Pour les lecteurs désireux d'en apprendre davantage sur la périodicité des glaciations, leurs causes et leur importance, on trouvera ci-après dans sa version originale anglaise un article du professeur Berger, très documenté.

Cet article s'appuie sur une analyse exhaustive des théories et des modèles successivement affinés. Il fait bien ressortir les contributions convergentes et l'interaction prospective des recherches dans l'établissement et l'interprétation des données conduisant à une formulation de plus en plus précise d'une théorie interprétative du passé climatique de la Terre.

Milankovitch effects on long-term climatic changes

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1. Milankovitch era and debate

It is only during the first decades of the 20th century that R. Spitaler rejected J. Croll's theory that the conjunction of a long cold winter and a short hot summer provides the most favorable conditions for glaciation. He adopted the opposite view, first put forward by J.J. Murphy already in 1876, that a long cool summer and short mild winter are the most favorable. The diminution of heat income during the summer half-year has also been claimed by *Brückner, Köppen and Wegener (1925)* as the decisive factor in glaciation. *Milankovitch (1920,1941)*, however, was the first to present a complete astronomical theory of Pleistocene ice ages which include computing the changes of orbital elements over time and linking the changes in insolation to climate *(Imbrie and Imbrie, 1979, Berger, 1988)*.

Milutin Milankovitch was a Yugoslavian astronomer born in Dalj on 28 May

1879 who died in Beograd on the 12 of December 1958. He was a contemporary of Alfred Wegener (1880-1930) with whom he became acquainted through Vladimir Köppen (1846-1940), Weneger's father-in-law *(Berger and Andjelic, 1988).*

It is roughly between 1915 and 1940 that Milutin Milankovitch put the astronomical theory of the Pleistocene ice ages on a firm mathematical basis. He calculated how the intensity of radiation striking the top of the atmosphere during the caloric summer and winter half years varied as a function of latitude and of the orbital parameters (eccentricity, e, obliquity ε and climatic precession, e sin ω). He then emphasized the importance of the summertime insolation at 65°N as a controling factor of the Northern Hemisphere glaciations, with its dominant obliquity-driven periodicity of 41.000 years. Finally, he estimated the magnitude of ice-age departures from the present-day air surface temperatures, estimating the radiation balance at the Earth's surface.

The essential product of the Milankovitch theory is his curve that shows how the intensity of summer sunlight varied over the past 600.000 years, on which he identified certain low points with four European ice ages reconstructed 15 years earlier by Albrecht Penck and Eduard Brückner and from which he concluded that these geological data constituted a verification of his theory.

If we consider this curve, however, we are left in no doubt that Milankovitch's success was only an apparent one, because the Quaternary has had many more glacial periods than was claimed during the first part of the 20th century (*e.g. Shackleton and Opdyke, 1976*) and because the ice volume record is dominated by a 100 kyr rather than by a 41 kyr cycle. Moreover, during the late 1960s, modern detailed studies of Alpine terraces showed that the climatic reconstruction of Penck and Brückner was wrong : the time scale was grossly in error and the terraces are tectonic rather than climatic features. Although it is now clear that the empirical argument used by Milankovitch to support his theory was misinterpreted, the modern evidence now strongly supports its essential concept, namely that the orbital variations exert a significant influence on climate.

From roughly 1950's to 1970's, the Milankovitch theory was largely disputed with discussions based on fragmentary geological records supported by incomplete and frequently incorrect radiometric data. The accuracy of the astronomical parameters and of the related insolation fields was not known, and the climate was considered too resilient to react to "such small changes" as observed in the summer half-year caloric insolation of Milankovitch. At the end of the 1960's, climatologists have attacked the problem theoretically by adjusting the boundary conditions of energy-balance models (EBM) and observed that the magnitude of the calculated response was indeed very small. However if these early numerical experiments are viewed narrowly as a test of the astronomical theory, they are open to question because the models used are far from being complete and contain untested parameterization of important physical processes.

