44. *Long Term Evolution of the Solar Insolation Variation over 4Ga*

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(Communicated by Syun-iti AKIMOTO, M. J. A., Nov. 12, 1993)

Abstract: Solar insolation variation due to the gravitational perturbation among the planetary bodies in the solar system, so called the Milankovitch cycle, is widely believed as a major cause of the climatic change such as the glacial-interglacial cycles in Quaternary, and its typical frequencies are supposed to be constant during Quaternary. However, the periods of these cycles must have been largely changed following to the dynamical evolution of the earth-moon system. We have studied the relation between the frequencies of the Milankovitch cycles and the rotation rate of the earth on the basis of theoretical and computational analysis of the earth-moon system. Our conclusion is that this cyclicity which can be recorded in the sediments are mutually related well as a function of the dynamical ellipticity and the absolute age. This fact implies that we can establish the standard time scale for measuring the relative age, in other words, the lap time clock or the chronometer for decoding the whole history of the earth, by comparing the stripes in BIF and other sediments of Archean or Proterozoic with a set of theoretical Milankovitch cycle and tidal cycle frequencies.

Key words: Solar insolation; Milankovitch cycles; earth rotation; banded iron formation; stromatolites.

Introduction. The mechanism of the Milankovitch cycles has been theorized quantitatively from so early times because it consists of classical celestial mechanics about point masses and rigid bodies (Milankovitch, 1941). However, in view of the longer time scale ($O(10^9)$years), secular change of the earth-moon distance and rotational velocity of the earth must have caused the great effect on the Milankovitch cycles. This effect was qualitatively pointed out by Walker and Zahnle (1986) up -2.5 Ga, and quantitatively computed by Berger *et al.* (1992) only up to -0.5 Ga.

The Milankovitch cycle is defined as the long period variation of solar insolation. This oscillation is considered to trigger the glacial and interglacial cycles in Quaternary. The power spectrum of the insolation variation of recent four million years by the standard Fourier transformation is shown in Fig. 1 (upmost one). Apparently we can see four sharp peaks. The peaks of 19 Kyr and 23 Kyr are due to the oscillation of precession angle, and the peaks of 41 Kyr and 54 Kyr is due to the oscillation of obliquity (though the peak of 54 Kyr is rather weak). Milankovitch cycles mainly consist of these four components (we call them *Mp1*, *Mp2*, *Mo1*, and *Mo2* respectively). During the short time scale of Quarternary the length of these periods (19, 23, 41, 54 Kyr) are thought to be nearly constant, but they must have been largely changed following the dynamical evolution of the earth-moon system in view of the longer time scale (10^9 years). Although the chaotic planetary

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perturbation effect does exist, we noticed that the effect of the planetary perturbation is non-systematic and minor in the variation of *Mp1*, *Mp2*, *Mo1*, and *Mo2* so the evolution of the Milankovitch cycles can be traced back to the ancient times when the earth was spinning much faster and the moon was much nearer. The purpose of this paper is to present the results of the possible evolution paths of the Milankovitch cycles on the basis of the standard calculational result of the dynamical evolution of the earth-moon system.

Equation of motion. The annually averaged equation of motion of the rotational axis of the planet is derived from the Euler's equation of rigid body rotation viewing from the inertial coordinate system (Ward, 1974; Bills, 1990)

$$\frac{ds}{dt} = \alpha(\boldsymbol{s} \cdot \boldsymbol{n})\ (\boldsymbol{s} \times \boldsymbol{n}) \tag{1}$$

where $\boldsymbol{s} = (s_x, s_y, s_z)$ is the spin axis unit vector of the earth. $\boldsymbol{n}$ is the orbital normal unit vector of the earth and expressed by the orbital inclination I and longitude of ascending node Ω as $\boldsymbol{n} = (\sin I \sin \Omega, -\sin I \cos \Omega, \cos I)$. In equation (1) α is called the precessional constant representing the magnitude of the gravitational torque obtained by the equatorial bulge of the earth (present value is 54.96 arcsec/year) and expressed as

$$\alpha = \frac{3n^2}{2\omega}\frac{C-A}{C}\left((1-{e_s}^2)^{-\frac{3}{2}} + \frac{M_m}{M_s}\left(\frac{a_s}{a_m}\right)^3 (1-{e_m}^2)^{-\frac{3}{2}}(1-\frac{3}{2}\sin^2 i_m)\right) \tag{2}$$

