the atmosphere and near the Earth's surface.

The general requirements are to keep peak overpressures below ~1 psi and peak thermal pulses below ~0.5 calorie/cm^2/minute and below ~1 calorie/cm^2 time-integrated for intervals of ~5 minutes or less, in order that there be no significant damage to people, structures or crops, under worst-case conditions. (Crops are probably the most sensitive, particularly during intervals of peak insolation in local summer, when they are already thermally stressed.) These requirement may be met by ensuring that no more than ~10 kilotons/km^2 of deeply penetrating debris-energy arrive at any location within the troposphere, e.g., that no more than ~100 tonnes/km^2 of threat object debris are incident (assuming a not atypical 30 km/sec atmospheric entry speed). This requirement is consistent with threat object pulverization with equipment designed to generate rubble of 1 meter scale, which ensures that debris objects as large as 10 meters in diameter will be exponentially rare. (One meter boulders will almost invariably disintegrate in the upper troposphere or even the lower stratosphere, while 10 meter ones may survive down to altitudes of a few kilometers and, if of unusually high strength-in-bulk, may even reach the ground.) If the projected cross-section of the Earth of ~10^8 km^2 were uniformly loaded at this level, 10^{10} tonnes of incident threat object rubble could be tolerated, from a blast and heat standpoint; this corresponds to a compact object of ~2 km diameter.

It is likely that particulate loading of the stratosphere poses a more stringent limit. Calculations, verified semi-quantitatively by observations over the past several years of the global effects of Mount Pinatubo's ejective loading of the stratosphere, suggest that stratospheric loadings of micron-scale particulate above ~100 megatonnes total mass will have sufficiently large global cooling effects for several years as to impair markedly a large fraction of agricultural activity in the sub-tropics. (Mount Pinatubo is estimated to have loaded the stratosphere with ~20 megatonnes of mostly sulfate particulates, most of them of eventual diameter of ≤1 μm.) Debris from pulverized comets and particularly fragile stony asteroids might load the stratosphere with fine particulate with moderately high mass-efficiency, e.g,. ≥10% of the incident mass could be retained in the stratosphere. It is therefore likely that, in order to reliably avoid the risk of an "asteroidal winter," the post-negation non-volatile debris allowed to impact the Earth's atmosphere will have to be upper-bounded at ~10^8 tonnes, that mass corresponding to a compact object of ~0.4 km diameter.

It appears highly unlikely that threat object dispersion would be done so gently or with so little time-to-go that debris mass of even this scale would impinge upon the atmosphere. The debris cloud resulting from the dispersal of a 1 km-diameter object would have to be virtually centered on the Earth and less than 4 Earth diameters in order to achieve this atmospheric loading. Such a compact cloud could be attained only if the product of time-to-go and mean dispersion speed were less than 25 megameters, e.g., if time-to-go was 10^6 seconds and mean dispersion speed were 25 meters/second. Both of these are improbably small.

Now, it is undeniable that even a highly effective defensive system may have non-zero "leakage" of objects sufficiently massive and mechanically strong to penetrate to the Earth's surface. Recalling that the Tunguska object was likely a stony asteroid of the order of 50 meters in diameter and the Barringer Crater in Arizona is attributed to a nickel-iron asteroid of perhaps 80 meters diameter, it is clear that leakage of a single 100 meter object escaping from the negation of a much larger one could result in millions of casualties.

It is therefore likely that defense-in-depth will be required of any system of active defense, and that defensive means which are robust even when time-to-go is minimal be deployed to undergird ones which are employed at earlier times and greater distances from Earth. If non-nuclear means constitute the outermost or first defensive layer, it will be necessary to withhold some space-launch capacity from this layer in order to have the necessary means to launch the under-layer. How much launch capacity must be reserved will obviously depend sensitively on the estimated mass and the number of "leakers" – and whether non-nuclear or nuclear means will be employed for leaker negation.

Needed Threat Objects Data, Defense-Validating Experiments And Diagnostics.
Perhaps the most crucial single parameter needed at any time in the life-cycle of an active planetary defense system is the time-to-go before the first Earth-strike of an object having a diameter of more than a few dozen meters. While such objects and associated times-to-go may be catalogued with considerable accuracy during the next 1–2 decades for the near-Earth objects presently orbiting in the inner solar system without large changes from the present situation, the corresponding information for high-eccentricity asteroids, long-period comets, etc., seems likely to become available only with considerable, sustained effort of types which are not well-represented in current observational endeavors. It is the latter objects which may present the greatest threat to the terrestrial biosphere, for though they are more distant, they arrive with greater speed and – most importantly – far less warning; they are the threats which could be uniquely "first pass deadly." Near-Earth objects, in qualitative contrast, very likely will be seen for many orbital periods – i.e., many years – prior to possible Earth-strike, soon after reasonably capable sky surveillance becomes operational.

Of comparably fundamental importance in threat characterization are diagnostic means for remotely assessing the composition and, most particularly, the mechanical conditions of potential Earth-impactors. It seems likely that active defenses against "flying rubble piles" will be significantly easier to implement (and reliable to use) than ones against nickel-iron asteroids of the same mass, with highly consolidated stony asteroids being the intermediate case. The use of diagnostic spacecraft of the *Clementine* class to probe distant threat objects well in advance of their arrival in near-Earth space will permit economies in defensive system operation, making it unnecessary to regard every incoming object as a nickel-iron asteroids and to expend defensive resources to defeat such relatively formidable threats. Such modest-mass spacecraft will presumably be dispatched on very high-speed trajectories, in order to return results sufficiently early to support launch of the appropriate number and class of pulverization or vaporization equipments.

After such remote diagnostic means are demonstrated successfully in the program of defensive system development and testing, it will become of immediate interest to test various defensive systems and schemes in small scale. (Such sub-scale experiments are appropriate both to minimize per-event costs and to maximize the number of experimental opportunities in any time-interval.)

Fortunately, sub-scale experimentation, followed by performance evaluation and then by defensive system validation, seems eminently feasible, in view of the relatively huge population of sub-100-meter diameter objects which pass within the lunar orbit of the Earth each year. Since all such objects are gravitationally unbound (by large margins) relative to the Earth-Moon barycenter, dispersion of them with various defensive prototypes and system operating in sub-scale can have no possible adverse consequences – once they are "kinematically downwind" of the Earth.

Obviously, it will be crucial to diagnose fully the interaction of defensive equipments with these sub-scale proto-threat objects. Doing so will require both survivable remote sensing platforms and telemetry-intensive non-survivable ones which will fly immediately behind objects launched by defensive systems to pulverize or vaporize the proto-threat objects and which will provide the high-resolution data on pulverization and vaporization events required for knowledge-based certification of full-scale active defensive systems. Indeed, preliminary work has already been performed in the specification and design of platforms and equipment suitable for such purposes, in connection with follow-on asteroidal exploration missions of the *Clementine* mission-family. Detailed planning of defensive systems will greatly benefit from such experiments. Such planning should, therefore, be deferred until experimental results are available.

Manifestly, defensive system robustness can be fully demonstrated only with full-scale experiments. These will logically follow the sub-scale experiments, and, in order to be performed in a timely manner, will necessarily involve test objects found and worked with at locations substantially more distant from the Earth.

Conclusions. Active defense of the terrestrial biosphere from all likely scales and natures of cosmic bombardment can be commenced during the next quarter-century. Contemporary technology is sufficiently powerful to negate threat-objects of all kinds heading for the Earth with diameters ≤10 km, by either pulverization or vaporization for objects ≤1 km in diameter and by pulverization-and-fragment dispersion for multi-km diameter objects. Deflection of a giant threat object – with diameter ~100 km – may be feasible by using these pulverization and vaporization techniques to steer an optimally chosen sub-kilometer-diameter near-Earth object into its path.

Critical enabling hardware for initial implementation of both nuclear and non-nuclear defenses is currently becoming available as "Cold War surplus," in the form of heavy ICBMs and associated post-boost vehicles. These can place the required defensive equipments in the immediate vicinity of the incoming threat objects, with great cost-savings. Other equipments of the types demonstrated in the recent *Clementine* lunar mission will greatly facilitate inexpensive, near-term defensive system testing, as well as the required maximally distant detection, tracking and categorization of small objects.

Near-term experimentation on the many relatively small objects passing the Earth every year at closest approach distances of a few thousandths of an AU will suffice to characterize most of the key features of representative threat objects, as well as validating various near-term approaches to active defense of the terrestrial biosphere. Full-up, full-scale exercising of capabilities validated in sub-scale will then provide the necessary assurance that active defenses will perform robustly when required.

Acknowledgments. We thank Drs. Yu-Li Pan and John Hunter for use of their computational and experimental data regarding hypervelocity penetrator interaction with targets, Dr. William Tedeschi for helpful comments and data regarding the explosive fracture energetics of natural materials and Gordon Wenneker, Gloria Purpura, and Linda Scott for expert assistance in preparing this manuscript and its graphics.

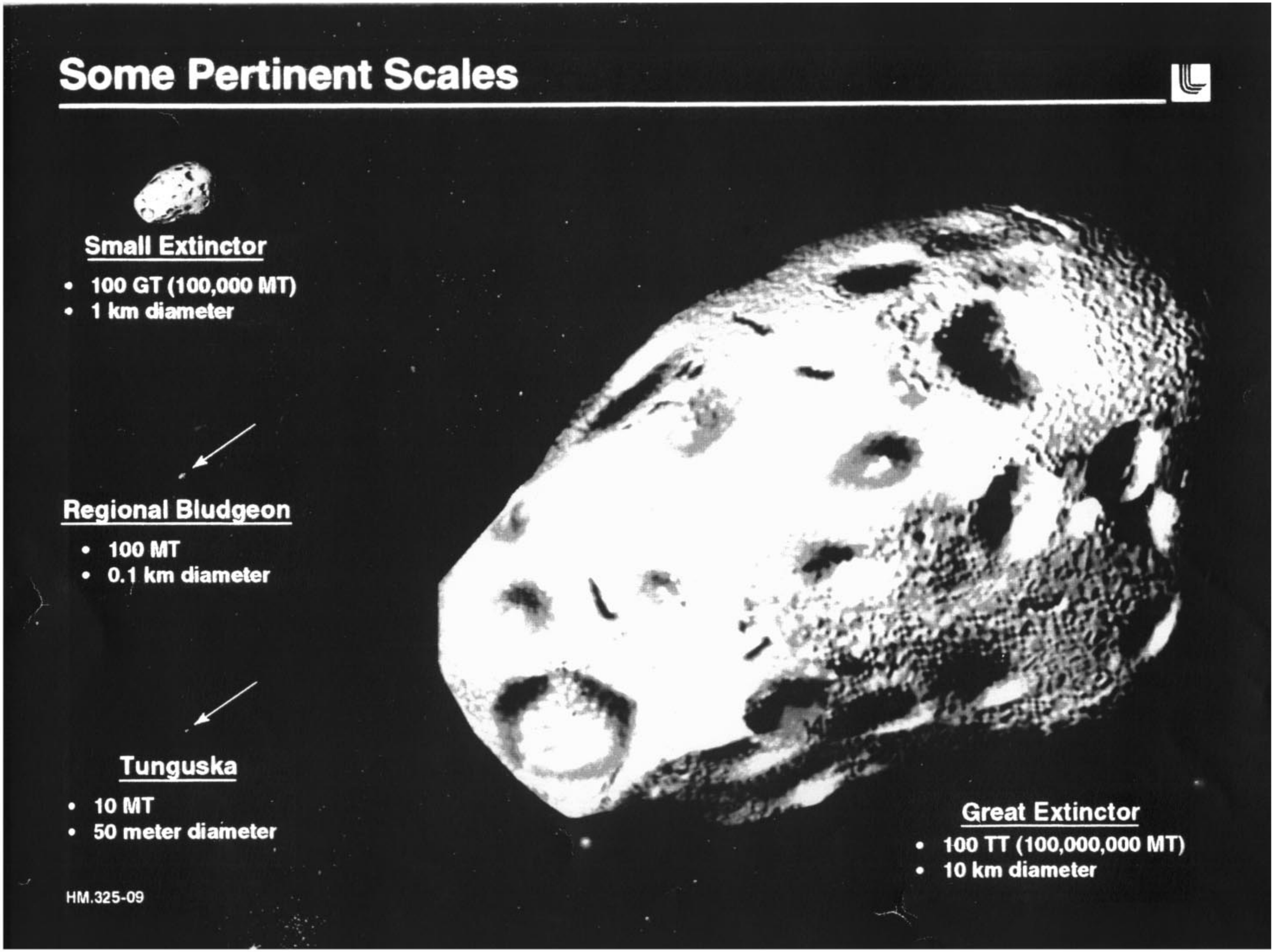

Some Pertinent Scales
Small Extinctor
• 100 GT (100,000 MT)
• 1 km diameter
Regional Bludgeon
• 100 MT
• 0.1 km diameter
Tunguska
• 10 MT
• 50 meter diameter
Great Extinctor
• 100 TT (100,000,000 MT)
• 10 km diameter
HM.325-09

Figure 1

THREAT OBJECTS

	Comets	Stony/Carbonaceous Asteroids	Metallic Asteroids
Composition:	Ice & Rocks	Rocks	Ni–Fe Metals
Strength:	Weak	Weak <–> Moderate	Strong
Relative Flux:	5%	85%	10%
Relative Energy:	4	1	1
Threat Nature:	Unpredictable	Predictable	Predictable
Warning Time:	Months –> Year	Years –> Decade	Years –> Decade

50517-RAH-02

Figure 2

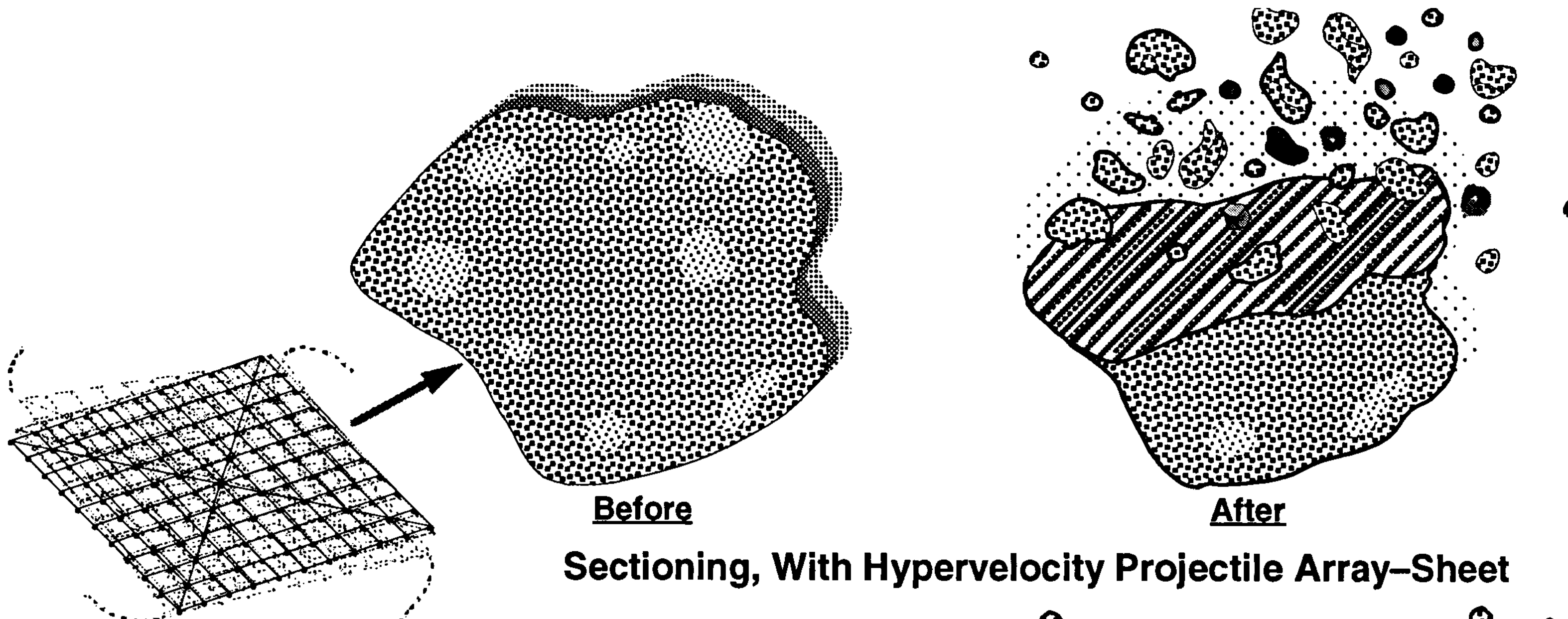
SPECIFIC ENERGY SCALES OF COSMIC BOMBLETS

$10^{-7} - 10^{-2}$	<<	$10^{-1} - 10$	<<	10^{3}	<<	$10^{5} - 10^{6}$	Joules/gram
Gravitational Binding Energy (0.03 – 10 km dia.)		Pulverization Energy		Vaporization Energy		Kinetic Energy (Earth–Frame)	

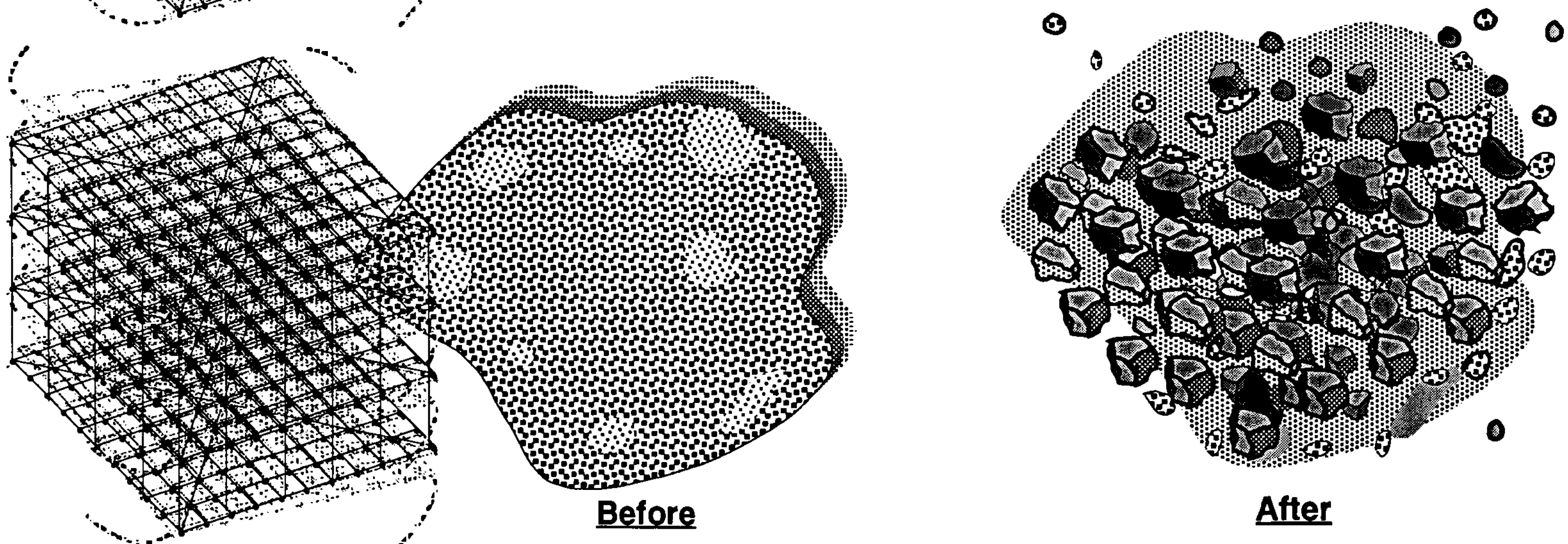
50511-LLW-05

Figure 3

THREAT OBJECT PULVERIZATION



Sectioning, With Hypervelocity Projectile Array–Sheet

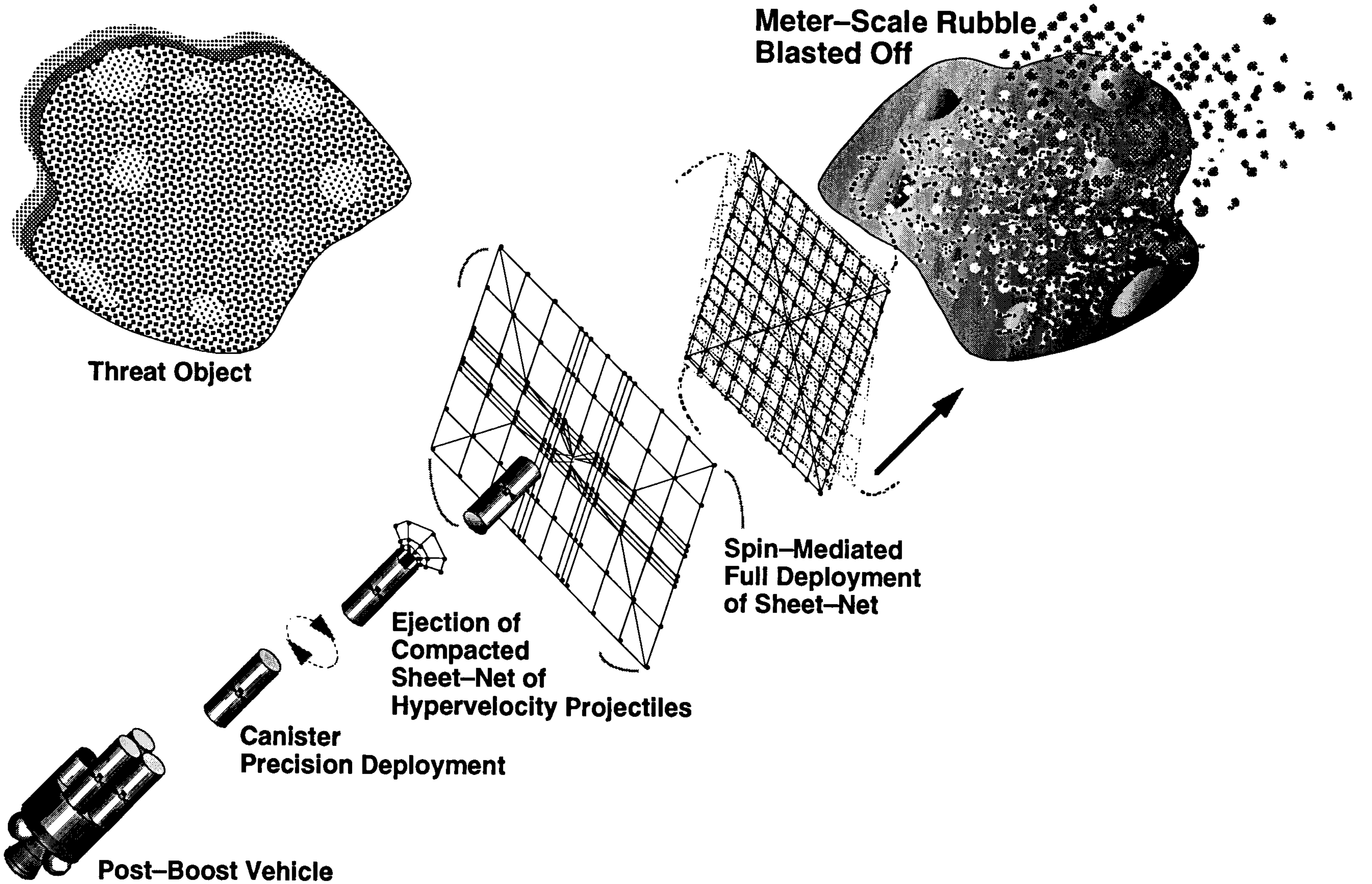


50511 LLW-03

Pulverizing, With Hypervelocity Projectile Lattice

Figure 4

A GENERALLY APPLICABLE APPROACH TO PULVERIZATION



50511-LLW-02

Figure 5

Initial Geometry of a Tungsten Penetrator Moving into a Very Thick Steel Slab

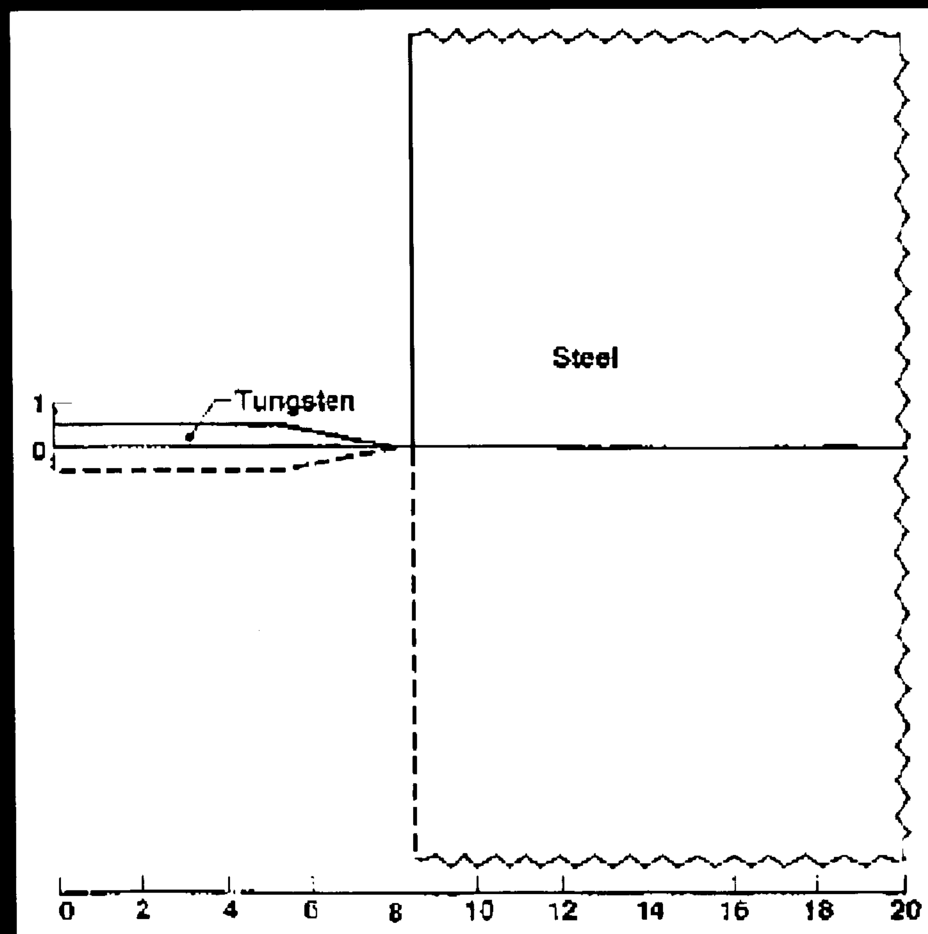


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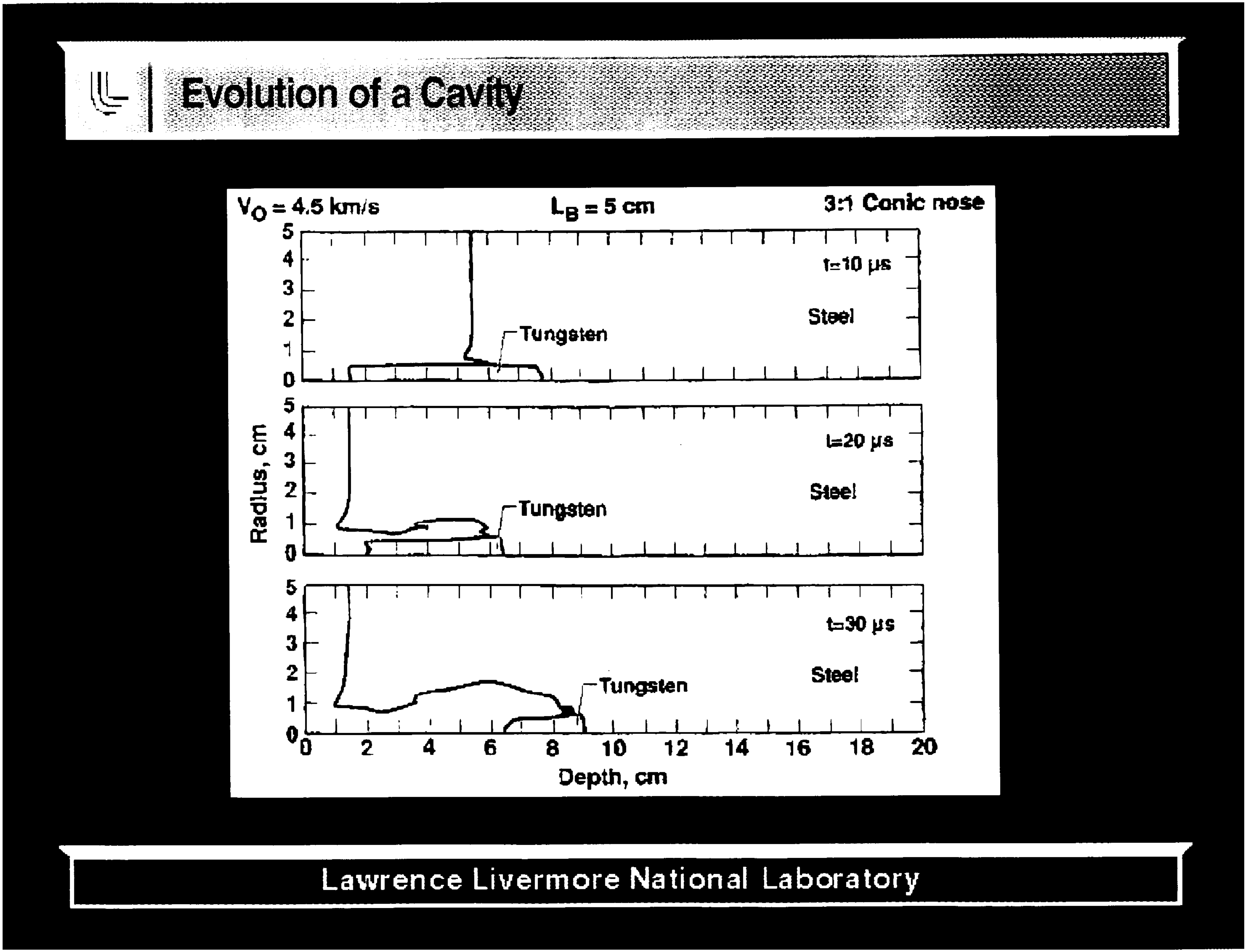
Figure 6A



Evolution of a Cavity
V_O = 4.5 km/s
L_B = 5 cm
3:1 Conic nose
t=10 µs
Steel
Tungsten
t=20 µs
Steel
Tungsten
t=30 µs
Steel
Tungsten
Radius, cm
Depth, cm
0
1
2
3
4
5
0
2
4
6
8
10
12
14
16
18
20
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Figure 6B

Evolution of a Cavity (cont.)

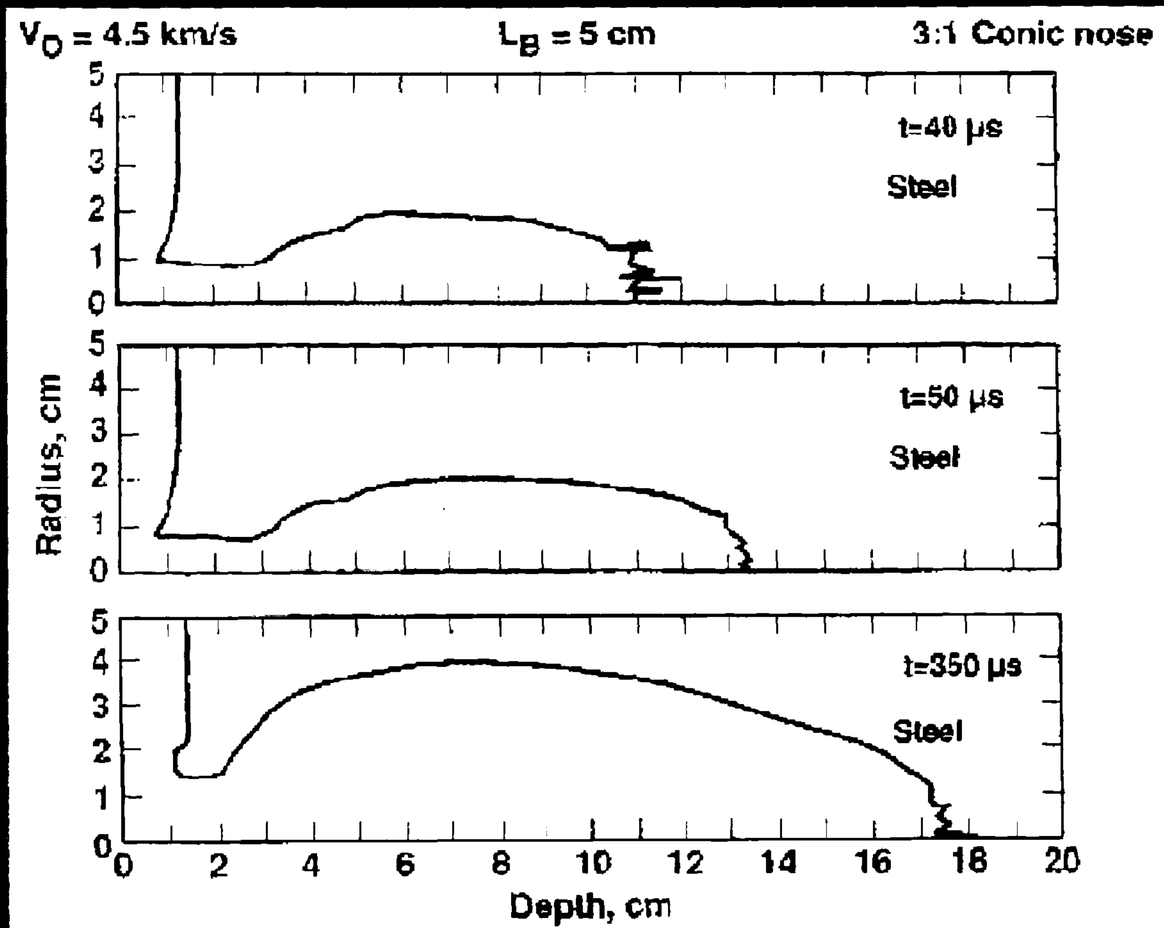

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Figure 6C

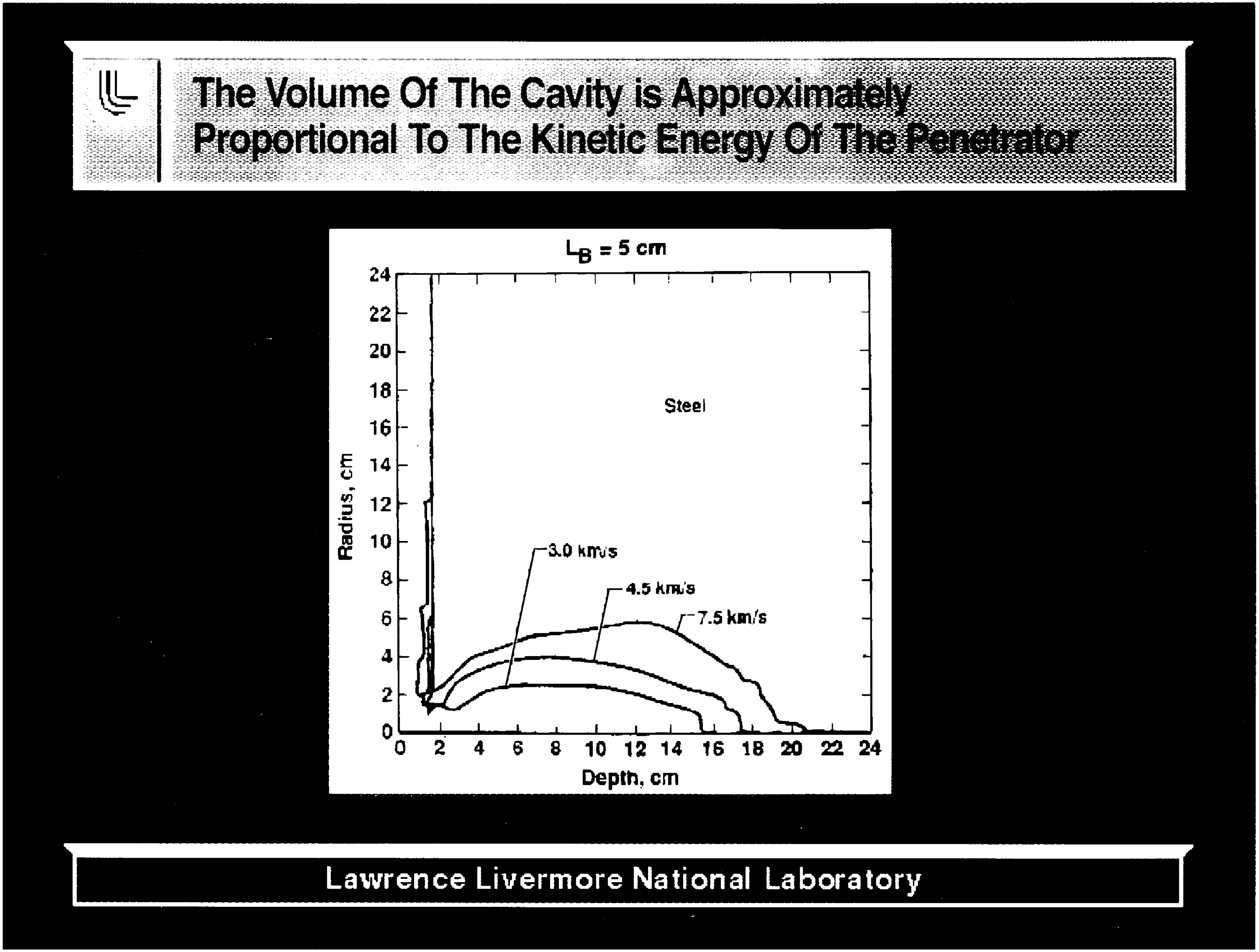
The Volume Of The Cavity is Approximately Proportional To The Kinetic Energy Of The Penetrator
L_B = 5 cm
Steel
3.0 km/s
4.5 km/s
7.5 km/s
Radius, cm
Depth, cm
0 2 4 6 8 10 12 14 16 18 20 22 24
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Figure 6D

2D Computer Simulation Results Indicate That The Normalized Penetration Depth Increases With Decreasing Penetrator Length

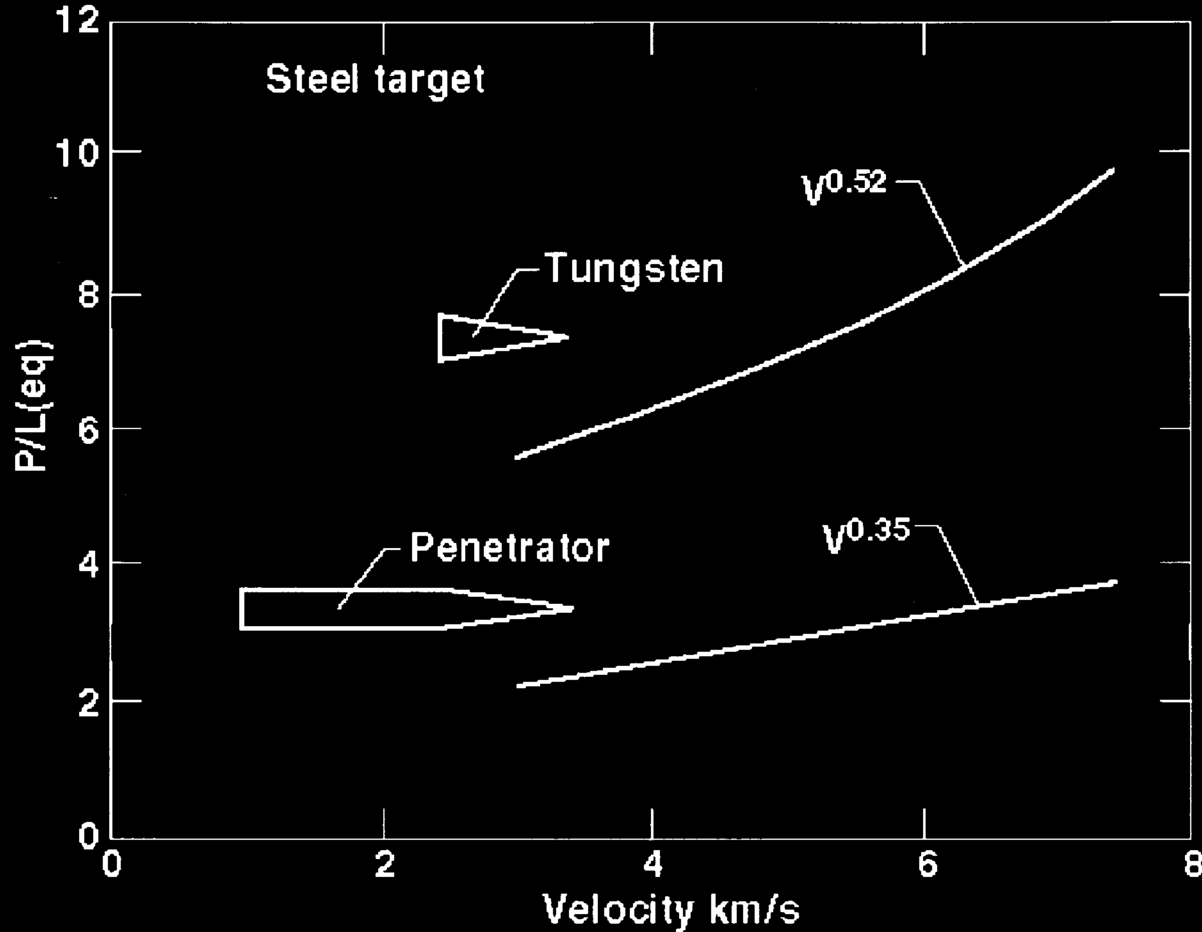

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Figure 6E

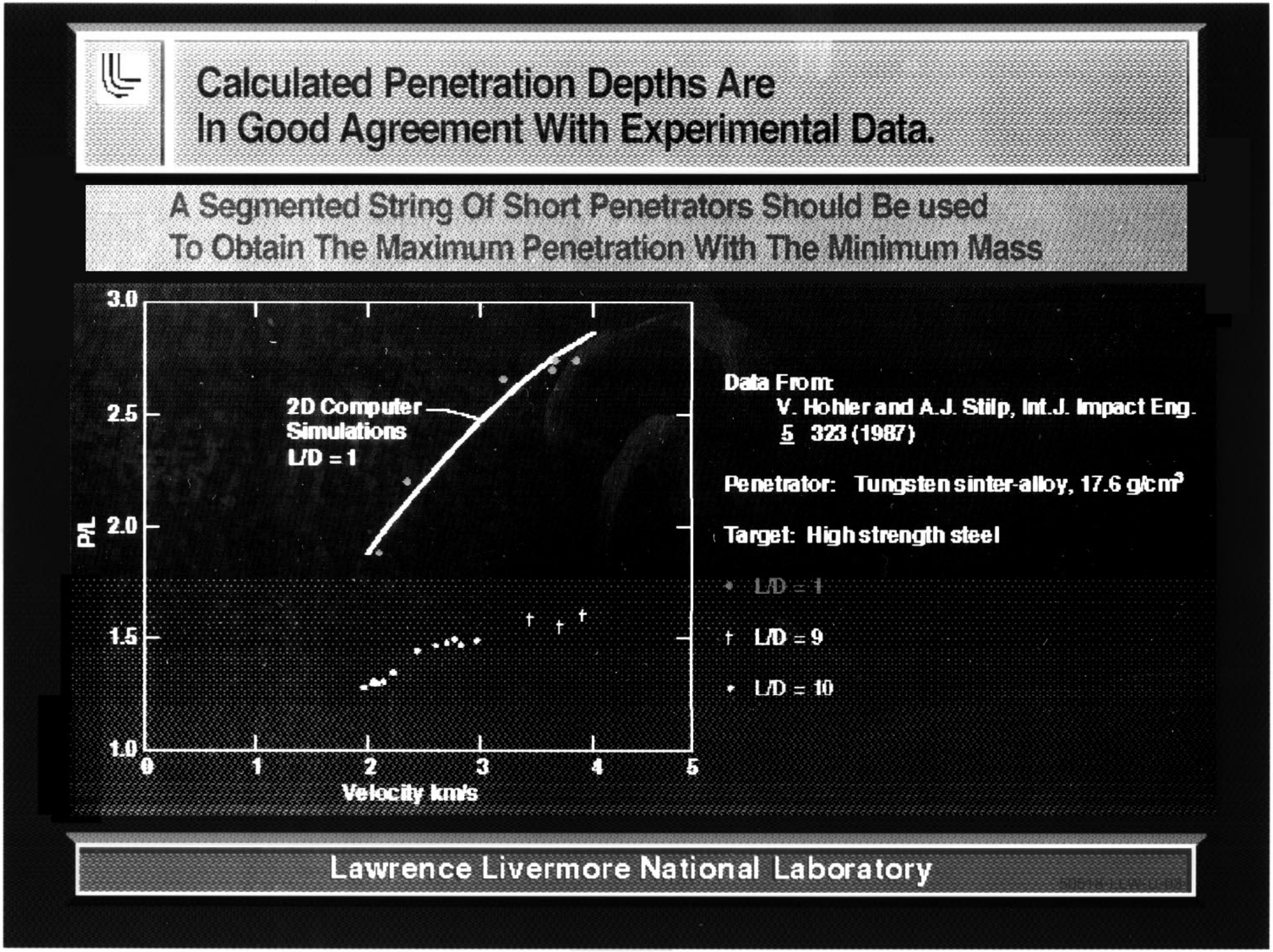
Calculated Penetration Depths Are
In Good Agreement With Experimental Data.
A Segmented String Of Short Penetrators Should Be used
To Obtain The Maximum Penetration With The Minimum Mass
3.0
2.5
2.0
1.5
1.0
P/L
0
1
2
3
4
5
Velocity km/s
2D Computer
Simulations
L/D = 1
Data From:
V. Hohler and A.J. Stilp, Int.J. Impact Eng.
5 323 (1987)
Penetrator: Tungsten sinter-alloy, 17.6 g/cm³
Target: High strength steel
L/D = 1
L/D = 9
L/D = 10
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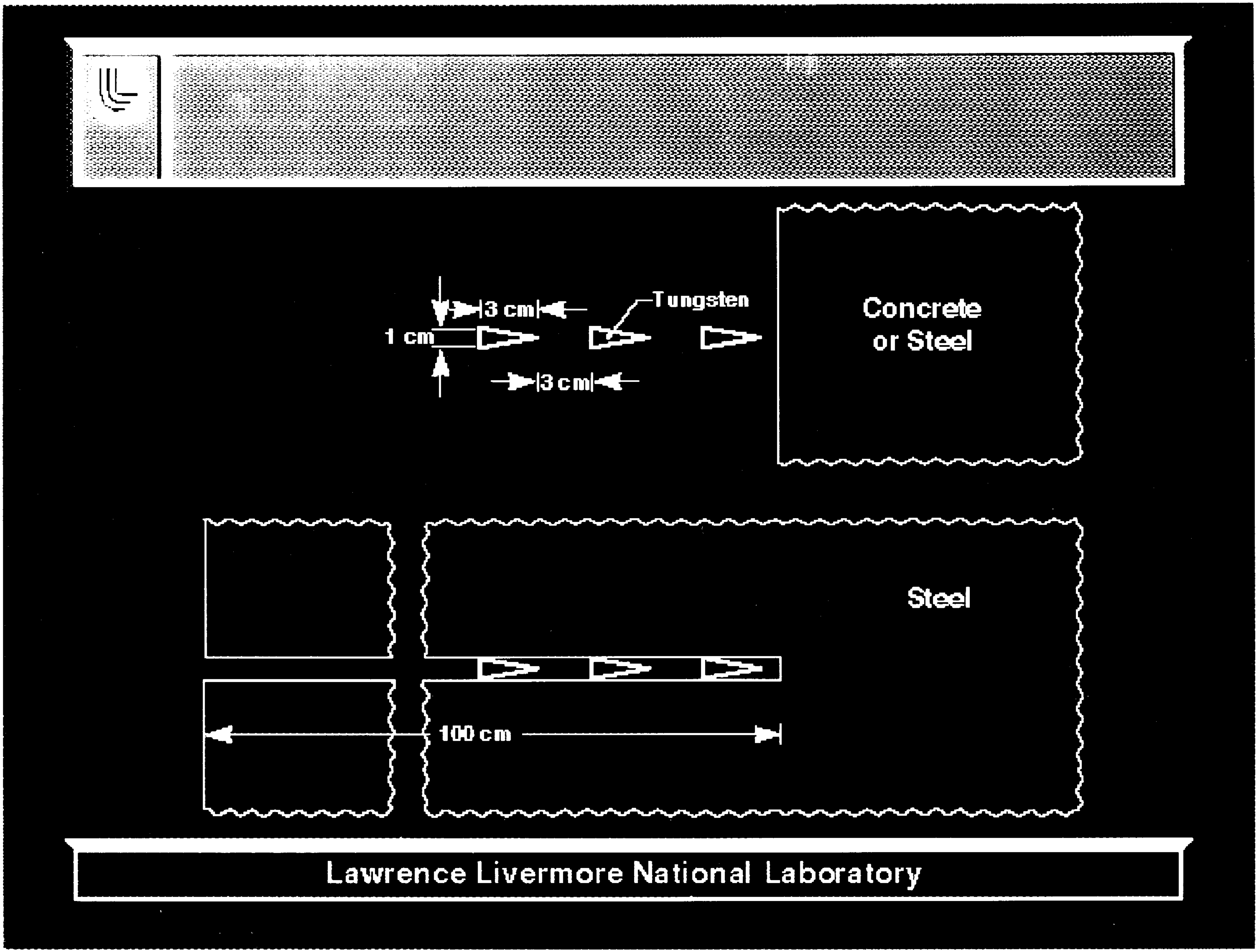
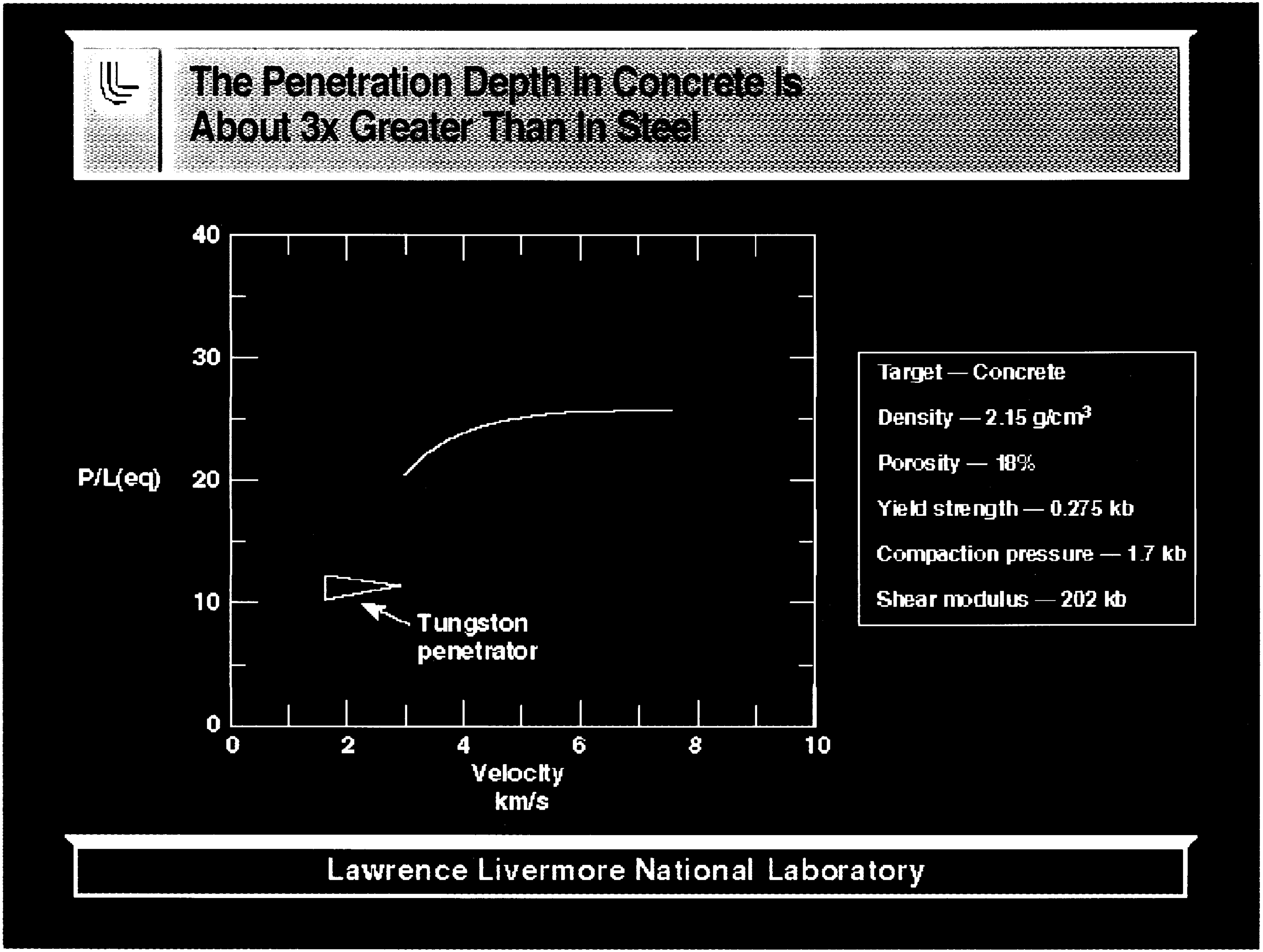
Figure 6F



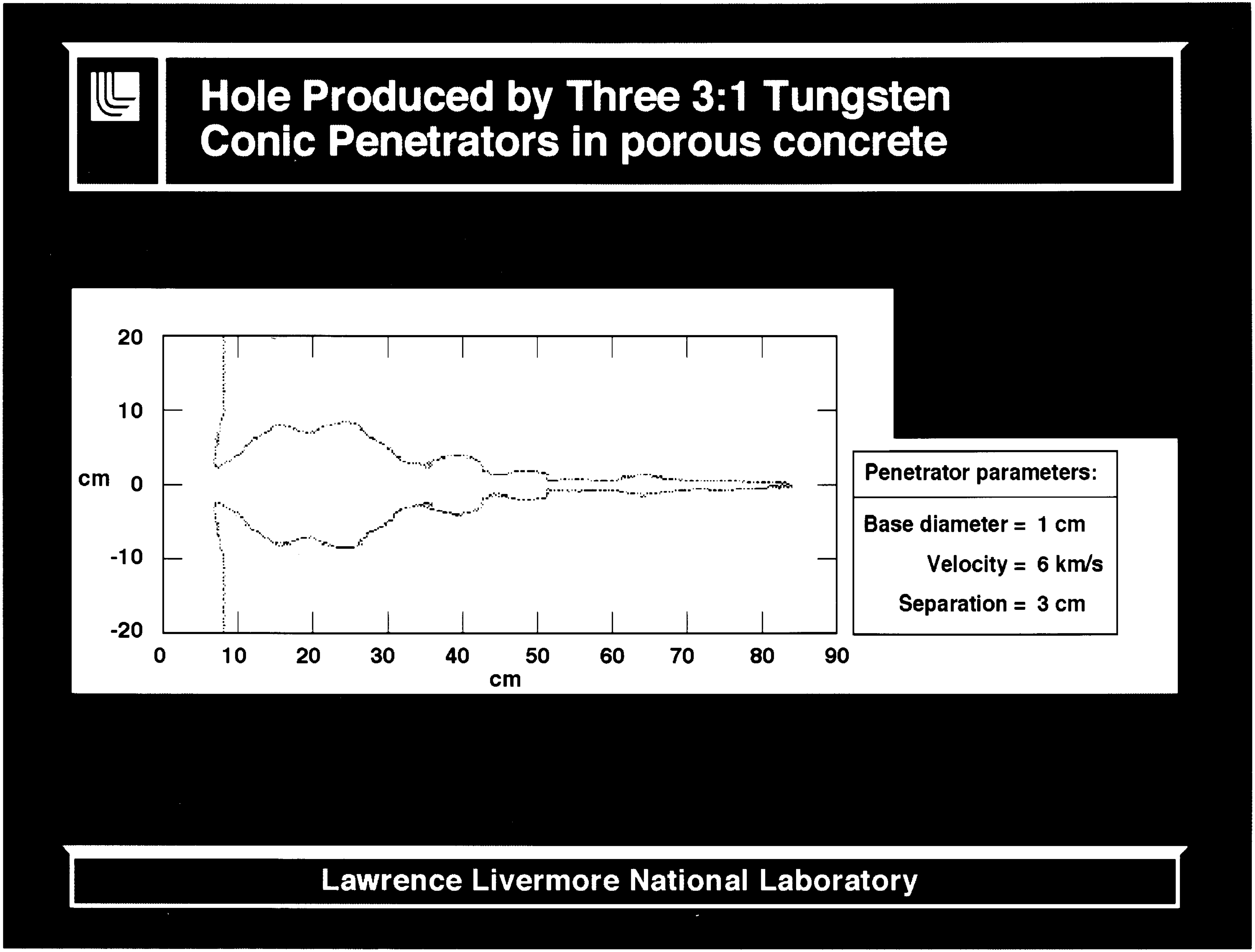
3 cm
1 cm
Tungsten
3 cm
Concrete
or Steel
Steel
100 cm
Lawrence Livermore National Laboratory

Figure 6G



The Penetration Depth In Concrete Is About 3x Greater Than In Steel
40
30
20
10
0
P/L(eq)
0
2
4
6
8
10
Velocity
km/s
Tungston
penetrator
Target — Concrete
Density — 2.15 g/cm3
Porosity — 18%
Yield strength — 0.275 kb
Compaction pressure — 1.7 kb
Shear modulus — 202 kb
Lawrence Livermore National Laboratory

Figure 6H



Hole Produced by Three 3:1 Tungsten Conic Penetrators in porous concrete
20
10
cm 0
-10
-20
0
10
20
30
40
50
60
70
80
90
cm
Penetrator parameters:
Base diameter = 1 cm
Velocity = 6 km/s
Separation = 3 cm
Lawrence Livermore National Laboratory

Figure 6l

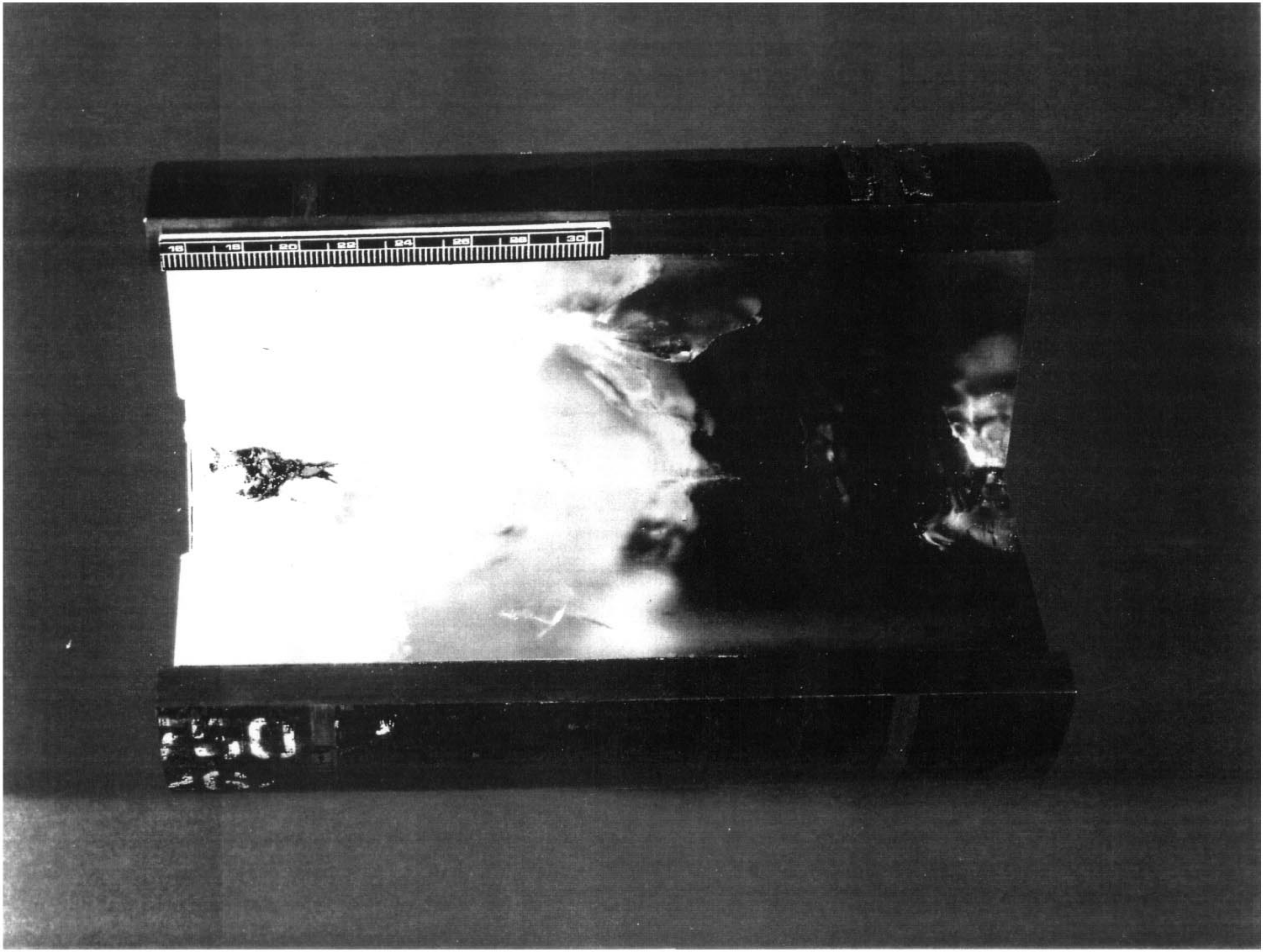


Figure 6J

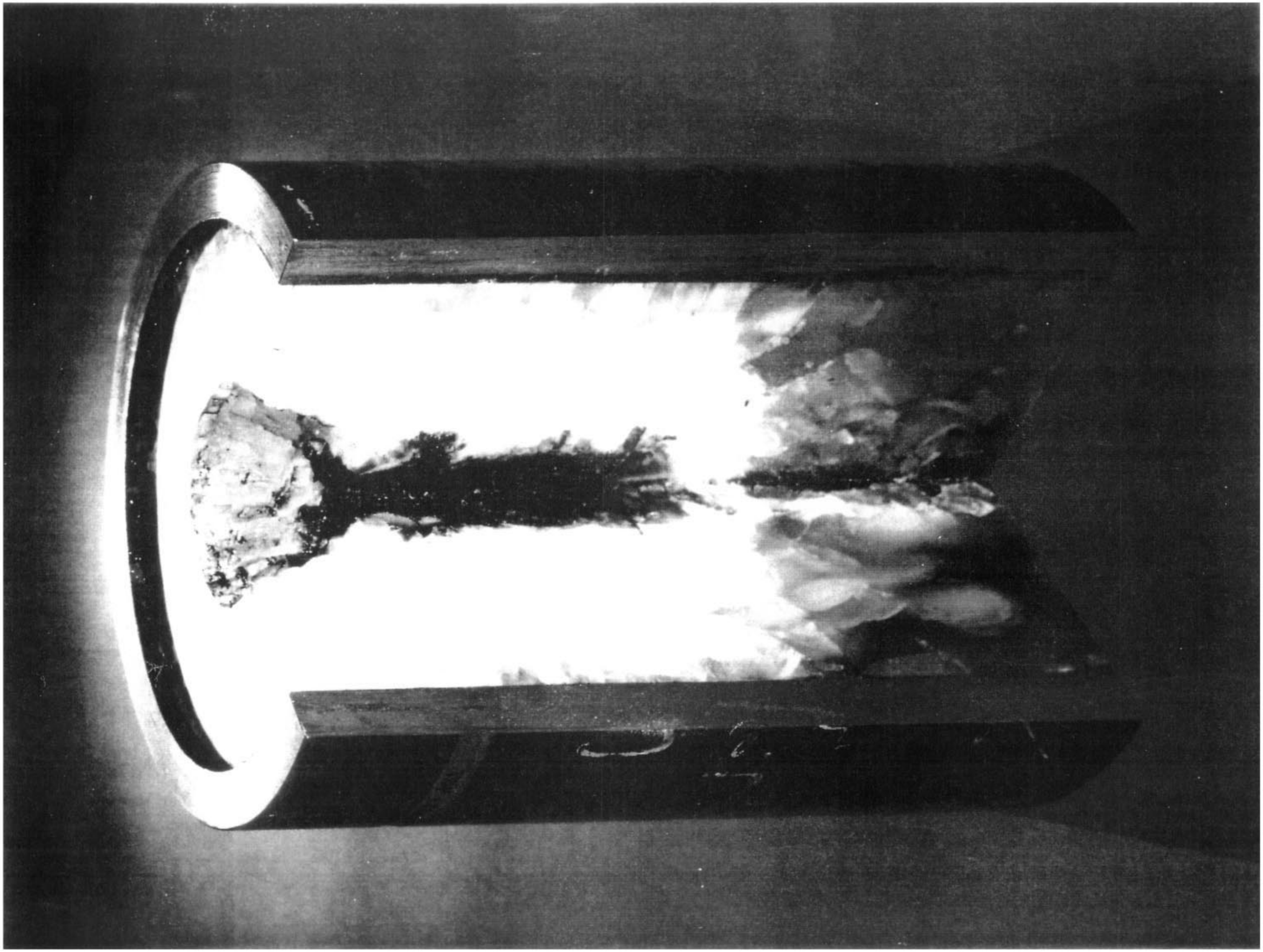


Figure 6K

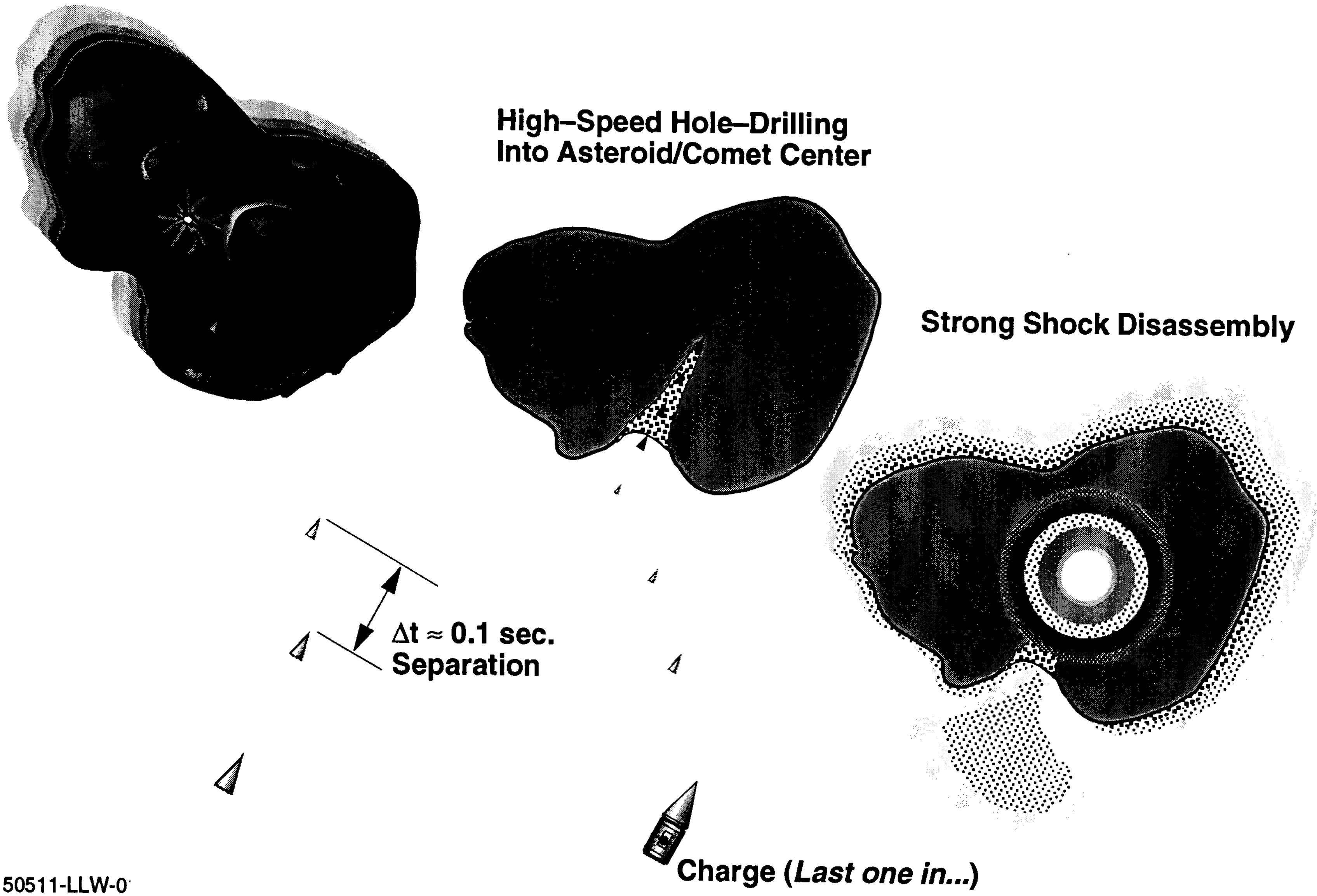
HL.302-08/YLP

Figure 6L

HL.302-01/YLP

Figure 6M

THREAT OBJECT VAPORIZATION

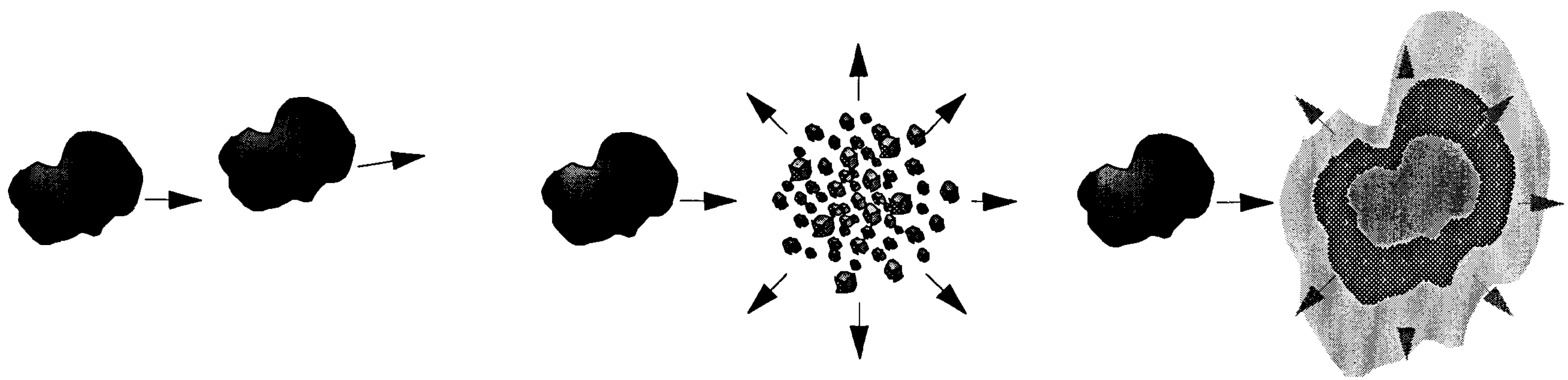


50511-LLW-0

Figure 7

THREAT NEGATION

Deflection | **Pulverization** | **Vaporization**



Required Energies

.01 — .10 J/gm | 10 — 100 J/gm | 1000 J/gm

- **Kinetic Energy:** $10^5 - 10^6$ J/gm
- **Nuclear Explosives:** 10^{11} J/gm

50517-RAH-01

Figure 8

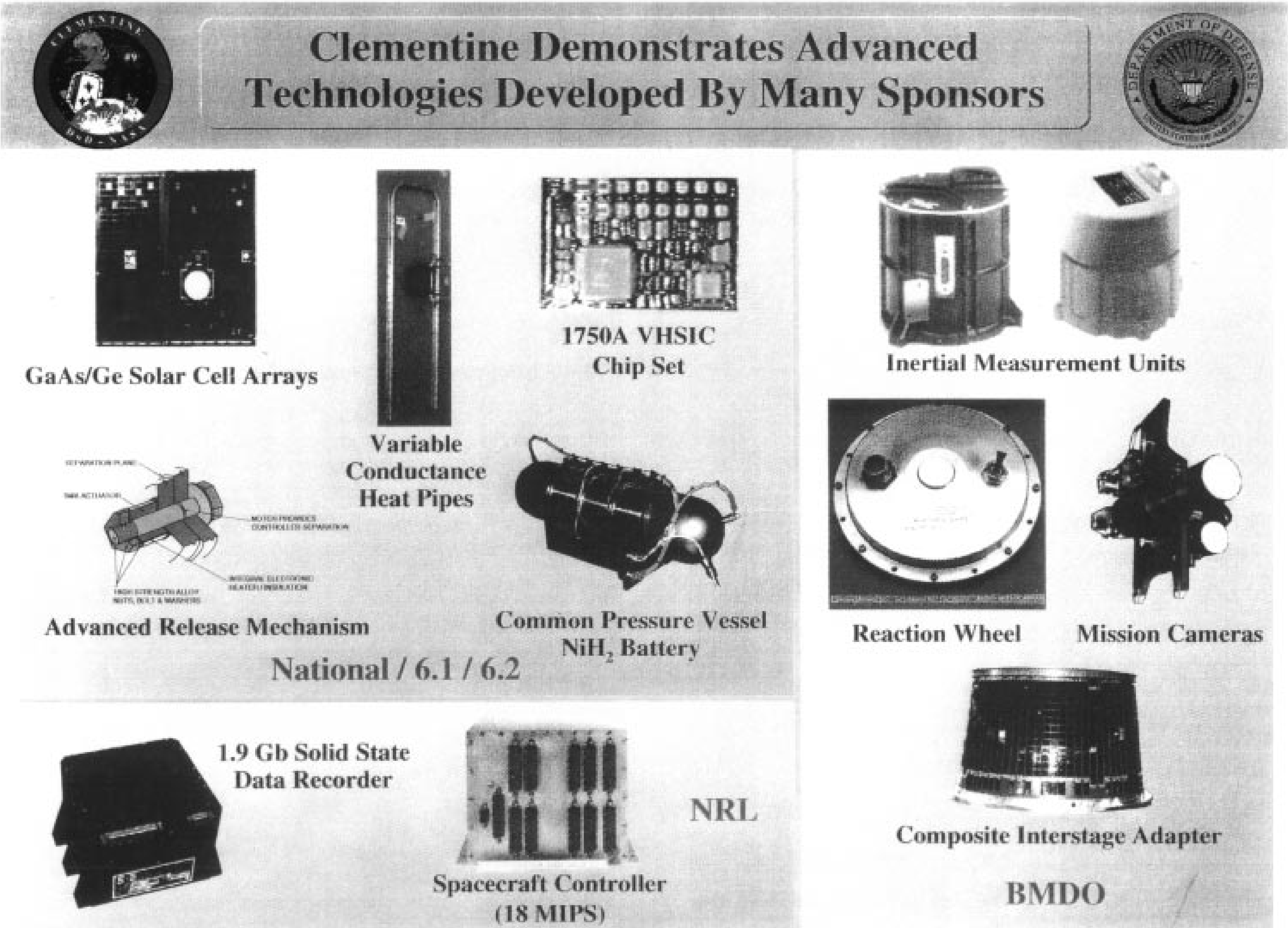
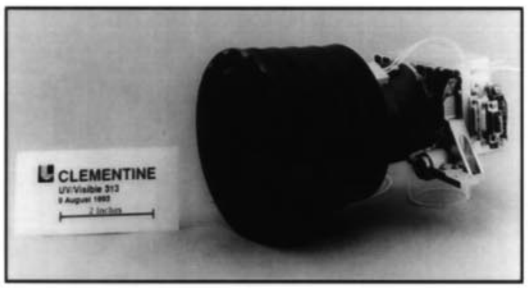
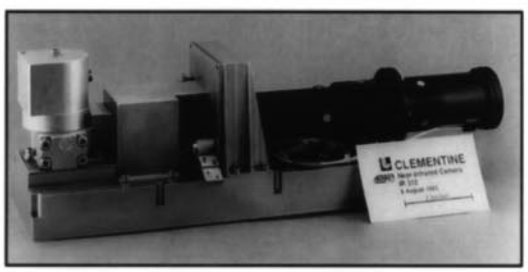
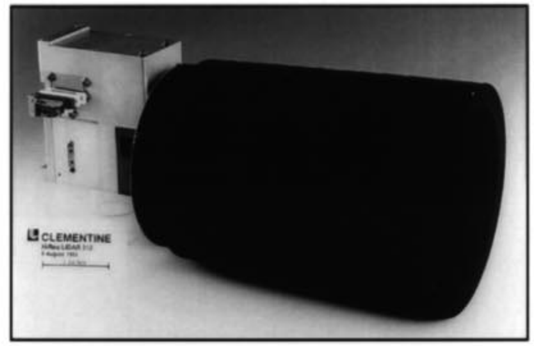

Clementine Demonstrates Advanced Technologies Developed By Many Sponsors
GaAs/Ge Solar Cell Arrays
Variable Conductance Heat Pipes
1750A VHSIC Chip Set
Advanced Release Mechanism
Common Pressure Vessel NiH_2 Battery
National / 6.1 / 6.2
1.9 Gb Solid State Data Recorder
Spacecraft Controller (18 MIPS)
NRL
Inertial Measurement Units
Reaction Wheel
Mission Cameras
Composite Interstage Adapter
BMDO

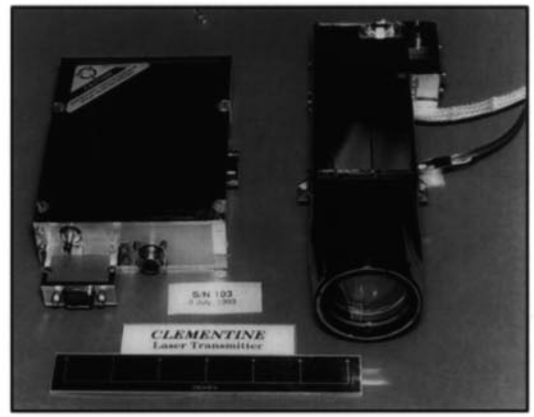
Figure 9A

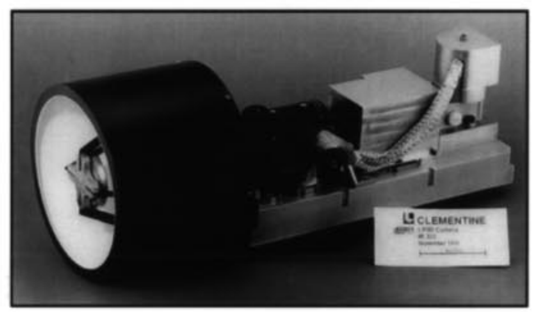
Clementine Sensor Suite









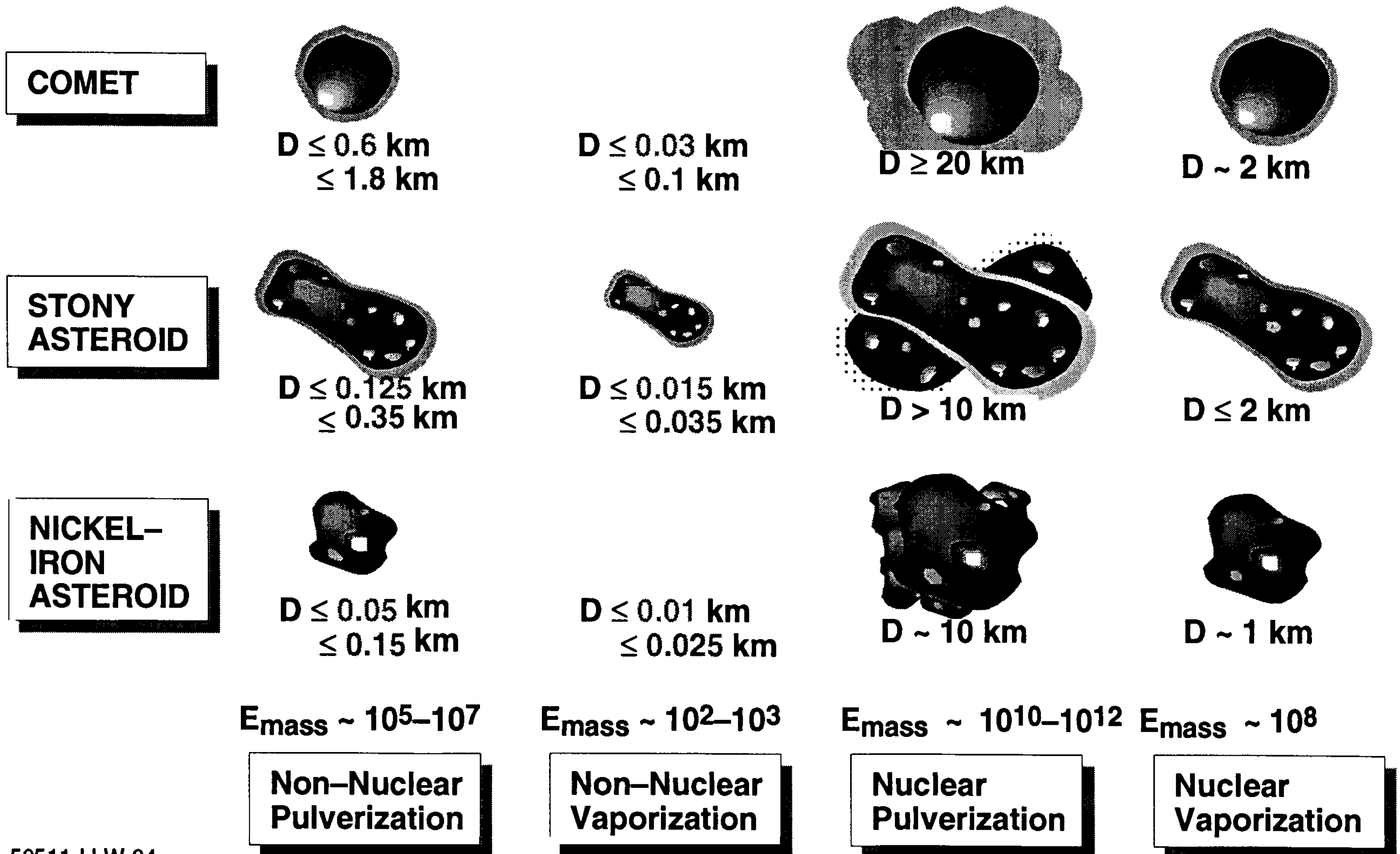


ATP-1293-02475-LDP
HC.097-01

Figure 9B

NEAR–TERM THREAT NEGATION CAPABILITIES

- Contemporary Technology
- Single Heavy–Lift Launch (e.g., ENERGIA or Fleet–of–100 SS–18s)



50511-LLW-04

Figure 10

Cost And Benefits of Near-Earth Object Defenses

Gregory H. Canavan
Los Alamos National Laboratory

The value of defenses against objects from space is evaluated by comparing the losses expected in their absence to the costs of defenses, which indicates that defenses should be technically and economically feasible for most threatening objects. Impact frequency data are converted into expected losses from objects of given diameters, and that into the marginal benefits of defenses. The marginal cost of search and deflection are estimated and equated to determine the sizes of objects that can be negated effectively. For objects detected long before impact, the analysis determines the optimum sensor size and cost. The programs for long and short period object search and interception have common technological features that make them essentially two phases of a single program.

Introduction

Historical evidence on the frequency and destructiveness of comet and near-Earth object (NEO) impacts can be used to estimate the damage future impacts are likely to produce, which suggests average losses of roughly $0.5 B/yr, dominated by the largest objects. It is also possible to use data from defense programs and studies of the last few years to make parametric estimates of the cost of search and interception, which are the major components of a defense. The cost of search dominates for small objects and long ranges, while the cost of interception dominates for large objects with short warning. For an object of a given size, it is possible to determine optimal combinations of search and interception that are not overly sensitive to uncertain cost and performance parameters.

The calculations are simplest for long-period comets (LPCs), which are analyzed explicitly. Equating their marginal benefits to the marginal costs of optimized defenses indicates that defenses are cost effective for LPCs or other objects detected on final approach up to ≈ 7 km in diameter. This result, and the technologies required to realize it, are reasonable, relevant, and weakly dependent on model parameters. The maximum size is insensitive to search cost; the maximum diameter is insensitive to interception costs as well.

These results are extended to objects that make many passes through the inner solar system before approaching the Earth. The detection rate is shown to depend primarily on the number of detectors in the focal planes of the search sensors used, whose optimization leads to systems somewhat larger than those currently contemplated. Such detection should be highly cost effective with or without interception capability.

Current levels of technology, if not of integration, could address most threats. For most, search and interception should be not only feasible and affordable, but cost effective. Technology assessments and integration studies could establish the feasibility of defenses within a few years. While only nuclear explosives are generally cost effective with today's technology, non-nuclear concepts could have a wider role, given advances in propulsion and search. Optimal combinations of detection and interception are such that defenses against LPCs could arguably be developed over a period of a decade for expenditures modest compared to expected losses.

Expected losses from NEO impacts

Estimating the value of NEO defenses is a new and still somewhat controversial subject. The first evaluation, presented at the NEO Interception Workshop, was based largely on the information presented there. While the *Proceedings* of that meeting was in preparation, newer data from the Spacewatch NEO search became available, which indicated a much larger contribution from ≈ 5 to 50 m NEOs. Additional Spacewatch data at the University of Arizona and Erice meetings led to further modification of the conventional "Shoemaker curve" shown in Fig. 1. The main feature of interest here is that the curve contains four rough groups of NEOs, which are distinguished by the power law, n, in the dependence of their collision frequency, f, on NEO diameter, D^{-n}. For $D < 50$ m, n is unknown but ≈ 6. For $50 \text{ m} < D < 200$ m, $n \approx 8/3$. For $200 < D < 2$ km, $n \approx 2$. For $D > 2$ km, $n \approx 3$.

These collision frequencies are converted into expected losses by multiplying f for each D by the loss expected from the impact of a NEO of that diameter. The loss generally takes the form of an area of destruction that depends on the NEO's mass and energy, which can be converted into a fraction of total value distributed over the Earth's surface through a phase-space argument. Integrating over diameters up to D gives the result shown in Fig. 2 (Canavan, 1994). Briefly, NEOs from ≈ 5 to 50 m make a contribution of ≈ $6M/yr; those from ≈ 50 to 200 m make another contribution of ≈ $6M/yr; those from ≈ 200 to 2 km make a contribution of ≈ $100M/yr; and those larger than ≈ 2 km make a contribution of ≈ \$400M/yr. Expected losses are dominated by the infrequent but devastating impact of very large objects, which account for 80% of losses.

Some sensitivities should be noted. The ≈ \$6M/yr contribution from 5 to 50 m NEOs is based on the assumptions that the Spacewatch collision frequencies are no more than an order of magnitude greater than the Shoemaker curve, that only 6% of the small NEOs are metallic, and that the 94% that are stony break up during entry without damage. Should the fraction of metallic NEOs prove larger, their contribution would increase accordingly. If each of these assumptions was in error by a factor of 3, the contribution from small NEOs could approach that of ≈ 200 m group. Conversely, should the number of NEOs in this group—or the damage they produce—be refined downward by such amounts, the losses would decrease to insignificant levels.