2. Milankovitch revival

In the late 1960's, judicious use of radioactive dating and paleomagnetic techniques gradually clarified the Pleistocene time scale. Better instrumental methods came on the scene by applying oxygen isotope in ice-age foraminifera relies (*Shackleton and Opdyke, 1976*) ecological methods of core interpretation were perfected global climates in the past were reconstructed (*CLIMAP, 1976, 1981*) and atmospheric general circulation models and climate models became available . With these improvements of dating and interpretating of geological data in terms of paleoclimates, with the advent of computers and the development of astronomical and climate models, a more critical and deeper investigation became necessary of all four main steps of any astronomical theory of paleoclimates, namely of :

1. the computation of the astronomical elements (*Berger, 1977*)
2. the computation of the appropriate insolation parameters (*Berger, 1978 a,b*)
3. the development of suitable climate models (*Kutzbach, 1985*)
4. the analysis of geological data in the time and frequency domains designed to investigate the physical mechanisms, and calibrate and validate the climate models (*Berger et al. 1984*).

It is this systematic approach with modern powerful techniques which has brought, mainly since 1975, the following major discoveries supporting progressively the astronomical theory.

2.1 Bipartition of the precessional period

In 1976, Hays, Imbrie and Shackleton demonstrated from spectral analysis of the climate sensitive indicators in selected deep-sea records that the astronomical frequencies (corresponding to the 100, 41, 23 and 19 kyr periods) are significantly superimposed upon a general red noise spectrum. It is the geological observation of the bipartition of the precessional peak (23 and 19 kyr were found instead of the usual average period of 21 kyr), confirmed in the astronomical computations made independently by *Berger (1977)*, which was one of the first most delicate and impressive of all tests for the Milankovitch theory.

2.2 Monthly insolations

The long-term deviations from today-values of the caloric half year insolation introduced by *Milankovitch (1941)* and revised by *Berger (1978b)* amount up to 3 to 4 per cent at the maximum. However, if the monthly insolation values *(Berger, 1978a)* are used instead, important fluctuations masked by the half year -averaging method become easily recognizable. For example, 125 kyr BP, during the Eemian interglacial, all latitudes were overinsolated in July with the positive anomaly reaching up to 12% ; and the same is for 10 kyr BP. This is especially significant when a delay of some thousands of years, required for the ice sheets to melt, is taken into account in climate modeling.

Moreover, a detailed treatment of the seasonal cycle is much more meaningful and indeed required for explaining climate variations in realistic climate models. Thus the computation of insolation variations over a complete seasonal cycle introduced in the early 1970's by A. Berger and their change in time are significant. The well-known high sea level stands of the Barbados III (124 kyr BP) and II (103 kyr BP) marine terraces (*Broecker et al., 1968*) clearly correspond in time to high summer insolation anomaly which amounts to some 10% of current values particularly in the high latitudes. An abortive glaciation at 115 kyr BP which separated these two warm intervals was successfully simulated by *Royer et al. (1983)* using the associated insolation minimum as the only external forcing. The main glacial transition between stages 5 and 4, at 72 kyr BP, was undersinsolated and, more important, this drop in insolation was not compensated by any significant increase during the whole Würm glaciation phase. On the contrary, yet another important decrease at 25 kyr BP augers the 18 kyr BP maximum extent of ice in the Northern Hemisphere. Indeed, between 83 kyr and 18 kyr BP there was an overall solar energy dificiency of 2.5 x 10^{25} calories north of 45°N, sufficient to compensate for the latent heat liberated in the atmosphere furing the formation of snow required by the buildup of the huge 18 kyr BP ice sheets.

2.3 Astronomical frequencies documented in diverse geological records

Since 1976, spectral analysis of climatic records of the past 800.000 years or so, has provided substantial evidence that, at least near the frequencies of variation in obliquity and precession, a considerable fraction of the climatic variance is driven in some way by insolation changes accompanying the perturbations of the Earth's orbit (*Imbrie and Imbrie, 1980*).

However, the interpretation of the results is not always as clear. The 100 kyr cycle, so dominant a lature of the late Pleistocene record, does not exhibit a constant amplitude over the past 2-3 million years Clearly, this periodicity disappears before 10^6 years ago, at a time the ice sheets were much less developed over the Earth, reinforcing the idea that the growth of the major ice sheets may have played a role in the modulation of the 100 kyr cycle.

Moreover, the shape of the spectrum depends also upon the location of the core and the nature of the climatic parameter analysed (*Hays et al., 1976*). For example in core V30-97, the 41 kyr cycle is not seen at all whereas the 23 kyr cycle is dominant in Atlantic summer sea-surface temperatures of the last 250.000 years *(Ruddiman and McIntyre, 1981).* This is not too surprising as these spectra depend upon the way the climate system reacts to the insolation forcing and upon which type of insolation it is sensitive too. Indeed, contrary to the well-received Milankovitch idea that the high polar latitudes must record the obliquity signal (as shown in the Vostok core, for example, *Jouzel et al., 1987*) whereas low latitudes record only the precessional one, the latitudinal dependence of the insolation parameters is more complex. Clearly the mid-month high latitude summer insolation displays a stronger signal in the precession band than in the obliquity one (*Berger et al 1993a*).

