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Nobel Lecture: From the Big Bang to the Nobel Prize and beyond*

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NASA's Cosmic Background Explorer satellite mission, the COBE, laid the foundations for modern cosmology by measuring the spectrum and anisotropy of the cosmic microwave background radiation and discovering the cosmic infrared background radiation. I describe the history of the COBE project, its scientific context, the people who built it, and the scientific results. The COBE observed the universe on the largest scales possible by mapping the cosmic microwave and infrared background radiation fields and determining their spectra. It produced conclusive evidence that the hot Big Bang theory of the early universe is correct, showed that the early universe was very uniform but not perfectly so, and that the total luminosity of post–Big Bang objects is twice as great as previously believed. The COBE concept was developed by a Mission Definition Study Team appointed by NASA in 1976, based on three competing proposals submitted in 1974. The COBE was built in-house by Goddard Space Flight Center, with a helium cryostat provided by Ball Aerospace, and was launched on a Delta rocket built by McDonnell Douglas. It is in a circular orbit 900 km above the Earth, in a plane inclined 99° to the equator and roughly perpendicular to the line to the Sun. It carried three instruments, a far infrared absolute spectrophotometer (FIRAS), a differential microwave radiometer with three channels (DMR), and a diffuse infrared background experiment (DIRBE). The helium cryostat cooled the FIRAS and DIRBE for 10 months until the helium was exhausted, but operations continued for a total of 4 years. Subsequent observations have confirmed the COBE results and led to measurements of the main cosmological parameters with a precision of a few percent.

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I. SCIENTIFIC INTRODUCTION

A. CMBR spectrum and the Big Bang

In the beginning was the Big Bang, so we now say with great certainty. The Cosmic Background Explorer (COBE) satellite, proposed to NASA in 1974 (see Fig. 1) and launched in 1989, provided very strong evidence for it: the spectrum of the cosmic microwave background radiation (CMBR) has the spectrum of an almost-perfect blackbody emitter at 2.725 ± 0.001 K, and the radiation is isotropic (the same in all directions) within 10 parts per million (rms) on angular scales of 7° and larger. This radiation is interpreted as the relic of an incredibly hot and dense early phase of the universe. In such a hot and dense phase, the creation, destruction, and energy equilibration of photons with one another and with all other forms of matter and energy would occur very rapidly compared with the expansion time scale of the universe. Such a state would immediately produce a blackbody radiation field. The expanding universe should preserve this blackbody spectrum, so measurement of any significant deviation from a perfect blackbody spectrum would either invalidate the whole idea of the Big Bang or show that energy (e.g., from decay of primordial particles) was added to the CMBR after the rapid equilibration ended.

B. Isotropy

The fact that the radiation is isotropic to such a high degree is key evidence for its origin in the Big Bang. All the local systems that we know, from our Solar System to our Galaxy and the local cluster and supercluster of galaxies, are recognized because they are not uniform. Indeed, the isotropy itself was hard to explain, because it demands uniformity in the initial conditions of the great explosion of the entire observable universe. This was one of the great mysteries facing science in 1974.

C. Anisotropy

Moreover, according to the COBE, this radiation shows the imprint of the primordial density variations. On large angular scales the primordial radiation suffers a small gravitational redshift on exiting from denser regions (Sachs and Wolfe, 1967). These measured fluctuations have a nearly scale-invariant noise spectrum, in which the mean square variations are plotted against spatial (angular) frequency. The scale-invariant form of this spectrum was expected on the basis of general arguments (Harrison, 1970; Peebles and Yu, 1970; Zeldovich, 1972). When the theory of cosmic inflation was developed (Guth, 1981), it neatly explained the general isotropy of the radiation, since the currently observable piece of presumably infinite universe was at one time contained in a small region that existed long enough to establish a uniform temperature.

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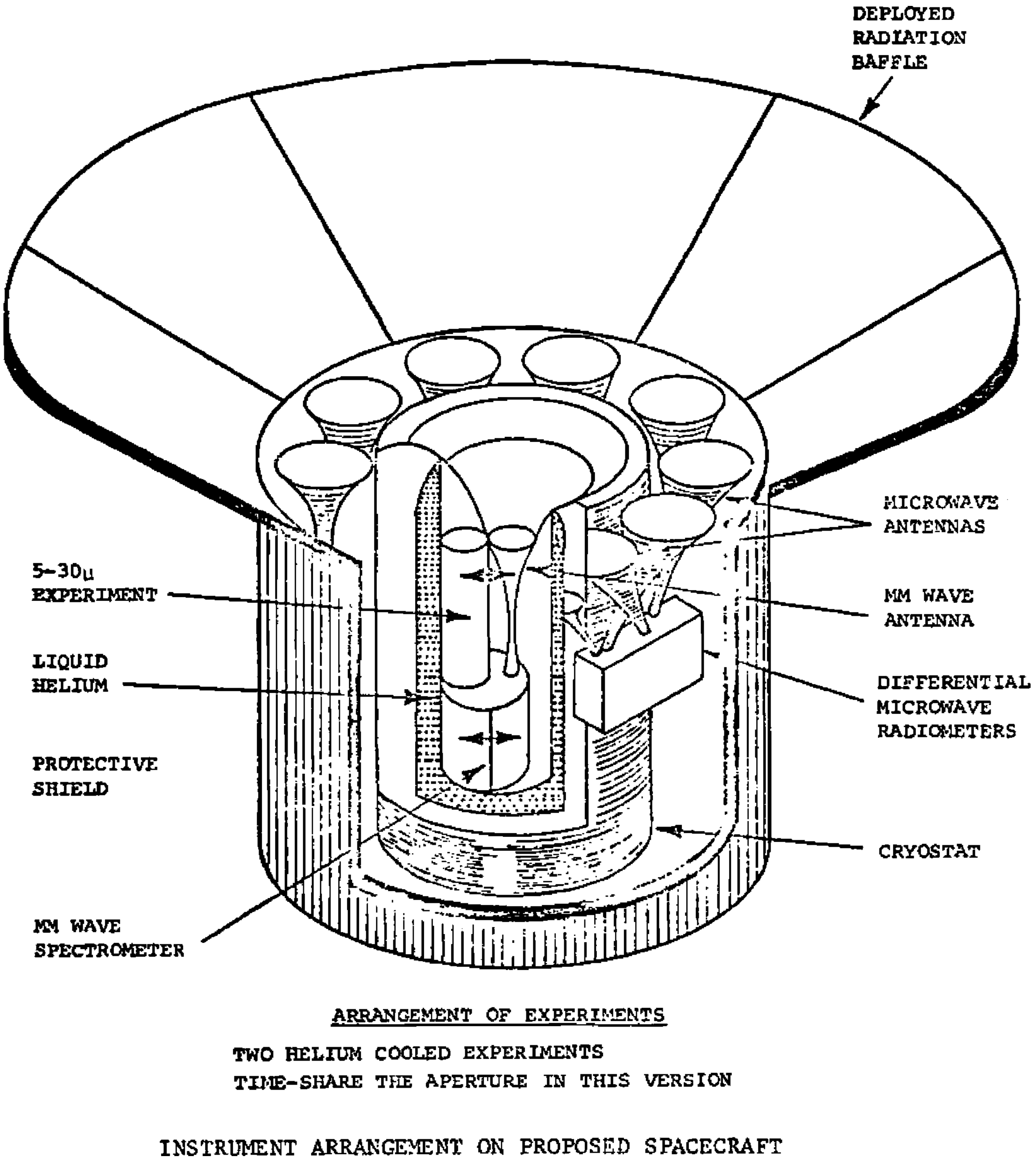

FIG. 1. Original concept for COBE as proposed by Goddard group in 1974.

D. Small angular scale anisotropy and primordial sound waves

On smaller angular scales, the measured fluctuation spectrum is dramatically modified, with a major peak at a typical angular size of a few degrees. According to the Big Bang theory, the universe became transparent when the temperature fell to about 3000 K, around 380 000 years after the Big Bang. At that time, regions of the universe smaller than 380 000 light years would begin to exchange information and begin to erase or amplify the primordial fluctuations. We can describe these fluctuations as primordial sound waves in a multicomponent fluid including photons (electromagnetic radiation), ordinary matter (baryons and leptons), dark matter (with mass but no electromagnetic interactions), and dark energy (causing the rate of expansion of the universe to increase).

E. Modern cosmology

Modern cosmology began in earnest with the recognition that galaxies are really far away and are made of billions of stars. This discovery depended on the continued production of ever larger telescopes, such as the four built by George Ellery Hale, each of which was the largest in the world for some years. Einstein's theory of general relativity provided a way of computing the effects of gravity on large scales, and Lemaître (1927, 1931) applied the theory to predict that the universe could not be static, but must be expanding or contracting. Einstein had introduced a constant of integration that could be adjusted to achieve a balance between the attractive forces of gravity and the "Λ constant," but the solutions were not stable. Hubble (1929) found that distant galaxies are receding from us and that the farther away they are, the faster they are going. This discovery, in the same year that the worldwide economy collapsed, changed cosmology from almost pure speculation to an observational subject. The apparent age of the universe was just the quotient of the distance divided by speed of recession, and the reciprocal of that number is called the Hubble constant.

II. MY INTRODUCTION TO COSMOLOGY

A. Childhood

In the 1950s, when I was a child, the space age had not started yet, and there were famous debates between advocates of the Steady State theory and the Big Bang theory. In the 1940s, George Gamow was considering the consequences of the Big Bang idea, and with his graduate students Ralph Alpher and Robert Herman, was working on the question of the formation of the chemical elements. One key result was that only hydrogen and helium would come from the Big Bang, which means that the others had to be formed in nuclear reactions inside stars (Alpher, Bethe, and Gamow, 1948). Even then it was already clear that we humans are made of recycled stellar material. Their second key result was that the universe would be filled with the heat radiation left over from that great explosion. There were various estimates of its temperature, but in any case it would have been difficult to measure this radiation at the time.