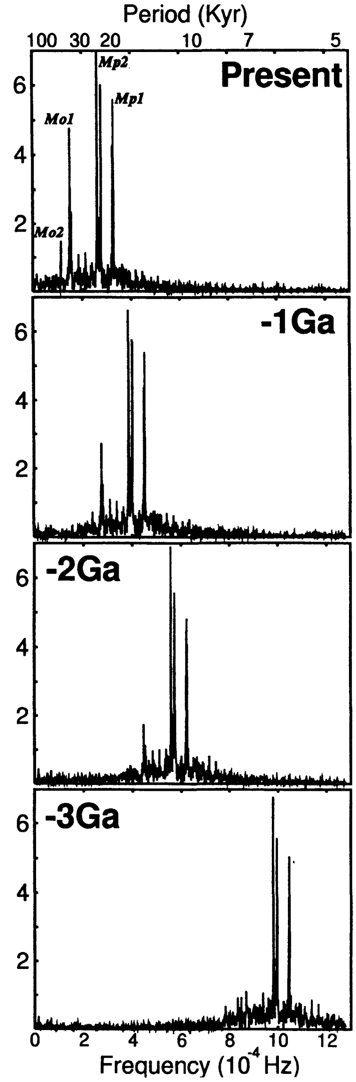
where A and C are the polar and the equatorial moment of inertia of the earth, n is the earth's mean motion to the sun, e_m is the eccentricity of the moon's orbit, M_m and M_s is the mass of the moon and the sun, a_m and a_s is the length of the semimajor axis of the moon's orbit and the earth's orbit, and i_m is the inclination of the moon's orbit relative to the orbit of the earth. We utilized the computational results of Abe *et al.* (1992) as the evolution of e_m and i_m. However the absolute values of e_m and i_m are originally so small that they have only slight effect on the change of the precessional constant α. Similarly $1 - {e_s}^2 \sim 1$ as a good approximation so actually we can consider that the precessional constant α is determined almost all by the relationship between three variables: dynamical ellipticity of the earth $\frac{C-A}{C}$, rotational angular velocity of the earth ω, and the earth-moon distance a_m. The changes of the earth-sun distance a_s and the masses M_s, M_m are not taken into account in this research.

Results and discussion. Below we show the calculational results of the evolution of the earth's rotational angular velocity ω and the earth-moon distance a_m by Abe *et al.* (1992) in Fig. 2. In Fig. 2(a) ω is replaced by LOD (Length of Day). Abe *et al.* (1992)'s method is completely numerical including the non-axis-symmetrical distribution of continents and oceans, and effect of the solar tide.

Table I. Origin of the present Milankovitch frequencies *Mp1*, *Mp2*, *Mo1*, and *Mo2* after Berger and Loutre (1987)

Peak	Frequency (arcsec/year)	Period (year)
Mp1	$k+g_4$=50.44+17.85	18977
Mp2	$k+g_5$=50.44+4.249	23697
Mo1	$k+s_3$=50.44−18.88	41064
Mo2	$k+s_6$=50.44−26.33	53753

Here $k \equiv \alpha \cos \overline{\theta} = 50.44$ (arcsec/year, present value), where $\overline{\theta}$ denotes the time averaged obliquity.



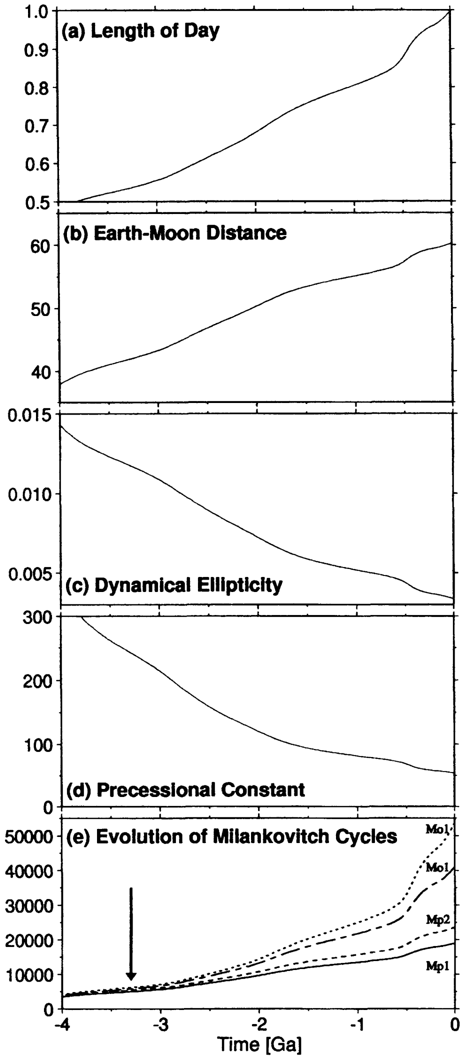


Fig. 1 (left). Power spectrum of the daily averaged solar insolation variation on 65°N at summer solstice, from −4 Ga to the present one. In the present one, notice on the peak of about 19 Kyr (*Mp1*), 23 Kyr (*Mp2*), 41 Kyr (*Mo1*), and 54 Kyr (*Mo2*). The major frequencies are all shorter at older era, and the power of the contribution of obliquity (*Mo1* and *Mo2*) are much lower than the present one. Each integration duration is four million years.

Fig. 2 (right). Transition diagram of the Milankovitch cycles including the dynamical evolution of the earth-moon system. (a) Length of Day (LOD, present value equals to the unity), (b) Distance between the earth and the moon (unit is the radius of the earth R_E). (a) and (b) are from the results of Abe *et al.* (1992). (c) Dynamical ellipticity of the earth (non-dimensional), (d) Precessional constant α (unit is arcsec/year), (e) Evolution paths of the major periods of the Milankovitch cycles *Mp1* (solid line), *Mp2* (dashed line), *Mo1* (dot-dash line), and *Mo2* (dotted line), the unit is year. (e) is the most important conclusion of this work.