2.4 Phase Coherency

As already shown by *Hays et al. (1976)*, the variance components centered near a 100 kyr cycle which dominates most climatic records, seem to be in phase with the eccentricity cycle (high eccentricity at low ice volume). The exceptional strengh of this cycle calls, however, for a stochastic amplification of the insolation forcing, or for a non-linear amplification through the deep ocean circulation, the carbon dioxide, the ice sheet related mechanisms and feedbacks, the isostatic rebound of the elastic lithosphere and of the viscous mantle and the ocean-ice interactions. The 100 kyr climatic cycle can indeed be explained both (i) from the eccentricity signal directly, provided an amplification mechanism can be found and/or (ii) by a beat between the two main precessional components as shown by *Wigley (1976)* from non-linear climate theory. It must be stressed here that the same arises for the 100 kyr eccentricity cycle in celestial mechanics : the frequency corresponding to the second period of the eccentricity (94945 years in Table 3 of *Berger (1977)* is obtained from procession frequencies number 3 and 1 in Table 2 of the same reference (1/18976 - 1/23716). The other ones (number 1 and 3 to 6) are coming respectively from the following combinations : 2-1, 3-2, 4-1, 4-2 and 3-4.

It is worth here to remember that Milankovitch requested a high eccentricity for an ice age to occur -which is just the reverse of the correlation claimed at the beginning of this section. He viewed indeed the effect of the eccentricity through the precessional paramater alone. However, if a higher degree of accuracy is used in the insolation computations, $(1-e^2)^{-3/2}$ appears as a factor in all insolation parameters at all latitudinal bands, reflecting the full equation of the elliptical motion and the variation of the Earth-Sun mean distance in terms of the invariable semi-major axis of the Earth orbit *(Berger, 1978 b)*. Although its absolute effect is relatively small (1% at the most), this term increases the insolation at high eccentricity times and decreases it during low eccentricity, a result coherent with the recent findings. It can, therefore, not be ignored any more, especially since it reinforces the impact on climate in the (i) variant of the 100 kyr cycle explanation.

However, it must be stressed that *Imbrie and his collaborators (1984)* have made it clear that the coherency of orbital and climatic variable in the 100 kyr band is enhanced significantly when the geologic record is tuned precisely to the obliquity and precession bands. Using the so-called orbitally-tuned SPECMAP time scale they indeed found a coherency in the astronomical bands significant at more than 99% level of confidence. This supports the second mechanism (beat) rather than the first !

Such a fairly coherent phase relationship was also reasonably well defined between insolation and ice volume in *Kominz and Pisias (1979)* where obliquity consistently lead the ^{18}O record by about 10.000 years, whereas precession seems to be in phase with the 23 kyr geological signal. However, the recent results obtained by SPECMAP *(Imbrie et al., 1988)* show that these leads and lags are more complicated.

2.5 Other astronomical frequencies

Ruddiman et al. (1986) succeeded in finding in the geological records one of the secondary astronomical periods that was predicted in 1976, the 54 kyr one *(Berger, 1977)*. A similar period of 58.000 years was found in a 400 kyr record of the paleomagnetic field from Summer Lake in South-central Oregon.

Although, the most important term of a 412 kyr period in the eccentricity was already predicted by A. Berger in 1976, it is only two years later that appropriate statistical techniques and geological time series, long enough to discover such a periodicity, became available. Shackleton suggested this periodicity in 1978 and *Briskin and Harrell (1980)* using 2-million year sediment cores from both the Atlantic and the Pacific found it in the oxygen isotopic record of planktonic foraminifers, in coarse sediment fraction and in the magnetic inclination (which lead them to propose that a relationship may exist between the eccentricity and the Earth's core modulation of the magnetic field). *Kominz et al. (1979)* reported it also from two spectra covering the 730.000-year long records.

The investigation by *Moore et al. (1982)* of calcium carbonate concentrations in equatorial Pacific sediments (core RC 11-209), have shown that the Pacific carbonate spectrum has been dominated for the past 2 million years by variance in the 400 kyr band, with more modest contributions in the 100 kyr and 41 kyr bands (matching the variations of respectively the eccentricity and obliquity).