The \$6M/yr contribution from 50 to 200 m stony asteroids is from damage on the ground due to shock waves from NEOs that break up tens of kilometers higher (Chyba, et al., 1993). While this has only been an active area of research for a few years, it appears unlikely that the losses from this group could be much greater than those shown, and they could be significantly lower. The \$100M/yr contribution from ≈ 200 m to 2 km NEOs largely represents damage by tsunami generated by asteroids that impact in oceans. Without tsunami, the losses from this group would scale much like those from smaller NEOs and lead to a similar contribution (Canavan, 1994). NEO-produced tsunamis have been studied little (Canavan, 1994). Although it is not clear that the historical record supports even the level of damage estimated, the concentration of population around coastal areas that have become heavily populated in modern times could make the damages much larger than those estimated above.

The losses from large NEOs are only rough bounds derived from the conventional assumption that NEOs larger than 1 to 2 km can cause global damage. There are suggestions that even smaller NEOs could cause global damage, but the arguments for even the larger values are largely qualitative, and not necessarily consistent with the paleontological record. The values shown follow from the following calculation, which both illustrates the method and is useful below. The Earth's gross product G is ≈ \$20T/yr. Thus, if the damage from a several kilometer NEO persisted for a time of T ≈ 20 years, the total loss would be about TG ≈ \$400T. The impact frequency of NEOs with D greater than ≈ 3 km is roughly $f \approx K/D^n$, where from Fig. 1, $n \approx 3$ and $K \approx 10^{-5}$ km^3/yr. The losses from NEOs with diameters between 2 km and D is

$$L = \int_2^D dD\, GT\,(-df/dD) = GT[f(2) - f(D)] = GTK(1/2^3 - 1/D^3). \qquad (1)$$

The expected annual loss from NEOs with 2 < D < 3 km is ≈ \$400T x 10^{-5} km^3/yr $(1/2^3 - 1/3^3)$ ≈ \$300M/yr, which is roughly the increment between the "sub-global" < 2 km and "global" 3 km contribution shown in Fig. 2.

Each factors in this estimate is uncertain. The collision frequency of large NEOs is uncertain by about a factor of two. The time persistence of the destruction is uncertain by about an order of magnitude. The expected loss is uncertain by several orders of magnitude. The loss of production is used above to denominate losses, but it is only a surrogate for value losses that are more difficult to quantify. Moreover, these losses are sensitive to the time for preparation available before impact. If a NEO of this size hit without warning or preparation, the devastation could be global and total. If there was adequate warning and preparation, the above estimate of losses should be reasonable. If there were adequate defenses, losses could be minimal. The first case corresponds to living in an uninsured house and hoping there is no fire. The second corresponds to building a spare house as insurance. The third corresponds to protecting the house from fire. The first is simply foolish. Whether the second or third is preferred depends on the costs of the defense relative to the losses estimated above, which is discussed below.

Benefits of defenses

Integrated losses alone do not determine the value of defenses. Deployment decisions are made on the basis of marginal economics. Since the benefits of defenses are measured by the losses they prevent, the value of NEO defenses is determined by the marginal benefits curves of Fig. 3, which are produced by differentiating the integral loss curve of Fig. 2. There are four segments, corresponding to the four groups of NEOs discussed above. The first starts at ≈ \$1M/yr-m at 5 m and falls to ≈ \$10K/yr-m at 50 m. The curves for 50 to 200 and 200 to 2 km NEOs fall from ≈ \$0.1M/yr-m to \$0.01M/yr-m. The curve for large NEOs falls from ≈ \$4M/yr-km at 2 km to ≈ \$10M/yr-km at 8 km. The calculation of the marginal losses of small NEOs is intricate; for large NEOs it is simpler. For them, Eq. (1) gives the integral losses, and its derivative gives the marginal losses due to NEOs of diameter D

$$L' = GT\,(-df/dD) = 3GTK/D^4, \qquad (2)$$

which explains the strong slope of the marginal benefit curve and reinforces their sensitivity to uncertainties in the extent and duration of the damage.

Detection

Detection is a significant fraction of the cost of defense. It varies strongly with technology and basing, varying from perhaps a few \$M/yr for search over centuries with existing ground-based telescopes through a few \$10M/yr for search over decades with improved ground-based telescopes to a few \$100M/yr for rapid search with space-based sensors for objects on final approach. The first is underway, productive, and running efficiently with modest funding. This section discusses the scaling of the latter two. Both require adequate signal to noise for detection, and both depend on recent advances in large format charge-couple detector (CCD) focal plane arrays, which provide high sensitivity over wide fields of view (Canavan, et al., 1994). In the next decade it should be possible to build arrays with a few tens of millions of detectors with high quantum efficiency (Q) throughout the visible and near infrared and very low dark currents and readout noises for a few cents per detector (Wood, et al., 1994). Under those conditions the signal, S, required to achieve a given signal-to-noise ratio (SNR) is approximately

$$S_{req} = \sqrt{(SNR^2B/Qt)}, \tag{3}$$

where t is the exposure time and B is the background, which can be approximated as $B = B''A\theta^2$, where A is the sensor aperture area, θ is its pixel diameter, and the constant $B'' \approx 0.25/m^2\text{-arcsec}^2$ for space-based systems and about 2.5 times that for ground-based systems. The signal received by a sensor of aperture A from a NEO of diameter D at range r near opposition is

$$S_{rec} = JAD^2/r^2(1 + r)^2, \tag{4}$$

where J is a constant. Equating S_{req} and S_{rec} specifies the sensor needed. That is done below, after a discussion of the proper choice of exposure time.

Rapid search

Rapid search is appropriate for either an improved ground-based system or a fast-response space-based system, both of whose detection rates are maximized by choosing an exposure time such that all of the accessible sky is covered once before any area is covered again (Canavan, 1995). For a ground-based system, that requires searching at a rate of $W' \approx 130$ degree^2/hour; for space-based systems, the search rate could be somewhat larger. For a sensor with a field of view (FOV) of w, full coverage in time t means that t must satisfy w/t = W', or t = w/W'. The exposure time for rapid wide-area search is quite different than that for earlier NEO searches, which maximized t in order to search to the largest magnitude possible with a given sensor. Wide-area search sacrifices limiting magnitude for broader coverage. More can be said about the details of rapid search (Harris, 1995), but that is all that is needed for this assessment.

Ground-based search

Ground-based signal requirements are determined by substituting t = w/W' into Eq. (3) and equating the result to Eq. (4) to produce

$$S_{req} = \sqrt{(SNR^2B''A\theta^2W'/Qw)}. \tag{5}$$

It would be difficult to improve the SNR ≈ 4 or Q ≈ 0.8 of current sensors. And θ, which is set by atmospheric seeing, cannot be greatly improved without degrading FOV. Thus, S_{req} essentially scales as $\sqrt{(A/w)}$. However, A and w are not independent. For optics of a given f number, f#, detector pitch, p, and number of detectors in the focal plane, N, the FOV scales with aperture area as $w \approx Np/f\#A$, so that $A/w \propto A^2/N$, so that $S_{req} \propto A/\sqrt{N}$ in terms of the fundamental sensor parameters A and N. Equating this result to S_{rec}, simplifying, and squaring the result produces

$$N \propto [r(1 + r)/D]^4. \tag{6}$$

Note that the aperture area A has canceled out. For rapid search, what matters is the number of detectors. To first order, the cost of the ground-based sensor is proportional to that of its focal plane, which is proportional to the number of detectors N. Thus, the cost of a ground-based search system capable of detecting NEOs of diameter D at range r is proportional to N and hence

$$C_{ground} = G[r(1 + r)/D]^4, \quad (7)$$

where L is a constant. L could be estimated from the parameters in the equations above; however, given the uncertainties in their values it is perhaps as well to estimate L from current systems. Spaceguard sensors intended to search for 1 km NEOs at ≈ 2 AU were intended to have 10 year campaign costs of about $100M (Morrison, 1992), which gives a value of L ≈ $100M/6^4 ≈ $0.1 M-km^4/AU^8. The defense GEODSS system appears to give similar costs. This value of L is used to construct the plot of C_{ground} versus r for D = 2 km NEOs shown in Fig. 4. The solid squares are the ground-based detection system costs, which are ≈ $100M at 3 AU and $20B at 6 AU. The former is about the same as that for the 1 km NEOs at 2 AU used to estimate L. The latter provides a rough bound on the ranges that can be used, in that at a nominal discount rate of ≈ 5%/yr, this $20B total expenditure would correspond to an annual expenditure of about 0.05/yr x $20B ≈ $1B/yr, which is more than the expected annual losses to large NEOs. But within this range of 3 to 6 AU, ground-based detection should be able to support affordable defenses.

Space-based search

Spaced-based search has an added degree of freedom because in space, seeing does not limit the pixel size, so that θ can be made much smaller. If the optics scale as diffraction limited, $\theta^2 \approx \lambda^2/A$, $B \approx B''\lambda^2$, and

$$S_{req} = \sqrt{(SNR^2 B''\lambda^2 W'/Qw)} \;\alpha\; \sqrt{(A/N)}. \quad (8)$$

Equating this to S_{rec} produces

$$NA \;\alpha\; [r(1 + r)/D]^4. \quad (9)$$

For space-based systems, A does not cancel out, so both N and A can be varied to maximize range. Costs typically vary as $C_{space} = nN + aA$, so optimization is accomplished by the choice $A = (n/a)N$, which gives $C_{space} = 2nN$, so that $NA \;\alpha\; N^2 \;\alpha\; C_{space}^2$, which produces

$$C_{space} = G'[r(1 + r)/D]^2, \quad (10)$$

where L' is again a constant to be estimated either by aggregating the parameters in the model or from related satellite systems. While there is no directly relevant scaling base, defense experience suggests that satellites of this complexity could be built for a few $100M. Thus, L' is evaluated from the premise that a system for detecting 2 km NEOs at 2 AU could be built for $100M, which gives L' ≈ $100M[2/6]^2 ≈ $10M. That value is used to construct the curve of C_{space} as a function of r for 2 km NEOs shown by the open squares in Fig. 4. From its benchmark $100M at 2 AU, where space search costs about 10 times as much as ground-based search, the curve rises to $1B at 4 AU and then to ≈ $10B at 8 AU. At the latter it is about 1/10th the cost of the ground-based system, which indicates that space-based systems could have application at longer ranges. Detailed studies could refine these costs, but the main observation needed here is that space-based detection appears to have higher costs for shorter range systems, which is compensated by weaker scaling on range that produces lower costs at the longer ranges of interest for large NEOs.

Interception

To make use of the marginal benefit and search cost curves derived above to optimize defenses, it is necessary to have the corresponding marginal costs curves for negation mechanisms and some knowledge of the ranges and warning times for which they are applicable. Figure 5. shows the ability of various interception technologies to negate 10 m to 100 km NEOs given reaction times of months to millennia (Canavan, et al., 1993). The top line, indicated by dark squares, is the deflection capability of nuclear explosives on interceptors with the high specific impulses and thrusts of nuclear rockets, which represents roughly the maximum capability of current technology. Given reaction times of years, this combination could negate NEOs several tens of kilometers across; given centuries, it could negate NEOs several hundreds of kilometers across. The diameter this combination could deflect increases by a factor of ≈ 20 as the reaction time, t, increases by a factor of 10^4; thus, the scaling is roughly $D \alpha t^{1/3}$. It also depends on the interaction technology and coupling efficiency, as discussed below.

The second curve shows the capability of nuclear explosives on conventional rockets, which merges with the top curve for reaction times of a few decades or longer, but falls a factor of 2 to 3 below it for times of less than a year. The third curve is for nuclear explosives on conventional rockets using standoff explosions, which wastes energy, but improves the symmetry of energy deposition and reduces the danger of fragmenting or spalling the NEO (Ahrens, et al., 1993). The fourth curve is for kinetic energy payloads on high specific energy rockets. The fifth is for kinetic energy impact with conventional rockets. The bottom curve is for mass drivers—mechanized conveyor belts that throw material found on the NEO's surface and throw it into space to generate recoil—or other low-thrust, high-efficiency deflection technologies of this type (Melosh, et al., 1994). While they have too little thrust to address NEOs larger than ≈ 100 m with less than a few years warning, with a few centuries warning, they could deflect ≈ 10 km NEOs.

The basic scaling can be understood from the requirement that given a time t to react, the defense must give a NEO on a collision course a deflection velocity just large enough to cause it to miss by the Earth by at least its radius. To do so, the interceptor delivers a final payload mass M_f, whose specific energy density, ϕ, depends on the concept. For nuclear explosives, $\phi \approx 2$ Megaton (MT)/tonne $\approx 9 \times 10^{12}$ Joule/kg. For deflection by the kinetic energy in head-on impacts, the specific energy is the NEO's $\approx (30 \text{ km/s})^2/2$, which is ≈ 100 times the specific energy of conventional high explosives, but $\approx 10^{-4}$ times the specific energy of nuclear explosives. The energy release $M_f\phi$ ejects a mass M_e at a velocity v_e, whose recoil imparts an incremental velocity $\Delta v \approx M_e v_e/m$ to a NEO of mass m. Conservation of energy gives the energy imparted to the ejecta as $M_f\phi \approx M_e v_e^2$, so that $\Delta v \approx M_f\phi/m v_e$. For $M_f \approx 10$ tonnes of nuclear explosives and $v_e \approx 100$ m/s, $\Delta v \approx 75$ m/s for a $D \approx 2$ km NEO. That would deflect it by an Earth radius, R_e, if applied at range $r \approx R_e\, v/\Delta v \approx 0.02$ AU, although applying the whole impulse in one explosion could lead to fragmentation.

The displacement depends on when and where this deflection is applied in the NEO's trajectory. The displacement can be written as $\delta \approx k \Delta v t$, where k is a numerical parameter. For deflection many orbits prior to impact, $k \approx 3\text{-}5$ is appropriate, but for LPCs and unobserved NEOs, detection occurs on first approach, most of the response time is used for interceptor fly out, and $k \approx 0.1$ is a more appropriate value (Ahrens, et al., 1993). The latter is used for the calculations below, although k is carried as a parameter for discussions of sensitivity. For defense of the whole Earth, it is necessary that $\delta \approx R_e$, which gives

$$M_f \approx R_e m v_e/\phi k t, \tag{11}$$

which produces the dominant scaling of Fig. 1. For a fixed M_f and NEO density, ρ, $D \approx (\phi k t M_f/R_e \rho v_e)^{1/3}$. Thus, all concepts scale basically as $t^{1/3}$, although that is modified by k, which transitions from ≈ 0.1 to ≈ 5 in the interval from a few years to a few decades. Nuclear explosives achieve the largest D because they have the largest ϕ by a factor of $\approx 10^4$. Nuclear propulsion increases k by about an order of magnitude at short t, because conventional rockets fly out at 10% of the speed of the NEO, spend 90% of their time in transit, and make use of only 10% of the detection range for deflection. Nuclear rockets can achieve velocities comparable to the NEO's and intercept it midway. The ejection velocity v_e is an important but poorly-defined parameter, which varies from ≈ 0.1 km/s for deeply buried bursts through ≈ 1 km/s for surface bursts to ≈ 10 km/s for standoff explosions. Thus, it is a measure of the efficiency of nuclear coupling, which produces a factor of $\approx (100)^{1/3} \approx 5$ variation in D. Since the precise value of v_e is not known and varies with the concept and application, the calculations below assume the v_e appropriate for shallowly buried burst and carry v_e as a parameter for sensitivity discussions. Thus, Fig. 5 represents an upper bound on most technologies, a significant extrapolation of propulsion and penetration, and a somewhat optimistic value of coupling efficiency.

In space, mass is directly related to cost, so M_f can be converted into a rough estimate of interceptor cost. An interceptor payload of $M_f \approx 10$ tonnes would require ≈ 30 tonnes into deep space and ≈ 100 tonnes into low-Earth orbit, which is about the limit of what a fully integrated international effort could now produce. Such a booster could cost on the order of \$100M. The upper stage and controls for rendezvous could cost another ≈ \$100M. The nuclear explosive could add ≈ \$100M more. If life-cycle operational costs were roughly equal to the total cost of the booster, payload, and controls; the total cost for the interceptor might be about \$500M, or \$50M/tonne of payload mass. Assuming that these values could be scaled continuously to other masses gives an interception cost of $C_{int} \approx B M_f = B R_e m v_e/\phi k t$, where B ≈ \$50M/tonne. This is of course just the cost for the booster, upper stage, controls, and explosives, but adding a fixed cost for the ground system and control would increase negation and total costs, but would not affect the optimizations in below.

Cost of defense

The dominant variable hardware costs of defense are those for search and negation. The former are bounded by the estimates above for search from ground and space. As the results are not overly sensitive to the details of the detection model or costs, they assume a cost for detection of the form of Eq. (10), i.e, that for space-based search, which appears appropriate for large NEOs and LPCs. The cost for negation is taken to be that for nuclear explosives on conventional boosters, i.e., the nominal $C_{negate} \approx BM_f$ with $B \approx$ \$50M/tonne. The total cost of defense is the sum of the costs of detection and deflection, which is

$$C = C_{search} + C_{int} \approx A[r(1 + r)/D]^2 + BM_f \approx A[vt(1 + vt)/D]^2 + BR_e m v_e/\phi kt, \qquad (12)$$

where detection range r is replaced by detection time $t \approx r/v$. Note that A is *not* the sensor aperture, which has already been integrated into it, but a parameter that is $A = \$50M\text{-km}^2/AU^4$. That value, which is about 5 times the value in Eq. (10), is chosen for a certain degree of conservatism and for consistency with earlier work (Canavan, 1994). Figure 6 shows the total cost C for nuclear deflection. For short times and small D the total costs are ≈ \$10M, which is too small for the model to be accurate. For large diameters they rise to ≈ \$100B. For long times, the total cost is dominated by the cost of detection, which increases as t^2, and is largest for small NEOs. At 1 year, for 0.1 km the total costs are ≈ \$1000B; by 10 km they drop to ≈ \$10B.

There is a progression in minimum-cost combinations that increases from a ≈ \$10M system to detect and deflect 0.1 to 0.3 km NEOs with 0.01 year warning, through a ≈ \$100M system that could detect ≈ 1 km NEOs with 0.1 year warning, to a ≈ \$1B system that could detect and deflect ≈ 3 km NEOs with 0.5 year warning. Of greatest interest here is that for a given D, at short times, the costs for deflection dominate, while for long times, those for detection dominate; thus, the total cost exhibits a minimum somewhere in between. For D = 3 km, at t = 0.01 year, C ≈ \$10B. C then falls to ≈ \$300M at ≈ 0.25 year before rising again to ≈ \$10B at 1 year. For D = 1 km, the minimum is ≈ \$50M at t = 0.06 year; for D = 10 km it is ≈ \$5B at ≈ 1 year. The time that produces the minimum total cost of defense can be determined by differentiating Eq. (12) with respect to time and setting the result to zero. The result is shown in Fig. 7 as a function of D and ϕ. For D less than 10 km and the ϕ of nuclear explosives, the optimal detection times are less than a year. For the smaller ϕ of kinetic and other concepts, the times reach a year at much smaller diameters. For nuclear energy densities there is a break in the scaling at about 3 km. For r >> 1 AU, i.e., t >> 1/6 year, the optimum time is approximately

$$t_{opt} \approx (BR_e m v_e D^2/4\phi k A v^4)^{1/5}, \qquad (13)$$

which scales as $(mD^2)^{1/5} \alpha (D^3D^2)^{1/5} \alpha D$, as seen from 3 to 10 km in Fig. 7. It also scales almost inversely on NEO velocity v, which is of interest with respect to defenses against LPCs, whose velocities are generally higher and more variable than NEOs. In this limit the nuclear t_{opt} is relatively insensitive to most other parameters. An exception is advanced interceptors with much higher fly out velocities, which could increase k from ≈ 0.1 to ≈ 3. That would reduce the optimal detection time by about a factor of $30^{1/5} \approx 2$. For a 10 km NEO that would reduce the optimal detection time and range from about 1 year and 6 AU to 1/2 year and 3 AU. When t_{opt} substituted back into Eq. (12), it gives the optimized (minimum) total cost, C_{opt}, which is shown in Fig. 8 as a function of D and ϕ. The costs vary from a few \$10M for nuclear deflection of 100 m NEOs to ≈ \$1T for nonnuclear deflection of 10 km LPCs. For nuclear deflection of 10 km SPCs, the optimal cost is ≈ \$1B. For t_{opt} large,

$$C_{opt} \approx 5(A/D^2)^{1/5}(BR_e m v_e v/4\phi k)^{4/5}, \qquad (14)$$

which scales as $D^{-2/5}m^{4/5} \alpha D^{-2/5}(D^3)^{4/5} \alpha D^2$, which is stronger than the $D^{4/3}$ scaling for smaller D. C_{opt} depends weakly on detection costs through $A^{1/5}$; more strongly on deflection costs through $B^{4/5}$. Thus, 20% of the total cost is devoted to detection and 80% to deflection just due to the scaling of search costs. Total costs are almost linearly sensitive to NEO and coupling parameters. Based on the expected losses of a few \$100/yr given above, it would appear that the costs for kinetic energy deflection are acceptable for LPC diameters up to ≈ 10 km, which covers the bulk of the threat. Kinetic energy deflection would only appear affordable to diameters up to a few hundred meters. Note that C_{opt} scales as $k^{4/5}$; thus, the 30-fold increase in k possible with advanced interceptors could reduce the total cost of intercept by a factor of $30^{4/5} \approx 15$. For a 10 km NEO that would mean a reduction to ≈

\$100M. For the analysis that follows, the result needed is the marginal cost of optimized defenses. C_{opt} can be written as HD^2, where H contains the parameters of Eq. (14) and is roughly \$20M/km^2 according to Fig. 8. The marginal cost is produced by differentiation as $C_{opt}' \approx 2HD$. This gives the total cost of defenses; the equivalent annual expenditure is determined by multiplying it by the appropriate discount rate, i, so the annual marginal expenditure is $iC_{opt}' \approx 2iHD$. For efforts of national importance, the conventional discount rate is i ≈ 5%/yr. For D = 10 km, these operations produce C_{opt} = \$20M/km^2 (10 km)^2 = \$2B, $C_{opt}' \approx$ 2 x \$20M/km^2 x 10 km ≈ \$400M/km, iC_{opt} = 5%/yr x \$2B = \$100M, and an annual marginal expenditure of $iC_{opt}' \approx$ 5%/yr x \$400M/km ≈ \$20M/km-yr.

Effectiveness of optimized defenses

Figure 9 adds these marginal costs for defense to the marginal benefits derived earlier. The bottom curve is for nominal costs; the other two are for costs 10 and 100 times higher to illustrate sensitivity. The bottom curve shows that defenses would be highly cost effective for NEOs with diameters up to ≈ 7 km, where the marginal cost and benefit curves cross. Figure 2 shows that defenses good to ≈ 7 km would prevent essentially all of the ≈ \$500M/yr expected damages. From the results of the previous section, such defenses should cost ≈ \$20M/km^2 x (7 km)^2 ≈ \$1B, or ≈ 5%/yr x \$1B ≈ \$50M/yr; thus, their net benefit would be ≈ \$500M/yr - 50M/yr ≈ \$450M. Note that this \$50M/yr expenditure from marginal economics is a small fraction of the amount estimated from average costs and benefits.

It is possible to derive analytically the NEO diameter at which the marginal benefit and cost curves cross. Equation (2) gives the former as $L' = 3GTK/D^4$, where GT ≈ \$400T and K ≈ 10^{-5}km3/yr for large NEOs. The latter is $iC_{opt}' \approx 2iHD$. Equating the two gives $D \approx (3GTK/2iH)^{1/5} \approx 7$ km. Because of the exponent of 1/5th, this combination of parameters would have to change by a factor of 30 to change the crossover diameter by a factor of two.

The curve indicated by closed diamonds shows that defenses with costs 10 times nominal would still be cost effective against essentially all small NEOs and large NEOs up to ≈ 3.5 km in diameter. Figure 2 shows that defenses to 3.5 km would still prevent ≈ \$400M/yr of the \$500M/yr expected damages. Even partial defenses could negate 80% of the threat, and they would negate the most likely portions of it. From the scaling above, such defenses should cost ≈ \$20M/km^2-yr (3.5 km)^2 ≈ \$250M/yr. However, the curve for 100 x nominal costs lies largely above the marginal benefit curves. It does cut the 5 to 50 m NEO curve about midway, indicating that defense might still be cost effective up to about 20 m diameters, but Fig. 2 indicates that would only justify an expenditure of ≈ \$7M/yr, or a total investment of about \$140M. It is difficult to envision a defense based on current technology for that amount.

This discussion can be extended to study sensitivities to the specific energy of the deflection technology used. The costs of optimized defenses scale as $1/\phi^{4/5}$ for D large NEOs. The specific energy of kinetic energy is ≈ 10^{-4} times that of nuclear explosives, so kinetic energy would increase the cost of defenses by a factor of ≈ $(10^4)^{4/5}$ ≈ 1000. That would increase the marginal costs another factor of 10 above the top 100 x cost curve on Fig. 9, which would be prohibitive. In some circumstances it might be appropriate to pay that penalty to avoid nuclear explosives, particularly the defenses could be built for the assumed scaling costs of ≈ \$50M/yr for small NEOs. However, the scaling of defenses at small D, where interceptor overhead is a larger fraction of payload, is much less certain than their scaling at large D. Thus, alternative and advanced concepts could play important roles in detection, interception, and deflection.

Search over extended periods

The discussion of the previous section applied to search for objects detected on final approach. For them, defenses would have to operate in months to years; hence, it is necessary for their sensors to see as far as possible to maximize warning time to minimize interception costs. For objects that pass close enough to the Earth for detection a number of times prior to impact, it is possible to use a more efficient search over an extended period of time, waiting for the NEO to come close to the Earth, and hence to the sensor, to minimize search costs. Even for extended search from the ground, the detection rate is maximized by rapid, wide-area search (Canavan, 1995), the requirements for which are determined by equating S_{rec} from Eq. (4) to S_{req} from Eq. (5) and using $w \propto N/A$ to produce

$$D \propto r(1+r)/N^{1/4}, \qquad (15)$$

for the minimum diameter NEO that can be detected at range r by a sensor with N detectors. For extended search, the detection rate R is proportional the product of the search rate w/t = W', and the integral over the volume containing detectable NEOs, which is

$$R \,\alpha\, W' \int dr\, r^2 \,(M/D^m), \tag{16}$$

where M/D^m is the density of detectable NEOs at r, M is a constant, and m ≈ 2 for most NEOs. Substituting from Eq. (15) produces

$$R \,\alpha \int dr\, r^2 M/[\, r(1+r)/N^{1/4}]^2 \,\alpha\, \sqrt{N}, \tag{17}$$

While it is possible to estimate the constant in this proportionality, it is adequate to use the current estimate that rapid search with N = 4 million detectors (4Mdet) should achieve ≈ 90% completeness in 10 years, which is consistent with $R = g\sqrt{N}$, where the constant is $g \approx 2/(10\text{ y} \times 2\sqrt{\text{Mdet}}) \approx 0.1/\text{yr-}\sqrt{\text{Mdet}}$. The time rate of increase of the loss is $dL/dt = GTfe^{-Rt}$, where $fe^{-Rt} \approx 10^{-6}/\text{yr} \times e^{-g\sqrt{N}t}$ is the collision frequency of all large NEOs that have not been detected as of t, so the cumulative loss after t years is

$$L = GTf(1 - e^{-Rt})/R, \tag{18}$$

which is shown in Fig. 10 as a function of time for N = 1 to 16 Mdet. For N = 1, the curve increases sharply until t ≈ 10 years. It subsequently rolls over, but the $2.5B loss after 10 years is till about 65% of the GTft ≈ $400T x 10^{-6}/yr x 20 yr ≈ $4B that would occur without any search. For larger N the curves level off earlier at a lower values. For N = 4 the curve levels off at ≈ $2B by t = 20, where the curve for constant N is about parallel to the $2B isocontour, so that increasing t would not increase L. For N = 16, L levels off at ≈ $1B, which is only 12% of the loss without search. It becomes parallel to the isocontour by about 10, illustrating that larger N permits shorter searches. The benefit of search is the difference between the loss without and with it, which is

$$U = GTf[t - (1 - e^{-Rt})/R], \tag{19}$$

which is shown in Fig. 11 as a function of t for N = 2 to 64. The benefits are about $1B after 7.5 years for N = 2, 5 years for N = 64. Thereafter, the loss contours show more gradient in t and N, reaching $4.5B for N = 2 and $7B for N = 64 at t = 20 years. This gradient favors large N, for which U increases more rapidly. In all cases, the linear growth of benefits after a decades results from the fact that most threatening objects are found after the first decade, so that the benefits are essentially equal to the losses in the absence of search. The marginal benefits are given by differentiating U, which produces

$$dU/dN = GTf[1/R^2 - (1/R^2 + t/R)e^{-Rt}]g/2\sqrt{N}, \tag{20}$$

which is shown in Fig. 12 as a function N for search durations of t = 5 to 25 years. While there is a significant spread in marginal benefits at N = 2—i.e., $100M for 5 years to 600M/Mdet for 25 years—it decreases to a factor of 2 at N = 10 and 10% at 64 Mdet. All of the curves fall more sharply as N increases, reflecting the diminishing marginal utility for improving on searches that are already more than adequate. At large N the slope approaches -3/2 because the exponential term in Eq. (20) is small, so that $dU/dN \approx GTfg/2R^2\sqrt{N} \,\alpha\, 1/N^{3/2}$.

The cost of ground-based search are roughly bounded by current university programs, the Spaceguard proposal, and the possible Air Force GEODSS program at roughly $100M for a 10 year campaign. That cost should be roughly proportional to the cost of the sensor used, which in turn should be roughly proportional to its number of detectors in it. If detection and warning alone are adequate to avoid most of the loss from a large NEO, the cost of search and hence of defense can be approximated by C ≈ nN, where n ≈ $100M/4Mdet ≈ $25M/Mdet. From Fig. 12, this m is equal to dU/dN at N ≈ 13Mdet for t = 5 and ≈ 20 Mdet for t = 10 to 20 years. For the latter, the cost of an optimal search would be about $25M/Mdet x 20 Mdet ≈ $500M, which is about 5 times the size of the currently proposed program. From Fig. 10, the residual losses from such a search would be ≈ $1M. From Fig. 11 the benefits would be ≈ $3B, so the net benefit would be ≈ $3B - 0.5B = $2.5B.

For an indication of sensitivity, for these conditions a 4 Mdet sensor would cost only $100M, but would only have benefits of $2.2B, for a net benefit of $2.1 B. A 64Mdet sensor would have benefits of ≈ $4B, but would cost $1.6B, for a net benefit of $2.4B. Thus, there is a larger penalty for undersizing the sensor than for oversizing it. The sensitivity to detector cost can also be seen directly. From above, for large N and t, $dU/dN \approx GTf/2gN^{3/2}$; thus, for dC/dN ≈ n, marginal equality gives $N \approx (GTf/2gn)^{2/3}$. That means that as the cost per detector falls, the number of directors increases almost inversely, which means that the total cost of the sensor varies as $Nn \alpha n^{1/3}$, so if the advance of technology continues to decrease the cost per detector rapidly, future search systems will become much more capable but no more expensive.

An important assumption in the analysis above is that warning alone would be enough to avoid catastrophic losses. Given the presence of some auxiliary system to handle objects that are detected only on final approach, that assumption seems reasonable. However, if a modest capability to deflect objects seen many orbits prior to impact is required , its cost can be roughly estimated from the earlier results. The costs for deflection fall rapidly with warning times on the order of the search times discussed above. They are likely to fall to levels determined by overhead, rockets, and externals more than interception technology. Assuming that a interception mission could be mounted for a cost of a few $100M, those costs would not upset the overall assessment of feasibility established above, and would not impact the marginal analysis at all. The costs of defenses would be added to C and should not be explicitly dependent on N. Thus dC/dN would remain at n, so the optimal number of detectors, and hence the cost of search, would not change. The main effect is that the total cost is increased by the cost of the interceptor. But even interception costing $1B would only reduce the net benefit from $2.5B to $1.5B. Thus, the extended search appears highly cost effective with or without defenses.

Relationship of extended and rapid searches and defenses

Defenses against NEOs and objects that can be detected many orbits prior to impact primarily require competent search for periods of a few decades. Some interception capability would be useful, but it should not be difficult or expensive to provide due to the efficiency of deflection long before impact. The search required can be provided by ground-based telescopes, although they should be somewhat more capable than those currently envisioned. Defense against LPCs and other unobserved objects requires rapid search and ready interception, which suggests space-based sensors, and large-scale nuclear deflection capability. On the surface there is not a ready match between extended and rapid searches and the defenses that support them.

On a deeper level there does appear to be. The extended search for NEOs is a transient problem; one to two decades of competent search should reduce expected losses well below those expected from LPCs. Defense against LPCs is a steady-state response to a threat that can never be eliminated. The only possibility is to reduce the losses they produce. For NEOs, improved search would be valuable; for LPCs, it is essential. Thus, there is need for continuing improvement in search to support both these activities, and any improvement in technology or capability, including space-basing, would help both. Since there is no reduction in the marginal utility of more capable search technologies, search is likely to be a key technology whose progressive development should be promoted for objects of any size and period.

Interception is a more complex issue. In the search for NEOs it is hoped that no objects will be found that threaten the Earth, or that if one is found that is threatening, its predicted impact time would be closer to a million years than a decade. But impact times are distributed uniformly, so there is a probability that an object could be found that would require faster response and hence stronger measures. Again there are transient and stead-state problems. There is currently concern about impact during the NEO survey, or on a time scale too short for limited measures, but after a few decades, that concern will merge into the steady-state concern over LPCs, which clearly take stronger measures. Thus, given the credibility of current assessments that LPCs produce large losses and deserve strong defenses, the development of such defenses is inevitable, and the only question is the time scale for developing them. Providing them on the time scale of a decades would also provide improved search for NEOs, a stronger backup to the interception technologies intended for the NEO search, and expected average savings from defenses against LPCs comparable to those expected from defenses against NEOs. Thus, the technologies and time lines for deployments of the two elements of an integrated defense would appear to be complementary in every way.

Summary

There is now rough agreement on the impact frequencies of objects of various sizes, their damage mechanisms, and the expected losses they produce. There is also some agreement on the uncertainties in each, although those uncertainties tend to be greatest for the largest objects, which have the greatest potential for global effects and which tend to dominate the expected losses from impacts of all sizes. Those losses are currently estimated as roughly $0.5 B/yr, but plausible arguments suggest that they could be an order of magnitude larger. They are in any case strongly sensitive to the amount of warning and extent of defenses available.

The decision to deploy defenses should be based on the equality of benefits and costs at the margin. The marginal benefits can be derived from the estimated losses. The dominant costs of defense are those for search and interception. For the long ranges needed for NEOs, space-based sensors appear competitive with ground-based ones, both appear affordable, and the marginal costs of each can be determined with enough accuracy for analysis. Interception costs can also be paramaterized to about the same accuracy. However, optima are much more sensitive to them than to detection costs—depending almost linearly on most of the parameters of the boosters and explosives. The sum of the costs for search and interception have a optimum detection time and range for any object diameter that can be determined analytically, which permits the analytic determination of the marginal costs of interception. Equating that to the marginal cost of search determines the optimal defense and its cost for objects of any size. Nominal loss and cost parameters indicate that defenses should be cost effective for objects up to about 7 km across, a result that is only weakly dependent on model parameters.

For objects that pass close enough to the Earth for detection a number of times prior to impact, it is possible to use a more efficient search over an extended period of time by waiting for the NEO to come close to the Earth, and the sensor, to minimize search costs. Even for extended searches from the ground, the detection rate is maximized by rapid, wide-area search, which to first order depends only on the number of detectors in the sensor. Since the cost of the sensor is also roughly proportional to the number of detectors, that leads to an analytic optimization, which for current detector cost would lead to sensors somewhat larger than those currently envisioned. The optima have benefits of several $B per decade and costs an order of magnitude less; thus, they are highly cost effective and would remain so even if modest deflection capability was added. As detector costs fall, sensors should become larger but cheaper.

Defenses against NEOs and objects that can be detected many orbits prior to impact primarily require competent search for a few decades. Defenses against LPCs and other unobserved objects requires rapid search and ready interception forever. While these requirements differ, there is a fundamental tie between them and the technologies that support them. The extended search for NEOs is a transient problem; a few decades of competent search should greatly reduce expected losses. Defense against LPCs is a steady-state response to a threat that can never be eliminated. For NEOs, improved search would be valuable; for LPCs, it is essential. Thus, there is need for continuing improvement in search to support both activities. Search is a key technology whose progressive development should be promoted for objects of any size and period.

In the search for NEOs it is hoped that no objects will be found that threaten the Earth, but impact times are distributed uniformly, so an object could be found requiring faster and stronger responses. Again there are transient and stead-state problems. After a few decades, the concern that the NEO survey will find a threat will diminish and merge into the steady-state concern over LPCs, which clearly take stronger measures. If current assessments of LPC withstand review, the development of defenses is inevitable, and the only question is the time scale. A time scale of a few decades would provide improved search for NEOs, a stronger backup to the interception technologies intended for the NEO search, and large expected savings. Thus, the technologies and time lines for deployments of the two elements of an integrated defense appear complementary.

On the basis of current technical assessments, it appears that current levels of technology, if not of integration, could address most threats detected either many orbits or only shortly before impact. On the basis of economics estimates, it appears that they could do so cost effectively. On the basis of the logic of the requirements, it appears that the required search programs could grow progressively from current sensor surveys and that the required intercept capability could grow from current space probes through modest long-response capabilities to those required for fast reaction. Moreover, it would appear that the programs for NEO search and LPC search and defense have in common key technological features that make them essentially two phases of a single program. These conclusions should be tested by more technology assessments and integration studies, which could establish the feasibility of defenses within a few years.

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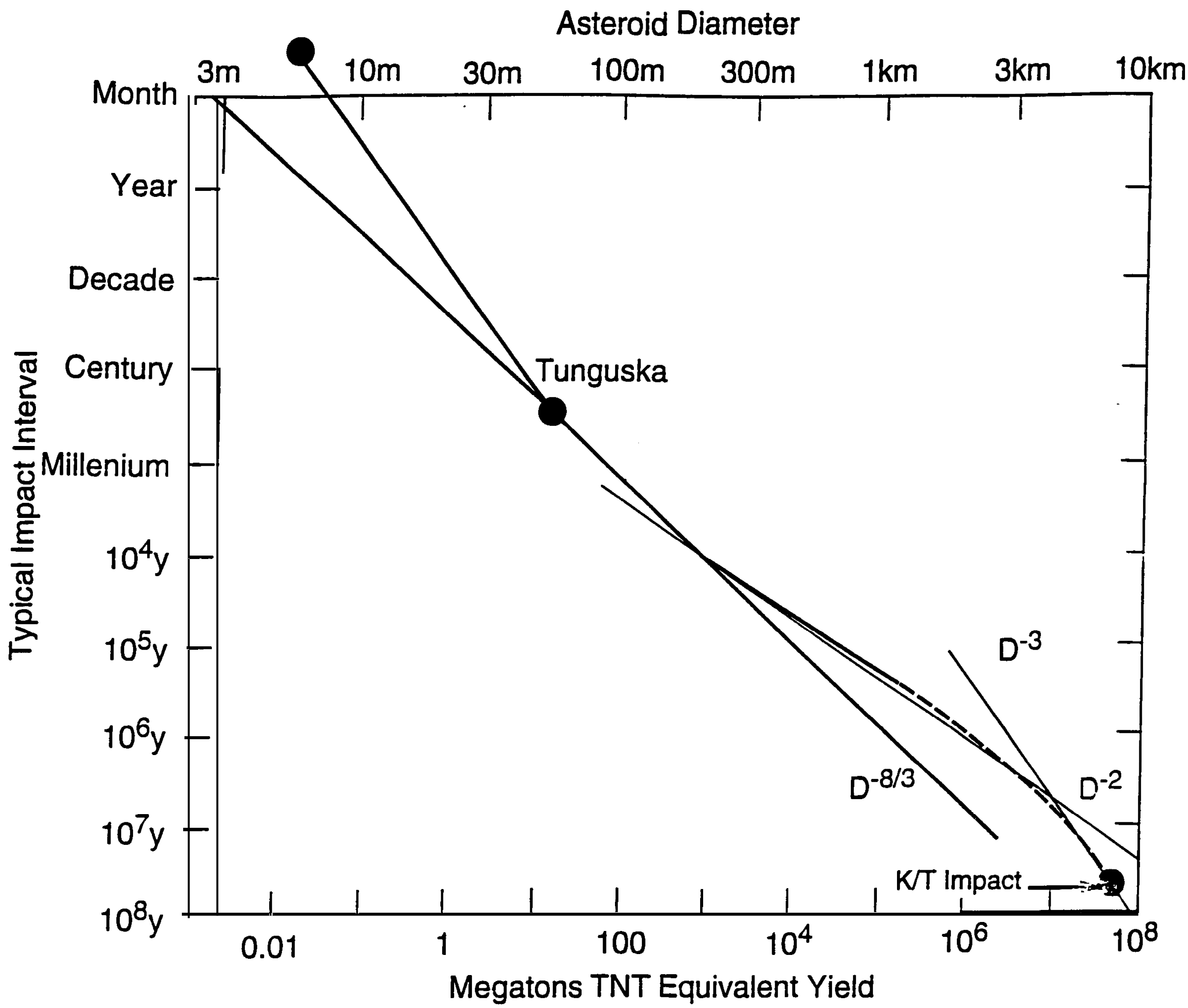
Fig. 1


Asteroid Diameter
3m
10m
30m
100m
300m
1km
3km
10km
Month
Year
Decade
Century
Millenium
10^4y
10^5y
10^6y
10^7y
10^8y
Typical Impact Interval
Tunguska
D^{-3}
$D^{-8/3}$
D^{-2}
K/T Impact
0.01
1
100
10^4
10^6
10^8
Megatons TNT Equivalent Yield

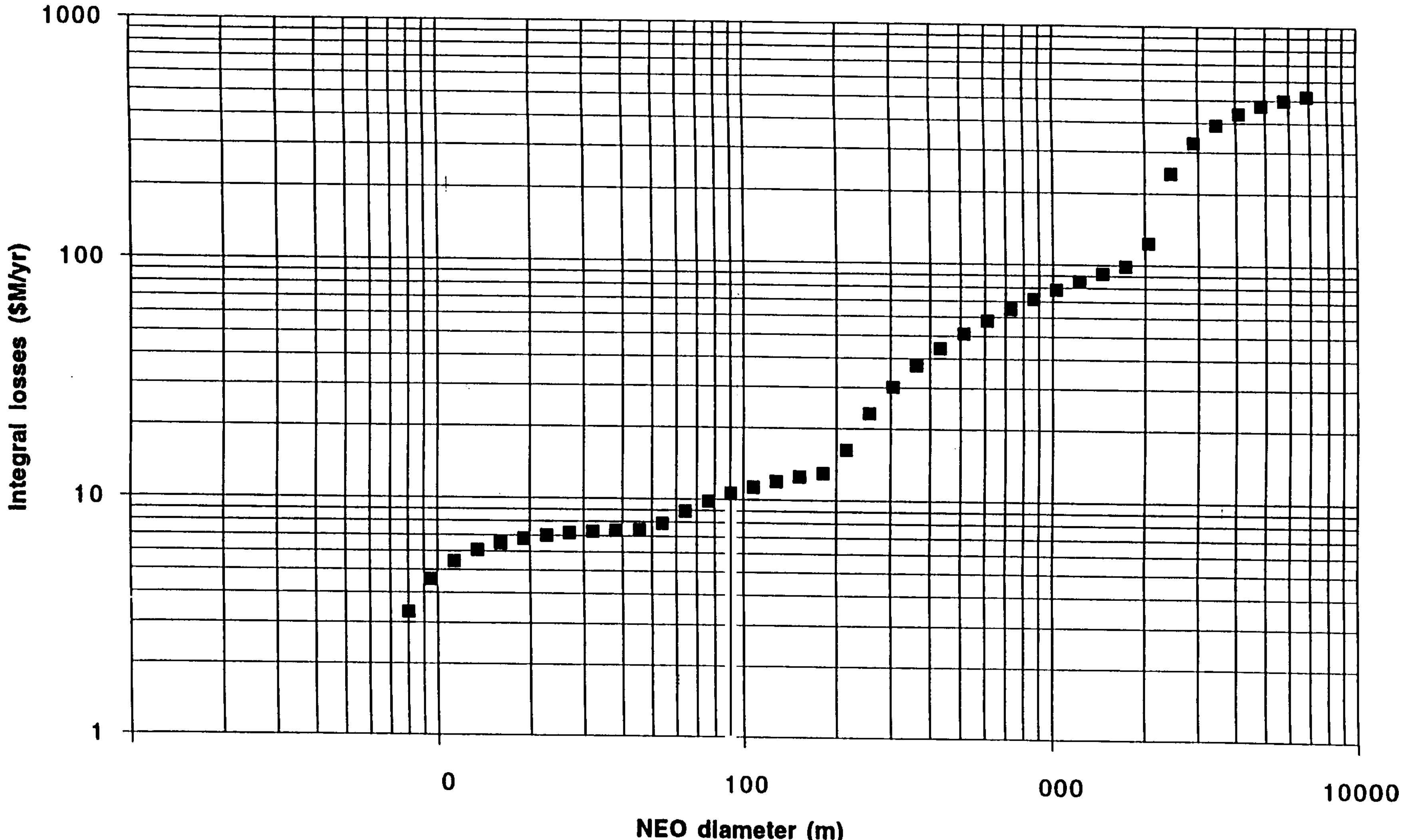


Fig. 2. Losses integrated over diameter.

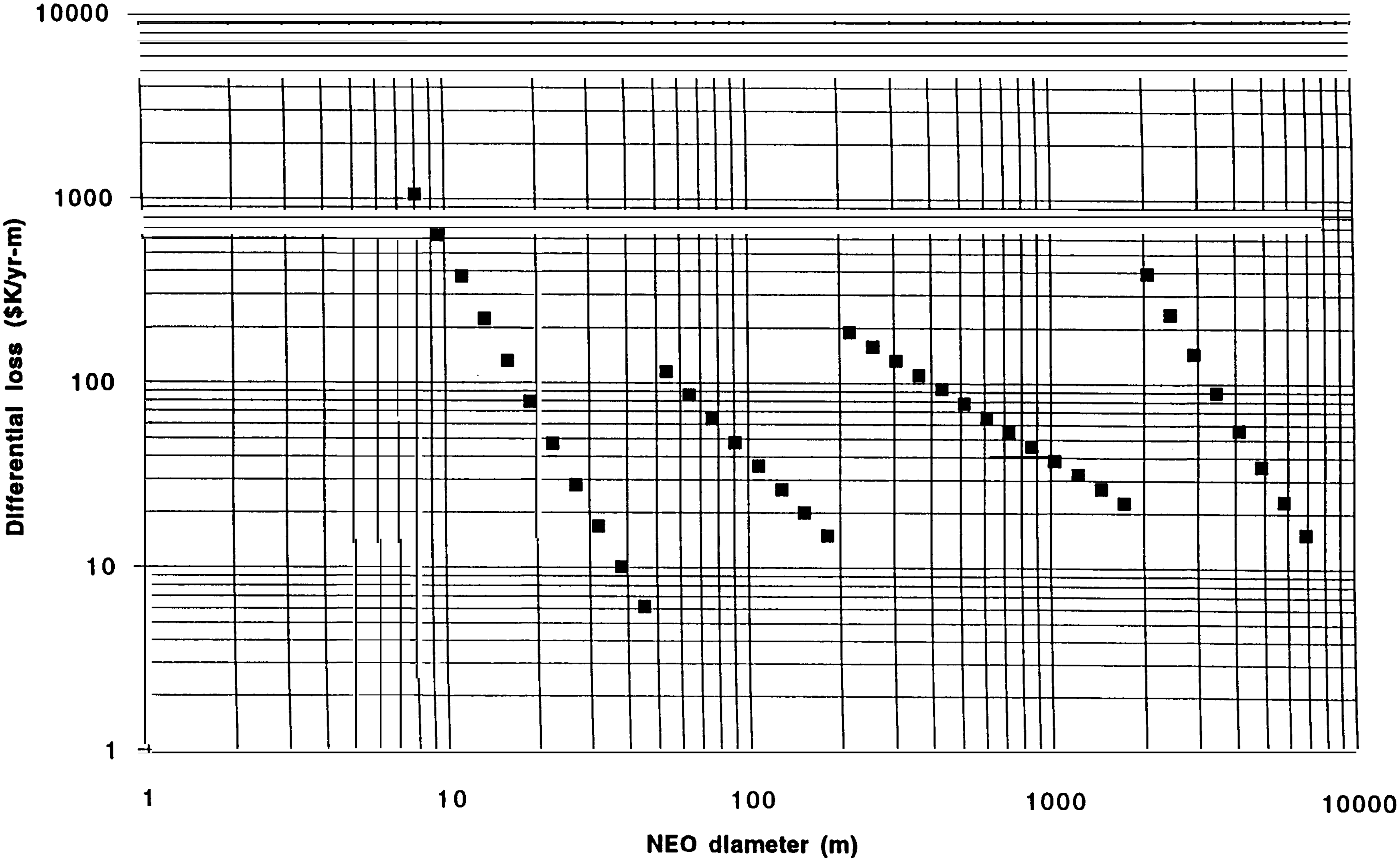


Fig. 3. Differential cost as a function of NEO diameter.

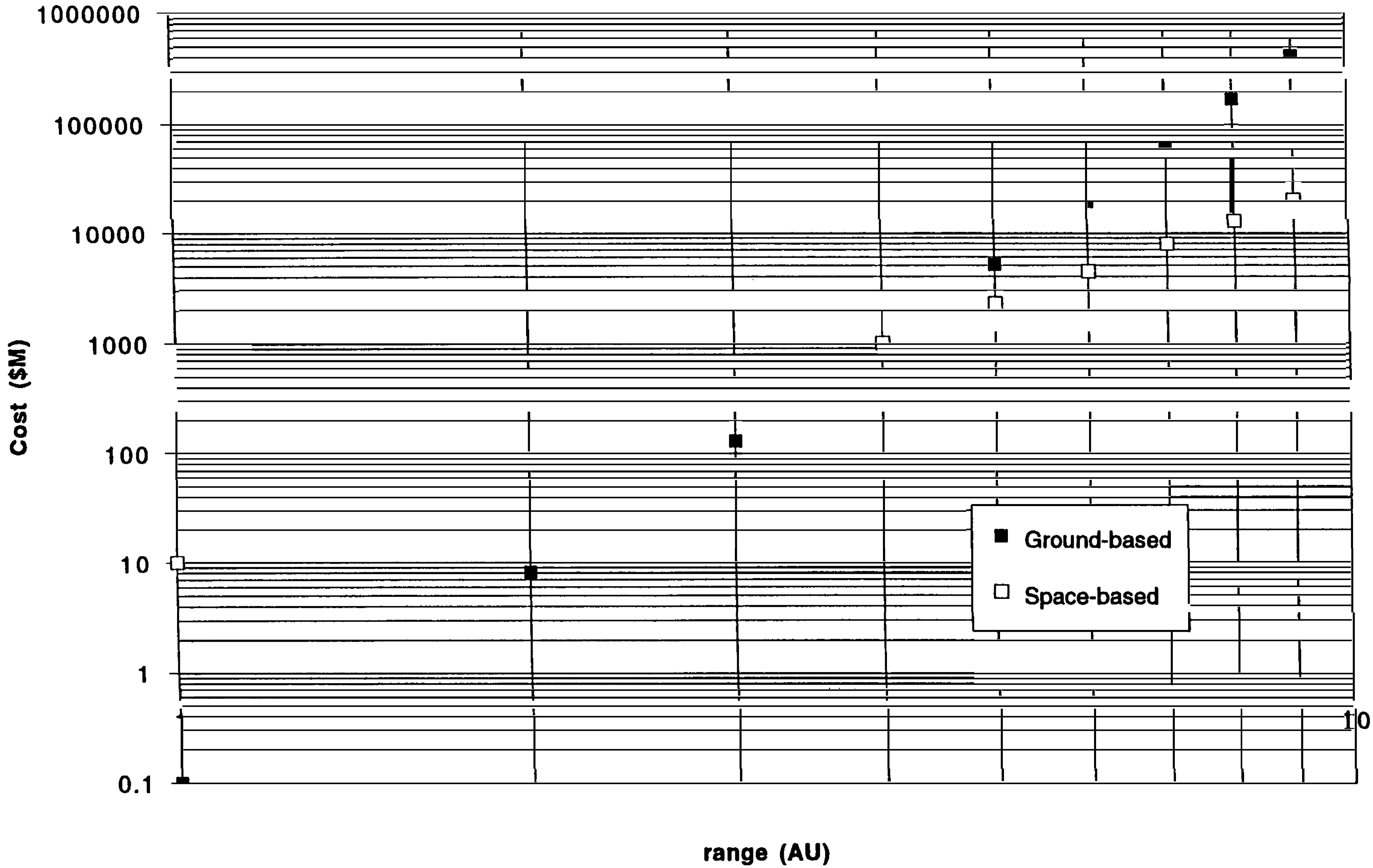


Fig. 4. Cost of ground- and space- based systems for detecting 2 km diameter NEOs at

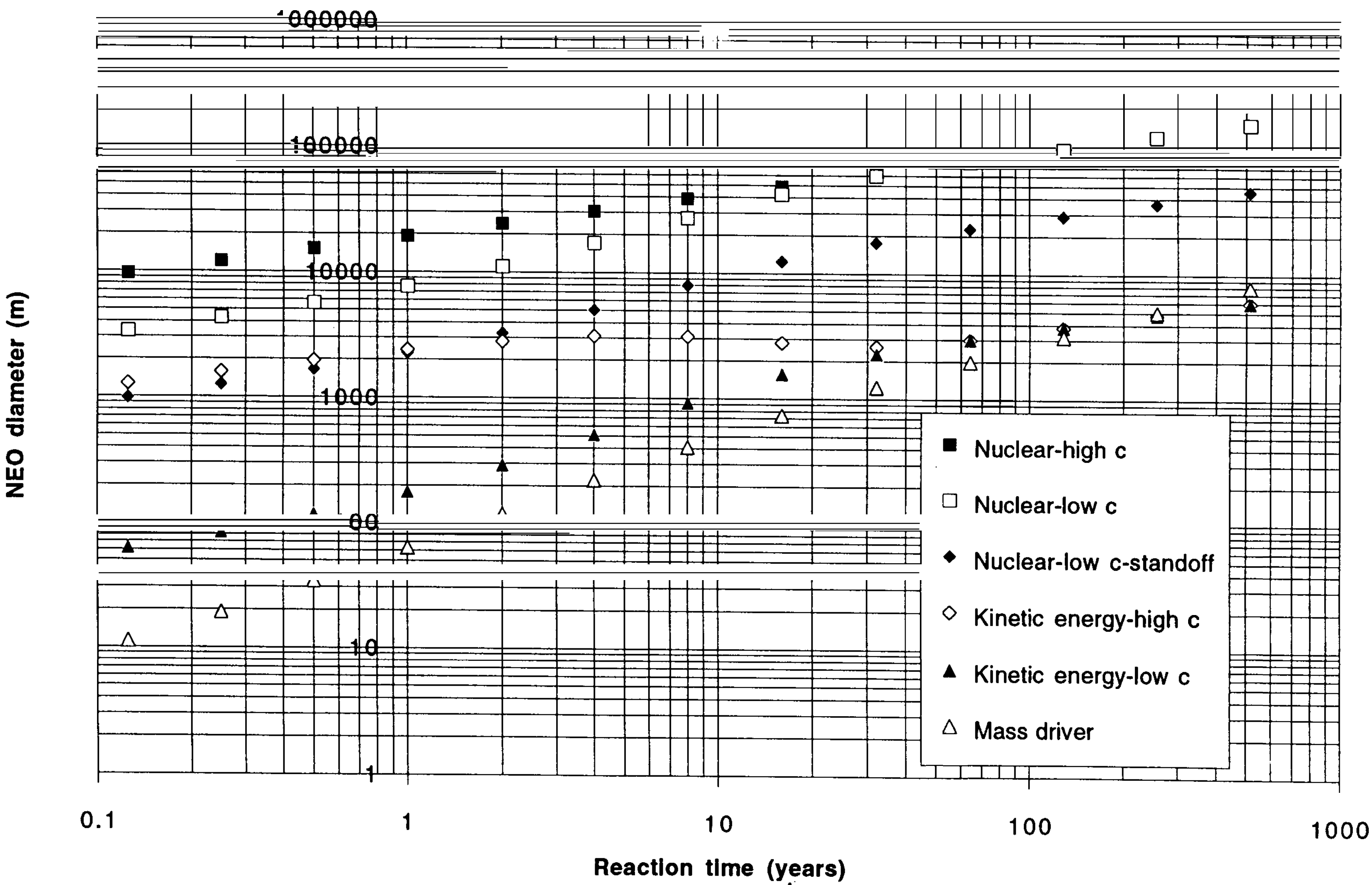


Fig. 5 Maximum NEO diameter that can be deflected as a function of reaction time.

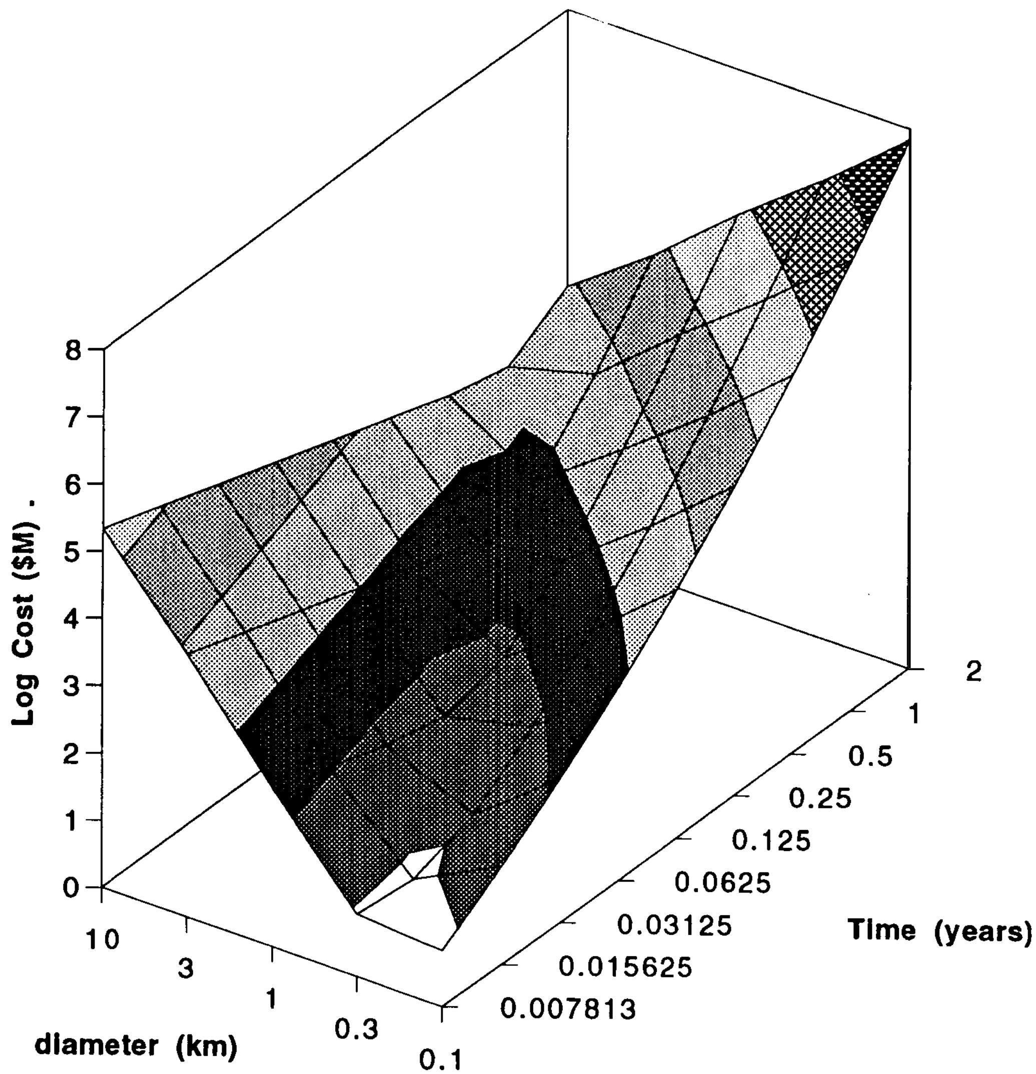


Fig. 6. Search and deflection cost versus time for various NEO diameters.

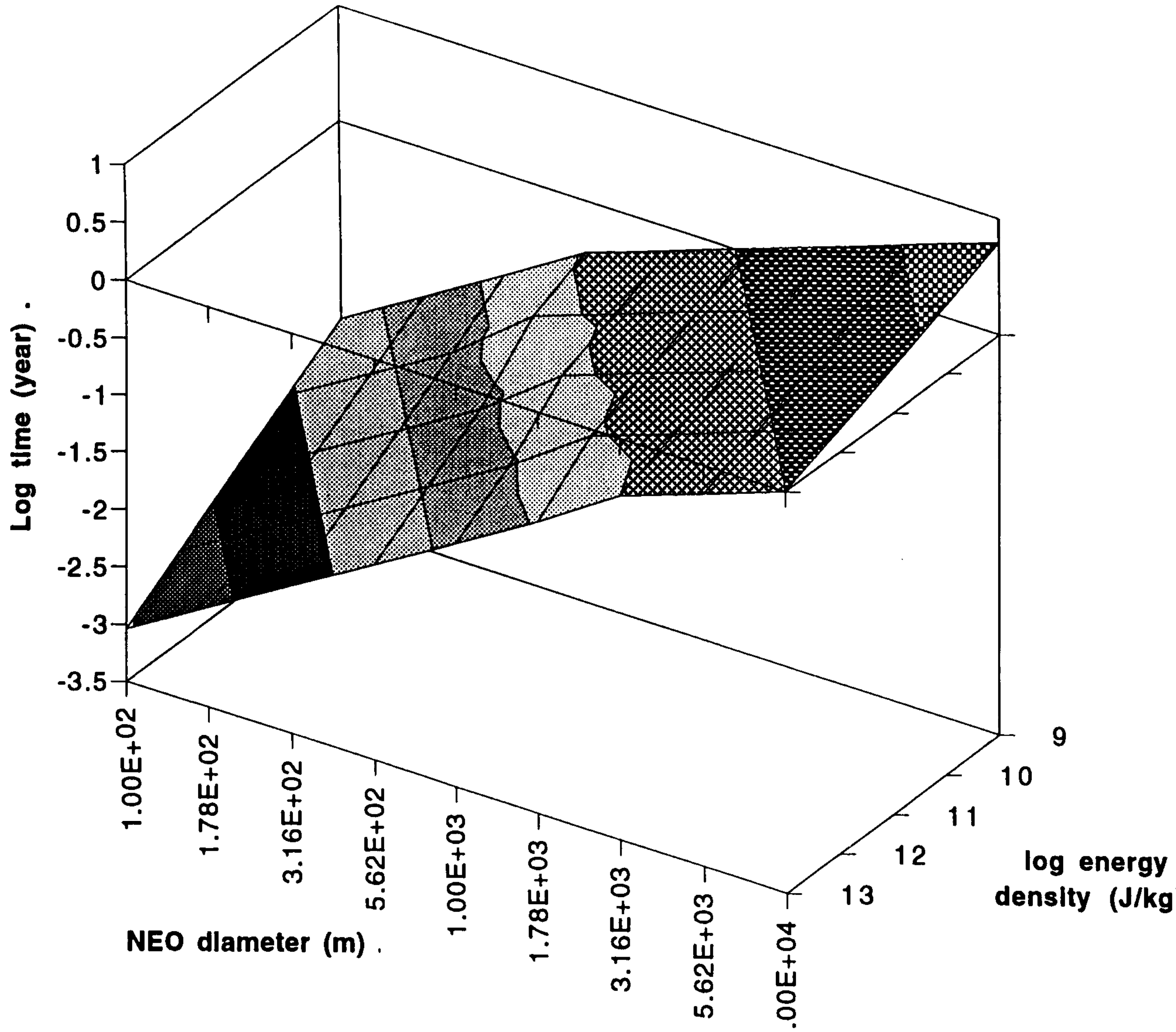


Fig. 7. Optimal detection time as a function of NEO diameter.

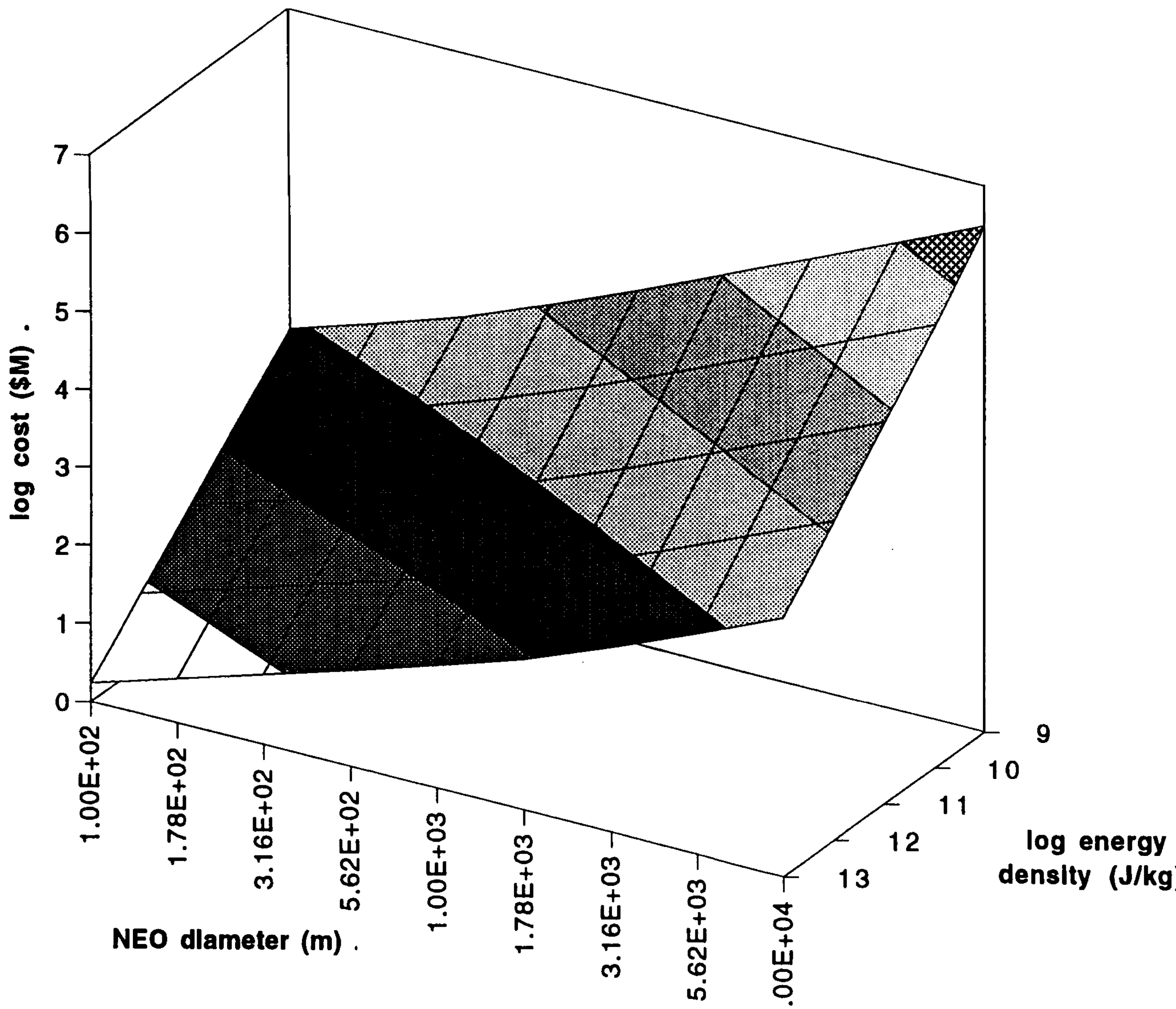


Fig. 8 Cost of optimized defense system as a function of NEO diameter.

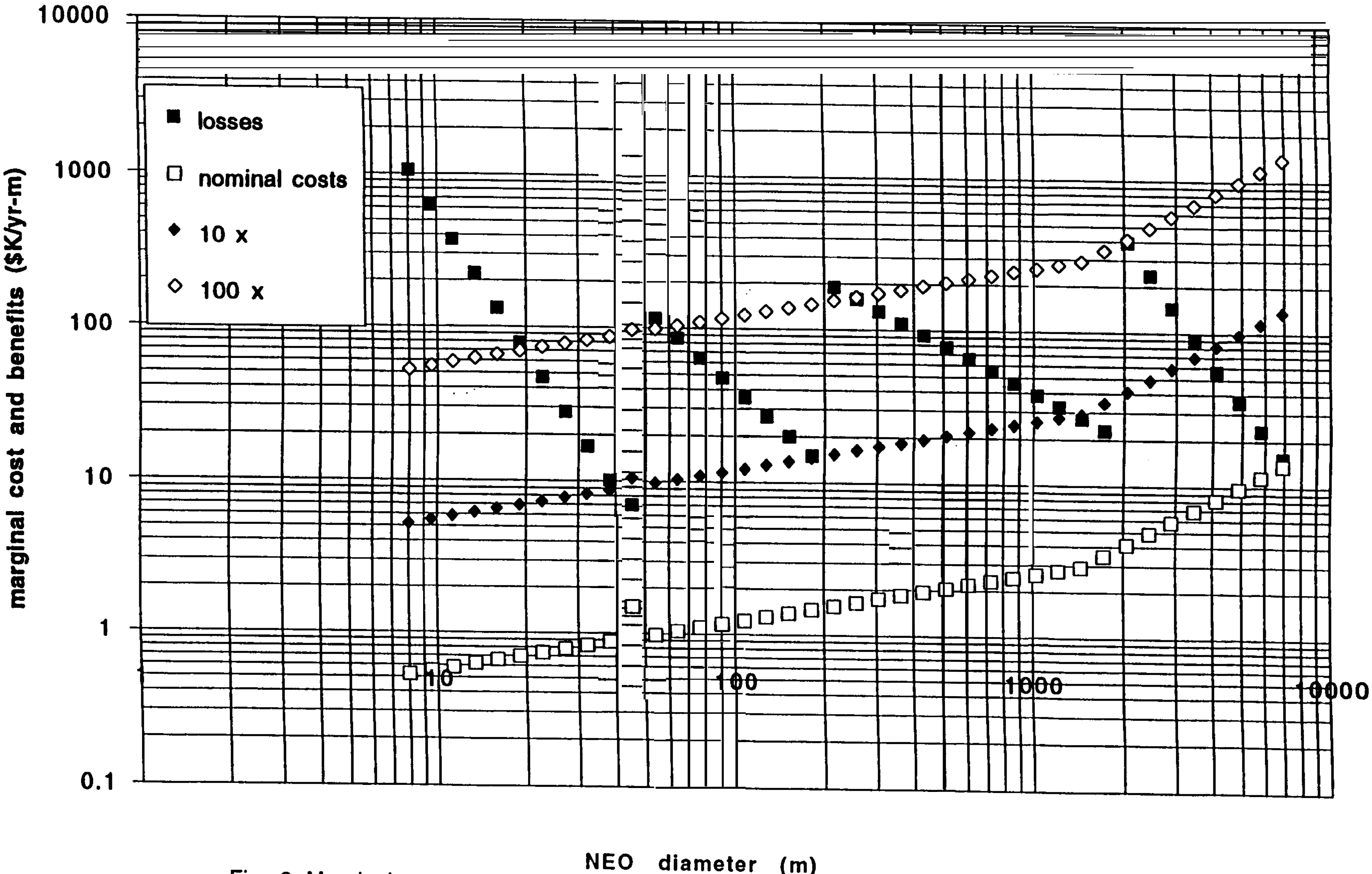


Fig. 9 Marginal costs and benefits of NEO defenses.

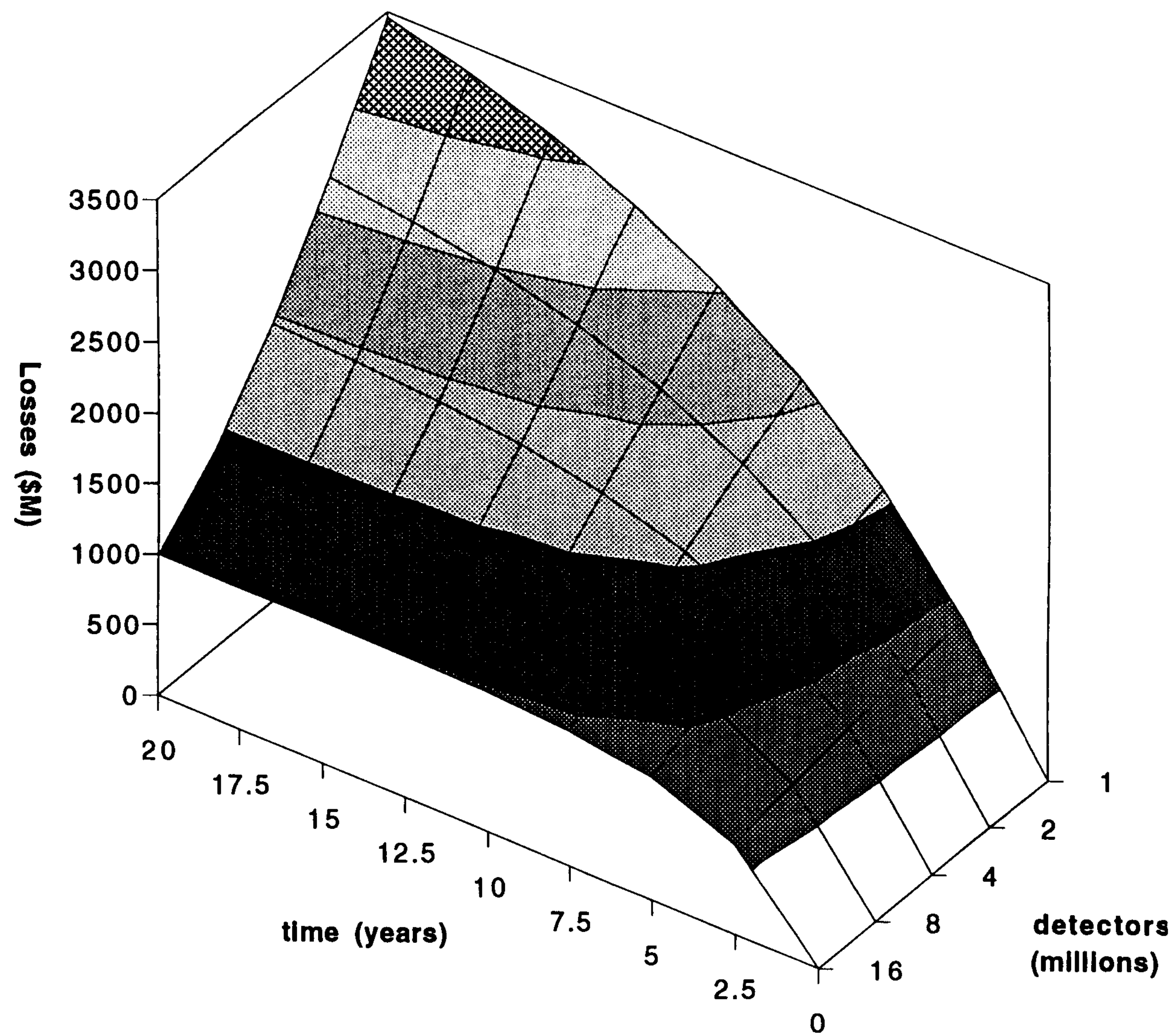


Fig. 0 Losses versus time for various sensors

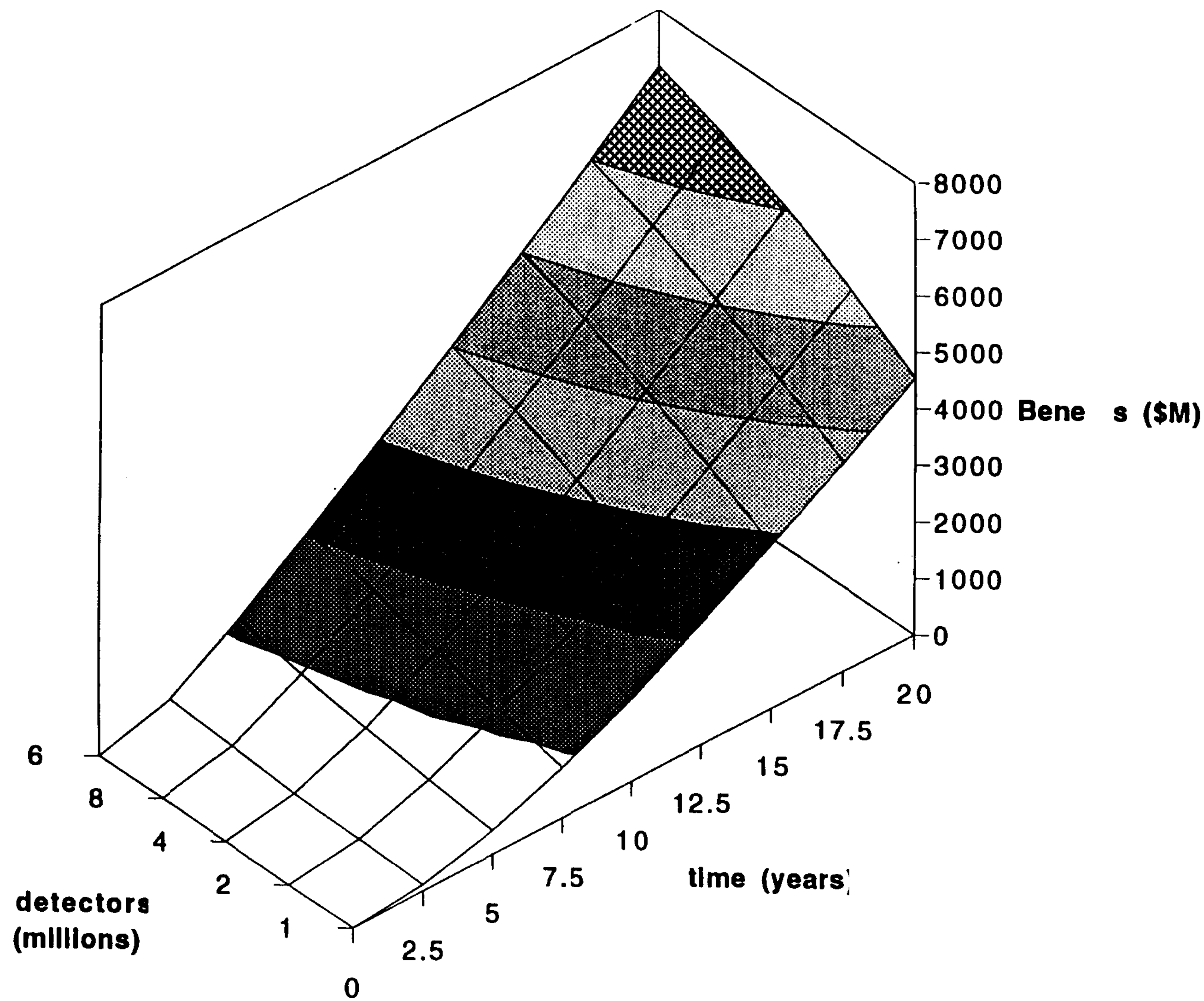
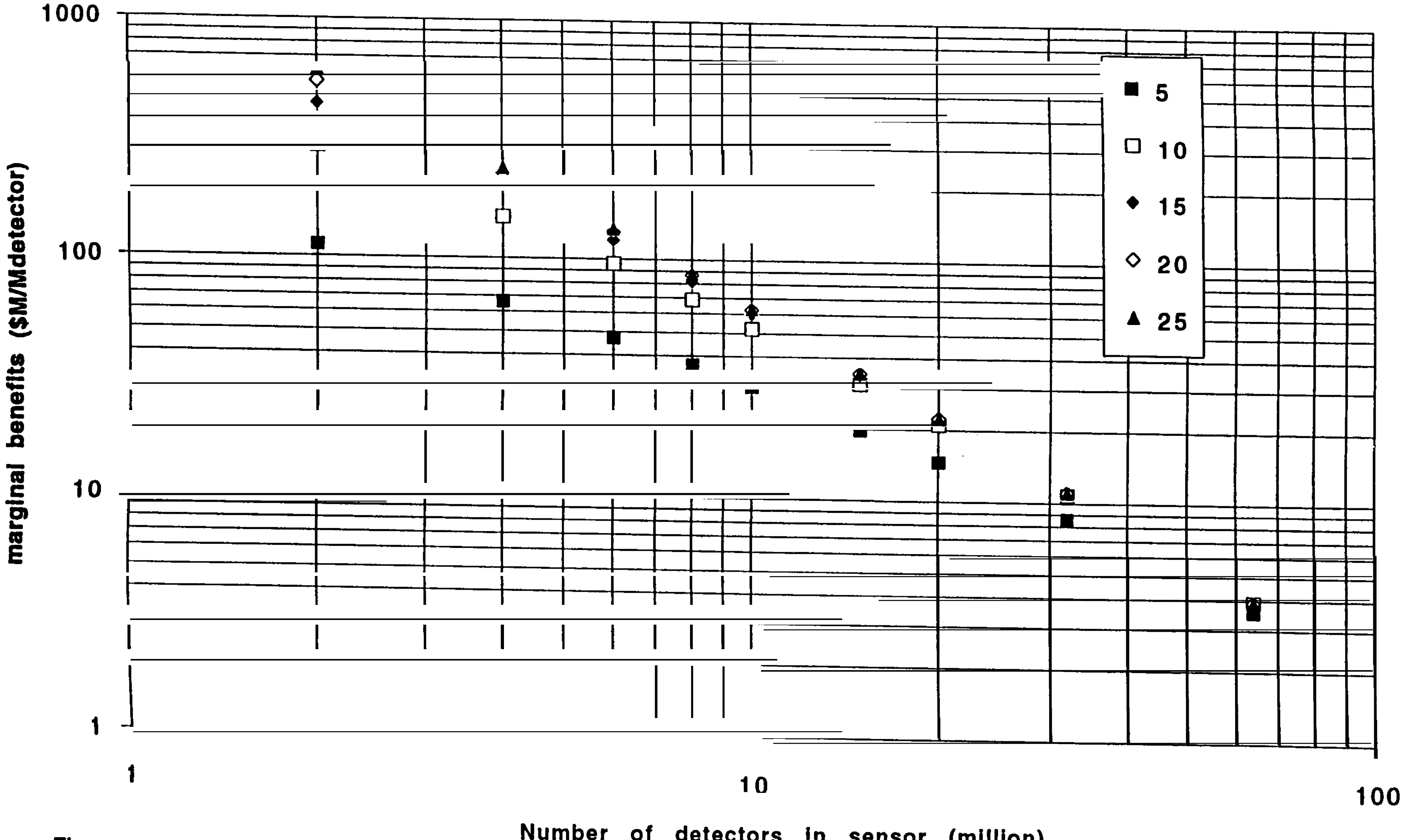


Fig. 11. Benefits as a function of time for various sensors.



Fig

Fig. 12 Marginal costs as a function of the number of detectors and search time.

Panel Papers

Optimal Trajectories for Interception of Earth-Orbit-Crossing Asteroids

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Optimal (minimum-time) trajectories are determined for the interception of asteroids which pose a threat of collision with the Earth. An impulsive-thrust escape from the Earth is used initially to reduce flight time but is followed with continuous low-thrust propulsion because of the significant propellant mass advantages of electric propulsion. The initial impulsive delta-v is no larger than that used for a Hohmann transfer to Mars, e.g. that used for Mars Observer.

The continuous optimization problem is formulated as a nonlinear programming (NLP) problem using a method (referred to as "collocation") in which the differential equations of motion are included as nonlinear constraint equations in the NLP problem. In this formulation the NLP problem parameters are the state and control variables at discrete points. Polar coordinate are used so that the state variables are radius, angle, radial velocity, angular velocity, and mass. The control variables are the thrust pointing angles. The optimizer is also free to vary the launch date (in the event that waiting might improve the geometry of the intercept) and the position in Earth orbit at which the impulsive delta-v is applied. The electric motor thrust and specific impulse are assumed constant, but as fuel is consumed the thrust acceleration increases.

Initial results have been obtained only for the 2D case, i.e. assuming the asteroid orbits in the ecliptic plane. The target asteroid is #1862 with a = 1.4711 AU and e = .56016. A false initial longitude of the asteroid is chosen so that collision with the Earth will occur in 90 days. With an initial low-thrust acceleration of 0.121 milli-g interception occurs after a flight time of 84.6 days. Assuming an I_{sp} of 1000 sec the final thrust acceleration is 1.753 milli-g; thus approximately 11% of the spacecraft mass, after escape from the Earth, remains at interception of the asteroid.

Substantiation of Required Characteristics of the Space-Rocket Complex for Interception of Dangerous Space Objects in the System of Earth Protection

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Asteroids and comets with trajectories intersecting the orbit of Earth represent a danger to our planet. The possible ways to prevent a dangerous object from colliding with Earth are splitting or deflecting its trajectory. For that purpose nuclear explosive devices with power up to 10...20 megatons are proposed to be used. The report based on statistical data processing embracing over 100 dangerous asteroids gives a substantiation of required performances of the Space Rocket Interception Complex - the basic component of the Earth Protection System. The calculated time of interception and required initial velocity depending on the time left until collision and efficiency of the available nuclear device are presented. The report shows the possibility of creating an interception complex consisting of a space interceptor with a nuclear explosive device, a booster, a launch-vehicle and supporting systems. The offered complex is able to attack a dangerous object up to several kilometers in diameter, provided the interceptor is launched several years prior to prospective collision. For interception of dangerous objects with diameter of 0.5...1.0 km the interceptor should launch approximately 0.5...1 years prior to collision.

Introduction

At present scientific and technical experts of a number of countries intensively discuss the possible ways of development of the Earth protection system to guard the planet against asteroid-comet danger.

In accordance with the materials of the International Conference "Problems of Earth Protection Against Collision with Dangerous Space Objects" (SPE-94) where these problems were discussed (September 26-30, 1994, Snezhinsk), the system can be developed by the international community in the foreseeable future on the basis of accumulated knowledge and experience in the field of space-rocket, nuclear and common industrial technologies. The basic component of the Earth Protection System is the Space Rocket Interception Complex (SRIC) for interception of Dangerous Space Objects (DSO) - asteroids and comet nuclei.

The report offered to Your notice gives a complex substantiation of required external performances of the SRIC.

Dangerous space objects

Asteroids and comet nuclei with trajectories intersecting the orbit of Earth represent a danger to the Earth's biosphere. Some asteroids approach the Sun closer than Earth and, thus, pose direct threat of collision with the planet.

For substantiation of required performances of the SRIC the accepted predicted characteristics of DSO, their mass and strength properties and space-time characteristics of their orbits are of decisive importance. For this purpose statistical data processing embracing about 200 asteroids was carried out. In the course of the processing it was assumed that the danger of collision with Earth is higher for those asteroids that are closer to the orbit of the planet at the instant of the processing. The results of the processing are presented in Fig.1...6. Fig.1...3 present statistical functions and histograms of distribution of asteroids' diameters, orbit inclinations concerning the ecliptic and periods of revolution around the Sun for a sample of 184 asteroids with perihelia below 1.33 a. u. Fig. 4...6 present the same dependencies for a sample of 91 asteroids (from the aforecited sample) that approach the Earth's orbit closer than 15 mill. km.(0. 1 a.u.). In accordance with the premises taken, in the near future collision is possible with the asteroids having the parameters presented in Fig.4...6, and in the more remote future - the ones presented in Fig.1...3.