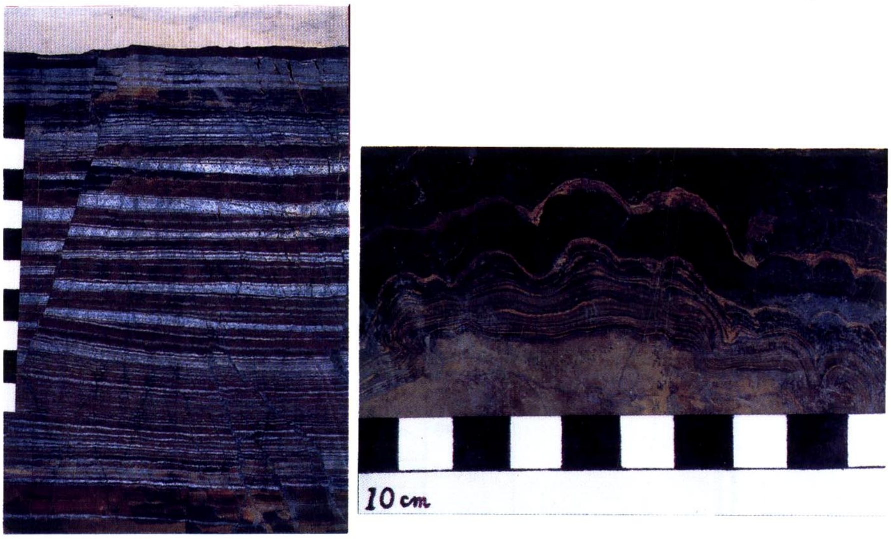


Fig. 3. (left) The banded iron formation from Creaverville, Australia. The firebrick colored bands consist of oxidized iron sediments and the white bands mainly consist of silica. Absolute age of the whole rock is estimated -3.3 Ga. There seems apparently a sharp dislocation from upper left to left side. (right) The stromatolite from Hamelin Pool, Australia. The unit of scale is centimeter. Though the way how they have been formed is still not clear, they must have some significant keys to decode the history of the surface environment of the earth.

Then we can calculate the motion of the rotational axis of the earth by solving the equation of motion (1) and obtain ancient Milankovitch cycles. Fig. 1 is the results, showing the power spectrum of daily average insolation of summer solstice at 65°N from -4 Ga to the present age. Of course we can directly integrate the equation of motion (1) as shown in Fig. 1 and digitize the peak frequencies manually, but typical frequencies of the Milankovitch cycles are known to consist of linear combinations of the fundamental frequencies of planetary perturbation g_i and s_i, and precessional constant α (Berger and Loutre, 1987). In this paper we concentrated on the four peak frequencies (*Mp1*, *Mp2*, *Mo1*, *Mo2*) described in Table 1 and traced their evolution back to -4 Ga. The results are summarized in Fig. 2(e). We can see that the major periods of Milankovitch cycles *Mp1*, *Mp2*, *Mo1*, and *Mo2* were much shorter in ancient ages.

There is another point here to notice. In the diagrams of Fig. 1, power of the obliquity term (*Mo1* and *Mo2*) of -3 Ga is apparently much lower than that of the present age. Magnitude of gravitational torque is much larger at -3 Ga than the present so the amplitude of obliquity oscillation is suppressed (cf. Ward (1974)). This is the reason why the power of *Mo1* and *Mo2* becomes low in ancient times (Fig. 1 lower two ones).

Shorter cycles of insolation variation must have made the surface climate system of ancient earth different from the present situation. Recently it became possible to obtain some geological observational data such as the striped banded iron formation (BIF) or the stromatolite (Fig. 3). The formation age of BIF in Fig. 3 are supposed to be -3.3 Ga (the solid arrow in Fig. 2(e)). Although the exact mechanism of the BIF formation is not known, these periodic and modulated striped bands indicate the presence of environmental variation with plural periods, hence they are believed to form either or both by the lunar tides and the solar insolation variation. These data imply that we can establish the standard time scale for measuring the relative age, in other words, the lap time clock or the chronometer for decoding the whole history of the earth by comparing the striped bands on BIF or stromatolite of Archean or Proterozoic with a set of theoretical Milankovitch cycle and tidal cycle frequencies. Since the Milankovitch cycles must have been playing an significant role in the climate change on the earth, what we did in this discussion indicates one possibility of the co-evolution of the Milankovitch cycles and the earth-moon system.

Acknowledgments. The authors are greatly indebted to Mr. Hideyoshi Yoshioka of Nagoya University for his special courtesy and helpful advice about taking the photographs of BIF and stromatolite. We also wish to express our appreciation to Dr. Syun-iti Akimoto, M. J. A., whose detailed and constructive reviews have considerably improved the presentation of this paper.

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