2.6 Data from the Pliocene and late Miocene

Very interestingly, with the existence of a few deep-sea cores extending through the first appearance of abundant ice rafted debris in North Atlantic, 2.5 million years ago, this most important eccentricity term of a period of 412 kyr, was confirmed in geological record. Using cross-spectral analysis, *Moore et al. (1982)* discovered that the 400 kyr eccentricity and sedimentary cycles were in phase over the last 8 million years, but the 100 kyr cycle which dominated climatic variability during the Pleistocene ice ages (29% of the total variability) had only a minor effect 5 to 8.5 x10^6 years ago, where it accounted for 6 times less variability than as today at the DSDP site 158. *Prell (1982)* also failed to find evidence of a strong 100 kyr cycle in pre-Pleistocene sediments at the DSDP site 502 in the western Caribbean and at the site 503 in the eastern equatorial Pacific. He did apparently find evidence of the 41 kyr cycle in a 7 million-year sediment record, as well as the evidence of a 250 kyr cycle.

Spectral analysis of DSDP Hole 552 A reveals also such a dominant quasi-periodicity associated with obliquity-induced temperature variations in surface water and weaker peaks at the eccentricity and precession periods in the Mediterranean Pliocene, rhythmic lithological variations in the Trubi and Narbone Formations of Sicily and Calabria show cycles that could be related to precession and eccentricity (*Hilgen, 1987*). In particular, the precession cycle corresponds well with the mean duration of the deposition of the basic rhythmites, the eccentricity cycle of about 400 kyr would match the average duration of the carbonate units and the 100 kyr cycle, the arrangement of the sapropelitic intercalations.

This late Miocene-Pliocene time scale, requires thus our most urgent attention. The upper Pliocene is indeed at the limit of validity of the astronomical calculations as far as the time domain is concerned. However there is still a large confidence in the value of the astronomical frequencies, in such a way that conclusions from a comparison between geological and astronomical data may still be convincingly drawn in the frequency domain. Moreover, a new astronomical solution valid over the last 5x10^6 years has now been constructed *(Berger and Loutre 1991 ; Laskar, 1988)*. It is thus challenging to see to which extent may the methodology developed for the Mid- and Upper-Pleistocene (*Berger, 1989*) be extended to Early Pleistocene, Pliocene and Miocene.

2.7 *Pre-Cenozoic evidence of astronomical signal*

There is also evidence that the orbital variations were linked to climate at periods shorter than 100 kyr during the past few hundred million years. This appeared at times when major ice masses were probably absent. Walsh power spectra of the Blue Lias Formation (basal Jurassic) show two cycles with duration less than 93 kyr which may record changes in orbital precession and obliquity (*Weedon, 1985/86*). Carbonate production in pelagic mid-Cretaceous sediments, quantified by calcium carbonate and optical densitometry time series, reflects the orbital eccentricity and precessional cycles (*Herbert and Fisher, 1986*). Fourier analysis of long sections of the Late Triassic Lockatong and Passaic formation of the Newark Basin show periods in thickness corresponding roughly to the astronomical periodicities (*Olsen, 1986*). All these interesting results encourage research of the stability of the solar system in order to determine to which extent the changing Earth-Moon distance, for example, influenced the length of the main astronomical periods. Recent astronomic computations (*Berger et al., 1992*) show (**Table I**) that the precession and obliquity cycles should indeed be reduced drastically prior to 2 billions years ago with the obliquity cycle starting to approach the precessional ones even if we take into account this varying Earth-Moon distance only. Already at 250 Myr ago, changes were not negligible : the main precessional periods were 17,6 kyr and 21,0 kyr and the obliquity one was 34,8 kyr.

Epoch (billion years Bp)	Precession		Obliquity
0	19,000	23,000	41,000
0.5	16,200	19,000	30,000
1	14,800	17,200	25,500
2	12,600	14,300	19,600
2.5	11,300	12,700	16,700

Table I

If we accept the astronomical theory of paleoclimates as a fundamental principle, a time will come when geology will provide astronomers with periodicities which will allow to test the theories of the planetary system and of its stability over much of the Earth's history.

2.8 Combination tones

Pestiaux et al. (1988) used cores with a high sedimentation rate covering the last glacial-interglacial cycle to resolve the higher frequency part of the spectrum. Besides the 19 kyr precessional peak, three other periods were detected at significant levels.