By the 1950s, the modern age had begun in earnest. Transistors were invented, the Atomic Age began when the Soviet Union exploded a hydrogen bomb in 1953, and the U.S. was worried. Then the Soviet Union launched the Sputnik in 1957. Suddenly, physicists and engineers were supposed to save the country from a really serious threat. Science fairs appeared in public schools, and government money flowed into civil defense and scientific education. I assembled a 5-tube shortwave radio kit, and I wanted to be a ham radio operator. Microwave technology grew to support the telephone network as well as radar, and in my rural neighborhood, a 4H club teaching children about electronics was sponsored by a small engineering firm. My father, one of the few Ph.D. scientists in the county, had a Geiger counter. In high school, I went away to summer math and physics courses sponsored by the National Science Foundation. In a few short years, the U.S. space program went from nothing to a declaration by President Kennedy that we would place a man on the moon within the decade.

B. College

By 1965, I was a freshman in college, and I had read one of George Gamow's (1947) popular books on the universe. I knew that the Big Bang might have produced a radiation field that filled the universe, so I was not surprised when it was discovered by Penzias and Wilson (Nobel prize in physics, 1978). Robert Dicke's group at Princeton was looking for the radiation at the same time. The story of the simultaneous publication of the results of the two groups has been widely told.

If the radiation is cosmic, it should have the spectrum of a blackbody and be equally bright in all directions (isotropic). Since the detections were made at relatively low frequencies, there was a contribution of emission from electrons in our galaxy that had to be measured and removed by some kind of modeling. At first, it was only possible to measure the Rayleigh-Jeans (long wavelength) part of the spectrum, and that part is a featureless power law, but at least the measurements were roughly consistent with a single cosmic temperature. There was also information from the measurements of the rotational temperatures of interstellar molecules, which could be accomplished by observing their absorption of starlight. It turned out that this measurement had already been made, by McKellar around 1939 (McKellar, 1940), but the significance was not recognized at the time. Then, in 1968, a rocket carried an instrument above the atmosphere, and found 50 times the brightness expected for the cosmic blackbody radiation (Shivanandan, Houck, and Harwit, 1968).

C. Graduate school

This was the situation when I started looking for a thesis project at the University of California at Berkeley in 1970. I met Michael Werner, then a new postdoctoral fellow working with Charles Townes (Nobel prize in physics, 1964 for masers), and Paul L. Richards, a young faculty member with expertise in low temperature physics. They were starting up projects to measure the cosmic microwave background radiation in the wavelength range around 1 mm. The first was a ground-based measurement using a Fabry-Perot interferometer to define wavelengths and liquid helium–cooled far infrared detectors. We took this instrument to White Mountain in California and used it to measure the CMBR temperature at those wavelengths that were not too badly blocked by atmospheric emissions (Mather, Richards, and Werner, 1971). Following that project, Richards took a Miller Fellowship sabbatical to England and learned about the newly developed Martin-Puplett interferometer (Puplett and Martin, 1970). He developed a concept to fly such a device as a payload suspended below a high-altitude research balloon, above 99.5% of the atmosphere. This idea later developed into the spectrometer that flew on the COBE satellite. Richards returned to Berkeley and explained the idea to two of his graduate students, David Woody and me.

The instrument concept included the polarizing interferometer, a modern version of that invented by Michelson (Nobel prize in physics, 1907), immersed in liquid helium to keep it cold, a far IR detector (a bolometer), a cold reference blackbody, and a conical metal light collector that defined a 7° beamwidth on the sky and fed the light through a small hole into the instrument (Mather, Woody, and Richards, 1974). Compromises had to be made, due to the presence of a warm atmosphere in close proximity to the liquid helium. First, the conical antenna had to connect to a stainless steel reflector that made the transition from helium temperature (1.5 K) to atmospheric temperature. Second, a Mylar window kept the atmosphere out of the aperture. Third, a small warm calibrator body could be moved over the aperture to measure the sensitivity of the instrument. A NASA review panel visited the Space Science Laboratory at Berkeley in 1973, and we presented our story. The panel immediately told us that this instrument ought to be proposed as a space mission.

The instrument failed on its first flight but was retrieved in one piece. I wrote my thesis on the ground-based work and on the design of the balloon payload, and David Woody continued with the project. He built a test chamber, found the reasons for the initial failures, fixed them, and prepared the payload for reflight. By now I had taken a postdoctoral position with Patrick Thaddeus in New York at the Goddard Institute for Space Studies (GISS). This time the flight was successful (Woody *et al.*, 1975).

III. ORIGINS AND DESIGN OF THE COBE

A. Initial Goddard concept

I joined Thaddeus's group to escape the perils of the CMBR field. However, a few months after I arrived at GISS at the end of January 1974, NASA issued an Announcement of Opportunity for new small satellites to be launched on Scout or Delta rockets. Thaddeus asked members of the laboratory for ideas. My thesis project had not worked right, but the main scientific difficulty was the atmosphere, and a space mission would be a lot better. Thaddeus was already very interested in the CMBR and had measured its temperature using spectroscopy of interstellar molecules of CN cyanogen (Thaddeus, 1972). He suggested that I call Rainer Weiss of MIT, Dave Wilkinson, one of the pioneers of the CMBR studies just a few miles away in Princeton, and Michael Hauser, who had just a few days before joined the Goddard Space Flight Center in Greenbelt, MD. We knew we would need a liquid helium cryostat, and we contacted Ball Aerospace in Boulder, CO to learn if it was possible to get one.

At that time, the Steady State theory still had strong advocates and ingenious defenders. The evidence for the age of the universe and for the age of the oldest stars seemed inconsistent. The evidence that the CMBR had a good blackbody spectrum was not very strong, and indeed most measurements were showing deviations from the prediction. There was not yet any serious theory for the fundamental anisotropy, but it was thought that the CMBR might not be the same brightness in every direction even if it were from the Big Bang.

We did not know we had competitors, but Luis Alvarez at Berkeley (Nobel prize, 1968) had hired several people to work on this cosmic background radiation, including Richard A. Muller and George F. Smoot. Their team prepared a proposal for a single instrument to measure the anisotropy, much simpler than our Goddard proposal, and similar to concepts they were developing for receivers that would fly on U-2 aircraft and on balloons. Samuel Gulkis and Michael Janssen of the Jet Propulsion Laboratory in Pasadena also prepared a proposal.

NASA did not choose any of us immediately. There were about 150 proposals submitted altogether, covering a huge range of topics. NASA was very interested in doing the Infrared Astronomical Satellite (IRAS), in cooperation with the Netherlands and the U.K. This mission would be a pioneering project, with a liquid helium cryostat in space, and new types of infrared detectors covering a huge wavelength range.

I started serious work on the flared horn concept. The balloon-borne thesis experiment used a design with an abrupt junction between the beam-defining cone and a stainless-steel reflector to protect it from stray radiation from angles far off the line of sight. My new idea was to make a gradual transition, with a curved flare like those in musical instruments. The mathematics for this had been developed already, by Keller (1962), under the title of the “geometrical theory of diffraction.” This approach said that light rays propagate in straight lines except at boundaries and obstacles, and that there were a variety of scattering and attenuation coefficients that could be computed for the boundaries and obstacles. The waves do diffract around curved surfaces, but they are attenuated exponentially as they go. This was just what I needed to protect the input of the instrument over a wide range of wavelengths (Mather, 1981; Mather, Toral, and Hemmati, 1986).

B. Building the COBE team

In early 1976, Michael Hauser offered me a job at the Goddard Space Flight Center (GSFC) in Greenbelt, MD, and thought the COBE idea would go forward. In any case, it was worth a try.

In late 1976, NASA started a study of the COBE idea, but chose a new team composed of six members of the three competing groups. There were four members of my group, with me, Michael Hauser, David Wilkinson, and Rainer Weiss, plus George Smoot from the Berkeley group, and Sam Gulkis from the JPL group. We were to work with Nancy Boggess of NASA Headquarters, who was responsible for all infrared astronomy at NASA, and a team of engineers at Goddard Space Flight Center, to define a new mission. We decided that one of the original four instruments on the Goddard concept would have to be omitted, and that the microwave radiometers should use corrugated horn antennas. We elected principal investigators and proposed to NASA Headquarters that these people be approved and given responsibilities for the individual instruments. These assignments were G. Smoot, differential microwave radiometers; M. Hauser, diffuse infrared background experiment; and myself for the far-infrared absolute spectrophotometer. We chose Rainer Weiss as Chair of the Science Working Group, and NASA assigned me the job of Study Scientist, to coordinate the scientific requirements with the engineering teams.

FIG. 2. (Color) COBE Science Working Group. Eli Dwek is missing. Left to right, Ed Cheng, Dave Wilkinson, Rick Shafer, Tom Murdock, Steve Meyer, Chuck Bennett, Nancy Boggess, Mike Janssen, Bob Silverberg, Sam Gulkis, John Mather, Harvey Moseley, Phillip Lubin, Ned Wright, Mike Hauser, George Smoot, Rainer Weiss, and Tom Kelsall.

We prepared our report with Martin Donohoe as engineering lead. Our study had to show that the mission could not be accomplished in any other way. We discussed whether a mission on board the newly approved Space Shuttle could possibly meet the scientific requirements, and we argued that all three instruments were really essential. We were soon directed to redesign our mission to use the Space Shuttle as a launch vehicle.

After this initial round of competition, we were told to continue and were given some funds to spend and people to work with. The Goddard engineering team assigned to us was led by Jerry Longanecker, project manager for the IUE, the International Ultraviolet Explorer. This engineering team was very experienced and quick to understand the challenges we brought them.

Around 1978, it was decided that Goddard would build the entire COBE mission in-house, which means that civil servants and neighborhood contractors would do most of the work. The advantage for Goddard was that this project was an excellent way to recruit bright young engineers and train them on a real space mission. The advantage for the COBE mission was that it would enable the scientists and engineers to work very closely together, without the impediments of contract management and physical distance. This was very important for the creative process and the give and take of solving problems. However, part of the plan was that the COBE had the lowest priority of all the Center's major projects.