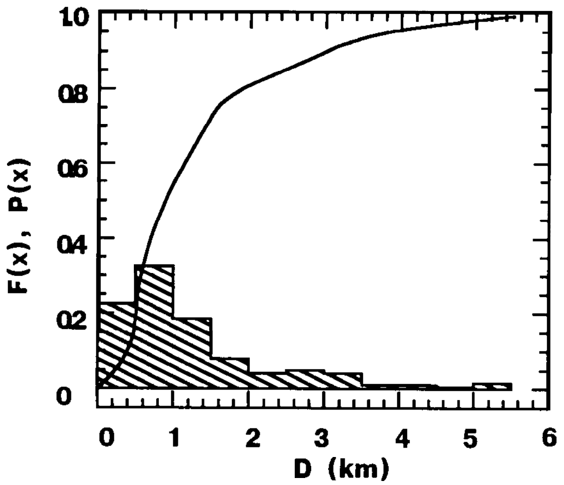

Figure 1. Statistic Function and Distribution Histogram of dangerous asteroids diameter
(the long-term prospect)

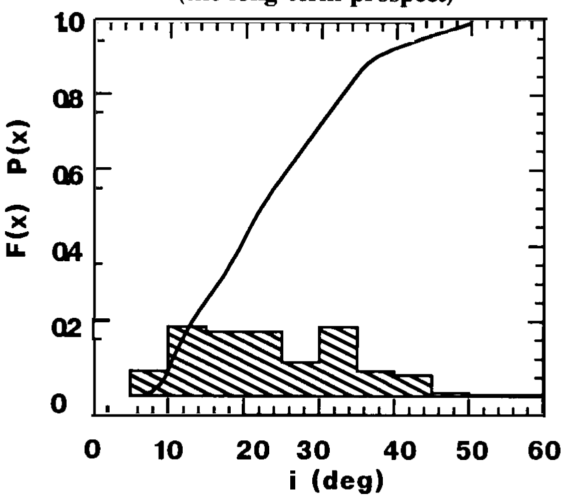

Figure 2. Statistic Function and Distribution Histogram of dangerous asteroids orbit inclination
(the long-term prospect)

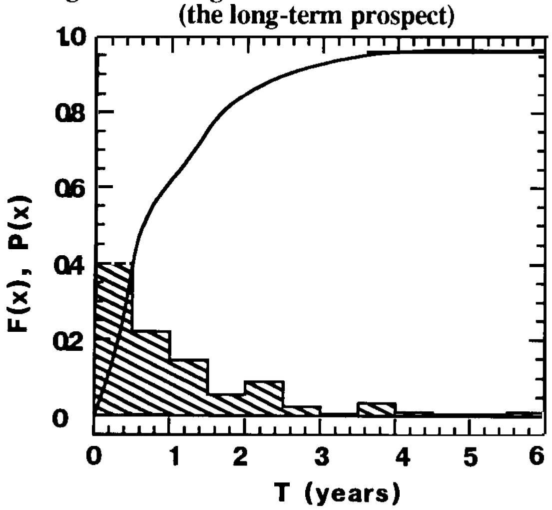

Figure 3. Statistic Function and Distribution Histogram of period of revolution of dangerous asteroids
(the long-term prospect)

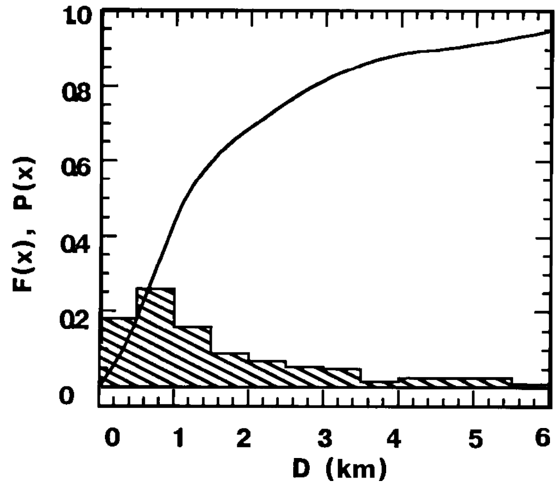

Figure 4. Statistic Function and Distribution Histogram of dangerous asteroids diameter
(the near-term prospect)

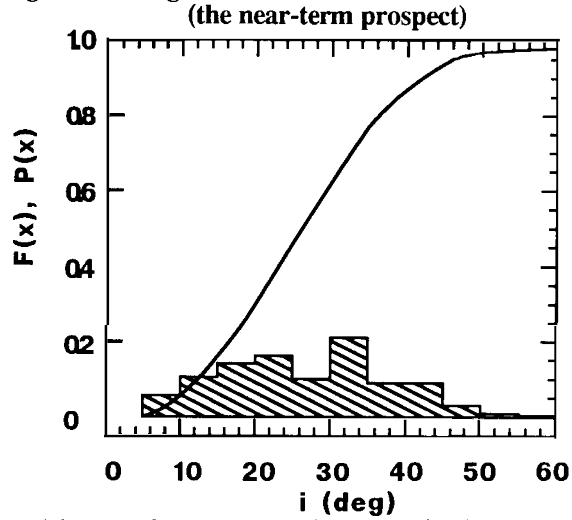

Figure 5. Statistic Function and Distribution Histogram of dangerous asteroids orbit inclination
(the near-term prospect)

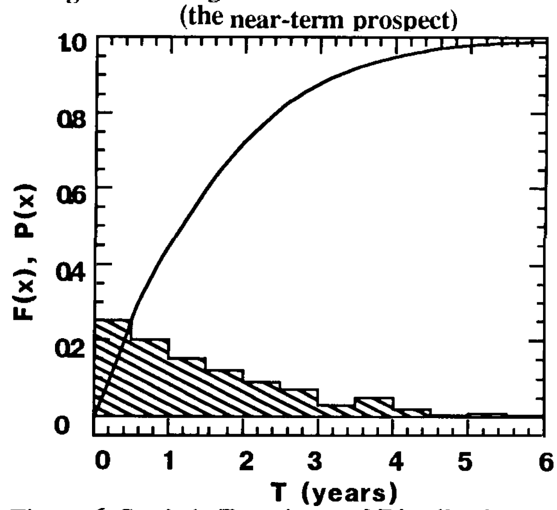

Figure 6. Statistic Function and Distribution Histogram of period of revolution of dangerous asteroids
(the near-term prospect)

Table 1 presents the results of the dependencies analysis for the near-term prospect and Table 2 - those for the long-term prospect.

Table 1. Basic parameters of dangerous asteroids of the near-term prospect.

Level of probability	Diameter (km)	Inclination (deg)	Period of revolutions (years)
F(x) = P{X<x}=0.5	< 1.0	< 8	< 2.5
F(x) = P{X<x}=0.9	< 3.0	< 25	< 3.5
Pmax	0.5...1.0	0...5.0	1.0...1.5 3.0...3.5

Table 2. Basic parameters of dangerous asteroids of the long-term prospect.

Level of probability	Diameter (km)	Inclination (deg)	Period of revolutions (years)
F(x) = P{X<x}=0.5	< 1.2	< 11	< 2.7
F(x) = P{X<x}=0.9	< 4.5	< 32	< 4.2
Pmax	0.5...1.0	0...5.0	3.0...3.5

In the course of the selection of required performances of the SRIC it is reasonable to take such predicted characteristics of DSO and their trajectories that embrace the whole range of significant characteristics, as a minimum for the near-term prospect, and the worked out performances of the SRIC should later provide the solution to the long-term prospect problems, for example by way of increasing the system power performances.

The space-time trajectory characteristics of the asteroids like Ikar and Adonis (periods of revolution 1.117 and 2.76 years respectively, inclination 0...25 deg.) are assumed to be the most appropriate predicted characteristics of DSO. Taking into account that among known meteos (DSO which have already impacted the Earth and reached its surface) stone chondrites are of absolute majority, as a DSO model substance we will consider a stone silicate material having a density of ca. 3500 kg/m^3 and mechanical properties close to those of rocks on the Earth's surface. The most probable diameter of dangerous asteroids is 0.5...1.0 km, though the possibility of collision with bigger ones, 3.0...4.5 km in diameter, should also be considered.

Possible ways of influence on dangerous space objects

The basic methods to prevent dangerous collision of DSO with Earth are the following:

- deflection of a DSO trajectory to ensure its safe pass by Earth;
- splitting or any other way of disintegration into small fragments of no danger to the Earth's biosphere.

In addition to the objects that collide with Earth directly, the objects "captured" by the Earth's gravitational field when passing at a distance are also dangerous to the planet. Fig.7 presents a DSO capture radius depending on its velocity relative to Earth. The DSO capture radius determines the maximum initial miss of the DSO, relative to Earth considered as a point mass, which leads to its fall onto Earth. If the miss is greater the DSO will not fall onto Earth, though its trajectory will be curved by the planet's gravitational field.

From the plot it is evident that with increase in the DSO relative velocity the value of capture radius decreases and from the values of 20...30 km/sec and on asymptotically approaches the Earth's radius. For the predicted parameters taken (Ikar and Adonis type) the capture radius is about 7000 km. Thus the effect means efficiency (the amount of momentum applied) and the time of advanced action should be determined so as to bring the DSO out of a range of 7000 km from Earth at the instant of the prospective collision. It should be noted that increase in the intercept range leads to essential decrease in the required increment of the DSO velocity. This principle is of decisive importance for determination of the SRIC parameters, its propulsion system capabilities of delivery of the DSO effect means, and for development of appropriate tactical application schemes.

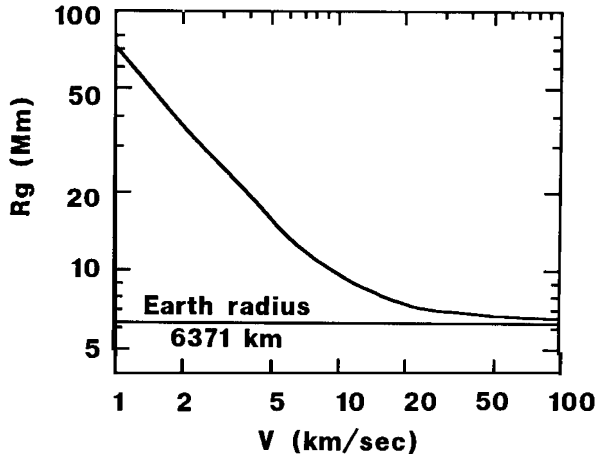

Figure 7. Gravitational capture radius (Rg) dependence of a space object approach velocity (V)

Practical realization of one or another application scheme will in many respects depend on to which extent the information services of the Earth Protection System (EPS) are capable of timely warning about the danger.

Effects produced on space objects by nuclear explosive devices

Complex coordination of the SRIC performances requires data on the DSO velocity increment caused by action of effect means. Nuclear explosive devices are taken as predicted effect means. Their merit is high concentration of energy in a nuclear charge, which allows to use an interceptor of comparatively small mass and dimensions.

The effects produced on a DSO by a nuclear explosion are the following:

- the momentum gained by the object from the shock wave of the explosion products and interceptor fragments;
- reactive forces caused by evaporation of thin superficial layer produced by penetrating radiation;
- reactive forces caused by rock ejection from the crater produced by the explosion;
- shock waves initiated by the explosion within the body of the object.

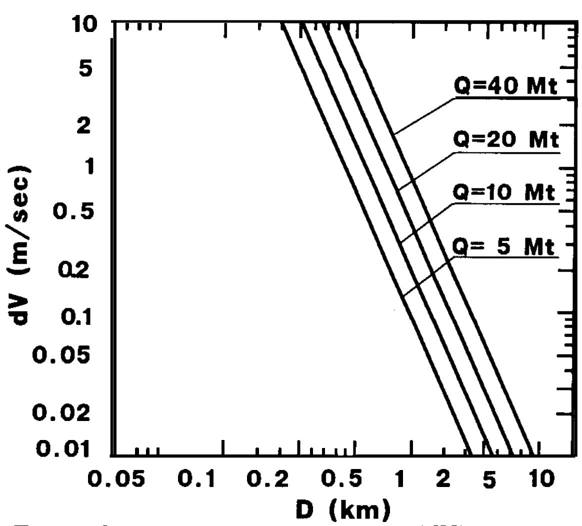

Figure 8. DSO velocity increment (dV), produced by contact explosion of a nuclear device of various power (Q), depending on diameter (D) of DSO with density of 3500 kg/m³.

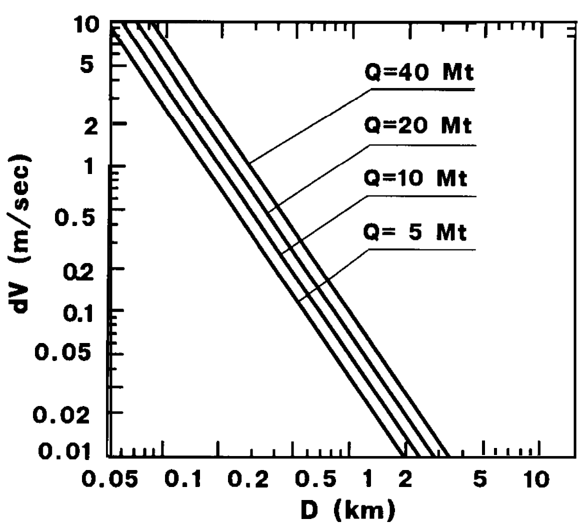

Figure 9. DSO velocity increment (dV), produced by non-contact explosion of a nuclear device of various power (Q), depending on diameter (D) of DSO with density of 3500 kg/m³.

Fig.8 presents the estimates of velocity increment, gained by an object as a result of contact explosion, depending on the nuclear device power. The calculations show that by way of contact explosion of power 10...20 megatons a velocity increment up to 1 m/sec can be imparted to an asteroid 1.3...2.0 km in diameter.

Fig.9 presents the values of velocity increment, gained by an object as a result of non-contact explosion, depending on the nuclear device power. In this case the altitude of the explosion is accepted so as to produce the maximum velocity increment. The calculations show that by way of non-contact nuclear explosion of power 10...20 megaton a velocity increment up to 1 m/sec can be imparted to an asteroid 200...300 m in diameter.

Estimations of the additional velocities imparted to DSO are obtained using methods available in SRC which are assumed to be further proved by specialized organizations in the next phase of research.

The nuclear devices application efficiency can be greatly improved by implementing deepened explosions within the object body. According to the estimation given by the Russian Federal Nuclear Center (RFNC-VNIITF) only 10...13 % of released energy spreads into the object interior as a result of contact explosion, with the rest of it dissipated into the outer space. With a nuclear charge put at certain optimum depth from 70...80 % to 100 % of the released energy goes into splitting and ejection of rock material. Therefore in this case approximately 7-fold increase in velocity increment of the DSO can be expected as compared with contact explosion of the same nuclear device.

Tactical capabilities of nuclear explosive devices of preventing asteroids from colliding with Earth (tactical interception mode) are adduced in Fig.10. It presents the maximum size of rock asteroids with density of 3500 kg/m^3 that can be brought at the required distance from Earth (about 7000 km) without destruction depending on a nuclear device power, the method used (contact, non-contact, deepened) and advanced action time (the time between the nuclear device explosion and prospective collision with Earth).

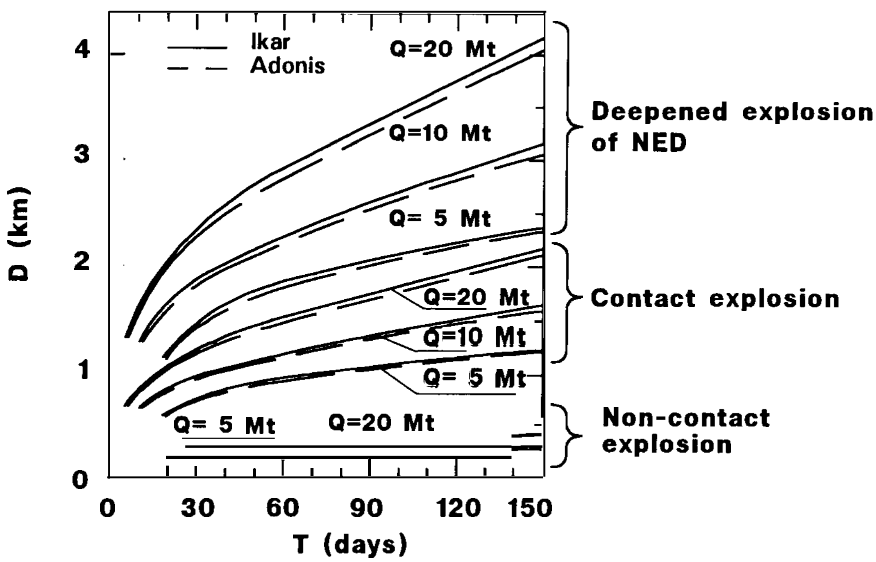

Figure 10. Maximum diameter (D) of DSO that can be brought at safe distance from Earth depending on NED power (Q), method of its application and advanced action time (T).

The analysis of the presented dependencies shows that asteroids belonging to the most probable class (in mass) with diameter of 0.5...1.0 km can be deflected from Earth by means of contact explosion of power 5...20 Mt. In this case the advanced action time can vary between 6...10 days and 80 days depending on the nuclear device power. More powerful nuclear explosive devices (NED) allow lesser advanced action time. Bringing larger asteroids (3...4.5 km in diameter) at safe distance from Earth requires deepened explosions of powerful NED and advanced action time about 120 days.

The alternative way of bringing asteroids away from Earth is strategic interception mode when the interception of a DSO is implemented during several revolutions of the object around the Sun. In this case the required power of NED can be greatly reduced because of the longer advanced action time.

Required parameters of the space interceptor delivery schemes

To obtain the predicted values of initial velocity and time of delivery of the space interceptor (SI) to DSO, which make it possible for the SRIC to implement tactical and strategic interception, the computer simulation of the process of interception was carried out. In the process of the simulation the trajectories requiring the least initial velocities were selected from the whole set of possible trajectories of the SI delivery to the interception point. Fig. 11...14 present the calculated values of initial velocities of the SI and the time

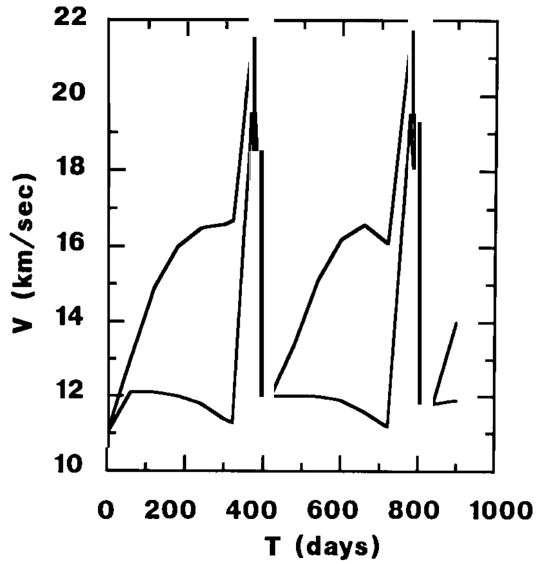

Figure 11. Required initial velocity (V) of SI for interception of an asteroid of Ikar type depending on advanced action time (T).
The upper plot - for the case of interception of an asteroid with orbit inclination of 23 deg. The lower plot - for the case of interception of an asteroid with an orbit lying in the ecliptic plane.

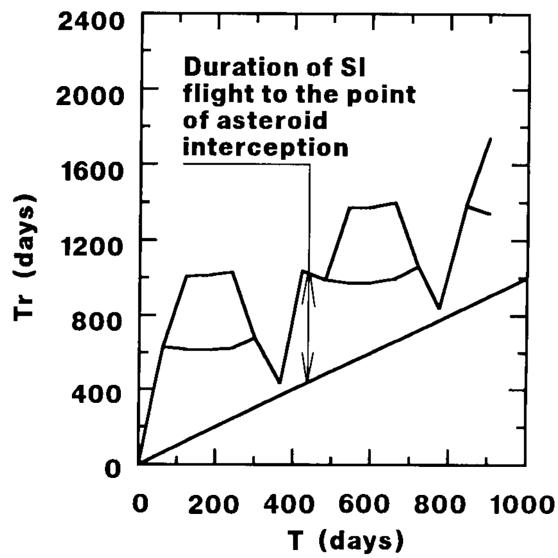

Figure 12. Reserve of time (Tr), necessary for interception of an asteroid of Ikar type, depending on advanced action time (T).
The upper plot - for the case of interception of an asteroid with orbit inclination of 23 deg.
The lower plot - for the case of interception of an asteroid with an orbit lying in the ecliptic plane.

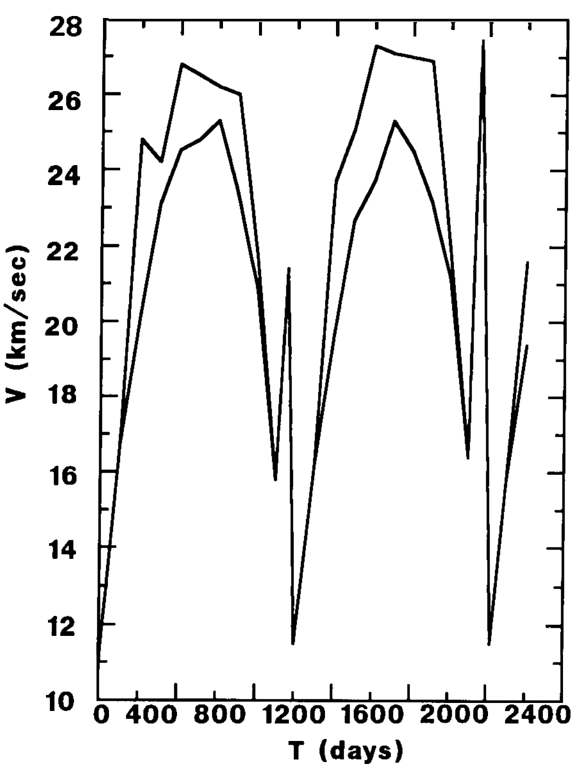

Figure 13. Required initial velocity (V) of SI for interception of an asteroid of Adonis type with orbit inclination of 25 deg depending on advanced action time (T). The upper plot - with maximum duration of the interceptor flight limited by 3 years. The lower plot - with duration of the interceptor flight not limited.

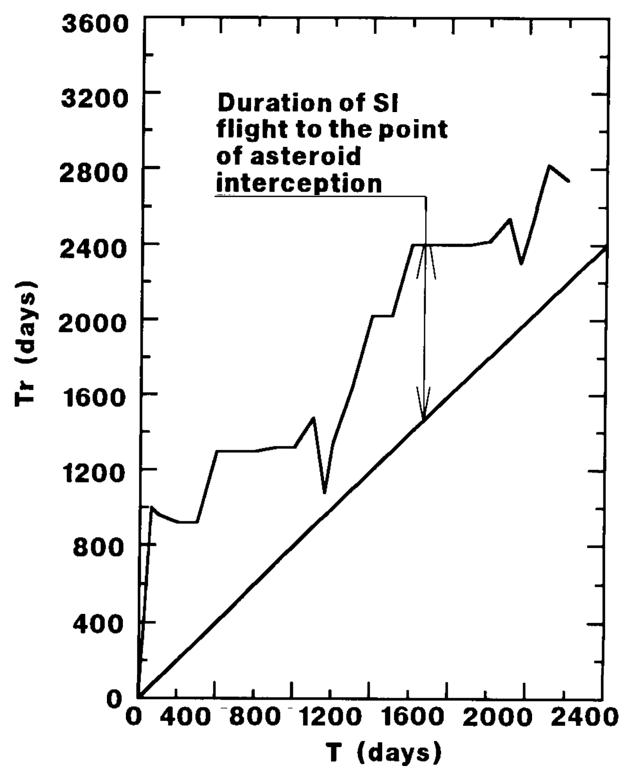

Figure 14. Reserve of time (Tr), necessary for interception of an asteroid of Adonis type with orbit inclination of 25 deg depending on advanced action time (T). Duration of the interceptor flight limited by 3 years.

necessary for tactical interception. These values are given for interception of asteroids of Ikar and Adonis type. The values of required initial velocities and interception time are presented depending on the advanced action time. Besides, time of interception is not limited by capabilities of the EPS information services. The results of calculations for interception of asteroids with diameter 0.5 . . . 1.0 km with the use of NED of power 5...20 Mt are presented in Table 3.

Table 3. Space-time parameters of tactical interception of asteroids with diameter of 0.5...1.0 km with the use of nuclear explosive devices of various power

NED power (Mt)	Time of advanced action (days)	Minimum required velocity of the SI (km/sec)			Time necessary for interception (days)		
5	15...80	11.3-12.1[a]	11.6-13.6[b]	11.6-15.5[c]	200-630[a]	200-760[b]	200-1000[c]
10	10...40	11.2-11.8[a]	11.4-12.3[b]	11.4-13.4[c]	140-420[a]	140-420[b]	140- 660[c]
20	6...20	11.1-11.3[a]	11.2-11.6[b]	11.2-11.6[c]	80-200[a]	80-200[b]	80- 200[c]

[a]Ikar-type asteroid (inclination 0 deg)
[b]Ikar-type asteroid (inclination 23 deg)
[c]Adonis-type asteroid (inclination 25 deg)

The analysis of the presented data shows the following. The use of more powerful NED for interception of asteroids of the most probable class (0.5...1.0 km in diameter) leads to a decrease in the values of required initial velocity of the SI and the time needed for interception.It appears inexpedient to use NED with power of 5 Mt, because in this case interception requires a long period of time (up to 1000 days) and initial velocity up to 15.5 km/sec. As far as these parameters are concerned the use of NED with power of 20 Mt is the most preferable. Nevertheless from the calculations follows that increasing the initial velocity of the SI to 14...15 km/sec makes it possible to increase time of interception in tactical mode up to 1 year even with the use of NED with power of 10 Mt.

The greatest efficiency according to these criteria (lesser initial velocity of the SI and lesser time of interception) can be obtained by using NED with power of 20 Mt. In this case required initial velocity of the SI is not greater than 12 km/sec with time of interception not greater than half a year.

As noted above, it is more preferable from the energetic standpoint to implement interception of the largest asteroids of the near-term and long-term prospects (with diameter up to 3 km and 4.5 km respectively) in the mode of strategic interception, performed at the intersection point of the asteroid and Earth orbits in one or more revolutions of the asteroid around the Sun before its collision with Earth.

Table 4 presents initial velocity and time required for interception with the use of NED with power of 5 Mt, 10 Mt, 20 Mt.

Table 4. Space-time parameters of strategic interception of asteroids with diameter of 3.0...4.5 km with the use of nuclear explosive devices of various power

Diameter of asteroid (km)	NED power (Mt)	Time of interception (years)[a]	Number of DSO revolutions before collision[a]	Initial velocity (km/sec)[a]
3.0	5	5 / 4	3 / 1	11.2 / 11.2
	10	2 / 4	1 / 1	11.1 / 11.2
	20	2 / 4	1 / 1	11.1 / 11.2
4.5	5	9 / 7	7 / 2	11.1 / 11.5
	10	6 / 4	4 / 1	11.4 / 11.2
	20	3 / 4	2 / 1	11.5 / 11.2

[a]Initial velocity of the SI and time of interception adduced in the numerator relate to interception of asteroids with Ikar-type trajectories, and in the denominator - with Adonis-type trajectories.

The presented data show that using NED with power of 5 Mt leads to considerable increase in time of interception, as compared with NED with power of 10 Mt and 20 Mt, which is inexpedient.

The estimations also show that in one revolution around the Sun the asteroids of the following size can be intercepted (see Table 5).

From the presented data follows that the size of the asteroids that can be intercepted in one revolution before collision with Earth exceeds the size of asteroids of the near-term prospect for all considered conditions of interception and NED with power of 10 Mt and 20 Mt. It should also be noted that realization of the SI velocities of 13...14 km/sec can reduce the time necessary for interception of DSO by 0.5 years approximately.

Table 5. Space-time parameters and the maximum diameter of an asteroid, intercepted in strategic mode in one revolution before collision, for nuclear explosive devices of various power.

NED power (Mt)	Time of interception (years)[a]	Initial velocity (km/sec)[a]	Diameter of asteroid (km)[a]
5	2 / 4	11.1 / 11.2	2.4 / 4.4
10	2 / 4	11.1 / 11.2	3.0 / 5.6
20	2 / 4	11.1 / 11.2	3.8 / 7.1

[a]Initial velocity of the SI, time of interception and diameter of asteroid adduced in the numerator relate to interception of asteroids with Ikar-type trajectories and in the denominator - with Adonis-type trajectories.

Interception of large asteroids of the long-term prospect will require from the SRIC and the EPS information services of advanced warning realization of longer time of interception (up to 7...9 years).

Thus, the results of calculations show that the whole list of the problems presented to the SRIC can be successfully solved by realization of tactical and strategic modes of the SRIC application. There are two equally effective variants of the SRIC:

- The SRIC with initial velocity of 14 km/sec and NED with power of 10 Mt;
- The SRIC with initial velocity of 12 km/sec and NED with power of 20 Mt.

Determination of parameters of the space rocket interception complex

Adduced in previous paragraphs of the report conditions of effective application of NED for bringing DSO at a distance eliminating collision with Earth manifest themselves in respect to the delivery means as requirements for the SRIC and determine its external parameters which, in turn, determine its internal parameters and characteristics as well. The basic of these conditions are the following:

- the necessity to ensure direct hit of DSO by NED;
- the necessity to ensure high velocities (up to 12...14 km/sec);
- long interception time.

For the realization of the adduced conditions the SRIC should consist of the following components:

- the space interceptor providing delivery of a nuclear explosive device to the specified point of the DSO surface;
- the booster providing putting the space interceptor with required accuracy into the specified trajectory of flight to DSO;
- the launch-vehicle providing putting the space interceptor with the booster into low Earth orbit;
- the supporting systems of the complex.

When operating together in space the SI and the booster form the Orbital Impact Module (OIM).

The functional scheme of the SRIC is presented in Fig.15.

The achieved level of development of space-rocket technologies allows to form an image of the SRIC from the most developed and accomplished systems, that enable the complex to solve the problems set to it.

For above considered NED with power of 10 Mt and 20 Mt Table 6 presents mass parameters of the SI, the booster operating on criogen components (H_2 +O_2) or having electric propulsion systems, and mass parameters of the whole OIM. A circular orbit with altitude of 200 km is taken as the basic (initial) orbit.

Table 6. Mass parameters of the space interceptor, the booster and the whole Orbital Impact Module for NED of various power

NED power (Mt)	Initial velocity (km/sec)	Mass of the SI (tons)	Mass of the booster (tons)[a]	Total mass of the OIM (tons)[a]
10	14.0	9.5	55.5 / 27.0	65 / 36.5
20	12.0	17.6	42.4 / 33.4	60 / 51

[a]Mass of the booster operating on criogen fuel $H_2 + O_2$ and corresponding to this booster total mass of the OIM are adduced in the numerator, and the same parameters for the booster with Electric Rocket Propulsion System (of TEM "Bars" type) - in the denominator.

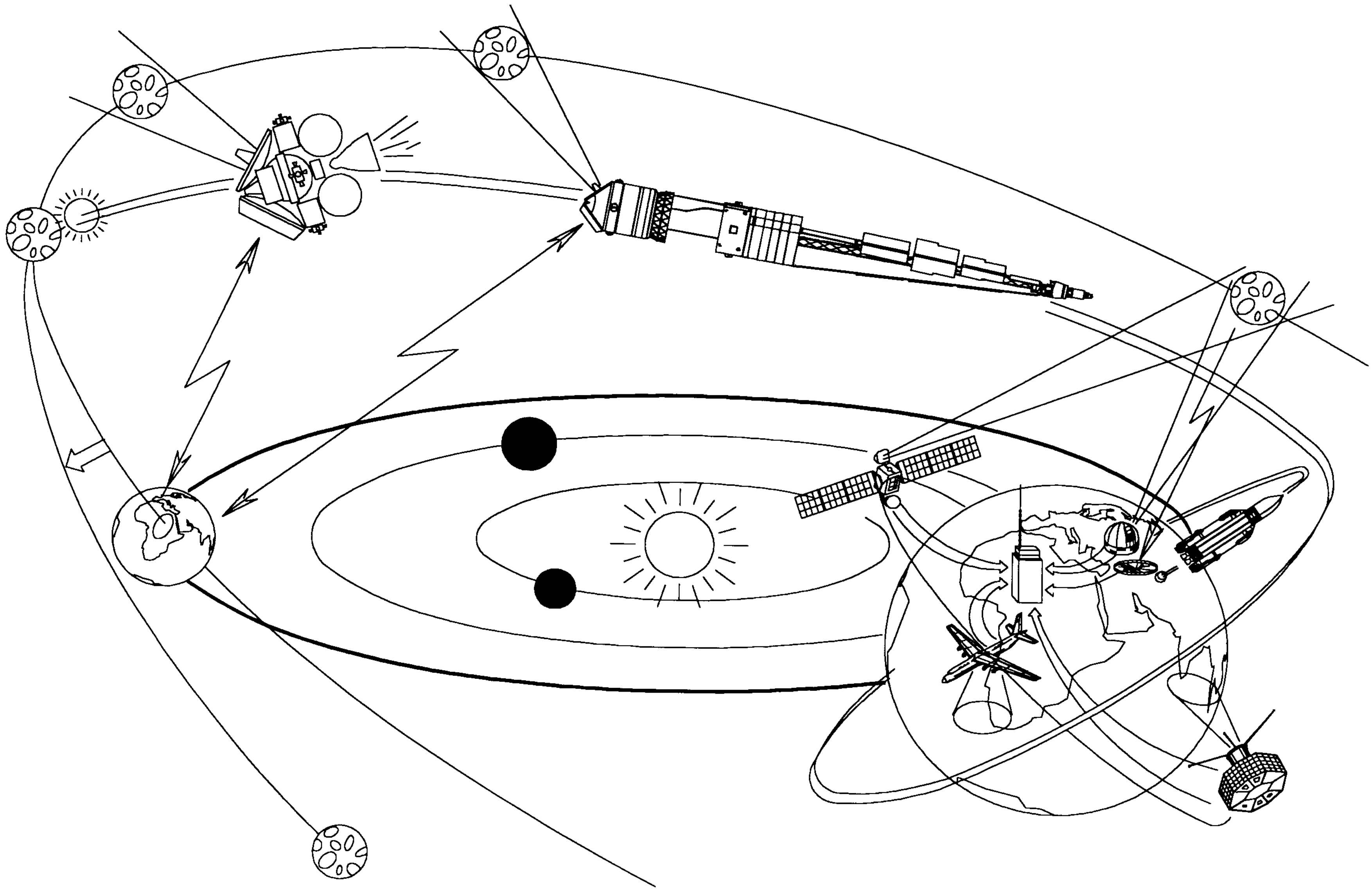

Figure 15. Functioning scheme of the Earth Protection System

According to our preliminary estimations, in the near-term prospect the space interceptors carrying nuclear charges with power of 10 Mt and 20 Mt for contact and non-contact application can be developed, as well as the boosters on criogen fuel components for the SRIC of the first generation that can solve the problems of the near-term prospect.As the OIM launch vehicle the "Energia" (at present the only launch-vehicle in the world capable of putting a payload of the required mass into low Earth orbit) possesses the highest degree of the availability.

The use of nuclear energized electric propulsion systems in the OIM makes possible an increase in the mass of the payload serving for interception, which allows to provide energy supply for realization of long interception time, that may be more preferable for interception of DSO of the long-term prospect, especially with the use for these purposes of alternative high-efficient non-nuclear effect means. The estimations show that the use of ERPS (Electric Rocket Propulsion Systems) makes possible delivery of the SI with a mass up to 42 tons (with a mass of the OIM about 100 tons) to DSO in the strategic mode of interception.

Conclusion

The carried out research allowed to form the image of the SRIC, based on the up-to-date achievements in space-rocket and nuclear technologies, that should become a basis for development of the system for protection of Earth against asteroid-comet danger.

This requires synchronous deployment of scientific research, design and experimental works for development of the basic systems of the EPS - the SRIC and the information services, and for creation of a catalogue of dangerous space objects and revision of space-time, mass and strength parameters of DSO.

Non-Nuclear Strategies for Deflecting Comets and Asteroids

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A number of authors have recently suggested that the only plausible defense against large Earth-threatening comets or asteroids is the use of very large (Gigaton) nuclear weapons. However, it can be plausibly argued that the mere existence of an arsenal of such weapons constitutes a danger to humanity far greater than the threat they are intended to mitigate. We have investigated other means of deflecting threatening asteroids. In particular, we have found a new solar collector strategy in which silicate and ice vapor from a heated spot on an asteroid or comet can provide sufficient thrust to deflect even a 10 km diameter asteroid with 10 years advance warning using a 1.5 km diameter collecting surface. Although this concept requires further technical development and suffers from at least one important problem (protecting the solar collector from the mass of gas and dust blown off the asteroid), initial order of magnitude estimates suggest that it could out-perform nuclear wepaons on a per-unit-weight basis. More importantly, the solar collector is big, fragile and slow, making it difficult to misuse this technology as a weapon of mass destruction.

Mitigation of the NEO Impact Hazard Using Kinetic Energy

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Kinetic energy impacts into an approaching Near-Earth object (NEO) on an Earth-colliding trajectory would be a very effective mitigation defense technique in some circumstances to protect Earth from the catastrophic effects of such a collision. The technology exists today to project kinetic energy over interplanetary distances and interact with comet and asteroid bodies to either deflect or fragment them. Technical details of how kinetic energy interacts with typical NEO materials are presented, along with some results from recent world-unique kinetic energy momentum deposition experiments. Qualitative target response phenomenology are discussed on cratering, momentum deposition, momentum enhancement factor, and fragmentation. A review of existing related data in the open technical literature is also presented and inferences drawn regarding the effectiveness of using kinetic energy to mitigate NEO impactors. Details of an actual Earth attempt at ramming a NEO (comet P/Grigg-Skjellerup) with kinetic energy (the Giotto spacecraft) will be described, along with some valuable lessons learned. Kinetic energy also provides a useful testbed for understanding the effects of other high energy sources on NEO materials. Future kinetic energy impact experiments and modeling opportunities are also articulated.

Introduction

Compelling evidence of a catastrophic asteroid impact on the Earth 65 million years ago (Alvarez et al., 1980 and Sharpton and Ward, 1990) has given rise to international discussions about the probability and prevention of future impacts. As a result of several recent near-misses (Morrison, 1992 and Scotti et al., 1991) and the comet Shoemaker Levy-9 impact of Jupiter in July 1994, considerable international attention has focused on defining the impact threat and determining potential hazard mitigation defense schemes for the protection of Earth against planetesimal impacts (Tedeschi, 1994). Initial studies indicate that hypervelocity impact is one of several favorable schemes for mitigating the possibility of Earth-impact by such bodies (Canavan et al., 1992 and Wood et al., 1995). A desirable characteristic for a defensive engagement would be to deflect the approaching body into a new, non-threatening trajectory by some type of momentum transfer or deposition. However, fragmenting the body into numerous pieces might make the problem worse, since some of the resultant debris might still possibly be on an Earth-impacting trajectory.

While there are some data on the fragmentation of planetesimal-type materials, e.g., basaltic rocks (Fujiwara et al., 1977) and ice (Kawakami et al., 1983), nowhere can one find experimental data on momentum deposition into such materials due to hypervelocity kinetic energy impacts. Of course, planetary geophysicists have been studying this type phenomena for years, but they can only infer the full-scale response of large asteroids to massive kinetic energy impacts (Housen and Holsapple, 1990). Simulating the macroscopic change in momentum of such bodies is difficult to do using modern shock-physics computational codes, e.g., hydrocodes, mainly due to inherent numerical limitations (Anderson, 1987). Therefore, a critical need exists to obtain well-characterized hypervelocity impact test data on actual NEO materials or NEO material analogs for code calibration purposes, and to conduct asteroid impact experiments in space to affect full-scale target response observational opportunities.

The scientific endeavors associated with geophysical planetary evolution also benefit directly from these types of impact tests. Hypervelocity impact interactions and their related catastrophic effects have traditionally been invoked as the major plausible mechanism that determines the mass spectra and velocity dispersions during planetary accretion and fragmentation (Hartmann, 1978). Modeling such impact interactions can be very complicated, especially when either the target or impactor are composed of natural materials which in many cases are inhomogeneous assemblages of minerals with faults, inclusions, grain and phase boundaries, and other imperfections which complicate the material response. The response of such materials to hypervelocity impact spans a wide range of material behavior, ranging from high impact temperatures and pressures, where hydrodynamic motion and thermodynamic effects predominate, to the low pressure regions where the mechanical properties dominate the process. In order to simulate such processes using sophisticated computer models it becomes necessary to understand the fragmentation effects of hypervelocity impact on related inhomogeneous targets through experimentation over a range of loading conditions, velocities, and target and projectile materials. Results from such experiments can then be used to test and validate computer models for the simulation of planetary interaction processes.

Why use kinetic energy?

Kinetic energy (KE) should be seriously considered for use in deflecting or disrupting threatening NEOs for the simple reason that it works. After all, kinetic energy is one of the fundamental drivers in the formation of our solar system; collisions between large bodies (and accretion) have been occurring for billions of years. When two objects collide there is an equal, but opposite, "reaction" on the receiving body caused by the incoming body, and total system momentum is conserved. The Second Law of Motion and the conservation of momentum (Halliday and Resnick, 1974) can therefore be exploited to do useful work on a NEO threatening to impact Earth. Kinetic energy is inherent to all things in motion, i.e., 1/2 x mass x $(\text{relative velocity})^2$ for non-relativistic relative motions. The ability to project kinetic energy (smart payloads) over interplanetary distances (by rockets) is well demonstrated, e.g., the grand tour of the outer planets by Voyager, flybys of asteroids Gaspra and Ida by Galileo, and Halleys comet flybys by several international spacecraft probes. All the requisite technologies exist. All that remains would be to actually use them someday against an approaching NEO threat, and to possibly demonstrate them against a benign NEO to learn how to do such long-range kinetic energy impact projections against a new class of targets hitherto unengaged in the manner described.

The conduct of precursor missions would allow intelligent technology downselect decisions to be made someday in the event of an actual emergency where kinetic energy might be called upon to protect the Earth. The effects of kinetic energy against NEO analog materials are well understood up to about 8 km/sec impact velocity, somewhat understood up to about 15 km/sec, and not so well understood beyond this. The physics behind kinetic energy impacts are shown in simple format in Fig. 1. The impactor strikes the NEO, creating a hydrodynamically induced crater and internal shock waves (on microseconds to milliseconds timescales) which propagate into the target (over timescales of many milliseconds to as much as 1000's of milliseconds), ultimately causing some type of target body response, i.e., an induced velocity (trajectory) change due to momentum deposition on the one extreme to body fragmentation and mass dispersion on the other.

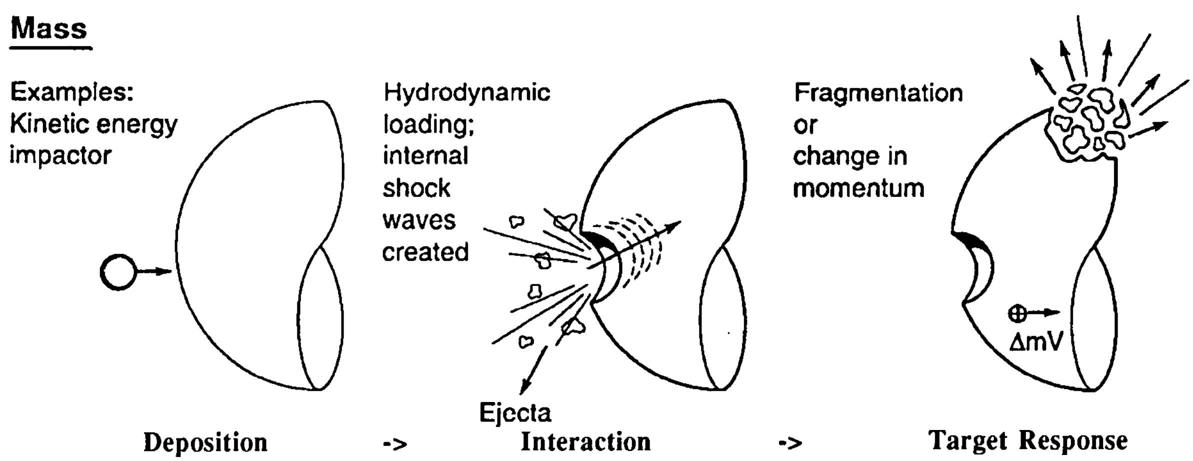


Figure 1. The kinetic energy coupling process into NEOs.

Critical issues

There are three critical issues which need to be extensively studied, if not actually resolved, before we can have confidence in the use of kinetic energy to reliably deflect or disrupt NEO bodies. They are given here as:

1. How hard can we push a NEO?

2. How hard will a NEO let us push it?

3. What are a NEOs material properties?

Upon cursory examination, these three issues may seem to be related, and in fact they are. We obviously can "push" a given NEO harder and harder by either increasing an impactor's mass or its velocity. It is obvious that increasing velocity buys us more since kinetic energy increases quadratically with increasing velocity, whereas KE only increases linearly with increasing mass. Initially, lower values of impactor kinetic energy relative to the mass of the NEO results in the formation of a small crater on the target, with some target body material blown outward and the net result being a change in target momentum (see Fig. 1). At higher values of impactor (projectile) KE per target unit mass, i.e., E_p/M_t, the crater in the target continues to grow in size. At some point, however, the target body will fragment thereby identifying the limit of how hard a body will let us push it. Above a certain E_p/M_t threshold, commonly called the fragmentation strength or specific strength (Mcknight, 1991 and Housen and Holsapple, 1990), where the largest remaining fragment is less than about half the original target mass, the target fragments into a spectrum of fragment sizes and dispersion velocities. This basically leads into the third issue - that of what are the material properties of the target body.

A number of target parameters ultimately will determine how hard we can push a NEO and how hard it will let us push it, thereby defining the need for NEO material properties. These properties can be fundamental in nature, or derived. Fundamental properties of interest include: material identification, molecular composition, density, volume, inheterogeneities and inclusions on both micro- and macro-scales, thermal and dynamic state, and three-dimensional structure. Derived properties include tensile and compressive elastic and plastic strength regimes - under both static ($<10^1$ sec^{-1}) and dynamic ($>10^8$ sec^{-1}) loading conditions - and including fragmentation, conductivity, thermal capacitance, and thermodynamic (EOS - Equation of State) properties under high pressure and temperature loading conditions, among others. An excellent treatment of the subject of material properties is given in Remo, 1994.

NEO fragmentation strengths

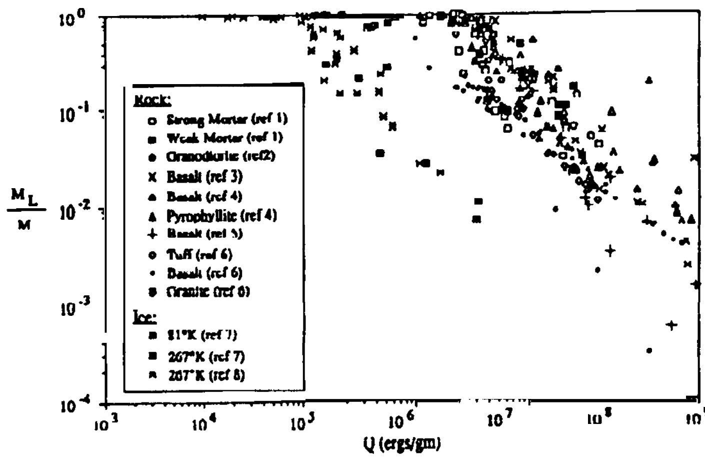
Table 1 contains an approximate listing of NEO material impact strength regimes (for basalt and ice only) as a function of M_l/M_t, the ratio of mass of the largest fragment to the original total mass, i.e., basically the net result to the target in terms of target mass dispersion. Catastrophic fragmentation can be defined here as the case where $M_l/M_t < 0.5$. Conversely, for $M_l/M_t > 0.5$ the target is still considered intact, but cratered.

Table 1. Experimental fragmentation strength regimes for rock and ice.

	Local crater		← Catastrophic Fragmentation →			
Target Material	E_p/M_t	M_l/M_t	E_p/M_t	M_l/M_t	E_p/M_t	M_l/M_t
Rock (basalt)	0.07	0.9	3	0.1	10	0.01
Ice	0.01	0.9	0.05	0.1	0.6	0.01

where: E_p/M_t=Projectile Energy/Target mass, J/gm; and M_l/M_t = Mass largest fragment produced/target mass

Other fragmentation strength data are shown in Fig. 2. It should be noted that the values in Table 1 are based on limited experimental data, and as such they should be considered only approximate, with large statistical variation in going from material sample to material sample. Nonetheless, these values suggest an upper limit on manageable energy deposition to rock and ice NEOs. Also, these values are considered conservative in that they could be high by an order of magnitude for a 1 km diameter body due to strain rate effects. At larger body sizes the strain-rate shock loading of the material is less (due to the effect of scale) and therefore the material failure level would be expected to be less. Materials are harder to fracture at higher strain rates, than the levels at which they fail for lower strain rates. Also, because of the general lack of obvious local inheterogeneities in the "pristine" laboratory samples (presumably unlike the case in nature) the target strength is considered "strength dominated" and, therefore, one would expect target fragmentation strength to be less in larger scale real materials. To first order, however, these data have direct application for estimating target responses for KE impacts, and perhaps for other high-rate energy deposition mitigation schemes as well.



Sources of Data. (1) Davis and Ryan (1988), (2) Cintala and Hörz (1984). (3) Fujiwara et al. (1977), (4) Takagi et al. (1984), (5) Fujiwara and Tsukamoto (1980), (6) Matsui et al. (1982), (7) Lange and Ahrens (1982), (8) Cintala et al. (1985)

Figure 2. Experimental rock and ice fragmentation strengths, $Q=E_p/M_t$ vs. M_l/M_t (Housen and Holsapple, 1990).

Modeling kinetic energy impacts

Ultimately it will be necessary to computationally model a kinetic energy intercept, that is an impactor striking a particular target NEO. It is impossible for us to expect to be able to test full-scale engagements on Earth, nor can we expect to do precursor impact experiments in space on many conceivable NEO bodies, if such missions are even conducted at all. Therefore some approach is needed to allow us to confidently predict (and assumably control) the full-scale outcome of such engagements. Much work has been done in empirically "curve-fitting" existing data sets, thereby resulting in a crude first-order approach which could be used to predict engagement outcomes. The danger in this approach is that the empirical model only applies over the range of parameters explored and assessed in its underlying experiments, and may not necessarily apply outside this parameter space, especially when "scaling-up" the engagement parameters many orders of magnitude in impactor and target body size (and mass) and perhaps up to an order of magnitude in velocity. The preferred approach would therefore be to use complex three-dimensional hydrocodes operating on high-speed computers to predict the outcome. Such an approach instills an increased level of confidence in the predicted outcome because these simulation codes are replete with the ability to model the complex temporal, three-dimensional, and physics-based aspects of this particular type of hypervelocity impact engagement. However, even hydrocodes need appropriate input data and should be validated against physics data and hopefully a representative engagement, i.e., a precursor mission.

Impact experiments

Impact experiments are necessary to provide both detailed material property data for predictive models, and also full-scale data to validate and verify the models against. Very little direct experimentation has been done in support of the planetary defense mission. Some material property (Furnish and Boslough, 1994), fragmentation (Hartmann, 1977; Fugiwara et al., 1978; and Davis and Ryan, 1990) and momentum deposition (Tedeschi et al., 1994) data have been collected. But these data are certainly incomplete for this application, and much more data are required. Much related work has been done which could serve as the basis for our initial understanding of using KE to deflect or disrupt NEOs. Examples are many in the area of planetary sciences: asteroid belt collisions/evolution, planetary impacts, ice and rock cratering and fragmentation, and the recent comet Shoemaker Levy-9 fragment impacts of Jupiter. The military arena has also done much work, e.g., in shielding, penetration, and cratering, and in the development of complex three-dimensional hydrocodes, e.g., Eulerian, Arbitrary Lagrangian Eulerian (ALE), and Smooth Particle Hydrodynamics (SPH).

Momentum deposition uncertainties

Current analytical and semi-empirical impulse deposition models may be underestimating high velocity impact effects, resulting in underestimated predicted momentum deposition values. Figure 3 shows a comparison of several analytically calculated normalized impulse parameters, I* (Shafer et al., 1994), for different impact velocities compared against some world-unique momentum deposition experimental data for rock, ice, and iron samples (Tedeschi et al., 1994). Observe that the experimental data are up to a factor of four higher than the calculations at the given impact velocity. It is interesting to note the monotonic trend that the lower density materials have higher I* values. This trend is probably due to the effect of target material phase change, especially in the vapor and ionized plasma states where secondary chemical reactions may even be possibly occurring on sufficiently short timescales to be increasing the apparent momentum deposition to the target due to more energetic mass blow-off effects. Obviously these speculations are preliminary and more research and analysis are required to provide a conclusive basis for this hypothesis. It is also interesting to note that the iron data point identically compares with two of the more realistic analytical momentum deposition models. This is probably so because the two models were formulated and benchmarked against data from low velocity impact tests against metal targets, where massive target-response phase changes did not take place, i.e., solid to liquid or solid to vapor. The analytical models in Fig. 3 most likely have limitations when extrapolated to higher impact velocities beyond which they were validated, and certainly beyond the point of significant phase-change effects in the target material.

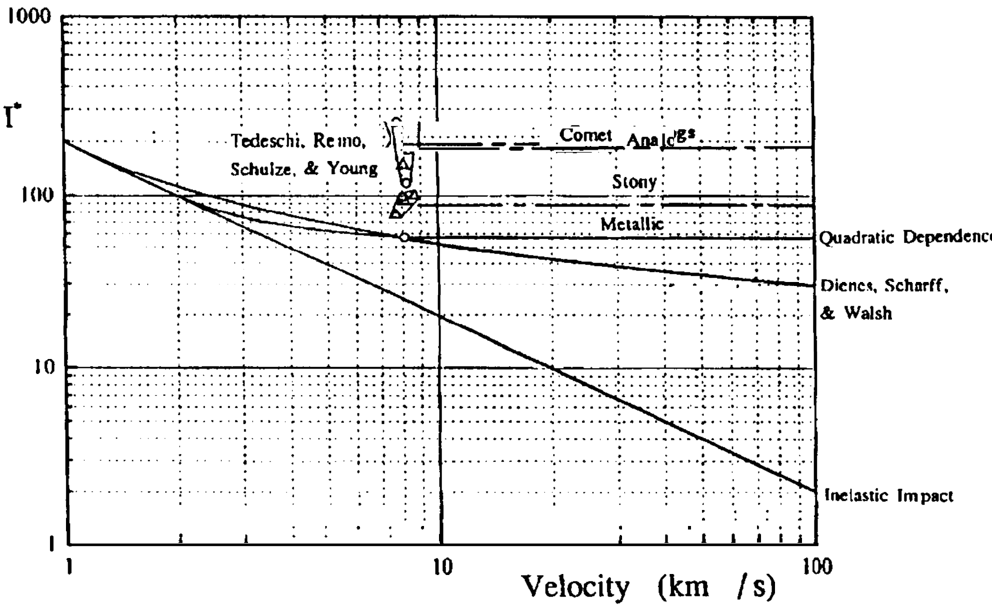


Figure 3. Comparison of analytical non-dimensional momentum deposition values, I* (Shafer et al., 1994), vs. world-unique experimental data (Tedeschi et al., 1994) for kinetic energy impacts into NEO analog materials.

Kinetic energy versus nuclear energy

It may be possible to at least study and model the effectiveness of higher-rate energy deposition nuclear mitigation technologies (see Fig. 4) using KE impact phenomenology to partially benchmark complex hydrocode models in higher energy state and phase change regimes. Of course, such models also have the ability to model other types of energy deposition schemes as well, e.g., lasers, microwaves, and concentrated solar energy. Both KE impact and nuclear explosive energy deposition schemes generate high-pressure shock waves in the target material. However, there are differences which need to be examined and understood. For example, a KE impact (of a "chunk" of mass) would appear to the body as a quasi-pointsource of deposited energy just below the surface, from which shock waves would than propagate radially outward from the source region into the body. Nuclear explosives, on the other hand, could be applied in two ways, i.e., stand-off explosion and sub-surface penetration or burial. The stand-off explosion would generate area shock-loading to the target body, while the sub-surface charge would appear as a quasi-pointsource of energy deposition, like the KE impact case. Therefore, kinetic energy should be pursued because of its apparent dual-benefit in modeling other rapid energy deposition schemes. Also, KE does not have to be a point source energy release within the target body, it has the marked advantage of being tailorable in its application to the target body. For example, it is possible for the mass of the interceptor to be spread out into a large area (i.e., a sheet of mass) to generate what would then appear to the target body as an area impulse, like that from a stand-off nuclear explosive irradiation. Issues to be resolved include:

1. What are the energy coupling efficiencies of KE and nuclear explosives?

2. How much of a dynamic stress state is imparted to the body during the energy coupling phase?

3. How will the dynamic stress state interact with the target body during the target response phase?

4. How will the target ultimately respond? Will it remain intact, or will it fragment to some degree?

These issues can only be resolved through a combined modeling and experimentation research program.

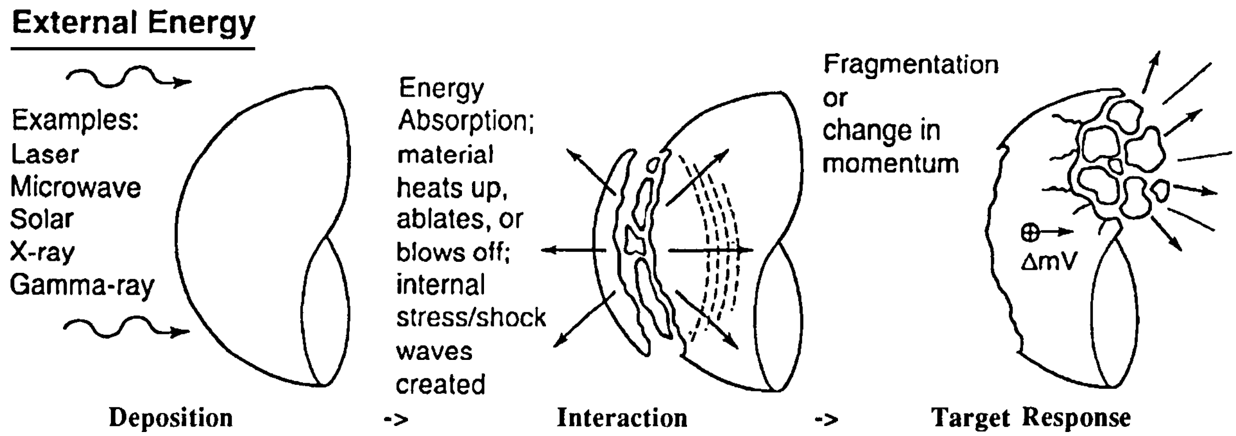


Figure 4. High energy nuclear mitigation technology examples; specifically: x-ray and gamma-ray deposition (neutron deposition is not shown).

KE mitigation strategy

In order to maximize the predictability and ultimately the controllability of a planetary defense KE impact mission someday, the following strategy is recommended (in order of priority):

1) Deflect the threatening NEO away from Earth through impact cratering, without breaking up the body.

2) Disrupt the threatening NEO by diverting as much mass as possible away from an Earth impact.

Deflection is the preferred approach because the outcome(s) of smaller-sized KE impactors on the target body would be more predictable and observable. This can work only if the warning time is adequate to allow us to marshal enough KE impactors (rockets with smart terminal maneuvering payloads) to deflect the NEO with an acceptable change in velocity to have the remaining body miss the Earth by a comfortable margin. However, if the amount of warning time is not adequate and there are no other viable mitigation technologies available, then disruption is the only logical course of action. It would be highly desirable to deflect as much mass as possible away from the Earth than to hope for an uncomfortable near-miss or adjusted benign Earth impact location. Of course, for the larger kilometer-class NEOs, kinetic energy will not be feasible without decades of warning time and therefore some other mitigation technology would be required.

Disruption capabilities against small NEOs

If a threatening NEO is small enough, i.e., on the order of 100's meters in size, KE impacts possibly could be used to predictably disrupt the body - literally independent of the amount of warning time. In this case, the bodies fragmentation due to the impact would be so complete that the resultant debris cloud would pose little or no danger to Earth, even if all the debris were still to impact the Earth. Existing experimental data (see Table 1) scaled up to full-scale engagements provides a means to assess to first order the approximate target body size regimes where KE impacts might play a role in disrupting small NEOs. Two upper bounding mass delivery systems were considered: 1) the Russian Energia and 2) the old American Saturn V rocket, capable of delivering 30,000 kg and 50,000 kg, respectively, in Earth escape trajectories (Isakowitz, 1991), although the largest demonstrated trans-Earth delivery was <6220 kg by the USSR Phobos mission (Wilson, 1994). It was assumed for calculational purposes that the impact velocity is 30 km/sec, mostly reflecting an approximate average approach velocity for a threatening NEO. Both rock and ice targets were examined for two different values of fragmentation strength, with the resultant mass of the largest post-impact fragment, i.e., M_l/M_t, as the metric of success for the hypothetical engagement. The results of the analysis are shown in Fig. 5.

Target/Frag. Strength Largest allowable frag.	Energia		Saturn V	
	Largest NEO Target	Largest Fragment	Largest NEO Target	Largest Fragment
Basalt/ E_p/M_t = 3 J/gm M_l/M_t = 0.1	128 m	60 m	152 m	71 m
Ice/ E_p/M_t = 0.05 J/gm M_l/M_t = 0.1	725 m	336 m	860 m	400 m
Basalt/ E_p/M_t = 10 J/gm M_l/M_t = 0.01	86 m	40 m	102 m	47 m
Ice/ E_p/M_t = 0.6 J/gm M_l/M_t = 0.01	316 m	147 m	376 m	174 m

Figure 5. Fragmentation capabilities of KE impacts against small NEOs as a function of impactor mass; target material, size, and fragmentation strength; and size of the largest post-impact target fragment generated.

The results clearly show the ability of KE impacts to suitably disrupt rock NEOs up to about 100 m in size and ice NEOs up to about 300 m in size, where the largest resultant debris fragment would pose a far less serious impact hazard to Earth, if it were to even hit Earth. Once disrupted, fragments from the NEO target body would disperse radially outward with some induced delta-velocity. Although typically the trend is for the larger fragments to have lower induced velocities, it is conceivable that provided enough warning time exists, the largest fragment might even miss the Earth, or, if need be, it could even be intercepted by another KE impactor and then rendered harmless. Fragment dispersion velocities are not so well understood, due mainly to very limited fragment velocity data (Davis and Ryan, 1990; Barge and Pellat, 1993; and Hartmann, 1985) and the relative inability to model such phenomena (Tedeschi, et al., 1992). Debris cloud fragment size and mass distributions are somewhat better understood, and can be modeled to first order (Tedeschi et al., 1994 and Tedeschi, et al., 1992). Given the fact that we do not now know or have an effective way of knowing the interior structure of a large NEO and its response to energy deposition, it would seem prudent to consider a precursor KE impact mission to provide data to address these issues.

Conducting a KE mitigation mission

Someday the need will arise to protect the Earth against a threatening NEO impact. A KE impact defense mission would involve the delivery of an appropriate amount of mass (and momentum and energy) to the approaching NEO either to gently deflect the body or to disruptively disperse all or a significant amount of the body's original mass away from an Earth impact. Related deep-space and defense missions have been successfully conducted in the past. They are complex, and they take time, resources, and great effort. Activities involved would include: threat detection, warning, and verification; tracking; authority to proceed; mission planning and end-game analysis; logistics and launch preparations; safety and security; delivery and survival in space of the mitigation technology; terminal homing and "intercepting" the target; assessing the result and trying again as necessary. Some level of mitigation planning now seems prudent to help ensure a timely future response, especially in light of our current inability to provide significant warning time in some particular cases, i.e., the smaller impactors (<100 m class) and long period comets. Such planning could include laboratory research and experimentation, as well as precursor impact experiments in space. Others have proposed geopolitical constructs for future planning purposes (Tedeschi and Teller, 1994).

The need for precursor KE impact missions

Precursor mitigation missions may be warranted if our ability to mitigate threatening NEOs with KE someday in the future is significantly hampered without them. However, the burden of proof for such a need rests clearly on the planetary defense community. A precursor mission would improve our understanding of: carrying massive smart spacecraft payloads long distances through the hostile environments of space, final approach and terminal homing with the target, target impact, the interaction of the KE impactor with the NEO to deflect or fragment it, the response of a NEO to an impact, long range tracking and control, modeling and planning assumptions, and scaling-up energy coupling experiments and analysis performed on Earth, among others. Doing precursor missions would allow smarter choices to be made in times of emergency. Others have either proposed NEO rendezvous missions (Nozette, 1995 and Tedeschi and Allahdadi, 1995) or are actively planning upcoming related missions, i.e., NASA/NEAR and ESA/Rosetta.

Future research opportunities

An effective KE impact NEO protection scheme for use against an approaching object would ideally require extensive study and research *a priori* to determine the best way to safely deliver and couple a given amount of mass, momentum, and energy into an approaching body to either fragment or deflect it. Experimentation might include not only laboratory experiments and simulations, but also the study of actual deflection or disruption of NEOs in non-menacing orbits. Doing so would provide an increased level of confidence in the effectiveness of KE against some future NEO impactor. Extensive modeling and analysis then would be required to explore the full parameter space for using KE against different NEO materials and dynamic states.

Knowing how kinetic energy couples into various target materials serves as the basis for predicting the effectiveness a kinetic energy impact defensive action. This can be done only through carefully controlled experimentation and modeling, whereby various target materials are probed and characterized experimentally and analytically by a number of kinetic energy fluences. The target material response is observed, measured, and quantified, and then scaled up in terms of it's effectiveness at imparting momentum to or physically fragmenting a larger body composed of this material. Figure 6 shows an experimental set-up for world-unique momentum deposition experiments conducted in 1994, as an example of how experimental testing (and analysis) can be conducted at low cost. While some experimental data are available, much more material property data and energy coupling experimentation are required (Remo, 1994; Shafer et al., 1994; and Tedeschi et al., 1994). Table 2 summarizes the types of research opportunities which exist to better understand and predict KE impact physics. Needless to say, laboratory experimentation and modeling are very cost effective options which should be pursued.

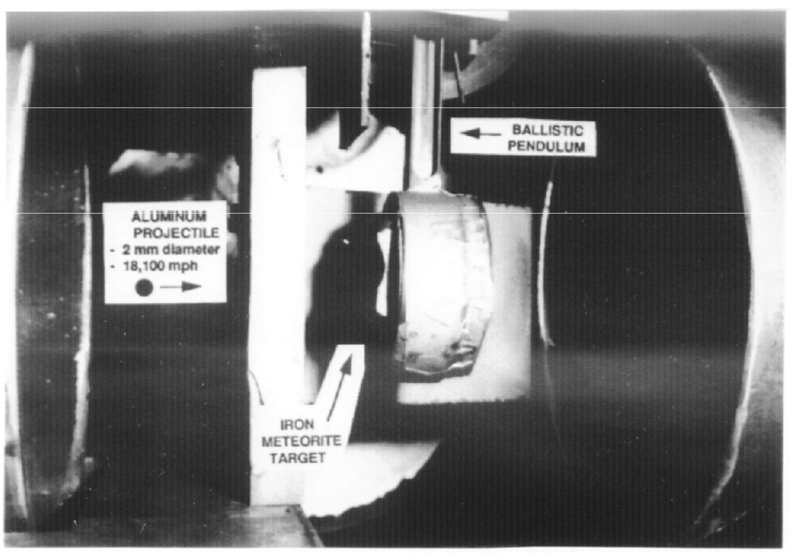


Figure 6. Experimental set-up at the U.S. Air Force AEDC impact range for measuring KE impact momentum deposition to an iron meteorite target mounted on a specially designed ballistic pendulum (Tedeschi et al., 1994).

Table 2. Future research opportunities in KE impact hazard mitigation physics.

Material Properties: Composition, micro- and macro-structure, rate dependencies.
- Examine and test Earth-analog materials and recovered meteorite samples, and collect & test samples in situ on comets and asteroids.

Equation of State: High-pressure loading conditions.
- Test samples and develop EOS models.

Computational Modeling: Better understand and simulate impact physics.
- Modify and expand existing capabilities to handle complex materials, structures, phase-changes, and late-time structural responses.

Early-Time (Local) Impact Physics: Crater Formation
- Conduct carefully designed tests at full scales and velocities, conduct modeling simulations and make improvements. Do space experiments.

Late-Time (Global) Impact Physics: Momentum Deposition or Fragmentation
- Conduct carefully designed tests at full scales and velocities, conduct modeling simulations and make improvements. Do space experiments.

ESAs unsuccessful attempt to impact a comet

Earth's only attempt at impacting a NEO with KE came in 1992 when the European Space Agency (ESA) tried to ram comet P/Grigg-Skjellerup with the Giotto spacecraft (Burnham, 1993; Grensemann and Schwehm, 1993; and Wilson, 1994). Giotto wasn't even close - it missed by some 200 km! But, nevertheless, valuable insights can be derived from this first of its kind encounter based on an examination of the facts. After its successful fast flyby of Halleys comet in 1986, Giotto went into hibernation for nearly four years in the hard vacuum and cold of deep space. It was reactivated in early 1992 to attempt not a flyby of comet P/Grigg-Skjellerup, but to actually impact the comet in July 1992 using ground-control directed guidance. Particulars of the interesting encounter are given in Fig. 7 and Table 3

Giotto Spacecraft

Encounter Geometry

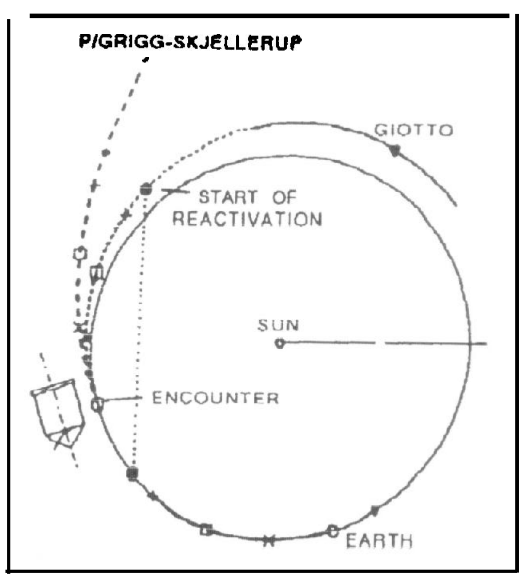


Figure 7. The Giotto spacecraft and encounter geometry with comet P/Grigg-Skjellerup.

Table 3. Particulars of the attempted impact of comet P/Grigg-Skjellerup by the Giotto spacecraft.

Encounter date: 10 Jul 1992
Last course correction: 8 Jul 1992
Spacecraft status: Many subsystems still operational after comet Halley fly-by
Spacecraft mass: 529 kg
Nucleus size: 2 km (est.) dia.
Relative approach velocity: 14 km/sec
Comet position uncertainty: < 650 km
Distance from Earth: 1.2 AU
One-way light time: 12 minutes
Dust coma encountered: 17,000 km range
Large dust particles encountered: near nucleus
Passed by: Dark (tail) side
Closest approach: < 200 +/- 100km (est.)

As can be seen in Fig. 7, the Giotto spacecraft basically tried to get in front of the fast moving comet and let it impact the spacecraft with a relative impact velocity of 14 km/sec. Because the encounter was controlled from Earth, which was 1.2 AU in range at the time, several problems were encountered which ultimately lead to the failure of Giotto to impact the comet. The position of the comet was not known accurately, therefore it was difficult to know exactly where to aim the spacecraft for the intended intercept. The spacecraft was 12 minutes away from command guidance instructions from Earth on what to do. Conditions obviously changed quickly in the final 12 minutes, especially upon final approach to the comet shrouded somewhere inside the dusty coma. It should be clear that future encounters, if they are to have a reasonable chance to succeed, should allow the interceptor spacecraft to autonomously acquire, track, and home in on the target to intercept. The homing spacecraft must also have a healthy divert capability to make final course corrections just before intercept or closest approach, probably on the order of 1-2 km/sec in velocity increment. A slower terminal approach velocity is also desirable, if practical, in that it provides more time to do final maneuvering and intercept.

It's also instructive in this case to ask the question of what would have happened had the 529 kg Giotto spacecraft impacted the comet. The answer is not much. While the impact energy would have been a respectful 5.17×10^{10} J, or 12 tons of TNT equivalent energy release, the E_p/M_t ratio was only 1.6×10^{-5} J/gm, where the target (comet) mass was estimated at a massive 3.14×10^{15} gm. This value is nowhere near the threshold value of ≈ 0.5 J/gm which would have been required to fragment the comet, therefore the encounter result would have been the creation of an impact crater and momentum deposition to the comet. There certainly would have been a large impact flash and significant expulsion of cometary material, both of which may have been visible from Earth-based sensors. Assuming a momentum deposition value of 5 (based on Tedeschi et al., 1994), the calculated induced velocity would have been a mere 0.012 mm/sec - far too small to have been measured from Earth. It should not be assumed that we know how to mitigate NEOs with kinetic energy by spacecraft impact. We have seen that not only do we not understand the impact physics of high speed NEO impacts, nor the composition, structure, and resultant response of such bodies, but we also failed to intercept a comet using modern spacecraft technology in this situation. We should perhaps not have to feel a little too uncomfortable about this, but rather we should resolve to seriously study this issue and generate viable options to protect Earth from the NEO impact hazard.

Summary

Kinetic energy is a viable mitigation technique to protect Earth from the NEO impact hazard under certain circumstances by either deflecting or disrupting an approaching body. However, for us to have confidence in the effectiveness of kinetic energy as a defensive capability, we must seriously consider the conduct of laboratory experimentation and analysis, and of precursor intercept missions, to allow us to better understand and model the delivery and deposition of kinetic energy into NEO targets and the resultant response, i.e., the dynamic induced stress state and the ultimate global structural response. Conducting low-cost experimentation and analysis now will allow timely and effective defensive responses in the future.

Acknowledgments

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Lasers Can Play an Important Rôle in the Planetary Defense

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Small comet nuclei and Earth-crossing asteroids (ECA's) are much more numerous than the "Doomsday asteroids", several passing within the Moon's orbit per month. Given a calibrated force, these could be deflected in a game of "cosmic billiards" to impact and disperse a much larger object on a well-known trajectory. Lasers have the advantage of agility and calibrated force release. High-power, ground-based, repetitively-pulsed lasers will be able to accurately deflect these objects via the impulse produced by surface ablation. The thrust vector is controlled by aiming the laser at the limb of the object. Aiming is verified by comparing the centroid of the detected object with the centroid of plasma plume emission. Appropriate laser targets are those a few tens of meters in size which are detected at a range of 1-10 light seconds and actively deflected during the final light second of approach. We consider deflection of a 40-m ice NEO with 15 km/s relative velocity. We discuss optimum beam director aperture, laser wavelength, pulse energy, duration and repetitition rate, stimulated Raman scattering in the atmosphere, detection of the object, creating an adequate laser guidestar, and phasing the elements of the large beam director aperture. We consider the 265-nm – 4 μm laser wavelength range.

Introduction: what Rôle for Lasers?

The purpose of this paper is to define and explore possible rôles for lasers in the planetary defense. In earlier work for the Los Alamos Interception workshop (see Phipps 1992a, 1992b), we estimated that a ground-based laser with several GW average power would be required to deflect even the smallest near-Earth objects (NEOs) which were still large enough (40 – 80-m diameter) to penetrate the atmosphere to a depth sufficient to cause significant damage on the ground. Here, we will extend those earlier calculations to give a more accurate deflection capability assessment for lasers. To do this, we will consider the entire range of practical laser wavelengths, and include second-order effects such as the impact of pointing stability on achievable range.

In our earlier work, we also mentioned that lasers are very good at producing precise deflection of small objects passing near the Earth and we will extend that concept in this paper.

How Lasers Play in NEO Mitigation

Depending on mass density and Earth-relative velocity, precise deflection of NEO's in the 40 – 80-m diameter class is readily achieved with lasers that we can afford to build. For example, we will show that small velocity changes of order 1 mm/s are sufficient to produce changes in NEO position of order 1 earth radius at 1 AU, and that the power requirements to do this are modest.

Further, lassers are agile. A ground-based laser can follow a small NEO with sufficient precision to control the direction of the laser-induced ablation jet. The laser can also address multiple objects.

Finally, it should be kept in mind that the laser will have other uses. Large lasers are expensive, but may be justified based on multiple rôles, such as power beaming, launching payloads into LEO (See Phipps and Michaelis 1994) and obtaining rare metals by the ton from asteroid mining (Blacic 1993).

Pulsed Lasers and Momentum Coupling

The laser momentum coupling coefficient C_m is defined (by custom, in mixed units) as the ratio of momentum flux delivered to a target system to the incident laser pulse fluence. Momentum transferred is mainly due to formation of an ablation jet on the surface of the target, and only very slightly due to light pressure. Where laser fluence is constant over the target surface, W is the laser pulse energy (joules) and J is the momentum delivered by the laser-produced ablation jet (dyne-s),

$$C_m = J/W \qquad \text{dyne-s/J.} \tag{1}$$

For opaque materials in vacuum irradiated by pulsed lasers at or above plasma threshold intensity [see Phipps, *et al.* 1988], C_m is given within a factor of 2 by (see Phipps, *et al.* 1988)

$$C_m = 3.95\, M_A^{0.44}/[Z^{0.38}(Z+1)^{0.19}(I\lambda\sqrt{\tau})^{0.25}]. \tag{2}$$

The two elements of the pairs (C_m , Q*) and (C_m , I_{sp}) are not independent, but increasing one decreases the other.

$$C_mQ^* = v_E = gI_{sp} \qquad \text{cm/s} \tag{3}$$

and
$$C_mI_{sp} = C_m{}^2Q^* = 2\cdot10^7\,\eta_{AB} \tag{4}$$

where v_E is the exhaust velocity of the ablation jet, Q* is the effective heat of mass removal (J/g), g = 980 cm/s^2 is the acceleration of gravity at Earth's surface, and η_{AB} is the efficiency with which laser energy is converted to exhaust kinetic energy. As a side comment, Eqn. (4) permits I_{sp} for laser ablation jets to achieve values much larger than those available in chemical reactions, and experimental results as large as 7,000 seconds are readily achieved (Phipps, *et al.* 1994).

Practically speaking, it is easy to obtain C_m = 5 dyne-s/J from materials such as would be found on the exposed surface of the NEO (see Figure 1, *ibid.*), given the right choice of laser intensity I, wavelength λ, and pulsewidth τ.

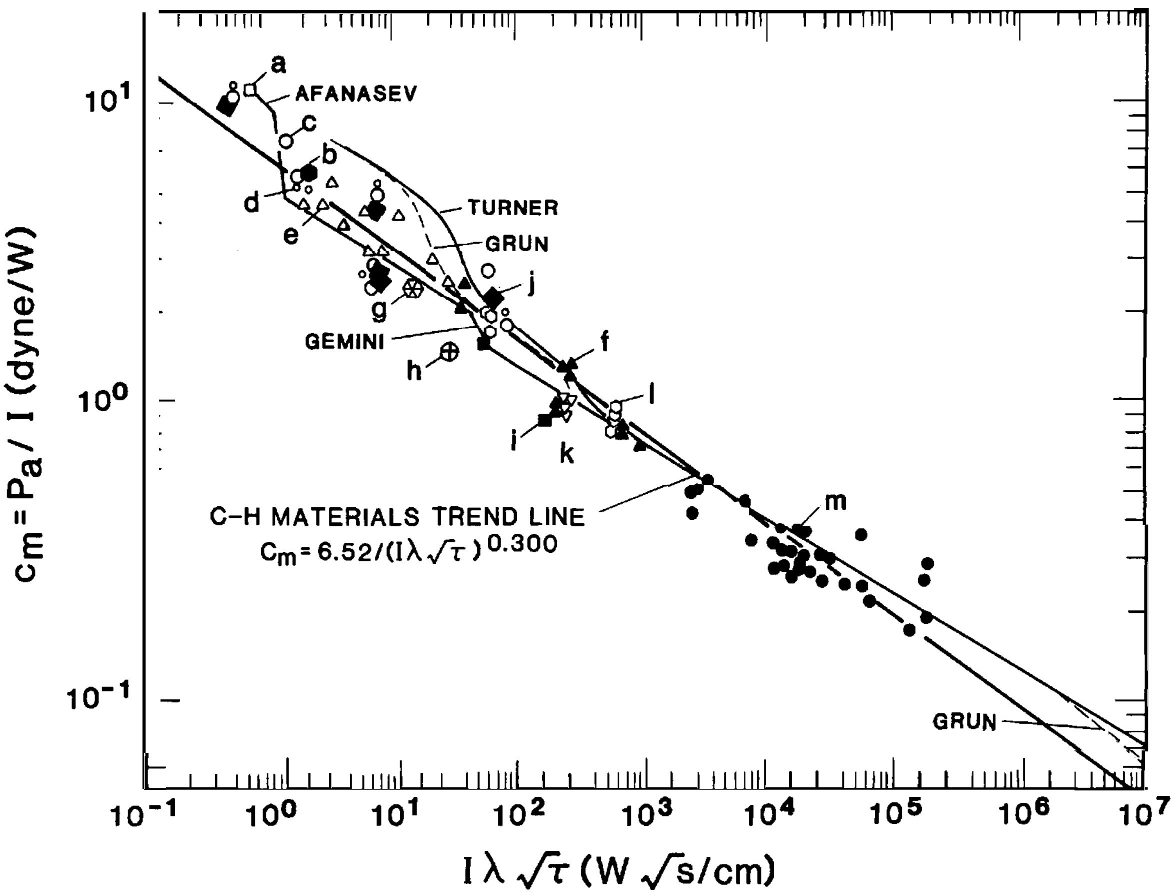

Figure 1. Compilation of experimental data for impulse coupling coefficient on C-H materials vs. the parameter (Iλ√τ). (a): Afanas'ev, *et al., Zhurnal Tekn. Fiz.* **39**, 894 (1969) [*Sov. Phys. Tech. Phys.* **14**, 669 (1969)], **1.5 ms, 1.06 μm on ebonite rubber**. (b): Afanas'ev, *et al., Zhurnal Tekn. Fiz.* **39**, 894 (1969) [*Sov. Phys. Tech. Phys.* **14**, 669 (1969)], **1.5 ms, 1.06 μm on carbon**. (c): Phipps, *et al.,* (unpublished), Sprite, **37 ns, 248 nm, on silica phenolic**. (d): Phipps, *et al.,* (unpublished), Sprite, **37 ns, 248 nm, on vamac rubber**. (e): Turner, *et al.,* (unpublished), **22 ns, 248 nm, on buna-n rubber**. (f): Phipps, *et al.,* (unpublished), Gemini, **1.7 μs, 10.6 μm on kevlar epoxy**. (g): Rudder, U. S. Air Force Weapons Laboratory Report AFWL-TR-74-100 (1974), **5 μs, 1.06 μm, on Grafoil.** (h): Rudder, U. S. Air Force Weapons Lab report AFWL-TR-74-100 (1974) **1 μs, 1.06 μm, on Grafoil**. (i): Phipps, *et al.,* (unpublished), Gemini, **1.7 μs, 10.6 μm on carbon.** (j): Phipps, *et al.,* (unpublished), Sprite, **37 ns, 248 nm on carbon phenolic**. (k): Phipps, *et al.,* (unpublished), Gemini, **1.7 μs, 10.6 μm on graphite epoxy**. (l): Phipps, *et al.,* (unpublished), Gemini, **1.7 μs, 10.6 μm on carbon phenolic**. (m): Grun, *et al., Phys. Fluids*, **26**, 588 (1983), **4 ns, 1.05 μ m, on C-H foils.**

Experimental data shows that the optimum target surface intensity for achieving the best coupling is (not surprisingly) just above that for plasma formation, and is given approximately for all opaque materials by (see Phipps, *et al.* 1988):

$$I_s = F\sqrt{\tau} \qquad \text{W/cm}^2 \tag{5}$$

where $F \approx 4\times10^4$ is a constant.

Continuous (CW) lasers are not indicated for the present application for two reasons. First, CW laser energy will be invested in melting the general target rather than in producing a jet at its surface. Second, in this case, melting could detonate the target, which would be catastrophic for our purposes. Furthermore, pulsed lasers allow the selection of τ and I for optimum penetration of the atmosphere.

Propagating the Pulsed Laser to the Target

The laser and beam director will be located on Earth because launching mass into orbit currently costs about \$10/g, and the benefit of locating these massive devices in space is not justified by the cost.

The earliest limit to atmospheric propagation is conversion of the laser energy to other wavelengths and propagation directions by Stimulated Raman Scattering (SRS), for which the threshold is given, for pulsewidths of interest to us, by the expression

$$I_{SRS} = D\lambda \qquad \text{W/cm}^2 \tag{6}$$

with $D = 2.83\times10^{10}$. Denoting by A_s and A_b, respectively, the laser beam area on the target surface and within the beam near-field (in the atmosphere), Eqns. (5) and (6) are both satisfied when we pick pulsewidth and laser pulse energy according to:

$$\sqrt{\tau} = \frac{F}{D\lambda}\left(\frac{d_s}{D_b}\right)^2 \tag{7}$$

and

$$W = \frac{\pi F^2 d_s^2}{4D\lambda}\left(\frac{d_s}{D_b}\right)^2 \tag{8}$$

Using these expressions, all that is needed to compute the best τ and W for both momentum generation and SRS avoidance is to choose beam director diameter D_b and the target spot size d_s.

Target spot size comes from propagation theory, slightly modified to describe beam diameters rather than radii as in the conventional theory (see Kogelnik and Li 1966).

Where z_R is the Rayleigh Range parameter, ψ is the farfield divergence angle, d_{so} is a defined parameter, and N is the beam quality factor by which beam divergence exceeds that of a diffraction-limited beam, we can calculate d_s in all circumstances from:

$$z_R = \frac{\pi D_b^2}{8N\lambda} \tag{9}$$

$$d_{so} = \frac{D_b}{z/z_R}\left[1 - \sqrt{1 - \left(\frac{z}{z_R}\right)^2}\right] \tag{10}$$

$$\frac{1}{d_s^2} = \frac{1}{d_{so}^2} + \frac{1}{D_b^2} \tag{11}$$

or,

$$d_{s+}^2 = d_s^2 + [2\psi(z-z_R)]^2 \qquad \text{beyond } z_R\text{, and} \tag{12}$$

$$\psi = \frac{2\sqrt{2}\,N\lambda}{\pi D} . \tag{13}$$

Target flooding & Pointing limit

In addition to these considerations, we make target spot size subject to two more constraints as they become necessary:

- Spot size d_s shall not be smaller than the target (here 40m), since laser energy is most efficiently used in creating momentum when I_{opt} is achieved all over the available target surface.
- At range z, the pointing angle jitter d_s/z shall not be smaller than 50 nrad. This requirement is based on our judgments that ground-based beam pointing cannot be done with less jitter, and that laser guidestars in the sodium

layer for adaptive optics correction of the beam phase for atmospheric turbulence will not be made smaller than 50nrad x 100km = 5mm for some time.

Results for Required Pulse Energy W and Duration τ

Figure 2 following shows the results of applying all the conditions expressed in the previous two sections of this paper simultaneously, with beam director aperture as the free parameter. In the Figure, two cases are considered, namely z = 1 and 10 light-seconds. Four wavelengths are considered: 1.06μm and its second and fourth harmonic, plus 4μm (the DF laser).