10,300 with a standard deviation of 2,200
4,700 with a standard deviation of 800
2,500 with a standard deviation of 500

These preferential frequency bands of climatic variability outside the direct orbital forcing band are still too broad to allow for a definite physical explanation. A tentative interpretation, though, may be given in terms of the climatic system's nonlinear response to variations in the insolation available at the top of the atmosphere. The 10.3, 4.7 and 2.5 kyr near-periodicities are indeed rough combinations tones of the 41, 23 and 19 kyr peaks found in the main insolation perturbations. Moreover, Pestiaux et al. (1988) succeeded to predict these shorter periods by using the Ghil -Le Treut- - Kallen non-linear oscillator climate model *(Ghil and Le Treut, 1981)*

On the other hand, a tendency to obtain free oscillations at periods up to several tens of thousands of years in complex climate models has also been mentioned by *Kallen et al. (1979).*

2.9 Ice sheets modeling and the 100.000 year periodicity

Hays et al. (1976) were among the first to suggest that the enhancement of the 100 kyr cycle may be due to non-linearities in the climate response. Wigley (1976) showed that it may indeed be a beat effect from the two main precession periodicities.

Imbrie and Imbrie (1980) have developed a simplified glacial dynamics model especially designed for the explicit purpose of reproducing the Pleistocene ice volume record from orbital forcing. The rate of climatic change is made inversely proportional to a time constant that assumes one of two specified values, depending on whether the climate is warming or cooling. Such a model tuned over the last 150.000 years, is forced with orbital imput corresponding to an irradiation curve for July 65 N, with a mean time constant of 17.000 years and a rate of 4 : 1 between the time constants of glacial growth and melting. Model's simulation of the isotopic record for earlier times are mixed and parametric adjustments do little or nothing to improve the matter.

The models based on a beat or on a simple form of non-linearity (like the asymmetrical response of Imbrie and Imbrie, 1980, in which the time constant governing ice decay is smaller than the time constant governing the ice growth), could hide a second problem : it is difficult to introduce substantial 100 kyr power into the climate response without also introducing power reflecting the 413 kyr eccentricity cycle in amounts that are much greater than have been detected in most Late Pleistocene climatic records *(Kukla et al, 1981)*. However, it is worth mentioning that the fit is much better in the results obtained by *Moore et al. (1982)* where the whole Pleistocene is considered as seen in section 2.6 !

The role if ice sheets in determining the long-period climate response, namely in the 100 kyr range, can possibly be clarified with some realistic parametric modelling of the ice sheet dynamics. Following *Birchfield and Weertman (1978)*, solar radiation variations seem to be large enough to account for the ice age cycles when glacier mechanics is properly taken into account. Adding calving of icebergs into a marginal lake in his ice sheet model, *Pollard (1982)* did create a sharp 100.000-year cycle that stayed roughly in step with the geological record of ice volume as far back as 600.000 years ago. He found also that the eccentricity cycle could impose itself only indirectly through its accentuation of the precession cycle and that a sharp termination resulted when an eccentricity-strengthened precession cycle coincided with a large ice sheet in existence.

Another mechanism for amplifying the effects of orbital variations, and namely of the eccentricity peak, is the interaction between the ice sheet and the underlying bedrock through isostatic rebound (*Oerlemans, 1980*). High latitude topography and the role of ice albedo-temperature feedback are also included in the models.

It must also be pointed out that recent ice sheet models show that the 100 kyr cycle can be stimulated with (*Saltzman et al. 1984*) or without internal free oscillations related to resonances when astronomically forced. It is significantly reinforced when isostatic rebound and iceberg calving are taken into account. (Pollard, 1982)

2.10 Equilibrium 3-D climate models astronomically controled

Another suggestion that has generated considerable interest is that geography may help explain climate's sensitivity (*North et al. ,1983*). So, when orbital variations are used that favor increasingly cooler summers (as at the transition between 125 kyr and 115 kyr BP and at the last glacial maximum 18 kyr BP), models with realistic distribution of continents and oceans generate the largest ice cap over northern Canada and Scandinavia. These are obviously the most sensitive spots of the climate system to orbital influences (*Royer et al., 1983*).

Glacial ice has generally received most of the attention but evidence exists that orbital variations also influence the behaviour of the North Atlantic deep ocean water and atmospheric features such as the intensity of the westerly winds and of the Indian monsoon. For example, changing the orbital configurations to that of 9 kyr BP, when insolation seasonality was 14 percent higher than today, leads to an intensified southwest monsoon (*Kutzbach, 1981*).