Our team membership changed with time, but two photographs (Figs. 2 and 3) show the engineering and science teams as of 1988. The captions list the team members and their roles. Roger Mattson was our Project Manager and Dennis McCarthy was the Deputy for technical matters.

C. Mission concept and design

The design included a protected region for the instruments, surrounded by a reflective shield. In the center is a liquid helium cryostat containing two instruments, a far-infrared absolute spectrophotometer (FIRAS) and a diffuse infrared background experiment (DIRBE). The differential microwave radiometer (DMR) receivers were mounted in four (later three) boxes just outside the cryostat. Solar panels surrounded the spacecraft, and massive cylindrical pins projected from the sides to attach the COBE to the Space Shuttle. Inside, hidden from view, were tanks containing hydrazine fuel, to raise the orbit from the maximum height the Space Shuttle could reach. The orbit chosen for the COBE was circular, at 900 km altitude, with the orbital plane inclined 99° to the equator, and nearly perpendicular to the Sun line (see Fig. 4). The altitude and inclination are chosen in combination so that the Earth's equatorial bulge causes a torque on the orbit plane, just sufficient to make it precess a full revolution once per year and follow the Sun. With this choice of orbit, the COBE stays in full sunlight almost all the time, and the Earth's limb is only 60° from the nadir. However, for about 3 months each year, the combination of the orbital plane inclination (9° past perpendicular) with the tilt of the Earth's spin axis of 23.5° from the ecliptic means that the COBE flies through the Earth's shadow for up to 20 min per orbit, and flies between the Earth and the Sun for an equal period of time. Both events require attention. During shadow, the COBE must draw electric power from batteries, and some heat must be provided to those parts that would cool off too rapidly. During the opposite part of the orbit, the Earth shines over the top of the

FIG. 3. (Color) COBE engineering team leadership. Left to right, top photo, Don Crosby, Jeff Greenwell, Bill Hoggard, Roger Mattson, Ernie Doutrich, Herb Mittelman, Eileen Ferber, Bob Schools, Joe Turtil, Maureen Menton, Bob Sanford, and Mike Roberto. Bottom photo, Pierce "Lee" Smith, Earle Young, Dennis McCarthy, Dave Gilman, Bob Maichle, Chuck Katz, Steve Leete, Bernie Klein, Loren Linstrom, Tony Fragomeni, John Wolfgang, and Jack Peddicord.

shield and illuminates the instrument apertures, causing stray light to reach the detectors.

The spacecraft design for the COBE had some very unusual features. The most interesting is perhaps the attitude control system, which was required to spin the spacecraft around its symmetry axis at about 1 rotation per minute (in flight, there was one spin per 72 sec), and keep the spin axis roughly perpendicular to the Sun line (actually 94° away), and roughly vertical, as the spacecraft orbited the Earth.

The spacecraft had a hybrid command and control system: it sent its engineering data through the tracking

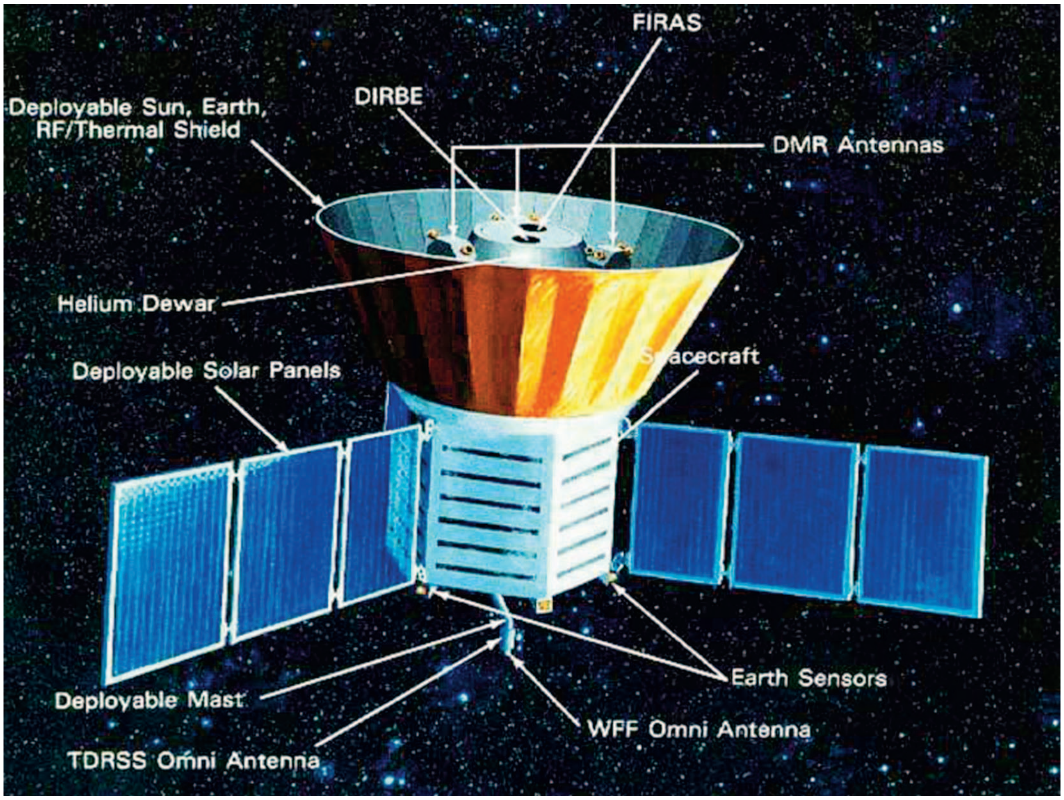

FIG. 4. (Color) Artist's concept of COBE as flown. COBE was in orbit 900 km above the Earth, with the Sun to the side and the Earth below.

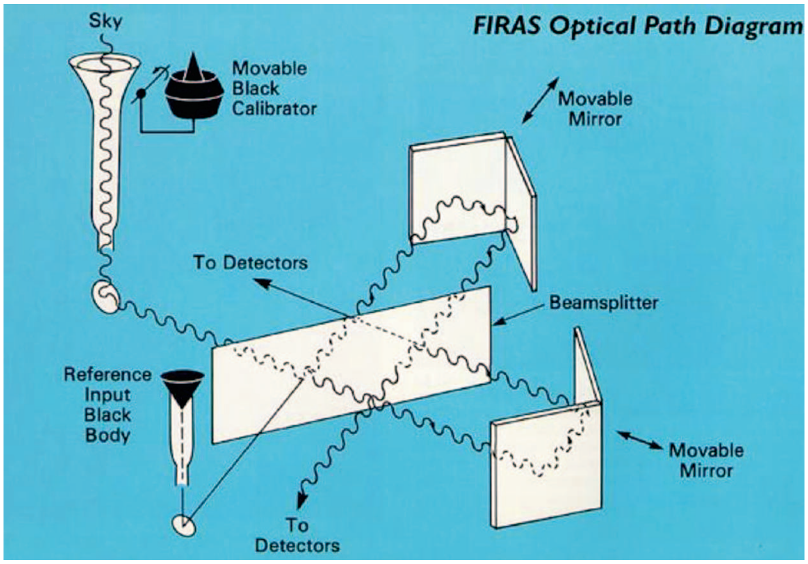

FIG. 5. (Color) Concept for the far infrared absolute spectrophotometer. The movable black calibrator emits the same spectrum of radiation that is received from the sky.

and data relay satellite system (TDRSS), but it sent its scientific data directly to a ground station at Wallops Flight Facility of the Goddard Space Flight Center.

The liquid helium cryostat was a great technological achievement of the Ball Aerospace Division in Boulder, CO. Ours was a nearly identical copy of the cryostat developed for the IRAS. The design has an outer vacuum tank with a cover that can be ejected after launch, a toroidal tank filled with about 500 liters of liquid helium at launch, and an instrument chamber inside the toroidal tank. The helium tank is suspended inside the vacuum shell by sets of fiberglass-epoxy straps in tension, and surrounded by concentric aluminum shells cooled by tubes carrying the escaping helium gas. Between the concentric shells are multiple layers of aluminized insulation blankets.

D. FIRAS

The purpose of the FIRAS was to determine whether the Big Bang radiation has the spectrum of a perfect blackbody. Even small deviations from perfection would signify that the universe is not simple, that there is some new phenomenon to be understood. Since the radiation comes almost equally from all directions, the instrument must be absolutely calibrated. Since there are processes in galaxies, and in our own Milky Way Galaxy, that produce radiation at wavelengths overlapping the CMBR, it is essential to map the radiation and see what part can be correlated with identifiable local sources. The main expected sources are dust grains, heated by starlight in the Milky Way, and interstellar molecules, atoms, and ions, heated by starlight and by collisions with other components of the interstellar medium. At longer wavelengths than those observed by the FIRAS, interstellar electrons, colliding with protons and spiraling in the magnetic field, are brighter than the CMBR, but all these local sources are easily recognized by their concentration in the plane of the Milky Way.

The FIRAS was an upgraded version of Paul Richards' original balloon-borne instrument (see Fig. 5). The main improvements were as follows: (1) The whole instrument was in space, above the atmospheric emission and potential condensation on the optics. (2) The light gathering power (étendue) was increased, to collect more light, and extend the sensitivity to longer wavelengths. (3) The interferometer was symmetrized, providing access to both input ports and both output ports, so that it could be used as a differential comparator between the inputs, and so all available input light could be detected. (4) The primary input from the sky could be entirely covered by an accurate external blackbody radiator, effectively a simulator of the Big Bang radiation, called the XCAL, the external calibrator. (5) The secondary input was fed by a smaller blackbody radiator, with an adjustable temperature to balance the input from the sky, called the ICAL, the internal calibrator. (6) The conical light concentrator of the balloon payload was improved to use a Winston cone, a nonimaging parabolic concentrator with a better beam profile, called the Sky Horn. (7) The stainless steel reflector that joined the balloon payload's input cone to the warm environment was replaced by a smoothly flared bell resembling that of a musical instrument. (8) The temperature of the Sky Horn and its flared section was controllable over a wide range of temperatures, as was the matching concentrator (the Reference Horn) on the secondary input. (9) The wavelength range was extended, and divided into two bands, short and long. (10) The detectors were improved. (11) The observing time was increased to 10 months instead of a few hours, and the entire sky was mapped with a single instrument. The main sources of improved accuracy were the differential mode of operation, reducing the dynamic range (contrast) between the signal level and the detector noise, and the accurate external blackbody calibrator.