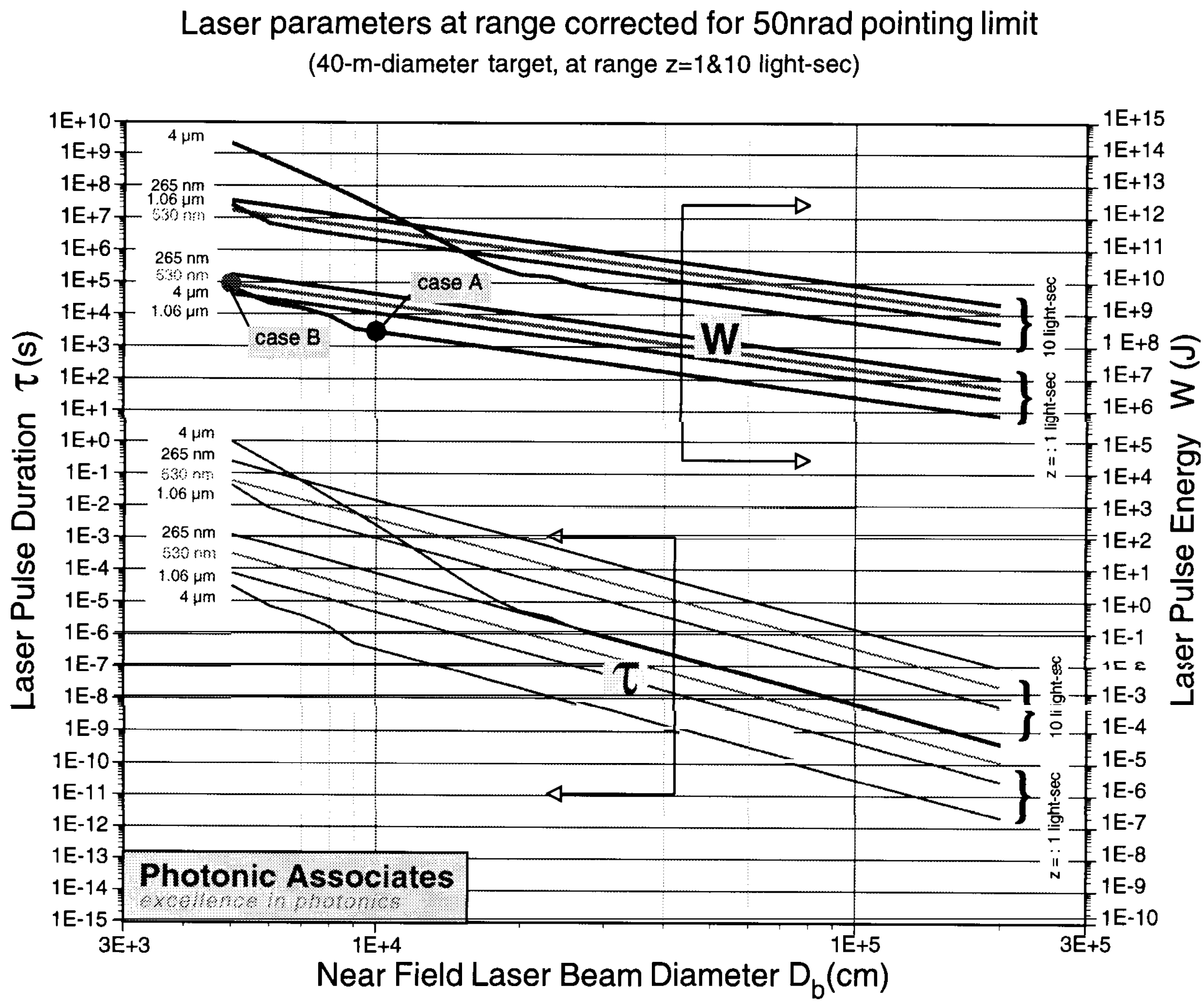

Figure 2. Laser pulsewidth τ and pulse energy W vs beam director aperture for two ranges and 4 choices of wavelength λ. Two cases are selected ("A" and "B") for further discussion.

From the graph, we pick two cases (A and B on the graph) for further consideration, based mainly on the impracticality at the present time of realizing beam director apertures larger than 50 – 100m. We note that phased element designs such as NASA's PAMELA concept might achieve such apertures with small individual mirror elements which could be built and manipulated at the bandwidth required for turbulence correction. Larger apertures will have to depend on different technology, for example, gas-density-gradient lenses (see Michaelis 1991).

These are: case A: λ = 4μm and D_b = 100m and case B: λ = 530 nm and D_b = 50m. We then use the tools in Eqns. (9) – (13) to compute optimum pulsewidth τ and pulse energy W vs. range for these two cases (Figure 3).

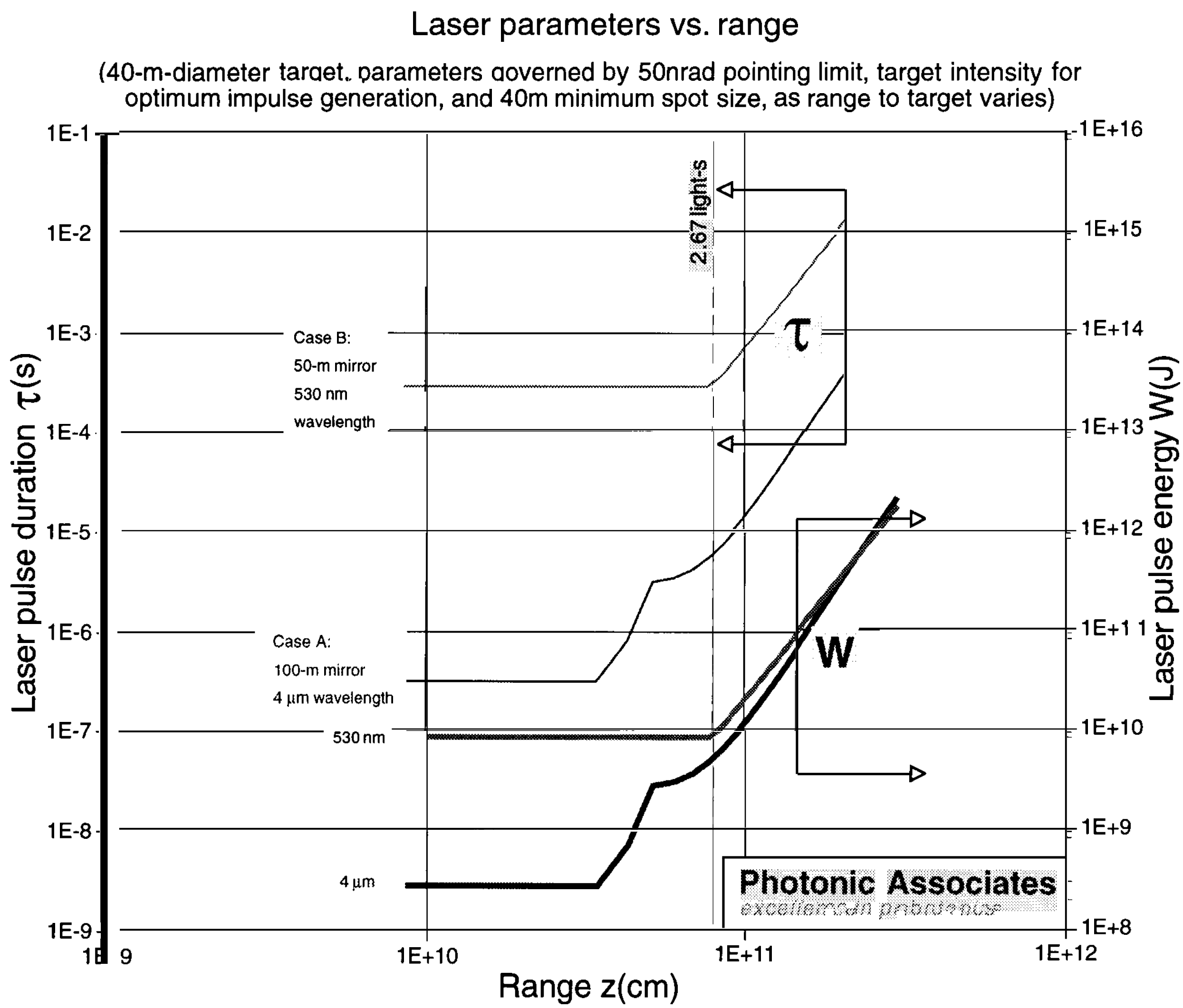

Figure 3. For cases A and B, optimum pulsewidth and pulse energy vs. NEO range are computed. Note the sharp discontinuity at z = 2.67 light-seconds. Here, N = 2 and $C_m = 5$.

Multi-GW Laser Power Needed to deflect a 40-m NEO by one Earth Radius

We found that multi-GW power level is needed to deflect even a small ice NEO approaching the Earth on a collision course with relative velocity v = 15 km/s. To obtain the plots in Figure 4, we applied the above energy to each range cell starting at acquisition range z at a rate sufficient to deflect the object by one Earth radius to obtain average power P and laser repetition frequency f.

The power minima (case B) at 2.67 light-seconds and (case A) at 2.67 and 1.7 light-seconds are artifacts of the pointing angle and spot size limitations discussed earlier as well as of the nonlinear way in which beam size varies with range, governed by propagation theory. Note that, when the NEO is closer than 1.7 light-seconds, laser power to deflect is proportional to $1/z^2$, as one might expect, since the Δv required to miss the Earth increases with decreasing time to collision, while decreasing time to act requires proportionally more power to achieve the same Δv. Laser power is roughly constant beyond a 2 - 3 light-second transition, since a progressively larger fraction of the laser beam spills over the NEO, requiring z^2 times more beam power to deliver the same power to the NEO surface, and the two range effects approximately cancel.

In any case, the laser power required is in the range 11 to 1.5 GW, depending on the wavelength chosen (4 μm or 530 nm), with a pulse energy of 6 – 9 GJ and a pulse duration of 6.5 μs or 290μs, respectively, for cases A and B. A laser with such power will cost tens of B$. The worst aspect is that, during the 15 hours between acquisition and Earth passage, more than one (probably three) laser stations will be necessary to give continuous access to the NEO.

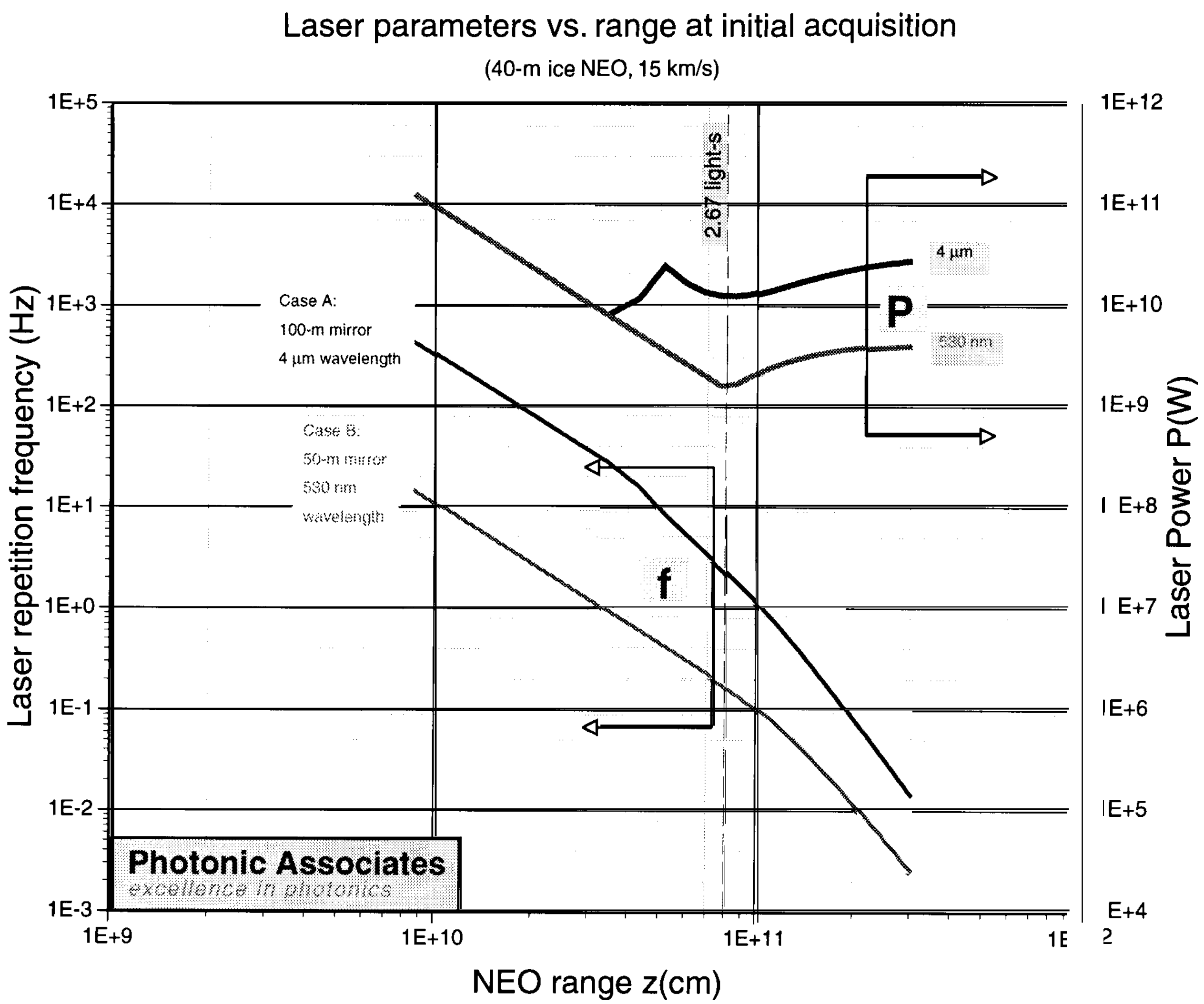

Figure 4. Laser power and frequency required to deflect a 40-m-diameter ice NEO on a collision course with Earth-relative velocity 15 km/s by one Earth radius, starting at acquisition range z. Here, N = 2 and $C_m = 5$ are assumed.

Reasonable Laser Power for Cosmic Billiards

We can use the same procedures to compute laser power required for a different problem: giving a small NEO a velocity increment of only a few cm/s, to produce relatively large position changes in the future at large range, for example, 1AU from Earth.

To assess this problem, it is only necessary to review central-force scattering theory (e.g., Goldstein 1950). The scattering angle ψ is related to the energy and velocity of the NEO at infinity (E_∞ and v_∞) and the scattering parameter b by

$$\cot\frac{\psi}{2} = \frac{2E_\infty b}{mMG} \tag{14}$$

where m and M are the mass of the NEO and the Earth, respectively, and G the gravitational constant.

The NEO will execute a hyperbolic orbit about the Earth. We wish to know what velocity increment δv (applied by laser near the point of closest approach to Earth) will produce a future transverse displacement $\delta z_\perp = z\delta\psi$ of NEO position after it has passed the Earth and gone out to range z. Differentiating Eqn. (14) and allowing a factor of 2 to account for the fact that we can modify the NEO trajectory over only half of the scattering event (after near-Earth passage) we obtain:

$$\frac{d\psi}{dv_\infty} = -4 \sin^2 \frac{\psi}{2} \frac{bv_\infty}{MG} \quad (15)$$

We take $\psi = \pi/2$, $v_\infty = 15$ km/s, MG = 3.988×10^{20}, and b = 1 light-second to find that

$$\delta v_\infty = 0.19\ (\delta z_\perp / R_E)(z/1AU)\ \text{cm/s} \quad (16)$$

For example, a 1.9 cm/s velocity change during near-Earth passage is sufficient to produce a 10 Earth-radius (R_E) shift of NEO position at z = 1AU.

Using the previously described analysis for power vs. range, we obtain the following results for the "cosmic billiards problem", using as a cue-ball a 40-m diameter object of density 0.97 (ice) or 9.0 (iron) with 15 km/s Earth-relative velocity. We consider the same best acquisition range (2.67 light-seconds) and laser wavelengths (530 nm & 4μm) as before.

Table 1. Laser Power for NEO Position Shift at 1AU range after Earth passage

	Average Power for Position Shift			
NEO	**530 nm,10 R_E**	**4 μm,10 R_E**	**530 nm,100R_E**	**4 μm,100 R_E**
40-m ice	230 kW	1.7MW	2.3 MW	17 MW
40-m iron	2.1 MW	15 MW	21 MW	150 MW

Conclusions

We have shown that lasers of relatively modest power (230 kW) are capable of precisely deflecting a 40-m ice NEO during near-Earth passage by an amount sufficient to produce a future shift in position of 10 Earth radii at a range of 1AU, in order to engage in a game of cosmic billiards with a much larger Earth-threatening object whose position is known well in advance. Such capabilities are unique to lasers among the devices which have been discussed for NEO deflection. Such a laser could be used for other purposes, as well.

Acknowledgment

The author is indebted to Dr. Edward Teller for the cosmic billiards concept.

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On the Possibility of Altering the Trajectories of Asteroids and Comets Using Plutonium Implantation

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It is pointed out that creation of a critical assembly by implantation of Pu239 inside an asteroid or comet could produce a substantial force on the asteroid or comet due to either explosive ejection or asymmetric sublimation of material off the surface of the asteroid or comet. This would allow one to make substantial changes in an asteroid's or comet's orbital elements using existing launch vehicles and spacecraft technology. It is particularly intriguing that recurrent sublimation induced by plutonium implantation could over a few months time deflect even kilometer-sized earth-intersecting objects enough to avoid the earth. For the more distant future nuclear-powered pulse jets might be a cost-effective way of altering the trajectories of asteroids and comets.

Introduction

A number of possible schemes for deflecting earth-intersecting asteroids and comets have been proposed. Indeed, a proliferation of ideas is desirable since one would like to have available a wide variety of options for dealing with such an emergency. For example, while using nuclear explosions is one obvious approach to interdiction, future bans on the production and maintenance of nuclear explosive devices may make it desirable to have other options available. In this note we would like to bring attention to the possibility of deflecting asteroids and comets by directly implanting plutonium in the body of the asteroid or comet using small spacecraft similar to the one used in the Clementine mission to the asteroid Geographos.

Given any material body and any subvolume of that body, there is a concentration of Pu239 in that subvolume such that the plutonium plus material will constitute a critical assembly. Furthermore, in some materials this critical assembly will be autocatalytic; i.e. the assembly will evolve with time in such a way that the effective neutron multiplication factor k increases with time. Instantaneous creation of an autocatalytic critical assembly would produce a rapid release of fission energy, and lead to a thermal explosion. It has been estimated [Bowman and Venneri 1995] that the energy release in such an explosion is a few tons per kilogram of plutonium. While this is less energy yield than can be attained with nuclear explosive devices, it is still a thousand times better than what can be achieved with high explosives. In materials where the critical assembly is not autocatalytic the energy release may or may not have an explosive character, depending on whether the initial critical assembly is supercritical or just barely critical, though in general it will also be transient. However, in the case of a non-autocatalytic assembly that is barely critical the energy release may be recurrent, leading to a significantly greater energy yield per kilogram of plutonium.

Implanted Critical Assemblies

One might question whether it is possible in practice to create a critical plutonium assembly inside the body of an asteroid or comet because implantation into an object using an "earth-penetrating" projectile arriving in a direction normal to the surface of the object requires that the projectile's velocity be subsonic with respect with respect to the object. On the other hand typical relative velocities between earth launched spacecraft and near earth objects will be supersonic. In order to prevent ejection of the material in a penetrating projectile back into space, the projectile would have to be incident at a very shallow angle. It is not obvious that this can be done in practice; however, assuming that a package containing several liters of plutonium can be injected into the comet or asteroid, one would have essentially instantaneously created a critical assembly.

In fact, recent calculations of the critical masses of Pu239 diluted with water and silicon dioxide [Fig. 1] suggest that implantation of a few hundred kilograms of Pu239 into a volume a couple of meters across would suffice for the creation of a critical assembly in a comet. We have carried out similar calculations for the case of a stony asteroid [Fig. 2], with the result that implantation of a few hundred kilos of Pu239 would suffice to create a critical assembly. Agreater amount of Pu239 is needed in this case because the iron in these asteroids acts as a neutron absorber. We have not yet investigated the case of nickel-iron asteroids, because apparently the amount of Pu239 that would be needed is very large and implantation would be problematical.

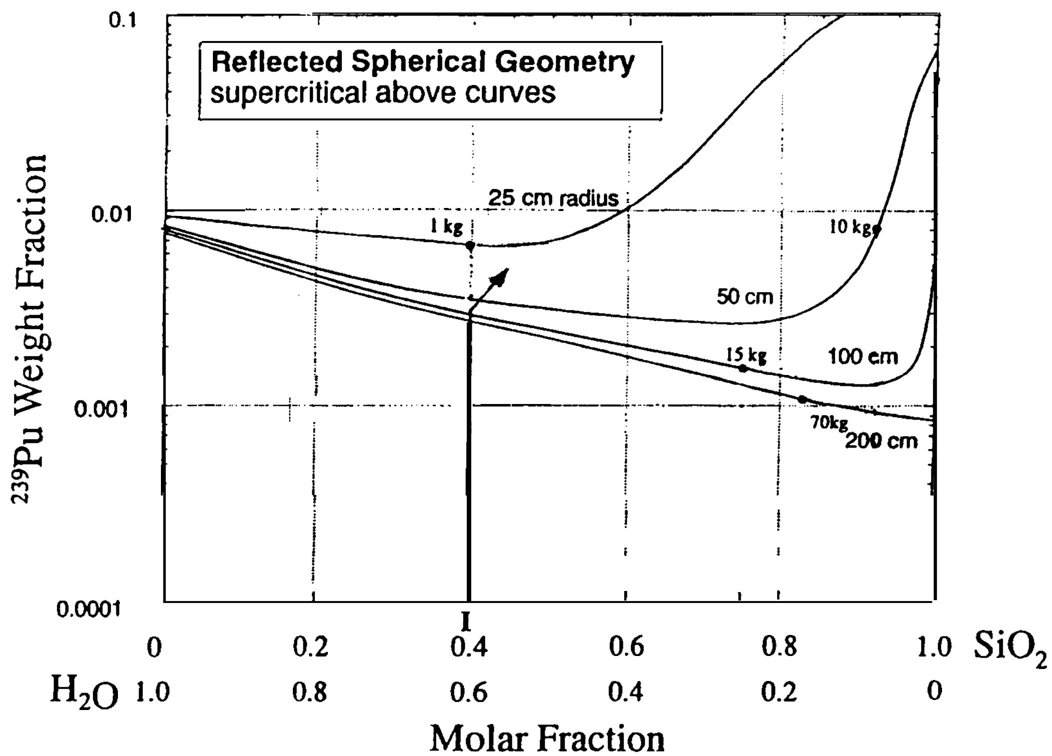

Figure 1. Criticality curves for spheres of Pu239 diluted with water and silicon dioxide and surrounded by silicon dioxide [Bowman and Venneri 1994]. The line "I" illustrates how a critical assembly can be created inside a comet by implantation of Pu239, and the arrow extending from the end of the line shows qualitatively how the resulting autocatalytic assembly would subsequently evolve.

Because the heat generated by the fissioning plutonium will cause the ice in a comet to vaporize and disperse, a critical assembly will tend to move to the right in Fig 1. If the initial critical assembly created by implantation lies on the left side of Fig 1, then the initial critical assembly will be autocatalytic; i.e. criticality will initially increase. Actually because the silicates in a comet are thought to be trapped in the ice as fine particles, the dispersing water vapor will probably also carry away much of the silicates, causing the critical assembly to evolve upwards as shown by the arrow in Fig1. Thus rapid implantation of Pu239 in a comet will most likely result in a situation wthere criticality will increase very rapidly, leading to a Chernobyl-like explosion.

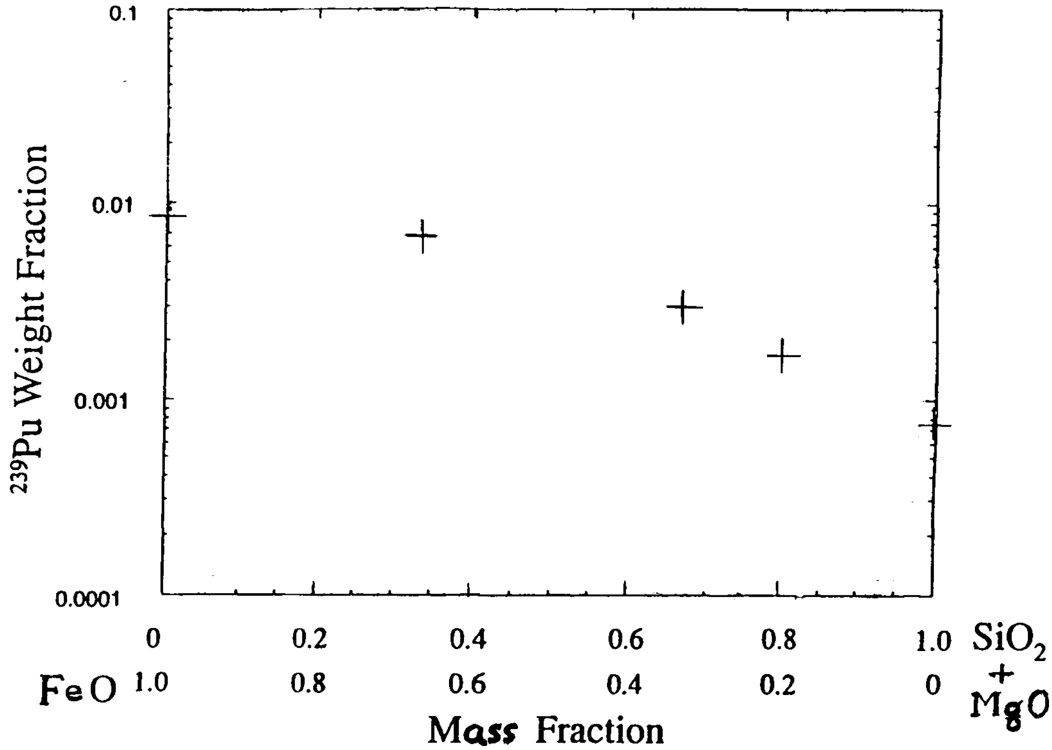

Figure 2. Criticality curve for a 2 meter radius sphere of Pu239 diluted with a mixture of iron oxide, magnesium oxide, and silicon dioxide and surrounded by silicon dioxide.

The explosive release of energy inside a comet or stony asteroid due to rapid implantation of plutonium could lead to ejection of fragments of the comet or asteroid. One would like the explosion to occur at a depth such that the velocity of ejection is as low as possible, since this would result in the greatest impulse. Unfortunately, the impulses that one can generate with a few hundred kilograms of plutonium are not very impressive, and would be only be useful for deflecting relatively small asteroids or comets. For example, let us assume that our autocatalytic or supercritical plutonium assembly yielded 250 tons, i.e. 1TJ, and the fragments were ejected with a velocity of 10 m/sec. Then making the optimistic assumption that 100% of the energy released appeared as kinetic energy of ejecta, the total impulse generated by the ejected fragments would be 200 billion Newton-seconds. This is clearly a gross overestimate of the impulse that would realistically be generated, yet even this impulse would be inadequate to produce desired deflections of any but the smallest asteroids or comets. For example, an impulse of 200 billion Newton-seconds would produce a transverse velocity of only 10 cm/sec or 3000 km/year in a kilometer-sized asteroid. Since the impulse generated varies inversely with velocity, a greater impulse might in principle be generated by lowering the velocity of the ejecta below 10 m/sec, but even this low a velocity would be difficult to achieve, since the fragmentation velocities associated with the explosive fracturing of rock are typically like 100 m/sec.

Sublimation Scenario

Fortunately, the picture for impulse generation brightens considerably if the critical assembly created by plutonium implantation can be operated in a regime where the energy generation is non-explosive, so that essentially all the energy goes into heating the surrounding material. If this heat is dissipated by sublimation of material off the surface of the comet or asteroid then a reaction force will be generated if the resulting momentum flow is not spherically symmetric. Now the interesting point is that if the energy generation is recurrent and uses up most of the plutonium, then the impulse generated by this asymmetric sublimation can be much larger than the impulse generated by explosive energy generation. If we assume that the velocities of the escaping molecules correspond to a temperature of roughly 0.1 eV, i.e. temperatures of about 1000C corresponding to escape velocities of about 400 m/sec, then the impulse generated by the consumption of 10 kg of plutonium would be on the order of a trillion Newton-seconds (note that sublimation occuring at lower temperatures would generate an even greater impulse). A trillion Newton-seconds is approximately the threshold impulse required to deflect kilometer-sized objects away from the earth in less than a year's time. In other words a critical plutonium assembly operating in a recurrent or quasi-steady state energy generation mode with an average power of several hundred megawatts could probably generate the desired deflection of a kilometer-sized object in a few month's time. Unfortunately a critical assembly producing a steady power of more than a hundred megawatts cannot be cooled by conduction alone. This level of average power production would require convection cooling, which means that the energy production could only be recurrent. Of course, if one had several years allowance in order to produce the deflection, then less power would be needed, and a critical assembly operating in a quasi- steady state mode might be adequate.

In order to ascertain approximately how much average power could be generated by implanting a given amount of Pu239, numerical simulations would have to be performed that simulated the implantation dynamics, as well as the relaxation processes that would be induced in the surrounding moderating material. Needless to say such numerical calculations would be very challenging, but the computational capabilities of the Los Alamos and Livermore Laboratories, as well as those of laboratories in the Soviet Union, could be profitably brought to bear on this problem. Obviously it would also be desirable to carry out experiments to check the numerical calculations, and demonstrate that a critical assembly operating at a desirable average power level could be actually be created by spacecraft implantation.

One obvious problem with the idea of using asymmetric sublimation to deflect asteroids or comets is that in general an unbalanced reaction force will not just deflect the asteroid or comet, but also cause it to rotate. Even in the presence of tumbling the deflection induced by a gigawatt of asymmetric sublimation will almost certainly be sufficient to avoid a collision with earth. Nevertheless it would be comforting if some means could be found to control tumbling. In principle this could be accomplished by implanting three independently controllable critical assemblies. However, this doesn't seem like a very practical proposal.

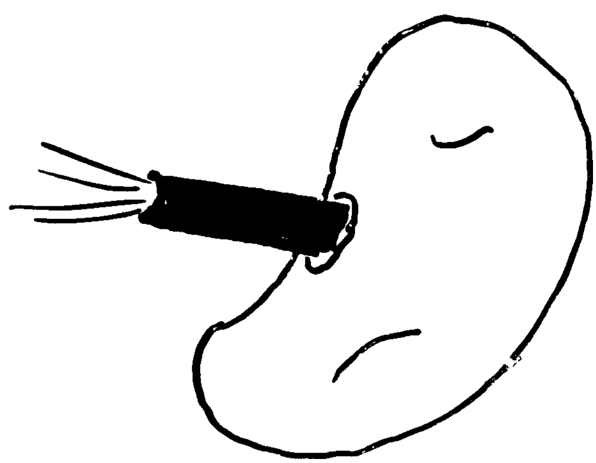

Figure 3. Nuclear pulse jet attached to an asteroid

Plutonium Powered Jet Engines

An elegant way of solving the tumbling problem would be to attach into the surface of the comet or asteroid a nuclear-powered jet whose position and orientation can be adjusted (Fig 3). The body of the comet or asteroid would provide a large reservoir of exhaust gas for the jet. In addition, the material of the comet or asteroid could be used as both a coolant and a moderator for pulsed nuclear power generation. For example, if the pulse jet reaction chamber incorporates a non-critical plutonium assembly, then a critical assembly might be formed by injecting material into the reaction chamber. If the critical assembly formed by this injection of material lies in a region of negative feedback (e.g. the right hand side of Fig 1), then the material will be gently heated and expelled from the reaction chamber. Evidently one would want to avoid forming an autocatalytic critical assembly, where the plutonium and injected material would be rapidly vaporized leading to an explosion. The reaction chamber should be designed so that the material in the reaction chamber is slowly heated, and after expulsion of the injected material from the reaction chamber the chain reaction will die out until more material from the asteroid or comet is injected.

Because of the typically large velocity differences between asteroids, comets, and the earth it would be nearly impossible to gently attach a nuclear jet (or anything else for that matter) to an asteroid or comet using existing chemical rockets. One may hope that in the future it will be possible to match the velocities of comets and asteroids relative to the earth using a high specific impulse nuclear rocket. Indeed development of nuclear rockets should be high on the list of technologies that one would want to develop for planetary defense. Not only would nuclear rockets allow one to approach asteroids and comets with a low relative velocity, but the transit time to these objects would be significantly reduced. Finally it should be be noted that the use of Pu239 in nuclear rockets for space exploration and in planetary defense schemes might be viewed as a socially responsible way of desposing of weapons grade plutonium.

Conclusion

Imparting an incremental velocity of 1 m/sec to a kilometer-sized object requires an enthalpy on the order of a TJ. Enthalpy yields of this magnitude can only be achieved in reasonable sized packages through the release of nuclear energy. Enthalpy from nuclear energy can be produced suddenly with a nuclear explosive device, or gradually with a nuclear reactor. Gradual release of heat in a nuclear reactor has the advantage that one may have more control over the consequences of the energy release, so the results achieved per unit of nuclear fuel used may be greater. Production of heat using a nuclear reactor is also desirable from the point of view that international agreements may in the future make it very difficult to build reliable nuclear explosive devices. One might have imagined that nuclear reactors are disadvantaged with respect to nuclear explosive devices because they are much heavier. However we have argued that by making use of the natural moderating and cooling properties of the in situ material of a comet or asteroid nuclear reactors are not disadvantaged with respect to nuclear explosive devices. Indeed it may be possible to gradually release energies on the order of a TJ inside an asteroid or comet simply by implanting inside the object a package containing plutonium that is subcritical before impact, but becomes critical after implantation by virtue of the environment.

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The Effect upon Asteroid by the Neutron Radiation of Nuclear Explosion

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The problem of affecting upon an asteroid by the neutron radiation of nuclear explosion was considered. This effect was estimated depending on time, the altitude of explosion, energy spectrum, asteroid density and chemical composition and the angle of fall for two-dimensional parallel flow of absorbed energy of neutron radiation. To a first approximation, the temperature fields generated in asteroid by the neutron irradiation were obtained and compared with the appropriate temperature field generated by the x-radiation of nuclear explosion.

The Problem Statement

Nowadays concentration of energy in the nuclear explosives is the highest if compared with the other well-known sources of energy. This fact allows to consider nuclear explosives as the most promising means of effect upon the near-Earth-objects (NEO).

In the course of nuclear explosion a space object is exposed to different types of effects, intensity of which depends on the nuclear explosion yield, the distance to the space object, the object dimensions, the constituent materials and the nuclear explosive design.

The fraction of energy transferred to the space object at the explosion defines the scale of the effect. For a buried explosion this fraction is maximum [1,2,3], but to provide such explosion is a very complicated technical problem. It is technically much more easy to conduct a surface or stand-off explosion. In addition to the fraction of absorbed energy there is one more significant characteristic, the area of energy absorption or what kind of source of gasdynamic motion appears in the asteroid.

The motion of the asteroid ground in the surface and stand-off explosions is determined by the amount of energy, which is transferred to the asteroid material directly. The energy of the explosion is transferred to the ground in the form of X-radiation, neutron radiation and the impact of nuclear explosive vapors upon the surface of the asteroid. As it is shown in the papers [1,2,3] the fraction of energy transferred to the ground by X-radiation is about 6% of the total energy of explosion and the contribution of the vapor impact is about 2%. However, the effect of neutron radiation of the nuclear explosive which results in the ground heating is not considered in these papers. In this paper we provide data allowing to estimate the heating effect. Note, that some issues of neutron effect upon the asteroids are examined in the papers [5,6].

The following types of the nuclear explosions with the yield of 1MT are under consideration:

surface explosions (1m above the surface);

stand-off explosions at the altitude of 1.5 m, 5 m, 10 m;

– distant explosions, when the neutron flux affecting the surface can be considered as two-dimensional parallel.

Asteroid is considered to be stony with two types of chemical composition: SiO_2 and $O_{0.569}Si_{0.167}Fe_{0.06}Mg_{0.139}Al_{0.065}$. The terrestrial rocks can play the role of analogs. The asteroid density is assumed to be 1, 2 and 2.7 g/cm^3.

In general, neutrons carry a small fraction of the explosion energy. Thus, in the process of fission the kinetic energy of neutrons is about 2.5% of total released energy. In the process of fusion the fraction of the kinetic energy of neutrons is much higher (it reaches 80% of total energy in the D-T process). However, in the current thermonuclear explosives about a half of total energy is produced in the process of fission. Moreover, the conditions of thermonuclear fuel combustion are provided by surrounding it with structurial materials of large mass. This leads to the moderation of neutrons and their absorption by the structure components and, as a result, to the distortion of spectrum of the emitted neutrons towards its softening. Ultimately, the main fraction of energy is released by the current thermonuclear explosives of gross yield in the form of x-radiation.

We assume, that during explosion having yield E (MT) the $E_f=\eta_f E$ fraction of energy is released due to fission and the $E_t=\eta_t E$ fraction is released due to thermonuclear reactions. We ignore the neutron spectrum distortion occurring while the neutrons pass the layers of the nuclear explosive structure. The λ coefficient expresses the absorption scale.

Estimate the number of neutrons produced in the process of fission. Each fission releases $\varepsilon_f \approx 180$ MeV$\approx 2.9 \cdot 10^{-14}$ KJ and produces ν neutrons. Considering the number of neutrons absorbed in the chain fission reaction, the total number of produced neutrons is the following:

$$N_{f0}=(E_f/\varepsilon_f)\cdot(\nu-1)\approx\eta_f(\nu-1)\cdot E\cdot 1.4\cdot 10^{26}$$

For $\nu \approx 3$ the number of produced neutrons is $N_f \approx \eta_f E \cdot 3 \cdot 10^{26}$. Assuming, that only f fraction of produced neutrons leaves the nuclear explosive, the total number of neutrons of fission spectrum, reaching the asteroid surface, is

$$N_f \approx \lambda_f \eta_f E \cdot 3 \cdot 10^{26} .$$

Similarly, the number of neutrons produced in the fusion reactions is the following:

$$N_{t0}=(E_t/\varepsilon_t)\approx\eta_t E\cdot 1.4\cdot 10^{27}, \text{ where } \varepsilon_t=17 \text{ MeV}\approx 3\cdot 10^{-15} \text{ KJ} .$$

Assuming, that only λ_t fraction of produced neutrons leaves the nuclear explosive, the total number of thermonuclear neutrons, is the following:

$$N_t = \lambda_t \cdot \eta_t \cdot E \cdot 1.4 \cdot 10^{27}.$$

Thus, the following number of neutrons comes off the nuclear explosive:

$$N \approx \lambda_f \eta_f E \cdot 3 \cdot 10^{26} + \lambda_t \cdot \eta_t \cdot E \cdot 1.4 \cdot 10^{27}.$$

To estimate the energy transferred to the asteroid by neutron radiation of the current thermonuclear charge it is sufficient to calculate separately the energy of thermonuclear and fission neutrons and substitute the appropriate η_f, λ_f, η_t, λ_t coefficients.

The Surface Explosion. Comparison with X-radiation

The energy of neutron radiation absorbed by the asteroid materials was calculated by the method of Monte-Carlo [4]. Computed were two problems in the following statement. Asteroid was simulated by the infinite semispace. The asteroid material was modeled by silicon oxide SiO_2 with the density of 2.7 g/cm^3. Instantaneous point isotropic neutron source was located at the altitude of 1m. In the first problem fission neutrons were considered. In the second problem neutrons had the energy of 14 MeV.

Calculation results of the first problem are given for E=1 MT, $\eta_f=1$, $\lambda_f=1$. Time-dependence of energy (in KT) absorbed by the asteroid material is presented in Figure 2.1. One can see that characteristic time of energy absorption is about ≈ 0.2 µs. In this case the fraction of absorbed energy is a bit greater than 0.5% of the total explosion energy and that is an order of magnitude less than for x-radiation.

The similar dependencies were obtained for the second problem. Figure 2.2 presents the results for $\eta_t=1$, $\lambda_t=1$. In this case the fraction of absorbed energy is $\approx 20\%$ and characteristic time of absorption is 0.1 µs.

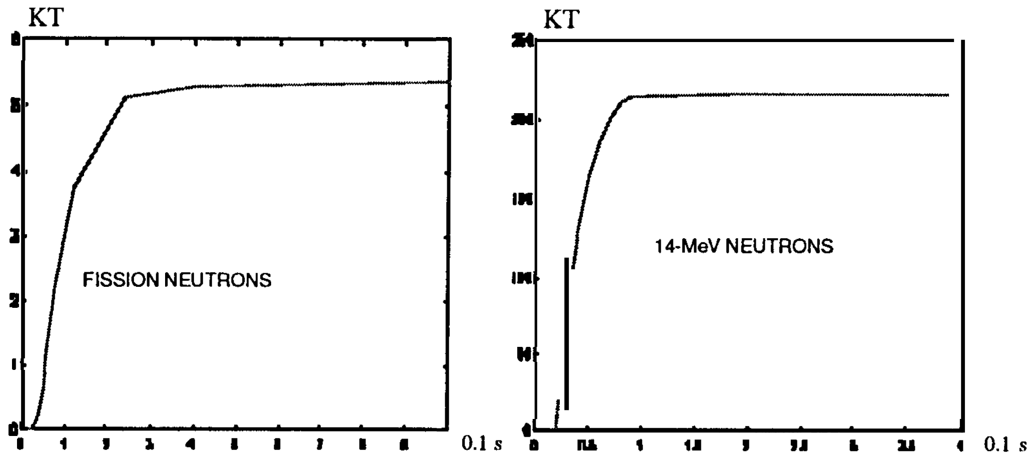

Fig.2.1,2. Time dependence of the absorbed energy fraction.

As mentioned above, for the current thermonuclear charges the fraction of absorbed energy, which neutron radiation transfers to the asteroid material, can be estimated by the simple superposition of the mentioned results with substitution of appropriate η_f, λ_f, η_t, λ_t coefficients.

The results presented lead to the obvious fact, that the fraction of energy absorbed by the asteroid material in the surface nuclear explosion can be rather significant if the thermonuclear explosives with the increased release of 14 MeV neutrons are used.

Since both the fraction of absorbed energy and the area of energy absorption are the important parameters, let us consider gasdynamic sources appeared due to 14 MeV neutrons (their effect is greater than that of the fission neutrons) and x-radiation. The temperature profiles, appearing due to x-radiation (2 KeV) and 14 MeV neutrons released by an 1 MT yield explosion at the level of 1 KeV, are shown in Fig. 2.3. It is obvious, that 14 MeV neutron radiation generates more effective gasdynamic source since the lens of heating is large in both longitudinal and cross directions.

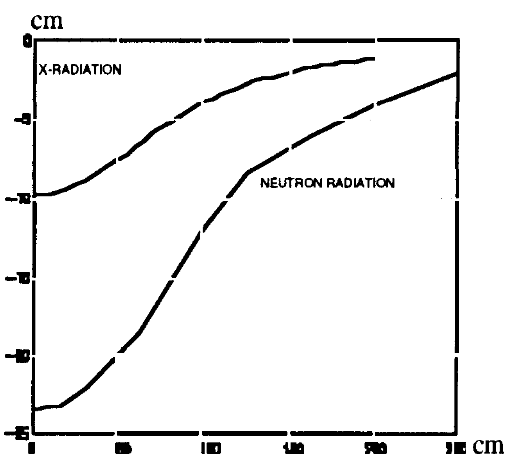

Fig.2.3. Heating lens for X-rays and 14-MeV neutron radiation at the level of 1 KeV.

The Effect of the Explosion Elevation Above the Asteroid Surface

It is a difficult technical problem to conduct a surface explosion at the typical velocities of a space interceptor and NEO. That is one of the reasons for some authors, for example [5,6], to propose above-surface explosions in order to transfer the maximum momentum and to mitigate the effect. A series of calculations was performed to estimate the dependence of a fraction of energy absorbed by an asteroid and of gasdynamic source creation on an explosion elevation. As in the previous paragraph asteroid was simulated by the infinite semispace. Asteroid's material composition is the following $O_{0.569}Si_{0.167}Fe_{0.06}Mg_{0.139}Al_{0.065}$ with the density of 2 g/cm^3. The altitude of the explosion was various: 1.5 m, 5 m, 10 m. Both spectra of fission and 14 MeV neutrons were studied. The results of calculations are presented in Table 3.1.

Table 3.1.

Elevation m	Spectrum	Absorbed Energy KT	T_{max} KeV
1.5	14 MeV	226	1.86
5.0	14 MeV	227	0.24
10.0	14 MeV	228	0.06
1.5	fission	6	0.07
5.0	fission	6	0.06
10.0	fission	6	0.0014

The data given in Table 3.1 show that the fraction of absorbed energy within the limits of calculation error does not practically depend on the explosion altitude. Nevertheless, the effects upon an asteroid are different, since the lenses of heating which are the areas where asteroid matter is heated to a high temperature differ grossly: the higher the elevation, the larger is the diameter and the lower are the temperature and width. Figures 3.1 and 3.2 show the temperature profiles in the lens of heating, illustrating this effect (for 14 MeV neutrons and fission neutrons, respectively). The plots demonstrate that when the explosion altitude increases the heated area becomes less deep and more flat. Comparing Figs. 3.1 and 3.2 one can see that gasdynamic source produced by neutron radiation with fission spectrum is less effective. Thus, for approximately the same areas of heating the temperature in the case of thermonuclear neutrons is 20 times as much as in the case of fission neutrons.

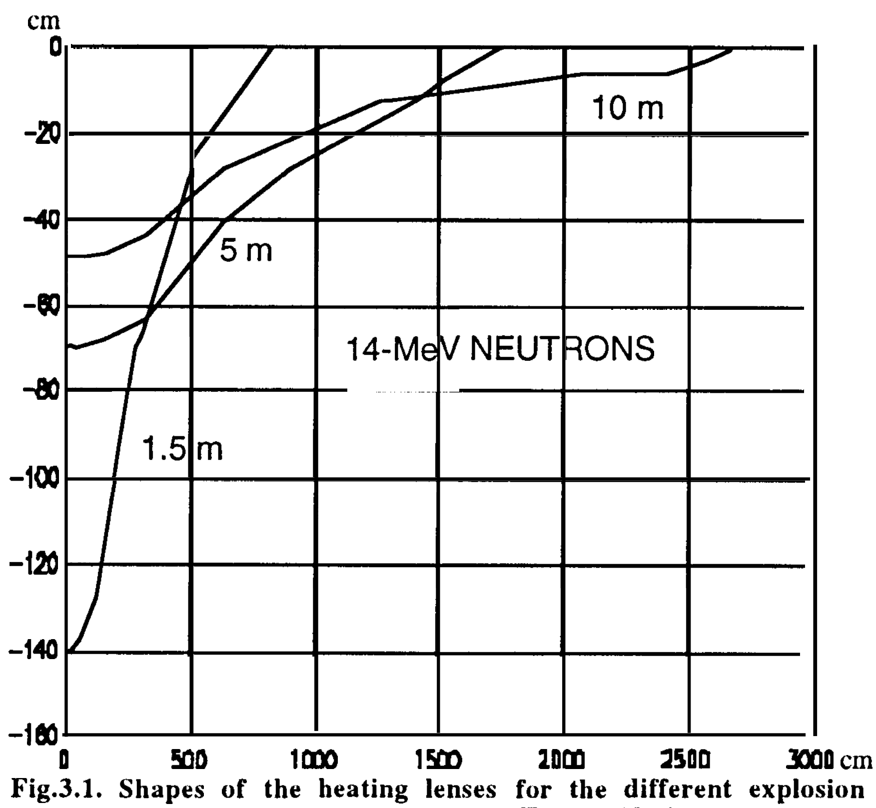

Fig.3.1. Shapes of the heating lenses for the different explosion altitudes at the level of T=0.01 KeV.

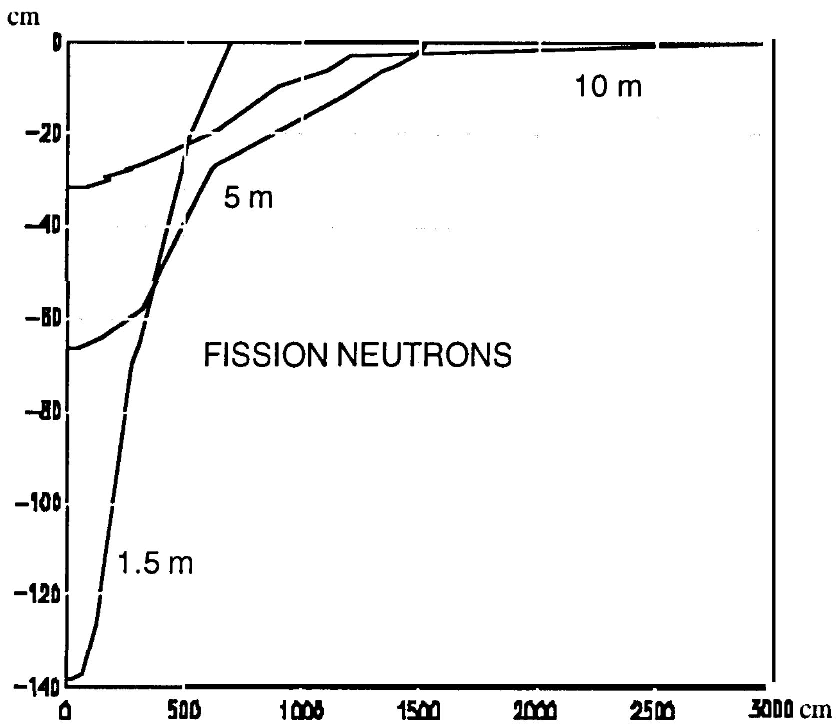

Fig.3.2. Shapes of the heating lensese for the different explosion altitudes at the level of T=0.0005 KeV.

The Effect of the Asteroid Density

Nowadays there is a significant uncertainty in the physical-chemical properties of the NEOs, in particular, in the density. For a subsurface explosion this issue is not a matter of principle. Situation is different for the surface and above-surface explosions, since creation of a gasdynamic source and, as a consequence, the momentum transferred to NEO are determined by the density to a considerable extent. Therefore, performed were the calculations of the problem described in paragraph 3 for various asteroid densities and the explosion altitude of 1.5 m (both for fission and 14 MeV neutrons). The results are given in Table 4.1.

Table 4.1

Density, g/cm3	Spectrum	Absorbed Energy KT
1.0	14 MeV	222
2.0	14 MeV	226
2.7	14 MeV	226
1.0	fission	6.1
2.0	fission	6.2
2.7	fission	6.3

Table 4.1 shows that within the limits of calculation error the fraction of absorbed energy does not depend upon the density of asteroid matter. The difference is in the gasdynamic source. Figures 4.1 and 4.2 present the levels of temperatures produced by 14 MeV and fission neutrons for different densities. It follows from the plots, that when the ground density decreases the dimensions of the lens of heating increases, in particular, the depth and the cross dimensions for the same levels of temperature.

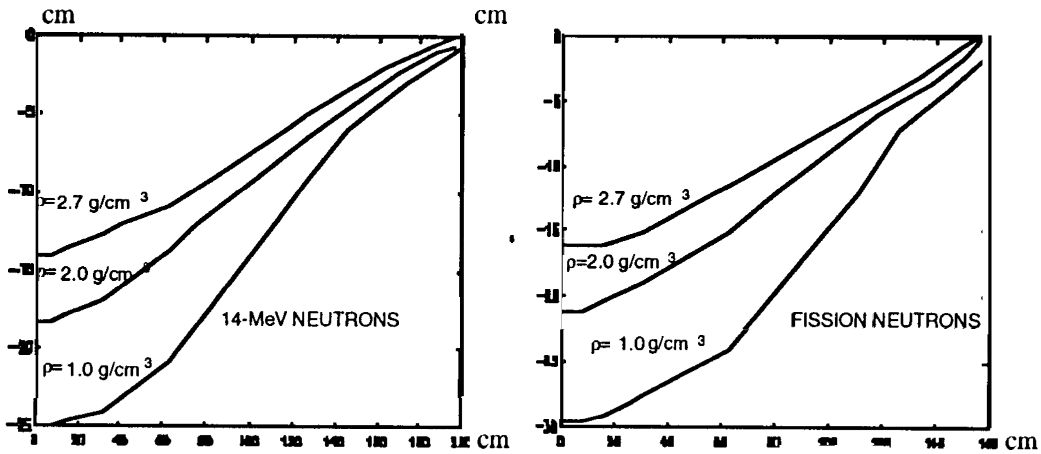

Fig.4.1,4.2. Shapes of the heating lenses for different densities at 1 KeV level for 14 MeV neutrons and at 0.03 KeV for fission neutrons.

The Effect of the Asteroid Chemical Composition

Evidently, the chemical composition of an asteroid should somehow influence both the fraction of absorbed energy and the temperature within the lens of heating. Consequently, calculations were performed related to the explosion at the elevation of 1.5 m for the asteroids with the density of 2.7 g/cm^3 and various chemical compositions. The results obtained are presented in Table 5.1.

Table.5.1

Composition	Spectrum	Absorbed Energy, kT
$O_{0.569}Si_{0.167}Fe_{0.06}Mg_{0.139}Al_{0.065}$	14 MeV	226
SiO_2	14 MeV	218
$O_{0.569}Si_{0.167}Fe_{0.06}Mg_{0.139}Al_{0.065}$	fission	6.3
SiO_2	fission	5.5

Table 5.1 argues, that the fraction of absorbed energy depends on the asteroid composition, the deviation for fission neutrons reaching 10% and for thermonuclear 3.7%. Note, that the discrepancy between considered compositions is not of a fundamental nature. This proves that in order to perform the exact calculations of the effect it is necessary to know chemical composition with reasonable accuracy.

The Effect of Two-Dimensional Parallel Neutron Flux

Papers [5,6] state that there is an optimal explosion distance from an asteroid surface determined by the value of transferred momentum. This distance is about 40% of an asteroid radius. At such distances the neutron flux affecting the asteroid can be considered as two-dimensional parallel neutron flux at any local point, including the case when the asteroid has irregular shape. The fraction of absorbed energy and temperature profiles with respect to the depth were calculated for the asteroid with the density of 2.0 g/cm^3 and chemical composition $O_{0.569}Si_{0.167}Fe_{0.06}Mg_{0.139}Al_{0.065}$ exposed to two-dimensional parallel neutron flux incident at some angle to the asteroid surface, which is simulated by the semi-infinite medium. Results were reduced to the flow of 1 kT/m^2. Figures 6.1 and 6.2 show the fraction of absorbed energy versus the incident angle for 14 MeV and fission neutrons, respectively. The plots argue that the fraction of absorbed energy can be well described by the law of cosine: $E_{abs} \sim \cos\theta$.

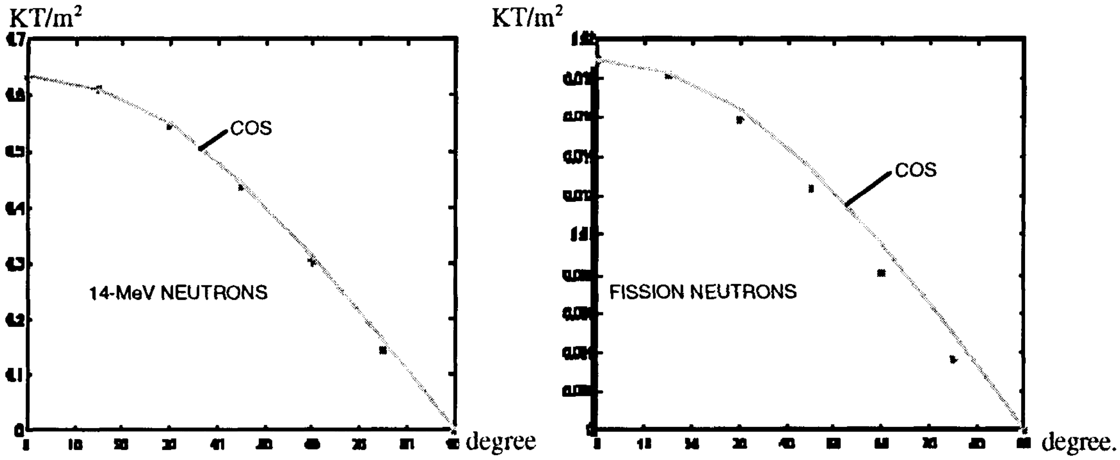

Fig.6.1,2.Dependence of absorbed energy fraction on incident angle.

The temperature profiles with respect to the depth, appearing in NEO are shown in Figures 6.3, 6.4. It follows from the plot analysis that the temperature at the asteroid surface depends only weakly on the incident angle, although the larger the angle, the greater decreases the temperature with the depth increase.

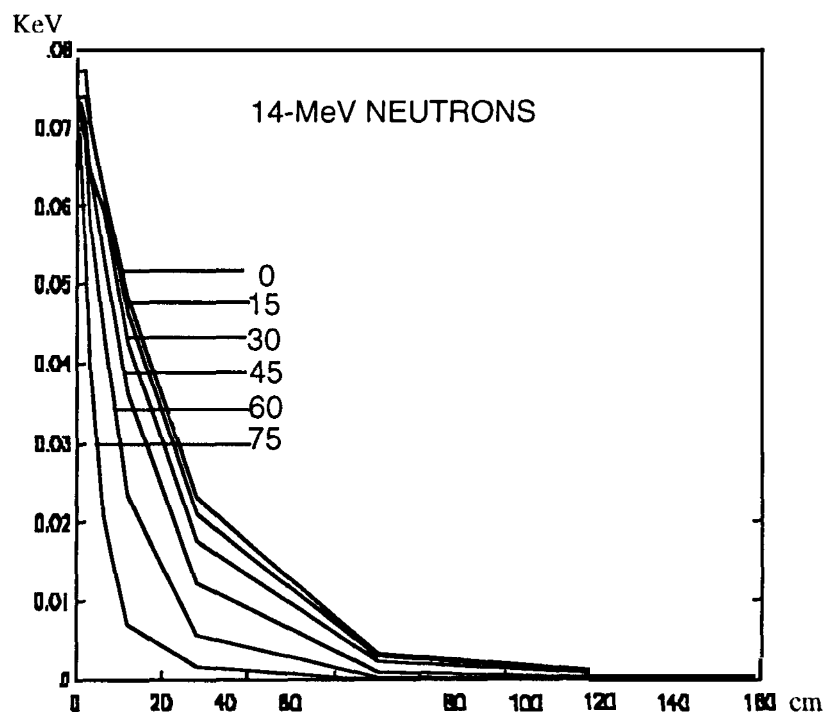

Fig.6.3. Dependence of temperature on depth for different incident angles.

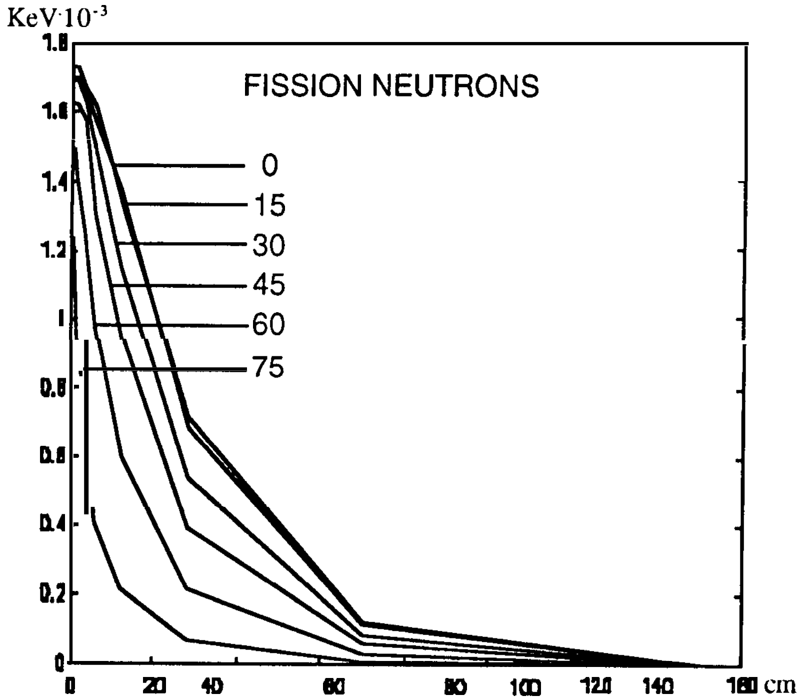

Fig.6.4. Dependence of temperature on depth for different incident angles.

Results and Discussion

We would like to comment the results obtained.

1. Since, in general, the surface and above-surface explosions are extremely complicated phenomena, all the calculations were performed for the simplified models. To describe the effect produced by neutrons correctly it is necessary to take into account X-radiation. Since the velocity of photons is considerably higher than that of neutrons, the phenomenon develops in the following way:

A. At first, the asteroid material is heated by X-radiation, then its scattering begins.

B. The neutron radiation comes with some delay (depending on the altitude of the explosion). The separation of neutrons according to spectrum takes place in the case of the above-surface explosion (for the surface one this fact can be ignored). !4 MeV neutrons are the first to come and they are followed by the rest (v-$E^{1/2}$). In a surface explosion thermonuclear neutrons impact into an 'undisturbed' asteroid, but in the case of above-surface explosion they are at first to pass through a dilute (rarefied) cloud of the ejected ground and only then they can impact into the asteroid material, which have been disturbed by energy deposition of the preceeding neutrons and other factors as well. Due to passing through the cloud the neutrons scatter, slow down and are taken away by the cloud material and all these lead to the reduction of neutron effectiveness. Consequently, the actual fraction of energy absorbed by the asteroid is lower than the value, calculated by the authors of this paper. Quantitative estimate of this effect requires further examination and development.

2. The effect of fission neutrons compared with that of x-radiation (0.5% versus 6%) can be ignored even without regard for the above-mentioned factor. This fact can be considered as proved.

3. Within the model the effectiveness of 14 MeV neutrons is much higher than of x-radiation, namely 20% versus 6%. However, the following aspects were not considered while modeling:

A. For a surface explosion of 1 MT yield the thermonuclear neutron radiation leads to high temperature of 2 KeV within the lens of heating. For such temperature radiation contributes to energy the most. Therefore the fraction of absorbed energy is reradiated until the temperature decreases to 1 KeV and, as a result, absorbed energy decreases

B. As it was already mentioned, for the above-surface explosion the neutron interaction with the ground ejected by x-radiation decreases and this leads to the decrease of absorbed energy.

Consideration of A. and B. factors can show that there exists the optimal altitude and/or yield of an explosion when addressing the asteroid with specific physical-chemical properties.

C. The softening of spectrum and the decrease of the number of neutrons due to their interaction with the nuclear explosive design lead to reduction of absorbed energy.

Above mentioned aspects should be considered in detail and they are beyond the scope of this paper. But these factors can equalize the effectiveness of 14 MeV neutrons and x-radiation.

Conclusions

1. The effect of neutron radiation of fission spectrum on an asteroid can be ignored, if compared with x-radiation produced by an explosion of the same yield.

2. 14 MeV neutron radiation in 'zero' approximation is more effective than x-radiation of an explosion of the same yield. But their effectiveness can appear to be equal, if the physical essence of an explosion is examined in detail.

3. Prediction of the asteroid behavior after the impact of neutron radiation requires reasonably accurate knowledge of the physical and chemical properties of the asteroid (such as shape, density, material composition, etc.), since gasdynamic source formation depends upon them.

4. The results obtained can be used as the initial data for determining the momentum, which NEO acquires due to the effect of neutron radiation of the nuclear explosion.

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Russian Federal Nuclear Center

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MEANS OF NEUTRALIZING THREAT COSMIC OBJECTS

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Livermore, California, USA, 22 - 26 May 1995.

April 1995

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MEANS OF AFFECTING THREAT COSMIC OBJECTS.

The aim of studies into the means of affecting threat cosmic objects (TCO) is to find out the TCO neutralization technologies:

- methods and technologies of exploding thermonuclear charges;
- specialized thermonuclear charges and means providing their efficiency which ensure an efficient terrestrial defense under restricting parameters presented by potential specifications of TCO detection systems and systems of the operation platform delivery to the point of TCO encounter over the range of TCO physical characteristics as wide as possible:
  - dimension form;
  - chemical composition;
  - mechanical and strength characteristics;
  - rotation;
  - gas and dust environments.

EXPLODING TECHNOLOGY OF TCO NEUTRALIZATION.

1. Contact exploding of thermonuclear charges.

2. Deepened exploding of thermonuclear charges.

3. Sequential exploding of thermonuclear charge series.

4. Remote TCO affecting. Technologies of "intermediate bodies". Technologies of "rendezvous" conditions.

RESULTS OF WORKS ON SELECTING TECHNOLOGIES OF TCO NEUTRALIZATION MEANS SHOULD INCLUDE:

- the maximum efficient set of thermonuclear charges (weight, energy release);
- technical safety means and exploding technologies;
- designs of platforms with charges and technologies of software-hardware procedures coordinated with capabilities of rocket delivery means for:
  - the "near interception" system on duty operating from ten hours to several days;
  - the "distant interception " system operating from several month to one year.

WAYS AND FORMS OF INTERNATIONAL COOPERATION.

- Set up the International Institute aegis of the United Nations Organization to coordinate the works on the system of terrestrial defense from TCO.
- Work out the Russian proposal for the World Community:
  - proposals for meetings at the summit;
  - proposal for the Anniversary Session of UNO;
  - proposal for cooperation at a yearly political and economic forum in Davos.
- Combine the unclassified project character and regime of rocket-nuclear technology nonproliferation;
  - the charge and explosion system environment excludes unauthorized explosion on the Earth; special safety requirements;
  - operation of the system in "UNO hands";
  - "equipping" the system on the principle of a "piston" setting at the last moment before the start by the nuclear club country operating the system of terrestrial defense from TCO.
- The system of terrestrial defense from TCO is the first stage of approach to employment of cosmic bodies for technologies of cosmic ecopower based on orbital solar mirrors:
  - night-time illumination of cities;
  - raising the productivity of agriculture in the regions of critical farming;
  - raising the sea productivity in circumpolar regions;
  - show melting control in threat zones;
  - solar central heating and power plants.

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"Efficiency of pulse transfer to an asteroid for deviation of its trajectory by distributed energy of a system of nuclear explosions near its surface"

Report at An International Technical Meeting
on Active Defense of the Terrestrial Biosphere from Impact
by Large Asteroids And Comets
22 - 26 May 1995, Livermore, California, U.S.A.

Authors: V.M.Danov, B.V.Pevnitsky, A.N.Popov, N.A.Popov, V.P.Sevastyanov.

The specific nature of effects produced by the nuclear explosion on hazardous cosmic objects (asteroids and comets) is an extremely high initial energy concentration at specific temperatures of about tens of millions of degrees. At such energy concentrations the specific weight of the radiant energi and hence the energy radiation into space become essential. This radiation specifies useless and irretrievable losses of the nuclear explosion energy.

Another aspect of the high energy concentration is a low efficiency of the explosion energy use for imparting momentum to an asteroid. The matter particle, leaving asteroid with the kinetic energi of E_K, takes momentum

$$P = \sqrt{2*M*E_K},$$

while giving to asteroid the same momentum of the opposite sign.

If in this case evaporation of the asteroid matter takes place and q portion of E energy acquired by the particle is spent for doing this, so that

$$E_K = E - q*E = E*(1 - q),$$

then

$$P = \sqrt{2*M*E*(1-q)}.$$

The value of q is never close to unity, and if the energy concentration in a diverging shock wave is lower than some limit (about 5-10 MBar for the iron asteroid), the expenditure on the cosmic body matter evaporation vanishes at all, and q = 0. In terms of maximum effects produced upon asteroid to change its trajectory the greatest possible nuclear explosion energy dispersion over the maximum mass of the body matter is thus seen to be advantageous.

In the context of the present work the factor of nuclear explosion energy losses by radiation has been estimated. These estimates show the following:

1. For the nuclear explosion over the iron asteroid surfase, taking place in a wide range of explosive capacities and distances to the surface (the radiation flux density changed from 10^{15} to 10^{19} erg/cm^2), the amount of energy absorbed by the asteroid surface changes between the limits 3% and 5%. If no special efforts are taken to reduce the energy radiation into the space, the nuclear explosion energy employment is found to be extremely low.

2. If special efforts are taken to reduce the energy losses by radiation (due to screens opaque to radiation), it is possible to decrease these losses by the order of magnitude at 4 kt/m density of distributed explosion energy, thus greatly increasing the nuclear explosion energy use.

R F N C - V N I I E F

Evaluating the Possibility of Asteroid Rock Conctituents Dispersion

Authors:
V. M. Danov, V. G. Zagrafov

The report
at An International Technical Meeting
on Active Defense of the Terrestrial Biosphere from Impaact
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1995

Abstract

In interception large asteroids at small distances from the Earth, when the time prior to impact is several hours or less, very high explosions yields are required to destruct asteroid into fragments posing no hazard to ecology. Under these conditions of great importance is the increase of the factor converting the explosion energy into kinetic energy of scattering fragments, which can be achieved by double sateroid affecting. The first "weak" effect makes sateroid fragments disperse at the velocity no more than the escape velocity (relative to asteroid). While asteroid is under dispersed condition, a more powerful charge is introduced into its center, which comes into action with collapse of asteroid rock constituents and provides a high factor of explosion energy transition to kinetic energy of its fragmets.

The efficiency of this method of asteroid affecting is the objective of present paper.

1. We consider conditions of asteroid rock constituents dispersion, when asteroid is first affected by a low-power explosion .

It is assumed that mechanically affected asteroid rock constituents uniformly disperse in space. Asteroid has a spherical shape. The fragment motion on the outer asteroid surface is described by the set of equations

$$\frac{dR}{dt} = v, \tag{1}$$

$$\frac{dv}{dt} = -\frac{GM}{R^2}, \tag{2}$$

with $t = 0$, $R = R_0$, $v = v_0$, initial conditions, where R is the asteroid radius, M is the asteroid mass, v is the velocity of its surface motion, $G = 6{,}7.10^{-8} cm^3 g^{-1} s^{-2}$ is the gravity constant.

Having divided the right and left sides of the set of equations (1), (2) termwise, we obtain

$$\frac{dR}{dv} = -\frac{vR^2}{GM}$$

equation, whose solution has the following form:

$$GM\left(\frac{1}{R_0} - \frac{1}{R}\right) = \frac{v_0^2 - v^2}{2} . \tag{3}$$

It specifies the maximum asteroid expansion dependig on its initial surface velocity v_0:

$$1 - \delta^{\frac{1}{3}} = \frac{1}{\beta} , \tag{4}$$

where $\delta = \frac{\rho}{\rho_0} = \left(\frac{R_0}{R}\right)^3$ is the ratio between the density at the end of the scattering stage and initial asteroid density, $\beta = \left(\frac{V}{v_0}\right)^2$, $V = \sqrt{\frac{2GM}{R_0}}$ is the escape velocity (relative to asteroid).

From (2) and (3) we derive the time relationship:

• $$t = -GM\int_{v_0}^{v}\left(\frac{GM}{R_0} - \frac{v_0^2 - v^2}{2}\right)^{-2} dv. \qquad (5)$$

•The total time of asteroid being in an expanded stage $T = 2t_{v=0}$ can be given as

• $$T = 2\frac{R_0}{V}\frac{1}{\sqrt{\beta}}I, \qquad (6)$$

where

$$I = \int_0^1 \left(1 - \frac{1-x}{\beta}\right)^{-2}\frac{dx}{\sqrt{x}} = \frac{\beta}{\beta - 1}\left(1 + \frac{\beta}{\sqrt{\beta - 1}} arctg \frac{1}{\sqrt{\beta - 1}}\right) \qquad (7)$$

(it has been obtained from (5) by substituting $v = v_0\sqrt{x}$).

Relations (4), (6) и (7) specify the time of asteroid being in an expanded state T depending on the required dispersion of asteroid rock constituents $\delta = \frac{\rho}{\rho_0}$.It should be noted that the dimension factor in relation (6)

$$\frac{R_0}{V} = \sqrt{\frac{R_0^3}{2GM}} = \frac{0{,}133 . 10^4}{\sqrt{\rho_0}} \quad s \qquad (8)$$

(ρ_0 is in g/cm^3) depends solely upon the initial asteroid densiny and is undependent of its other parameters (dimesions, mass). By this is meant that the derived relationship is also true for all fragments within the asteroid space, i. e. all parts of asteroid move during scattering and later compression in a similar manner. In particular, the state corresponding to the escape velocity is attained for all asteroid fragments at one time. It is not unlikely that this situation is trivial.

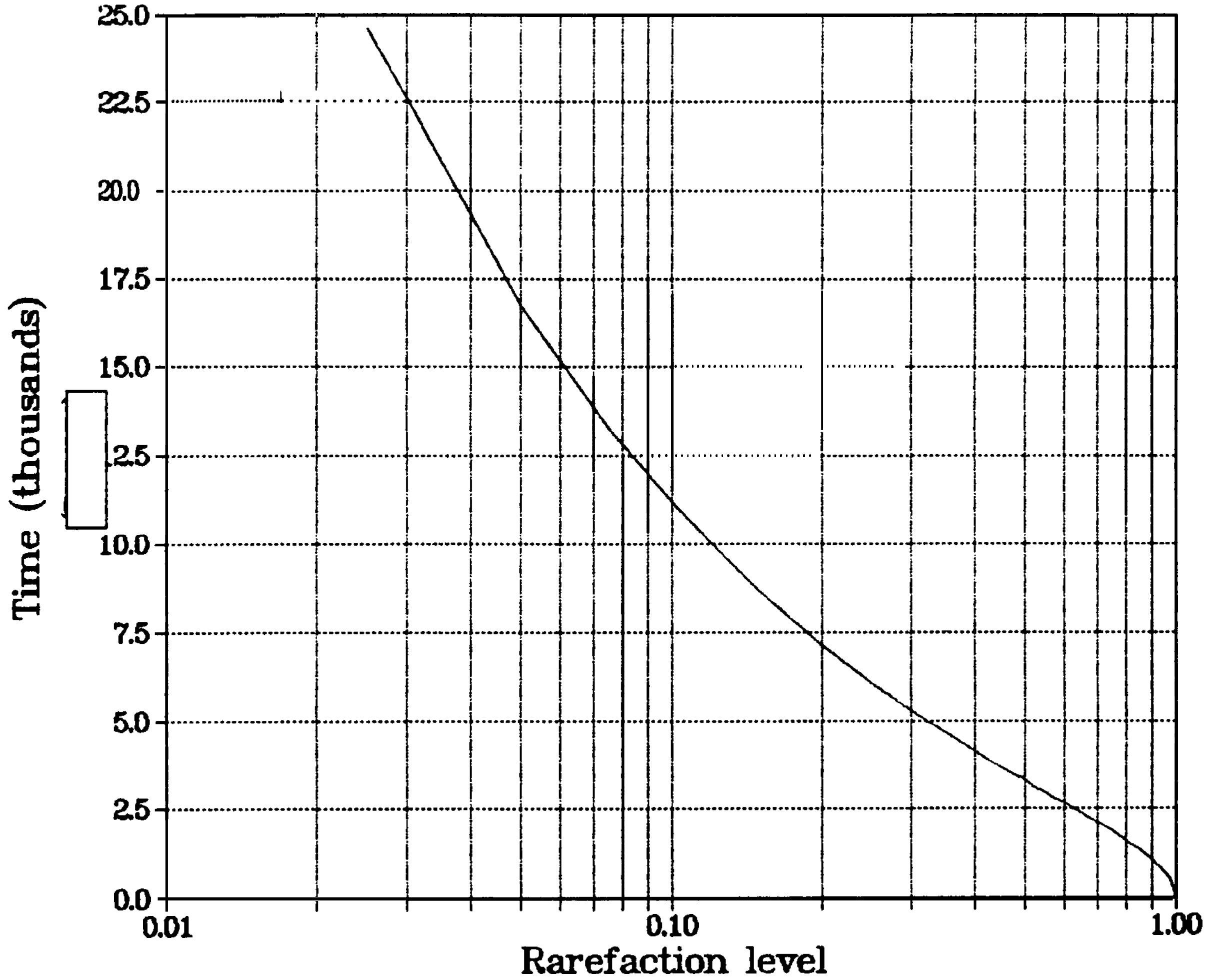


Fig. 1.

Dependance of time of asteroid being under dispersed conditions on its rarefaction level, which is described by relations (4), (6), (7) and (8).

$\delta = \frac{\rho}{\rho_0}$ has been plotted on the abscissa, $T\sqrt{\rho_0}$ has been laid off as ordinate (T is in seconds, ρ_0 is in g/cm^3).

By way of example let us find, how much time the asteroid, having the density of rock constituents ρ_0=3 g/cm^3, will be in an expanded state, if it is required to disperse it in an average density by an order of magnitude ($\delta = 0{,}1$). In this case we derive $T=0{,}64.10^4$s, i. e. about two hours irrespective of asteroid dimentions or its mass..

2. We estimate the kinetic energy W that should be spent on asteroid expansion to the required averige density. As the asteroid radius increases f rom R_0 to R the following energy is spent on expanding the spherical layer having initial dimensions r_0, $r_0 + dr_0$:

$$dW = \frac{Gmdm}{r_0}\left(1 - \frac{R_0}{R}\right), \qquad m = M\left(\frac{r_0}{R_0}\right)^3, \qquad dm = 4\pi r_0^2 \rho_0 dr_0, \qquad (9)$$

where m is the mass of asteroid part within the spherical layer.

Integrating (9) with respect to the asteroid space, we derive

$$W = \frac{3}{5}\frac{M^2 G}{R_0}\left(1 - \delta^{\frac{1}{3}}\right). \qquad (10)$$

Consider an example: the radius of asteroid is R_0=100 m, the density ρ_0=3g/cm^3, the required dispersion of rock constituents is $\delta = \frac{\rho}{\rho_0} = 0{,}1$. Based on relation (10), the kinetic energy needed for that will be $W = 3.4 \cdot 10^{14}$erg=8,1 kg of explosive. If ~1% of explosion energy goes over into kinetic energy of scattering, the energy of ~1t of explosive will be needed for the required dispersion of asteroid rock constituents (by an order of magnitude in an average density).

It should be noted that in the case above it will take only twice as much energy ($6{,}35.10^{14}$erg) to give the escape velocity to asteroid fragments (in relation (10) δ=0). That is in our example the asteroid scattering with no later gathering of its fragments can be easily done without the second effect produced by explosion of a more powerful charge at its centrer. The efficiency of double effecting would increase, if the level of rock constituents rarefaction δ lowered. However, in this case the delivery of the second charge to the asteroid center poses greater difficulties. .

It seems likely that the low power of the first ("weak") effect W as compared with the power nesessary for imparting the escape velocity to asteroid fragments $W_2 = \frac{3}{5}\frac{M^2G}{R_0}$ could be taken as the criterion for the double affecting efficiency, that is

$$\frac{W}{W_2} = \left(1 - \delta^{\frac{11}{3}}\right) << 1. \tag{11}$$

Non-fulfilment of this condition means that the power of the first ("weak") effect is comparable to the power necessary for imparting the escape velocity to asteroid fragments, I. e. the problem of irrevocable asteroid dispersion can be solved without the second explosion, for which purpose the first effect energy release is to be slightly increased (as in the above example). On the other hand, satisfaction of requirement (11) limits the possibility of asteroid rock constituents dispersion in an average density by $\delta^{\frac{1}{3}} \sim 1$ region, that is the possibility of the second more powerful charge delivery to the central asteroid region. Note that the conclusion made is independent of particular asteroid parameters.

The interrelation between $\frac{W}{W_2}$ and $\delta = \frac{\rho}{\rho_0}$ which is specified by (11), is shown in Fig. 2 as an illustrative example. .

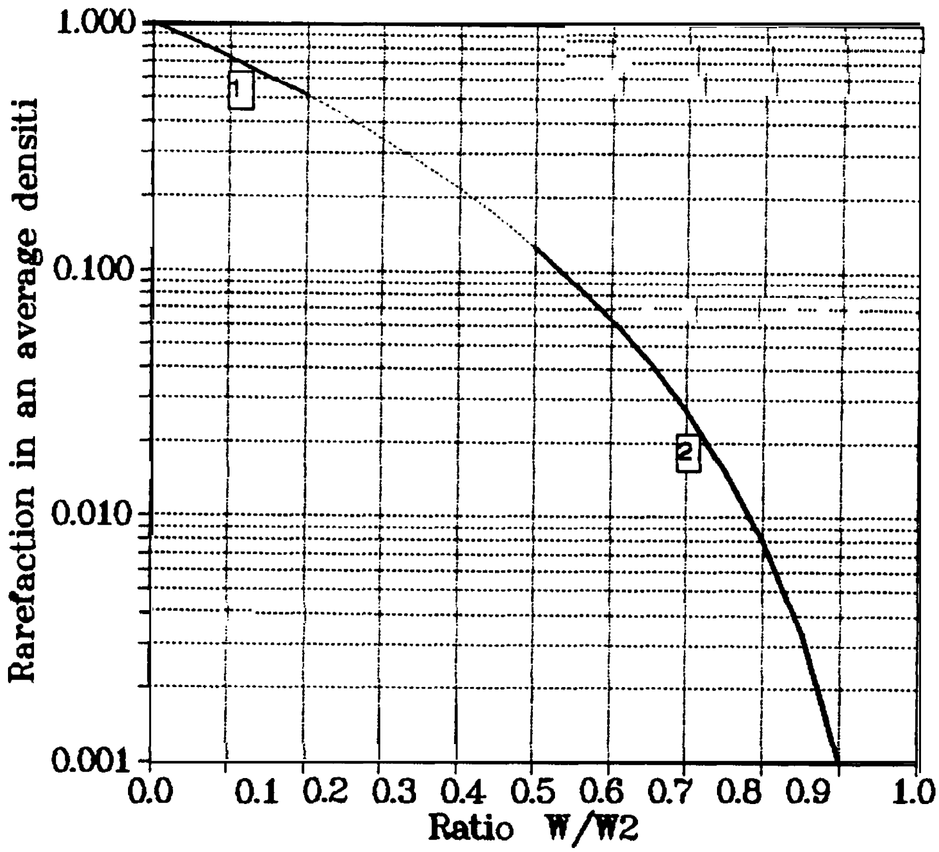


Fig. 2

Interrelation between the power of the first effect W produced upon asteroid and dispersion in an average rock constituents density $\delta = \frac{\rho}{\rho_0}$, which is attained in this case.

Portion [1] in Fig. 2 corresponds to rather low values of the first explosion energy release W as compared to W_2, therefore the tactics of double asteroid affecting can hardly be considered as justified ($W \leq 0{,}2W_2$). Portion [2] corresponds to the condition, according to which asteroid rock constituents dispersion is to be sufficient for making it possible to implement thesecond more powerful effect ($\rho \leq 0{,}1\rho_0$). We see that these regions do not meet, which points to the difficulties associated with implementation of efficient double asteroid affecting irrespective of its parameters.

3. The above considerations are true for the case of "distant interception", when asteroid is affected in advance and there are no time limitations. However, in "near interception" under limited time conditions the escape velocity imparting to asteroid fragments may turn out to be insufficient for the required asteroid rock constituents dispersion prior to its impact against the Earth. To estimate the asteroid expansion velocity in this case we refer to equations (1) and (2), having added $t=\infty$, $R = \infty$, $v = 0$ condition to them. We have

$$v = \left(\frac{2GM}{R}\right)^{\frac{1}{2}} . \qquad (12)$$

Note that the relations close to those above can be also derived for other considered asteroid expansion models (breaking down into two or more fragments).

Substituting (12) in (1) we obtain the time dependence of asteroid radius R

$$\frac{2}{3}\left(R^{\frac{3}{2}} - R_0^{\frac{3}{2}}\right) = \sqrt{2GM}.t , \qquad (13)$$

or

$$\delta = \frac{1}{\left(1+\sqrt{6\pi G\rho_0}\, t\right)^2} . \qquad (14)$$

Our interest is with the late scattering snage, when $\delta << 1$. In this case relatione (14) takes the following form:

$$\delta = \frac{1}{6\pi G\rho_0 t^2} = \frac{0{,}79.10^6}{\rho_0 t^2} , \qquad (15)$$

where the time prior to impact against the Earth t is expressed in secondes, the initial asteroid density ρ_0 is in g/cm^3. For example, if there is a day before impacting against asteroid, whose rock constituents density is 3 g/cm^3, asteroid having been affected with imparting the escape velocity to its fragments will disperse in an average density by a factor of $\delta^{-1} \approx 2{,}8.10^4$ before falling on the Earth. If the sateroid radius is R_0 =100m, its fragments will disperse over the area with radius $R = R_0 \delta^{-\frac{1}{3}} \approx 3$ km, which is known to be insufficient for preventing after-effect of its fall. Thus, to disperse asteroid over rather large areas in "near interception" releases of energy are required, which impart velocities to its fragments being much higher than the escape velocity, $v_0 >> V$. Dependence of asteroid dimention on its scattering time defined by relation (3) and (5) can be presented for this case as

$$\tau = \frac{V}{R_0} t = \frac{\beta^{\frac{3}{2}}}{1-\beta} \left\{ \frac{\sqrt{x}}{x+\beta-1} - \frac{1}{\beta} + \frac{1}{\sqrt{1-\beta}} \ln \left[\frac{\left(\sqrt{1-\beta}+1\right)}{\left(\sqrt{1-\beta}+\sqrt{x}\right)} \sqrt{\frac{x+\beta-1}{\beta}} \right] \right\}, \quad (16)$$

where $\quad x = 1 - \beta \left(1 - \frac{R_0}{R}\right).$

Recall designations: $x = \left(\frac{v}{v_0}\right)^2, \quad \beta = \left(\frac{V}{v_0}\right)^2.$

In the limiting case of $\beta \to 1$ expression (16) goes into (15). We are interested in the limiting case of "rapid expansion", when $\beta \to 0$. In this case formula (16) becomes an evident relation

$$R = R_0 + v_0 t \approx v_0 t,$$

or expressing the initial asteroid surface velocity v_0 in terms of the total kinetic ehergy of asteroid fragments relative to its center during a uniform expansion $W = \frac{3}{2} \frac{M v_0^2}{R_0^5} \int_0^{R_0} r_0^4 dr_0 = \frac{3}{10} M v_0^2$, we find that to expand asteroid to R radius the following kinetic energy should be imparted to its fragments:

$$W = \frac{3}{10} M \left(\frac{R}{t} \right)^2 . \qquad (17)$$

We take the falling asteroid energy E dispersion over area $\alpha = \frac{E}{\pi R^2} = 10^{15}$ erg/m^2 as ecologically safe. This value is comparable to thermal solar radiation energy release over a unit of the Earth surface area during twenty-four hours. For the asteroid having rtadius R_0 =100 m and rock constituents density ρ_0=3g/cm^3, which is moving to the Earth at the velocity of 25km/s, and has kinetic energy 10^3 Mt of TNT equivalent, such density of energy release can be realized with the radius of the falling area of its fragments $R \cong 100$ km. Relation (17) specifies the kinetic energy needed for that, which should be imparted to asteroid fragments, depending on the interception time t (from explosion to potential fall on the Earth), $W \cong \frac{3{,}8.10^{26}}{t^2}$erg, where t is expressed in seconds. If asteroid interception has been made at a distance of 10^5 km from the Earth, I. e. an hour before its fall, the required kinetic energy imparted to fragments will be $W \cong 0{,}3.10^{20}$erg $\cong$ 0,7 kt of TNT equivalent. If ~1% of explosion energy goes over into kinetic energy of scattering, the energy of ~100 kt of TNT equivalent is needed for the required dispersion of asteroid rock constituents..