In fact, a simulation over the last 150.000 years has shown that under glacial conditions, the simulated monsoon is weakened in Southern Asia but precipitation is increased in the equatorial west Indian Ocean and equatorial North Africa. Moreover, the monsoon is strongly tied to the precession parameter (their maxima coincide) as it is also the case for the variations in tropical and equatorial climate.

2.11 Transient response fo the climate system to the orbital forcing and change in the seasonal pattern of insolation.

In addition to the calculation of the Earth's climate which is in equilibrium with a particular insolation pattern and other boundary conditions (the ice-sheets, for example), the simulation of the transient response of a realistic climate system to orbital variations must allow better understanding of the physical mechanisms linking astronomical forcing with climate. *Berger* suggested earlier *(1979)* that the long term astronomical variation of the latitudinal distribution of the seasonal pattern of insolation is the key factor driving the climate system, and the complex interactions among its different parts. A 2.5-dimension time-dependent physical climate model, which takes into account the feedback between the atmosphere, the upper ocean, the sea-ice, the ice-sheets and the lithosphere, thought to be the most important at the astronomical time scales, strongly supports such hypothesis (*Berger et al., 1990*). In this model, the simulated long-term variations of the global ice volume over the past 125.000 years agree remarkably well with the reconstructed sea-level and ice volume curves of *Labeyrie et al. (1987*).

Using climate models of various complexity, astronomically forced, researchers have shown that the dynamic behaviour of the climate over the last 400.000 years reproduced fairly well (*Imbrie and Imbrie, 1980 , Berger et al., 1990*). Extrapolation thus begins to be allowed at least for a period over which we can assume there is sufficient predictability : assuming no human interference at the astronomical scale, orbital forcing predicts that the general cooling that began 6 kyr BP will continue with a first moderate cold peak around 5 kyr AP, a majour cooling about 23 kyr AP and full ice age conditions 60 kyr AP (*Berger, 1988*).

3. Conclusions

Recent evidence seems thus to have laid to rest the argument that orbital variations might cause minor climate fluctuations but not major climatic changes as the Pleistocene glacials and interglacials. Among the number of competing theories to explain the coming and going of the Pleistocene ice sheets and other climatic variations of the past, only the astronomical theory (of which Milankovitch theory is a particular version) has been supported so far by substantial physical evidence.

This evidence, both in the frequency and time domains that orbital influences are felt by the climate system imply that the astronomical theory of climates has the following advantages :

1. It provides an absolute clock with which to date Quaternary sediments with a precision several times greater than is otherwise possible.

2. It provides the boundary conditions necessary for a better understanding of the climatic system and the interactions between the atmosphere, hydrosphere, cryosphere, biosphere and lithosphere, which, at the astronomical time scales, all play a role.

3. It allows a better understanding of the seasonal cycle and can be used to test the performance of the climate models over a broad spectrum of climatic regimes.

4. It allows a better understanding of the other forcings, in particular the CO_2 cycle (*Berger et al., 1993b*), by extracting the astronomical signal from the climate variability.

5. It predicts gross natural climate changes to be expected at the geological time scale in the next 100.000 years, an approximate decay period of radioactive wastes.

6. It allows a better understanding of the sensitivity of our present-day interglacial climate and of the possible superinterglacial that could be generated by human activities whithin the next 50 years or so.

7. It may provide data for astronomers with which to test the stability of the planetary system in pre-Quaternary times.

8. It enables accurate computation of the insolation changes at the decadal time scale due to change in orbital elements, in relation to the satellite measurements of the solar constant and its variations.

9. It allows a better understanding of the planetary system and the climatic variations of the planets (*Pollack, 1979*).

10. It allows us to transfer theoretical knowledge (spectral analysis, numerical schemes, etc...) and technologies (deep-sea drilling, satellites, supercomputers, etc...) to society at large.

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Références bibliographiques

Berger A. (1977) Support for the astronomical theory of climatic change, Nature, 268, 44-45

Berger A. (1978a) Long-term variations of daily insolation and Quaternary climatic changes, J. Atmospheric Sciences, 35(12), 2362,2367

Berger A. (1978b) Long-term variations of caloric insolation resulting from the Earth's orbital elements, Quaternary Research, 9 139-167

Berger A. (1979) Insolation signatures of Quaternary climatic changes, Il Nuevo Cimento, 2C(1), 63-87

Berger A. (1988) Milankovitch astronomical theory of paleoclimates : a modern review, Vistas in Astronomy 24(2), 103-122

Berger A. (1989) Pleistocene climatic variability at astronomical frequencies. Quaternary International, 2, 1-14

Berger A., Tricot Ch., Gallée H. and Loutre MF, (1993b) Water vapour, CO_2 and insolation over the last glacial-interglacial cycles. Phil. Trans R. Soc London B, 341, 253-261

Berger A., Imbrie J., Hays J., Kukla G and Saltzman B. (Eds) (1984) Milankovitch and Climate. Understanding the response to orbital forcing. D. Reidel Publ Company, Dordrecht, Holland, 895p.