We have received many questions about the calibrator. According to Kirchhoff's laws, the emissivity of a body is the same as the absorptivity. The emissivity is the ratio of the emission from the actual body to that from an ideal blackbody at the same temperature. The absorptivity is the fraction of incident radiation that is absorbed. Hence an ideal absorber is an ideal emitter. The chief aim of the calibrator design was to ensure that the only rays reaching the spectrometer input came from the calibrator, and not from other locations. We define the spectrometer input as the junction between the calibrator and the input concentrator. There are three possible sources of radiation crossing this boundary that do not come from the calibrator emission. These are as follows: (1) Emission from the concentrator that strikes the calibrator and is reflected back into the acceptance angle of the Sky Horn. (2) Emission or reflection from the spectrometer that comes towards the calibrator and is reflected back towards the spectrometer by the XCAL. (3) Leakage of radiation from the sky or the calibrator support hardware or other objects above the XCAL, around the junction of the calibrator with the concentrator, or through the XCAL material. We analyzed all of these possible errors and as far as we know we avoided them at the level of a few parts per million. The details are given by Mather *et al.* (1998).

In order to achieve this level of performance we needed a highly absorptive material. We chose Eccosorb®, an epoxy filled with very fine iron powder. The epoxy has a refractive index of about 2, so that its surface reflections, about 10% at normal incidence, are not negligible (Hemmati, Mather, and Eichhorn, 1985). We therefore designed the XCAL as a re-entrant cone, like a trumpet mute, so that a light ray entering the cone would have to suffer at least five specular reflections before it could exit again.

Thermal gradients produce a second-order effect and we believe the effect was less than a few parts per million on the spectrum. However, for comparison with measurements by other instruments, we needed to know the absolute temperature very well. Our thermometers were germanium resistance thermometers traceable to the National Institute of Standards and Technology, but after launch there was doubt about the stability of their calibration, at the level of a few millikelvin. Fortunately, there were other methods to confirm the temperatures after launch.

To prevent leakage of radiation around the edge of the calibrator, where it meets the Sky Horn, the calibrator was provided with two rings of aluminized Kapton leaves, adjusted so that they barely made contact with the Sky Horn.

The detectors for the FIRAS were kept as cold as possible with copper cooling straps that reached directly from the detectors to the liquid helium cryostat attachment fittings. They were composite bolometers, built at Goddard. Each bolometer had a very thin diamond sheet, with a partially conductive coating optimized to absorb the incoming radiation, and suspended by thin Kevlar fibers. Attached to the diamond was a tiny cube of silicon, doped to become a temperature-sensitive resistor. Incoming radiation was absorbed by the coating on the diamond, converted to heat, and conducted to the silicon thermometer. A dc voltage was applied to the thermometer through a resistor, and the voltage on the thermometer was amplified by a JFET transistor nearby. The transistor would not work at the 1.5 K temperature of the rest of the instrument, so was suspended inside a small chamber on Kevlar threads, and heated electrically to around 70 K.

In developing concepts for the detectors, I pursued an idea I had from graduate school, to establish a convenient theory for the noise and ultimate sensitivity of bolometers. I worked on the manuscript while my future wife Jane was teaching ballet; I was driving her to work because we had broken her arm doing the samba. This work developed into a series of papers (see, e.g., Mather, 1984) which have ended up being my most cited publications. The reason was unexpected: our bolometers were good detectors for every kind of radiation, including cosmic rays. Harvey Moseley saw this as an opportunity, knowing that the detectors could be greatly improved. The improved detectors have been flown in space on the x-ray mission Suzaku, and they worked beautifully, able to measure the energy of a single 6 keV x-ray photon with a precision of a few eV.

The interferometer mirrors had to move precisely, smoothly, without friction, for millions of strokes on a parallelogram linkage, with leaf springs at the joints, driven by a solenoid. This easily met the friction and lifetime requirement. The position of the mirrors was measured precisely by a scale. The scale was read out optically through fiber optics leading to light sources and detectors outside the cryostat. This led to a problem during flight, when cosmic rays hit the fiber optics and caused light flashes that confused the position measurement and led the control circuit to drive the motor hard against a physical stop. Fortunately, a timer circuit had been implemented to protect the equipment from such an event.

E. DMR

The DMR instrument was not inside the cryostat but shared the objective of measuring the CMBR. I trust that the story of this instrument will be more fully told by my co-recipient, George Smoot. Its purpose was to measure the anisotropy, the difference in brightness of the CMBR across the sky. When the COBE was first proposed, there was no serious theoretical prediction for the amount or pattern of such variations, but our view was that whatever it was, it had to be measured. Over the 17 years from proposal to our first data release, predicted amplitudes of the variations declined exponentially with time, as new equipment repeatedly failed to find anything but the dipole term due to the Earth's motion.

Not being guided by theory, we set the objective of measuring the anisotropy as well as our environment would allow. As with the FIRAS, there are local sources of radiation in the Milky Way Galaxy that are bright compared with the anisotropies we sought to measure. Our approach was to map the sky at three (originally four) frequencies, with identical receiver antenna patterns, and take advantage of the fact that only the cosmic microwave background radiation would have the spectrum of a blackbody. The electrons in our Galaxy produce two kinds of radiation, by colliding with protons and by spiraling in magnetic fields. Both of these types of radiation are strong at long wavelengths and drop rapidly as the wavelength gets shorter. The dust in our Galaxy has the opposite sort of spectrum and its emission spectrum is strongest at shorter wavelengths than the CMBR. In any case, measurements at multiple wavelengths are required to model and compensate for these emissions. We chose three frequencies: 31.4, 53, and 90 GHz.

The central idea of the instrument was the Dicke switch. This is a device that could switch the input of the microwave receivers rapidly between two sources, so that a difference in brightness seen from them could be recognized by a lock-in amplifier. For mapping the CMBR, it is possible to just compare two antennas pointed in different directions. Our special observing scheme swept the two antennas rapidly around the sky, measuring all possible pairs of directions separated by the fixed angle between the two antennas. Our spinning spacecraft, with its spin vector smoothly rotating around the Sun line on each orbit, and gradually moving around the Sun through the year, was an excellent solution. Over the course of the mission, the radiometer would observe hundreds of millions of differences in brightness between points on the sky 60° apart. Then, a least-squares fitting computer program would build a map from them that best represents all the data, including detailed modeling of the systematic errors.

The particular challenges for this instrument were sensitivity and immunity to systematic errors. The microwave receivers available in 1974 were almost all made with diode mixers, microwave circuits that combine the signal from the sky with a local oscillator signal to produce a new signal at an intermediate frequency. This intermediate frequency signal can then be amplified and its intensity measured. As the COBE design progressed, improvements in the mixers were made, and eventually we decided to sacrifice one of the original four frequency channels to gain the resources to use the new technology. The improvement was based on cooling the receivers. In our case there was plenty of cooling available, since the receivers were protected inside the sunshield and had to be heated to keep them warm.

Some systematic errors were obvious. First, the Dicke switches were made with ferrite beads activated by magnetic fields, and there was sensitivity to external magnetic fields from the Earth and from the magnetic torquer bars. We provided magnetic shielding, but we knew that we would have a residual problem. Second, the receiver antennas were susceptible to interference coming from other directions. We chose corrugated horn antennas and learned how to make them so precisely that the stray radiation sensitivity was very small. We had to measure this effect after launch and compensate for it. The major source of stray radiation was the Earth, which is 10 million times as bright as the cosmic fluctuations that we eventually found. The Earth is hidden from the receivers most of the year, but some of its emission diffracts over the edge of the sunshield and reaches the antennas. Third, the receivers and switches were sensitive to temperature, and presumably to power supply voltages, and all sorts of other minor disturbances. Since we were looking for signals remaining after processing hundreds of millions of observations, we had to devise ways to find very small effects that could have ruined the data. Most of these were found and fixed before launch, but some had to be measured and compensated in software after launch. During the months when the Earth rose slightly above the plane of the sunshield for part of the orbit, and the satellite passed through the Earth's shadow on the opposite side of the orbit, the residual thermal, stray radiation and other effects were sufficiently large that the data were not entirely trustworthy.

F. DIRBE

The DIRBE instrument was designed for a different purpose: to search for and measure the diffuse infrared background light at shorter wavelengths than the CMBR. The accumulated light of distant galaxies should produce a nearly uniform glow in the sky. If the universe were infinite, stationary, and uniform in both time and space, then every line of sight would terminate on the surface of some star, and we would be bathed in light as though we were just inside some such star. The expanding universe gives only a finite observable volume and a finite time, and the most distant parts are highly redshifted. Nevertheless, the cosmic glow is one of the most important traces of the distant universe, the cosmic reservoir of lost photons. Measuring it would tell us about those faint, most distant early galaxies, even if no telescope could ever observe them.

The main obstacle to measuring the diffuse IR background light is our local astrophysical environment. There are several bright sources, beginning with the interplanetary dust in our Solar System. This grayish dust reflects some sunlight and absorbs the rest, coming to a temperature around 200 K, and re-emitting the light at mid-IR wavelengths. This dust is visible to the naked eye as the Zodiacal Light, and is much brighter at infrared wavelengths. Farther out, the interstellar dust behaves in similar ways. Its temperature depends on its distance from stars, and ranges from a few K to much higher values in shock waves or near stars. Very small dust grains are also heated momentarily to very high temperatures, up to 1000 K or more, by absorption of individual visible or uv photons, or by cosmic ray impacts.