For illustration purposes Fig. 3 shows W dependence on the interception time for asteroid having R_0=100m and 1000m.

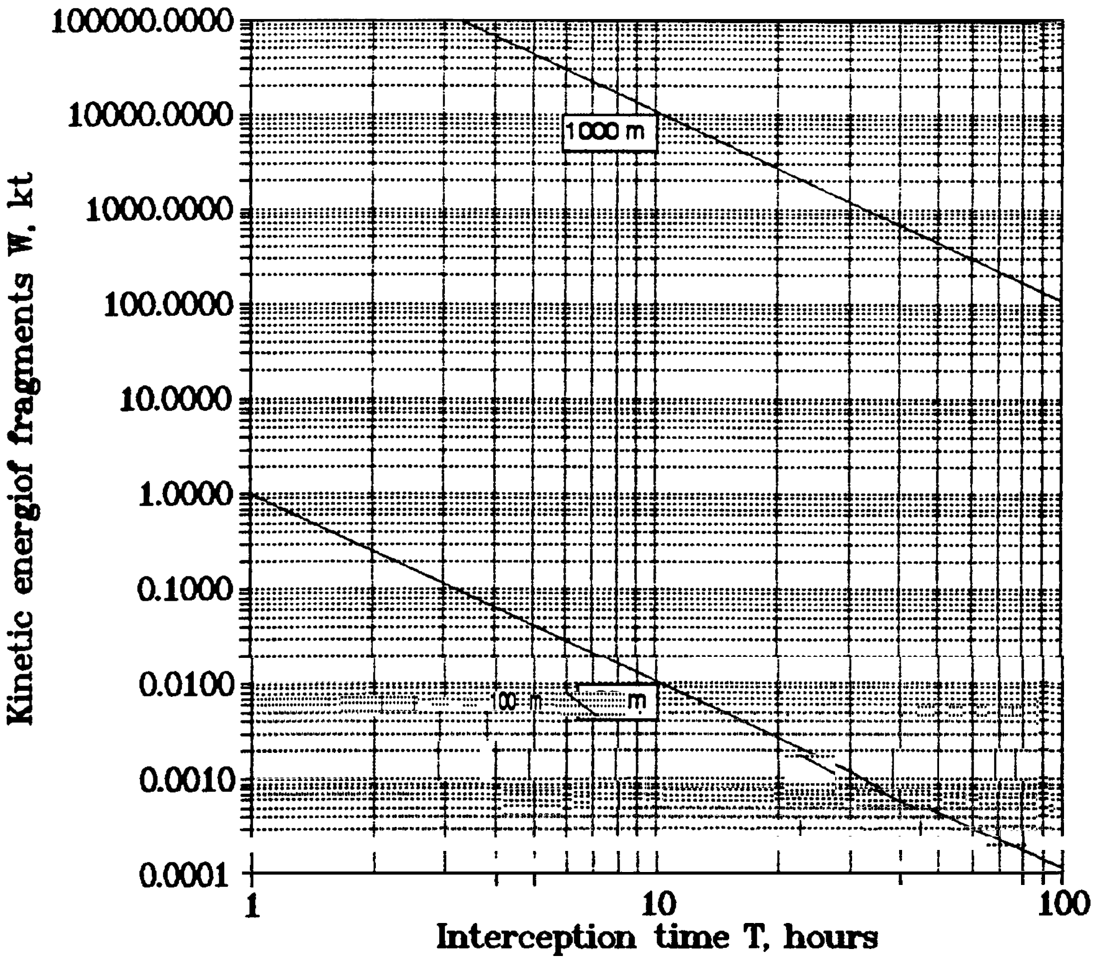
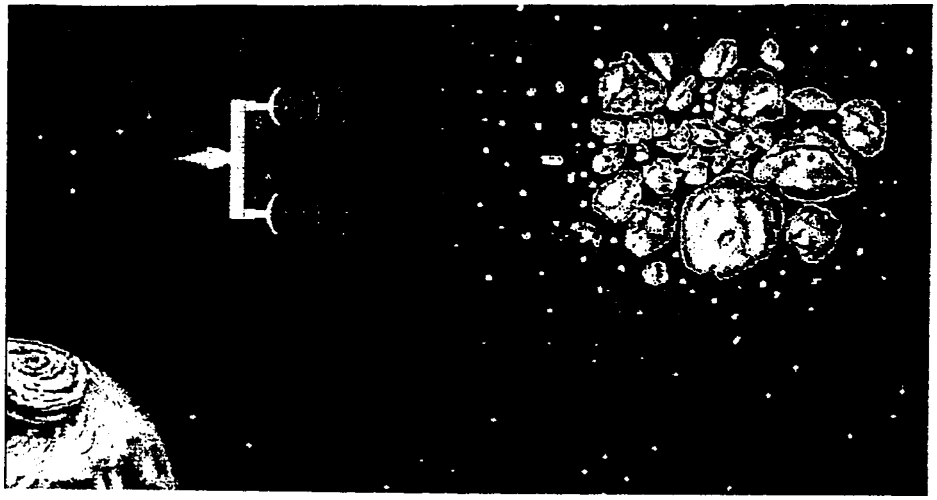
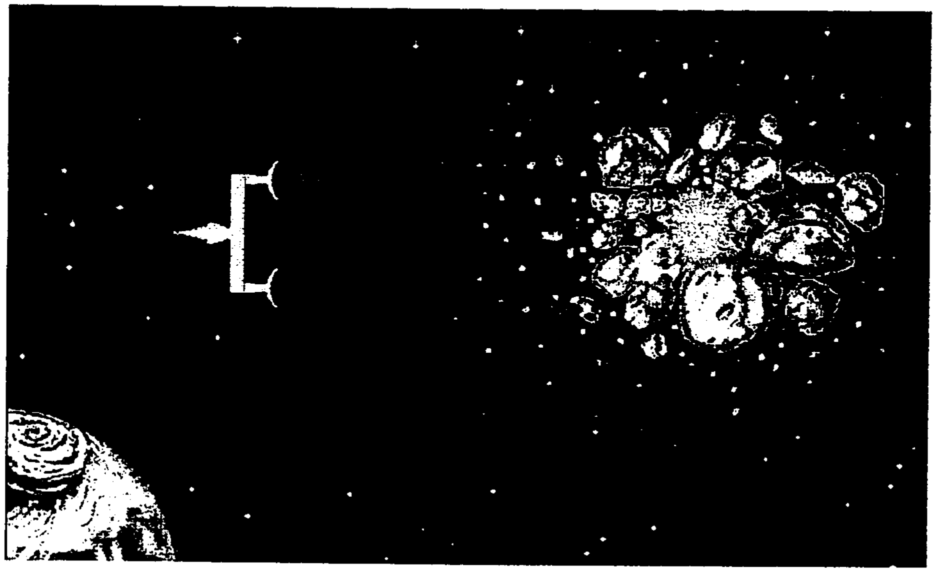


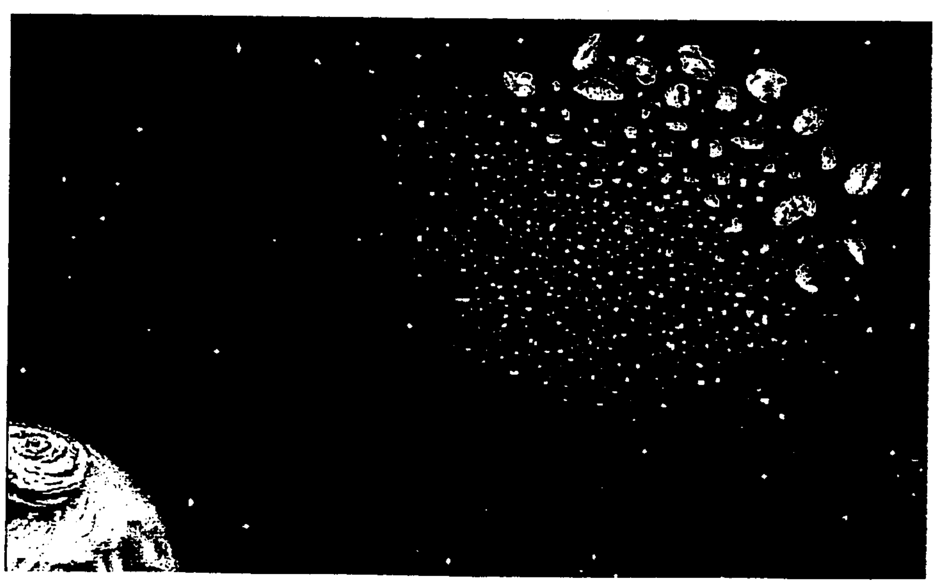
Fig.3

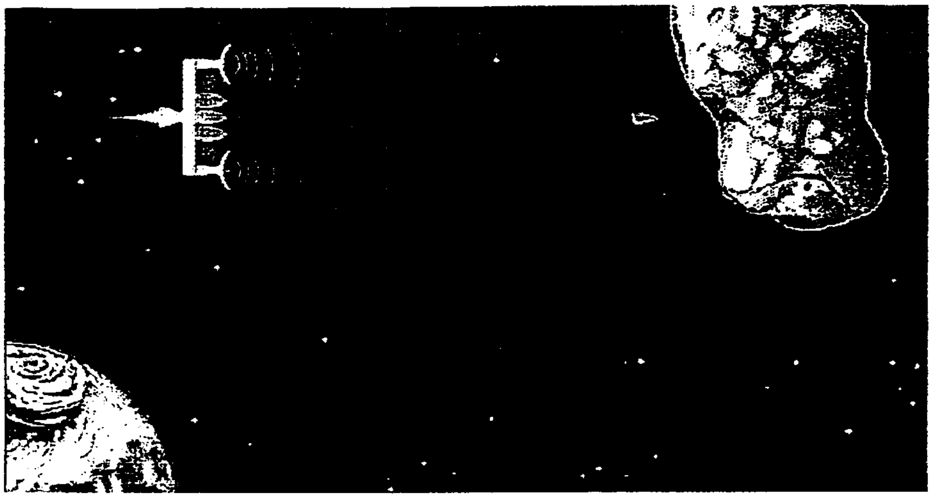
Dependence of kinetic energy of asteroid fragments, necessary for their dispersion to the required level, on the interception time (before its fall on the Earth) for asteroids having R_0=100 m and 1000 m.

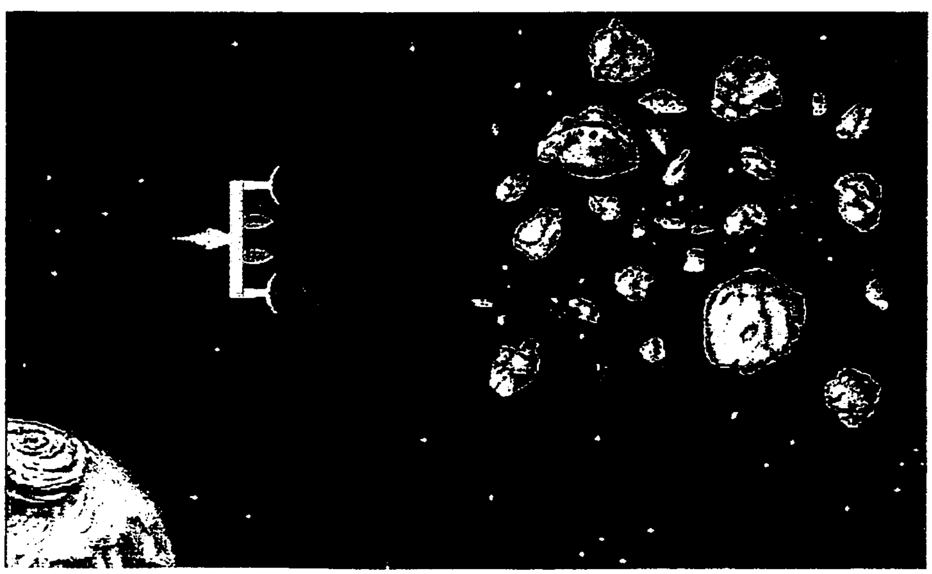
As Fig. 3 shows, the energy release necessary for asteroid neutralization rises sharply as its dimention increase ($W \sim R_0^6$). Therefore, to intercept large asteroids having R_0>100m of great importance is the increase of the factor converting the explosion energy into kinetic energy of fragments, which can be attained through double asteroid affecting: the first "weak" effect is used to disperse fragments; it is followed by a more powerful explosion at the center after asteroid rock constituents have collapsed.

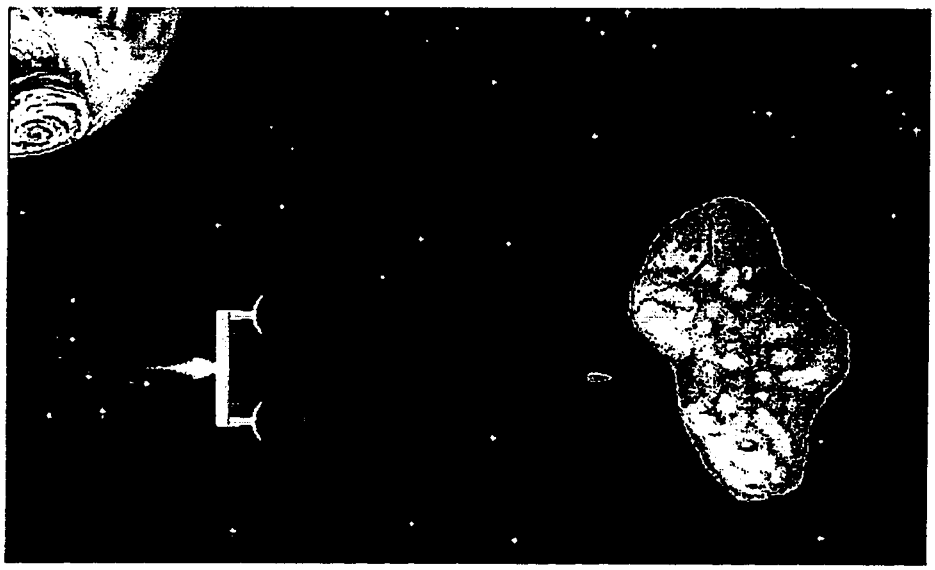


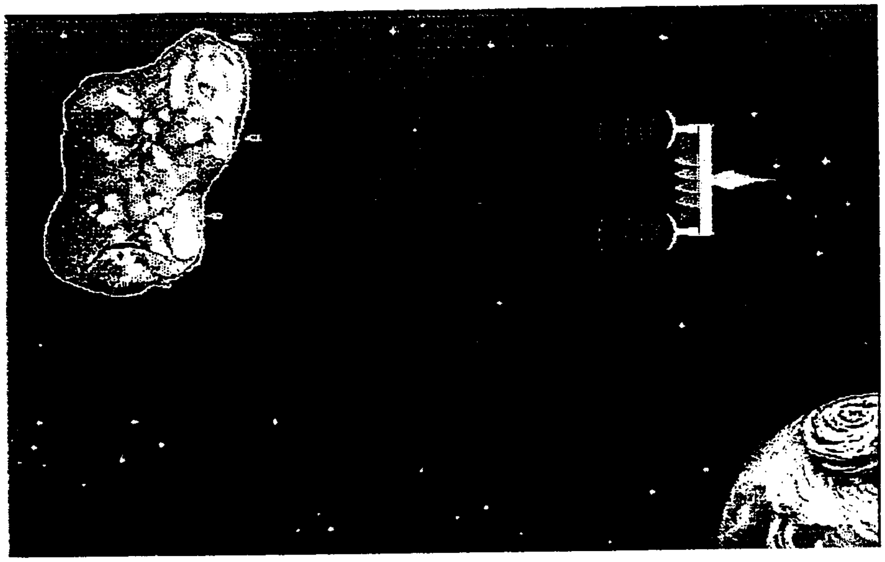


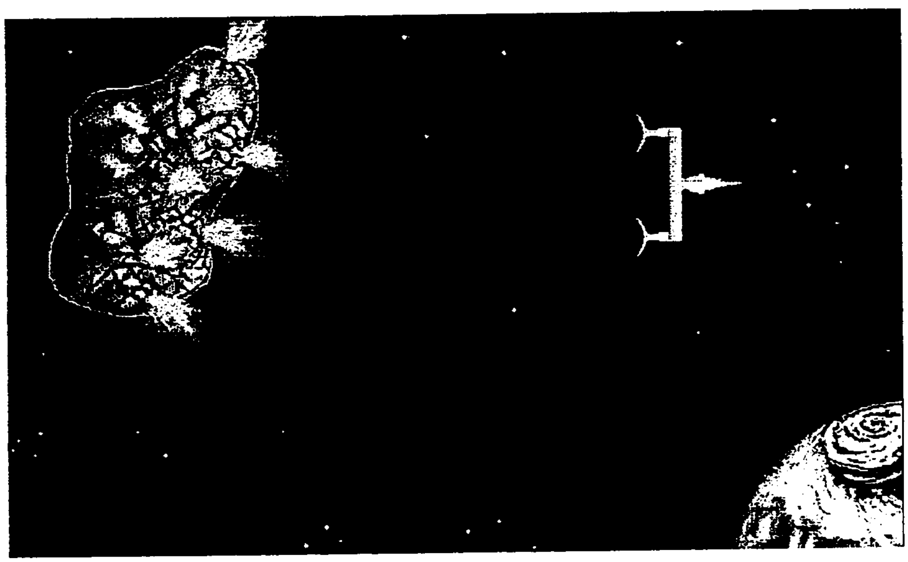


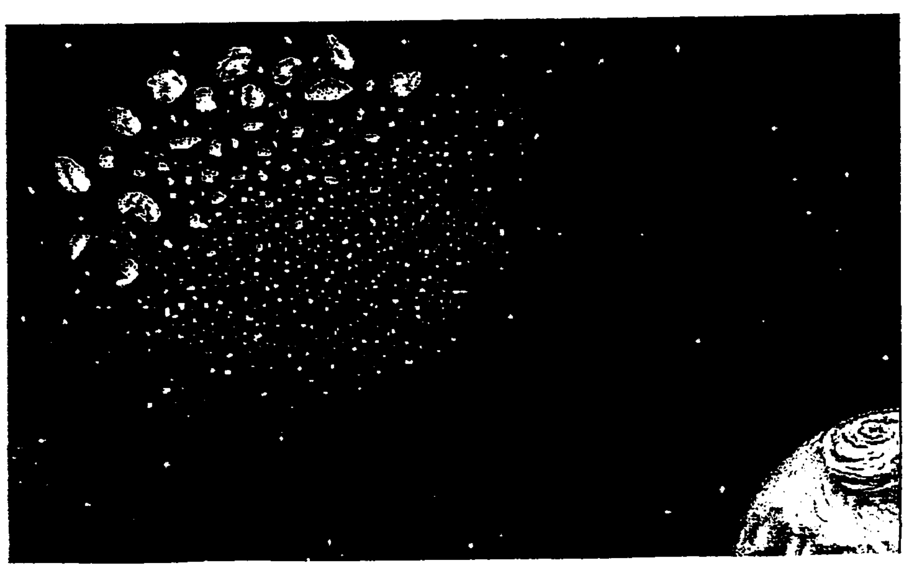












Effect of Nuclear Shallow Burst on Asteroids

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The effect of the nuclear explosion on the asteroid will be the most intensive, if the nuclear explosive device is buried into the asteroid ground before the explosion. This is associated with the fact, that at such type of explosion (unlike the surface and the stand-off explosions) the explosion energy at the initial stage of the process is entirely transferred to the asteroid ground. As the result the effect of the buried explosion on the asteroid is equivalent to the effect of the surface explosion with the yield tens of times greater [1]. Therefore, consideration of the buried explosion effect on the asteroids is of peculiar interest.

In this paper we consider the problem of the effect of the nuclear buried explosions on the stony asteroid (as the most wide-spread type of the NEOs). On the basis of numerical modeling of nuclear shallow bursts in the dense crushable medium we studied some regularities of their effects as a function of the depth -of-burst.

Some results of calculating the explosions in granite at the scaled depth of 1, 2, 3, and 15 m/kt$^{1/3}$ are given. Configurations of the calculated destruction zones and dependences of the shock amplitude decrease upon the depth are given. The change in the effect intensity with increase of the explosion depth is illustrated on the basis of calculated values of energy withdrawn by the elastic wave.

The possibility of schematizing the phenomenon by using the concept of the explosion equivalence at different scaled depth is discussed. This concept facilitates the process of taking the engineering decisions using the numerical simulation results. The limits of the equivalent explosion concept applicability are illustrated on the basis of the calculations.

The numerical modeling was carried out using the complex of codes called "SD-TOM". The mathematical formulation of the problem is considered. Some characteristics of the medium model and the difference method are given.

Introduction

The effect of the nuclear explosion on the asteroid will be the most intensive, if the nuclear explosive device is buried into the asteroid ground before the explosion. This is associated with the fact, that at such type of explosion (unlike the surface and the stand-off explosions) the explosion energy at the initial stage of the process is entirely transferred to the asteroid ground. As the result the effect of the buried explosion on the asteroid is equivalent to the effect of the surface explosion with the yield tens of times greater [1]. Therefore, consideration of buried explosion effect on the asteroids is of peculiar interest.

If time till the assumed asteroid encounter with the Earth is small (~1 year) the response must be organized under conditions of the minimum warning time. In this case to provide the required change of the asteroid trajectory we need to transfer to it a rather large momentum using the explosion of appropriate yield. As the assessments show [1] for the given asteroid dimensions to transfer the necessary momentum we need the explosion of such yield that the destruction zone will be commensurable with the asteroid dimensions. Thus, the effect on the asteroid will be reduced not to altering its orbit, but to the asteroid disintegration into separate fragments. These fragments will scatter in space at velocities significantly higher than change of the asteroid mass center velocity caused by the explosion. Some part of the asteroid fragments will pass by the Earth, and the remaining part with appropriate dimensions will burn in the Earth atmosphere at a large distance from one another without causing any damage.

The experimental data show [2] that the ground fragmentation in direct shock wave of the nuclear explosion proceeds very intensively, and maximum dimensions of the fragments (~5 m) are significantly less than the critical dimensions (~30 m) at which the complete burning in the atmosphere is provided. However, if the asteroid dimensions to some extent exceed dimensions of the fragmentation zone, the fragments with dimensions exceeding the critical one may be formed. Impact of such fragments into the Earth may cause hazardous consequences, though essentially less severe than in the case of the not destroyed asteroid impact.

Due to the spall phenomena during propagation of the rarefaction wave from the back side of the asteroid dimensions of the fragmentation zone during the explosion at the asteroid of appropriate diameter exceed dimensions of the fragmentation zone in the case of the explosion near the semispace surface. Therefore, from the engineering standpoint to achieve the guaranteed disintegration of the asteroid into the fragments it is sufficient to affect the asteroid with the explosion of such yield and at such depth as to provide exceeding of the fragmentation zone dimensions at the same explosion near the surface of semispace over the asteroid dimensions. It should be pointed out that we don't consider the problem of destroying the asteroid of complex shape, e.g., looking like a long galosh. For such asteroids we'll need to use several simultaneous explosions if it is technically feasible. In the opposite case the necessary effect is achievable only by several simultaneous surface explosions (that is also technically difficult), or by the stand-off explosion of high yield. We believe it is possible to perform consecutive explosions if time interval between them is large enough.

Thus, we are faced with the problem of determining dimensions of the fragmentation zone at the buried explosion near the semispace surface. This paper is primarily dedicated to consideration of this problem.

Description of the Problem

The main increase of intensity of acting on the asteroid during transition from the surface explosion to the buried explosion is observed at the depth-of-burst (DOB) up to 0.2 $m/kt^{1/3}$. This is associated with increase of the explosion energy fraction transferred to the ground at the initial phase, when the processes of energy transfer by radiation are considerable, from less than 10% up to 100% [1]. During subsequent increase of the explosion depth the growth of the effect intensity is significantly less, and is associated with increase of the depth at which the rarefaction wave from the free surface will overtake the shock propagating in the ground.

On the other hand, the actually achievable values of the DOB make up from several meters up to several tens of meters. Therefore, assuming that for the asteroid destruction by the buried explosion we'll use the nuclear devices having yield of ~1 Mt, below we consider the explosions with the DOB 1,2,3 $m/kt^{1/3}$. The main task of the calculations was to determine configuration of the fragmentation zones at such explosions in the uniform semispace.

It is known [3] that the gasdynamic flows formed during the explosion even with account for many elastic-plastic and strength effects possess similarity. Namely, there is a characteristic dimension - dynamic radius $r_d = (E/\rho_0 c_0^2)^{1/3}$ characterizing the explosion scale, and generally speaking, the characteristic radius of the energy dissipation (for rocks $r_d \approx 4...5$ $m/kt^{1/3}$). In this expression E is the explosion yield, ρ_0 is characteristic density of the ground, c_0 is characteristic sound velocity in the ground. While considering some class of the grounds rather similar in terms of their properties, the term containing the density and sound velocity can be dropped. Therefore, in particular, the flows formed during the buried explosions of different yield at the same scaled depth $\overline{H} = H/E^{1/3}$, exceeding 0.2 $m/kt^{1/3}$ will be similar for the given class of the grounds. If the explosion depth is significantly less than the dynamic radius, we might expect that with the shock propagation in the ground the details of the initial source will be "forgotten", and at some distance from the centers of the explosions the flows will turn to be also quasi-similar. This allows us to introduce a notion of the explosion equivalency [4] very convenient to generalize the results of the calculations and engineered applications. That is, in this case the explosion with the yield E_1 at the scaled depth $\overline{H}_1$ will at some distance significantly exceeding the depth of the explosion create the same flow field, as the explosion having yield $E_0 = \eta(\overline{H}_1) \cdot E_1$ at the scaled depth $\overline{H}_0$. The coefficient of equivalence η characterizes change of the effect intensity with increase of the explosion scaled depth.

The second problem we were considering was assessing feasibility of using the principle of the buried explosion equivalence, and determining limits for applicability of this principle. Therefore, we also computed the explosion at the scaled depth 15 $m/kt^{1/3}$.

Calculations: Model of Medium

Numerical simulation of the buried explosions was done using the complex of codes called "SD-TOM". As a ground we took a rock which was described by one of the models which have been widely considered in literature in association with study of mechanical effects of powerful underground explosions [5]-[8]. The medium parameters were selected to simulate the results given, e.g., in [12] for explosion in granite.

To carry out the calculations were made a number of assumptions:

1. The two-dimensional calculation started from the moment when the shock reached the free surface. During that as initial conditions we used results of one-dimensional calculation by other authors obtained in gasdynamic approximation taking into account the energy transfer in approximation of radiant heat conductivity.
2. To simulate behavior of the material evaporated in the shock we used the equation of state of the type of Mi-Gruneisen with transition to the ideal gas at compression less than 1.
3. To simulate behavior of the scattering destroyed ground in the case of its essential decondensation and mixing with the evaporated ground we used the same equation of state as for the evaporated ground.
4. Periodically, when pressure in remote part of the cloud reduced by several orders this region was omitted from the calculation.
5. Gravity influence was not taken into account.

Some remarks on the used model of the crushable medium.

The medium element is considered as a totality of the matter and voids (fractures, pores). Specific volumes of the matter V_m and the voids V_n are determined during the calculations.

The tensor of stress in the medium element is determined by the tensor of stress in the matter.

The spherical part of the tensor of stress in the matter (pressure) is determined by equation of state of the type $p = p(V_m, e_1)$, where e_1 is internal energy which doesn't include the work of the stress deviator at the elastic shear. In the calculations we used the equation of state of the Mi-Gruneisen's type.

In the directions where the medium strength was preserved the components of the tensor-stress-deviator are related to the components of the tensor of the strain rates through the Hooke's law.

Rock possesses breaking strength and shearing strength. The rock weakened by the fractures of any directions possesses less strength.

Material destruction during extension occurs when the maximum extending stress exceeds the breaking strength limit (σ_{cr}). At the moment of the fracture opening in the medium element the stress orthogonal to the fracture surface is assumed to be zero until the complete closure of the fractures of this direction. Deformations of matter in the directions corresponding to the strong state of the medium are considered to be coinciding with the medium strains. When the medium element turns like a solid body the fractures turn together with it.

As a criterion of the medium destruction during the shearing the generalized condition of Hubert-Mises is used. If this criterion is not met the medium looses strength in all the directions.

In the completely destroyed medium the components of the tensor-stress-deviator are related to the components of the tensor of the strain rates through the law of flow of Prandtl-Reiss with the yield limit proportional to pressure.

The Difference Method

The complex of codes SD-TOM is intended for computing two-dimensional non-stationary motions of compressible media taking into account the strength effects and the elastic-plastic properties. The calculation is done by the regions, each region has its own regular quadrangular mesh. Boundaries of the calculation region do not necessarily coincide with the substance interfaces. Each calculation region may have several substances, but the calculation cell must have not more than three.

The main equations are written with account for the tensor properties of the medium. For simultaneous solution of the equations of hydrodynamics and elastic-plastics the SD-TOM uses explicit method which has elements of several known difference setups. Lagrangian and Lagrangian-Eulerian description is allowed. At the Lagrangian phase the equations of energy and elastic-plastics are solved as in the program "SPRUT" [8], the equations of motion - as in [10]. In the zones of large strains the Lagrangian-Eulerian description is used, where at the second phase the meshes are reformulated, and the quantities are transferred to the new meshes. In the case of small change in the meshes to transfer the quantities we use the method accounting for the convectional flows through the cell borders [11]. In the case of considerable change we use the method of "fractional design" based on [12]. If the substance interface doesn't coincide with the mesh lines it is described approximately using the method of "concentrations" and the special algorithm preventing excessive diffusion of substances during the mesh reconfiguration, analogously to [10].

Calculation Results and Discussion

Configurations of the destruction zones obtained in the numerical calculations are shown in figure 1.

The numerical calculations showed that the principle of equivalence is applicable to explosions with the scaled DOB at least, up to 3 $m/kt^{1/3}$. To illustrate this figure 1 shows isobars for the explosions with the DOB 1 and 3

$m/kt^{1/3}$. Change of the shock intensity with the distance along the axis of symmetry in the direction from the free surface for $15\ m/kt^{1/3} < r < 150\ m/kt^{1/3}$ at good accuracy can be presented in the form $p = A(\overline{H}) \bullet (r/E^{1/3})^{-1.62}$. Calculation of the explosion at the depth $15\ m/kt^{1/3}$ showed that the principle of equivalence is violated for such depths.

We can understand the character of the dependence of equivalence coefficient $\eta(\overline{H})$ if, e.g., we consider the fraction of energy withdrawn by the elastic wave. This energy E_s can be estimated by the work A_s at the boundaries lying within the region of applicability of the theory of elasticity where the destruction is absent, and the compression is not large, i.e. the energy dissipation is absent. For the contained explosions the boundary of this region has the radius r_s>100...150 $m/kt^{1/3}$. While comparing the shallow-burried explosions we should consider work at the boundaries the distance to which is proportional to $\eta(\overline{H})^{1/3}$. It should be pointed out that accurate determination of E_s/E is difficult in our calculations since time of the elastic wave formation is much larger than the characteristic explosion time. The calculated values of A_s/E are given in Table 1.

Table 1. Dependence of the work A_s at the boundary r_s upon the DOB

$\overline{H}$, $m/kt^{1/3}$	r_s, / $kt^{1/3}$	A_s/E
15	200	0.0111
3	183	0.0086
2	160	0.0056
1	137	0.0036

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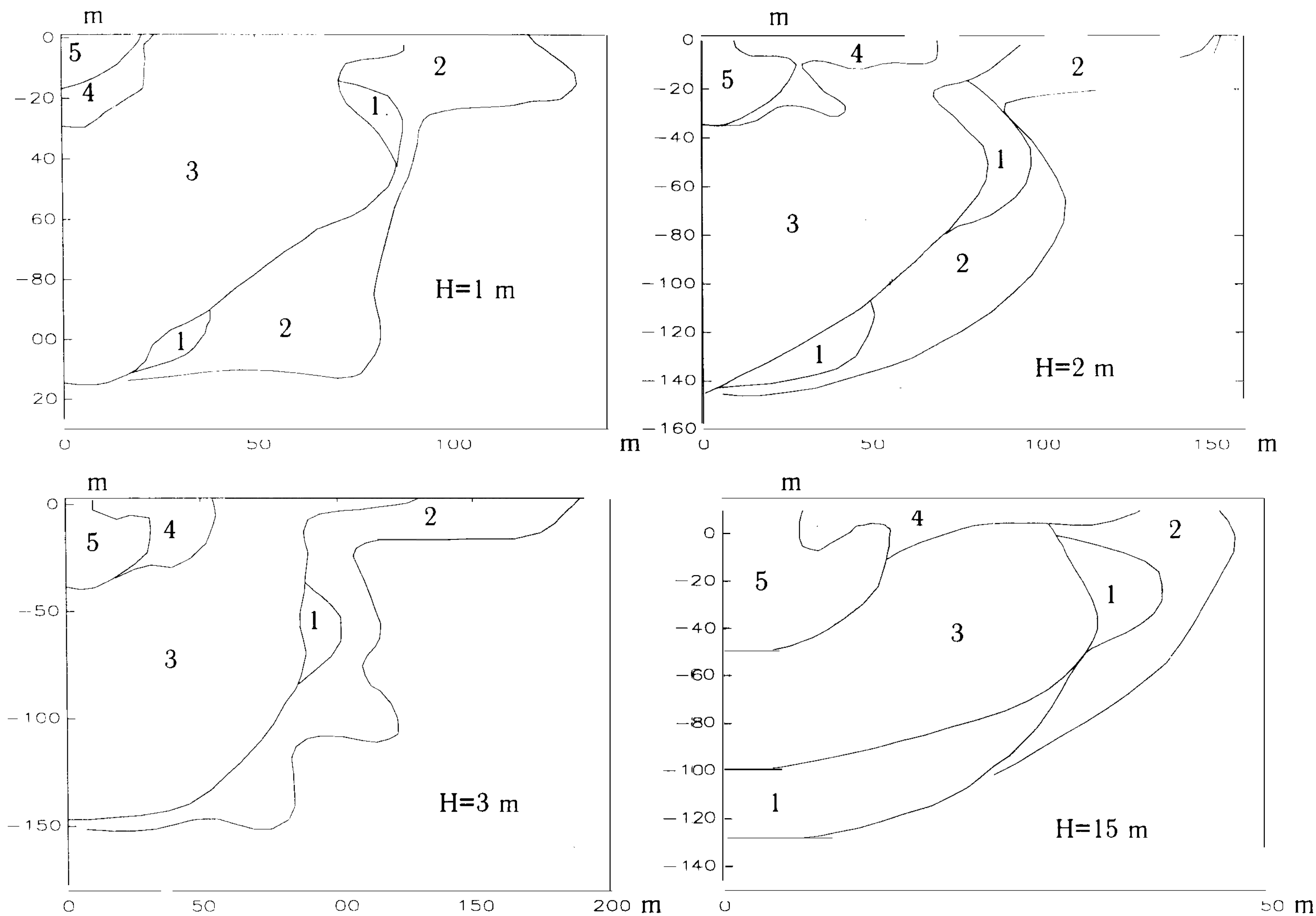

Figure . Configuration of he destruction zones.

Figure 1. Configuration of the destruction zones.

"1" - the fractures of family "1" - the surfaces repeating the front of rarefaction wave (spherical surfaces in the case of spherical symmetry);

"2" - the fractures of family "2" - the surfaces ortoganal to the front of rarefaction wave (radial fractures in the case of spherical symmetry);

"3" - the fractures of two families - "1" and "2";

"4" - the fractures of three families ("1" and "2") - the material is comletely crushed under stretching;

"5" - the material is comletely crushed by shock wave (under compression).

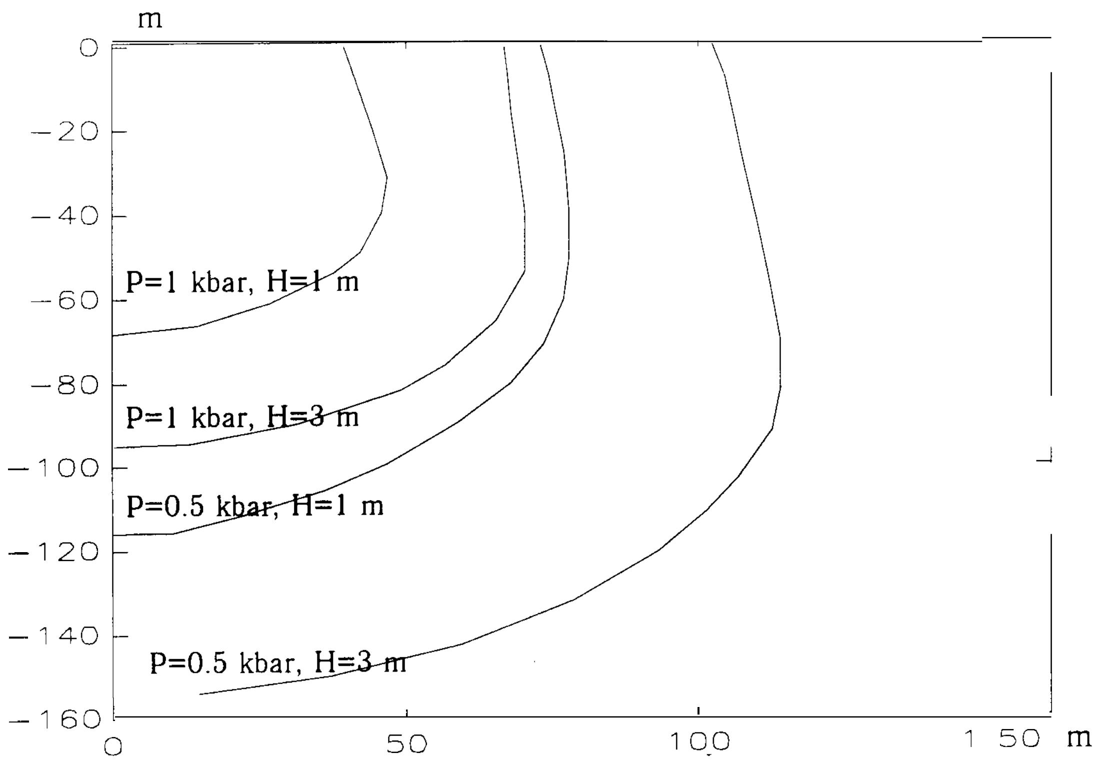

Figure 2. Peak stresses isobars

Experiments

Panel Papers

NEOs Experimental Study: Conventional Missions and Nuclear Thrust Experiments

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The great value for future Space Protection of the Earth (SPE) system will have the long-time exploratory program for direct experimental study of various types of NEO's properties of each object as a whole and of matters constituent of them. Two types of programs for possible space experiments are analyzed. The first one (conventional missions includes flyby, rendezvous, landing, sampling and fly back. The second type consists of exploration of nuclear explosive influence upon the chosen space bodies. Possible programs for both types of experiments are discussed.

The experiments will be targeted on the exploration of near-Earth asteroids (Atons, Appollons and Amours - AAA-objects -AAAO) and those asteroids from the basic belt that may be classified as representative for AAAO. The definite value may have "short-distance missions" to close frequently flyby small asteroids within several distances to the Moon.

Strategy for organization of possible experiments with nuclear pulsed influence upon NEOs is presented. Merits and difficulties of such the program are discussed. Several possible programs for separate nuclear pulsed thrust space experiments are analyzed. Environmental aspects for these experiments are discussed.

The direct NEO's space experimental program should be international. It is advisable to have the International coordinating Center for the program to ensure solving of economic, technical and organizational problems. Great attention has to be devoted to political, social and educational issues. All these aspects are briefly discussed.

The direct NEO's space experimental program will be virtually as an immediate verification of the future Space Protection of the Earth (SPE) system.

Nuclear Explosion Near Surface of Asteroids and Comets: Common Description of the Phenomenon

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Abstract

Nuclear explosion at the NEO, such as asteroid or comet, may have consequences of two main types:

- *disintegrate the NEO into the fragments of such size and impart such velocities on the fragments, that near the Earth the NEO fragments will appear to be at large distances from one another, and will partially pass by the Earth, partially burn in the upper atmosphere without affecting its surface;*
- *without damaging the NEO impart such a momentum, which will change the NEO trajectory and provide its safe passing by the Earth.*

Respectively, two main problems arise, which need to be solved for assessing feasibility of creating the system of the Earth protection on the basis of nuclear weapons and for determination of such system parameters:

- *predict state of the NEO after the nuclear explosion near its surface;*
- *assess the momentum transferred to the NEO as the result of the nuclear explosion near its surface.*

It is possible to influence the NEO by nuclear explosions of different types: buried explosion, surface explosion, and stand-off explosion. Each type has its own peculiarities.

This report considers peculiarities of the three types of nuclear explosions in association with the above formulated problems. A short description of the processes and characteristic parameter values are given. A feasibility of schematizing the phenomena of the surface and buried explosions within the concept of explosion "equivalence" is discussed. Peculiarities of numerical description of the explosions and possibilities to calibrate the numerical methods using the experimental data on underground nuclear explosions and cratering experiments are discussed. The issues of the numerical assessment accuracy are considered and the strategy of the nuclear explosion calculations within the framework of the asteroid problem is proposed.

Introduction

Nuclear explosion at the near-Earth-object (NEO), such as asteroid or comet, may have consequences of two main types:

— disintegrate the NEO into the fragments of such size (<10...30 m) and impart such velocities (>0.1...1 m/s) on the fragments, that near the Earth the NEO fragments will be at large distances from one another and burn in the upper atmosphere without affecting the surface of the Earth;

— without damaging the NEO impart such a momentum, which will change the NEO trajectory and provide its safe passing by the Earth.

Respectively, two main problems arise which need to be solved for assessing feasibility of creating the system of the Earth protection on the basis of nuclear weapons and for determination of such system parameters:

- predict state of the NEO after the nuclear explosion near its surface;
- assess the momentum transferred to the NEO as the result of the nuclear explosion near its surface, i.e. assess velocities at which the NEO fragments will be ejected from its surface.

The NEO can be affected by nuclear explosions of different types: buried explosion, surface explosion, and stand-off explosion. Each type has its own peculiarities both in physical pattern of the phenomenon, and in technical design of respective nuclear module. Without considering the subject of affecting asteroids of complex shape or very large dimensions that may require several consecutive or simultaneous explosions, we would like to discuss the general pattern of single explosion near the asteroid surface, and to discuss experimental and theoretical basis which will enable to find certain engineered solutions.

Below we consider the different types of the nuclear explosions, the determining processes and characteristic parameters.

Underground Contained Explosions

Release of main fraction of energy during the nuclear explosion takes place within approximately one hundredth of a microsecond, and as result of this pressure in nuclear explosive device reaches value of hundreds of megabars (1 bar = 10^5 N/m^2 = 1.02 atm) under temperature of several kev (1 kev = $1.16 \cdot 10^7$ °K).

Density of initially released energy is so high that its transfer occurs mainly by radiant heat conductivity. It results in propagation of thermal wave in the ground [1]. While the dimensions of the region involved in the movement increase, the temperatures decrease, and the flow becomes of purely gasdynamic character. This leads to formation of gasdynamic source determining the subsequent evolution of the explosion. Characteristic energy density in such gasdynamic source is ~10 kJ/g. It can be shown [2] that the processes of the energy transfer by radiation become minor when the ground layers with radius more than 0.2 m/kt$^{1/3}$ are involved into the movement. Beginning from approximately this moment a strong shock is released. While the shock is propagating its intensity is decreasing, and as the result, at different distances from the explosion center zones of evaporation, melting, fragmentation, and fracturing are consecutively formed, and elastic wave (seismic wave) is released.

As it is known [3], development of processes under powerful explosions in infinite uniform medium has similarity. This means that all spatial (cavity radius, radii of the fragmentation and fracturing zones, etc.) and time (time of the cavity formation, etc.) characteristics of the explosion alter with the explosion yield E change proportionally to $E^{1/3}$.

The explosion at sufficient depth doesn't destroy the earth surface. Such explosion is called contained. Without considering some details, such as formation of spall lens on the ground surface, the contained explosions can be regarded as explosions in infinite medium.

Data obtained from underground nuclear explosions comprise and will comprise the basis for calibration of calculation methods for determining effect of nuclear explosion on asteroids due to:

- large number of conducted tests;
- variety of media in which the tests were performed (coral reef, alluvium, rock-salt, limestone, granite, basalt);
- detailed experimentation accompanying the tests.

To such data we refer the following:

- motion laws and parameters of the shock wave (in the region r<5...10 m/kt $^{1/3}$ where the strength effects play minor role);
- parameters of seismic explosion waves in the zone of elastic-plastic flows;
- parameters of irradiated seismic (elastic) wave;
- amount of rock irreversible evaporated in the shock wave (≈70 t/kt);
- amount of rock melted in the shock wave (~500...900 t/kt);
- dimensions of intensive fragmentation zones (~25 m/kt$^{1/3}$);
- dimensions of fracturing zones (~100 m/kt$^{1/3}$);
- distribution of fragments of rock disintegrated in the shock by dimensions;
- dimensions of the formed cavity (from 9..11 m/kt$^{1/3}$ in rock-salt, granite, and dolomite up to 14...17 m/kt$^{1/3}$ in alluvium and tuff).

Experience of the underground nuclear explosions, numerous published and not published calculation results identify that without speaking about physics of nuclear device operation, by now scientists have studied well and with high accuracy described in calculations the equations of state for terrestrial rocks, their elastic-plastic properties, and (by one-dimensional methods) the main parameters of flows appearing during the underground explosions.

It should be pointed out that during the underground nuclear explosions a very intensive fragmentation of rocks takes place [4], and maximum dimensions of the formed rock fragments are ~5 m. This makes us hope that affecting the steroid we'll be able to achieve not only considerable change in its momentum, but also to provide its necessary fragmentation.

Nuclear Surface Explosions

To change the trajectory or to disintegrate the asteroids with diameter exceeding 50...100 m we'll need nuclear device having yield of 1 Mt and more. This proceeds from values of the above given characteristic dimensions of the destruction zones during the underground nuclear explosions. Therefore, we consider the surface explosion of rather powerful nuclear device (thermonuclear) at the height on the order of 1 m.

The ground motion during the explosion near its free surface is determined primarily by the fraction of the explosion energy transferred directly to the ground. In the modern thermonuclear charges the duration of the energy release is on the order of one hundredth of a microsecond [2]. If the device is exploded above the asteroid surface the main part of released energy will be radiated out of the nuclear device in the form of x-rays during a time period of several hundredths of a microsecond. The part of the x-radiation directed downwards illuminates the asteroid surface in the form of short pulse of quanta. This will cause its radiation heating which will be completed within tenths of a microsecond, and this leads to formation of high temperature region of ground having the lens shape.

Temperature in the ground is so high during that (~1 kev) that on one side a thermal wave propagates in the ground, and on the other side, intensive reradiation from the surface into air proceeds. This results in absorption of small fraction of the radiation energy (less than 10%) by the ground. Even less fraction of the energy is transferred to the ground due to impact of the nuclear device vapors. After the thermal wave stops in the ground the shock is released. When the shock propagates through the ground its intensive destruction takes place. Due to rarefaction from the surface the ground moves back, upwards. As the result, the ground mass is thrown upwards at high velocities, and a crater is formed.

Quantitative characteristics and some qualitative peculiarities of the surface explosion phenomenon have been considered in details , e.g. [2, 5]. In particular, it appears to be that:

- fraction of the full explosion energy transferred to the ground depends little on the explosion yield over the range 0.1...10 Mt (at least this value is more sensitive to details of the nuclear device design which, in their turn, determine share of the explosion energy irradiated in the form of x-ray rays, the radiation time and spectrum);
- the fragmentation region has approximate shape of hemisphere with radius ~100 m/Mt$^{1/3}$;
- momentum transferred to the asteroid makes up ~10^8 (t·m/s)•Mt.

Calculations of the surface explosions are most complicated compared to other types of the explosions. This is associated with the necessity to describe large strains during the impact of the nuclear module vapors into the ground and during the ground scattering with simultaneous account for energy transfer by radiation. Besides that, for the surface explosion the approximation of radiant heat conductivity is not always applicable, we need to take into account the spectral effects. For example, temperature of radiation leaving the surface of the nuclear module, and temperature in the heating lens can differ significantly.

A special problem in calculational description of the surface explosions is caused by almost absolute absence of the experimental data. To avoid strong radioactive contamination of the test sites the surface explosions were not conducted during nuclear weapons testing.

Nuclear Shallow Bursts

Effect of the nuclear explosion on asteroid will be the strongest if the nuclear device is buried into the ground before the explosion. This is associated with the fact that during such type of the explosion, unlike the surface and stand-off explosions, the explosion energy at initial (thermal) phase of the phenomenon evolution is transferred to the asteroid ground practically completely. So, at depth-of-burst (DOB) exceeding 2 m/Mt$^{1/3}$ the thermal wave doesn't reach the ground surface, the full energy at the initial stage remains in the ground. At subsequent increase of the explosion depth the depth at which the rarefaction wave from the free surface overtakes the shock propagating downwards also increases. The explosion effect increases respectively. As the result of this process the effect of the buried explosion on the asteroid turns to be equivalent to effect of the surface explosion with yield tens of times higher [2. 5, 6]. Therefore, consideration of affecting the asteroid by the buried explosion is of especial interest.

Apparently, really achievable values of the DOB are within the limits of the first tens of meters. Therefore, using the nuclear modules having yield of ~1 Mt and more the values of the scaled DOB of practical interest for us are 0.2 up to 3...5 m/kt$^{1/3}$ For such depths the characteristic value of momentum transferred to the asteroid will be ~10^9..10^{10} (t·m/s)·Mt. Dimensions of the fragmentation zone will be at least two times larger than the dimensions of the fragmentation zone of the surface explosion of the same yield. For DOBs of 6...8 m/kt$^{1/3}$ radius of the fragmentation zone will exceed the fragmentation radius of the contained explosion, since the rarefaction wave from the free boundary will overtake the shock propagating downward at the distance ~25 m/kt$^{1/3}$, and additional fragmentation will be provided by the spall phenomena in the zone of intensive development of radial fractures.

Unlike the surface explosion the calculational description of the buried explosion initial phase currently is not difficult. At the same time at the phase of the explosion crater development we have to face the problem of adequate description of elastic-plastic flow with large strains.

Experimental data on the nuclear explosions which can be referred to the shallow bursts are rather poor. Table 1 shows the list of all nuclear cratering explosions conducted in the USA and the USSR [7]. From among 16 specified explosions most of them were carried out at depth close to optimum for obtaining maximum dimensions of the crater, but which are of less interest for the asteroid problem. It should be also pointed out that effect of the buried explosions on the Earth is to large extent determined by the gravity influence. This also hampers use of the experimental data for the calibration.

Table 1. Summary of Nuclear Cratering Explosions [8,9]

Name	Yield kt	Depth-of-burst,m	Crater radius, m	Crater depth, m	Medium
Jangle S	1.2	1.1	14	6.4	Alluvium
Jangle U	1.2	5.2	40	16	Alluvium
Teapot ESS	1.2	20	45	27	Alluvium
Neptune	0.115	31	31	11	Tuff
Danny Boy	0.42	34	33	19	Basalt
Johnnie Boy	0.5	0.53	18	9.1	Alluvium
Sedan	100	194	184	98	Alluvium
Palanquin	4.3	85	36	24	Rhyolite
Cabriolet	2.6	52	54	37	Rhyolite
Buggy	1.1	41	76	21	Basalt
Row of 5		spacing 46			
Schooner	35	108	130	63	Tuff
1003	1.1	48	53.5	31	Siltstone
1004	~125	~178	204	100	Sandstone/shale
T-1	0.2	31.4	40	21	Sandstone
T-2	0.2	31.4	32.5	16	Sandstone
Row of 3		spacing 40			
Pechora-Kama	15	~127	150 .. 170	10 .. 15	Alluvium
Row of 3					

On the other hand, we have rich experimental data on the buried explosions of chemical HE. To use these data we need additional calculation efforts. Some of the experimental data on the chemical HE explosions directly identify that hopes for sufficiently accurate calculation description of the buried explosion effect on the asteroid may not come true, especially taking into account our limited knowledge on properties of a specific NEO we'll need to affect. So, in the classical review [6] it is pointed out that the most numerous data on explosions of a given yield and in a given ground were obtained in the experiments with 256-pound spherical charges of TNT in alluviums of Nevada Test Site and Albuquerque Test Site. It turned out that volumes of the craters at a given depth changed from one experiment to another by the factor of 2...3. and systematic deviations associated with the test site difference turned to be less than deviations within each test site. This may mean that the experimental data on the craters under conditions of limited knowledge of the ground properties can't be the serious basis for the numerical method calibration, at least, while computing such characteristic as the momentum transferred to the asteroid. This conclusion is also confirmed by characteristics of the craters of the nuclear explosions Jangle S and Johnnie Boy.

During the buried nuclear explosion, as during the contained explosion, a very intensive fragmentation is provided. Table 2 gives some data on dimensions of rock fragments formed during explosions [8,9]. These data show that by nuclear explosions we can provide disintegration of asteroids into fragments with dimensions sufficient for their burning in the Earth's atmosphere.

Table 2. Dimensions of Rock Fragments Formed During Nuclear Cratering Explosions [8,9]

Name	Medium	Yield, kt	Minimum size, m	Medium size, m	Maximum size, m
Sulky	Basalt	0.085	0.03	0.55	4.0
Danny Boy	Basalt	0.42	0.006	0.36	1.8
Palanquin	Rhyolite	4.0	—	0.1	—
Cabriolet	Rhyolite	2.6	0.015	0.061	1.2
Schoolner	Tuff	35	—	0.6	6.0

Stand-off Nuclear Explosions

The nuclear explosion at rather large altitude over the asteroid surface turns to be also effective. This is associated with absence of air which under terrestrial conditions causes transformation of high temperature radiation from the nuclear device into relatively low temperature radiation in air thermal wave.

As the stand-off explosion we call the explosion during which the thermal wave propagation in the asteroid matter is weak or absent, and the reradiation is minor. Such explosion mode is realized when the explosion height exceeds approximately 10 $m/Mt^{1/3}$.

During the stand-off explosion the x-ray radiation from the nuclear module surface falls onto the asteroid and heats up the surface layer. This causes corresponding gasdynamic phenomena: scattering of evaporated surface layer accompanied by the shock propagation and scattering of partially evaporated and disintegrated matter. It is evident that selecting the explosion height at a given yield of the nuclear device we can achieve the situation when initial temperatures of the surface layer are sufficiently small to exclude the reradiation from the free surface. Respectively, we can achieve higher explosion energy withdrawal by the asteroid ground than in the case of the surface explosion.

The processes during the stand-off explosion can be illustrated by simple estimates. If the ground heat conductivity and the reradiation are not significant, then in the problem of dissipation of gas having density at instantaneous energy release in a layer with characteristic thickness z there are two dimensional parameters:

$$[\varepsilon]=kJ/cm^2,\ [\rho]=g/cm^2,\ [z]=cm,$$

out of which we can compose the only combination with the momentum dimension:

$$I = \xi\sqrt{2\varepsilon\rho z}$$

Accounting for the evaporation energy q which is near 4 kJ/g for silicate rocks, this expression will become the following:

$$I = \xi\sqrt{2(\varepsilon - q)\rho z}.$$

From this simple expression we can make several important conclusions on the character of the momentum change with increase of the incident radiation intensity and the thickness of the heated layer. In particular, it is easy to show, the momentum depends upon the angle of the incident radiation as $I(\beta) = I(\beta = 0)\cdot \cos\beta$. The latter expression is confirmed with high accuracy (~1%) by numerical calculations [11].

In the case of small energy release when the momentum withdrawn by initially evaporated matter significantly exceeds the spall momentum the problem under consideration can with some approximation be reduced to the problem of the gas layer dissipation near a rigid wall at instantaneous uniform energy release. This problem has an analytical solution according to which ξ depends little on the gas adiabat index γ and makes up $\xi \approx 0.8$ [10].

In the case of higher energy release we need to take into account additional evaporation of matter in the shock and the spall momentum, and it is possible to obtain appropriate estimates only within the framework of numerical calculations, though the similarity ideas mentioned above remain in force.

Thus, increase of momentum transferred to the asteroid during the stand-off explosion can be achieved by increasing the energy release in the surface layer (owing to increase of the radiation flow intensity), increasing thickness of this layer (e.g. by changing spectrum of the incident radiation), and increasing area of the asteroid irradiated surface (increasing the explosion height). It is evident, that for each specific asteroid and the specific nuclear module we'll have a certain optimal (in terms of maximum effect) explosion height.

Thus, the problem of computing the x-ray radiation effect of the stand-off explosion on the asteroid involves determination of density of energy released in the surface layer and determination of formed gasdynamic flows at different levels of the radiation. For the stand-off explosion above the asteroid due to relatively small (compared to the asteroid dimensions) thickness of the layer in which the gasdynamic processes develop, the calculations can be done in one-dimensional approximation (with account for the radiation incidence angle). Currently it is not difficult to carry out such calculations.

While considering effects of the stand-off explosion on an arbitrary asteroid, unlike the surface explosion and shallow burst, we are faced with a purely engineered problem of results representation associated with the multi-parameter character of the problem. The effect on the asteroid, besides the explosion yield, height, the asteroid dimensions, will significantly depend upon its shape, chemical composition, density, strength, spectrum of radiation released from the nuclear module. And what's more, even such details as presence of a thin layer of dust on the asteroid surface will significantly influence the value of the momentum transferred to the asteroid. For example, the numerical calculations showed [11] that at values of full flow of the incident radiation of 10^4 kJ/m^2 up to 10^6 kJ/m^2:

- the spall strength change by an order causes change in the momentum by several times;
- at porosity of 30% the momentum decreases several times compared to the rock with zero porosity.

Therefore, to take effective engineered decisions while considering the issues of the Earth protection against asteroids we need to develop a set of typical asteroid models, and compute effects of the stand-off explosion for them

According to the above, in this report we only consider several parameters. Table 3 shows characteristic values of the momentum during the silicate rock surface irradiation by normally incident flow of x-rays of nuclear explosion of Planckian spectrum with temperature T_{eff} for several values of the full flow [11].

In the case of the stand-off explosion with the yield of 1 Mt above the asteroid having the spherical shape with radius 750 m the momentum transferred to the asteroid will be maximum at the height ~200...250 m and will be equal to ~$4\cdot10^6$ t·m/s for T_{eff} = 3 keV, ~$30\cdot10^6$ t·m/s for T_{eff} = 15 keV and ~$60\cdot10^6$ t·m/s for T_{eff} = 30 keV. The latter value is close to the value of momentum transferred to the asteroid during the surface nuclear explosion of the same yield.

Table 3. Momentum (t/m·s) transferred to the silicate rock surface during its irradiation by normally incident x-rays of planckian spectrum with temperature T_{eff}

Full flow kJ/m^2	T_{eff} = 3 keV	T_{eff} = 15 keV	T_{eff} = 30 keV
10^4	~0.5	~0.9	~0.6
10^5	~2	~9	~10
10^6	~8	~60	~100

Conclusions and Discussion

The nuclear explosion phenomenon has been studied pretty well both from the theoretical and experimental points of view. A great progress has been achieved in the sphere of mathematical simulation of the processes taking place during the nuclear explosion. However, this doesn't mean that we can predict result of the explosion near the asteroid surface with high accuracy. This is associated with two circumstances:

• the process of nuclear explosion near the asteroid surface has a number of specific peculiarities which we practically haven't come across during the underground nuclear testing under terrestrial conditions;

• physical properties of material composing the asteroids are practically unknown for us, or known with very high error (for brevity we'll subsequently call the matter of the asteroid or comet, the asteroid ground, or just the ground).

However, the situation is not so bad as it may seem at first sight. The accumulated experience of the underground nuclear testing allows us to state that we know rather well and describe with calculations the properties of terrestrial grounds and propagation of the shock under sufficiently high pressures — up to amplitudes corresponding to the ground destruction.

Using the nuclear explosions we can provide very intensive effect on the asteroids. In this case the most intensive will be the buried explosion effect. The surface and stand-off explosions provide approximately the same effect from the standpoint of momentum transferred to the asteroid. The surface explosion provides more intensive fragmentation of the asteroid than the stand-off explosion.

From the standpoint of numerical simulation it is most easy to describe the stand-off explosion, and the most complicated are the surface explosions. The most valid numerical estimates of affecting the asteroid can be obtained for the buried explosion, the less valid — for the stand-off.

As a whole, under conditions of the limited knowledge of a specific asteroid properties assessment of the necessary yield of the nuclear module may change by several times depending upon the proposed parameters of the asteroid ground. Respectively, from the engineering point of view, to provide the guaranteed achievement of the effect the yield of the nuclear module must be somewhat excessive.

Schematizing Nuclear Explosion Phenomenon (Engineered Approach) and Possible Directions of Future Research

To take engineered decisions it is expedient to have a single approach to at least some part of the above described types of the explosions. Such a single approach as applied to the asteroid problem is possible if we somehow schematize the phenomena of the surface and buried explosions.

Then, within the framework of the asteroid program we'll be interested in processes of the shock propagation in the ground, the crater formation and the ground ejecta. At any type of the nuclear explosion at the asteroid we can separate a main region of effective energy release with energy E_g:

- the region heated through by the thermal wave at the buried explosion;
- the lens of heating and the nuclear charge vapors at the surface explosion;
- thin layer of the ground of a large area in the case of explosion at a considerable height above the asteroid surface.

Therefore we may introduce some coefficient $\eta_t(E_o,H,C)$, such as $E_g = \eta_t E_o$. Subsequently we'll call this coefficient the coefficient of thermal phase equivalence.

We can conveniently schematize the phenomenon at the phase of gasdynamic and elastic-plastic movement using the dimension theory. Select dimensions of mass M, length L, and time T as the basis. Designate the parameter A dimension, as it is commonly used, with the symbol [A]. After completion of the processes of energy transfer by radiation the explosion evolution near the surface of uniform semi-space will be determined by the following system of dimensional and dimensionless parameters:

E_0 - is full energy released during the explosion $[E]=ML^2T^{-2}$;

E_{gi} - full energy of the i-th region of effective energy release in the scheme of the phenomenon development assumed by us, and which corresponds to completion of the thermal phase of the explosion evolution (the full energy of the i-th gasdynamic source) $[E]=ML^2T^{-2}$;

r_{gi} - is characteristic dimension of the i-th region of the effective energy release corresponding to completion of the thermal phase $[r_{gi}]=L$;

H - is depth of the explosion $[H]=L$;

ρ_{oo} - is the ground density $[\rho_{oo}]=ML^{-3}$;

c_o - is characteristic sound velocity, e.g. dimensional parameter in the equation of state $[c_o]=LT^{-1}$;

ρ_o - is characteristic density, e.g. dimensional parameter in the equation of state having the meaning of the grain density $[\rho_o]=ML^{-3}$;

γ_i - are adiabat indices for the material of the i-th region (dimensionless);

c_p - is velocity of elastic p-waves $[c_p]=LT^{-1}$;

ν - is Poisson's coefficient (dimensionless);

k - is coefficient of internal friction (dimensionless);

Λ - is dilatance rate (dimensionless);

Y_o, σ_o - are strength limits for compression and destruction, and their analogs under conditions of plasticity and destruction $[Y_o]=[\sigma_o]=ML^{-1}T^{-2}$.

For terrestrial conditions we must also include another several parameters, such as acceleration of free fall g, initial air pressure, etc., which play a certain role at various phases of the explosion.

Select as the basis parameters the explosion energy E_0, characteristic sound velocity c_0, and characteristic density ρ_o. It is known [3] that out of the selected parameters we can formulate the only combinations with dimensions of length and time:

$$R_d = \left(\frac{E_0}{\rho_o c_o}\right)^{1/3}, \quad td = \frac{1}{co}\left(\frac{E_0}{\rho_o c_o}\right)^{1/3}$$

Respectively, any characteristic of the explosion evolution A will be the function of the dimensional parameters and dimensionless combinations:

$$A = [A] \cdot f\left(\frac{r}{R_d}\ \frac{t}{t_d}\ \frac{H}{R_d}\ \frac{r_{gi}}{R_d}\ \frac{E_{gi}}{E_0}\ \vartheta\ \ C\right),$$

where [A] is the combination of the basis parameters with dimension of A; r, ϑ -are spherical coordinates (we assume the flow being axisymmetric), and the set C includes all the other parameters:

$$\frac{\rho_{00}}{\rho_0}, \quad \frac{c_p}{c_0}, \frac{\sigma_0}{\rho_0 c_0^2}, \nu, \frac{Y_0}{\sigma_0}, \gamma, \text{ etc.}$$

Now consider some radius R_h corresponding to some characteristic pressure, or the shift value, or the shift rate at the shock front:

$$R_h = \left(\frac{E_g}{\rho_0 c_0^2}\right)^{1/3} \cdot f\left(\frac{H}{R_d}, \frac{\rho_g}{R_d}, \vartheta, C\right),$$

where f has the meaning of the dimensionless radius and , generally speaking, for the characteristics interesting for us, it is much more than one. Consider

$$\ln f = \ln f(0,0,\vartheta,C) + \frac{\partial f}{\partial \bar{H}}\frac{\bar{H}}{f} + \frac{\partial f}{\partial \bar{r}_g}\frac{\bar{r}_g}{f} + 0\left(\frac{\bar{H}}{f}\frac{\bar{r}_g}{f}\right),$$

where $\bar{H} = H/R_d$, $\bar{r}_g = r_g/R_d$.

Ignoring the terms of the second order, we obtain the following:

$$f = \phi(\bar{H}, \bar{r}_g, C) \cdot f_0(\vartheta, C).$$

Introduce the following designations

$$\eta_g = \phi^3, E_{eff} = \eta_g E_g = \eta_t(E_0, H, C) \cdot \eta_g(\bar{H}, \bar{r}_g, C) \cdot E_0 = \eta \cdot E_o$$

Then

$$R_h = \left(\frac{E_{eff}}{\rho_0 c_0^2}\right)^{1/3} f_0(\vartheta, C) .$$

Thus, if $H \ll R_d$, $r_g \ll R_d$, then beginning from some moment of time details of the gasdynamic source are forgotten, and the flow similarity of a new type is formed, when the solution can be presented in the form:

$$A = [A] \cdot F\left\{\frac{r}{R_{eff}}, \frac{t}{t_{eff}}, \vartheta\right\},$$

where

$$R_{eff} = \left(\frac{E_{eff}}{\rho_0 c_0}\right)^{1/3}, \quad t_{eff} = \frac{1}{c_0}\left(\frac{E_{eff}}{\rho \rho_0 c_0}\right)^{1/3}, \quad E_{eff} = \eta \cdot E_e, \eta = \eta_t(E_0, H, C) \cdot \eta_g(\bar{H}, \bar{r}_g, C).$$

Thus, despite of the significant differences in the initial phase, the gasdynamic flows of the ground during the surface explosion, explosions at small enough depth and height possess the geometrical similarity with some coefficient proportional to $E_{eff}^{1/3}$, where E_{eff}, is the explosion effective energy determined in a special manner. In such form the last expression is the expression of "the principle of equivalency" [5, 12]. This principle states that the explosion having yield E_1 at some scaled depth $\overline{H}_1$ is equivalent to the explosion having yield E_2 at the scaled depth $\overline{H}_2$ by the flow parameters at large distances.

For the explosions at some depth the moment of the beginning of the approximate geometrical similarity realization is determined by time of rarefaction wave arrival from the free surface, and respectively, by the explosion depth. In particular, if , $H \ll R_d$, the similarity establishes at the gasdynamic phase of the explosion evolution when the strength properties of the medium are practically insignificant. If the explosion depth H exceeds R_d by several times the flow similarity won't be observed.

The described similarity of the explosions is really observed in the numerical gasdynamic calculations. This means that detailed calculations of the nuclear explosion with account for elastic-plastic properties of ground can be carried out for several classes of grounds (e.g. strong rock with density , $\rho \sim 2.7$ g/cm^3, soft ground with density $\rho \sim 2$ g/cm^3, ice) at some given yield and rather small depth of the explosion. The explosions at other depths can be described, having determined values of the coefficient η on the basis of gasdynamic calculation of the initial phase only.

To carry out such comparison it is convenient to use calculations of powerful explosions at the depth of ~2 m/Mt$^{1/3}$ taking such an explosion as a bench-mark. In this case the initial phase of the explosion requiring the energy transfer by radiation is of one-dimensional character and is easy for being described. At the same time, the chosen depth is significantly less than the dynamic radius for the grounds R_d~40...50 m/Mt$^{1/3}$, and the flow phase corresponding to the geometrical similarity is established quickly enough.

When the asteroid hits the ground surface at sufficiently high velocity we may also expect the similarity of the formed flow with the flow in the case of the nuclear explosion at small depth. This will enable, after computing the value η for the asteroid impact, to use the earlier obtained results of calculations and experiments for the nuclear explosions.

In our opinion, a possible direction of work in the sphere of physics of nuclear explosion effect on the asteroids and comets can be computation of coefficient η for several typical asteroid models (which must be developed). Such work will enable to coordinate the efforts of physicists and mathematicians from different laboratories and to provide engineers and designers with the tools necessary for developing the basic characteristics of the system of the Earth protection against the near-Earth-objects. RFNC-VNIITF plans to do some part of this work within the framework of the International Science and Technology Center.

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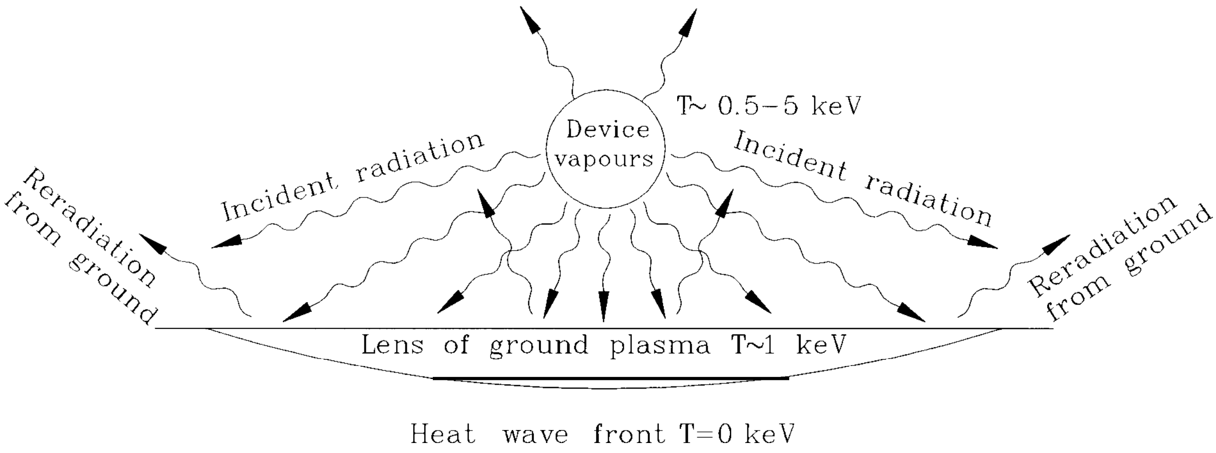
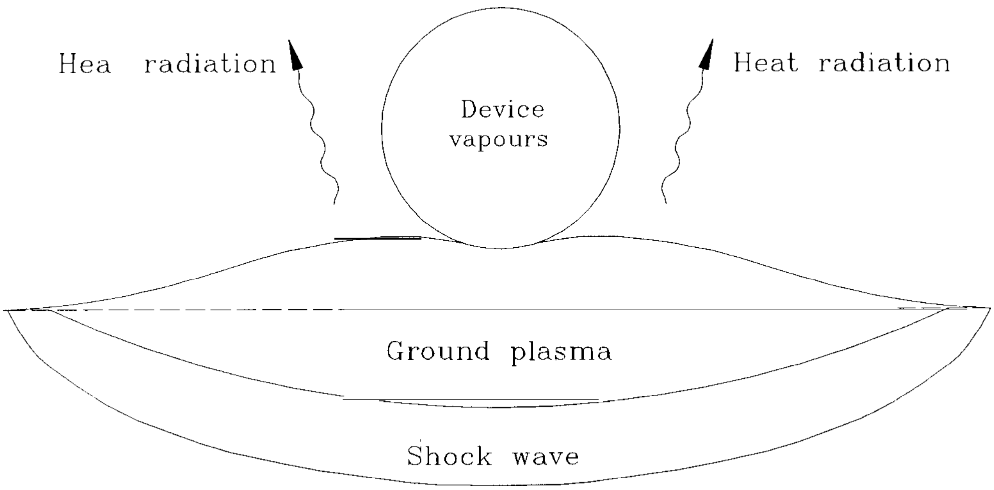
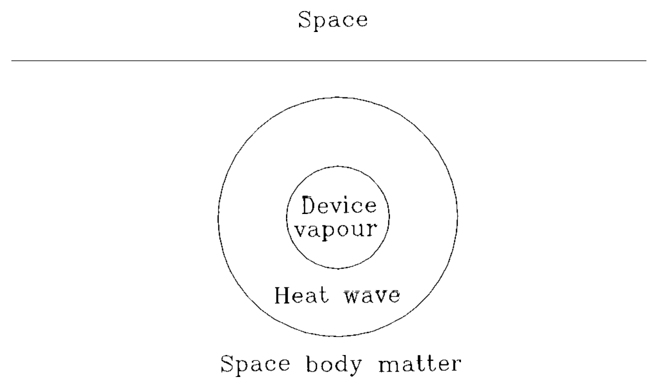


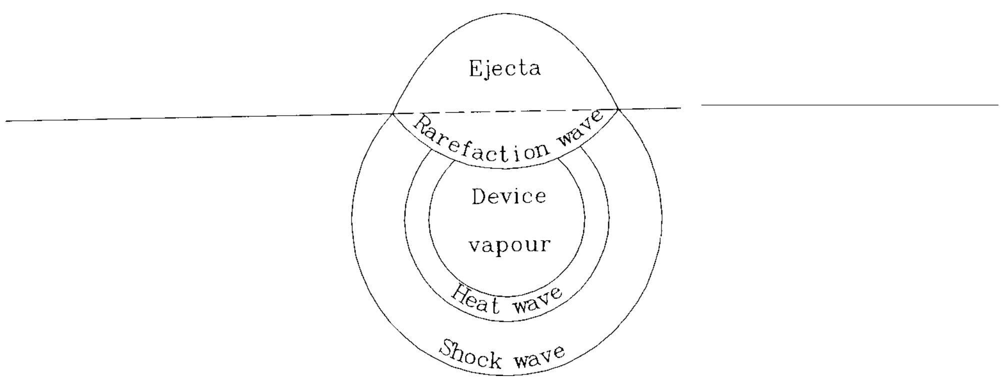
X– ray and heat wave stage



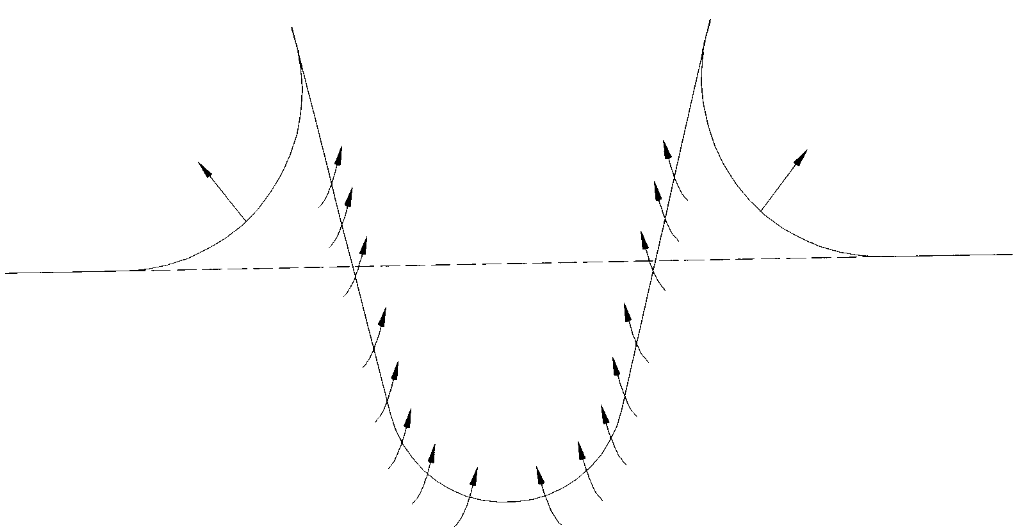
Stage of shock wave formation



Heat wave stage

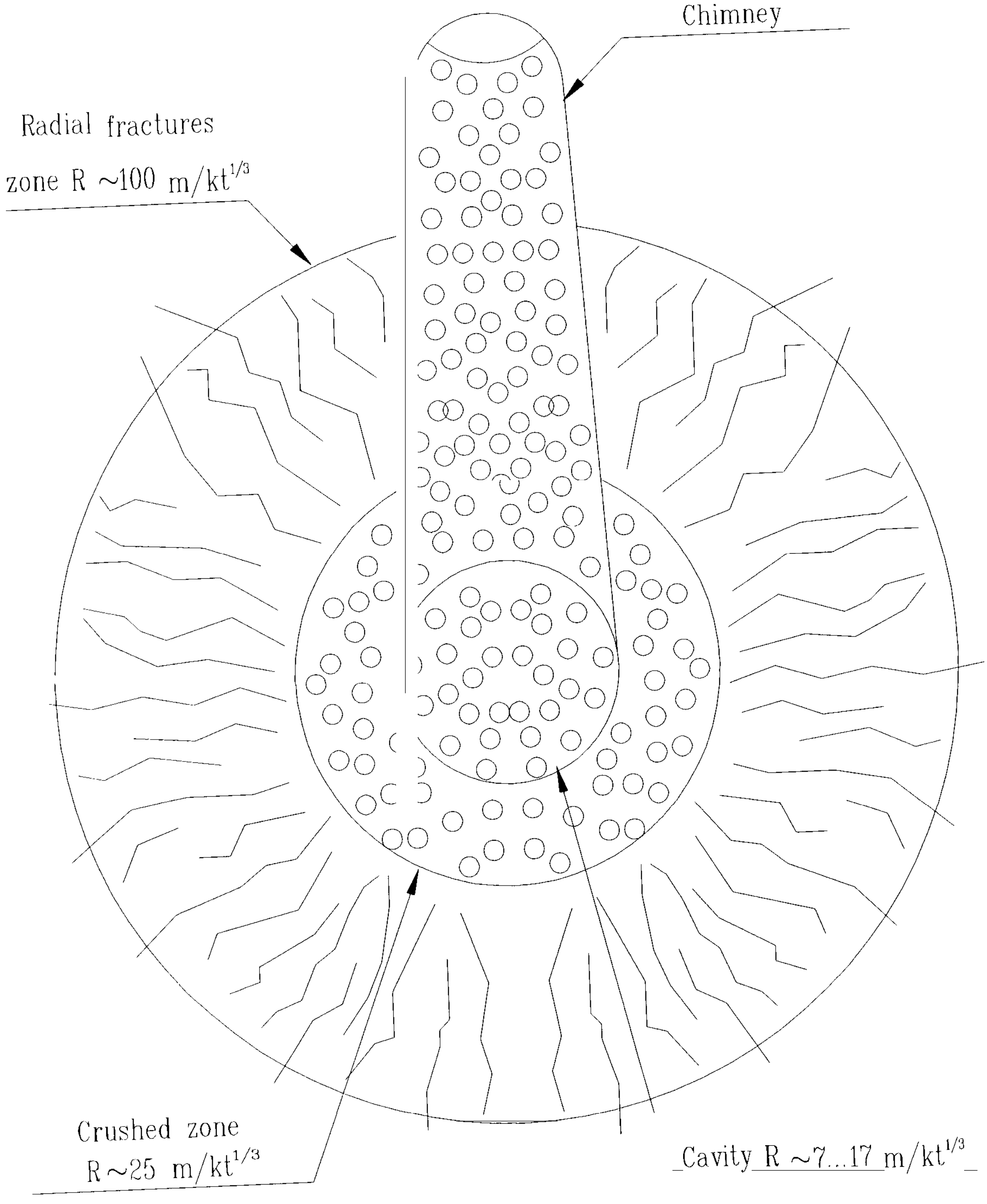


Shock wave stage



Stage of cratering formation

EFFECT OF THE UNDERGROUND NUCLEAR EXPLOSION



Near-Earth Asteroid Rendezvous Mission

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F. A. Allahdadi
US Air Force Phillips Laboratory

We propose an extremely quick and inexpensive asteroid rendezvous mission in near-Earth space using existing off-the-shelf technology which would allow nations of the world to start learning about cooperatively detecting, characterizing, and mitigating approaching asteroid impact threats. A solid-fueled space launch vehicle would be on standby status with a small, smart, lightweight spacecraft in the payload compartment. Once notified by an electronically connected net of worldwide astronomers of an asteroid on a verified close approach to Earth, the rocket would be quickly prepared and sent on a rendezvous trajectory with the approaching body. The spacecraft would conduct either an instrumented fly-by or a penetration of the body, while collecting and transmitting real-time scientific data. Radars, telescopes, and antennas on Earth would observe the rendezvous and gather data from the encounter. Technical details of the rendezvous mission are given, along with the scientific and mission-specific data to be collected and the types and levels of understanding to be derived from each. Three-dimensional calculations of an example penetration mission using the SPH hydrocode are also shown.

Introduction

Compelling evidence of a catastrophic asteroid impact on the Earth 65 million years ago (Alvarez et al., 1980 and Sharpton and Ward, 1990) has given rise to international discussions about the probability and prevention of future impacts. As a result of several recent near-misses (Morrison, 1992 and Scotti et al., 1991) and the comet Shoemaker Levy-9 impact of Jupiter in July 1994, considerable international attention has focused on defining the impact threat and determining potential hazard mitigation defense schemes for the protection of Earth against planetesimal impacts (Tedeschi, 1994). Protection of Earth from comet and asteroid impacts is something that has been discussed over the past decade or so, but which has never been seriously considered until recently. This paper offers a proposed approach for nations to learn how to conduct a cooperative, quick, low-cost NEO rendezvous mission.

We assume that rocket-delivered mitigation technologies will be the defense option of choice in the near-term, and ignore the promising potential of longer-term mitigation technologies, like directed energy mitigation technologies beamed directly from Earth to an approaching body. Initial studies indicate that hypervelocity impact is one of several favorable schemes for mitigating the possibility of Earth-impact by such bodies (Canavan et al., 1992; Tedeschi, 1995; and Wood et al., 1995). A desirable characteristic for a kinetic energy impact would be to deflect the approaching body into a new, non-threatening trajectory by a momentum transfer process. However, fragmentation of the body into numerous pieces is to be avoided since some of the resultant debris might still be on an Earth-impacting trajectory, although this may be a desirable approach against smaller NEOs, or the option of last resort if the warning time is short and no other mitigation options exist. See Tedeschi, 1995 and Wood et al., 1995 for more details on the applications of kinetic energy to deflect or fragment NEOs.

While there are some data on the fragmentation of Earth-derived planetesimal-type materials, e.g., basaltic rocks (Fujiwara et al., 1977) and ice (Kawakami et al., 1983), literally nowhere can one find experimental data on momentum deposition into such materials due to hypervelocity kinetic energy impacts. Tedeschi et al., 1994 contains world-unique data in this regard. Of course, planetary geophysicists have been studying this type impact phenomena for years, but they can only infer the full-scale response of large asteroids to massive kinetic energy impacts (Housen and Holsapple, 1990). Simulating the macroscopic change in momentum of such bodies is difficult to do using modern shock-physics computational codes, e.g., hydrocodes, mainly due to inherent numerical limitations (Anderson, 1987). Therefore, a critical need exists to not only obtain well-characterized hypervelocity impact test data from actual sub-scale NEO materials or NEO material analogs for code calibration purposes, but also to conduct asteroid impact experiments in space to affect full-scale target response observational opportunities. There is no other apparent way to obtain detailed in-depth material property data, energy coupling, and structural response characteristics of NEO bodies due to kinetic energy impacts, or any other mitigation technology for that matter, in the absence of full-scale rendezvous tests. Spacecraft flybys can collect information on NEO dynamic, geometric, and surface mineralogical characteristics. Spacecraft sample return missions provide opportunities to additionally characterize surface and nominal subsurface materials, while seismic probings would provide some additional detail on first-order internal structural characteristics, but not about how the body would actually respond to an actual impact. Large-scale testing in space appears to be the only alternative. Some would argue that every NEO target may be different. This may be so, but having one or two, well-characterized, full-scale data points would be much preferred.

The scientific endeavors associated with geophysical planetary evolution would also benefit directly from the proposed NEO rendezvous mission. Hypervelocity impact interactions and their related catastrophic effects have traditionally been invoked as the major plausible mechanism that determines the mass spectra and velocity dispersions during planetary accretion and fragmentation (Hartmann, 1978). Modeling such impact interactions can be very complicated, especially when either the target or impactor are composed of natural materials which in many cases are inhomogeneous assemblages of minerals with faults, inclusions, grain and phase boundaries, and other imperfections which complicate the material response. The response of such materials to hypervelocity impact spans a wide range of material behavior, ranging from high impact temperatures and pressures, where hydrodynamic motion and thermodynamic effects predominate, to the low pressure regions where the mechanical properties dominate the process. In order to simulate such processes using sophisticated computer models it becomes necessary to understand the fragmentation effects of hypervelocity impact on related inhomogeneous targets through experimentation over a range of loading conditions, velocities, and target and projectile scale and materials. Results from such experiments can then be used to test and validate computer models for the simulation of planetary interaction processes.

Why a quick asteroid rendezvous mission?

The end of the Cold War has allowed some nations of the world to focus more attention on common global threats to humankind, e.g., global warming, ozone depletion, and, of course, the threat of NEO impacts. The proposed quick asteroid rendezvous mission would allow interested nations to begin the process of learning how to solve the NEO impact hazard through multinational multidisciplinary teaming and cooperation. Conducting such a mission would also allow various scientific disciplines the opportunity to learn more about NEOs and the role they have played in the origin and evolution of our solar system and Earth and the dynamics of the current space debris environment.

What we would learn

There are a number of things we would learn by conducting this specific asteroid rendezvous mission. In the area of impact threat detection we would be creating added emphasis for astronomers and military observers to spot, track, and catalog near-Earth objects. In the case of a promising candidate NEO detected to be on a close-approach trajectory to Earth, we could then exercise a worldwide network to provide warning to all concerned. In the area of scientific discovery we would all be richer because of the increased understanding of small NEOs which would result. We would be able to learn more about their composition and structure; their cratering record; and perhaps even insights into how they were formed. With regard to mitigation, or actual defense of the planet, we'd first and foremost learn about how to conduct a mitigation mission, which is no easy undertaking (Tedeschi, 1994). More specifically, we'd learn how to do planning, build smart maneuverable spacecraft payloads, survive the harsh environments of space, acquire the rapidly approaching NEO target, do terminal homing, impact the target or deposit the mitigation technology in some stand-off mode of energy deposition, and deposit energy and create a useful deflection or fragmentation response in the NEO. Perhaps most importantly we would learn more about international teaming and cooperation to solve this long-term, albeit low probability - but high consequence, threat to humankind.

Asteroid targets of opportunity

Using existing Earth-impacting NEO fluxes (Morrison, 1992 and Tedeschi, 1994), we estimated to first-order the NEO flux in the near vicinity of Earth (within the Moon's orbit and reachable by rockets in a short period of time) by simply ratioing the cross-sectional area of some window of rendezvous opportunity to the cross-sectional area of Earth. For this example, we assumed a window of rendezvous opportunity of radius 120,000 km from the center of

Earth. The estimated flux of NEOs through this window of opportunity compared to the Earth-impact flux is shown in Fig. 1. As can be seen, there are perhaps a few dozens of rendezvous opportunities each year of 5-10 m diameter-sized NEOs passing within this window. Of course, warning of their approach would have to be timely to allow launch preparations, mission planning, launch of a rendezvous spacecraft, and transit time to the approaching NEO. Approximately 24-30 hours minimum warning would be needed, although current warning times are less than this, approximately 1/2-day (Scotti et al., 1991 and Gehrels, 1995) for this class of NEOs. So the NEO rendezvous targets of opportunity exist, what remains is to enlist the astronomers to detect and provide early warning of their approach.