Berger A., Gallée H., Fichefet Th., Marsiat I., Tricot Ch. (1990) Testing the astronomical theory with a coupled climate-ice sheet model. Paleogeography, climatology, ecology, global and planetary change section, 89, 125-141

Berger A., Andjelic, TP (1988) Milutin Milankovitch, Père de la théorie astronomique des paléoclimats, Histoire et Mesure, Editions CNRS Paris III-3, 385-402

Berger A. et Loutre MF. (1991) Insolation values for the climate of the last 10 million years, Quaternarly Science Reviews, 10, 297-317

Berger A., Loutre MF, and Laskar J. (1992) Stability of the astronomical frequencies over the Earth's history for paleoclimate studies. Science, 255, 560-566

Berger A., Loutre MF. and Tricot Ch. (1993a) Insolation and Earth's orbital periods J. Geophys. Res., 98 (D6), 10.341-10.362

Birchfield GE and Weertman J. (1978) A note on the spectral response of a model continental ice sheet, J. of Geophysical Research, 83 n°C8, 4123-4125

Briskin M. Harrell J. (1980) Time series analysis of the Pleistocene deep-sea paleoclimatic record using periodic regression, Marine Geology, 36, 1-22

Broecker W.S, Thurber D.L, Goddard J. Ku T. Matthews R.K. Mesolella K.J (1968) Milankovitch hypothesis supported by precise dating of coral reefs and deep sea sediments, Science, 159, 297-300

Brückner Ed. Köppen W. Wegener A. (1925) Uber die klimate der geologischen vorzeit. Zeitschrift für Gletscherkunde, vol 14

CLIMAP Project Members (1976) The surface of the ice-age earth. Science, 191 1131-1137

CLIMAP Project Members (1981) Seasonal reconstruction of the earth's surface at the last glacial maximum, Mc Intyre A. and Cline R. (Eds), Geological Society of America, Map and chart series MC-36, Boulder, 1-18

Ghil M. and Le Treut H. (1981) A climate model with cryodynamics and geodynamics J. of Geophysical Research, 86, 5262-5270

Hays JD., Imbrie J. and Shackleton NJ (1976) Variations in the earth's orbit : pacemaker of the ice ages. Science, 194, 1121-1132

Herbert TD and Fisher AG (1986) Milankovitch climatic origin of mid-Cretaceous black shale rhythms, Central Italy, Nature 321 (6072) 739-743

Hilgen FJ (1987) Sedimentary rhythms and high resolution chronostratigraphic correlations in the Meidterranean Pliocene, Newsl. Stratigr 17(2), 109-127

Imbrie J. and Imbrie KP (1979) Ice Ages, Solving the Mystery, Enslow Publishers, New Jersey

Imbrie J. and Imbrie JZ. (1980) Modelling the climatic response to orbital variations, Science, 207, 943-953

Imbrie J., Hays J., Martinson DG, McIntyre A., Mix AC, Morley JJ, Pisias NG, Prell WL, Shackleton, NJ (1984) The orbital theory of Pleistocene climate : support form a revised chronology of the marine ^{18}O record. In : A. berger, J. Imbrie, J. Hays, G. Kukla, B. Saltzman (Eds) "Milankovitch and climate", 269-305, D Reidel Publ Company, Dordrecht, Holland.

Imbrie J., McIntyre A. Mix A. (1988) Oceanic response to orbital forcing in the late Quaternary : observational and experimental strategies. In : A. Berger, S. Schneider and J.C Duplessy (Eds) Climate and geo-sciences" D. Reidel Publ Company, Dordrecht, Holland

Jouzel J., Lorius Cl, Petit JR., Genthon C., Barkov NI, Kotlyakov VM (1987) Petrov Vin, Vostok ice core : a continuous isotope temperature record over the last climatic cycle, Nature, 329 (6138) 403-408.