The observational strategy for understanding and compensating for these foreground sources was to measure at as many wavelengths as possible (ten), over as wide a wavelength range as possible (from 1.2 to 240 μm), to measure the polarization at the three shortest wavelengths because the scattered sunlight is polarized, and to measure over as wide a range of angles from the Sun as possible because the Zodiacal Light is strongly concentrated towards the Sun and towards the ecliptic plane. Our range of angles was from about 64° to 124°, achieved by placing the DIRBE line of sight 30° from the spin axis of the COBE. The wide wavelength range required four different detector technologies: InSb photovoltaic detectors from 1 to 5 μm, Si:As photoconductors for 12 and 25 μm, Ge:Ga detectors for 60 and 100 μm, and bolometer detectors for 140 and 240 μm.

The instrument also had to be designed to be absolutely calibrated. To achieve this we needed the following features: (1) A dark interior of the instrument, representing zero signal. (2) A modulator, switching the instrument beam rapidly back and forth between the sky and the interior of the instrument, the infrared equivalent of the Dicke switch. (3) A calibrator body that could intercept the instrument beam and replace it with zero emission. (4) A light source that could establish the gain of the instrument and verify its stability with time. (5) A precise measurement of the beam profile of the instrument, to compare calibration from standard stars with a diffuse background surface brightness. (6) Detailed understanding of the response to standard stars. (7) Suppression of stray light from bright objects (such as the Moon, Earth, Sun, Galactic Center, and Jupiter) outside the field of view.

The optical design for the DIRBE was optimized for these purposes. The aperture was only 20 cm, but the field of view was large (0.7°), to optimize sensitivity for the diffuse radiation. The DIRBE was enclosed in the cryostat, so its interior was truly cold and dark. The modulator was a specially designed tuning fork "chopper" with vanes that opened and closed at 32 Hz. The telescope was a Gregorian design, so that field and pupil stops ahead of the chopper could limit stray radiation. A carefully designed baffle system in the telescope tube intercepted light that might be scattered into the instrument, a shiny cone at the entrance to the telescope tube intercepted and reflected away any light coming in from angles just grazing the top of the cryostat, and a tightly fitted cover protected the telescope from molecular or dust contamination before reaching orbit. All of the detectors had the same field of view, so that relative colors of the detected objects would always be correct. The field of view was square, so that a star passing through the field would always produce about the same response, regardless of exactly where it was in the field.

The DIRBE instrument was also used to provide accurate pointing information. As the COBE spins, the DIRBE beam sweeps rapidly around the sky, and the precise timing of signals from bright stars passing through the beam is available. With an algorithm developed by science team member Edward L. (Ned) Wright, these timing signals were combined with a model of the spin of the COBE and its other pointing sensors to give accurate pointing information.

IV. REBUILDING AND LAUNCHING THE COBE

The COBE project was officially approved in 1982, when it became clear that the IRAS was going to fly. The IRAS cryostat was extremely challenging, and the COBE depended completely on its success, since we had almost the same design. Also, the NASA budget was very tight in those days, with cost growth in the IRAS, the Hubble Space Telescope, and other projects. The IRAS was at last launched successfully on January 25, 1983 and our way seemed clear. Michael Hauser was a member of the science working group for the IRAS and was responsible for the data analysis, so he was very familiar with the technological details and the scientific results of the IRAS. The IRAS produced some very remarkable surprises: many nearby stars were surrounded by dust clouds, like our own Zodiacal Light but far brighter; and distant galaxies were extremely bright at far-infrared wavelengths, sometimes 100 or 1000 times brighter than they are at visible wavelengths. Our project proceeded with many minor revisions and major review meetings. Our budget requirements also grew, but NASA Headquarters did not have the extra funds to give, so we made many risky decisions and cut some corners. We were lucky about them.

By January of 1986, we were assembling flight hardware, and a full-scale plywood mockup of the spacecraft was built for setting up the electronic boxes and the electrical cables. Then came the fateful frozen day in Florida when the Space Shuttle Challenger and our seven astronauts perished in flames. For us on the COBE team, and for most of NASA, the future looked bleak. Dennis McCarthy, the Deputy Project Manager, started looking around for alternate launch vehicles. NASA had been forced to abandon its trusty Delta launchers and all the other one-shot rockets in favor of the Space Shuttle, so we had nothing ready. Fortunately, there were still spare parts for the Delta rockets, and it was possible to assemble a complete set. However, the Delta could certainly not carry our payload as it was. The COBE was far too large and weighed too much. Our engineering team was not deterred. The COBE was proposed in 1974 for a Delta launch, and the shuttle design we had was using 5000 lb of fuel and a physical structure that would not be needed if a Delta rocket could take us all the way to the needed orbit. In the end, it was just barely possible to launch the COBE on the Delta.

One really new design was now needed though: the sunshield would have to be folded up and deployed after launch. The unfolding would be propelled by spring energy after a circular strap around the folded shield was cut by an explosive charge.

One minor change was then needed for the DMR instruments. The available space between the new folding sunshield and the cryostat shell was not quite enough to fit the microwave receiver boxes without modification. New box designs and some new waveguide hardware were needed, but this was also possible.

Now that we had a new mission concept, we presented it to NASA Headquarters. It was quickly recognized that the COBE could now be NASA's first scientific mission to fly after the Challenger explosion. We were given the green light in late 1986, and urged to be ready for launch as soon as possible. Suddenly our project went from the bottom of the priority totem pole almost to the top, behind the Hubble Space Telescope. We began round-the-clock work, as much as people could stand, to finish the redesign, rebuild the hardware, and fix all known problems with the instrumentation.

Our payload was finally ready, and was loaded into a huge truck and driven around the Capital Beltway to Andrews Air Force Base. There, the truck was driven right into a waiting C5-A transport aircraft, and flown to the Vandenberg launch site in California. At the launch site, final assembly was completed, and final tests were made. On October 17, 1989, the Earth trembled with the San Francisco earthquake, but COBE was bolted down that day because two of our engineers had gone off to be married.

On the evening before November 18, 1989, we were ready to launch. Ralph Alpher and Robert Herman had come to watch the launch of the mission that would test their theory. In the early morning of the launch day, the main question was about the winds. If the wind direction and speed changed too rapidly with altitude, the rocket control system would be unable to compensate and the rocket could break up. Weather balloons were launched and tracked to determine the wind shear, and the assembled crowds stood in a cold and dark field 3 km away from the launch pad. We watched the rocket ascend, dropping its spent booster rockets, and go out of sight, in just a few minutes. A few minutes later, the high altitude winds twisted the trail of rocket exhaust into contorted loops, making quite visible the hazard that the Delta had just traversed.

The COBE was not heard from again for about an hour, when it passed over the tracking station in Alaska, and it was alive and well. In the first few days it faced new hazards. First, the outside of the cryostat was cooling off rapidly. We worried that if it got too cold, the cover might not come off. Second, one of the gyros in the pointing control system failed a few days after launch. Fortunately our engineering team had designed the system to keep right on going. Then, we rediscovered Antarctica. The power system was designed to cope with a certain amount of sunshine, but we had not remembered how much sunlight would be reflected up to the COBE by the ice in Antarctica. Next, trapped electrons and protons in the Van Allen belts disrupted the functioning of the mirror control electronics for the FIRAS, but we commanded the FIRAS not to run there.

The liquid helium in the cryostat lasted about 10 months. The end was abrupt, and within a minute the temperature was rising rapidly. We continued to operate the DIRBE because its short wavelength detectors, made with InSb, worked just fine at the higher temperature. The interior of the cryostat ended up around 60 K. The DMR, which did not use helium, was operated for a total of 4 years.

The fate of the satellite was to be used for communications practice. It is still in the same orbit, and still spinning in its proper orientation, as it needs no fuel to do so, and the guidance system is highly redundant and reliable. It was estimated that the orbit will decay in about 1000 years.

V. DATA ANALYSIS AND INTERPRETATION

The command and control of the spacecraft and the analysis and interpretation of the data required up to 100 software engineers and scientists. All three instruments required special analysis to deal with instrument systematic errors and calibration, and then with understanding the local astrophysical environment.

A. FIRAS

The first instrument to produce scientific results was the FIRAS. We adjusted the temperature of the internal reference body to null the signal from the interferometer as well as possible. The depth of the null was a direct measure of the match between the internal body and the spectrum of the CMBR. Even before we had a precise calibration, we knew immediately that the match was excellent. With a rough calibration, we added the difference we observed to the Planck function for the matching temperature, and plotted the result. Not yet knowing the error bars, we assumed 1%. When I presented this spectrum at the January 1990 meeting of the American Astronomical Society in Crystal City (a suburb of Washington, D.C.), the audience of over 1000 people rose in a standing ovation. None of us on the COBE team anticipated this response, since it was not a surprise to us.

In retrospect we now appreciate the reason for the enthusiasm. Not only was the spectrum beautiful to look at, but at one stroke it banished the doubts of almost everyone about the Big Bang theory. For so many decades, the intense combat between the Big Bang and Steady State advocates had continued, and for so many years a series of small discrepancies between theory and measurement had been explained by ingenious people. Now it was over, although some Steady State proponents do not agree. The Big Bang theory was safe, and the universe was simple, simple enough for theorists to go on to the next problem.

Only a few weeks after the COBE was launched, Herb Gush and his team from the University of British Columbia launched a sounding rocket with their version of the FIRAS instrument (Gush, Halpern, and Wishnow, 1990). This payload had been flown several times, each without success, but this time it worked. Their results agreed with the FIRAS results, with the same temperature within the error bars, and showed no deviation from the blackbody spectrum either. With a little better luck they might have stolen some of our thunder years before the COBE was launched, but to achieve our final conclusions we really needed the all-sky maps that only COBE could provide.