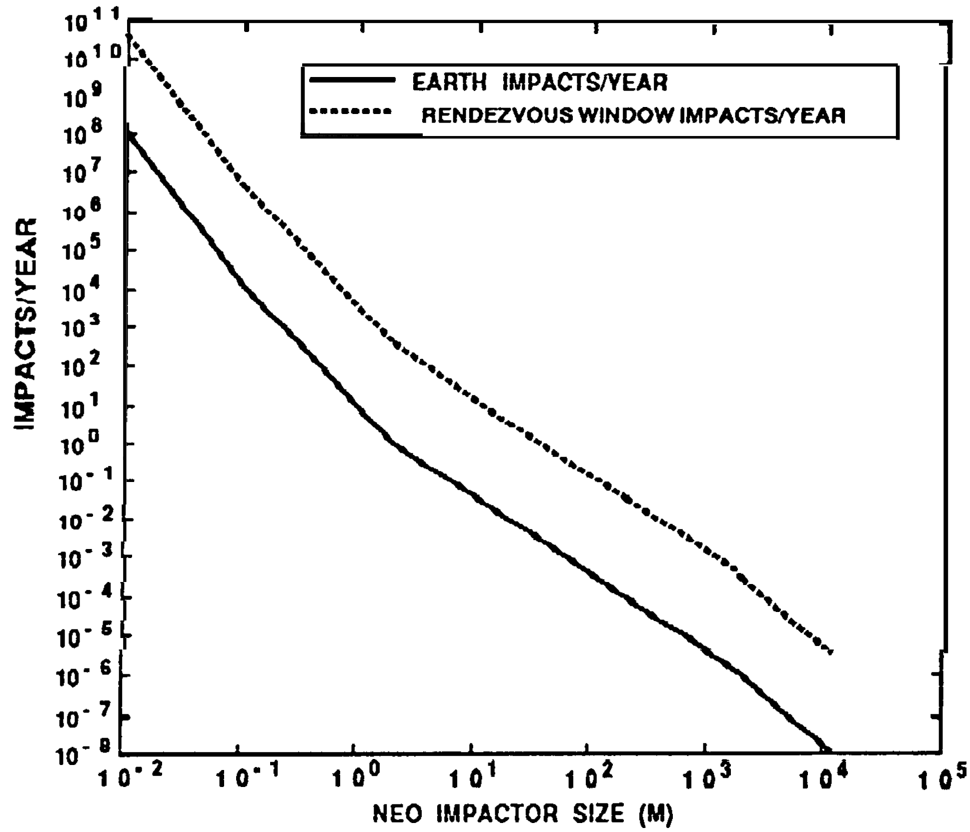

Figure 1. NEO impact flux comparison to Earth versus a 120,000 km window of rendezvous opportunity centered about the Earth.

Astronomers provide early warning

Early warning of a close-approaching asteroid would be provided by a world-wide network of electronically connected astronomers and military observation sites. The Internet could be used effectively to alert others of an apparent close-approach NEO discovery. The current approach for reporting new NEO discoveries to the IAU's Minor Planet Center appears to be a good model for a central clearinghouse to receive and disseminate information. Other existing rapid communication systems might also be used. Other observers in the approaching nighttime sector would then follow-up with optical and radar tracking to obtain a more accurate trajectory assessment. The very initial early warning would also allow the launch site to begin preparations for launch. Ground-based telescopes (see Fig. 2) would be used for the initial detection of approaching NEOs, with follow-up astrometric tracking provided by ground-based radars (see Fig. 3). The example NEO used in this study was the December 9, 1994 asteroid XM1 discovery by the University of Arizona Spacewatch group (Gehrels, 1995). An Apollo (carbonaceous) asteroid estimated to be 6-13 m in size and 30 km/sec in relative approach velocity passed within 105,000 km of Earth. It was detected only about 12 hours before closest approach. Using this as the target we sized an approximate mission (timeline, trajectory, and spacecraft) to rendezvous with the target in about one day's time.

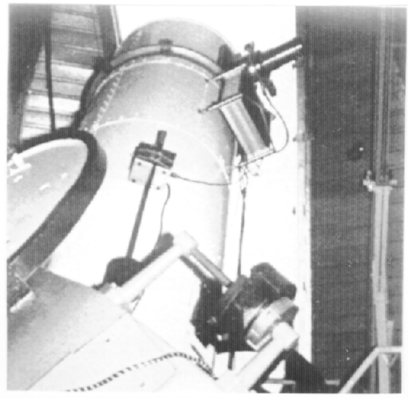

Figure 2. Spacewatch 0.9 m scanning CCD telescope.

Figure 3. NASA-JPL 70 m deep-space Goldstone radar.

Use a solid rocket booster with a smart rendezvous package

It is proposed for discussion purposes that the Russian Start 1 (SS-25) booster (see Fig. 4) be used as the launcher for a specially designed and built spacecraft, the front of which could be the smart and small LEAP rendezvous package (see Fig. 5). The Russian Start 1 rocket is being developed as a low-cost, low-end commercial spacecraft launcher (Covault, 1995). Once fully developed, its 4 stages are estimated to have the ability to place a 370 kg payload into a 500 km, low-inclination Low-Earth Orbit (LEO). We selected this booster because of its relatively low $/kg LEO delivery capability. The spacecraft payload would consist of an orbit transfer motor (to go from LEO to a rendezvous trajectory), an observer package (with scientific instruments), and the LEAP vehicle.

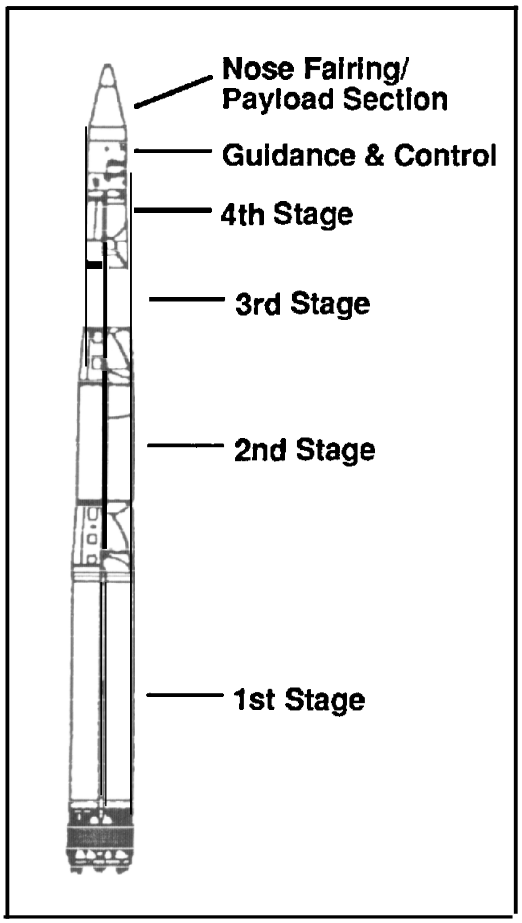

Figure 4. Russian Start 1 Launcher.

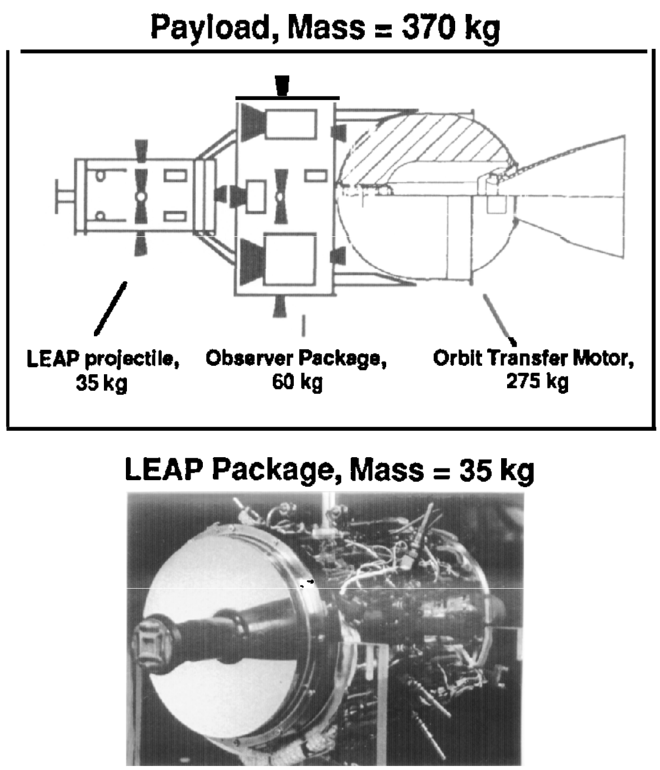

Figure 5. Spacecraft payload diagram and LEAP.

Launch preparations, flyout trajectory and rendezvous location

The launch site would be notified as early as possible of an approaching NEO rendezvous target of opportunity. Because of the short timelines, the amount of prep time for the launcher and payload could be as short as 4 - 8 hours, thereby necessitating maximum payload readiness at all times. This would undoubtedly require on-site technicians to check the payload and booster every few days or so during the perhaps 2 - 4 month wait for a NEO target of opportunity. Once the warning is received, a final check-out of the payload subsystems states-of-health would be made, followed by mating with the booster (or it may already have been mated with the booster), assent shroud attachment, and preparations for launch. The complete rendezvous mission profile would also have to be calculated on-site and then loaded into the booster as part of the preparation phase. The launch should be done from a low latitude (< ≈ 30°) site, such as either Kourou, French Guiana (5.5° N) or Cape Canaveral (28.5° N), to take advantage of maximizing on-orbit payload insertion mass due to the velocity assist provided by the Earth's eastward rotation (Isakowitz, 1991 and Wertz and Larson, 1991). Insertion into a LEO parking orbit would occur approximately 15 minutes after launch, followed by perhaps 1 - 2 hours for on-orbit spacecraft check-up. While in LEO, we would also want to refine the rendezvous trajectory mission profile in the onboard G&C computer, based on updated trajectory parameters supplied by the net of astronomers tracking the NEO. At the precise time, the orbit transfer motor (in this case a Thiokol Star 26 motor; 271.7 sec ISP, 270 kg mass, 7,800 lbf avg. thrust, and 91% propellant mass fraction) would be ignited to give the spacecraft a ΔV of 2.93 km/sec into a Hohmann transfer orbit (see Fig. 6) with a 105,000 km apogee. For this example, rendezvous with the approaching NEO would occur 18 hours later. The orbit would be posi-grade so that basically the spacecraft would be near apogee at the time of rendezvous. The payload would be in front of the approaching NEO and would use its lateral divert capability to maneuver itself such that the NEO would hit it from behind. Of course, it's possible to have a quicker, more direct assent to the NEO rendezvous location, but at the expense of less payload or a larger booster.

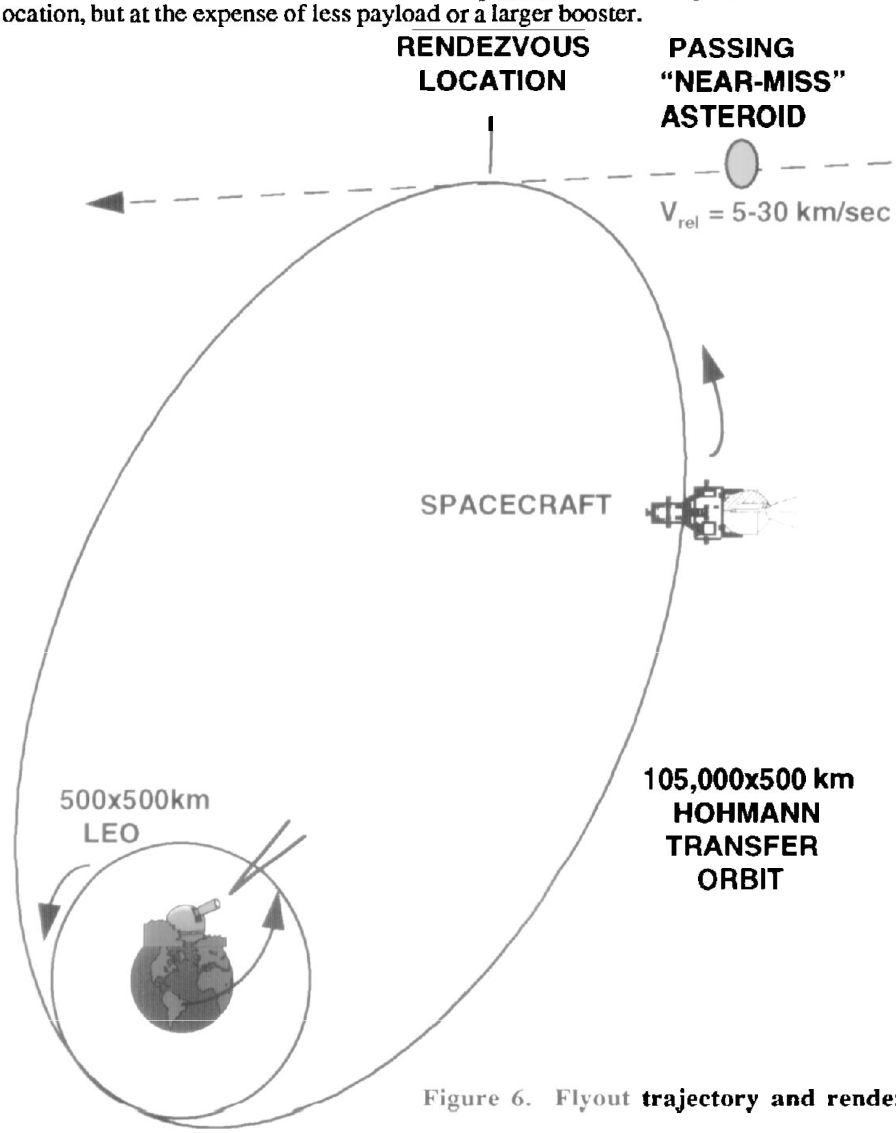

Figure 6. Flyout trajectory and rendezvous location.

Data collection

Observations of the asteroid rendezvous would be made by two principle means; the space-based penetrator and observer packages, and the ground-based instruments. Proposed space-based sensors on the two spacecraft packages are shown in Fig. 7. The exact sensor mix is, of course, subject to further mission planning and sensor availability. Ground-based world-wide assets would include: telescopes (optical, UV, and IR - broadband and discrete spectral coverage), radar (for tracking the spacecraft and NEO target beforehand and measuring target momentum change and debris cloud characteristics after the rendezvous), and telemetry collection of the data transmitted from the space-based assets (from the two spacecraft and in the 1-10 GHz range).

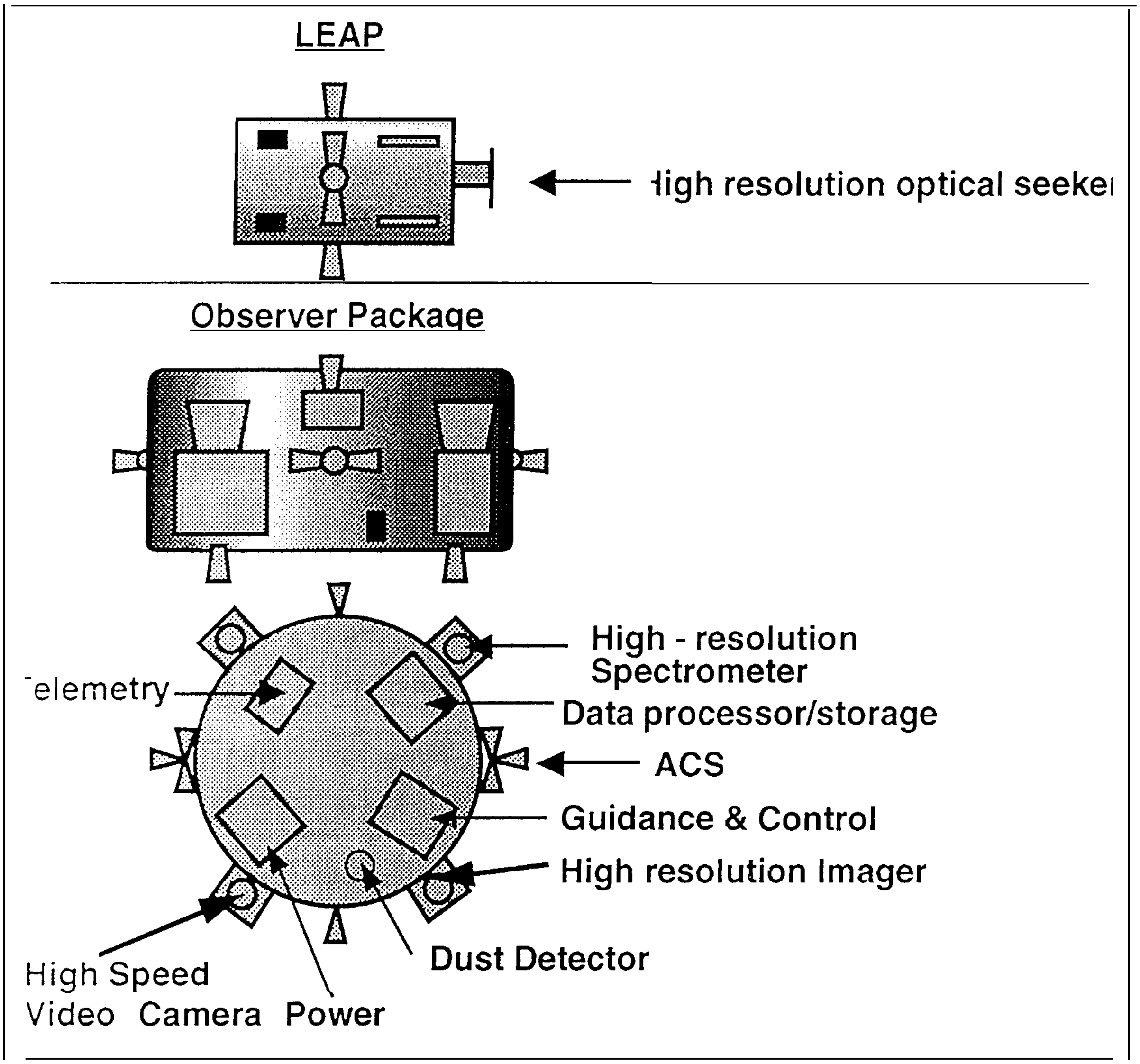

Figure 7. LEAP and Observer Package sensor suite.

Asteroid rendezvous - target penetration

The primary rendezvous mission would involve penetration of the target NEO by the LEAP vehicle (see Fig. 8), with the observer package watching the penetration from about 1 km away. The LEAP vehicle would separate from the observer package minutes before closest approach and then use its lateral divert capability to perform final homing on the rapidly approaching NEO. The observer package needs to be removed from the direct vicinity of the NEO because of the debris field the impact will create, so as to maximize data collection by the observer package.

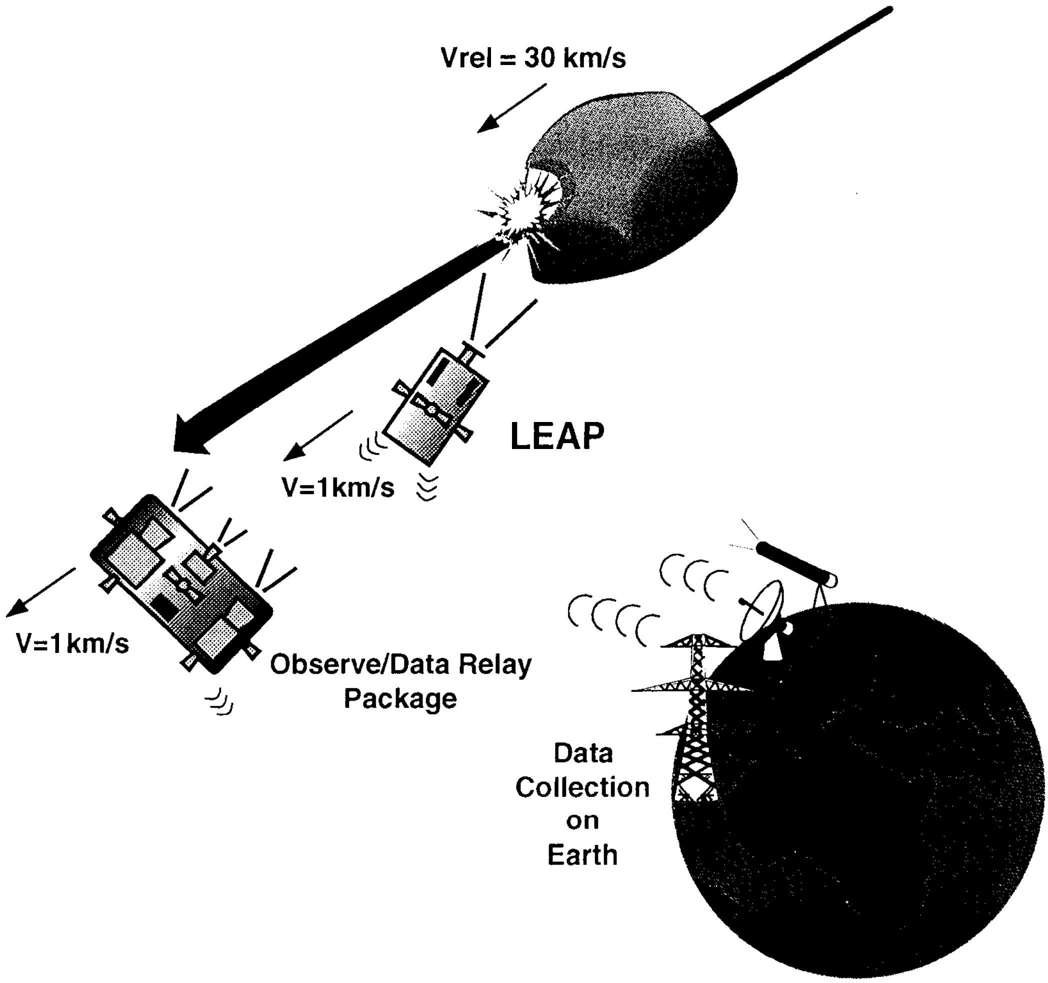

Figure 8. Impact of the target NEO by the LEAP package, with the observer spacecraft nearby, and data collection on Earth.

Data analysis and interpretation - penetration mission

For a successful asteroid rendezvous penetration mission, there would be many sources of data for subsequent analysis and interpretation (see Fig. 9).

DATA ANALYSIS ACTIVITY	INTERPRETATION
Spectral Data	Elemental and molecular composition of the asteroid along the penetration shotline.
Impact Flash Data	Increased understanding of the impact physics.
Radar Data	Initial body dynamics; Level of momentum deposition (trajectory alteration) and/or creation and trajectory of a fragmentation debris cloud.
Dust Detector Data	Increased understanding of the impact physics.
High-Resolution Images	Shape and surface texture; Cratering record; Clues to the origin of the body

Figure 9. Data to be derived from the impact mission and possible interpretations.

Simulations of the interaction of the LEAP penetrator with a 5-meter class NEO body (see Fig. 10) were performed with the Smoothed Particle Hydrodynamics (SPH) model (Libersky et al., 1991 and Luehr and Allahdadi, 1994). Interesting features in these calculations are: 1) the projectile penetrated only about one body length into the target and subsequently coupled all its kinetic energy into the NEO material - typical for a HV impact, 2) a massive crater has formed in the target after just 1 microsecond, and 3) the target may possibly fragment as a result of the impact.

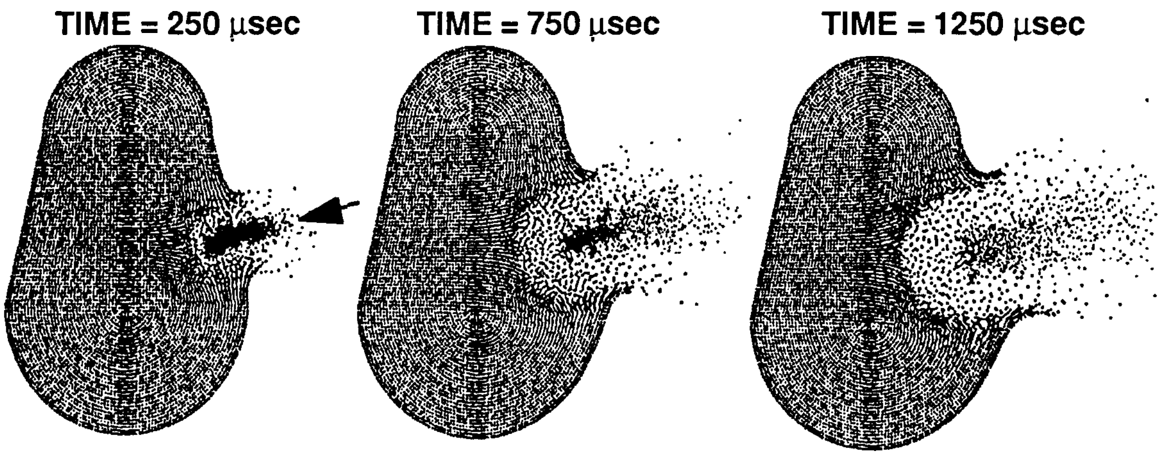

Figure 10. Hypervelocity impact simulation using the SPH code of the LEAP penetrator impacting a 4 by 7 m rock NEO target at 30 km/sec.

Of concern from a safety perspective would be the resultant debris cloud if the target NEO were to catastrophically fragment due to the LEAP package impact. Using existing breakup models (McKnight, 1991), Figure 11 gives estimated parameters for the debris cloud produced by the 35 kg LEAP penetrator impacting the 4 by 7 m sized NEO shown in Figure 10. Obviously an extremely energetic and well-populated debris cloud is created. Range safety would therefor dictate that the rendezvous mission parameters be such that any resultant debris cloud be directed away from Earth or that a larger NEO target be sought where the expectation of catastrophic fragmentation is remote, i.e., the projectile energy to target mass ratio is well below the fragmentation threshold of about 3 - 10 J/gm (Tedeschi, 1995), versus 56 J/gm for the estimation made above.

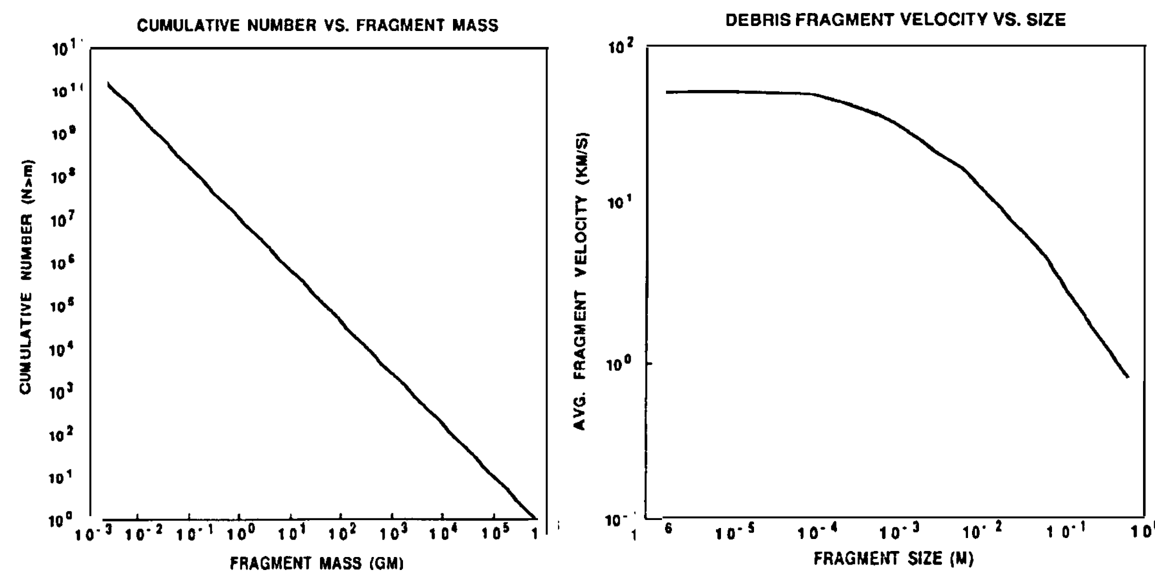

Figure 11. Estimated debris cloud characteristics for the 4 by 7 m target NEO impacted by the LEAP penetrator.

Fast Flyby asteroid rendezvous/data analysis and interpretation

Should the primary mission objective of a target penetration not be achieved, then for the case of a near-miss we would still have a fast flyby mission, from which much could still be learned. Many sources of data would still be available for subsequent analysis (see Fig. 12) and interpretation (see Fig. 13).

DATA ANALYSIS ACTIVITY	INTERPRETATION
Spectral Data	Molecular composition of the asteroid's surface.
Radar Data	Body dynamics and trajectory.
Dust Detector Data	Presence of nearby particulates.
High-Resolution Images	Shape and surface texture; Cratering record; Clues to the origin of the body.

Figure 12. Data to be derived from the fast flyby mission and possible interpretations.

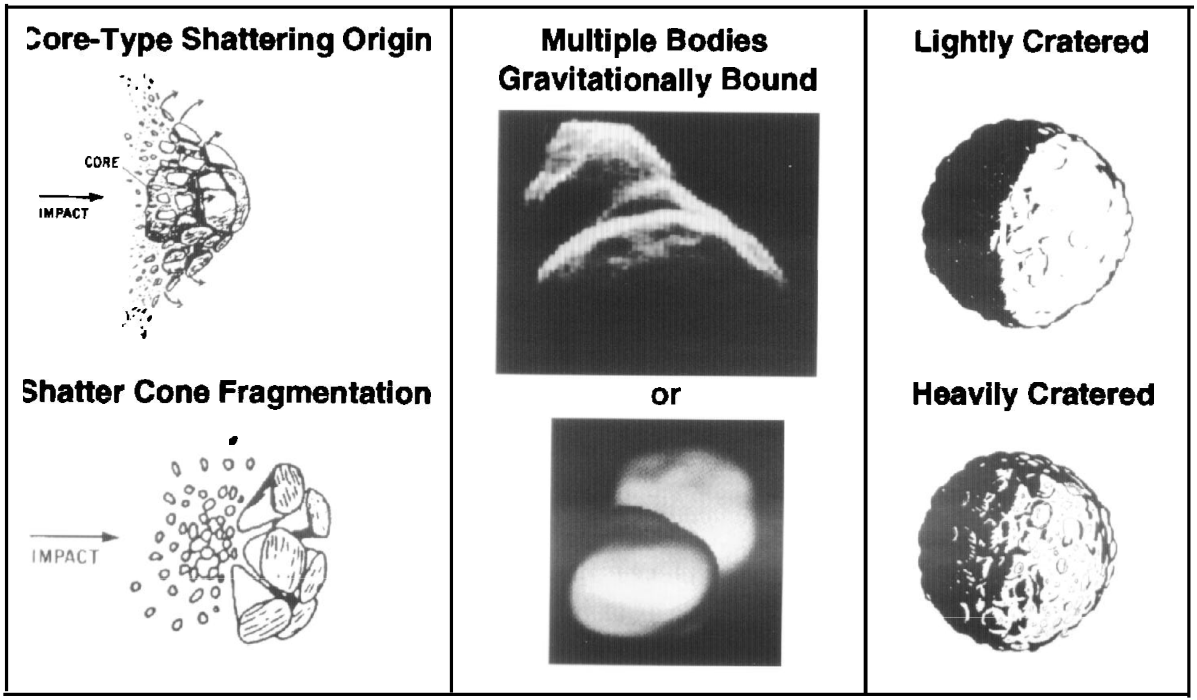

Figure 13. Possible conceptual interpretations from a fast flyby mission.

International participation and cost

It is recommended that the proposed asteroid rendezvous mission be a joint one between many nations. We all are stakeholders in the consequences of massive NEO impacts on Earth, we should all therefore consider working together to understand the problem and generate reasonable and acceptable solutions for the protection of life on Earth against NEO impacts. Figure 14 is a preliminary and most certainly incomplete listing of possible members of an asteroid rendezvous team and their potential contributions. As this proposed mission, and others like it (Nozette, 1995), are discussed in the coming years, many changes will undoubtedly be made to the list below before the mission team, investigators, and contributions are set. Initial cost estimates are for the total mission to cost approximately $15M using almost exclusively off-the-shelf hardware and existing worldwide space assets (sensors, hardware, facilities, and other capabilities). Each nation must be willing to provide resources, assets, and capabilities to make this proposed mission a success.

WHO	WHAT
Chinese	Sensors, mission services, analysis
DOE National Labs	Analyses/Data Interpretation Observer Package Design & Integration
Europeans (ESA)	Dust Sensors, planning, mission services
International Scientists	Principle Investigators, data interpretation
Japanese	Observer package sensors, mission services
NASA	Sensors, planning, mission services
Russians	High-energy impact physics, sensors Start Rocket, launch integration
USAF Phillips Laboratory	LEAP Penetrator Impact Response/Data Interpretation
USAF Space Command	Mission planning, launch & mission services, systems integration

Figure 14. Possible asteroid rendezvous mission team members and contributions.

Summary

Kinetic energy is a viable mitigation technique to protect Earth from the NEO impact hazard under certain circumstances by either deflecting or disrupting an approaching body. However, for us to have confidence in the effectiveness of kinetic energy as a defensive capability, we have proposed for broad consideration the conduct of a quick and relatively inexpensive (albeit high risk) asteroid rendezvous mission. Doing so would result in many benefits, not only would it increase our scientific understanding of NEOs, but it would also allow us to better understand and model the delivery and deposition of kinetic energy into NEO targets and their resultant response, i.e., cratering and deflection, or fragmentation. Conducting low-cost space experiments now is more likely to allow timely and effective defensive responses in the future.

Acknowledgments

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CYMBELINE —A High Velocity Impact Experiment

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Objective: We propose to collide two thoroughly instrumented satellites at a relative velocity of 20 km/sec and use the transient high pressures generated in the collision to measure thermodynamic properties (shock Hugoniot equation of state) for dozens of materials at pressures of 7-35 Megabars (million atmospheres). These pressures far exceed anything which has been achieved on Earth in a comparably precise experiment. The experiment will provide data of fundamental scientific interest.

The Role of Experimentation for NEO Material Models and Computational Validation of Risk Assessment and Mitigation Schemes

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Experimental impact methods are used to study the dynamic states of matter in temperature, pressure, and strain-rate regimes inaccessible by other means. These techniques have been employed for many years in a wide variety of scientific, military, and commercial applications. Impact experiments make two major contributions toward ensuring the accuracy of computational simulations of dynamic high-pressure events. First, they provide the data for generating the realistic material models that are a necessary component of the shock physics codes. Second, they provide the "ground truth" by which the output of code calculations can directly be compared for validation. The range of phenomena that can be studied by impact experiments includes fracture and fragmentation, phase transitions, shock-induced melting and vaporization, impact cratering, and penetration mechanics. Material properties that can be studied include constitutive equations of state for materials, shock Hugoniots, strength, and residual microstructural effects. Because of the nature of the threat from comets and asteroids, both risk assessment and analysis of mitigation schemes will primarily be computational modeling tasks. It is crucial that the material models be physically accurate so that the analysis and prediction of impact-related and high-energy events involving comets and asteroids can be performed with a high degree of confidence. An intimate interaction between dynamic experimentation and computational analysis is required.

Dual Use Technology for Planetary Defense Applications

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Quantametrics Inc.

Six technologies, CCDs, optical sensors, space propulsion, materials, hypersonic impact, and nonlinear modeling which are important support technologies relevant to planetary defense are discussed in terms of dual technology utilization. It is suggested that due to the uncertain and long term nature of the NEO threat, the technology resources allocated to developing a planetary defense should also provide economic and social benefits. Such research and development efforts dedicated to assisting critical enabling technologies that support overall economic vitality are likely to have the best opportunity for long term funding.

Introduction

The prologue to appropriate planetary defense is the development of a firm understanding of the scientific and engineering principles involving operations in a space environment and the nature of the interactions with those objects which must be defended against, ie. Earth-crossing asteroids and comets (ECACs). For example, some estimates of the chances of a 0.1km or larger ECAC colliding with the Earth are about 10 percent per century (Canavan, 1995). Assuming this number to be realistic, to some this may still appear to be a long period of time to continually support a defense system with only a small likelihood of it actually being used. This is because maintenance of such a defense system will require an extensive and detailed effort involving several areas of natural and applied science as well as the application leading edge technologies which must be supported over extraordinarily long periods of time . If the resources allocated to such an undertaking is directed purely towards planetary defense with the initial stages operating totally within and dependent upon the existing (space) research and technology development infrastructure, it may not be considered economically worthwhile. This is especially trues for those who do not accept the parameters of the NEO threat. For this reason it may be politically difficult to support a planetary defense system that does not provide some economic or social feedback. However, if this research and development is carried out from a perspective of dual use technology utilization, research and development in planetary defense can take advantage of current technology as well as provide needed stimuli for critical enabling technologies, thereby becoming cost effective while providing substantial economic benefits. Furthermore, if this planetary defense system can be integrated within ongoing space missions with a reasonable probability of economic return in the long term, the chances of support for a planetary defense system will increase accordingly.

This paper discusses aspects of some areas of science and technology relevant to planetary defense against ECACs. In particular, the relevance of charge coupled devices (CCD) and other optical detection technologies, space propulsion, materials science, hypersonic impact, and nonlinear dynamic modeling are briefly described. Issues regarding command, control, and communications are also extremely important for planetary defense issues. However, they are discussed elsewhere in the workshop proceedings (Canavan, 1995). In the technology areas outlined, it is suggested that the aforementioned technologies can significantly benefit from research being carried out both in the national/defense laboratories as well as in the industrial/commercial sectors. This cooperation between the industrial sector and the national laboratories can provide the necessary impetus to initiate research in areas critical to technological and commercial leadership. For example, the development of the SSTO as a successor to the space shuttle, which potentially represents a low cost, economically viable, gateway to LEO (low earth orbit) could provide economic benefits to private sector launch operations. Likewise, the national labs with their uniquely suited facilities will be indispensable in carrying out basic research related to radiation and hypersonic impact experiments on ECAC-type materials that would be difficult to do at industrial laboratories where the research emphasis is more on product development and quality control. Related to the above but from a slightly different perspective is the development of enabling technologies such as the CCD and its associated image processing software which are internationally market driven. Such technology provides excellent commercial opportunities, especially in medical diagnostics, public safety, and entertainment. Both ground and space based planetary defense operations using specialized CCDs will each provide valuable input into extending commercial and civil CCD applications. Finally, nonlinear analysis of celestial mechanics, which is still partially in an academic stage of development and might be considered somewhat esoteric, may generate valuable information for the development of nonlinear signal processing and chaotic control methodologies. It is therefore be suggested that by taking the appropriate and carefully measured steps focused on critical areas of technology development, research involved in long-term planetary defense can provide both near and long term economic and technological stimuli for the aerospace and electro-optics industries, as well as produce better consumer products and services.

Dual Use Technologies

The topics selected for this discussion of dual use planetary defense applications include detection, space propulsion, materials science, hypersonic impact, and non-linear analysis. Other very important topics which are not be covered in this presentation include those associated with space communications and operations, searching strategies, and overall systems analysis, for instance. These topics are discussed elsewhere in the proceedings. The five technology categories listed below are essentially described topically with little or no detail regarding the specifications of designs, observations, experiments, or analysis. It is not the intention in this brief communication to provide a technical description of these technologies. Rather, for each of the five categories the technology is first briefly described, then the planetary defense application is outlined, and finally the dual use applications are discussed.

CCD Detection

Technology

The first task is to seek, detect, track, and if possible optically characterize NEOs. Earth-crossing asteroid and comet (ECAC) observation, tracking and categorization will likely be achieved primarily using high performance large format charge coupled devices (CCDs) with 2560 x 1960 pixels coupled to 1-2.5 meter class telescopes. Automated operation of these telescopes will detect the NEO and reduce (analyze) the data. Those objects which are found to be scientifically unusual and/or pose a possible threat will be further analyzed by follow up observations from specialized facilities.

Planetary Defense Application

a) Ground based observations - immediate need for funding for northern (Spaceguard) and southern hemisphere 1024 x 1024 pixel telescopes to maintain observational continuity. A proposal to build and install an array of nine 2,000 x 2,000 CCDs at the Schmidt telescope at ESO in Chile has been submitted. Also, plans exist to install a 1,500 x 1,000 CCD at the 67 m Schmidt telescope at Asiago, Italy (Hahn et al, 1995). JPL is currently fabricating a CCD camera system with a 43096 x 4096 pixel, 15 micron CCD to be installed on a 1 m telescope; the limiting visible magnitude will be about 22 (Helin, 1995).
b) Space based observations - continued development of high performance (2560 x 1960 pixel) CCDs with enhanced spectral resolution especially in the infra-red (Stokes and Kostishack, 1995). GEODSS which is designed to have a very high search rate makes it possible to envision an automated production oriented cataloging (Darrah, 1995).
c) Radar Echoes - furnish high-resolution images of near-Earth asteroids (NEAs), substantially improve the accuracy of trajectory predictions, determine rotation states, gross morphologies, and, in some cases, the (metallic) composition (Ostro, 1995a, b).

Dual Use Application

The development of large format high resolution CCD technology is a fundamental (enabling) electro-optic technology with numerous applications in the commercial marketplace including the entertainment industry, environmental monitoring, law enforcement surveillance, and in industrial production. Versions of this technology adopted for space operations are extremely valuable for evaluating Earth resources.

In particular, Matsushita Inc. is currently producing a CCD device with 10,000 half-tone levels, as opposed to conventional CCDs which produce about 500 levels of halftone. A CCD with 10,000 half-tone levels can record a composition that combines both bright and dark subjects within the same composition. This capability is especially useful in detecting passive type comets, which are highly pervious, against a background, e.g. star, field. Other applications of this technology include pocket size camcorders for professional use, navigation systems, and medical research sensing.

The software algorithms involved in the sky survey will also have several applications in industrial automated inspection and quality control, medical image scanning, and basic research in materials science. The three-dimensional computer models derived from the radar images of NEAs, in addition to challenging ones imagination with the stimulus of the unusual, are directly applicable to such critical industrial production processes as robotic vision (active and passive) and remote operations either on Earth or in space.

The coupling of an automated CCD based optical system with interpretive software is a key technology of the future, and as such its applicability to commercial, civil, social, military, medical, and industrial applications is virtually impossible to overestimate.

Optical Sensors for Environmental and Public Safety

Technology

One of the most difficult tasks in near-Earth object (NEO) mitigation is determination of their physical properties (Remo, 1994). The use of optical scanning, spectroscopy, and penetration probes can provide the means to obtain the necessary information required for hazard mitigation. Optically based technologies which can aid in these tasks include:

a) Subsurface monitoring can be carried out by laser excitation-emission spectroscopy, IR fiber optic sensors, tunable laser spectrometry, FTIR spectroscopy, and Raman spectroscopy in a cone penetrometer probe.

b) Image processing encompassing image reconstruction and restoration, image filtering, object detection and classification as well as image restoration (deconvolution) can increase the dynamic range and improve shape resolution.

c) The penetrator will also provide a good estimate, in the region of penetration, of the mechanical properties and can assist in extracting a core sample, if necessary.

Planetary Defense Application

Image processing will assist locating a faint NEO in a degraded image amid other emission sources and therefore assist in remotely determining the NEO trajectory. Image filters may also assist in estimating the NEO material properties category: ie. 0-comet type, 1-carbonaceous chondrite type, 2-stony type, and 3-iron or stony iron type. Image reconstruction will assist in estimating the size and morphology of the NEO. Knowledge of size and material composition will provide an excellent basis for evaluating the level of the NEO hazard.

Subsurface monitoring with a cone penetrator can provide an evaluation of the internal constituents of the NEO, thereby yielding information on the mechanical structure. These results can be compared with those obtained through imaging. Spectroscopy obtained from the penetrator and the surface imaging can be compared. Knowledge of the material properties and the related mechanical strength is critical for NEO hazard mitigation strategies.

Dual Use Application

a) The image processing technology which can detect faint NEOs in a noisy background is also useful, for instance, in finding small formations in tissue. For example, microcalcification clusters on the order of 50 to 100 microns can be detected amid the complex background structures in a mammogram through image processing. These structures are often indicative of breast cancer and appear as faint point-like spots. Since current mammography shows micro calcifications of 250 microns or larger, image processing is required to see the smaller spots. Additional clinical applications of image processing abound. Other areas of image processing include law enforcement and traffic safety technologies.

b) Spectroscopic probes both on the surface as well as subsurface can provide environmental monitoring above and below the ground. Also in-situ measurements of contaminated soil, water, and air can be carried out with these optical techniques. Other environmental applications include optical particle sizing for on-line monitoring of particulate emission from industrial plants, remote sensing of smoke stack and flare emissions, and remote sensing and gas analysis of aircraft exhaust.

c) Penetrator probe technology can be used in civil (construction) ground sampling, mining, hazard location and assessment, and space exploration in general.

Space Propulsion

Technology

Once a threatening ECAC has been detected, tracked, and optically characterized, the next step is to probe or otherwise engage and interact with the object at a safe distance and within a reasonably short amount of time. Repetitive missions may also be required. A long range rocket with a substantial payload will be desirable for such missions. Also, for mitigation missions a long range rocket will permit engagement with the threatening NEO at distances that allow follow up interactions with a range of kinetic and explosive devices of choice.

Planetary Defense Propulsion Applications

The need for research and development in space propulsion includes:

a) Long range propulsion - there will be a need to carry out in reasonably short periods of time an ECAC flyby, rendezvous, probe, or interception at ranges on the order of 1 AU. Such a mission calls for a (hybrid) combination of a Type I impulsive thruster which rapidly accelerates to coast speed, and a Type II propulsion system with a continuous acceleration (Sforza and Remo, 1995).

b) Single stage to orbit (SSTO) propulsion - an SSTO provides the capability for low cost LEO operations from which NEO surveillance and interception operations could be launched (Sforza et al, 1995).

c) Small, smart, and lightweight spacecraft - combined with the systems described in a and b as an option are solid- fueled (Type I version) space launch vehicles which can be quickly launched (Tedeschi and Allahdadi, 1995). This vehicle could deliver a low cost, small and lightweight instrument as a flyby, probe, (Nozette, 1995), or other device as the needs require.

Dual Use Application

The major dual use application for space propulsion systems is derived from the SSTO which will significantly reduce the cost to carry out commercial, communications, reconnaissance, and experimental operations in LEO. In addition, a low cost LEO platform will permit otherwise cost prohibitive operations to be carried out in space, thereby opening up a new horizon in space utilization and commercialization. A use for a Type II propulsion is for planetary exploration and resource exploitation.

Materials Science

Technology

Strategies for changing the trajectory of a threatening NEO by means of momentum coupling will generally consider the use of high energy radiation fluxes in the form of x-rays, γ-rays, and neutrons as well as kinetic impact. Research must be carried out on the interaction (ablation, absorption, and scattering) with the different categories (0, 1, 2, & 3) of NEO materials. The goal of this research will be the determination of the momentum coupling by radiation to the directly threatening NEO

(Hammerling and Remo, 1995). Related laser (ablation) effects can be obtained from experimental work at inertial confinement fusion (ICF) facilities which can provide additional data on X-ray absorption cross sections and related scattering effects as well as on shock wave equations of state.

Planetary Defense Application

X-ray, γ-ray, and neutron interaction cross sections with the NEO material categories 0, 1, 2, & 3 must be experimentally measured and computed over a wide variety of energies and fluxes. Initial work in computer modeling for X-ray and neutron radiation in this area as well as for kinetic and even laser coupling has been carried out by Shafer et al (1994 and 1995). The goal of this experimental and analytical research will be to model the impulse coupling to the various type of NEO materials in order to model the effects of these radiations on their velocity change.

Dual Use Application

The experimental measurements and analysis, and computer modeling on the NEO material categories will provide a very valuable date base that will have a broad range of applications which include, but are not limited to the following;

a) Development of ionizing radiation shields and scattering suppressing surfaces for medical, industrial, and military environments,
b) Nuclear radiation detection methods for environmental monitors and hazardous waste site remediation, e.g.. low level counting of neutron activated environmental samples.
c) X-ray and neutron materials processing and activation, and
d) Modeling stellar, planetary, comet, and meteorite interactions and evolution from ionizing radiation at high energy densities, e.g.. Laboratory planetary and astro-physics.

Hypersonic Impact Experiments

Technology

Experiments which involve the projectile impact on NEO materials categories 0-3 and related surrogates at 1-10 km/s must be continued to be carried out (Furnish and Remo, 1995). The goal of these experiments is to measure momentum transfer (Tedeschi et al 1995) and enhancement as well as the effects of ultra-high strain rates on the micro- and macro- structural responses.

Planetary Defense Application

The major applications of these experiments to planetary defense are to understand the response of the various NEO size, material, and morphological categories and to collect a database on the following properties:

a) kinetic impact and high energy induced shock effects,
b) momentum enhancing impacts, and
c) spallation effects.

Dual Use Applications

The numerous dual use applications resulting from hypersonic impact experiments include:

a) modeling space debris impact effects, spacecraft shielding, and EOS and constitutive models to develop improved structural materials for earthquake and blast resistant structures,

c) planetary surface penetrator design,
d) development of techniques for ECAC mining (Gertsch et al 1995), and
e) solar system formation and planetary impact dynamics.

Nonlinear Dynamic Modeling

Technology
Numerical modeling and analysis of fuzzy orbital boundary trajectories such as those involving invariant hyperbolic manifolds and "hops" between resonance states.

Planetary Defense Applications
The above nonlinear dynamical modeling may;
a) provide new routes for ECAC flybys and rendezvous and
b) interpret comet orbital trajectories.

Dual Use Application
The understanding of nonlinear analysis can provide a basis for interpreting chaotic signal processing as applied to;
a) medical, industrial, military applications,
b) provide hitherto forbidden orbital routes to asteroids, comets, or planetary bodies, and
c) lead to methods by which chaos can be controlled to enhance systems performance in general.

Conclusions

If it is perceived that there is a clear and present danger from NEOs, numerous technologies will be required to detect, track, characterize, target, and if necessary to mitigate the threat to the Earth. It is also clear that such a long term allocation of research, development, and defense resources exclusively for a NEO defense which may take thousands of years or even longer (or if at all) to pay-off by preventing a catastrophic impact on the Earth may not be politically viable over the long term. Planetary defense should be built within a technologically evolving framework that provides some benefits to society while preparing for a clear threat, should it materialize materialize. This approach will also take advantage of additional technological innovations that may be developed in the interim. Therefore, the first step in coordinating an overall planetary defense against NEOs determining which technologies are required. The next step is determining which of these technologies are currently available to the military or can be adopted from the industrial or commercial sectors. Technologies, especially those which are enabling and need to be developed in partnership with industry with the intent of providing economic and social benefits should be supported. In this way the challenge of NEO mitigation can be met in an economically, technologically, and politically realistic manner. This last comment is directed towards the realization that the plan for planetary defense against may last for centuries, if not millennia without any threat manifesting itself. A defense from such a threat runs the risk of becoming an unpopular economic burden, and therefore ultimately not be supported. If a positive economic spin-off can be maintained through dual use technology, planetary defense will rest on a better foundation and become socially more viable. By continuously developing a broad science and technology base over decades and centuries, it is not only possible, but very likely that profound new insights on the nature and mitigation of NEOs will manifest themselves. Such developments will continually change the parameters of the planetary defense strategy. We must therefore be rational and open-minded about the realistic time scales for a NEO threat to develop, evolving technological capabilities, and the need for mitigation.

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Integration

Panel Papers

Technology Assessment for Defense Against Asteroids or Comets

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This paper presents an overview of promising defense strategies against asteroids or comets that may be discovered and found to be on a collision course with Earth. It reviews the technology needed to make defense missions against this kind of threat feasible, assessing threat conditions that can be met by currently available space technology and launch capability and those that require major technology advances. Issues of concern include launch, orbit transfer, terminal guidance, automation and robotics, as well as possible options for deflecting the threatening object from its collision course, or destroying it. Currently used space mission analysis and design procedures can be applied here to select the most dependable and cost-effective mission and system concept and identify technology advances that are required for its implementation.

Introduction

The potential threat of catastrophic impacts on Earth of asteroids or comets has become more widely recognized, and several major conferences on this subject, preceding the current Workshop, have been held in the past years. The recently published comprehensive book entitled "Hazards due to Comets and Asteroids", edited by Gehrels (1994) contains information that was presented at the 1993 University of Arizona Conference by the same title, an up-to-date source of knowledge and ideas concerned with the nature of the threat and the means to defend against it. As such, it also is the source of some of the material presented in this paper.

This article gives an assessment of technologies that will be essential in future missions designed to defend against the threat. Along with various mission concepts advanced in the literature - and in this Workshop - and techniques for their implementation, it lists specific technology fields critical to undertaking defensive action, in particular those that need further advances and evolution.

Technologies that may evolve in future decades to become available for conducting defense missions against threatening near-Earth objects (NEOs) are difficult and risky to project. Evolution generally tends to outpace projections. This is well illustrated by the 35 years of past space technology growth. Similarly, any large resources that would be available for achieving this evolution and for undertaking a defensive mission, are highly unpredictable. Bold projections are needed, nevertheless, to help stimulate technical evolution, and the process may benefit from the growing recognition of the threat, in general, and from global cooperation to support technical preparedness (Morrison and Teller, 1994). Technology assessments and projections presented in this article should be viewed in the light of these comments.

The following sections address issues of technical preparedness for NEO defense; principal defensive mission concepts and mitigation techniques; NEO deflection or destruction options, technologies available for this purpose; and technology drivers, limiting factors and constraints. Methods of mission and system engineering used for current more conventional missions, and their application to NEO defense missions also will be discussed.

Principal Threat Mitigation Techniques

Threat mitigation techniques that are currently of principal interest include NEO deflection by propulsive means, by direct impact, also known as kinetic energy deflection, and by nuclear detonation. Other techniques being proposed include NEO surface heating and evaporation by ground- or space-based lasers or space-based solar reflectors. An impulse generation technique that would use mass drivers such as electromagnetic linear accelerators for ejection of processed NEO surface material (Canavan, 1994) also has been proposed, but it involves highly complex surface operations and requires a power source in the Megawatt range. Only the three first-mentioned threat mitigation techniques will be considered here. Specific quantitative impulse requirements and interceptor initial mass at Earth departure typical for these defense modes are given in the next sections to indicate their respective usefulness, effectiveness and cost.

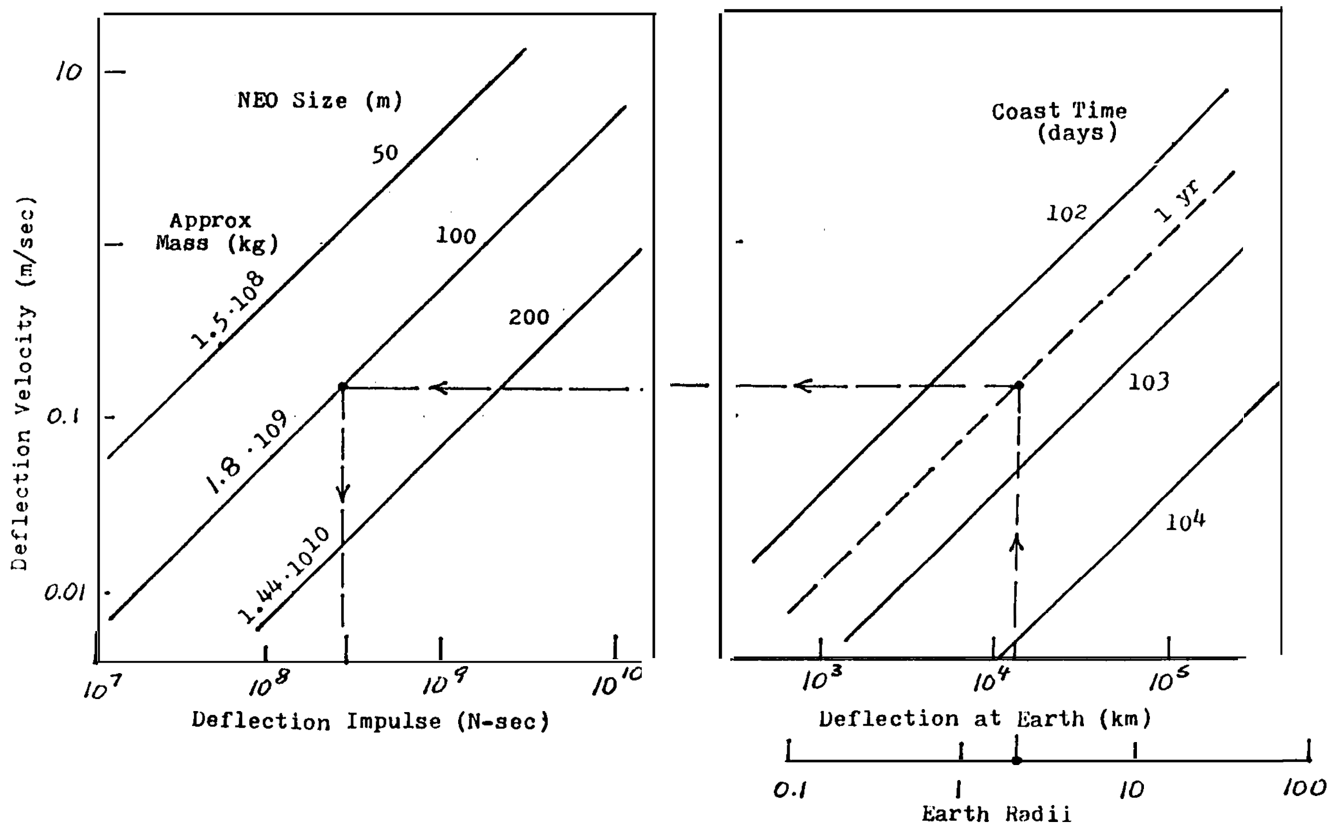

Figure 2 -Relation Between Asteroid Size, Deflection at Earth, Coast Time, Deflection Velocity and Deflection Impulse

Interceptor Mass Data for the Principal Deflection Modes

From the impulse requirements derived above the corresponding initial mass of the interceptor spacecraft can now be determined for the three principal deflection modes considered here. It depends on the final mass transferred to the target and the amount of propellant needed in the process.

In the propulsive NEO deflection mode the interceptor system must generate three separate velocity impulses: first, to start the transfer from Earth; second, to apply retro-propulsion at the target, for soft landing; and third, to deliver the required target deflection impulse on the surface. The third impulse is by far the largest.

The kinetic energy deflection mode, by contrast, requires only a single velocity impulse, that of starting the outbound transfer. The nuclear detonation mode requires one or possibly two velocity impulses, the second one only if zero-velocity rendezvous for a standoff blast is to be achieved. Therefore these two modes require much less propellant than the propulsive mode, and consequently the required initial mass is very much smaller (see below).

For the propulsive mode, the initial interceptor mass is given approximately by

$$M_i = M_{p,3} * \exp[(\Delta V_1 + \Delta V_2)/gI_{sp}] \qquad (1)$$

where $M_{\eta,3} = M_a * \Delta V/(g\, I_{sp})$, and ΔV_1 and ΔV_2 are the required first and second velocity impulses applied at departure and arrival. The relatively minor effect of tankage, structure and other interceptor subsystem mass is neglected in this approximation. Figure 3 shows the interceptor initial mass M_i versus the time remaining after the intercept to reach Earth's vicinity, for NEOs of 50, 100 and 200 m size. Near-term propulsion technology with 500-sec specific impulse (solid lines) and future technology with 1000-sec specific impulse (dashed lines) are reflected

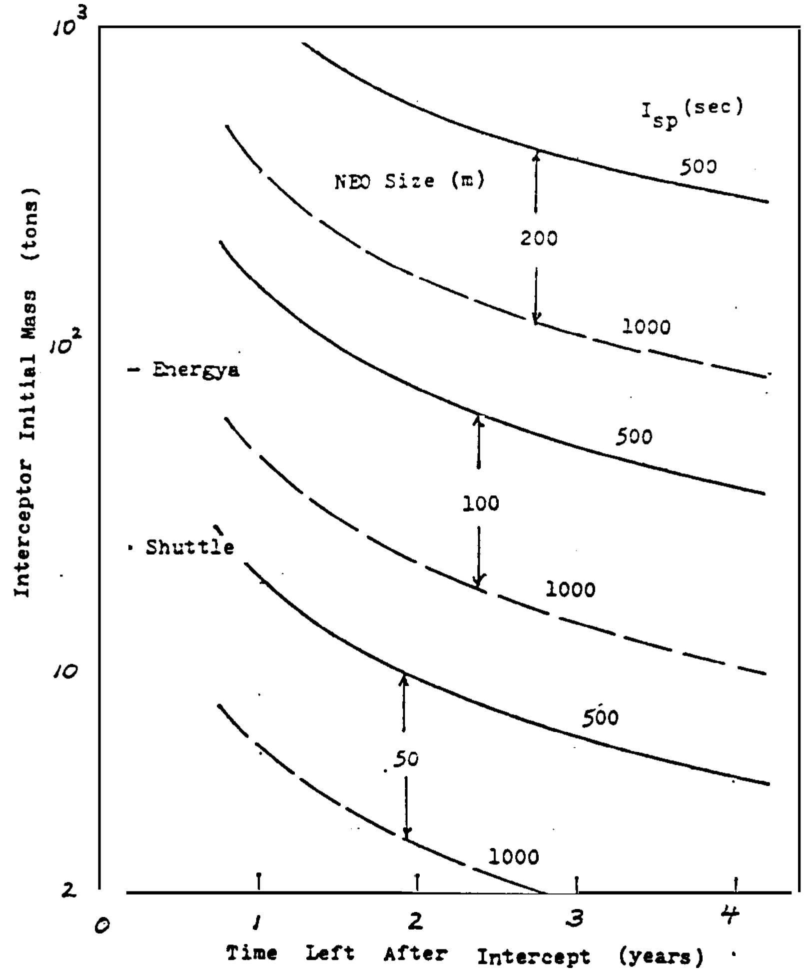

Figure 3 - Interceptor Initial Mass vs Coast Time Remaining after Deflection for Three NEO Sizes (Propulsive Deflection Mode)

in the figure. The second set of M_i values is 3.5 to 4 times smaller owing to the dominant exponential effect of the I_{sp} increase in equation (1). The results shown are based on an assumed near-minimum energy interceptor transfer trajectory with 3 km/sec hyperbolic excess velocity at Earth departure, and 2 km/sec arrival velocity at the target, prior to the retro-maneuver. Only the initial mass for the 50-m NEO intercept is seen to be well within the Space Shuttle's maximum payload capacity of about 25 tons, without the benefit of advanced propulsion technology, and for elapsed times as low as 1 year. For the 100-m intercept mission the interceptor initial mass would be within the Shuttle's payload capacity only for the higher-I_{sp} propulsion technology, and for elapsed times of at least about 2 years. With the much higher, 80 to 90 ton payload capacity of the powerful Russian Energya launch vehicle a 100-m NEO defense mission could be performed using near-term propulsion technology, given at least 2 years of elapsed time.

The required burn time of the rocket landed on the NEO surface will be a major concern considering the very large amount of propellant involved. Figure 4 shows the burn time, t_b (dashed lines), for the propellant mass needed in the 50 and 100-m NEO deflection missions, assuming a thrust force of $4 * 10^4$ Newton. The propellant mass M_{rp} is shown in the same graph by solid lines. Burn times range from 25 to 101 minutes for the 100-m, and from 3 to 13 minutes for the 50-m NEO deflection impulse. Clearly, the excessive burn time required in some of these cases would be unacceptable and indicate that a higher thrust level than that assumed here is needed. Note that the burn time shown is independent of the specific impulse since it is defined by $t_b = M_a * \Delta V/F$, where F is the thrust force.

For comparison, initial mass data for the kinetic energy and the nuclear detonation (surface blast) threat mitigation modes, adapted from Solem and Snell (1994), are shown in Figure 5. In this figure, the M_i values vary with the NEO distance, R_I, at the time of interceptor launch and the NEO size, d (in meters),. They apply to greatly different target encounter conditions and extremely short response times, of only few weeks. The NEO approach velocity is assumed as 25 km/sec, and relative intercept velocities range from 40 to 50 km/sec, i.e., the engagement reflects a head-on encounter after a critically late threat detection. The results were derived originally for a 1000-km deflection distance at Earth, to shift the impact from a land mass to the nearest ocean. Reinterpreted for a deflection distance of 2 Earth radii, this requires increasing the initial interceptor mass values by a multiplication factor of 15

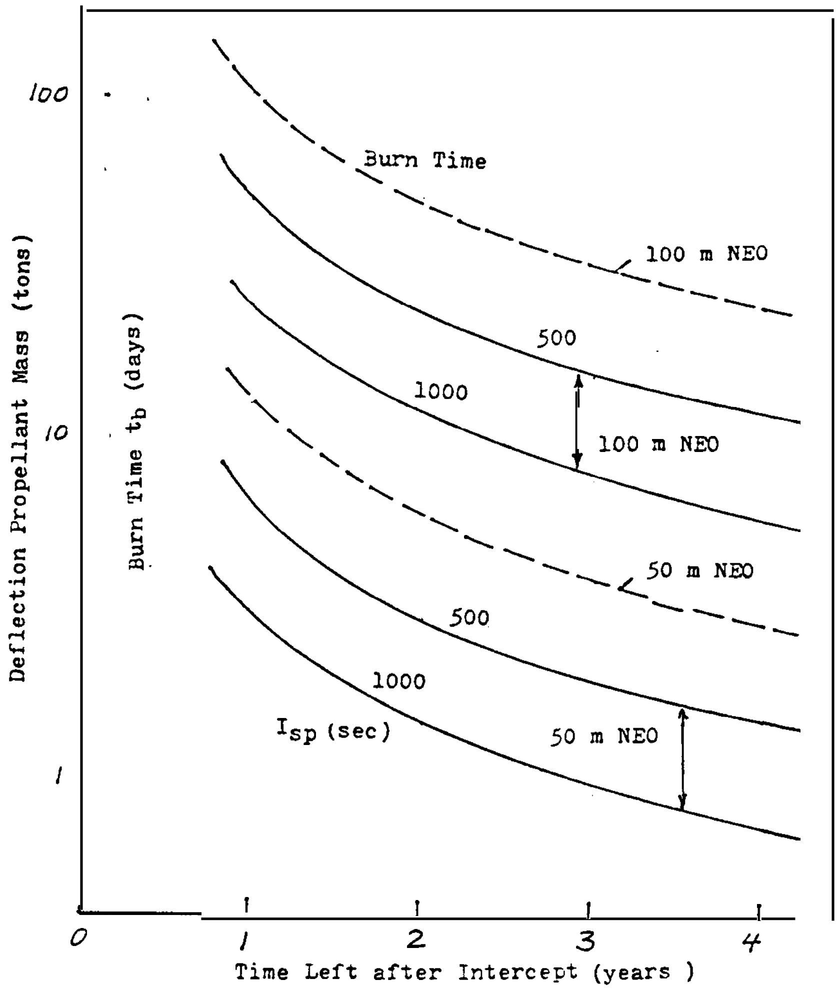

Figure 4 - NEO-Deflection Propellant Mass and Burn Time for a 50 and 100m Diameter NEO vs Remaining Coast Time

(see the numbers shown in parentheses in the figure). For this 12 times larger deflection distance the kinetic energy mitigation mode (left hand graph) of a 100-m object at an initial range of 0.01 AU requires an initial interceptor mass of 15 kilotons, while for a 0.1 AU initial range it would require only 1.5 kilotons.

Results obtained for the nuclear detonation mode (right-hand graph in Figure 5) are presented in terms of the same parameters. They show a mass reduction of about three orders of magnitude, e.g., for d = 100 m and R_I = 0.01 AU, M_i is only 15 tons compared with the corresponding 15 kilotons obtained for kinetic energy deflection, again assuming a shift of 2 Earth radii.

Referring back to the results obtained for propulsive deflection, (Figure 3), it is apparent that the two high-energy modes require a many orders-of magnitude smaller interceptor mass. Results such as those given here and in several other references (see Gehrels, 1994) lead to the conclusion that an effective defense against NEOs larger than 100m and allowing only little reaction time demands the use of the nuclear deflection mode, except under conditions where the simpler kinetic energy mode is adequate.

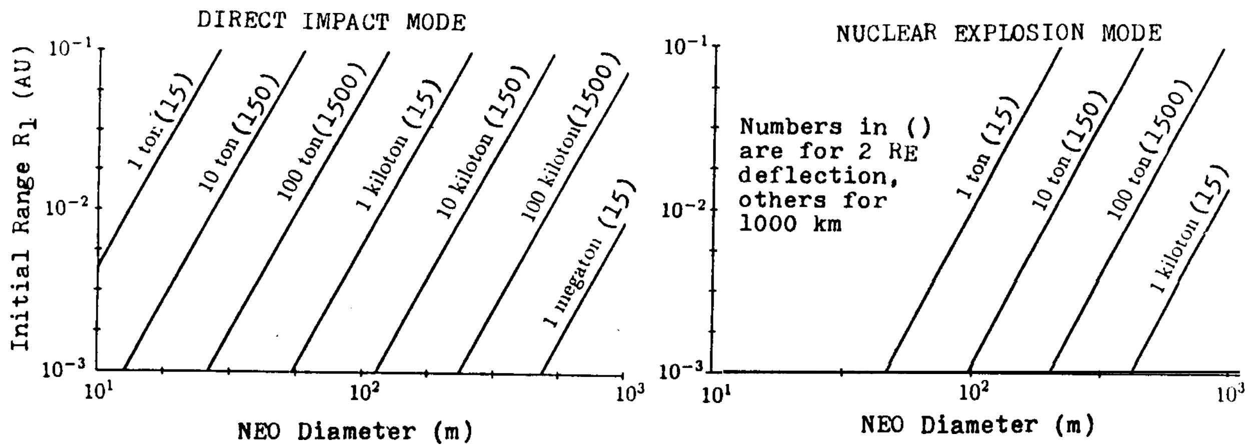

Figure 5 - Interceptor Initial Masses for NEO Deflection by Kinetic Energy and Nuclear Explosion Modes, Depending on NEO Size and Initial NEO Distance (Ref. Solem and Snell, 1994)

Technology Assessment

Key Technologies Essential to NEO Defense

Data presented above indicate that defense mission requirements for the least demanding NEO threat conditions can be met by today's technology, e.g. for NEOs of less than 100 m diameter and sufficiently long warning times, of the order of several years. The launch capability of the Space Shuttle or some of the largest expendable launch vehicles available today can support defense missions requiring from 15 to 85 tons initial mass in Earth orbit, as shown in Figures 3 and 5.

Advances in spacecraft and space mission technology anticipated in the near future will allow responding to a much wider spectrum of NEO threats. Of particular interest are advances in propulsion technology, spacecraft and subsystem miniaturization, refinement of terminal navigation and guidance, and greater automation and robotics capability.

Propulsion Technology

Extensive efforts to increase the specific impulse of space propulsion systems have been in progress in laboratories and test facilities over several decades, both in chemical and electric propulsion. After reaching a mature state, this advanced technology will be applicable to NEO threat defense missions, and will greatly enhance performance.

Technology advances of particular interest here are those in nuclear-thermal rocket engines with specific impulse increasing up to 1000 sec (Jones, 1992a; Venetoklis et al., 1994; and Willoughby et al., 1994). Also of interest are electric propulsion systems such as ion and plasma thrusters with specific impulse in the 3000 to 5000 sec range (Jones, 1992b; and Pollard et al., 1993). Compared with current high-performance cryogenic chemical rockets, such systems achieve very large reductions in propellant mass ratios for high- ΔV missions, as indicated by the equation

$$M_p/M_f = \exp(\Delta V/g\,I_{sp}) - 1 \qquad (2)$$

where M_p and M_f are the propellant mass and final mass respectively. Assuming as an example a 5000-kg final mass and a total ΔV of 3 km/sec, an I_{sp} increase from 450 sec (cryogenic chemical rocket) to 3000 sec (ion or pulsed plasma thruster) reduces the propellant ratio from 0.973 to 0.107, and hence, the propellant mass from 4,865 to 535 kg. Considering the much greater ΔV requirements of some cases previously discussed, a propellant mass reduction of 15/1 or 20/1 would be achievable by this increase of the specific impulse.

The required propulsion system power, proportional to the product of thrust force and I_sp is a factor in assessing benefits and drawbacks of applying this new technology. In the above example pulsed plasma thrusters would require 113 kW of propulsion power to produce the very low thrust force of 5 N, which implies a thrust phase duration of 37 days. Generally, this long thrust phase can be accommodated in the mission design. The necessary power can be provided by a space-nuclear-power generator such as the SP 100 system which has been under development for a number of years. The alternative of a solar-electric power source appears impractical, unless the power level and hence, the thrust force can be significantly reduced, provided a further increase in thrust time is acceptable. This kind of trade is typical for introducing advanced technology to enhance system and mission capabilities.

The greatly reduced propellant mass inherent in applying electric propulsion technology reflects in major spacecraft initial mass reduction and thus a smaller-size, less expensive launch vehicle. The technique of planetary gravity assist that has been proposed to reduce NEO-intercept ΔV requirements (Landecker and Gurley, 1992) would become unnecessary, and the longer trip time and greater mission profile complexity associated with it are avoided. Also, the need for on-orbit assembly of an excessively large and massive interceptor may be circumvented, along with the complexity and cost of such operations, multiple Shuttle launches, and the loss of time inherent in the process.

Miniaturization of Space Systems and Spacecraft Components

The mass of spacecraft and subsystems have been greatly reduced in the last two decades, notably in structures, power generation and control, and electronic subsystems. In Earth-orbiting spacecraft these advances have led to major mass and size reductions, with gross mass as low as one half to one quarter of the mass of earlier-generation vehicles, 10 to 20 years ago.

In NEO defense the benefits of this evolution can lead to initial and final mass reductions . However, in missions with a large nuclear payload or with a large propellant mass, the shrinkage of carrier mass alone becomes less significant in the overall mass budget. As shown by Gurley et al. (1994) in a comparison of mass characteristics of a system with chemical vs. one with advanced (nuclear-electric) propulsion, only the former benefited enough from miniaturization and subsystem mass reduction to permit the use of a smaller, lower-cost launch vehicle. Thus, any weight benefits from miniaturization will have to be assessed relative to advances in other areas of space system technology.

Terminal Guidance

The high precision required for delivering the NEO interceptor at exactly the intended location on or above the surface of the small target object demands an extremely high terminal guidance accuracy.

In past and current planetary flyby and orbit missions, terminal guidance accuracies of several and even tens of kilometers have been considered adequate and have been achieved consistently by correction maneuvers performed days or weeks before arrival at the target. Closest approach distances in such missions typically range from tens to hundreds of km. Terminal guidance corrections are performed with the aid of Earth-based or spacecraft-based error detection techniques. Currently, autonomous navigation techniques without dependence on Earth-based tracking and command are being studied intensively, as they tend to simplify mission operations and reduce cost.

In an asteroid or comet intercept, terminal guidance must be refined to reduce the approach error by several orders of magnitude, to a range of hundreds, or even tens of meters, depending on target size and intended approach geometry.

Table I lists some intercept mission modes and summarizes terminal guidance requirements and issues of concern. Modes (a) and (b) achieve target deflection by kinetic energy, chemical high-explosive, or nuclear energy transfer. Mode (c) may be used to initiate surface operations such as implanting a propulsive or explosive energy transfer device, or to explore physical target characteristics, e.g., in a precursor mission conducted prior to threat mitigation. Modes (d) and (e) may serve various options such as close observation or deferred - time detonation above the surface.

TABLE I
Target Acquisition and Terminal Guidance Requirements

Intercept Mode	Mission Type	Approach Velocity (km s^{-1})	Required Acquisition Range[a] (km)	Required Terminal Accuracy[a] (m)	Issues and Concerns
(a) Direct impact at high velocity	Close intercept: Kinetic energy deflection Nuclear explosive deflection or fragmentation	15–30	3000	50	Early acquisition, prompt lateral guidance maneuver Critical guidance accuracy with advanced sensor technology
(b) Tangential impact at high velocity	Close intercept: Kinetic Energy Deflection Nuclear explosive deflection or fragmentation	15–30	3000	20	Early acquisition, prompt lateral guidance maneuver Critical guidance accuracy with advanced sensor technology
(c) Soft landing, following retro maneuver	Distant intercept: Implant energy transfer device or mass driver Implant nuclear device	2–5	300	100	Early retro maneuver, several days before acquisition[b] High terminal accuracy Soft landing adaptable to uncertainty in gravity
(d) Injection into near-circular orbit, following retro maneuver	Distant intercept: Close observation Deferred detonation, standoff or surface	2–5	300	200	Early retro maneuver, several days before acquisition[b] Moderate terminal accuracy Orbit insertion adaptable to uncertainty in gravity
(e) Zero-velocity rendezvous/formation flying	Distant intercept: Close observation Deferred detonation, standoff or surface	2–5	300	500	Early retro maneuver, several days before acquisition[b] Moderate terminal accuracy Requires periodic altitude correction

[a] Rough estimates; 100 to 300 m class target object assumed. Less terminal accuracy required with larger target.
[b] Earthbased relative trajectory information and maneuver commands can be used.

All of these scenarios demand the development of advanced guidance techniques to meet the unprecedented requirements of extremely high terminal accuracy. These accuracy requirements critically depend on the selected encounter mode. A direct frontal impact, mode (a) or a nearly tangential impact, mode (b) are likely to be used in a late-intercept situation (Ahrens and Harris, 1994). Frontal impact requires a lower terminal guidance accuracy than tangential impact and depends less critically on early guidance error detection by the homing sensor, and therefore, appears preferable.

In the distant intercept scenario the optimum orientation of the deflection impulse generally is parallel, or anti-parallel to the heliocentric target velocity, as discussed previously. In this scenario modes (c), (d), or (e) are likely candidates for executing the target deflection at lower guidance accuracy requirements compared with modes (a) or (b). On approaching the zero-range-rate and zero-range-error condition by intermittent retro-thrust application the sensitivity to thrust and coast duration increases, along with rapid improvement of the error detection capability.

In developing sufficiently accurate, dependable terminal guidance capabilities, major demands are placed on sensor technology advances, to provide a large detection range for faint target objects and extremely high angular resolution. Earth-based remote guidance currently uses on-board sensors to provide the required high error-detection accuracy during the final approach to a planetary target. However, the large communication delays of 10 minutes and more, inherent in this technique, are not consistent with instant terminal guidance error corrections necessary when arriving at a small NEO, at the approach speeds involved. Therefore, autonomous guidance will be essential.

Hypervelocity target intercept techniques have been under development by the U.S. Military for ballistic missile defense (Nozette et al., 1994). Such techniques, when available without security restrictions, promise to provide critically needed advances toward solving the difficult autonomous terminal guidance problem, especially under short-response-time conditions.

Automation and Robotics

Advances in automation and robotics will be essential to several phases of NEO defense missions. These include assembly in Earth orbit of separately launched interceptor segments; autonomy of operations near the target or on the target surface such as implanting and operating high-energy propulsion systems or mass drivers, performing subsurface placement of a nuclear explosive, or collecting and processing surface material for propulsive purposes.

At present, spacecraft automation techniques, originally developed for lunar and planetary exploration, are being further advanced for use in a new generation of space exploration missions. The projected international space station requires development of advanced robotic manipulation, assembly and maintenance techniques, to save cost, minimize human operator workload and reduce hazardous task exposure. This evolution is an important step toward automated performance of some of the NEO defense mission phases. Demonstration during the construction of the space station will stimulate further growth of this technology.

Technology Drivers and Limiting Factors

Table II summarizes principal factors that influence the evolution of advanced and novel technology needed for use in NEO defense missions. The issues involved are listed as they relate to various mission phases or activities, grouped into eight categories. Also listed are limiting factors and constraints that apply in each of these advanced technology fields. The last column ranks these developments according to their relative priority: very high, high and medium. High, or extremely high cost, although not listed here, will be a critical constraint on almost all items included in the table.

Mission activities included in the list, but not previously discussed, are tests or demonstrations of feasibility and performance; nuclear device adaptation for NEO defense purposes; and communication and tracking operations.

- Test and demonstration requires novel techniques specifically related to the unprecedented NEO intercept and mitigation tasks. The key technologies discussed above should be included in these demonstrations. Ultimately, a demonstration mission to a non-threatening "NEO-of-opportunity" may have to be flown to attain sufficient realism in testing key operation sequences.

- Nuclear detonation development should include testing of explosives of the type that would be employed for NEO deflection, fragmentation or pulverization, although not necessarily devices of the required actual size and yield. Clearly such tests cannot be carried out on or near Earth but should be performed in deep space. This would require internationalnegotiations and agreement, based on the general, global interest in NEO defense.

TABLE II

Technology Drivers and Limiting Factors

[illegible] Mission Phase	Technology Drivers	Limiting Factors or Constraints	[illegible]	Priority
1. Test and demonstration	Test facility development and testing	Realism and validity	High	
	Precursor missions to NEO	Enough time available	High	
2. Launch (*see also* Propulsion)	Launch vehicle capability	Unprecedented vehicle size	Very high	
	Launch readiness	Long standby periods	High	
	Unprecedented scope	Coordination	Medium	
	On-orbit assembly	Feasibility and risk	High	
3. Interplanetary transfer (*see also* Propulsion)	Complex mission planning & execution, possibly with gravity assist	Launch windows	Medium	
4. Guidance, navigation & control	Target detection, terminal guidance sensing	[illegible] limitations	Very high	
	Pinpoint terminal accuracy			
	Autonomous rendezvous & landing	Risk, safety	High	
5. Propulsion (Phases 2, 3 & 4)	High specific impulse	Safety	High	
	Endurance & reliability	Development cost & schedule	Medium	
6. Nuclear detonation	Control, safety, & high yield	Adequate test program	Very high	
		Long development time		
7. Communications & tracking	Comm time delay compensation	Autonomy requirements	High	
	Continuous coverage	Possible Sun interference	(NA)	
8 Automation & robotics	O [illegible] as [illegible] m	Human assistance essential	Very high	
	R [illegible] m [illegible] m [illegible] control near or at target	Backups burden design, increase launch weight	High	
	Safety & reliability			

- Communication and tracking activities to be employed in the NEO defense context present novel technology requirements. These include the ability to conduct continuous uplink/downlink data transfer during critical mission phases; compensation of communication delay; rapid interpretation of observation data received and immediate reaction in terms of ground-based interceptor control. Rapid detection of, and response to the effect of mitigation activity at the target also is a requirement, particularly if a second (back-up) interceptor is en-route and must be controlled in accordance with observed results achieved by the first interceptor.

Technology Evolution for Conventional Missions and for NEO Defense

One of the principal obstacles to technology advances dedicated to NEO defense requirements is the lack of major funding that would be available prior to the discovery of an actual NEO threat. At best, some technology evolution that is related to general, i.e., conventional space mission objectives can also be utilized for development of future NEO defense capabilities, as a "spin-off".

Figure 6 depicts the relationship between the two inherently related fields of space technology. The scale on the right indicates technology requirements and development criteria of NEO defense missions, increasing from the easiest to the hardest mission demands. The left side indicates technology advances to be expected in coming decades, driven essentially by conventional mission needs, and supported by research and development funding.

The figure indicates that the least-demanding NEO defense missions are feasible based on the present state of technology. Inputs from the NEO defense engineering side may help in directing needed technology developments, without being supported officially.

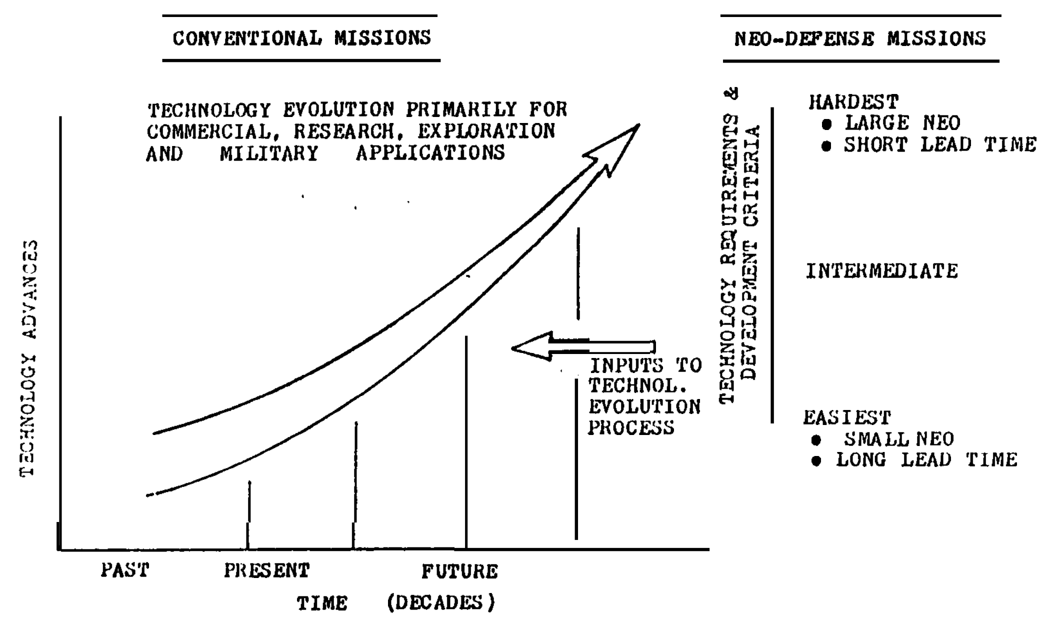

Figure 6 - Technology Evolution Serving Both Conventional and NEO-Defense Mission Needs

Mission/System Design and Technology Requirements Flow

Methodology used in mission and system engineering for finding the most efficient and cost-effective design and operating concepts in conventional space projects can also be applied in the NEO defense field. Figure 7 schematically illustrates the process of selecting the most advantageous mission and system concept among various alternatives. This involves a trade between system design options and technology requirements. The choice may be between a more costly design that can be implemented with existing technology and a less costly design that requires higher technology development expenditures. The selection process is based on a set of applicable figures of merit, listed on the right, that are agreed upon at the start. Extensive iteration of design concepts and technology demands is vital to this selection and decision making process.