Laskar J. (1988) Secular evolution of the solar system over 10 million years. Astron. Astrophys 198, 341-362

Kallen E., Crafoord C. and Ghil M. (1979) Free oscillations in a coupled atmosphere-hydrosphere-cryosphere system, J. of Atmospheric Science, 36, 2292-2302

Kominz MA and Pisias NG. (1979) Pleistocene climate : deterministic or stochastic ? Science, 204, 171-173

Kominz M.A, Heath GR, Ku TL. Pisias NG (1979) Brunhes time scales and the interpretation of climatic changes, Earth Planet Sci. Letters, 45, 394-410

Kukla G., Berger A., Lotti R., Brown J. (1981) Orbital signature of interglacials, Nature, 290 (5804), 295-300

Kutzbach JE (1981) Monsoon climate of the early Holocene : climate experiment with the earth's orbital parameters for 9.000 years ago, Science, 214, 59-61

Kutzbach JE (1985) Modeling of paleoclimates, Adv. Geophys. 28A, 159-196

Labeyrie LD. Duplessy JC, Blanc PL. (1987) Deep water formation and temperature variation over the last 125.000 years, Tellus 327, 477-482

Milankovitch MM. (1920) Théorie mathématique des phénomènes thermiques produits par la radiation solaire, Académie Yougoslave des Sciences et des Arts de Zagreb, Gauthier-Villars.

Milankovitch M ; (1941) Kanon der Erdbestrahlung. Royal Serbian Academy, Spec. publ. 132 section of Mathematical and Natural Sciences, vol 33 (published in English by Israël Program for Scientific Translation, for the U.S Department of Commerce and the National Science Foundation, Washington D.C. 1969).

Moore TC, Pisias NG, Dunn DA (1982) Carbonate time series of the Quaternary and late Miocene sediments in the Pacific ocean : a spectral comparison, Marine Geol. 46, 217-233

North GR., Mengel JG and Short DA. (1983) Simple energy balance model resolving the seasons and the continents. Application to the astronomical theory of the Ice Ages. J. of Geophysical Research, 88 C 11, 6576-6586

Oerlemans J. (1980) Model experiments on the 100.000-yr glacial cycle, Nature 287(2) 430-432

Olsen, PE. (1986) A 40-million-year lake record of early Mesozoic orbital climatic forcing, Science 234, 842-848

Pestiaux P., Duplessy JC. van der Mersch I. and Berger A. (1988) Paleoclimatic variability at frequencies ranging from 1 cycle per 10,000 years to 1 cycle per 1,000 years : evidence for nonlinear behavior of the Climate system, Climatic change, 12(1) 9-37

Pollack J.B (1979) Climatic change on the terrestrial planets, Icarus, 37, 479-553

Pollard D. (1982) A simple ice sheet model yields realistic 100 kyr glacial cycles, Nature 296, 334-338

Prell WL (1982) Oxygen and carbon isotope stratigraphy for the Quaternary of Hole 502B : evidence for two modes of isotopic variability. In : "Initial reports of the deep sea drilling project" 455-464 WL Prell and JV Gardner et al. (Eds), vol LXVIII, Washington D.C

Royer, JF, Deque M. and Pestiaux P. (1983) Orbital forcing of the inception of the Laurentide ice sheet, Nature, 304, 43-46

Ruddiman WE., Shackleton NJ. and Mc Intyre A. (1986) North Atlantic sea-surface temperatures for the last 1.1 million years. From summerhayes C.P and Shackleton NJ (Eds), North Atlantic Palaeoceanography Geological Society Special Publication, 21,pp 155-173

Ruddiman WF and McIntyre A. (1981) Oceanic mechanisms for amplification ot the 23.000-year ice-volume cycle, Science, 212 617-627

Saltzman B., Hansen AR. and Maasch KA (1984). The late Quaternary glaciations as the response of the three-component feedback system to earth-orbital forcing, J. of Atmospheric Sciences, 41 nr 23 3380-3389

Shackleton NJ and Opdyke ND (1976) Oxygen isotope and paleomagnetic stratigraphy of Pacific core V28-239 late Pliocene to latest Pleistocene, Geological society of America, memoir 145, PP 449-464

Weedon GP (1985/86) Hemipelagic shelf sedimentation and climatic cycles : the basal Jurassic (Blue Lias) of South Britain, Earth and Planetary Science Letters, 76, 321-335

Wigley TML (1976) Spectral analysis : astronomical theory of climatic change, Nature, 264, 629-631