Our spectrum plot now graces many astronomy textbooks, but people still ask one elementary question: Why does the plot not look like the ones in other textbooks? The key point is that our plot gives the intensity versus frequency in reciprocal centimeters, the number of waves per centimeter. Textbooks usually plot the intensity versus frequency in Hz, or versus wavelength, usually in micrometers. The plots do not appear to match, not only because the scales are different, but because the differentials are different: the plots give the power per unit area per frequency interval or per wavelength interval, and those intervals also have to be converted. When these conversions are done, the plots agree.

The full calibration and analysis of the FIRAS data took many years. The systematic errors that we discovered in the data were not complete surprises, but developing accurate models for them required a least-squares fit with thousands of parameters, a few of which were critically important. Dale Fixsen was the main architect of this process. The main errors to be compensated were as follows: (1) The cosmic rays that hit the detectors produced voltage impulses that had to be detected and removed. (2) Temperature variations from many causes caused the detector gain to vary. (3) There was a small amplitude vibration in the mirror mechanism, due to torsion in the parallelogram linkage, that was excited by the servo circuit. Although this was minimized in the servo by a notching filter at 57 Hz, there was a small residual effect on the shape of the interferograms. (4) The internal reference body was not a very good blackbody. (5) The thermometer calibrations apparently changed after they were done, years before launch, and the three thermometers on the external calibrator did not agree at the expected millikelvin tolerance. (6) There was a small optical effect in which radiation could make multiple passes through the interferometer and appear to be modulated at two or three times the proper frequency. Fortunately, the instrument had four detectors, two on each side and two in each frequency band, and it had two different stroke lengths, for a total of eight different ways to observe. Comparison of the multiple detectors and stroke lengths gave many ways to understand and detect the errors. Observation of interstellar spectrum lines, particularly that of [C II] at 157.74 μm, gave ways to confirm the absolute frequency scale, and hence to confirm the temperature scale (Fixsen and Mather, 2002).

Understanding and compensation for the local astrophysical sources was also difficult. One result was that the dust in the Galaxy is almost all at about the same temperature and has about the same spectrum, but not quite. There are also some directions in the galactic plane where there are clearly multiple dust clouds with different temperature in the same line of sight. Our analysts were amazed to see that some interferograms appeared to be "contaminated" with sine waves. These were just the expected response to bright interstellar spectrum lines. The fine structure line of ionized carbon [C II] at 157.74 μm is by far the brightest we saw, and carries about 0.3% of the total luminosity of the Milky Way. We observed the [N II] line at 205.178 μm for the first time; it was then observed in the laboratory. Other lines from CO, [C I], and H_2O were also seen (Bennett *et al.*, 1994). The 157.74 μm line is so bright that we were able to measure the differential Doppler shift of the line due to the rotation of the Galaxy, even though our spectral resolution was very modest.

The main measurement is that the spectrum of the CMBR matches a blackbody at 2.725 ± 0.001 K with an rms deviation of 50 parts per million of the peak brightness. The interpretation of that result is that less than 0.01% of the energy of the CMBR was added to it after the first year of the expanding universe. Energy added before that time would just change the temperature of the radiation (Wright *et al.*, 1994).

Energy added between redshifts of 10^5 to 3×10^6, roughly the first 1000 years, would give the radiation a modified spectrum with a chemical potential μ, as worked out by Sunyaev and Zel'dovich (1970). In this case the photon mode occupation number is $\eta = 1/(e^{x+\mu} - 1)$, where $x = h\nu/kT$, h is Planck's constant, ν is the oscillation frequency, k is Boltzmann's constant, and T is the temperature. Our measured value (Mather *et al.*, 1994) was $\mu = -1 \pm 4 \times 10^{-5}$, or $|\mu| < 9 \times 10^{-5}$, with 95% confidence.

Radiation added later would give a CMBR spectrum that is a mix of blackbodies at a range of temperatures, parametrized by y, as described by Zeldovich and Sunyaev (1969). Here $y = (1/m_e c^2) \int k(T_e - T_\gamma) d\tau_e$, where m_e is the electron mass, c is the speed of light, T_e is the temperature of the scattering electrons, T_γ is the temperature of the CMBR at the time, and $d\tau_e$ is the differential opacity of the scattering electrons. The distortion of the spectrum produced by this kind of mix of blackbodies is described by $dS_y/dy = T_0\ [x \coth(x/2) - 4]\ dB_\nu/dT$, where S is the spectral brightness, B is the Planck function, and T_0 is the average temperature. We found $y = -1 \pm 6 \times 10^{-6}$, a very small number.

There is a long list of hypothetical energy sources that had been used to explain prior measurements of deviations from the blackbody form, including turbulence, proton decay, other unstable particles, decaying massive neutrinos, late photoproduction of deuterium, explosive or normal galaxy formation, cosmic gravity waves, cosmic strings, black holes, active galactic nuclei, Population III stars, hot intergalactic medium, etc. Our results do not rule out small contributions from these sources but do show that they could not have been responsible for most of the universe that we see today.

The FIRAS instrument also measured (1) the spectrum of the far IR cosmic background radiation, first detected by the DIRBE instrument (Fixsen *et al.*, 1998); (2) the spectrum of the far IR Zodiacal Light, showing that the responsible dust particles are large, ~30 μm in size; (3) the spectrum of the part of the CMBR due to the motion of the Earth through the cosmos, called the dipole (Fixsen *et al.*, 1994); (4) limits on spatial variation of the CMBR spectrum (Fixsen *et al.*, 1997).

The FIRAS also confirmed Planck's formula for the blackbody spectrum (Nobel prize, 1918). If Planck's formula were incorrect, the calibration software would not have produced self-consistent results. The FIRAS calibration depends on temperatures through the form for the photon mode occupation number $\eta=1/(e^x-1)$, and this is the part of the Planck function that we tested.

A recent paper by Fixsen and Mather (2002) argued that modern detectors and instrument designs could produce a factor of 100 improvement in sensitivity and accuracy. In that case the astrophysical interference from dust and molecules would certainly limit the cosmological conclusions. However, if these foregrounds could be managed, it is not unlikely that the distortions of the CMBR spectrum from known forms of energy release [e.g., the reionization of the universe at a redshift of 10–20 as detected by WMAP (Wilkinson Microwave Anisotropy Probe)] could be detected.

Several papers have been written about the possibility of detecting distortions of the CMBR spectrum from small effects during the recombination era. For instance, small opacities due to the molecule lithium hydride LiH might be seen, if the level populations of the molecule were slightly out of thermal equilibrium. A common question concerns the Lyman-α photons remaining from the last recombination for each H atom. There would be approximately one photon per H atom, at a wavelength of $(1+z)(0.1216\ \mu\text{m})$, where $z\sim1089$, and a fractional line width of a few percent. H atoms are very much less numerous than CMBR photons, by a factor of more than 10^9, and the expected wavelength is in a region of the spectrum that is filled with galactic dust, atomic and molecular emission, and zodiacal dust emission, so these few photons are very unlikely to be observable.

Improved measurements of the CMBR spectrum at longer wavelengths are now in progress. The ARCADE project (Kogut *et al.*, 2004) is a balloon-borne microwave radiometer with a full-beam external blackbody calibrator. Operating without a protective window, it depends on high-speed flow of helium gas to keep the residual atmosphere at balloon altitudes from falling into the instrument and condensing on the antennas. Preliminary results show that the measured temperature is consistent with the FIRAS number. Eventually, this approach will provide improved measurements of the μ parameter for early energy release, since this distortion is greatest at long wavelengths.

B. DMR

The DMR instrument was the second to produce cosmological results. The data analysis team worked diligently to understand the needed corrections for known systematic errors, particularly the magnetic and thermal sensitivities of the Dicke switches, and the stray light from bright objects like the Earth. The first hint that we had detected a cosmic anisotropy was shown to the Science Working Group at a special team meeting at Nancy Boggess's home in October 1991 by Ned Wright, who had written his own analysis program for the first year of DMR data. The immediate response of the science team was that this was very important, too important to release quickly. We were well aware of recent junk science results on polywater, cold fusion, and other topics, and we were determined to get the answer right.

There were three main issues. First, were all known instrument errors properly modeled and compensated? Second, had we properly understood and removed the effects of the galactic foreground electrons and dust? Third, were the elaborate computer programs reliable?

To tackle the first issue, we held team meetings devoted to brainstorming about everything that could possibly affect the accuracy of the data and devising strategies to measure and analyze each effect. For each one, we needed two different people and computer programs to agree, and we needed a science team review of the results. Alan Kogut and Ned Wright were the key analysts, and David Wilkinson was our most determined skeptic. This process took many months.

The second issue was analyzed at Goddard by Charles Bennett and Gary Hinshaw, and by the rest of the team, and described in Bennett *et al.* (1992). Their strategy was to represent the two kinds of foreground emission by galactic electrons and the dust emission by models with adjustable coefficients, and then to determine those coefficients by comparing the maps made by the DMR and other equipment at different wavelengths. The result was that a linear combination of the three DMR maps, weighted with particular coefficients, would eliminate almost all the galactic emission for directions outside the galactic plane.

The third issue, that of software reliability, was managed by thorough tests of each computer code, and comparison of results of the personal code written by Ned Wright with the official code written by the DMR team at Goddard and the code developed independently by George Smoot and his team at Berkeley.

An additional verification came from the data from balloon-borne instruments. We had agreed to delete the long-wavelength channel (at 23 GHz) from the DMR, and to fly a balloon-borne maser instrument to map part of the sky at that wavelength. The maps from this instrument contained strong signals from the Milky Way galaxy, but they were consistent with the DMR data (Fixsen, Cheng, and Wilkinson, 1983). Also, the MIT-Princeton team of Stephan Meyer, Edward Cheng, Ken Ganga, and Lyman Page, including two COBE team members, flew a balloon-borne instrument with bolometer detectors at shorter wavelengths, and achieved enough sensitivity to see the cosmic fluctuations (Ganga *et al.*, 1993). Their data were processed just in time to show that they were consistent with the cosmic fluctuations seen by DMR, before the DMR data were made public. Indeed, if the DMR had not been built, it is possible that the balloon data would have eventually been accepted as the first detection of cosmic structure. For our purpose, it was enough that we knew the DMR data, covering the whole sky, were sound.