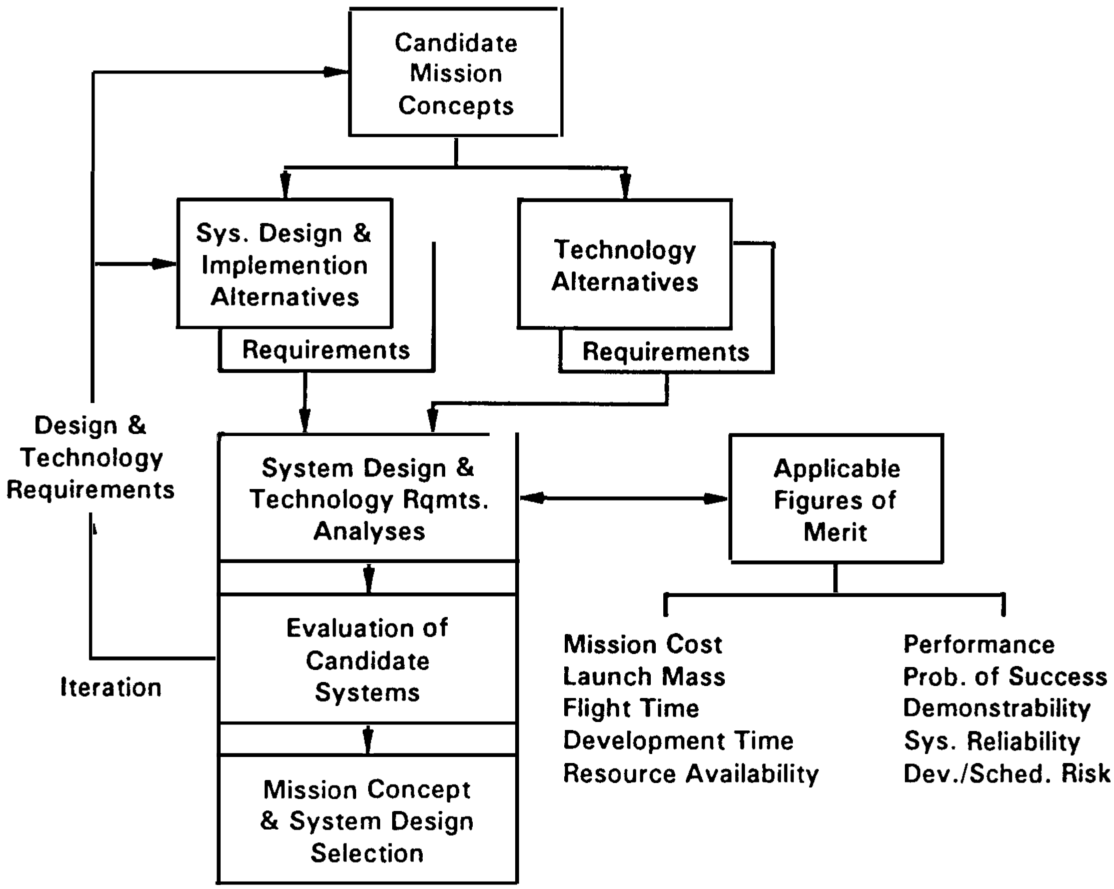

Figure 7 - Methodology of Mission and System Concept Selection

A related technology requirements flow chart is shown in Figure 8. It complements the preceding chart by indicating three levels of technology status - currently available, extended, and entirely novel - that should be assessed in the process of selecting the best mission and system concept. Some assessment criteria listed in the lower part of the chart are used in the feedback and iteration process that leads to the concept selection, including the design, its implementation and operation procedure. The flow charts represent a system engineering approach, discussed in greater detail by Larsen and Wertz (1994), that relates to the requirements trades referred to in this section.

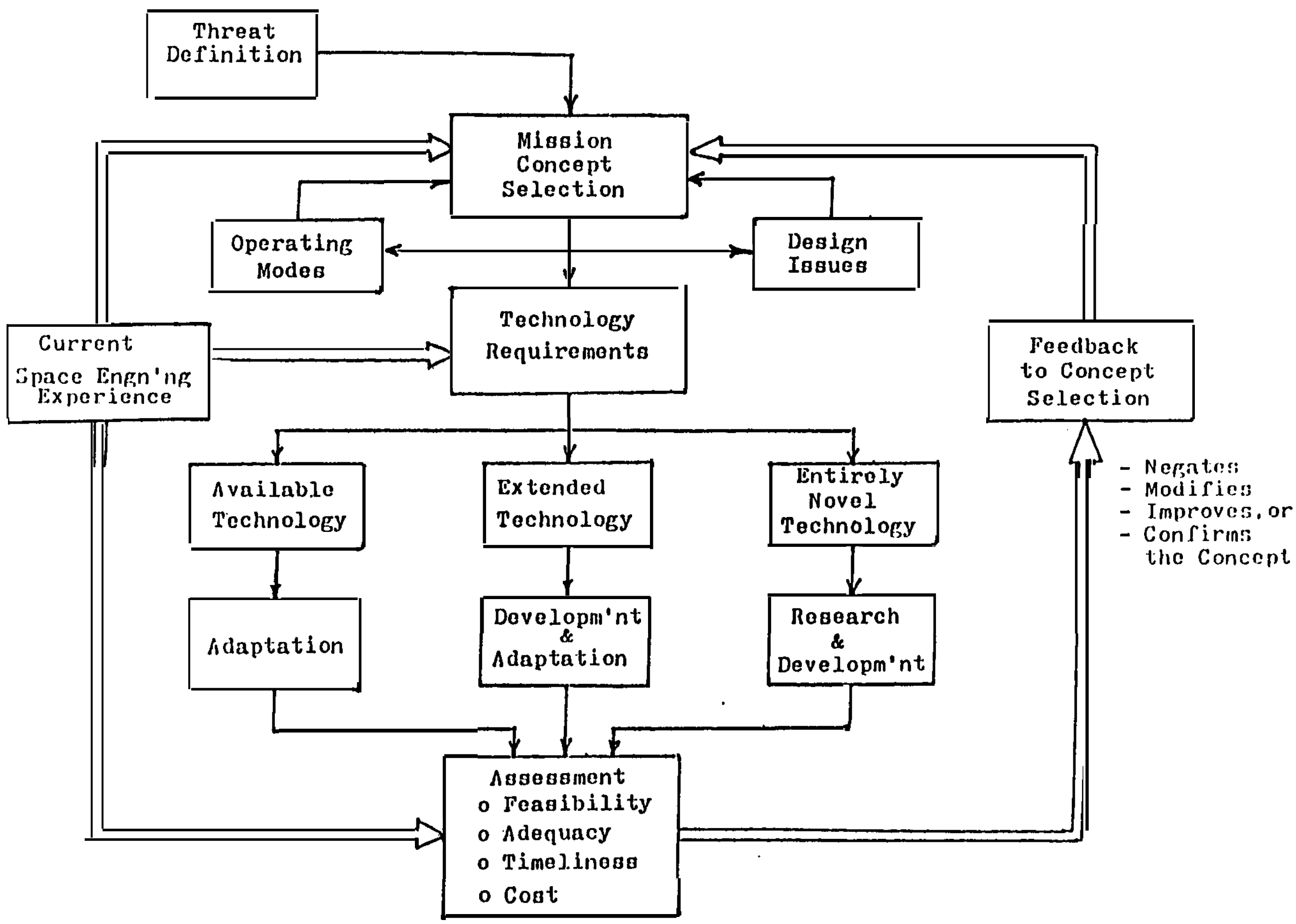

Figure 8 - Technology Requirements Analysis Flow

Preparedness for NEO Defense

There are many constraints and obstacles to being prepared for undertaking a NEO defense mission, now or in the immediate future - except perhaps the least demanding type referred to in the preceding sections. This is due not only to a lack of resources available before a major threat is detected and identified, but also to public indifference in the absence of an identified threat.

To develop and build a system for NEO defense ahead of time, ready to be launched on short notice, would be impractical and probably wasteful. Different types of impact threat will require different types of defense systems, mission modes and scenarios. Also, evolving advanced technologies tend to make a system, built in advance of actual threat detection, obsolete by the time it would be needed. That time might be many decades, perhaps even centuries, from today. New technologies such as those referred to above will make different and potentially more effective defense strategies feasible.

A fundamental dilemma concerning the desired threat response preparedness needs to be resolved: (a) there is no point in detecting a threatening NEO if no feasible program for defense against it is available; (b) a program for defense against a threatening NEO is useless, unless we search for and detect it sufficiently long in advance of the projected impact time (Dixon, 1993).

To resolve this dilemma requires reasonable and economically affordable steps toward developing and maintaining some threat response capability within the framework of current and continually evolving technologies. These steps include:

- Stepped-up search for, and cataloguing of potential NEO threats. Such efforts are now in progress under Space-Watch auspices

- Ongoing mission and system design activities, within existing and advancing technology capability. Results reported in these proceedings are encouraging evidence of the initiation of such activities.

- Technology development and tests required to achieve greater preparedness. Still hampered by lack of re sources.

- Organizing global cooperation to support future threat response capabilities. International participation in recent conferences and workshops is an encouraging step forward.

Preparedness within the capabilities and constraints of the technology available at a given time means that efforts must be pursued continuously to define and develop preliminary mission and system design concept consistent with that state of technology. Thus, by the time a threat warning is received from the ongoing NEO search and detection activities, there would be at least a blueprint available for system development, implementation and test that could serve to accelerate the threat response as needed. At the same time detailed mission profile data, launch and arrival dates, as well as, ground support plans and schedules would have to be worked out. In this way the results of the preceding threat defense planning studies could be utilized to full advantage, updated as appropriate under the circumstances.

For an effective implementation of the intended threat response with the highest probability of success, it as imperative to launch more than one interceptor. For example, assuming a 95-percent best estimate of the success probability of the defense mission being initiated, if one interceptor is launched, then two launches would increase the combined success probability to 99.75 percent, and three launches to 99.99 percent, provided the causes of failure are unrelated, random events. Multiple launches will generally not increase the total cost by the same multiplying factor.

Conclusion

Technology requirements of missions to avert a NEO impact on Earth are dictated by the nature of the threat, i.e., object size and physical composition, orbit characteristics, arrival velocity, and the time remaining before the predicted collision. All phases of such missions place unprecedented demands on the technology to be used for their implementation, particularly the launch phase, the terminal guidance and landing phase - if planned - and the deflective impulse generation at the target, or its destruction. Robotics and automation play a key role.

The least demanding threat class may allow a defense with today's technology. Results of most of the current studies favor nuclear detonation over kinetic energy (direct impact) deflection, because it requires an up to three-orders-of-magnitude lower initial interceptor mass. On-site propulsive deflection is much less likely to be feasible with currently available propulsion technology because of the very much greater total propellant mass required, compared with the two alternative deflection modes.

For NEO defense with a short reaction time there will be practically no alternative to nuclear detonation options. However, many concerns regarding deployment risks and safeguards against misuse remain to be addressed and resolved.

System engineering methods developed for more conventional mission classes also are applicable to system selection, evaluation and implementation trades required in missions for NEO defense. Assessment of technology requirements is a principal step in this selection process, in order to eliminate impractical, potentially risky, unacceptably costly and otherwise unsuitable implementation concepts.

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SPACECRAFT ORBITAL MECHANICS ANALYSIS

FOR INTERCEPTION SERVICE

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At present time about 6120 asteroids are discovered, they are catalogued and have reliably determined elements of orbits. About 17 thousands asteroids are discovered, but they have not reliably determined orbits. In a main asteroid belt between a Mars and Jupiter is concentrated 99,8 % of asteroids.

Among asteroids outside of a main belt group of bodies, approaching with the Earth, is the most important forus. Quantity of such asteroids with the size more than 1 km is estimated in 1700 - 2200 bodies (on data T. Gerels, USA). Asteroids of Amor, Appolo and Aton group have name near - Earth asteroids. These asteroids can come nearer to the Earth less than on 45 mln. km. If to accept, that the distribution near - Earth asteroids by sizes is close to distribution of small-sized asteroids of a main belt, we shall receive the following estimations of quantity near - Earth asteroids:

Diameter of bodies

Diameter of bodies	near - Earth
>1 km	2000
>100 m	200 thousand
>50 m	800 thousand

If to take into account, that the asteroids are distributed in tube with diameter 1 a. u., easily to receive, that in a vicinity of the Earth with radius 1 mln. km one asteroid appearls on the average in 2,5 days from number potentialy dangerous bodies with the size of 50 m.

Asteroids, the orbits of which are located near to an Earth orbit have small values of the asimptotic approach velocity (0 - 3 ...5 km / m). Small relative velocities of such asteroids permit to have a large reserve of time before expected collision, however they approach with the Earth from any direction practically with equal probability. Therefore for their timely detection it is necessary to carry out scanning of whole celestial sphere. Other important peculiarity of such asteroids is the fact, that for them the cross section of capture it can be more than diameter of atmosphere of the Earth (effect of the gravitational pressing for trajectories), fig. 1.

Other dangerous space objects (DSO) can be divided into two groups:

- DSO, orbits of which pass between orbits Mercury and Jupiter;
- DSO, perihelions of orbits of which lay inside an orbit of the Earth, and apoceuter lay at an orbit of the Jupiter or Pluto.

On fig. 2 are shown curves of possible relative velocities of approaching

DSO with the Earth for both above mentioned groups. It is visible, that the asteroids of the first group have maximum velocities of approaching from 8 up to 28 km / m, and asteroids of the second group - from 32 up to 71 km / m.

The possible variants of collision DSO with the Earth are shown on fig. 3.

For detection of asteroids and comets can be used optical, infrared and ultra violet telescopes of ground and space basing. Therefore the ground-space service of detection should form in view of an optimum combination of their opportunities.

It is necessary to note, that accommodation of telescopes in space will make their independent from weather and will allow to decide a problem of detection DSO coming nearer on the part of the Sun. It is for this purpose possible to place S/C with a telescope in a point libration L1 the sun - Earth system were between the Sun and Earth on distance 1,5 mln. km [1]. It will ensure a reserve of time more days, at velocity of approaching V=1 7 km / m.

Space segment of a service of detection of asteroids will include in self a little S/C with telescopes, working on near - Earth and heliocentric orbits (fig. 4). For detection DSO coming nearer on the part of the Sun it will be possible to place 1-2 S/C in a point libration L1, and then and on other heliocentric orbit in a vicinity of the Earth, and on large distances, for example in points libration L4 and L5, located on distances in 150 mln. km from the Earth. It will allow with significant forestalling to find out DSO.

On fig. 5 boundaries of interception DSO on interplanetary trajectories are resulted. Times of flight in given points of a meeting are determined from the moment of start S/C from an Earth parking orbit in height of 200 km.

The boundaries resulted on fig. 6 of interception on interplanetary trajectories are given for case of velocity of start from a basic orbit in 4 km / m. It is visible, that for interception on distance 40 thousand km (the range of a geostationary orbit) is required 6 hours, and in region of an orbit of the Moon 4 days.

Proceeding from available time of achievement of a boundary of interception, easily to determine from fig. 7 detection required to range DSO depending on their velocity of approach to the Earth. Than it is less interval of time between start and interception, that large velocity is necessary for informing S/C, that is shown on fig. 8 and 9.

For a withdrawal DSO with getting in the Earth of a trajectory that smaller change of its speed is required, than on greater distance it will be carried out.

As an example it is possible to estimate power expenses for a withdrawal of asteroid with getting trajectories in days before collision with the Earth. Velocity required to a lateral pulse will in this case make 100 m/s. For asteroid by a diameter 100 m, type consisting of a material basalt, it will correspond to energy of the order 1013 j. Such energy is allocated at explosion nuclear charge by capacity of 2 kt. Were available data show also, that for destruction basalt asteroid the diameter 500 m require charge by capacity 3-5 mt. Weight such charge will make about 3 tons, that lays within the limits of opportunities on insertion payload by the modern LV.

The results of lead design-ballistic studies show a technical opportunity of creation of a service of protection of the Earth from dangerous space objects within the framework of wide international cooperation [2].

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Diameter of the Earth approach trjectory pipe

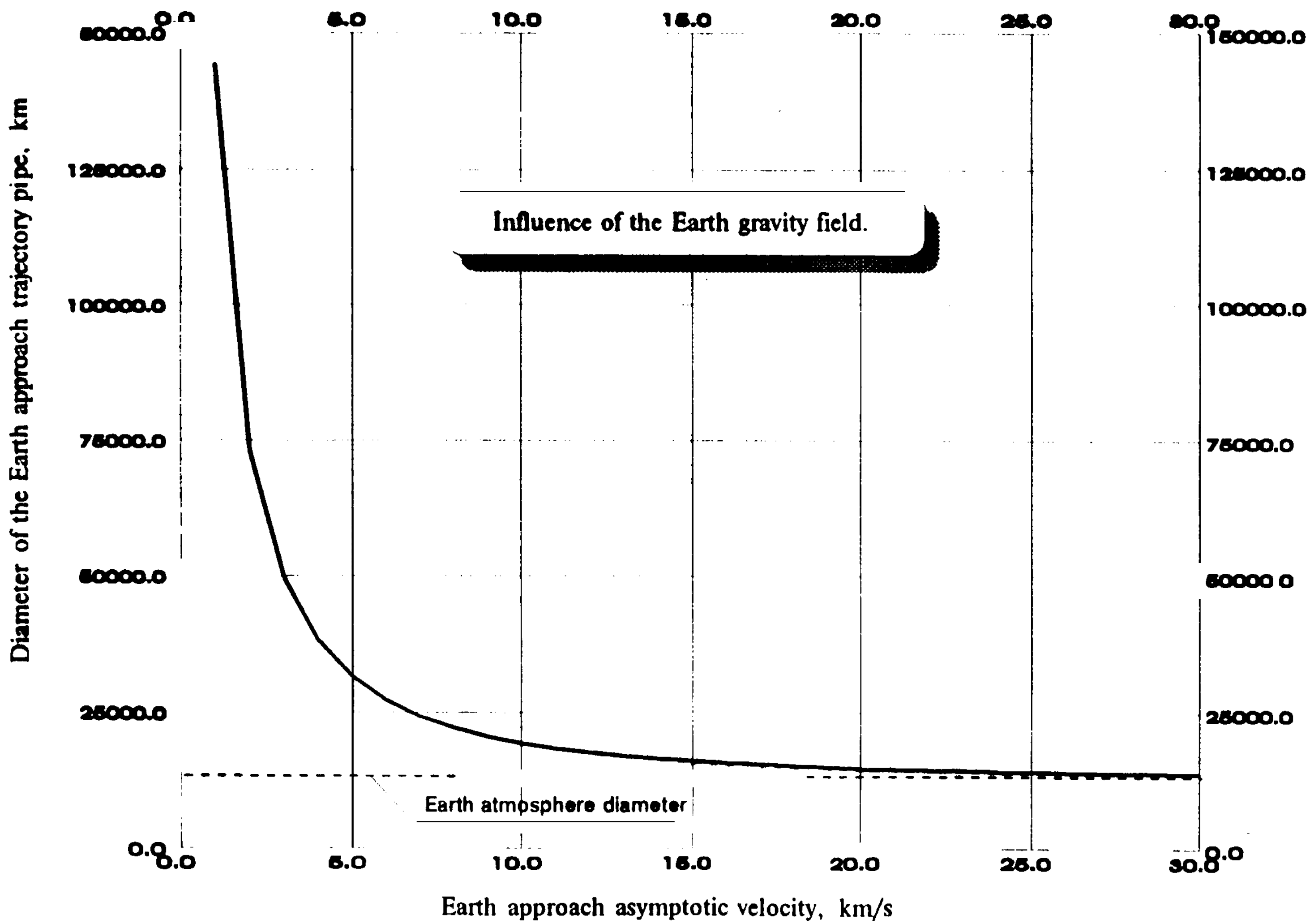


Fig 1

Possible relative velocity for collision DSO with Earth

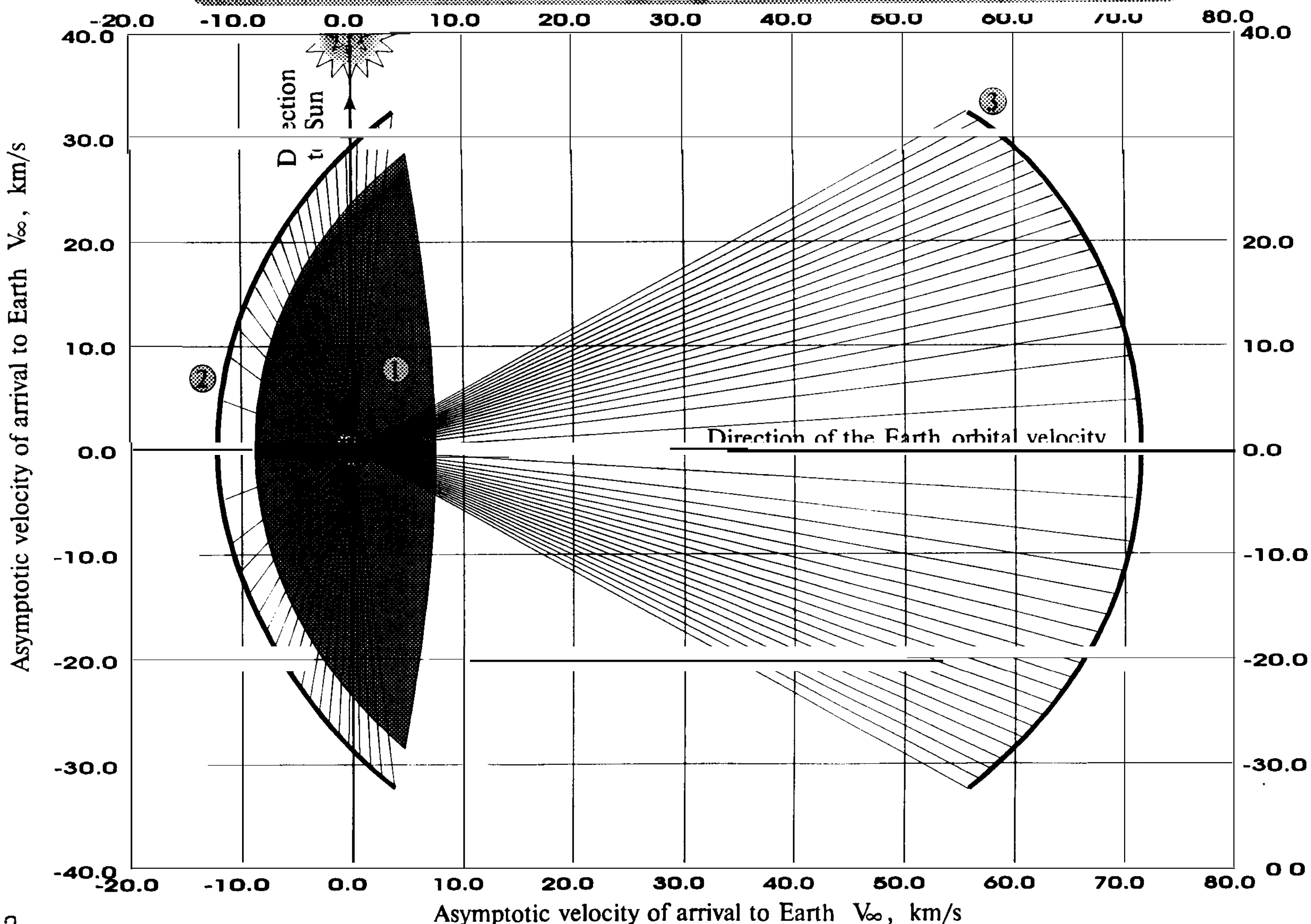
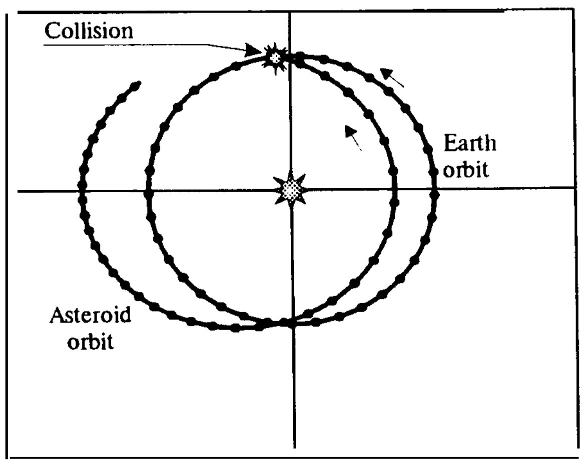


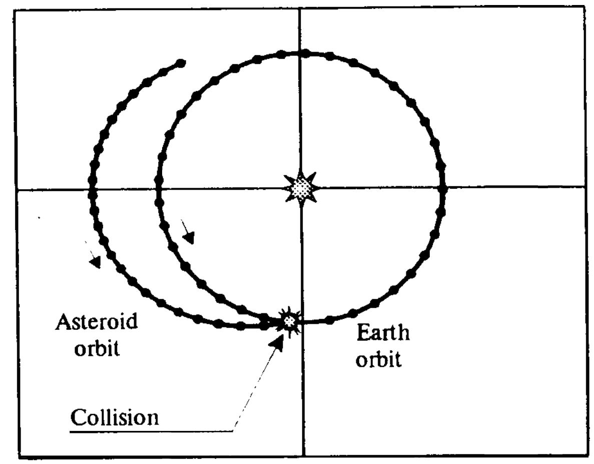
Fig. 2

Possible options of collision with Dangerous Space Objects (DSO)

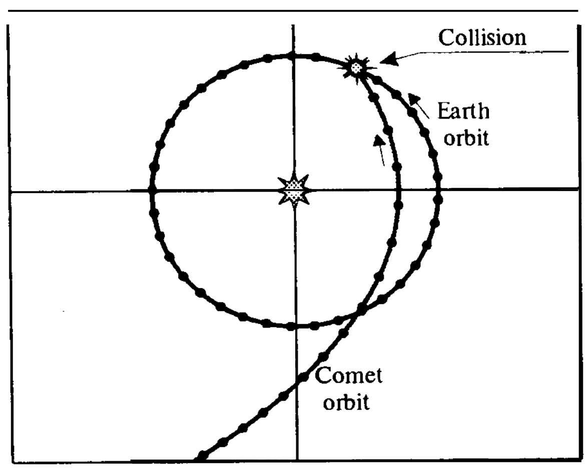
Time ticks - 10 days



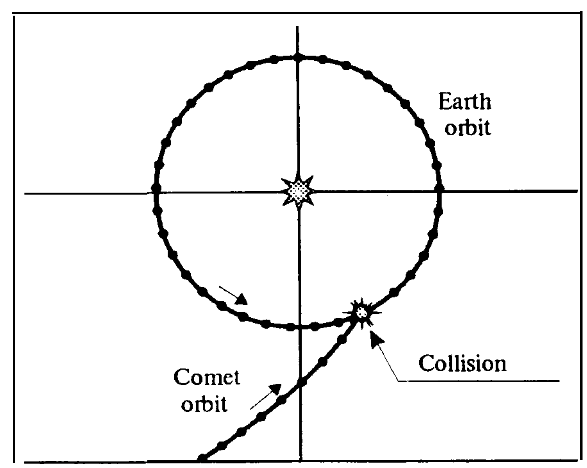
Collision with asteroid, moving from perihelion



Collision with asteroid, moving to perihelion



Collision with comet, moving from perihelion



Collision with comet, moving to perihelion

Fig 3

SPACE OBSERVERS POSITION

ON THE HALO-ORBIT AROUND LIBRATION POINT L1

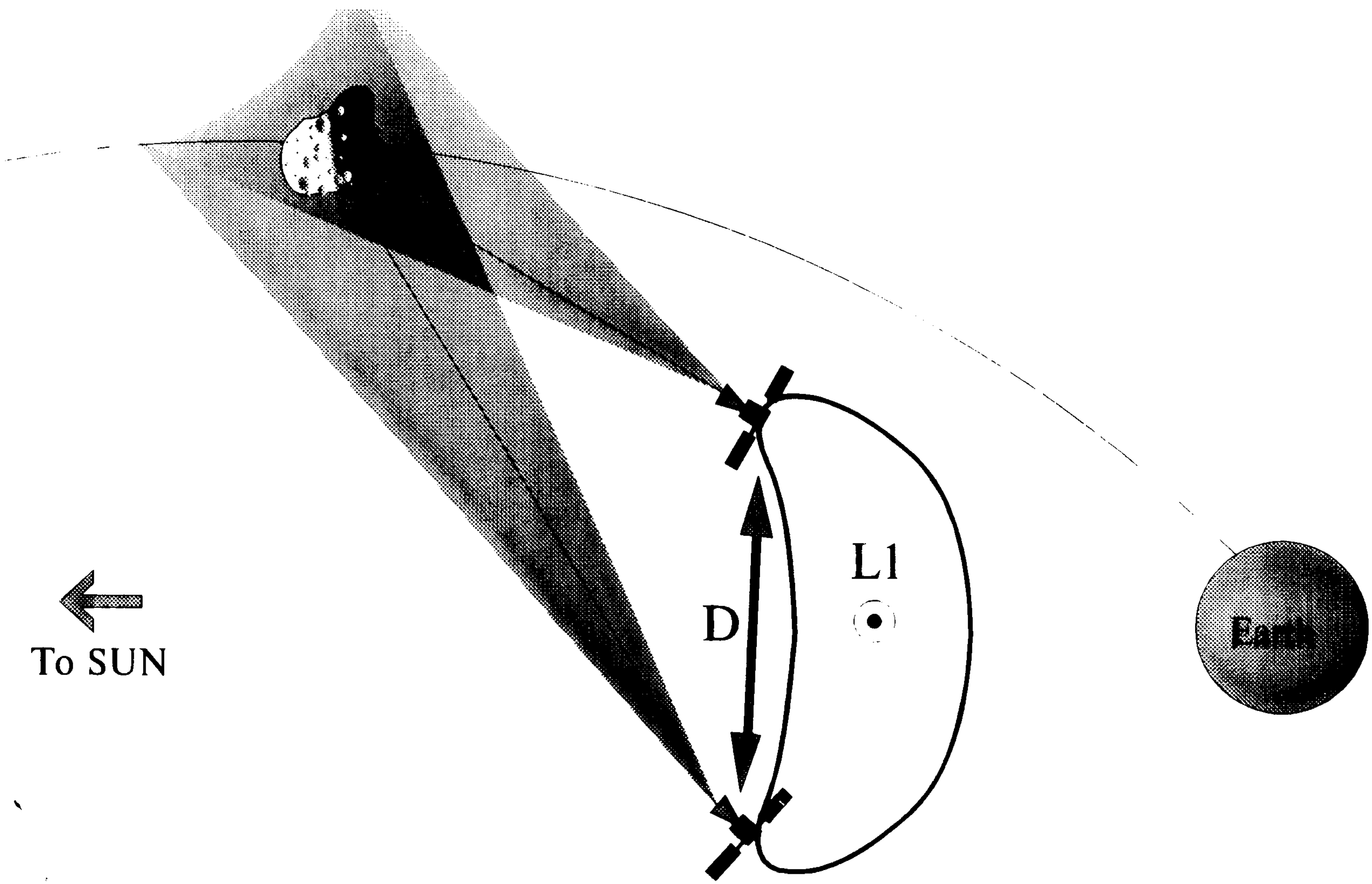


Fig. 4

INTERCEPTION TIME VS DISTANCE

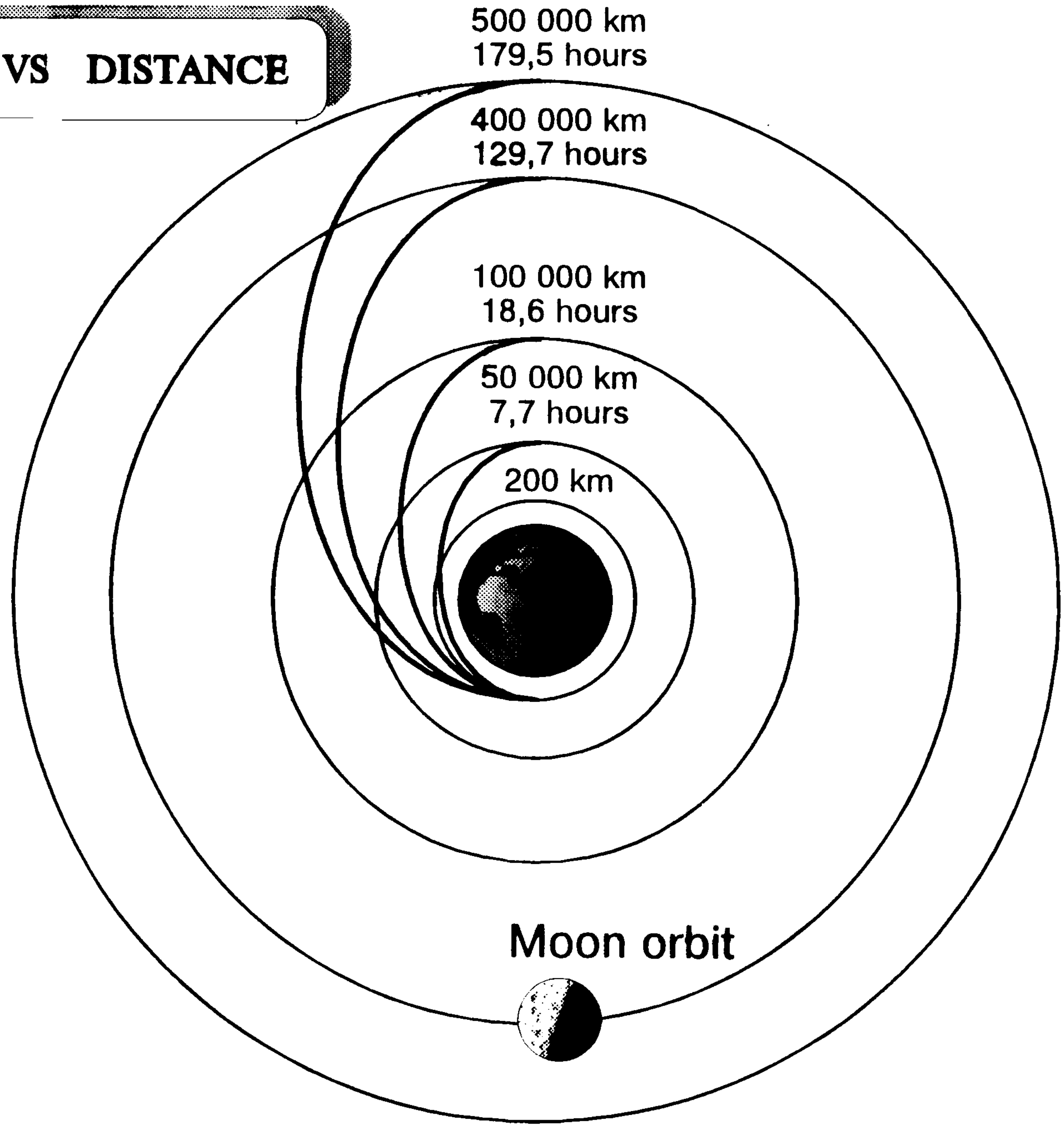


Fig. 5

Boundary of zone which can be reached during different time (days)
(Earth departure velocity is 4 km/s)

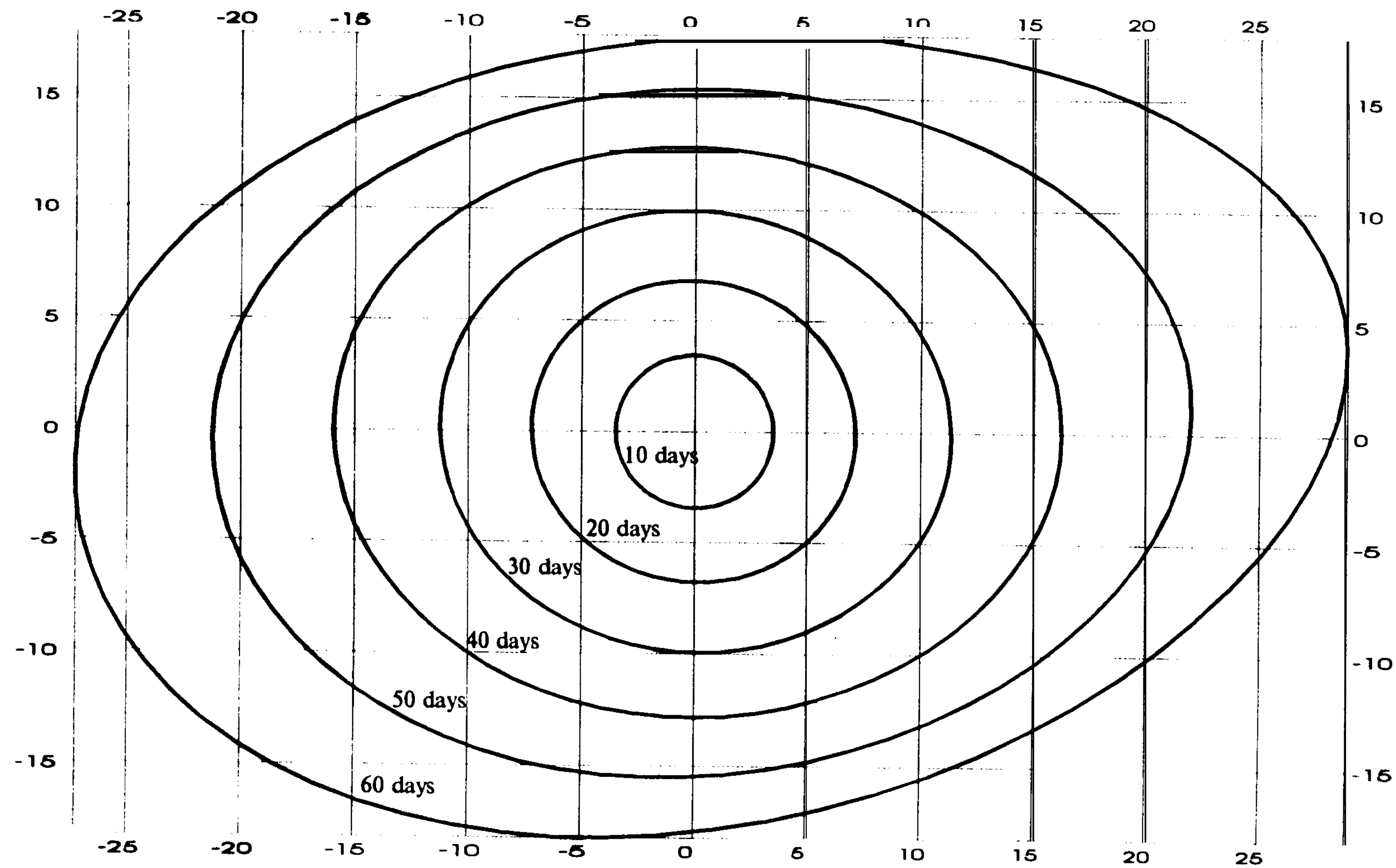


Fig. 6

Distances to DSO vs. time of the moving to the Earth for the different volumes of approach asymtotic velocity (V_∞)

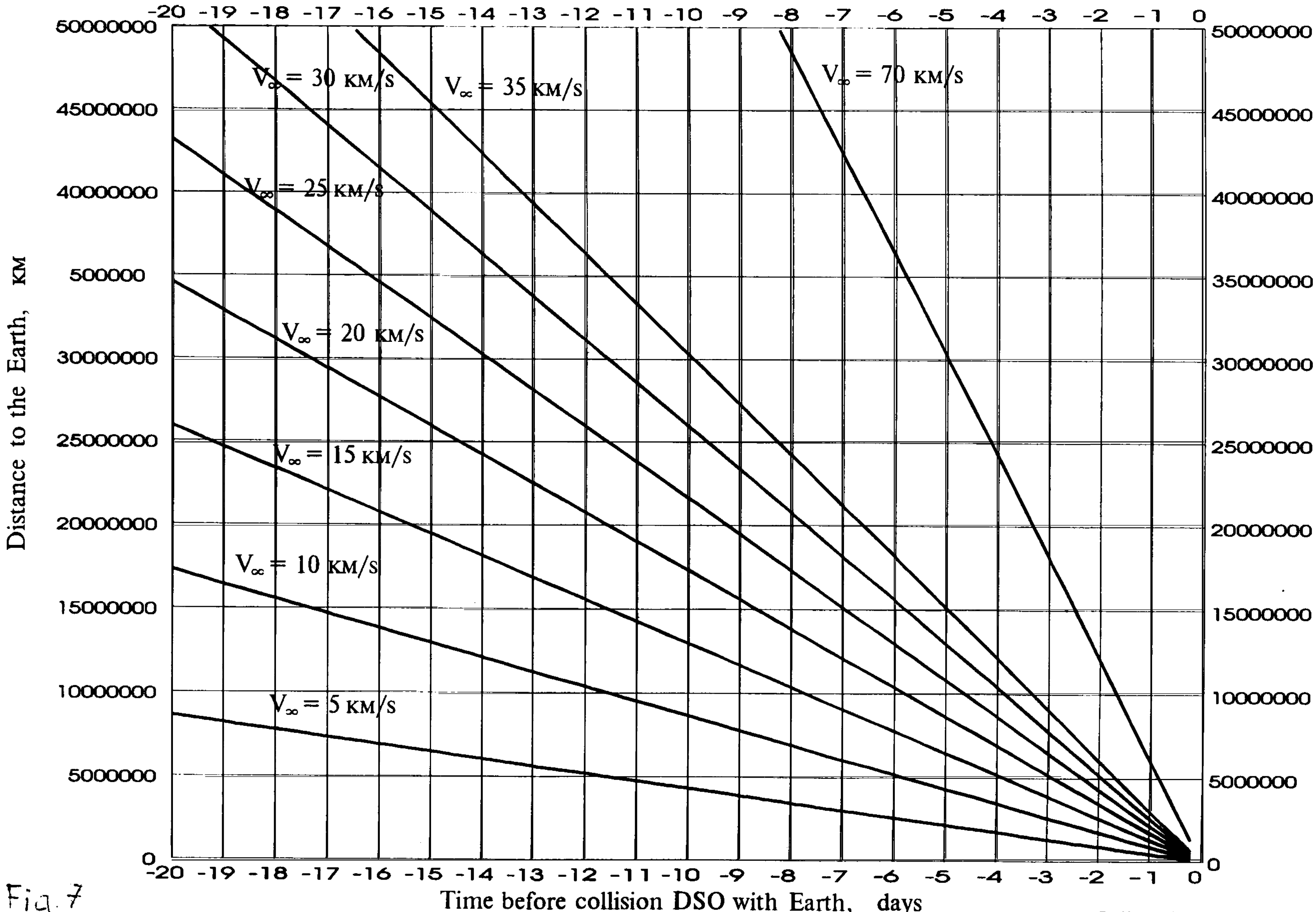
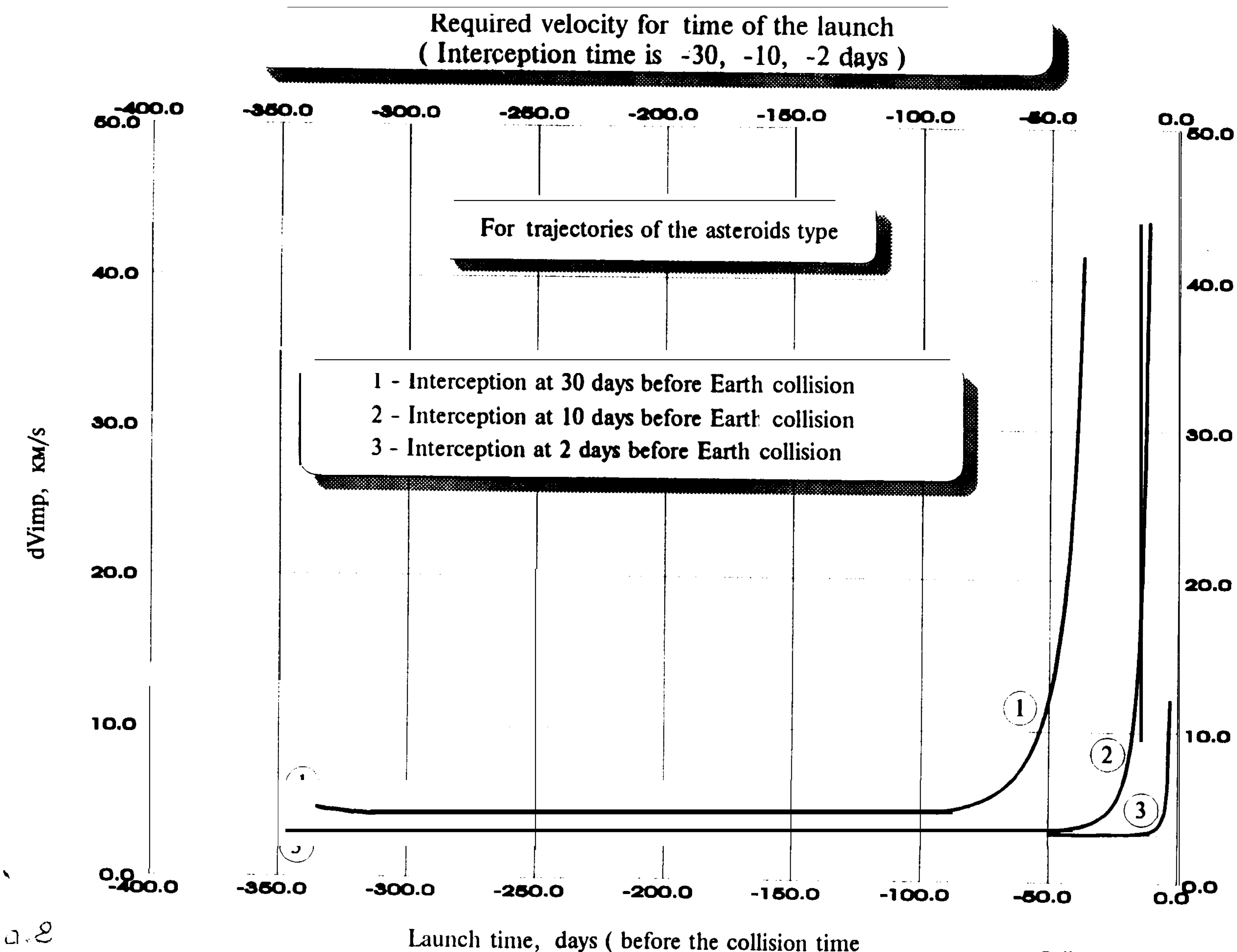


Fig. 7



Required velocity for time of the launch
(Interception time is -30, -10, -2 days)
For trajectories of the asteroids type
1 - Interception at 30 days before Earth collision
2 - Interception at 10 days before Earth collision
3 - Interception at 2 days before Earth collision
dVimp, KM/s
-400.0
-350.0
-300.0
-250.0
-200.0
-150.0
-100.0
-50.0
0.0
50.0
40.0
30.0
20.0
10.0
Launch time, days (before the collision time

Fig. 2

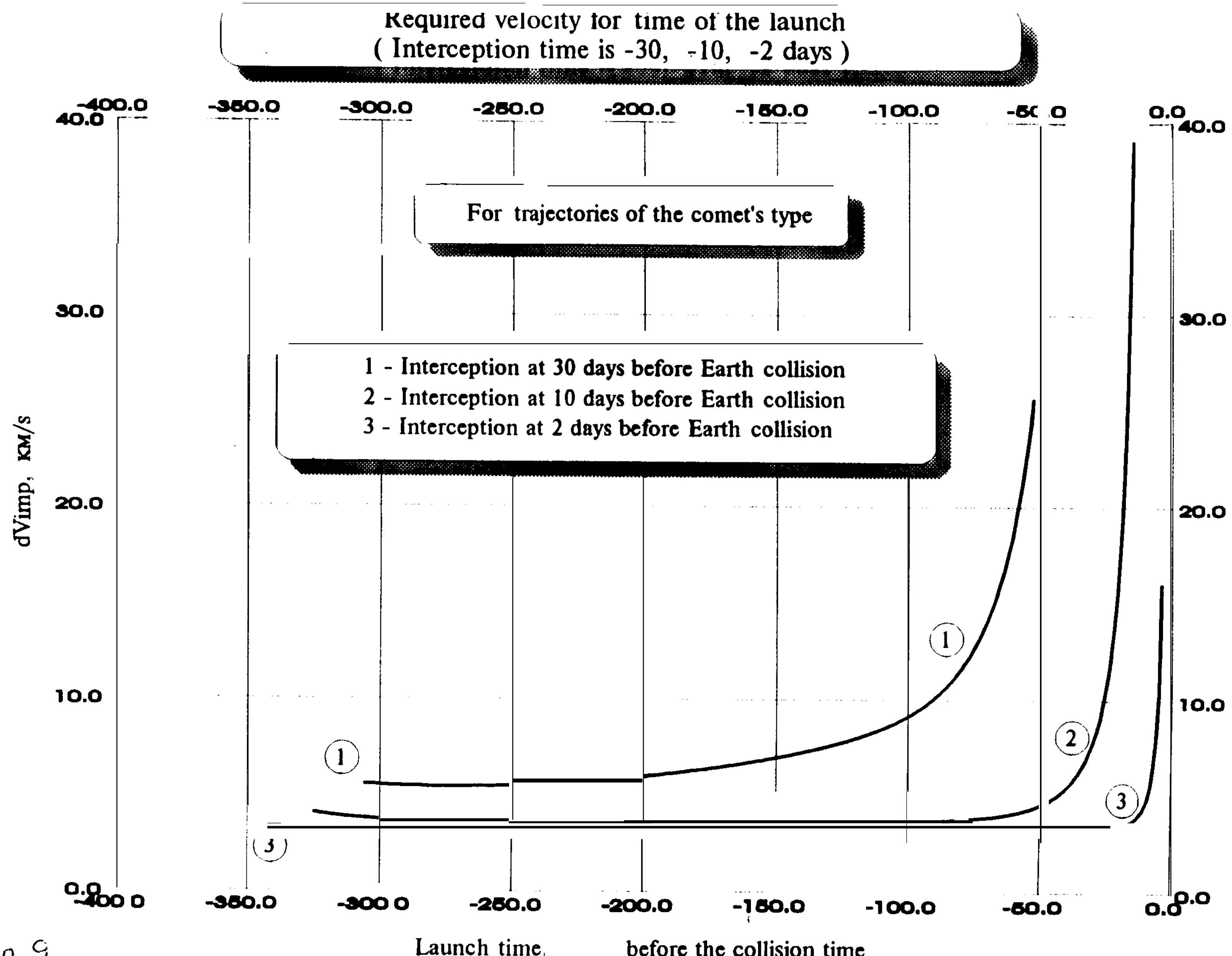

Required velocity for time of the launch
(Interception time is -30, -10, -2 days)
For trajectories of the comet's type
1 - Interception at 30 days before Earth collision
2 - Interception at 10 days before Earth collision
3 - Interception at 2 days before Earth collision
dVimp, KM/s
40.0
30.0
20.0
10.0
0.0
-400.0
-350.0
-300.0
-250.0
-200.0
-150.0
-100.0
-50.0
0.0
1
2
3
Launch time, before the collision time

Fig 9

OPPORTUNITY TO CREATE THE SYSTEM FOR SPACE PROTECTION OF THE EARTH AGAINST ASTEROIDS AND COMETS ON THE BASE OF MODERN TECHNOLOGY

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The main purpose of our report is to show, that already right now it is possible to begin practical steps on creation of main components of the System for Earth Protection(SEP) from hazardous space objects (HSO) - asteroids and comets. Thus we shall consider basically space components of the SEP, leaning mainly on experience of the Lavochkin Association and some other Russian and foreign firms.

For creation the SEP there is the set of the suppositions [1 ,2]. Among major of them are as follows:

- *Biological* - aspiration of whole live, and consequently the mankind, to preserve a stable equilibrium (homeostasis);
- *Ecological* - possibility of evolving of a global ecological catastrophe as result of a "trigger effect" induced by the collision even with a relatively small celestial body;
- *Political* - the end of "cold war ";
- *Technological* - creation of rocket and space means, nuclear weapons, means of telecommunication, control etc.

The development and creation of such System should satisfy to a number of requirements and restrictions. Among the major of them are:

- maximum use of actually available means;
- integration of special SEP equipment with instruments for other purposes;
- presence of a space segment of a service of HSO detection ;
- presence at least of two echelons of HSO interception service: for near (operative) and distant interceptions;
- providing of ecological safety of interception service application;
- international status of the system and etc..

It is obvious, that a pioneering stage of creation SEP should be creation of a HSO Ground and Space based Detection Service (GSDS). The necessity of creation of a space segment of the GSDS does not cause doubts. The main purpose of the segment will be providing of the celestial sphere fast review and preliminary determination of asteroids and comets trajectories. The more accurate measurements the will be carried out by ground instruments and spacecraft of a "Space Hubble" type.

Tentative estimations of the space detection means capacities, carried out by different researchers [3,4], show, that such telescopes will have rather moderate mass and energy consumption.

It will allow to install the detection means not only on special space vehicles (SV), but also as a piggy-back payloads for SV , intended for other purposes.

For this purposes may be proposed space platforms developed by Lavochkin Association: "OKO", "Spectr" and other.

SV "OKO" is regularly launching (2-3 times per year) to high elliptical and geostationary orbits; a series of the "Spectrum" SV are scheduled for launching in the nearest years.

Technical characteristics of the above mentioned SV and means of insertion to orbit permit to generate various variants of the orbital configuration of a SEP space segment (Fig. 1).

SV with telescopes can be injected to high elliptical, geostationary and heliocenrtic orbits. It may provide optimum conditions for HSO observations.

For instance, observations carried out in the L1 libration point (Earth-Sun system) may permit to find out objects, approaching to the Earth from the Sun side [5].

Instruments for HSO observation (as a part of the space segment) in this case may be easily integrated with developing now in Russia system for global heliophysics monitoring "GEKATA"[6]. It will allow to execute a complex monitoring of a space environment for SEP, branches of a national economy and science purposes. At the same time it also will stimulate development of ground means of HSO observation.

Thus use of actually existing technological potential will provide fast creation of a SEP space segment, with relatively low cost and at small technical risk.

In the long term, it will be possible to install miniature patrol complexes for HSO detection and the data processing on interplanetary SV. It will allow to register asteroids and comets in various areas of Solar system.

After creation of the GSDS all asteroids with the size more than one kilometer through some time will be detected and registered in a Catalog. It will allow make a forecast of possible collisions on many years ahead and to arrange on prevention of collisions with the help of a Distant Interception Service of SEP.

It will be impossible to register all HSO with the size less than one kilometer. Therefore they must be intercepted on near approach to the Earth by operative interception service.

It is obvious, that developing of the of distant interception service must be based on an infrastructure, created for of interplanetary space vehicles. The Lavochkin Association has considerable experience of developing, production and operation of such robotics spacecraft.

For these purposes a wide spectrum of launchers and some existed SV may be used. Modern space launchers ("Energia") are capable to inject to the interplanetary trajectories spacecraft with mass up to 25-30 metric tons.

As example of possible SV-interceptor may be considered the vehicle of a "Phobos" type (or "Mars-96"). This spacecraft where developed in the Lavochkin Association. Mass of such SV, launched by the "PROTON" LV, reaches 5-6 tons. It is capable to work at the distances, corresponding the asteroid belt. This SV can to deliver to asteroid nuclear unit with power of several megatons. It may be a single charge or several individual nuclear charges. In the last case charges will be delivered by the individual means of delivery. If necessary, several SV-interceptors may be launched.

Several problems must be resolved during development of the of interception service . In particular, one of such problems is very high accuracy required for pointing of SV-interceptor to the HSO.

For solution of the above mentioned problem may be used a method, tested during approaching of Soviet SV "VEGA" and West Europe SV "Jotto" to the Haley comet nuclei. This scheme use at first fly by of the HSO by small SV-pathfinder and then approaching of the main SV. SV-pathfinder will adjust parameters of HSO orbit and study the physical characteristics of HSO. That information will be used for selection of the scheme of the interceptor affect on the HSO.

The possible scheme of a distant interception service structure is shown on the Fig. 2.

So, even already existing space means may be substantially used for distant interception of HSO.

However, creation of a special echelon of distant interception and the maintenance of this structure in constant readiness will be extremely expensive.

Therefore it is offered, having developed the international concept of an interception service, to keep the project in permanent readiness for realization ("postponed realization "). At the same time basic components of the service may be worked off during realization of missions for Solar System exploration. It will allow to support a necessary level of readiness of the service, and to deploy the system in shortest time in case of the threat of collision with a large celestial body.

Hence, the future space missions to Solar system objects must be formed with taking in account the interests of SEP. In particular, during realization of developed in our enterprise mission "Mars-Aster" (delivery of probes to asteroid) some experiments for interception service may be fulfilled.

As against an echelon of distant interception, the echelon of close (operative) HSO interception should be maintained in a condition of permanent readiness.

For realization of practical steps on creation of an operative interception service we offer to develop the international demonstration project "Space patrol " (Fig. 3).

The purposes of this project are:

• development and testing of main components of an operative detection service and interception the asteroids, approaching to the Earth;

• study of asteroid physical characteristics from flyby and impact trajectories;

• adjustment of methods and means of action upon the HSO.

We want to stress that practically all components of the "Space Patrol " project actually exist or have a prototypes, the completion of which will not require large efforts. It will allow to realize the project by use of wide international cooperation in the shortest terms and at rather small expenses.

The realization of the "Space Patrol" project becomes possible in connection with recent new data concerning rather high frequency of flyby (about an once in a week) asteroids with diameter 50-100 m in vicinities of the Earth (fly-by distances less than 1 million km).

Such asteroids can be detected several days before closest approach to Earth. It permits, at already achieved terms of SV and LV preparation to launch, to execute the mission for asteroid inspection and testing of methods and means of action upon the HSO.

Thus, it is possible to use the near-Earth space as range for study of small celestial bodies and improvement of SEP components.

For increase of asteroids detection probability, in the nearest years alongside with development and the perfection of ground detection instruments, space telescopes must be developed within the framework of the "Space Patrol" project.

In a complex with available and prospective Russian and foreign ground instruments, including American system " Spaceguard Survey ", will be work out detection means and technology of interaction between observation centers of different countries.

In parallel with deployment of components of ground and space based detection service, small SV (SSV) with mass of 200-300 kg (as US "Clementine" spacecraft launched in 1994) should be created, for inspection of asteroids from flyby trajectories. This SSV may be used as SV-pathfinder in the structure of future SEP.

Probably, it is most attractive to use as a launch vehicles the modified decommissioned ICBM (in particular in frames of "Start-1" and "Start-2" Treaty). For these purposes can be used ICBM "SS-18" (LV "Conversion") and "SS-19" (LV "Rokot").

After installation of SSV on LV they are put on "battle" watch with use of a modified military launch complex. Thus the control of start of the given space-rocket complex should be carried out from International Center of Coordination and Management.

Fig. 4 illustrates possible variant LV "Conversion" with upper stage and SV for injection to Earth orbits or to interplanetary trajectories. In the first case mass of SV may be about 2200 kg, in second one - about 500 kg.

Two variants of SSV mission to asteroid may be considered:

- to newly discovered suitable asteroid, the trajectory of which passes on distances from the Earth achievable for SSV;
- to asteroid, the returning of which can be predicted beforehand.

In the first case the launch of SSV should be carried out at some days or hours before closest approach to the Earth. In second - with considerably large time margin.

When suitable approaching to Earth asteroid will appeared, the launch will be carried out for injection of SSV to approaching to asteroid trajectory.

During pass of a space vehicle on a flyby trajectory remote sensing will be carried out for study of the asteroid characteristics. At the same time methods of SSV control and precise navigation will be fulfilled. In this mission it is possible to deliver surface probes to asteroid (like penetrators).

After asteroid flyby the SSV can continue space researches, for example, in area of solar-Earth ties, within the framework of the developed project "GEKATA".

At the subsequent stages of work, after creation of the SV-interceptor, work out of methods and means of action on HSO will be fulfilled. Thus, for pointing of the SV-interceptor the information from earlier started SV-pathfinders will be used.

Moreover more powerful LV may be used (for instance, LV "ZENIT"). It will allow considerably to expand opportunities of study asteroids, flying close to the Earth, including, probably, asteroid sample return. This may become logic continuation of the project NEAR.

Thus, realization the first demonstration stage of SEP creation will allow essentially to expand our knowledge of properties of small celestial bodies of Solar system. But at the same time this will help to preserve and to develop the best achievement of Russia, USA and whole world community in the field of a science, engineering, manufacture, defense and etc. in interests of maintenance of safety of the whole mankind.

For realization of the "Space Patrol" project wide cooperation among main suitable organizations and enterprises should be generated.

All work should be carried out with wide cooperation of space agencies, academies of sciences and their institutes; defensive etc. organizations of all technologically advanced countries.

The limited frameworks of the report do not permit consider a set of other technical, ecological, political etc. aspects and problems of SEP creation. However, more detailed analysis, lead by the authors of the report and by other scientists and experts [7-1 2], permits to make a conclusion about necessity and opportunity of SEP development already in the near future.

Thus the expenses on space and launching components of System will be rather moderate, because in constant operation there will be only few space telescopes, and on " battle watch " will be a several LV with SV of an operative interception service. It will require much less expenditures, than is now spent by some countries on creation and maintenance of some kinds arms.

LIST OF ABBREVIATIONS

HSO	- Hazardous Space Objects
SEP	- System for Earth Protection
GSDS	- Ground and Space Based Dedection Service
LV	- Launch Vehicle
SV	- Space Vehicle
SSV	- Small Space Vehicle

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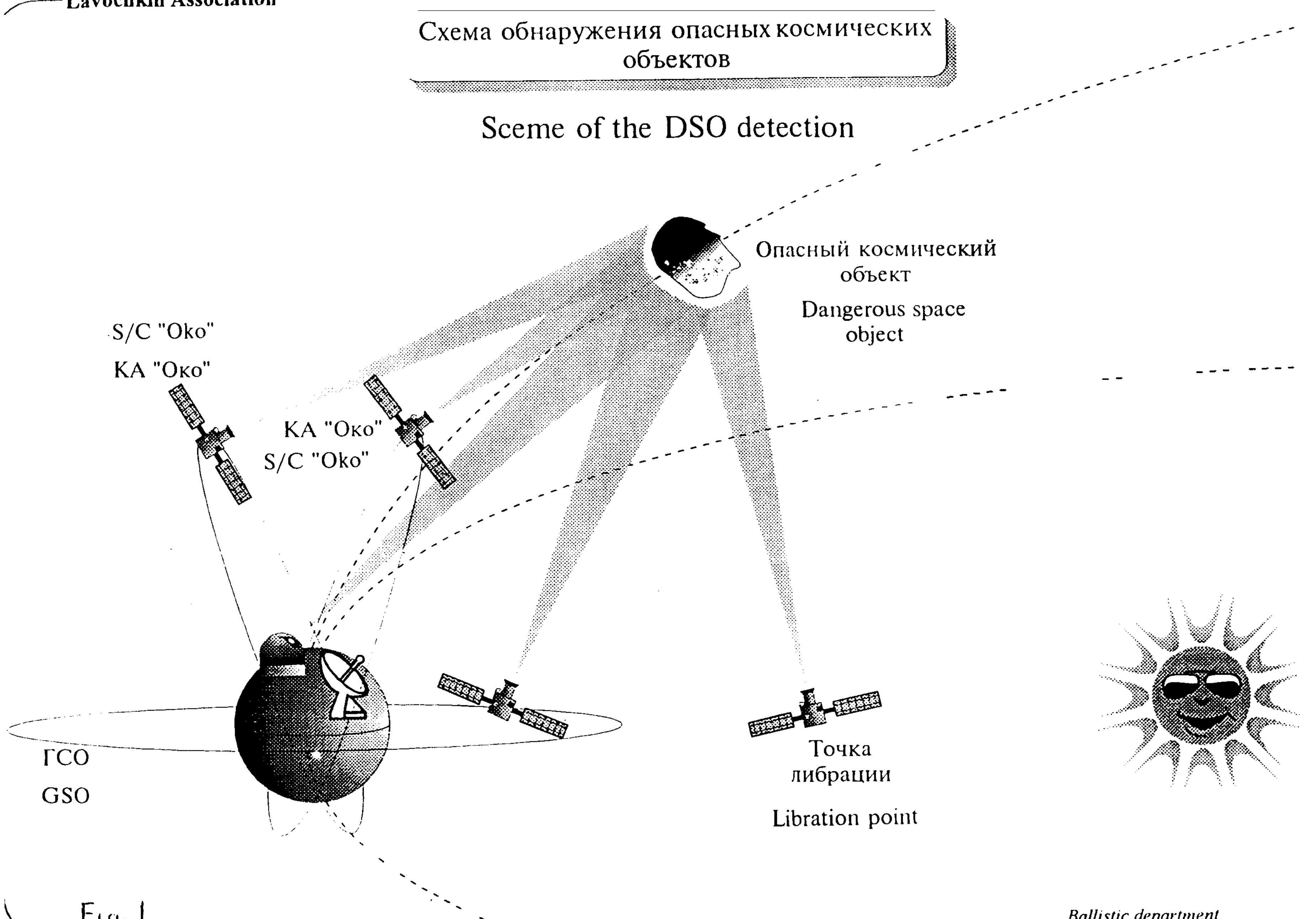
Схема обнаружения опасных космических объектов
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Опасный космический объект
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Точка либрации
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Fig. 1

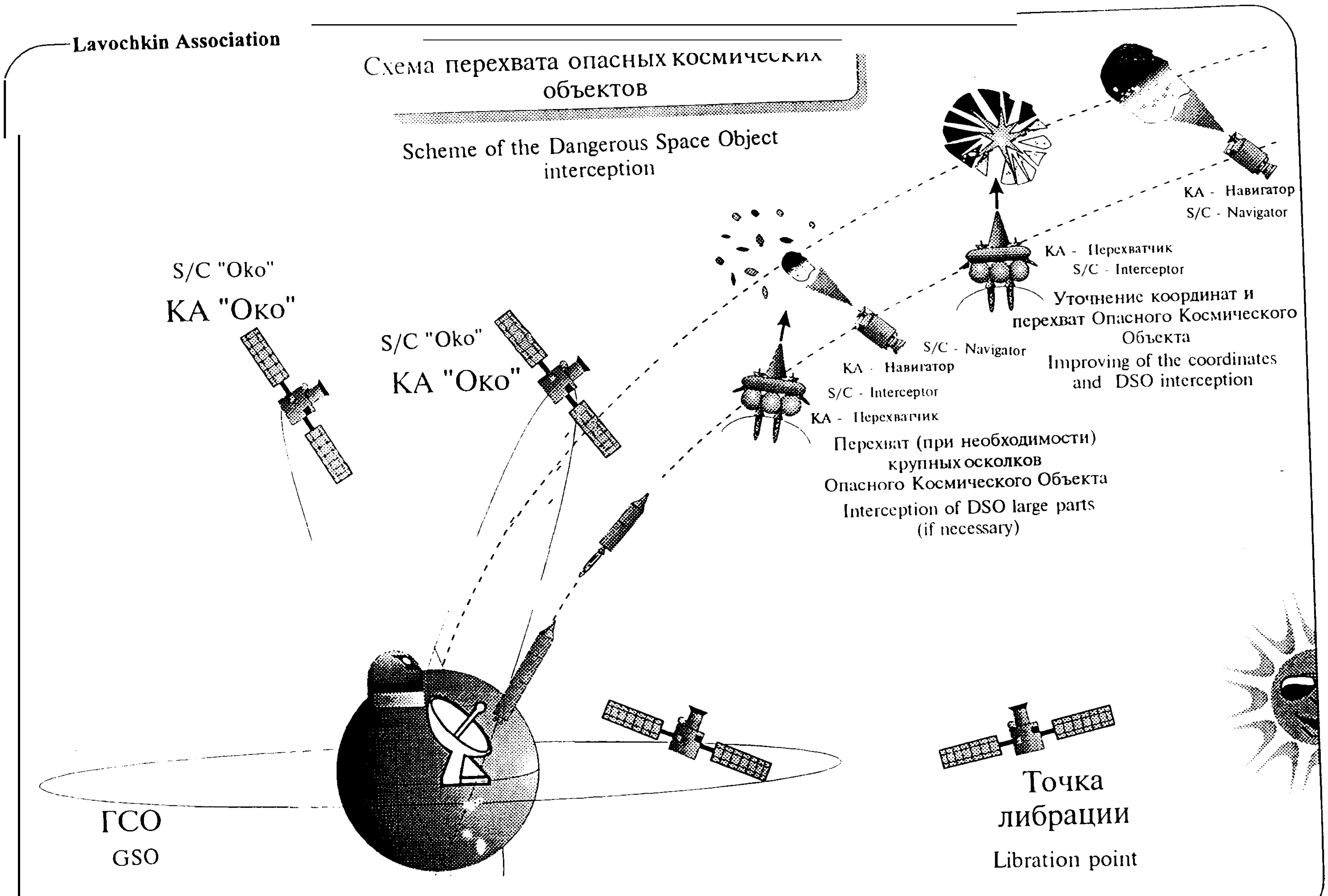
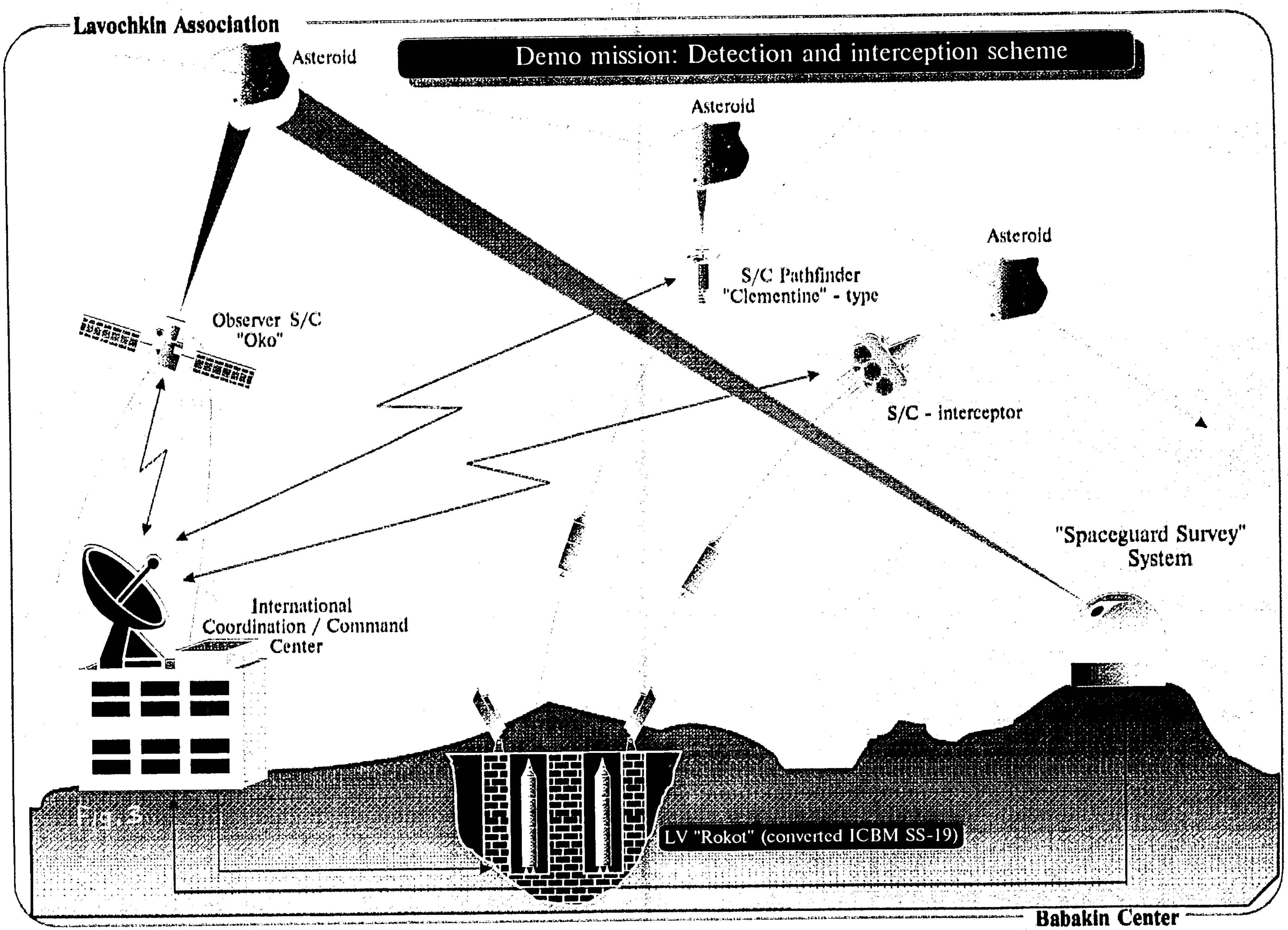


Fig. 2

Ballistic department
Babakin Center


Lavochkin Association
Demo mission: Detection and interception scheme
Asteroid
Asteroid
Asteroid
S/C Pathfinder
"Clementine" - type
Observer S/C
"Oko"
S/C - interceptor
"Spaceguard Survey"
System
International
Coordination / Command
Center
LV "Rokot" (converted ICBM SS-19)
Fig. 3
Babakin Center

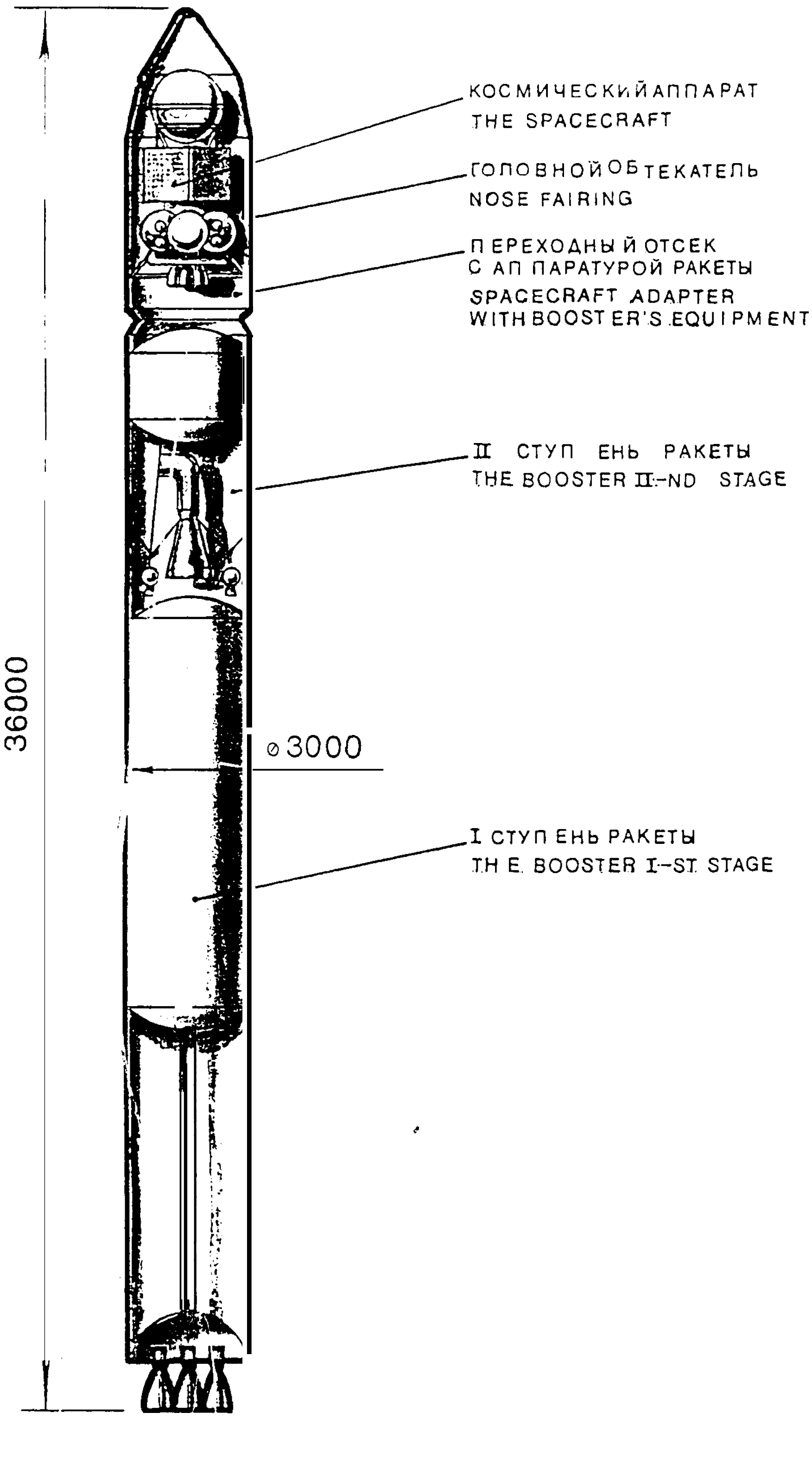


Fig. 4.

РАКЕТА-НОСИТЕЛЬ „СС-18„ С КОСМИЧЕСКИМ АППАРАТОМ

THE „SS-18„ SPACE BOOSTER WITH THE SPACECRAFT

Defense against small asteroids: priority tasks

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Any defense techniques (using nuclear devices or nonnuclear strategies) should be based on the knowledge of NEO'S characteristics. Investigation of NEO'S, in flight-by missions and by probing, is an important part of the planetary or regional defense programs and should be regarded as a priority task. A large number of space missions should be organized to obtain this information. To reduce cost it is preferable to use light launchers, e.g. "Rokot", and special space modules.

It is now well recognized that large asteroids (with sizes of about 1 km and more) may cause global catastrophes. Such asteroids are to be intercepted in space by heavy launchers ("Proton", "Arian", "Angara" etc.) at the distances of the order of 1 AU and months or even years before impact. Though the consequences of large impacts are grave they are rather rare. Probability of impacts of smaller asteroids (0. 3 km and less) is much higher. These small cosmic bodies are much more numerous and it is difficult to detect them. They may cause local and even regional catastrophes.

A recent impact of Comet Shoemaker-Levy 9 on Jupiter is an example of natural experimental modeling of rather small impact on the Earth's surface, as the mass of the Earth is 300 times smaller than that of Jupiter and the size is 11 times smaller. Many consequences that have been predicted for the case of the Earth (Adushkin and Nemtchinov, 1994) have been confirmed by observations of SL-9 impact, i.e. ejection of large air masses to high altitudes, fallback causing heating of the upper layers of the atmosphere due to formation of the reflected shock wave, and the subsequent infrared radiation emission in the area which is a substantial part of the total surface of the planet (a regional catastrophe). What we have not anticipated beforehand is that the energy release would be in the form of multiple bursts due to formation of large number of fragments caused by tidal forces and that these fragments probably consist of a large number of subfragments or grains (Neukum et al. , 1995). This fact clearly shows the necessity of investigation of composition and structure of cosmic objects.

Consequences of rather small impacts on the Earth may be even more severe than is usually anticipated, if such impacts occur in industrial areas where poisonous chemical substances are produced or stored, near dams, hydroelectric and nuclear power stations, nuclear waste repositories and other vulnerable objects (Adushkin and Nemtchinov, 1994). Seismic waves may be one of the most important factors causing damage of such objects. We should underline that the regions with increased number of dangerous objects (nuclear power stations, chemical plants etc.) are usually regions with high density of populations.

Tsunami caused by the impacts into oceans and seas may also cause severe damage of the industrial areas and casualties among population living at the ocean shores (Hills and Goda, 1993; Hills et al., 1994; Nemtchinov et al., 1994). Analyzing hazards due to comets and asteroids and ways of mitigation, one should not think only about the global planetary defense systems but must also consider regional defense systems, though this idea causes a large number of problems (ethical, of international law and others). An increasing population density and a cost of human life, complexity and vulnerability of the modern human society decrease the level of damage and casualties which should be considered as not admissible.

The best way to avoid hazards due to comets and asteroid impacts (small or large) is to divert them from the Earth. Fragmentation of small objects headed into the industrial areas or oceans may help to avoid seismic effects and tsunami, even if fragments hit the solid surface of the Earth or oceans, as such impacts cease to be coherent sources of waves. But fire ignition and even demolition by shock waves remains, if the number of such fragments and their total energy per unit area is large enough. Electromagnetic effects caused by the impacts into to the atmosphere can also be a serious problem in our information age. These effects substantially depend on the number of fragments, their masses, angle of divergence of stream of fragments and altitude of their energy release in the atmosphere, i.e. on the structure and strength of the cosmic bodies. Apparent strength of the meteoroids (determined as the stagnation pressure leading to the breakup during the atmospheric entry) is much less (usually by an order of magnitude) than the strength of meteorites (parts of meteoroids found at the Earth's surface) determined by usual tests (Svettsov et al., 1995). This fact once more underlines that it is very important to obtain real data on the structure, strength and other properties of cosmic bodies.

Any defense technique (using nuclear devices or nonnuclear strategies) should be based on the knowledge of NEO'S characteristics. Cosmic bodies may belong to various types, differently react on the action of the external force and differently behave during atmospheric entry. Not only observations of light flashes caused by rather large meteoroids (Tagliaferri et al., 1994), but investigation of NEO'S in flight - by flight-by space missions and by probing is an important part of the planetary or regional defense programs and should be regarded as a priority task. Large number of space missions should be organized to obtain necessary information. To reduce a cost it is preferable to use light launchers and special space modules. This idea is in many respects similar to that by Tedeschi and Allahdadi (1995).

One of the possible type of such light launchers is the Russian rocket "Rokot". An energy of this rocket makes possible to launch a spaceship to the asteroid with a payload of about 350 kg. A price of such a launch is much lower than that of analogous foreign launchers. In the case of international cooperation in construction of the spaceship and instrumentation, the price may be decreased for each of the participants.

Such launches may be regarded as an attempt to test many of the aspects of the defense system against small NEO'S. We should underline that to avoid tsunami's and seismic effects the interception should be fulfilled at distances no less than about 5,000 to 50,000 km. To avoid hazards caused by the objects headed to the densely populated regions one should organize interception at distances no less than about 0.25 to 1 million km, with a warning time of about 3 to 12 days.

A very important part of the defense system is an optical-electronic space based information system, which must detect such NEO'S at distances of about 0.1 AU, supplemented by a ground based radar tracking. Even if the interception system is not ready, one can get warning from the information system and use methods of civil defense and thus decrease damage and casualties (Alimov et al., 1995). On the other hand, elements of such system may be used for detection of small NEO'S and for organization of launches to investigate them and to determine the flux of such bodies in the near - Earth space.

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Systems-Level Considerations for Mitigating the NEO Impact Hazard

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Systems-level issues are given in regards to the study, research, development, and deployment of a mitigation system for the protection of Earth against impacts by massive comets and asteroids, i.e., near-Earth objects (NEOs). A number of guiding considerations will define in the coming years the extent to which humankind prepares for protecting ourselves against the impact hazard. Topics to be discussed include: detection (in the context of hazard warning), warning time, threat definition, safety and safeguards, technical research and peer review, information exchange, international teaming, precursor mitigation missions, mitigating smaller NEO impactors (25-100 m), mitigation planning, system deployment, trends in technology and geopolitics, and cost.

Introduction

Compelling evidence of a catastrophic asteroid impact on the Earth 65 million years ago (Alvarez et al., 1980 and Sharpton and Ward, 1990) has given rise to international discussions about the probability and prevention of future impacts. As a result of several recent near-misses (Morrison, 1992 and Scotti et al., 1991) and the comet Shoemaker Levy-9 impact of Jupiter in July 1994, considerable international attention has focused on defining the impact threat and determining potential mitigation schemes for the protection of Earth against planetesimal impacts (Tedeschi, 1994). Because asteroid and comet impacts pose a grave danger to all humanity, preventive defensive measures should appropriately be based on international cooperation and action. Action may consist of detection research, experimentation to prevent the impact, public education on the issues, emergency planning, and actual protection if required. This paper provides background information on the impact threat posed by NEOs and discusses associated technical and geopolitical issues requiring attention.

Basic human instincts

The fundamental issue at stake here is the core human instinct of survival - the will to live both individually and collectively. We all obviously relate very well to the individual survival instinct, and we certainly understand the need for collective approaches to protect ourselves and social institutions from danger and the ways in which we acknowledge this in our social contracts. Good collective examples are the preamble of the U.S. Constitution which contains the phase, "provide for a common defense," and Article 51 of the United Nations Charter (Nijhoff, 1985) which gives member nations the inherent right of individual or collective defense against attack. The need and desire to defend ourselves against an urgent an obvious NEO impact threat in the future is quite clear. A problem arises in the case of when there is no urgent and obvious impact threat and we must therefore prioritize meeting this need with other competing needs, some of which are definitely much more urgent and obvious. However, as humans, we have the unique ability to understand our surroundings, rationalize our existence, balance our competing needs, and act accordingly.

Impact consequences

When a large NEO (10's of meters to kilometers in size) impacts the Earth at velocities in excess of 5-10 km/sec, massive amounts of energy (10's to greater than 10^8 MT of TNT equivalent) are explosively released on very short time scales (seconds), with a resultant potential to cause damage to the Earth's biosphere. Short-term effects (< 1 second to many seconds) can include blast waves, x-rays, thermal heating, crush, and cratering (Melosh, 1989; Chyba et al. 1993; and Chapman and Morrison, 1994). Long-term effects (minutes to years) can include dust and debris, fires, tsunamis, global cooling, atmospheric and oceanographic chemistry changes, and even global warming (Gehrels, 1994). All of these effects can lead to loss of human life on unprecedented scales, depending on the size of the impactor (see Fig. 1). The scientific evidence is undeniable that Earth has been and will continue to be impacted by comets and asteroids (Morrison, 1992). Space-based optical sensors looking downward toward Earth have detected a steady flux of smaller meteoroids impacting our atmosphere (Tagliaferri et al., 1994). Before we can hope to protect ourselves against such impacts we must be able to detect such threats with ample warning time to allow us to respond effectively. The key is to find the minimum impactor size which poses a threat under some set of particular circumstances and then assure protection against it. We also must learn more about past impacts and the resultant consequences, as this will allow us to more confidently assess future impacts.

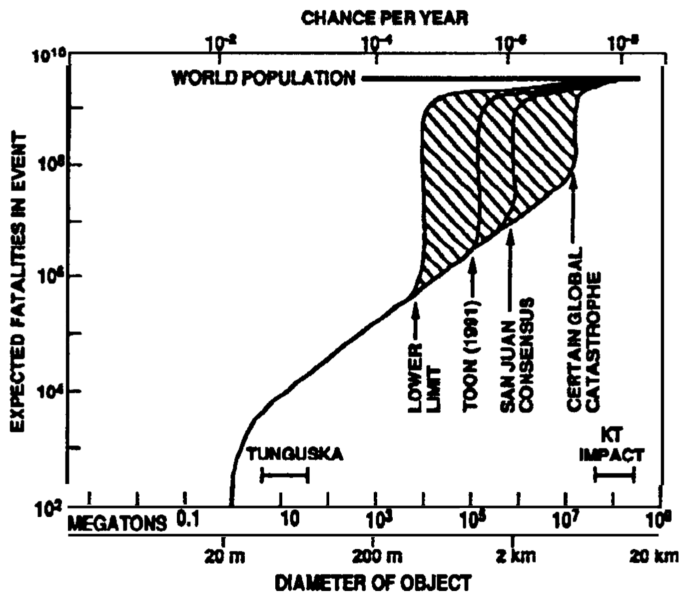

Figure 1. Estimate of expected human fatalities in an impact event versus impactor diameter (Morrison, 1992).

Detection

For any NEO protection system (detection and mitigation) to be effective, adequate warning of an Earth-approaching NEO is absolutely necessary. Currently, warning times for some small- to medium-sized NEOs, which have recently passed by Earth, are woefully short to nonexistent (Morrison, 1992 and Scotti et al., 1991). Some detections are made only hours to days before closest approach, other detections of passing NEOs have occurred only *after* closest approach with Earth. Of course, trajectories of already discovered and catalogued objects can be (and are routinely) projected forward to predict possible future close-approaches with Earth. It would seem that existing worldwide observational facilities (telescopes and radars) would be ideally suited for this mission of detection, and that the need for new facilities might only be required to ensure suitable coverage, e.g., in the Southern hemisphere or daytime sky, or establish a new type of detection capability. Once detections are made and orbit determinations made, the information must be placed in a catalog for use in refining the impact flux estimates on Earth and learning more about the threat.