Finally, the results were ready and prepared for publication. The announcement was made at the meeting of the American Physical Society in April 1992 in Washington, D.C. There had been enough advance publicity, and some leaks, that the press conference was filled with TV cameras and reporters. Within the day, the results were reported worldwide, and George Smoot's famous remark about seeing the face of God made the news everywhere. Steven Hawking is quoted as saying something like this was "the most important discovery of the century, if not of all time." The next day, interpretive papers had been submitted and distributed on the worldwide web by leading cosmologists, who had everything written in advance except the conclusions. Within the year, there were thousands more papers citing our results.

The results we showed were in the form of maps and fluctuation spectra. The maps were nicely adjusted to show pink and blue blobs to represent hot and cold parts. As Sachs and Wolfe (1967) had pointed out, the colder regions represent higher density, because of the gravitational redshift of the photons leaving potential wells. The spectra were statistical characterizations of the spatial fluctuations, mathematically precise descriptions of the typical sizes of the blobs. To a first approximation, we found that there is no typical size—blobs of all sizes are equally likely and equally bright. This is called "scale invariant," as predicted by Harrison and Zeldovich and by simple forms of the theory of cosmic inflation. On closer examination, the fluctuations are a little too weak on large angular scales (90° and larger), and they increase a little on the smallest angular scales we could see (7°), as they should according to theory. The first point has still not been explained, and may not be statistically significant. The second is very important, and is due to the motions of matter at the time of the cosmic decoupling.

So what had the DMR measured? We had indeed discovered and mapped the primordial density fluctuations of the universe. If these had not been found, theorists would have been extremely disappointed, because by 1992, there was a nearly complete theory of the origin of the large scale structure of the universe, built on the idea of cosmic inflation to set initial conditions and guarantee large scale uniformity of the universe. The theory holds that very small amplitude primordial density fluctuations are the seeds for large scale structure, and that ordinary matter falls into the regions with greatest initial density, leaving empty regions (cosmic voids) where the initial density is least. The only needed force is gravitation. A remarkable result of the theory is that the density fluctuations grow linearly with time, and not exponentially like so many other natural phenomena. The reason is that the gravitational attractions of distant parts of the universe diminish with the expansion, slowing down the exponential growth to linear growth. Therefore measurements of the large scale structure of the universe as represented by galaxies and galaxy clusters should also represent the initial conditions, the primordial fluctuations. By 1992, we had measurements of the large scale fluctuations traced by galaxies, and so we thought we knew what to expect.

However, there was trouble with this picture. Ordinary matter alone gives the wrong patterns, and it is not free to move relative to the rest of the universe until it becomes a neutral gas at the cosmic decoupling era. Fortunately, it was already recognized that some kind of additional matter might fill the universe, called cosmic dark matter. By hypothesis, it is invisible, and has no interactions with light except through gravitation. On the other hand, since it is not tied to the CMBR radiation field, it is free to start moving before the cosmic decoupling, and can fall into the primordial gravitational wells and make them grow deeper. Also, nothing is known of this dark matter except what astronomers claim to know: there is no agreed theory of it, no measurement of any of its particles in laboratories, and no knowledge of the masses of the particles, their stability, or anything else. Only one kind of dark matter has so far been observed in the laboratory, the neutrinos, with their three flavors and their antiparticles, and it seems that their masses are not enough to explain the cosmic dark matter.

The other thing at issue in 1992 was whether the universe is spatially flat or not. Theorists felt that a zero curvature universe was simple and pleasing and somehow ought to be true. To make such a universe, we would have to have a cosmic acceleration term in the equations, like the Λ constant that Einstein (Nobel prize, 1921, but not for this work) proposed and later rejected. Perhaps just the right amount of such a term, which produces negative spatial curvature, could balance the positive curvature produced by ordinary matter and dark matter. That would be an amazing coincidence, unless there is some unknown law of nature that requires this to be true. This acceleration term is now called the cosmic dark energy, which points out that it might not be just a constant of mathematical integration as Einstein saw it, but could perhaps be a new kind of force or matter with its own peculiar equation of state. So the interpretation of the measured cosmic fluctuations has become a major scientific industry.

The DMR was operated for a total of 4 years, and the additional data were statistically consistent with the first year's data. The new data gave much better ways to hunt for and correct systematic errors of all sorts, so the final results improved much more than the factor of 2 in random noise levels.

The DMR data were analyzed to hunt for many interesting things, none of which have been found with much statistical significance. For instance, there was a suggestion that cosmic strings might exist, stretching across vast regions of space. At one time it was thought that they could produce the cosmic density fluctuations all by themselves. If they were strong enough, they would produce discontinuities in the temperature maps, and should be visible. Since none have been found, they apparently were not responsible for the CMBR anisotropy, but perhaps they are just very rare. Searches were also made for non-Gaussian fluctuations; perhaps there were specific localized objects, with either positive or negative temperatures, that could be found by close examination. None of these have been found either, above the levels that should appear from ordinary Gaussian fluctuations and from known point sources like Jupiter. The DMR angular resolution is too coarse for it to respond much to fainter objects. Another possibility is that the universe has a peculiar topology: suppose that we found the same object or pattern in two different places on the map. In that case, the universe could have the topology of a sphere or a torus, in which the same object could be viewed in two different directions. None of these searches have returned positive results either.

Following the DMR announcement, there have been many more instruments built, and hundreds of scientists worldwide have continued to measure and analyze. Ground-based and balloon-borne instruments have measured with improved angular resolution. COBE team members Charles Bennett and David Wilkinson conceived, proposed, and built the MAP, the Microwave Anisotropy Probe, launched in 2001 and still operating. It was renamed the Wilkinson Microwave Anisotropy Probe in 2002, following Wilkinson's death on September 5, 2002. The WMAP has extended the DMR all-sky maps to much higher sensitivity and angular resolution, and has confirmed that the DMR data are accurate. With the WMAP data, we now know many of the cosmic parameters (matter, dark matter, dark energy density, age of the universe, etc.) to precisions of a percent or two. It has also detected a wonderful surprise: evidence of the effects of the reionization of the universe, at a redshift around 13. This is recognized through the polarization of the CMBR, produced as a result of the quadrupole anisotropy of the CMBR seen by electrons when they scatter the radiation towards us for the last time. The angular scale of the polarization pattern we observe measures the redshift at which the scattering occurs, and the amplitude measures the optical depth of the scattering.

There are several remaining challenges for future CMBR anisotropy measurements. The one receiving the most attention now is the hunt for the polarization induced by gravitational waves in the Big Bang itself. A Task Force on Cosmic Microwave Background Research, chaired by Rainer Weiss, prepared a summary report about the benefits, challenges, and strategy for measuring this polarization. The polarization map is a vector field on a sphere, and can be decomposed into two parts: the divergence of a scalar field, called E mode, and curl of a vector field, called B mode. According to theory, the primordial gravity waves should produce a polarization pattern with a curl, and no other subsequent process should be able to do so. The polarization pattern would be much fainter than the temperature anisotropy map, and the curl component would be much fainter than the divergence component. Hence this is very difficult to measure, but it may already be possible with current generations of detectors. The generic name for this space mission in the US is "Inflation Probe" and three design studies have been supported by NASA. Technically, such a mission could be flying in a decade, but competition for scarce resources may delay it. In any event, the measurement of the B-mode polarization is the most direct method available to learn about the forces prevailing in the Big Bang itself, could help us come to the long-sought theory of everything, and presumably would be a Nobel-winning discovery. It is no surprise that elementary particle physicists, both theorists and experimenters, have been turning to CMBR studies as their next exciting opportunity.

C. DIRBE

The DIRBE instrument was the last to produce cosmological results, largely because the local foregrounds at DIRBE wavelengths are very bright and complex. The definitive DIRBE results are given in a series of papers (Hauser *et al.*, 1998; Kelsall *et al.*, 1998; Arendt *et al.*, 1998; Dwek *et al.*, 1998). The surprise found in the DIRBE data is that the universe is twice as bright as previously believed from measurements of individual galaxies. There is a general glow called the cosmic infrared background (CIB) composed of two parts, at near IR wavelengths of a few μm, and far IR wavelengths of a few hundred μm. The near IR background is not yet understood (see the review by Hauser and Dwek, 2001), but the far IR background is apparently produced by a previously unknown population of very bright dusty galaxies at redshifts of 2 to 3.

To get to this result, the DIRBE team had to go through a much more complex process than was required for the other two instruments because the main foreground faced by DIRBE is variable in time and space. It is produced by the interplanetary dust, which is smoothly distributed in a thick disk orbiting the Sun. This disk is not so simple though. It has several sources, in collisions among asteroids, in the disintegration of comets, and in the migration of small particles from the outer solar system. From the IRAS data, we know that there are at least three rings of dust orbiting as though they are collision debris from certain families of asteroids. Also, these particles move under the influence of gravity, radiation pressure, and the Poynting-Robertson drag, and electromagnetic forces for those particles with electric charges. The drag force makes the particles spiral in towards the Sun over time scales of thousands to millions of years, depending on size, and the particles may experience close encounters with the planets, and repeated gravitational impulses when their orbital periods are commensurate with the planets. Some become locked in orbital resonances for long periods of time, as the gravitational forces overcome the Poynting-Robertson drag. Some even become locked in orbital resonance with the Earth, producing leading and trailing blobs that were seen in the DIRBE data. This phenomenon, an annoyance for those seeking the cosmic IR background radiation, is of great interest for those hunting for planets around other stars. Indeed, it has already been seen in the dust clouds of bright stars such as Fomalhaut, where a large planet is presumed to be organizing the dust into a ring (Kalas, Graham, and Clampin, 2005).

In addition, the Earth, and the COBE with it, move through the dust cloud. The major effects are that the plane of the Earth's orbit is not the symmetry plane of the dust cloud, which feels greater forces from Jupiter, and that the Earth's orbit is not circular, so the Earth moves in and out as well as up and down in the cloud. Moreover, the dust cloud is not centered on the Sun, since it feels the strong pull of Jupiter.

The model for this dust was built in a heuristic way, and contains many free parameters, adjusted to fit the time and spatial variations of the sky observed by the DIRBE. Full documentation of the model has been given by Kelsall *et al.* (1998). The parameters include the dust temperature and its power-law variation with distance from the Sun, the dust number density and its power-law variation with distance, the emissivity and reflectivity at each wavelength, and the phase function of the scattering. There is a model of the particle resonances with the Earth to explain the leading and trailing blobs. There are parameters to describe the thickness of the dust disk, and the shape of its density distribution near the ecliptic plane, and parameters for the tilt and forced eccentricity of the dust disk presumed to be due to Jupiter. Even the symmetry plane of the dust distribution is warped, presumably by the competing gravitational perturbations of nearby planets. Even with all this complexity, there are significant residuals from the model, and Kelsall believes there are real time variations at the level of a percent that are not explained.

Understanding the foreground emission from the Galaxy was also difficult and done in a heuristic fashion. The majority of the sky at most wavelengths has detectable stars and dust clouds, the brightest of which can be masked out and ignored. The fainter ones are not resolved by the large DIRBE beam and can be modeled based on *a priori* galactic models with no free parameters (Arendt *et al.*, 1998).

The result of all this subtraction is that there are a few favored directions where the galactic foregrounds are least, possibly due to supernovas which have cleared out the dust and gas for large distances. As any true cosmic background must be roughly isotropic, it was important that observations in these favored directions must give the same answers.

The DIRBE results were essential to both the FIRAS and DMR interpretations. First, they showed that the local universe was well understood, so that the FIRAS and DMR observations really do represent the distant Big Bang. This was important, for instance, in arguing that it is only a coincidence that the cosmic dipole due to the Earth's motion lies in the Ecliptic Plane. Also, the DIRBE maps of galactic dust agreed with the FIRAS maps, showing that there were no new and strange effects. Conversely, after the DIRBE team determined that there is a far IR cosmic background field, the FIRAS data were used to confirm it and measure its spectrum (Fixsen *et al.*, 1998).

VI. SUMMARY: COBE'S PLACE IN HISTORY AND WHERE ARE WE NOW?

The COBE mission, started in an era when slide rules were common and aerospace designers used pencils and large sheets of paper, led to a revolution in our understanding of the universe. It confirmed the Big Bang theory and discovered the primordial density fluctuations that formed the large scale structure of the universe. It found that the universe is twice as bright as previously thought. It led to a series of ever more powerful instruments to measure the CMBR, one of which (the WMAP) has already tested the idea that the earliest times in the universe included an exponential expansion called inflation. We now have precise values (especially from WMAP) of many cosmic parameters, and CMBR studies now in preparation could reveal the nature of the forces in the Big Bang by discovering the primordial gravity waves. The Planck mission, a project of the European Space Agency with NASA participation, is due for launch in 2008 and will extend the WMAP results to smaller angular scales by using shorter wavelengths. It will also have greater sensitivity, using bolometric detectors, and has a chance to measure the cosmic polarization signals even better than WMAP.

Our team members have continued on with many other projects. Rainer Weiss is one of the leaders of the LIGO project, the Laser Interferometer Gravitational-Wave Observatory. George Smoot is a full professor at the University of California at Berkeley. Charles Bennett, now at Johns Hopkins University, and David Wilkinson (who died in 2002), led the WMAP, with many of the engineers and scientists who built the COBE. Edward Wright is Principal Investigator for the WISE mission, the Wide-field Infrared Survey Explorer, which will survey the entire sky with 1000 times the sensitivity of the IRAS. Michael Hauser is Deputy Director of the Space Telescope Science Institute, which operates the Hubble Space Telescope and will operate the James Webb Space Telescope. Edward Cheng started a small company, Analytical Concepts, and Stephan Meyer is Deputy Director of the Enrico Fermi Institute and Associate Director of the Kavli Institute for Cosmological Physics at the University of Chicago. Most of the senior project managers and engineers have retired.

The COBE observations also lead on to new missions to observe the first stars and galaxies, such as the James Webb Space Telescope (JWST). This is my current project, for which I serve as the senior project scientist. The JWST is a deployable 6.5 m infrared telescope, to be launched in 2013 to an orbit around the Sun-Earth Lagrange point L2. With its protected environment and the latest in modern infrared detectors and instruments, it could also produce stunning discoveries. Theory confidently predicts that star formation began at very high redshifts (>20), and that some of the first protogalaxies and supernovas may be observable at redshifts of 15 or more.

ACKNOWLEDGMENTS

The COBE mission was first proposed in 1974, and our team owes tremendous thanks to those who read our thin booklets and recognized their importance. Dr. Nancy Boggess, Program Scientist for infrared astronomy at NASA Headquarters, was one of those people. She advocated the COBE even when many astronomers were not interested, and she backed other infrared astronomy missions like the IRAS, the Kuiper Airborne Observatory, the SOFIA (the Stratospheric Observatory for Infrared Astronomy), and the Spitzer Space Telescope. After the COBE was started, we benefited from strong and steady support from a series of managers at NASA Headquarters and Goddard Space Flight Center, who had patience and faith in our work. Our team was large, and most of the team members (not quite all) are listed in the books by Mather and Boslough (1996) and by Smoot and Davidson (1993). We also thank the taxpayers, who, whether they knew it or not, were funding the COBE mission. Benjamin Franklin, one of the greatest scientists of his day, and Thomas Jefferson, the first U.S. president to support a major scientific research project, would be proud to see that the country they helped to found has carried on with its support of science for the public good.

We also thank our families, who were participants in the COBE mission whether they knew it or not, and supported or at least tolerated the long hours and weekends that we worked to make the mission a success. For myself I thank especially my wife Jane, who has known me since before the COBE was imagined in 1974, and who has taken a keen interest all along. My parents sent me to school, led by example (my father was a geneticist working with dairy cattle and my mother was a teacher), and paid astronomical sums for tuition. My teachers showed me the way and encouraged my curiosity. I especially thank my thesis advisor Paul L. Richards, who started our balloon payload, and my fellow graduate student David Woody, who made the balloon payload work after all. For sponsoring and participating in the 1974 COBE proposal, my postdoctoral advisor Patrick Thaddeus gets the credit—without his influence, there would not have been a COBE, or at least this one. Within the COBE team I owe special thanks to our project manager Roger Mattson and his deputy Dennis McCarthy, and to the instrument manager for the FIRAS, Robert Maichle, the FIRAS instrument engineer, Michael Roberto, and to Richard A. Shafer, deputy principal investigator. Dale Fixsen was the architect of the FIRAS calibration, and Richard Isaacman and Shirley Read led the two software teams for the FIRAS. I also thank my coauthor John Boslough, without whom our book “The Very First Light” would not have been written.

With the funds from the Nobel Prize and the Peter Gruber Foundation prize in cosmology, and the concurrence of my wife Jane, I have started the John and Jane Mather Foundation for Science and the Arts. George Smoot has also set up a foundation with similar purposes. This is one way of giving thanks to the many people who contributed to the COBE project.

APPENDIX A

The COBE project archive is now located at http://lambda.gsfc.nasa.gov/ and includes project information, images, data files, and documentation. Ned Wright’s online Cosmology Tutorial, http://www.astro.ucla.edu/~wright/cosmolog.htm includes a history of the COBE project, with online images of early versions of the COBE. The Wikipedia entry on COBE is well written (http://en.wikipedia.org/wiki/COBE) and Richard A. Muller’s summary of the history of the Berkeley anisotropy measurements is at http://muller.lbl.gov/COBE-early_history/preCOBEhistory.html. My favorite textbook on cosmology is by Peebles (1993). An excellent recent summary of cosmology has been given by Bennett (2006).

APPENDIX B: COBE TEAM MEMBERS

SCIENCE TEAM

Charles L. Bennett, Deputy Principal Investigator, DMR
Nancy W. Boggess, Deputy Project Scientist for Data; formerly Program Scientist for Infrared Astronomy, NASA Headquarters
Edward S. Cheng
Eli Dwek
Samuel Gulkis
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Michael A. Janssen
Thomas Kelsall, Deputy Principal Investigator, DIRBE
Philip M. Lubin
John C. Mather, Project Scientist, and Principal Investigator for FIRAS
Stephan S. Meyer
S. Harvey Moseley, Jr.
Thomas L. Murdock
Richard Arrick Shafer, Deputy Principal Investigator, FIRAS
Robert F. Silverberg
George F. Smoot, Principal Investigator, DMR
Rainer Weiss, Chairman, Science Working Group
David T. Wilkinson
Edward L. Wright, Data Team Leader

ENGINEERING AND MANAGEMENT TEAM

Donald F. Crosby, Instrument Engineer, DIRBE
Ernest C. Doutrich, Flight Assurance Manager
Irene K. Ferber, Project Secretary
Anthony D. Fragomeni, Observatory Manager
Thomas J. Greenwell, Integration and Test Manager

David Gilman, Program Manager, NASA Headquarters
William D. Hoggard, Delta Liaison/Launch Operations Manager
Charles Katz, Systems Engineer, Instruments
Bernard J. Klein, Instrument Engineer, DMR
Loren R. Linstrom, Systems Engineer, DIRBE
Robert J. Maichle, Instrument Engineer, FIRAS
Roger A. Mattson, Project Manager
Dennis K. McCarthy, Deputy Project Manager
Maureen J. Menton, Secretary
Herbert J. Mittelman, Resources Officer
Stephen Servin-Leete, Systems Engineer, DMR
Earnestine Smart, Project Support Specialist
Pierce L. Smith, Ground Data Processing Systems Manager
Jack W. Peddicord, Deputy Project Manager (Resources)
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Robert G. Sanford, Mission Operations Manager
Robert T. Schools, Project Support Manager
Joseph F. Turtil, Systems Engineer
John L. Wolfgang, Software Systems Manager
Earle W. Young, Instruments Manager

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