Warning Time

Upon detection of an approaching NEO impactor of consequence, rapid dissemination of warning information is absolutely essential, especially for smaller objects and newly discovered long-period comets and larger asteroids. For smaller NEOs < 200 m in size, weeks of warning at the very minimum are required, however months would be preferable. For large NEOs > 1000 m in size, a year of warning at the very minimum is required, while multiple years of warning would be preferable. The size and composition of the impactor and amount of warning time available will determine which mitigation technology (or technologies) is (are) used. Currently there are a number of existing formal (e.g., International Astronomical Union Central Bureau for Astronomical Telegrams) and informal (e.g., telephone and internet) networks for reporting and learning of NEO discoveries. Warning must be timely and open. An alternative complimentary approach may be worthy of consideration. Some of the more advanced militaries of the world have observational sensors, both optical and radar, and communication networks which might add to our ability to detect NEOs and increase the warning time provided. A U.S. Air Force optical site has several 1+ meter telescopes which are now being used to detect and characterize orbital debris (Nordwell, 1993), and the Russians are devoting some of their assets to similar missions (Batyr et al., 1993). It has been postulated (Tedeschi and McKnight, 1995) that a worldwide integrated surveillance system should be considered for detecting and warning of NEO impact threats, in addition to performing other useful functions (see Tab. 1 and Fig. 2).

Table 1. Postulated worldwide integrated surveillance system (Tedeschi and McKnight,1995).

ID	TITLE	TARGETS TO SURVEIL	SUPPORTING SENSORS	COMMENTS
NDISS	National Defense ISS	Ballistic Missiles and ASATs	Ground: Radar, optical, and electro-optical Space: IR and possibly coronograph, UV, and IR/optical	National Defense
CISS	Civil ISS	LEO and GEO man-made objects	Ground: Radar, optical, and electro-optical Space: Possibly coronograph, UV, and IR/optical	For manned space safety, hazardous reentries, and GEO traffic management
IISS	Interplanetary ISS	Comets and asteroids	Ground: Optical, electro-optical, and radar Space: IR	To detect incoming natural objects and support basic research

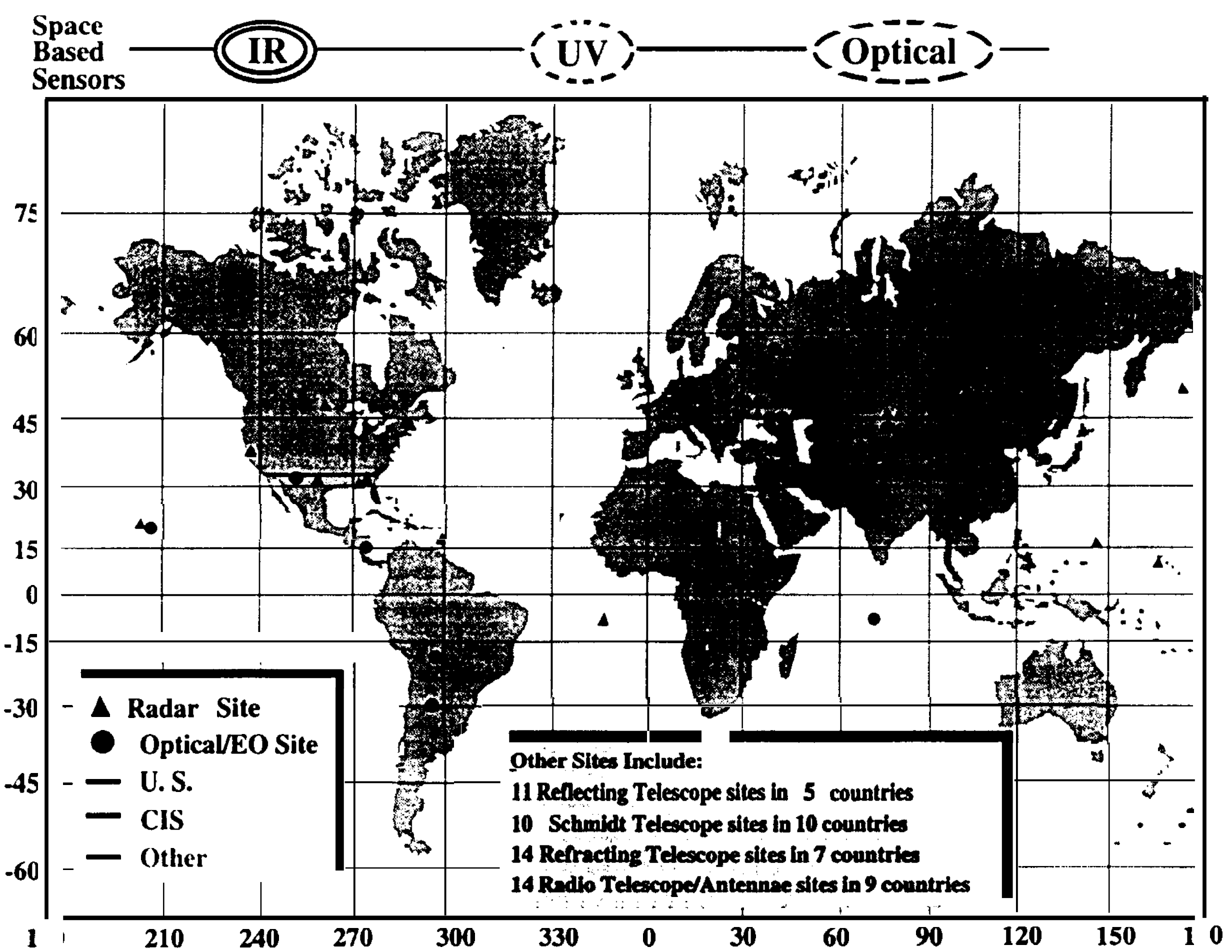

Figure 2. Worldwide Surveillance sensors ideal for NEO and orbital debris observations (Tedeschi and McKnight, 1995).

Threat Definition

Once an approaching NEO is detected and before an effective defense could be mounted, it would be necessary to know as many specifics as possible about its physical characteristics, e.g., geometry, mass, dynamic state, elemental and molecular composition, macro- and micro-structure, and material properties. The detection community has the ability now to ascertain a NEO's simple spatial and temporal characteristics, i.e., dimensions, shape, and trajectory dynamics. The bodies optical and radar returns can be used to provide information on its surface characteristics, e.g., mineral composition and geometry, but not the internal composition and structure of the body. The NEO's internal state will be a driving factor in determining its response to a particular mitigation fluence. The threat definition issue, therefore, speaks directly to the need to conduct exploratory missions to NEOs beforehand or, as a last resort, to have the ability to send precursor spacecraft to a particular approaching NEO to probe and characterize it so that a follow-on spacecraft can deploy our mitigation response of choice. The ability to perform high-speed rendezvous' with comets and asteroids has already been demonstrated successfully, e.g., by U.S. (ICE) to comet Giacobini-Zinner; by Russia (Vega), the Europeans (Giotto), and Japan (Suisei) to comet Halley; and U.S. (Galileo) to asteroids Gaspra and Ida. The technology to rendezvous with other planets, to go into orbit and even soft-land on some of them has also been demonstrated. The follow-on Clementine mission to another Near-Earth asteroid is considering probing the surface with a small kinetic energy impactor to help assay its surface composition. What is also required are missions to either rendezvous and soft-land on a NEO and assay its surface, i.e., the canceled Comet Rendezvous and Asteroid Flyby (CRAF) mission which would have been a great start - however it was canceled, but the upcoming Rosetta and Near-Earth Asteroid Rendezvous (NEAR) missions may provide additional information, or penetrate a passing NEO to probe its internal characteristics (Tedeschi and Allahdadi, 1995 and Wood et al., 1995).

Treaties, agreements, and understandings

Several international treaties, agreements, and understandings exist which may someday limit or possibly even preempt our ability to do mitigation (see Tab. 2), e.g., the 1967 Outer Space Treaty prohibits the placement of weapons of mass destruction in orbit, in space, or on other celestial bodies. It may be necessary, therefore, to discuss the creation of new agreements (treaties, conventions, resolutions, protocols, etc.) or the modification of existing instruments to legally and morally allow NEO mitigation schemes to be someday conceptualized, developed, built, and used in space - if required. This is necessary for two reasons: 1) it allows all nations of the world to understand and participate in the process leading to a defensive mitigation action and 2) it allows us to carefully plan for and respond to a detected NEO threat so that the likelihood of misuse or accidental use of powerful mitigation devices is minimized and our chances of success are maximized. At a minimum it has been proposed that some discussion is warranted on how a mitigation process might unfold from a legal perspective (Tedeschi and Teller, 1994).

Table 2. International agreements and resolutions affecting our mitigation response.

Agreement	When	What
Threshhold Test Ban Treaty	1963	Prohibits atmospheric testing, even in outer space.
Outer Space Treaty	1967	Prohibits weapon placement in orbit, in space, or on other celestrial bodies, including the moon.
Nuclear Non-Proliferation Treaty	1970	Prohibits transfer of weapons or devices.
Convention on International Liability for Damage Caused by Space Objects		Prescribes liability protocol for damage caused by man-made space objects.
Convention on Registration of Objects Launched into Outer Space		Prescribes registration protocol for space launches.
Convention on Prohibition of Military or any Other Hostile Use of Environmental Modification Techniques	1978	Prohibits certain environmental modification techniques
Convention on Prohibitions/Restrictions on Certain Conventional Weapons	1979	Prohibits certain weapons with indiscriminant effects.
Resolution on Prohibition on Development of New Weapons of Mass Destruction and New Systems	1985	UN resolution prohibiting development and manufacture of weapons of mass destruction.

Mitigation Technologies and Research

An effective NEO protection scheme for use against an approaching object would ideally require extensive study and research *a priori* to determine the best way to safely deliver and couple a given amount of mass, momentum, and/or energy into an approaching body to either fragment or deflect it. Experimentation might include not only laboratory experiments and simulations, but also the study of actual deflection or disruption of NEOs in non-menacing orbits. Doing so would provide an increased level of confidence in the effectiveness of a particular mitigation scheme against some future NEO impactor. Such means of mitigation could include: conventional and unconventional rockets, high explosives, nuclear explosives, robotic mass drivers, high-velocity kinetic energy impacts, solar sails, or lasers (Canavan et al., 1992 and Tedeschi, 1994). Figure 3 shows a compilation of different possible mitigation fluence coupling schemes into NEOs.

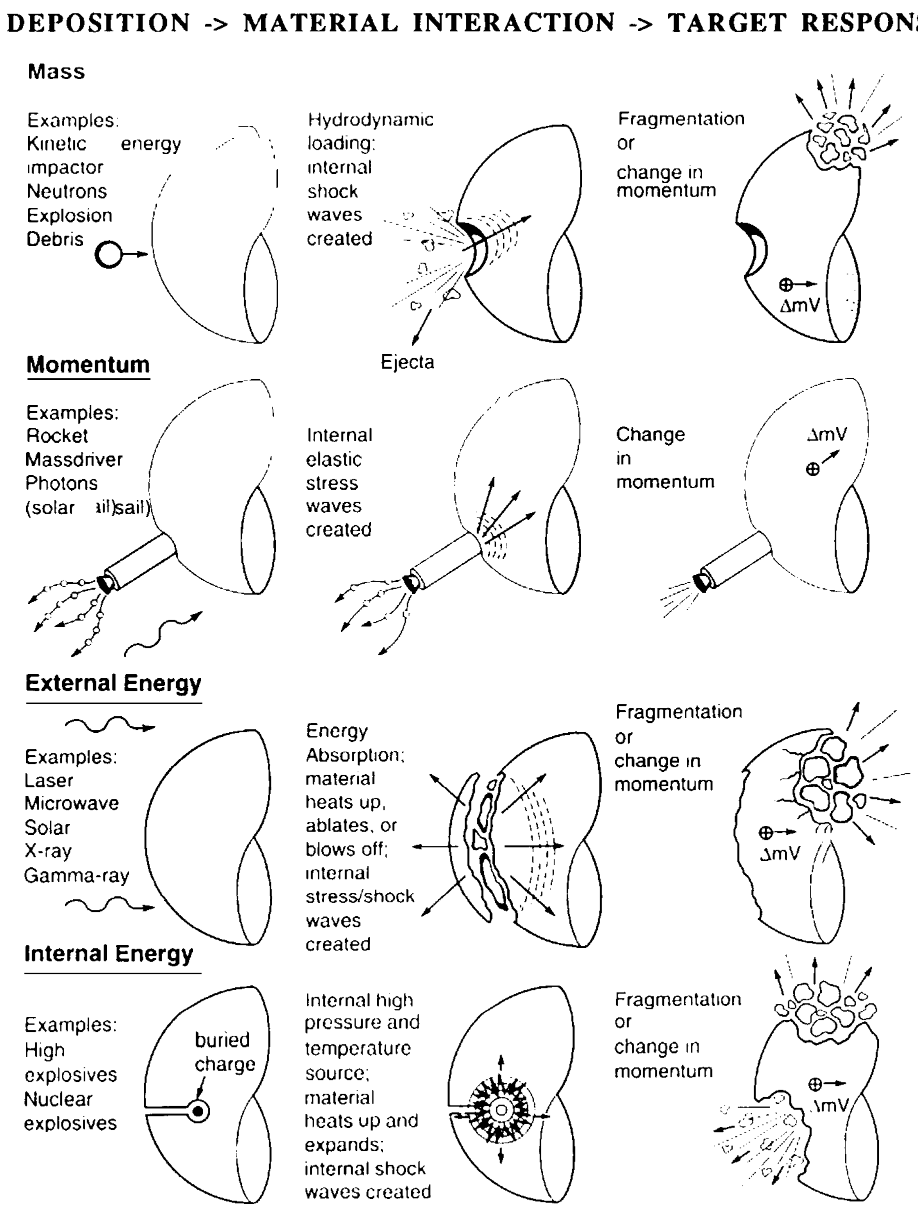

Figure 3. Mitigation schemes for deflecting or fragmenting NEO threats.

What would be involved is the delivery of a quantity of mass, momentum, and/or energy to the approaching target body, or in proximity to it, which would then be "coupled" into the body to accomplish the intended objective. The key element here is the efficient coupling or deposition into the target of the incoming mitigation fluence and the resultant physical processes by which useful actions occur to the target body, like velocity changes or body fragmentation. Mass, momentum, and/or energy deposition is the initial step in the process of altering the target body's state. The delivered energy fluence interacts with the target body thereby causing a change in thermodynamic state - usually by some form of heat transfer and/or hydrodynamic loading process, i.e., from impact shock heating and compression, solar heating, or radiation/electromagnetic heating - which can result in either material blow-off with a resultant impulse to the body, or body fragmentation because the target material could not structurally sustain the induced loading conditions.

Knowing how energy couples into various target materials serves as the basis for selecting one defensive scheme over another. This can be done only through carefully controlled experimentation and modeling, whereby various target materials are probed and characterized experimentally and analytically by a number of viable energy fluences. The target material response is observed, measured, and quantified (i.e., scaled up) in terms of it's effectiveness at imparting momentum to or physically fragmenting a larger body composed of this material. While some experimental data are available, much more material property data and energy coupling experimentation are required (Remo, 1994; Shafer et al., 1994; and Tedeschi et al., 1994). Laboratory experimentation and modeling provides very cost effective mitigation option choices and should therefore be pursued.

Arms Control

The current international arms control environment is summarized best by the phrase, "reduce the danger of weapons of mass destruction." A number of bilateral and multilateral international protocols have either been signed or are being negotiated to limit the spread, impact, and reduce the numbers of weapons of mass destruction worldwide; e.g., 1970 Nuclear NonProliferation Treaty, 1995 Nuclear NonProliferation Treaty, Strategic Arms Limitations Talks, Strategic Arms Reduction Talks - 1 and - 2, Biological Weapons Convention, Chemical Weapons Convention, Threshold Test Ban Treaty, Peaceful Uses for Nuclear Explosives Treaty, Intermediate Nuclear Forces, and Comprehensive Test Ban Treaty. The planetary defense community must be congruent in their activities vis-à-vis these constraints and the current geopolitical environment.

Safety

Mitigation schemes which might contain massive amounts of stored energy would have to be very carefully safeguarded against accident or unintended use. In no way can the cure be potentially worse than the malady. The main issue here must be to ensure that powerful mitigation technologies accountably include reliable safeguards against accidents and misuse. The potential impact to people and our environment must be minimized and balanced against the risk. In the current case of high consequence activities, such as the high explosives business, extreme care in every phase of the process is taken to protect the public safety and that of our environment against accidents and unintended misuse. Formal accountability back to the people and governments through mandatory process control protocols are the checks and balances necessary to help maximize the probability of a safe outcome.

Safeguards

Concern has been raised over the possibility of misuse of mitigation technologies [Harris et al., 1994 and Sagan and Ostro, 1994]. In perspective, though, during the 40-year Cold War with 10's of thousands of nuclear warheads in existence [Brown et al., 1994], there has not been a single case of an accidental or unintended nuclear detonation anywhere. This has been the case because of exceedingly careful attention having been given to meeting exacting requirements of security and use control throughout the lifetime of a weapon system. Misuse is a valid concern, but one which can be addressed to minimize the risk through suitable design hardware and procedures, as well as through the continuation and strengthening of appropriate international control protocols, e.g., IAEA and NPT, and other confidence-building cooperative activities. It has been proposed for consideration that a high-level international agency be charged with rationally coordinating the worldwide response, including that of safeguards, to the NEO impact threat (Tedeschi and Teller, 1994).

Perhaps of graver concern is the proliferation of certain information on powerful mitigation technologies (both systems and component materials). Extreme care must be taken to safeguard such information and hardware against unintentional dissemination. In the case of nuclear explosives and their effects on NEO materials, it may be highly prudent to limit dissemination of this information to countries already possessing such capabilities. Just as in the case of safety, formal accountability back to the people and governments through mandatory process control protocols are the checks and balances necessary to help maximize the probability of a secure and predictable outcome.

Information exchange, public awareness, and accountability

This is a critical aspect of the whole issue because everyone is affected therefore everyone should know. Exchange can be accomplished by a multitude of techniques, e.g., conferences, meetings, public forums, TV, radio, newspapers, articles, and individual interactions. Only open, honest, factual, and widespread dissemination will allow careful decisions of support (or lack thereof) to be made. Biases and alarmist scare tactics must be avoided. Thomas Jefferson once said that "diffusion of knowledge among the people" is the only sure strategy "for the preservation of freedom and happiness [i.e., well-being]." It is reasonable to expect, however, that for obvious reasons some information on mitigation technologies and safeguards cannot be widely shared. There is also the issue of this community being accountable to the people for all our planetary efforts. They are our customers. They support our activities with their hard-earned financial resources. And, they (and all of us!!) are affected ultimately by the outcome(s) of our collective activities. Should some type of formal planetary defense protocol or deployment ever be required, it must be justifiable, reasonable, and affordable when balanced against the risks of not doing it. We must also be good stewards of the environment; not just here on Earth, but in near-Earth space as well. How many times have we belatedly learned about the "effect" part of cause-and-effect regarding the consequences of science & technology on a global scale, for example, ozone depletion, acid rain, orbital debris, DDT, and so forth. We each individually (and collectively) as researchers have a public trust to uphold as we carefully address this issue of global importance.

Peer review and consensus

This is necessary, as part of the accountability process, to ensure that all related planetary defense issues (and impact hazard issues, too) have been considered, addressed, reviewed, and accepted by all qualified and cognizant researchers, and by a majority of the general public as well. The consensus should consist at a minimum of a hierarchy of viable and accepted defense solutions which are dependent on the amount of warning time, physical characteristics of the approaching NEO, and timely availability of mitigation technologies. Periodic fora for discussing and forging consensus statements are an absolute must. The so-called "Swift-Tuttle" affair three years ago - that comet Swift-Tuttle could collide with Earth with some finite probability of occurrence during its next apparition in 2126 - was a good example of why this type of technical information should be thoroughly peer reviewed before release to the media/public.

International teaming and dialogue

Again, because the problem affects everyone, we should all have the opportunity to contribute to the solutions. The problem is very complex. As such, no one group has all the answers, nor should they. As a confidence- and team-building measure, we should resolve to be open to and participate in new research and policy-level opportunities between different individuals, organizations, and nations. While we have the astronomers to credit for starting the avalanche of interest in the NEO threat issue, it will now require the active interdisciplinary participation of many other scientific and technical experts. This is an international issue and it requires cooperative international participation and contribution between many different sectors, i.e., nation-to-nation, individual-to-individual, detectors-to-mitigators, university-to-military lab, private concerns-to-public/government concerns, and so on. Let us strive to work cooperatively together, everyone will benefit as a result. Suitable forums include national and international technical and policy-level meetings, gatherings, colloquia, personnel exchange programs, and even one-on-one interactions.

Precursor Mitigation Missions

Precursor mitigation missions may be warranted if our ability to mitigate someday in the future is significantly hampered without them. However, the burden of proof for such a need is on the planetary defense community. As such we could improve our understanding of: carrying deflection technologies long distances through the hostile environments of space, final approach and terminal homing with the target, the interaction of the mitigation technology with the NEO to deflect or fragment it, long range tracking and control, modeling and planning assumptions, and sub-scale energy coupling experiments on Earth, among others. Doing precursor missions allows smarter choices to be made in times of emergency. Others have either proposed NEO rendezvous missions (Nozette, 1995 and Tedeschi and Allahdadi, 1995) or are actively planning upcoming missions, i.e., NASA/NEAR and ESA/Rosetta.

Mitigating small vs. large NEOs

Should we mitigate smaller NEOs (like the Tunguska impactor), which have a higher impact probability, but which only cause local damage, or should we wait for the K-T class impactors? For the smaller impactors, it depends. If the impact is over water or remote land areas, which is likely to be the case - like Tunguska, we don't have to do anything, except perhaps evacuate the area for a short period of time. And provided, of course, that we have ample warning time, accurate tracking capability, and are confident in our trajectory and impact point calculations. If it's predicted to impact in a location where the resultant damage would be unacceptable to us, for example, at population or resource centers, then - yes, obviously - we will attempt to mitigate it. The time for debate will promptly end and someone or some group will make the decision to mitigate the threat as best we can. Whether we're successful or not will depend on how well prepared we were to mitigate it. And, of course, we must be prepared to defend against the K-T class impactors.

Deployment

Should we build and deploy a mitigation system for Earth? No, not right now. Premature deployment could be dangerous and expensive. Besides, what's the hurry? We don't even understand the problem yet. Therefore, how can we proclaim to have the mitigation solution in hand? Someday, however, if required, we may wish to deploy a mitigation capability to meet the shortest warning time threats and provided that the international geopolitical climate is hospitable for doing so. Another viable future option may be to store the mitigation system as separate parts, safely and securely under national and international safeguards, with proven contingency plans to rapidly generate a viable mitigation capability and respond to any NEO impact threat emergency. Deployment in one form or another can not be ruled out, but would necessarily first have to be preceded by many years and much effort defining the threat and the need for such action, and potential mitigation options.

Mitigation planning

Some level of mitigation planning seems prudent to help ensure a timely future response. Actual protection against NEO impacts could consist of passive and/or active measures. Passive measures could involve local evacuation from the impact zone, retreat to protective shelters, and other measures, like food and water storage, to safeguard people and their supporting infrastructure, if adequate warning time is provided. Some countries have similar plans in place now in the event of natural disasters, e.g., the U.S. Federal Emergency Management Agency (FEMA) and the international Red Cross agency. Active measures would involve the delivery and use of an existing mitigation scheme against a menacing object, or the existence of detailed plans to rapidly do so in the event of a detected threat.

One of the driving mitigation planning considerations is the amount of warning time provided before predicted impact. If the warning time is short, a more energetic mitigation device (or devices), a quicker delivery system, or an existing defense system may be required. In light of the current capability to provide little, if any, warning time against smaller objects and little time for newly discovered long-period comets and potentially some asteroids, it would seem prudent to at least consider different mitigation scenarios.

From the opposite perspective, that of having to conduct a mitigation mission, it should not be assumed that existing weapons and delivery systems can be quickly "reprogrammed" and used against an approaching NEO. This is so because existing weapon/delivery systems were built for very specific missions, with limited flexibility for other uses on short notice. Like planetary space exploration missions and to do things right, it takes years of effort to design, build, test, and qualify a complex weapon/delivery system, especially against an undefined threat like NEOs. The risk in not doing mitigation the right way is in fielding an ineffective system or fielding one with an unacceptably high probability for accidents - in which case the cure might be worse than the disease. Nor should it be assumed that appropriate mitigation technologies will even be available someday in the future when they might be needed.

Conducting a mitigation mission

Finally, mitigation would involve the delivery of an appropriate amount of mass, momentum and/or energy to an approaching NEO either to gently deflect the body or to disruptively deflect all or a significant amount of the body's mass away from an Earth impact. Related deep-space and defense missions have been conducted in the past. They are complex, and they take time, resources, and great effort. Activities involved include: threat detection, warning, and verification; tracking; authority to proceed; mission planning and end-game analysis; logistics and launch preparations; safety and security; delivery and survival in space of the mitigation technology; terminal homing and "intercepting" the target; assessing the results and trying again if necessary.

Summary

A number of systems-level issues were presented in regards to the study, research, development and deployment of a worldwide defense system for protection against catastrophic impacts by comets and asteroids. A number of guiding considerations will define in the coming years the extent to which humankind prepares for protecting ourselves against the impact hazard. Defensive preventive actions should be based on international cooperation, the level of which required has never before been witnessed in human history, but which could be the start of an exciting new chapter in the evolution of humankind on Earth. Through careful and appropriate preparation and timely action lives can be saved and the rich diversity of life on Earth preserved.

Acknowledgments

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The Application of Risk Management to the NEO Threat

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In the spring of 1995, the author, as Adjunct Professor of Engineering at the University of Southern Cal ifornia, developed a new graduate level course in risk management applied to problems in systems engineering and program management. The class project for this course was the near-earth-object (NEO) threat. Twelve graduate students --many with at least a decade of industrial experience -- received final credit towards their MS or PhD programs. Systems engineering has been converging to a more formal discipline over the last several years, but risk management has been one of the most recent arrivals to be recognized within this relatively new field. If risk management is performed at all, it is usually ad hoc and qualitative. The core of this new course established risk management on the foundation of probabilistic decision theory. For the class project, the students were asked to develop decision networks, probability assessments, and alternative criteria relating to the conduct of a planetary defense program. A remarkably good consensus was obtained: all investments for acceleration of NEO detection and characterization as well as preliminary design of mitigation systems were shown to be very cost effective, key risk reduction tests on mitigation technologies were recommended within limits, and the full deployment of actual mitigation systems should be paced by the results of the NEO detection program.

Introduction

Virtually every identifiable trend is driving humanity's enterprises into more intimate interaction and conflict. Increased population, accelerated exploitation of resources, and transportation have brought the previously decoupled worlds of economics, energy and the environment into a tight zero sum game. With the greater efficiency of travel and communication, the emergence of global marketplaces and the revolution in military strategies, the international world is incredibly more interactive, multidimensional and complex than even a decade ago. All of these issues have been aggravated by an explosion of new technology and -- especially in the United States -- a compulsion to force these new technologies into early and simultaneous application. Humanity's challenge is either to manage this complexity or the complexity will manage us, and we will be overwhelmed by ineffective, costly and late systems which are unbalanced, incomplete, incoherent, irrational, divergent, polluting, and generating unnecessary risk at every turn.

Responding to this need, the University of Southern California (USC) has embarked upon an academic strategy which will develop the theoretical and practical foundation to manage complex systems. New courses in systems engineering, management of technology and interdisciplinary studies are being established. Having just retired after four decades in the aerospace industry and having been one of the founders of the National Council on Systems

Engineering (NCOSE), the author was invited to initiate a new graduate course in risk management within systems engineering. This course was designated ISE 599 and was given for the first time in the spring of 1995. The twelve graduate students who received credit for this course were unusual in that the majority were working full time and had at least a decade of experience in the development and analysis of complex systems. Most were in the aerospace industry, working for Rockwell, Northrop Grumman, the Aerospace Corporation, or were junior officers in the US Air Force, working for an advanced degree.

Risk Management within Systems Engineering

Even within such a young organization such as NCOSE (only five years old), risk management is a relative newcomer; many argued that it was more appropriately included within program management than systems engineering. Prior to the eighties, risk management was primarily practiced in the business and insurance worlds and was generally unknown as a formal engineering discipline. When risk management first began to be used, it was almost entirely on a qualitative basis: likelihoods and consequences of adverse events were characterized as "high, medium, or low" rather than by quantitative probabilities or negative financial impacts. The technique was frequently used to convince a program office that the management reserve should be used to mitigate a problem which was not identified at the program start. Often, only risk analysis was accomplished, without the follow-through of developing a coherent risk mitigation plan which was fully recognized and managed by the program office. Worse yet, there are many recorded incidents of engineers being punished, not rewarded, by identifying new risks in mid-program.

The premise of the new ISE 599 course was that engineering risk management should be quantitative whenever possible and based on the rigorous foundation of modern decision theory. The primary references for the course were: Baird, B., *Managerial Decisions Under Uncertainty,* (Wiley, 1989) and Raiffa, H., *Decision Analysis,* (Random House, 1968), plus about a dozen more references in specific risk domains.

The core of the decision theory methodology covered in these references involves the rigorous use of tree-like decision networks which are comprised of two types of junctions: *action* forks and *event* forks. At the action forks, the decision maker chooses from a finite set of possible actions; at the event forks, a discrete set of possible events -- each with its specific likelihood -- is identified. The action forks must recognize all reasonable decisions available to the decision maker and the sum of all the likelihoods emanating from each event fork must be unity. Where appropriate, costs are associated with actions and payoffs (or penalties) are associated with the probabilistic events. A value function is defined -- usually the Expected Monetary Value (EMV) -- as the optimization criterion and the "best strategy" is defined as that sequence of decisions -- coupled by the set of probabilistic events -- which maximizes EMV. For risk management problems, EMV can be negative. The methodology encourages the insertion of early tests to minimize uncertainty regarding later events which may have very expensive consequences.

Although the decision network clearly shows the exact sequence of decisions, it is usually assumed that the time interval between events is so short that the value of money is constant. Perhaps the most controversial aspect of modern decision theory is that -- in contrast to classical statistical theory -- probabilistic *assessments* are employed in situations where a detailed empirical data base is not available. This is termed the subjectivist approach, or the "Bayesian" approach, (after Thomas Bayes), wherein carefully considered estimates optimally mixed with new data develop "best estimates" to quantify the likelihoods of the events which are the result of decisions.

In summary, modern decision theory depends on three rather distinct cognitive functions: the establishment of a logical network of decisions and events, the assignment of probabilities to the uncertain events, and the choice of optimization criteria. Once these three areas are agreed upon, decision theory's greatest strength is that the optimum decisions or strategies can be derived with mathematical rigor. The author has been in many situations in his career where the basic elements have attained a reasonable level of agreement but the decision process was ad hoc, subdimensional and driven by prior biases. Decision theory provides a rational basis for the collection of data and for attaining a consensus from a diversity of viewpoints.

Although this methodology has proven to be an effective decision tool for a great variety of situations, its simplifications should be clearly recognized: Some problems may involve more complex decision structures than trees, or require continuous probability distributions rather than discrete probabilities, and for many problems with several years between the decision junctions the time value of money (interest, inflation, etc.,) cannot be neglected.

The Near-Earth-Object (NEO)Class Project

The class project for the ISE 599 course in risk management was the evaluation of the NEO threat from the standpoint of its credibility, likelihood, consequences, criteria, and optimum pace of managerial decisions and investments. The inputs to the students consisted of *Project Icarus,* (MIT Press, 1968), the reports on *NASA's Detection and Interception Workshops*, the *Congressional Record* covering the hearings on the Asteroid Threat (GPO, March 24, 1993), the AIAA 1990 and 1995 position papers on the NEO, and a series of five lectures on systems aspects of the NEO threat that the author presented as part of MIT's Independent Activities Program in January 1995.

The class project work package, with supplementary data is appended in its entirety at the end of this paper. Twelve questions were asked covering a wide variety of issues related to the NEO threat as well as a diversity of requested responses ranging from mathematically rigorous to purely judgmental. The students were asked to respond from the perspectives of various roles: The head of the International Planetary Defense Agency, the Chair of the Congressional Committee on Science and Technology, the visionary leader of an activist organization, and a graduate student in the management of technology. Also provided were a "starter list" on alternative optimization criteria, monetary values of detection and mitigation systems costs and effectiveness as a function of the time-to-go from detection to impact. *(Note that these cost and effectiveness data are notional only and intended to be merely inputs into an examination on decision theory methodology. The data are smoothed simplifications of values found in the literature and they should not be presumed to be the result of new analysis.)*

The consensus of the students on the qualitative questions was that, without more spectacular "wake-up calls," or substantially more education, the public support for a new NEO program is insufficient to overcome existing priorities, that developing sanctuaries for humanity's survival would be a failed strategy, that international planetary defense is a proper role for the governments of all the developed nations to support, that nuclear contamination of the atmosphere for the purpose of planetary defense would be considered no more justifiable than contamination for military development and that creating a "stunt" involving a false threat is really a terrible idea.

Quantitatively, the students generally agreed that the collection of more threat data was in the fundamental spirit of decision theory, that the perceived threat is reduced as the catalog of NEOs is made more complete and that the value of long range radars -- even at a cost of billions of dollars -- would be a good investment in rapid orbit determination, especially during the terminal trajectory of a long period comet.

The central problem was number nine, which asked the students to develop a "best strategy" for detection and interception system investment against a threat of a 1km asteroid impact which destroys civilization and kills half the human race. A spectrum of investment alternatives, ranging from "continue as-is" to "full development and deployment of both detection and mitigation systems" was to be considered, each with it particular costs and effectivenesses. The primary criterion chosen was to minimize the expected value of rebuilding civilization. A remarkably coherent consensus among the students was attained using the decision theory tools learned during the term:

All investments for the acceleration of NEO detection and characterization, as well as preliminary design of mitigation systems were shown to be very cost effective. Key risk reduction tests on mitigation technologies were valuable for interception development but not deployment. Full development of actual mitigation systems should be paced by the results of the NEO detection and characterization program and coordinated by a central office. The cost to rebuild civilization was given to be one quadrillion dollars, but the conclusions were not very sensitive to this assumption.

Conclusions

The first-order decision theory tools applied to the NEO threat developed a good consensus and derived an optimum strategy on a rational, easily verified basis. However, in order to go more deeply into the details of decisions regarding NEO detection and interception investments, it is recommended that the standard methodology be extended to cover the weaknesses mentioned earlier: permit non-tree decision structures so that investments made today could increase options in the future, permit continuous in addition to discrete probability distributions to capture more accurately the likelihood of future NEO events, and recognize that the very long periods of time between key events and decisions have crucial inflation implications.

CLASS PROJECT ON NEAR-EARTH-OBJECTS

To: Students of ISE 500, "Risk Management within Systems Engineering"
From: George Friedman, Adjunct Professor of Engineering, University of Southern California

Here is your class project. Your response is due 6PM, May 8, 1995. A few comments may be in order.

Many of the problems are analytic exercises which have a unique quantitative answer. Many others, however, are more qualitative and judgmental -- on these there will be no absolutely correct answer. I'm interested in your opinion as an informed, technically educated citizen; please don't give me an answer you believe *I* might prefer. Of course, I'd like you to back up your assumptions and opinions with good discussion.

In the "Spectra, Part I", four personalities associated with the NEO world are described. They may have different viewpoints, depending on their jobs. Help them think through the answers to the questions as if you yourself had the defined responsibilities. It would be advisable for you to read all the spectra before you start answering questions.

Good luck!

G Friedman

George Friedman

CLASS PROJECT ON NEOs; RISK MANAGEMENT

1) Person C: You have been involved in many crusades in your career and can take pride in the fact that some of today's legislated environmental regulations are due to your efforts. Now, relatively suddenly, you are becoming aware of a new potential threat to humanity: an NEO impact. How do you place this threat within the list of more familiar threats? Why don't you think Walter Karplus included it in the eight risks he discusses in his book, "The Heavens are Falling"?

2) Person C: As you delve more deeply into NEOs, you become intrigued with the concept of developing survival sanctuaries as an alternative to saving humanity from an NEO strike. These sanctuaries could be on earth, on planetary surfaces, or in asteroids or space habitats. Their population should be on the order of a thousand to preserve humanity's genetic heritage and on the order of millions to preserve humanity's cultural heritage. In order to provide an overall balanced perspective, you define these probabilities with respect to some future time, t:
P_1 = probability that humanity will survive
P_2 = probability that a globally destructive NEO will strike the earth
P_3 = probability that humanity will develop an effective NEO defense system
P_4 = probability that at least one human sanctuary will be developed
Derive the logical statement which relates P_1 as a function of P_2, P_3 and P_4.

3) Person C: Is the concept of human sanctuaries morally and practically viable? Even if a few million can survive, why would over 99.9% of the population willingly perish? How would the survivors be chosen? How would they defend themselves and their food supplies from the overwhelming hungry masses? What about the true costs of the sanctuary -- taking into account the required security forces -- relative to the costs of a planetary defense system?

4) Person A: You have just read the 3/24/93 Congressional Record and accept the astronomers' judgmental estimate that the *average rate* of globally destructive NEO impacts on earth is once per million years. Given this assumption of low unit probability and average rate, what type of probability distribution does this suggest? Based on this distribution, what is the probability that there will be an impact this century? In the next 50,000 years? In the next million years? In the next 5 million years?

5) Person A: Fig. 2-5 on p129 of the 3/24/95 Congressional Record compactly relates NEO size, impact energy, chance per year and expected fatalities per event. Is this a cumulative or a probability density function? According to this figure, what diameter NEO is associated with the largest fatality rate? What assumptions had to be made in order to establish such a simple relationship between NEO size and megatons of impact energy?

6) Person A: By analysis of a wide variety of data, the astronomers estimate that there are 2000 NEOs which have the potential of being globally destructive (end of civilization, billions of casualties, and possibly the extinction of mankind). From the interview of David Morrison by

Congressman Ralph Hall (page 177, Cong. Record), how would you assess the quality of the data and the standard deviation about the estimated mean? If 2000 is correct, we have presently catalogued only about 6% of the globally destructive NEOs. It is further estimated that 75% of these NEOs are ECAs and SPCs (with orbital periods on the order of a few years) and 25% are LPCs with orbital periods which can range from thousands to even millions of years.) The Spacewatch program is designed to accelerate the discovery of ECAs and SPCs so that we grow from the 6% knowledge level to the 95% level in less than two decades instead of in two centuries as we would at our present pace. Assume that the Spacewatch program is approved and during its first decade a thousand new NEOs were discovered -- with no NEO detected which would come close to earth within the next 100 years. Could it be said that Spacewatch was therefore a waste? Given this new information, would it be likely that we would change our opinion regarding the entire NEO population? Regarding the average rate of NEO impacts? Regarding the likelihood of a short term NEO hit from the still undiscovered population?

7) Person A: Assume this terminal scenario: A 2km NEO is heading toward earth. If the standard deviation (std dev) of its orbital error projected to earth's vicinity is 100 miles, then we would feel fairly comfortable in applying enough momentum to the NEO to move it an earth's radius transversely. That is, it would be highly unlikely that the NEO would miss and our efforts would result in a hit. However, if the std dev were 10,000 miles, the risk would be far more likely that, in deflecting the NEO's orbit transversely by an earth's radius, we would actually convert a miss into a hit! Assuming that the errors are distributed normally, plot the relationship between the probability of inadvertently converting a miss into a hit vs. the orbital std dev and the number of earth radii we are willing to deflect the NEO. Holding this probability to a limit no greater than .01, plot the tradeoff curve between orbit determination error and NEO deflection energy. If the energy to deflect the NEO by an earth radius cost $1B and a long range laser radar costing $200M could reduce the orbital std dev by a factor of 10, would the radar be a good investment? (Note: energy required is proportional to the transverse distance *squared*)

8) Person B: One of your predecessors, George Brown, authorized two workshops -- one for detection and one for intercept. However they had divergent views regarding the size of NEOs which should be considered seriously, the time frame for new technology development and, perhaps most significantly, the detection workshop claiming that work on intercept was postponable while the intercept workshop claiming that we must get started on intercept concepts and key testing as soon as possible. As we look to future activity, how can these efforts be better coordinated? Is systems engineering and risk management really that important? Do you agree with the AIAA position paper that a program office to assure that the systems aspects are emphasized and to manage interagency and international cooperation would be valuable?

9) Person A: Responding to the urging of Person B, you wish to provide a rational basis for the allocation of resources between varying degrees of detection and intercept activities. For this exercise, you decide to examine the threat of the 1km NEO, with an average impact rate of one per million years, resulting in the destruction of civilization and half of the human population. You consider these six near term decisions: a) No additional investment; continue as is with the search for NEOs; b) Fund Spacewatch - the passive terrestrial detection system - only; c) Fund

Spacewatch plus an active space-based detection system only; d) Fund a full intercept system now, without Spacewatch; e) Fund Spacewatch plus a full intercept system; and f) Fund a full detection system as defined in c, plus a full intercept system. For choices a, b and c, if we discover an incoming NEO, we will launch a crash intercept program. Refer to Spectra IV and V for the performance and costs of alternative detection and intercept systems. For criteria, use: maximization of the probability of preventing the impact, minimization of the loss of human life, the cost to rebuild civilization, the investment costs of planetary defense or some rational combinations of these. Refer to Spectrum II for other possible criteria and introduce more variations if you believe they can illuminate the issue. Draw a decision diagram to illustrate these alternatives and probabilities and discuss the relative merits of the alternatives with respect to the several criteria.

10) Person B: The Nation's science and technology budgets are presently supporting a very wide variety of activities that are perceived to be important to our health, welfare, security or other national objective. (See Spectrum VI) Reflecting on prior federal investments in medical electronics, agriculture, aviation and national security where we attained international prominence, what do think is the appropriateness for federal investment in planetary defense? Given that there are now about 200,000 scientists and engineers in the employ of the federal government, how salable would it be to add about another 100 to get started on a long term planetary defense program? Are you concerned that the issue of the NEO threat is so new, so unrelated to any precedent, of such an incomprehensibly low probability and so closely related to science fiction exaggerations that your credibility, political respect and chance for reelection in two years is seriously affected?

11) Person C: You were previously involved in the advocacy to ban atmospheric nuclear tests and nuclear weapons in space. It now appears that it may be necessary to include nuclear warheads as an option in future planetary defense systems because of their factor of millions advantage in energy density over chemical propulsion and intercept techniques. In an extreme case of nuclear intercept, where an incoming NEO is intercepted but some of the radioactive fragments enter the earth's atmosphere, the radiation level may range from 10% to 1000% of that experienced as a result of the nuclear atmospheric tests of the 1950's. Would you consider these levels an acceptable risk in view of the far higher risk of an NEO impact? Or do you think this nuclear risk -- as well as all other nuclear activity -- is so unacceptable that you would work toward the establishment of a truly long term strategy which relies on chemical energy only and establishes massive stores of energy in space which could be used for a great variety of scientific, exploration, exploitation and colonization purposes in addition to planetary defense?

12) Person D: A professor of engineering at a prestigious eastern university suggested that a tactic to gain worldwide attention and support for planetary defense would be to secretly launch an inflatable 2km "dummy asteroid" to the vicinity of Jupiter and then put it into an orbit that clearly would impact the earth within three years. This object is eight times the volume of the one hypothesized in problem 9 and would doubtlessly put the whole world on a crash program to save itself. This "stunt" could probably be accomplished for $50M, he felt. What do you think of the effectiveness of this tactic?

SPECTRA

I PEOPLE

Person A: Head of the International Planetary Defense Agency (IPDA). You report to the U.N. and receive resources from the Space Agencies and Ministries of Defense of the world's developed nations. You were chosen for your objectivity, communication and managerial skills as well as your understanding of the methods of risk management and decision theory. Your initial budget is relatively small ($50M/yr) and your job is to allocate and manage it rationally and, if appropriate, argue for increased/decreased budgets.

Person B: Chair of the U.S. House of Representatives Committee on Science and Technology. Your constituency is the entire population of the United States. You were chosen for your understanding of the coupling between federal investments in Science and Technology and US industrial competitiveness, health and social needs, environmental quality, and space exploitation and possible defense. Your job is to argue for the proper total level of S&T budget and for rational allocations of the budget dedicated to specific goals.

Person C: Visionary Leader of an Activist Organization to Save Humanity and Maximize its Future Quality of Life. You are supported by the private contributions of 500,000 people worldwide. You were chosen for your balanced idealism, practicality and scientific judgment. Your job is to fund key studies and research with the ultimate purpose of advocating governmental legislation and funding of programs you consider essential to humanity's survival and quality of life.

Person D: You, the Graduate Student who may Become Any of the Above.

SPECTRA

II CRITERIA

C1 Minimize cost of saving the human race *absolutely.*
C2 Minimize cost of saving the human race with a probability of X

C3 Maximize the probability of saving the human race *absolutely.*
C4 Maximize the probability of saving the human race using Y% of GWP.

C5 Maximize the expectation of lives saved per dollar invested (FAA).
C6 Save any life at any cost.
C7 If the risk is nonzero, drive the risk to zero at any cost.

C8 Minimize the regret that humanity will suffer (temporarily) if it learns it will perish and could have survived if it had invested an affordable amount (such as half the consumption of tobacco, alcohol and drugs).

III MONETARY VALUES

M1	Planetary Defense Management Office:	$2M/yr
M2	Continue Present NEO Search Programs:	$3M/yr
M3	Invest in Spacewatch (passive) hardware:	$50M
M4	Develop and Deploy a "Decoy" Asteroid:	$50M
M5	Operate and analyze Spacewatch System:	$10M/yr
M6	NEO Exploration and Characterization Program	$100M/yr
M7	Human Sanctuary on Earth:	$100B
M8	Human Sanctuary on Asteroids and Space Habitats:	$1T
M9	Human Sanctuary on Mars and the Moon:	$10T
M10	Preparing for and waging war:	$1T/yr
M11	Gross World Product (GWP):	$20T/yr
M12	Rebuilding a destroyed civilzation:	$1Q
M13	The irreversible loss of humanity:	**Uncalculable**

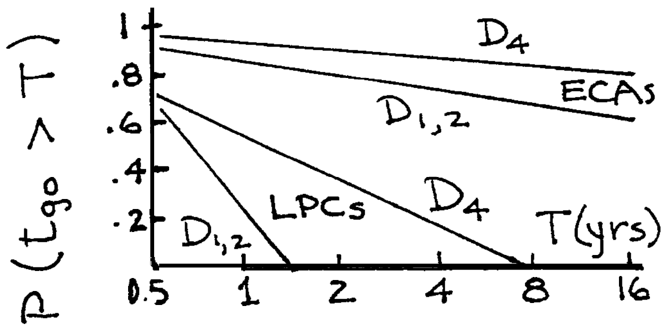
$M = 10^6 $B = 10^9 $T = 10^{12} $Q = 10^{15}

SPECTRA

IV DETECTION SYSTEMS:

D1 Continue as-is; in 200 yrs we'll catalog 75% of NEOs (95% of ECAs)
D2 Spacewatch; passive ground-based; accelerate above by factor of ten
D3 Spacewatch plus long range ground radar; more rapid p(hit) prediction
D4 Spacewatch plus space-based active sensors; 95% of NEOs in 30 yrs

PERFORMANCE



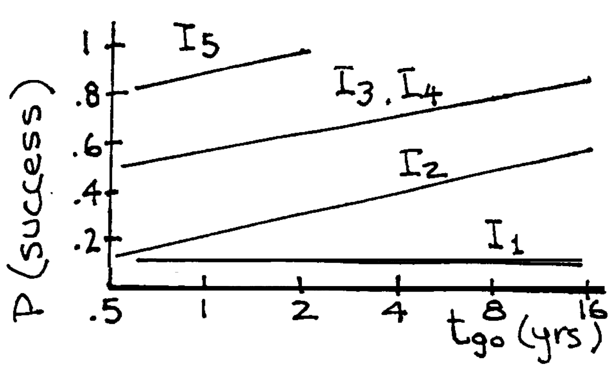
SCHEDULES AND COSTS

D1 $0 Development, $5M/yr Ops
D2 $50M, 10 yr development
$10M/yr operations
D3 $200M, 10 yr development
$10M/yr operations
D4 $10B, 15 yr development
$50M/yr operations

V INTERCEPT SYSTEMS

I1 Rely on retargeted ICBMs only
I2 Use existing nuclear warheads delivered by a vehicle and guidance system developed on an emergency basis
I3 Redesign warheads based on key tests and rendezvous with NEOs and deliberate optimized vehicle and guidance system development
I4 Development of a chemical intercept system including storing energy in orbit in advance of a threat detection

PERFORMANCE



SCHEDULES AND COSTS

I1 $0 development, $50M/yr ops
I2 $100B, 3 yr development
$100M/yr operation
I3 $100B, 10 yr development
$50M/yr operations
I4 $50B, 10 yr development
$1T 30 year lift energy to orbit

Recent Activities

Report on

Space Protection of the Earth—1994
Problems of Earth Protection Against the Impact with Near-Earth Objects

September 26-30, 1994

Presented by

Vadim A. Simonenko
Russian Federal Nuclear Center-VNIITF
Chelyabinsk-70, Russia

The participants of the conference, having considered presented materials and papers, came to the following conclusions:

1. The Near-Earth objects, such as asteroids and comets, which cross the Earth orbit, are of serious danger to human civilization.

2. Accumulated knowledge of the behaviour of space bodies and their interaction with planets as well as knowledge and technologies in the fields of space-missile, nuclear and production technologies are sufficient to begin the development of an international project of the Earth protection system against Near-Earth objects.

3. The most important current problems is refinement of risk assessment of NEO impact with the Earth, including:

   detection of the large NEOs with diameter 1km and more by astronomical means, determination of their orbit parameters and formation of applicable catalogues;
   evaluation of the numbers of small NEOs and their distribution by size;
   assessment of the detectability of NEOs of different size and composition;
   estimation of the consequences of NEO impacts with the Earth as a function of their dimensions and types.

4. It is necessary to conduct comprehensive researches of physical and chemical properties of NEOs.

5. It is necessary to investigate and estimate the possibility of preventing NEO impact with the Earth using technical means and technologies available for mankind.

6. It is necessary to determinate basic characteristics of the Earth protection system against impact with NEO and to estimate the efficiency of that system and the social-political and ecological consequences of its development by international efforts.

7. The conference should recommend "Program of Scientific-Technical Research for Development of Space Protection of Earth Against Near-Earth Object Impacts."

Conference appeal to the world community, governments and scientific organizations to pay attention to this problem and encourage its solution.

Preliminary Report on Policy Issues and Research Recommendations of the United Nations International Conference on Near-Earth Objects (NEOs)

John L. Remo
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Topics presented at the April 1995 United Nations International Conference on Near-Earth Objects are outlined and panel discussions are briefly summarized with emphasis on policy issues and research recommendations. Specific proposals based on an interpretation of international law and its relationship to the near-Earth object (NEO) hazard problem are suggested. Technical and research objectives to facilitate international cooperation for NEO discovery, exploration, and hazard mitigation are outlined.

Introduction

In April, 1995 a conference on near-Earth Objects (NEOs) was held at the United Nations world headquarters in New York city. Supporters of this conference included the National Aeronautics and Space Administration, the Planetary Society, and Sandia National Laboratories. The purpose of this plenary conference was to put into perspective recent discoveries in the natural sciences which describe the part played by Earth-crossing asteroids and comets (ECACs) in the extinction of a large range of species (e.g. from dinosaurs to ammonoids) and the resultant effect on the evolution of those mammalian ancestors from which Homo sapiens ultimately developed. These perspectives include the effects of past terrestrial impacts contained within the fossil record, current astronomical observations of NEOs, and future exploration missions to understand the properties of NEOs and the hazards they may pose to the planet Earth. Participants included scientists from both the major industrialized nations, as well as from many developing countries. It is anticipated that this representative cross-section of U. N. member states and the cooperative spirit of the meeting may provide a basis for future international cooperation in NEO research.

The conference was characterized by the open and rational analysis of the various discoveries of natural science and a willingness to share information associated with the collision of NEOs with the Earth in the past, present, and future. A considerable amount of observational data and information was exchanged during the first two days of formal sessions. During the third day fora were held to discuss NEO observations, exploration, and policy issues. This report briefly outlines the scientific topics reviewed at the formal session and some of the ideas presented at the discussion groups. The emphasis of the latter was on observations, exploration, and policy issues. The policy recommendations presented in this paper are primarily based on my interpretations of the group consensus and the current space treaties.

A Brief Summary of Some NEO Topics Covered at the Conference

Modern theories on the origin and evolution of the solar system all argue that NEOs (which are primarily Earth-crossing comets and asteroids or their ancient equivalents have influenced the history of the Earth since its formation. Over the past few decades we have learned to recognize scars both on the Earth's surface as well as on other planets, moons, and asteroids in the solar systems as marking past asteroid and comet impacts (Chapman, 1995; Melosh, 1995, and Neukum and Ivanov, 1994; and Neukum 1995, Sharpton 1995). On the Earth the largest of these scars are over 100 km in diameter. The worldwide distribution of craters ranges in age from 2 billion years to about 4,000 years (Henbury), demonstrating that NEO impacts on our planet represent a continuing process (Grieve and Shoemaker, 1994 and Grieve, 1995). With the discovery of the global effects associated with the Cretaceous/Tertiary (K/T) boundary event (Alvarez et al, 1980; Sharpton 1995;) it appears likely that NEOs have also been influential in the evolution and extinction of many terrestrial species (Black, 1995; Jablonski, 1995; Smit, 1994 and 1995; and Ward 1995). Not only were the dinosaurs eliminated; it is also thought by some (Jablonski and Raup, 1995) that the K/T mass extinction caused a 70-80% reduction in biodiversity at the species level and a 50% reduction at the genus level. Such analyses suggest that some biotic factors that enhance survival during times of low extinction rates are ineffectual during mass extinctions. However, we note that the association of the K/T extinction with extraterrestrial impact is not universally held (Keller, 1995). Nonetheless, the overwhelming scientific evidence points to an extraterrestrial impact as the agent for the great extinctions at the K/T. This conclusion has recently been dramatically underscored by the impact of comet Shoemaker-Levy 9 on Jupiter (Ahrens and Harris, 1995; Crawford et al 1995; Hammel, 1995 and D. Levy 1995). Had any of these fragments impacted Earth, a global catastrophe would have ensued bringing enormous property damage and loss of life (Morrison 1995 and Toon et al, 1995). Fortunately, based on the established terrestrial impact crater record, it appears such an event is extremely unlikely, (about one chance in 6,000 over the next fifty years), but not impossible. Although the probability is small (and may even be correlated through planetary dynamics-Bottke at al , 1994; Rabinowitz at al, 1994; and Steel 1995), the consequences are so dire they cannot be ignored. To involve the world community with this issue of planetary importance is the reason the U N with the cooperation of the Office for Outer Space Affairs was chosen as a forum for this interdisciplinary conference.

Conference Objectives

As stated in the introduction, one of the reasons for calling the International Conference on NEOs was to present combined research results from several scientific disciplines describing how the human race was provided an opportunity to evolve from mammalian predecessors. That extraterrestrial objects could be demonstrated to dramatically influence the evolutionary course of terrestrial life is a powerful concept that provides unique perspectives on the unfolding of the human race. The relationship between adaptation and evolution becomes particularly interesting in this context. While biological adaptation can be interpreted through natural selection, accumulated changes at the gene level can generate evolutionary changes. From such models it can be understood how the impact of large NEOs, catastrophically disrupting the terrestrial biosphere, initiate substantial (catastrophic) geological changes on the surface of the Earth over extended periods of time and provide new boundary conditions for adaptation. These impacts modulate geological changes on the surface of the Earth which is otherwise interpreted to have developed continuously and uniformly over long periods of time by plate tectonic activity. Thus, the NEO impact at the K/T boundary provides an exciting overlay to the interpretations of Darwin, Lyell, and Hutton which still provide the interpretive matrix of natural science. Following in this tradition of resolving the domains of uniformatarianism and catastrophism, the astronomers, planetary scientists, paleontologists, environmental scientists, and other scientists interpreted and restated the impact data from their own disciplinary perspective. In a sense, the conference was a celebration of interdisciplinary science whose objective was the cross calibration and interpretation of data from different disciplines. This activity served as a stimulus for gaining further knowledge through education, exploration, and research in the natural sciences as well as providing a warning of possible future hazards.

This conference also provided an example of how science and exploration are an important cultural endeavor that defines our civilization, bestowing a model for free enquiry that is the underpinning of self-government and its freedoms. From this perspective, one can interpret science as an endeavor worthy of societal support. Therefore, another objective of this conference was to initiate an organizational framework through which scientists, explorers, and amateur astronomers, in all countries can participate in research projects critical to human development and survival.

There is a singular reason why the United Nations was chosen as a venue for this conference. Since the initiation of the space age, the need to establish international cooperation for the peaceful uses of outer space was clearly perceived by the member states. Currently the United Nations is coordinating a large number of cooperative space activities at international, regional, and national levels. Most important in implementing this international cooperation in space are the treaties and principles governing the activities of states in the exploration and use of outer space as adopted by the United Nations General Assembly (United Nations Treaties and Principles on Outer Space, 1994). It is within this framework that the International Conference on Near-Earth Objects was convened. Therefore, a primary objective of this meeting was to interpret the NEO threat within the cooperative framework of existing guidelines of international space law. Such inclusion will essentially provide a mechanism for states which are parties to these treaties to include the possible threat from NEOs within these treaties. Other conference objectives including issues associated with cooperative space exploration, research, and education in the natural sciences are also compatible with this very important objective.

To carry out these tasks, this conference required assembling an extraordinary group of international scientists to discuss a broad range of scientific and technological problems associated with a NEO impact, as well as the encompassing humanistic aspects. The historical precedence of our scientific and educational institutions foster a tradition of inquiry and discovery for the advancement of all peoples. These shared ideals promote cooperation among nations, give guidance to leaders, and provide motivation for young people, who are the future, to work in an open way towards common goals. The very survival of our species depends on the appropriate use of our intellect to work together in a cooperative manner. To this end, space provides an unique challenge. In accepting this challenge, we must pursue our scientific goals with the utmost integrity, rigor, and humility, while also diligently communicating our findings to a literate public, from whom we ultimately draw our support. However, we must be careful not to over-react or seek temporary acceptance or prominence by promoting sensational or alarmist views in the pursuit of short term recognition and funding.

Interpretations

It is clear that the overall intent of the U.N. treaties and agreements on outer space are directed towards the peaceful exploration and utilization of space. It is also clear that nuclear and other weapons of mass destruction are prohibited from being placed in orbit around Earth or being stationed in space. However, if a NEO threatens Earth how can the mitigation be effectively carried out within the current framework of the treaties? Of course, Article 51 of the U.N. Charter gives member nations the right of self defense. But certainly a more specific protocol is needed to address the NEO hazard issue. This may be carried out through an extension of the U.N. outer Space treaties to include NEOs. A first step is to coordinate the identification and cataloging of NEOs. Second, is the identification of a clear and direct threat; this is a problem in NEO observation, identification, and tracking which requires adequate ground based observations sensitive to objects of magnitude 22 or greater. The third step is establishment of rapid and clear lines of communication regarding NEO hazards, which are already in place for certain space emergencies, TV direct broadcast satellites, radio communication satellites, reconnaissance satellites, etc. and need only be extended to cover NEOs. This will minimize the chance for misinterpretation of NEO motives and will facilitate, if necessary, a coordinated worldwide response. The next steps will involve an actual interaction with the threatening NEO. Such a response to the threatening NEO, if necessary and prudent, will depend on the availability of mitigation technology delivery systems and energy sources.

It may be argued that there may be more to fear from an apparently overzealous or unjustified desire by some to use weapons of mass destruction on a NEO body that may not be an immediate threat. The use of such a weapon may create a greater threat. Even worse is the deliberate, calculated misuse of assets whose ostensible purpose is for NEO mitigation. Such dilemmas will always be with us. Clearly, The NEO hazard threat cannot be used as a pretext for re-armament, and appropriate safeguards must be taken to minimize the threat of misuse.

If mitigation methods and devices are to be developed, safeguards and rigorous controls against their misuse must play a dominant role at every stage of their design, development, testing, and deployment. However, in the absence of specifically developed mitigation technology it would be prudent to have available that technology and hardware which can most effectively deal with an Earth threatening NEO. We must and can establish the appropriate custodial mechanisms that allow us to maintain those options which can best protect the Earth.

Finally, we must remember that the entire discipline of NEO studies and even their mitigation is driven by observations. Without a sky survey program, the discovery rate will not be adequate to provide even a minimal inventory of the threats from NEOs in the near term. Clearly, observational activities and imaging research (e.g.. CCDs) must be supported as a first priority. Other research on materials and their interactions with shock waves and ionizing radiation, rockets, space systems and communications, and a general understanding of asteroid and comet properties must be supported in order to interpret observations and assess possible hazards and mitigation options. Science, technology, and education are all mutually supportive and must be adequately funded to achieve the requisite knowledge regarding NEO mitigation and the wisdom to effectively deal with the hazard aspect in a rational manner.

Conclusion

The hypotheses originally put forth by Alvarez et. al. (1980) that an extraterrestrial impact on the Earth about 66 million years ago caused massive extinctions, based on the best current natural science data available, is correct. That there are currently many thousands of Earth-crossing asteroids and comets that can do considerable environmental damage to the Earth and its inhabitants has also been shown. The impact of SL-9 on Jupiter provided a timely example of the devastation that could occur from such an impact. The question is how should the Earth deal with the possible NEO hazard?

It is therefore proposed to the United Nations that, as a first step, Articles V and XI in the 1967 Outer Space Treaty be considered to extend to cover NEOs. It is also suggested that the 1979 Agreement Governing Activities of States on the Moon and other celestial bodies be modified in order to be acceptable to additional Member States and that it be extended to include the NEO impact hazard.

Steps towards mitigation should focus on, in the order of priority:

1. A vigorous NEO sky search with adequate follow-up for objects of special significance.
2. Laboratory experiments on surrogate NEO materials emphasizing spectral observables (especially for passive comet-like materials) and their response to mechanical and radiative interactions.
3. Development of long range rockets to carry out flyby, orbital, and penetrator reconnaissance missions.
4. Maintenance of the scientific and technological capabilities of the academic and industrial bases and the research and development laboratories.

The views, interpretations and opinions presented in this paper are those solely of the author (JLR).

Acknowledgments

This document is the outgrowth of many interactions and comments throughout the conference, and I wish to thank all the participants for their candid and informed positions, much of which is contained in this document. In particular he wishes to thank my colleagues on the program review committee; C. Black, C. Chapman, T. Gehrels, B. Marsden, and P. Sforza for their critical assistance in making the conference a success and continually providing advice and assistance. Critical input to this document were provided by P. Lala and H. Haubold of the U.N. Office of Outer Space Affairs. Special thanks are also given to L. Friedman, R. Hagengruber, P. Hammerling, H. Haubold, W. Tedeschi, R. Warasila, and H.York for constructive criticism and encouragement. Finally, this meeting could never have taken place without the cooperation and encouragement of N. Jasentuliyana, director of the U.N. Office of Outer Space Affairs to whom we are especially grateful, and M. Whaba, Executive Office of the Secretary General. A final thanks to all the participants of this conference for their complete commitment to making this conference a success.

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AIAA Position Paper
Responding to the Potential Threat of a Near-Earth-Object Impact

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In 1990, the AIAA published a position paper on the hazards due to asteroids which stimulated substantial recognition within Congress and helped cause the establishment of the Detection and Intercept Workshops. The 1995 position paper is an update of the previous paper and has four recommendations: a) accelerate the detection of near-earth-objects, b) establish a systems engineering and analysis program to plan followon activity, c) perform experiments in accordance with the results of b, and d) establish a management focal point to coordinate the domestic and international activity. In addition to the AIAA, this new position paper was endorsed by the Institute of Electrical and Electronic Engineer's Aerospace and Electronics Society, the National Council on Systems Engineering, and the Space Studies Institute. The planetary defense domain has received the benefit of the world's finest scientists over the past several years and it now judged timely to introduce more formal systems engineering discipline as the foundation for more progress and acceptance. Key systems issues include the deeper integration of detection and intercept parameters, the smoother flow of accuracy requirements from initial acquisition to final tactics and the choice of systems level performance criteria. Although recent progress has been good, as evidenced by the publication of the T. Gehrels edited, "Hazards due to Comets and Asteroids," and the integrated Planetary Defense Workshop which recognized the importance of systems issues, much remains to be accomplished.

Introduction

The near miss of Asteroid 1989FC encouraged the Space Systems Technical Committee (SSTC) of the American Institute of Aeronautics and Astronautics (AIAA) to publish a position paper, *Dealing with the Threat of an Asteroid Striking the Earth* in April, 1990. This paper, written by E. Tagliaferri, the chair of the SSTC, was submitted to Congress as part of AIAA's annual testimony. According to T. Dawson, then on the Congressional Staff, this position paper had a "seminal effect" on the Committee on Science, Space and Technology of the U.S. House of Representatives. The credibility of the threat of an impact from space to humanity was immediately elevated from its previous science fiction fringe status to a serious, scientifically and technologically sound issue facing all the nations on earth. This committee stated, in the NASA Multiyear Authorization Act of 1990,

"The Committee believes that it is imperative that the detection rate of Earth-orbit-crossing asteroids must be increased substantially, and that the means to destroy or alter the orbits of asteroids when they do threaten collisions should be defined and agreed upon internationally.

The chances of the earth being struck by a large asteroid are extremely small, but because the consequences of such a collision are extremely large, the Committee believes it is only prudent to assess the nature of the threat and prepare to deal with it."

NASA was directed to conduct two workshops as recommended by the AIAA position paper: one on the detection and another on the interception of large space objects. Over the next two years, the Detection Workshop, chaired by D. Morrison, and the Intercept Workshop, chaired by J. Rather, completed their work, wrote their reports and presented their findings to the Committee on March 24, 1993. The report on *The Threat of Large Earth-Orbit Crossing Asteroids; Hearing before the Subcommittee on Space of the Committee on Science, Space, and Technology, U.S. House of Representatives,* not only contains the full detection and interception workshop reports and the AIAA position paper, but very illuminating dialogue between the presenting scientists and the Congressional Committee members. In particular, George E. Brown, Jr., the committee chair stated,

"If some day in the future we discover well in advance that an asteroid that is big enough to cause a mass extinction is going to hit the Earth, and then we alter the course of that asteroid so that it does not hit us, it will be one of the most important accomplishments in all of human history."

Those concerned with the threat of Near-Earth-Objects, (NEOs) could hardly have asked for a more supportive statement made by the chair of this powerful committee. The presentations were received with great interest and spirited discussion. The workshop chairs were warmly thanked and praised for their efforts. However no significant new funding resulted. The 1989FC "wake-up call" and the first AIAA position paper were insufficient to effect a change in the face of tight budgets and existing priorities.

Within a day of this Congressional hearing, we were provided with another wake up call: Comet Shoemaker-Levy 9 was discovered at Palomar.

The Role of Engineering Professional Societies

As AIAA's SSTC was observing these events with great interest, they were joined by other professional societies. Since we are dealing with issues of constituency and advocacy, it would be useful to outline the diverse motivations of these organizations who wish to further the greater understanding of and appropriate response to the NEO threat:

At the most general level, these are engineering, not scientific societies. There may be astronomers, paleontologists, or nuclear physicists among their members, but these societies strive to serve the professional engineering goals of their membership, industry and society at large rather than the advancement of scientific research. Specifically, regarding the NEO threat, all the endorsing societies share the common belief that, although the likelihood of an impact is extremely low its devastating power is unprecedented and that, furthermore, humanity has the technology and the means to respond effectively and economically. Beyond these common beliefs, the endorsing organizations have different shades of emphasis:

The AIAA is interested in the general health and advancement of the aerospace industry, as well as the effective development of applied technology. It has proven to be a leader in the recognition and support of key technologies as well as the development of key systems concepts which optimally merge new technologies with new missions. The SSTC is specifically interested in space systems. AIAA's Systems Engineering Technical Committee (SETC), which did not exist in 1990, concentrates on the application of modern systems engineering processes and principles to the management of complexity.

The National Council on Systems Engineering (NCOSE), has similar goals to the SETC, but it draws from a larger applications and personnel base. For example, it has a set of working groups, each dedicated to a specific subdiscipline such as risk management and requirements management. Also, one of NCOSE's highest priorities is to broaden the applications to include domains other than military systems, where most of its members gained their experience.

The Institute of Electrical and Electronic Engineers' (IEEE) Aerospace and Electronic Systems Society (AESS) is interested in the development of its members, professional standards, and the advancement of key electronic technologies such as digital electronics, communication, navigation, guidance, control and radar which it feels will be relevant to the NEO problem.

The Space Studies Institute (SSI) has the long-term goal of the exploitation and colonization of space, and recognizes in the anticipated populations of NEOs vast opportunities to fulfill Gerard O'Neill's vision of the "High Frontier."

The 1995 Update of the NEO Position Paper

The AIAA and its supporting organizations felt that it was timely to issue an update of the 1990 position paper for several reasons: Most significantly, although the NEO threat is far better known by scientists and far better recognized by government than just five years ago, it has not yet achieved the crucial breakthrough as a high priority program with appropriate funding. All the endorsing organizations want to help support this breakthrough in these times of high budgetary pressure and reorganizations. Additionally, the organizations had many concerns of a systems engineering nature on the progress of NEO systems concepts and wish to add their constructive advice. More detail on some of these concerns is provided below.

The AIAA position paper, *Responding to the Potential Threat of a Near-Earth-Object Impact* is appended to these preliminary remarks. Briefly, it recommends four interrelated actions: 1) Approve an accelerated detection program, 2) Initiate total systems studies *now,* 3) Perform key tests paced by the results of these studies, and 4) Establish a focal point to manage domestic and international NEO activity.

Systems Aspects of the Planetary Defense Problem

The enormous progress achieved during the first quarter of this decade continued into the second quarter as evidenced by the publication of *Hazards due to Comets and Asteroids, Tom Gehrels, Editor,* the far greater participation of the US Air Force Space Command, the accelerating international participation, and perhaps most importantly, the holding of a single integrated Planetary Defense Workshop rather than continue with separate Detection and Interception Workshops. However, there are aspects of planetary defense associated with extrapolated policies, subsystem optimizations, accuracy balance and system level criteria, which the endorsing organizations believe will impede further progress and acceptance.

These issues will be discussed briefly in the following sections. It must be emphasized that no criticism of the extremely dedicated, intelligent and idealistic group of people working the planetary defense problem is intended. We merely wish to point out that as the problem is more deeply analyzed, it is becoming more interdisciplinary, more complex and more dangerous as a potential threat to humanity. It is timely to add another, relatively young discipline to our array of problem solving and management tools: systems engineering.

The Heritage of Extrapolated Policies

A half century after the end of World War II, we are again at a crucial juncture in human affairs. Most of the military and space strategies of both the United States and the Soviet Union were directly responsive to the perceived demands of the cold war. With the termination of the cold war and the dissolution of the Soviet Union, the former superpowers and their allies are struggling with a multitude of new priorities which for decades have been considered subordinate to military preparation and space.

Yet, the heritage of extrapolated policies which dominated the cold war years remains as a very influential background to today's decision making and resource allocation. The very substantial allocation of resources to national defense the past several decades was resented by those involved in other worthy activities and there is a vigorous movement to cut the military back substantially. Within the department of defense, one of the highest level allocation issues was the proper balance between strategic/nuclear and tactical /conventional warfare, and there is a vigorous movement to cut back the nuclear and to view new applications of nuclear technology with great suspicion. Within NASA, high level allocations involved manned versus unmanned missions and today's struggle is how to convert from competition with the Soviets to Cooperation with the Russians and other developed nations. Within astronomy, with its centuries-old tradition of terrestrial optical observations, new options of space platforms and long range radars present a rich selection of technological alternatives.

Compared to priorities associated with education, health, crime, drugs and the environment -- which have been identified for decades and which have developed advocacies since at least as far back as the fifties -- the planetary defense problem has literally burst upon the scene only recently. It is further tainted with the impression that its only precursor in our consciousness comes from science fiction and the fact that the probabilities of global devastation due to an NEO impact are so low that they are without precedent.

The turmoil in today's decision making can be viewed as an opportunity. We need more advocacy -- which can only come from an intensified educational program and the most responsible reporting of the nature of the threat, its probability and the alternatives for mitigation. Extrapolations of old policies and strategies should not impede our selection of the best technologies, people and organizations to respond to the NEO threat.

Subsystem Optimization

As originally defined, the Spaceguard program appears to be an enormous bargain. Its claim that it will provide ample warning for global devastating impacts due to earth-orbit-crossing asteroids and short period comets -- representing an estimated 75% of the threat -- for about $50M in capital investment and $10/yr labor indicates an extremely attractive cost/benefit ratio.

One of the most fundamental tenets of risk management is to invest in early testing and experiments to characterize the nature of the risk. The AIAA position paper recommends immediate approval of such a program to accelerate the detection of NEOs.

However, many observers are concerned about the tendency to postpone the search for the remaining 25% of the threat and to postpone the development of mitigation systems until after a threatening NEO has actually been identified. First of all, the "detection community" appears to be giving the "interception community" excessive respect in assuming that the tremendous challenge of intercepting a 1km (or larger) object can be met from a "standing start," without the normal phases of conceptual formulation, development, testing and prototyping. Without the benefit of these phases, the inevitable response to a large, threatening NEO would involve existing nuclear warheads, with uncertain interception effectiveness and the possibility of actually aggravating the threat.

On the other hand, the "interception community" appears to be giving the "detection community" excessive respect by assuming that the warning will be given with at least a year to go until impact and with such a high confidence of hit probability that the energy required for interception will be only that required to move the NEO an earth's radius. (This assumption is discussed more in the next section.)

From the standpoint of a citizen of the world who only recently emerged from the risk of dying from a massive thermonuclear exchange and is now grappling with new risks such as global warming and ozone layer depletion, there is much confusion about the NEO risk. Only a decade ago he was completely unaware of such a risk. Then very suddenly, he was told that the estimated population of NEOs exploded by about a factor of a thousand, but with an uncertainty of about a factor of two in quantity, of about a factor of ten in effect, and at least another factor of several thousand in when the next big one is coming! In the face of all these new and gigantic uncertainties, he can perhaps be forgiven for not being very impressed that the risk is being reduced by a factor of only four -- especially when he is told that most of earth's large craters are due to comets, which are *not* the primary objects for the initial search. He could correctly classify a program like Spaceguard which makes excellent progress at very low cost as "gathering the low hanging fruit" -- or as a systems engineer would put it: optimizing a subsystem with insufficient regard to the broader context of the whole system.

In response to these concerns, the AIAA position paper also recommends that a broad systems approach be taken to the planetary defense problem and that studies and analyses be undertaken immediately to examine the systems engineering, risk management and programmatic aspects of planetary defense. The accelerated detection program should look past its most efficient task of searching for asteroids and short period comets to the more difficult (and unfortunately more expensive) task of searching for *all* threatening NEOs. Because of the recently improved understanding of the tsunami effects, the search must also include objects below 1km in size. Passive, terrestrial sensors should probably be augmented by space-based and/or active, long range radars. These extensions are far more expensive than the first phase detection system but they are necessary for the complete solution and they therefore should be designed with a total systems viewpoint. Then, beyond the augmented detection system, preliminary designs and risk reducing tests associated with potential mitigation systems should be undertaken.

Spectrum of Accuracy

As was indicated above, the previously disparate activities of the various contributing communities addressing planetary defense should be more tightly integrated. One important parameter of such integration is the accuracy and speed of convergence of the NEO's orbit determination. Although accuracy should be properly considered as smoothly transitioning along a continuous spectrum, the following very simplified five stages are worthy of comment:

The first stage involves the initial observation that a given NEO is indeed *new* and not a previously acquired and catalogued object. As the NEO catalogue grows over the next several decades this becomes increasingly important and a significant data management task.

The second stage is to develop sufficient accuracy that the object is not lost -- especially as it enters the sun's glare. In the early days of planetesimal discovery, most of the initial acquisitions were lost.

The third stage is to develop sufficient accuracy to predict probability of hit on earth, or more likely, predict an insignificant likelihood of hit on earth within x centuries.

Another stage is to predict probability of hit on earth for an object which is on its terminal trajectory toward earth and which was not previously measured.

A final stage is to predict hit probability with sufficient accuracy and time-to-go that interception resources can be deployed effectively. Most interception system analyses assume that the orbital error projected to the vicinity of the earth will be very small compared to the radius of the earth. In this case, the "Planetary Defense Commander" will be able to effect a successful NEO defense by deflecting the object transversely one earth's radius, at the most. If, however, the orbital error is on the order of an earth's radius, the commander's decision becomes far more complex: the probability of hit if he does nothing becomes 0.68; if he deflects the NEO by one earth radius, the probability of hit becomes 0.48; and if he deflects the NEO by two earth radii, the probability of hit becomes 0.16. With the future of humanity at stake, this is hardly reassuring. Worse yet, for deflections of one and two earth radii, the probability of converting what would have been a miss into an inadvertent hit would be 0.14 and 0.16 respectively. This would clearly be unacceptable no matter how the probability of hit were diminished: to go to all the effort of an interception only to cause the (perceived unnecessary after the fact) deaths of billions of humans! (The probabilities were based on a *very* simple normal error model.)

Yet there may be circumstances where the first acquisition of a high velocity comet which hasn't ever visited the inner solar system before is made with less than a year to go and the error projected to the vicinity of the earth would be greater than an earth's radius. The terminal kinematics of such an object would present a small angular rate and an enormous range rate to an earth based sensor. In this scenario, the value of a "several AU" range radar would be worth a billion souls. Yet, long range radars seem to have "fallen between the cracks" of analyses whose perspective was limited to detection only or intercept only. When suggested as a robust method to converge orbital accuracy rapidly, replies such as: "they're not good for search," or "they're very expensive; r-fourth law, you know" are forthcoming.

It is suggested that the long range radar is but one example of an issue involving time, energy and accuracy which can only be properly examined from the total systems view since it contributes so intimately to both the detection and intercept phases. Another was mentioned by Dr. Teller at the Planetary Defense Workshop, "Achieving greater accuracy is probably a far more intelligent strategy than deploying great amounts of energy." The context of his remark was his realization that about a million NEOs could be employed in the "brilliant mountains" concept only if we knew their orbits with great precision. *All* forms of astrometry would be required to realize this concept. A systems analysis regarding the kinetic energy available in nonthreatening NEO to deflect threatening ones could cast a different light on the real cost and value of "several AU" long range radars and other terrestrial and space borne sensors.

System Level Criteria

The establishment of meaningful criteria to guide the design of complex systems and to assure that the stakeholders are truly satisfied is one the most important and difficult tasks in all of systems engineering. This is especially true for the planetary defense problem due to its newness, its multidimensionality and its unprecedentedly low probability coupled with its dreadful severity.

The work published by Morrison and Canavan in the "Hazards" book and elsewhere appears correct, thoughtful and consistent with risk analyses performed on other risks to humanity. They claim accurately that the NEO threat is really in a class by itself -- nothing else comes close regarding such a low probability of occurrence and such devastating consequences. In the final analysis we will probably have to rely on a combination of several criteria.

The most rigorous mathematical analysis can be performed employing the techniques of decision theory and using the criterion of "expected monetary value" (EMV) of the loss, given that risk mitigation is not employed. Although this criterion is respected in making business decisions and is preferred for many applications of risk management within systems engineering and program management, where the loss of human life is concerned there is usually a resistance to placing a monetary value on a casualty. An important exception is the FAA's policy of evaluating safety and maintenance alternatives on the basis that the expected value of a human casualty from a commercial aircraft accident is $2.6 Million. This is relevant because as the NEO threat is listed within the context of other risks, it comes quite close to the risk of traveling on commercial aircraft. Moreover, the threat from space and the threat of air travel are broadly related as being involved with high technology regarding both their generation and their solution.

Other criteria have employed the "one in a million" threshold used by the EPA as well as the "cost to rebuild civilization" standard, which lies in the neighborhood of one $Quadrillion. However, the highest level allocations seem to be made on a qualitative, not quantitative basis.

Morrison, in his papers and speeches commented that these criteria many be useful in other, more traditional domains, but they fail to capture the incomparable, unthinkable, and incredible *dreadfullness* of the extinction of humanity. In addition to the above "cost to replace" paradigm, perhaps we should give more emphasis to the "insurance" paradigm. For example an international budget of $3B/yr would substantially mitigate the NEO threat, as well as advance science and open up vast resources of material and energy in near earth space. This will cost each human being one cent per week. Is this worth it? What percentage of world-wide traffic in drugs, alcohol and tobacco would we have to give up to fund this planetary defense program?

In the introduction, George Brown was quoted to say that a successful planetary defense would be one of the most important accomplishments in human history. Perhaps the dual of his statement drives the point home more dramatically:

"If some day an object does strike the Earth, killing not only the human race but millions of other species as well, and we could have prevented it but did not because of indecision, unbalanced priorities, imprecise risk definition and incomplete planning, then it will be the greatest abdication in all of human history not to use our gifts of rational intellect and conscience to shepherd our survival, and that of all life on Earth."

Conclusions

The threat is real and deserves a response. Clearly, the first step is to learn more about the threat with an accelerated detection program. More thorough detection programs are far more costly than Spaceguard but any rational criterion can show that they are worth it. Long range studies and plans on the total planetary defense system should be instituted immediately and key tests should be implemented to mitigate technological risk. Compared to other risks to humanity, the technologies to mitigate the NEO threat are near at hand and ample human and physical resources are available and waiting the decision to act. The total cost of a working planetary defense system will be an enormous bargain in terms of the mitigated risk as well as the advance of science and the exploitation of space resources. What is now required is to gain a broad acceptance and program initiation. This can be accomplished by education, accurate and clear communication of the true risks and effective application of a rational, balanced program and systems design. *We can do it.*

The following four pages present the version of the NEO position paper which was approved by AIAA's Space Systems Technical Committee (SSTC), and Systems Engineering Technical Committee (SETC), IEEE's Aerospace and Electronic Systems Society (AESS), the National Council on Systems Engineering (NCOSE), and the Space Studies Institute (SSI). As these proceedings are going to press, the position paper is being reviewed by AIAA headquarters.

RESPONDING TO THE POTENTIAL THREAT OF A NEAR-EARTH-OBJECT IMPACT

An AIAA Position Paper

Prepared by the
Space Systems Technical Committee
and the
Systems Engineering Technical Committee

Approved by the
AIAA Board of Directors

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SUMMARY

Evidence that the Earth may be impacted by an asteroid or comet large enough to cause global devastation is increasing rapidly. Recent fundamental research indicates such impacts have been primary causes of past dramatic changes in the Earth and its environment. As recommended by AIAA's 1990 position paper, congressionally-directed workshops on Near-Earth-Object (NEO) detection and intercept were conducted and interagency and international collaborations began. This position paper recommends continuing the NEO activities by: a) accelerating the search for asteroids and short period comets, and b) developing concepts and plans for follow on detection, identification and mitigation systems. Should the activities in a) and b) begin to point the way to a more substantial program in the future, the government should consider establishing an office to provide a focal point to coordinate efforts to improve detection and risk alleviation.

BACKGROUND

In April 1990, AIAA's Space Systems Technical Committee published the position paper, *Dealing With the Threat of an Asteroid Striking the Earth.* This paper, precipitated by the close passage of asteroid 1989FC — with zero warning time — helped stimulate broad interest and concern in this potential threat to civilization and even to the survival of humanity. Soon afterwards, the U.S. House of Representatives Committee on Science, Space and Technology directed NASA to conduct two workshops related to the asteroid threat as recommended in the position paper; one for the detection and characterization of the threat, including determining the orbits with a precision which would allow the accurate prediction of an impact, and another which dealt with issues related to mitigating the threat. On March 24, 1993, the results of these workshops were summarized and discussed in a formal hearing before this same congressional committee. The class of potentially threatening objects was enlarged to include long period comets as well as earth-orbit crossing asteroids; together they were defined as near earth objects.

World-wide attention to this issue has increased enormously over the past decade, based on the knowledge and understanding acquired in recent years by sophisticated research and increasing recognition of the reality of the NEO threat. Scientific consensus that a NEO impact was the primary cause of the Cretaceous/Tertiary boundary and the sharp end of the age of the dinosaurs was further consolidated with the identification of the probable impact crater on the Yucatan Peninsula. As requested by Congress, the participation by the U.S. Department of Defense and the developed nations worldwide has begun. Public attention has been captured by the prediction of an impact on Earth by comet Swift-Tuttle (later retracted) and then by the actual impact on Jupiter by comet Shoemaker-Levy 9. This not only proved to be the most violent event in the solar system during recorded history, but was also an excellent example of rapid and accurate orbit determination.

The American Institute of Aeronautics and Astronautics (AIAA), the National Council on Systems Engineering (NCOSE), the Aerospace and Electronic Systems Society (AESS) of the Institute of Electrical and Electronic Engineers (IEEE), and the Space Studies Institute (SSI) agree that our nation has a responsibility to continue focusing national and international attention on the issues raised by the NASA workshops. By providing a forum open to a diversity of views and specialties, we can perhaps help illuminate and resolve issues with broad system and technical implications.

CONSENSUS AND RECOMMENDATIONS

It is the consensus of these organizations that, although the likelihood of an NEO impact is extremely low, the consequence can be catastrophic, ranging from the devastation typical of a nuclear warhead for small objects to billions of fatalities, the end of civilization and even the extinction of mankind for large objects. Such consequences are significant enough that the scientific community and worldwide governments should investigate whether detection and even mitigation capabilities are within reasonable grasp.

In recognition of this, these organizations recommend:

1) Immediate approval of a program to accelerate the discovery, identification and characterization of NEOs. Extrapolating the present rate of discovery of kilometer-size NEOs by a small and dedicated team of astronomers, it would take hundreds of years to discover the 2000 objects of this size that are currently estimated by astronomers to be in earth-crossing orbits. The investment in a system to accelerate the discovery schedule to about 10 years seems to have an extremely attractive cost benefit ratio. This first phase postpones the investment of a detailed identification and mitigation system since it is estimated that 75% of the objects discovered will be asteroids or short period comets where the impending impacts will have ample warning times for the development and deployment of mitigation systems.

2) Begin immediately, and at a modest level, to study various concepts for responding to a risk, should one materialize. These studies would be devoted to a broad perspective examination of the systems engineering, risk management and cost effectiveness in such areas as:

   Improving the accuracy and speed of orbit determination.

   Improving the detection capability and warning time against large, long-period comets.

   Improving the capability against smaller NEOs capable of major mortality and destruction.

Determining the feasibility of NEO rendezvous for characterization regarding potential intercept concepts as well as scientific and potential exploitation purposes.

Developing mitigation system concepts.

Establishing a plan to reduce technical uncertainties.

Examining potential architectural issues in command. control and communications. and

Analyzing alternative plans for detection and mitigation that weigh cost. implementation time. and risk.

3) Begin planning. pending the results of actions 1) and 2). for efforts to explore capabilities to deal with collision threats in the next century. The modest investment over the next decade to accelerate detection. and the results of studies identified in 2) above. will begin clarifying for the U.S. and other nations the nature of the risk of collsions and the potential for alleviating them in the future.

In the future. the U.S. should consider establishing an office for coordinating the U.S. response to this risk and should invite other nations to participate. The objective of this office is to provide the focal point for overall program management. planning and systems engineering. as well as coordinate delegated responsibilities regarding NEO detection. intercept. rendezvous. command and control systems and activities with our international partners.

EPILOGUE

In his opening statement to the congressional hearings on the NEO threat on March 24. 1993. George E. Brown. Jr.. Chairman of the Committee on Science. Space and Technology stated:

> "If some day in the future we discover well in advance that an asteroid that is big enough to cause a mass extinction is going to hit the Earth. and then we alter the course of that asteroid so that it does not hit us. it will be one of the most important accomplishments in all of human history."

AIAA and its cooperating organizations strongly believe Congressman Brown's statement is true. as well as its converse:

> If some day an asteroid does strike the Earth. killing not only the human race but millions of other species as well. and we could have prevented it but did not because of indecision. unbalanced priorities. imprecise risk definition and incomplete planning. then it will be the greatest abdication in all of human history not to use our gift of rational intellect and conscience to shepherd our own survival. and that of all life on Earth.

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