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a climate regulator for the Earth

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According to Milankovitch theory, the ice ages of the Quaternary, are related to the variations of insolation in the northern latitudes resulting from orbital and orientation changes of the Earth under long term planetary perturbations[1,2].

We have investigated the global problem of the stability of the orientation of the Earth for all possible values of the initial obliquity. We found a large chaotic zone in the phase space which extends from 60° to 90° and results from overlapping of secular resonances. In its present state, the Earth avoids this large chaotic zone and its obliquity is essentially stable. But if the Moon were not present, the torque exerted on the Earth would have been smaller, and the chaotic zone would have extended from nearly 0°, up to about 85°. This would have changed drastically the climate on the Earth. It can thus be claimed that the Moon acts as a climate regulator for the Earth, by maintaining its path outside from this large chaotic zone. Moreover, this study gives some new light on the origine of the obliquity of the Earth and on the possible origine of the Moon.

The general precession in longitude ψ, and the obliquity of the date ε are determined by the motions of the equatorial and ecliptic pole. The precession equations are written by using the action variable $X = \cos\varepsilon$ and the associated angle variable ψ. Let us denote $p = \sin(i/2)\sin(\Omega)$, $q = \sin(i/2)\cos(\Omega)$, ($i$ is the inclination of the Earth with respect to a fixed ecliptic, and Ω

the longitude of the node), the equations of precession[3–5] can be written

$$\frac{d\psi}{dt} = T(X,t) - \frac{X}{\sqrt{1-X^2}}\big(\mathbf{A}(t)\sin\psi + \mathbf{B}(t)\cos\psi\big)$$
$$\frac{dX}{dt} = \quad -\sqrt{1-X^2}\big(\mathbf{B}(t)\sin\psi + \mathbf{A}(t)\cos\psi\big)$$

with

$$T(X,t) = C_1X + C_2(2X^2-1)/(1-X^2) + C_3(6X^2-1) + C_4S_0X - 2\mathbf{C}(t) - p_g$$

and

$$\mathbf{A}(t) = 2\ \left(\dot{q} + p(q\dot{p} - p\dot{q})\right)/\sqrt{1-p^2-q^2}$$
$$\mathbf{B}(t) = 2\ \left(\dot{p} - q(q\dot{p} - p\dot{q})\right)\sqrt{1-p^2-q^2}$$
$$\mathbf{C}(t) = (q\dot{p} - p\dot{q})$$

The coefficient C_i and the geodetic precession p_g depend on the orbital parameters of the Moon and the Sun (C_1 = 37.526603 ″/yr, C_2 = −0.001565 ″/yr, C_3 = 0.000083 ″/yr, C_4 = 34.818618 ″/yr, p_g = 0.019188 ″/yr). We have also $S_0 = (1-e^2)^{-3/2}/2 - 0.522\ 10^{-6}$ where e is the eccentricity of the Earth[4]. The initial conditions for the Earth are $\dot{\psi}(t=0)$ = 50.290966 ″/yr, $\varepsilon(t=0)$ = 23°26′21.448″. These equations can be associated with the hamiltonian depending on time

$$H(X,\psi,t) = T(X,t) + \sqrt{1-X^2}(\mathbf{A}(t)\sin\psi + \mathbf{B}(t)\cos\psi)$$

where

$$T(X,t) = (C_1 + S_0C_4)/2\ X^2 - C_2X\sqrt{1-X^2} + C_3(2X^3 - X) - (2C + p_g)X$$

In order to understand the dynamics of this hamiltonian, its small terms ($C_2, C_3, p_g, \mathbf{C}(t)$) can be neglected, although they will be taken into account during the numerical computations. We shall also neglect the eccentricity of the Earth and the Moon as well as the inclination of the Moon. In this case, $C_1 = (C - A)/C \times 3n_M^2 m_M/2\nu, S_0 = 1/2$, $C_4 = (C - A)/C \times 3n_\odot^2 m_\odot/\nu$, where ν is the angular velocity of the Earth, $(C - A)/C$ its dynamical ellipticity (which is proportional to ν^2), n_M and m_M, the mean motion and mass of the Moon, and $n_\odot$ and $m_\odot$ the same quantities for the Sun. The hamiltonian then reduces to

$$H(X, \psi, t) = \frac{1}{2}\alpha X^2 + \sqrt{1 - X^2}(\mathbf{A}(t)\sin\psi + \mathbf{B}(t)\cos\psi)$$

with $\alpha = C_1 + S_0 C_4$. The expression $\mathbf{A}(t) + i\mathbf{B}(t)$ (as well as the eccentricity e of the orbit of the Earth), will be given by the La90 solution of Laskar[5]. The solution of the orbital motion of the Earth being chaotic[7-10], a quasiperiodic approximation of $\mathbf{A}(t) + i\mathbf{B}(t)$ is not well suited for obtaining accurate solution over a few millions years, but will be useful for a qualitative understanding of the behavior of the solution. In the Fourier spectrum of $\mathbf{A}(t) + i\mathbf{B}(t)$ (Fig.1) we can observe peaks which are well identified as the main planetary secular frequencies in inclination. Around each of these main peaks, several secondary peaks appear, which reflect largely the non regular behaviour of the solution. A frequency analysis[6,11,12] of $\mathbf{A}(t) + i\mathbf{B}(t)$ can be performed in order to find a quasiperiodic approximation of this function over a few million years on the form

$$\mathbf{A}(t) + i\mathbf{B}(t) \approx \sum_{k=1}^{N} \alpha_k e^{i(\nu_k t + \phi_k)} \ .$$

With this approximation, the hamiltonian now reads

$$H = \frac{1}{2}\alpha X^2 + \sqrt{1 - X^2} \sum_{k=1}^{N} \alpha_k \sin(\nu_k t + \psi + \phi_k) \ ,$$

which is the hamiltonian of an oscillator of frequency αX, perturbed by a quasiperiodic external oscillation with several frequencies ν_k. Resonance will occur when $\dot{\psi} \approx \alpha X = \alpha \cos \varepsilon$ will be opposite to one of the frequency ν_k.

The value for the mean precession speed of the Earth over 18Myr is $\dot{\psi}_M = 50.4712\ ''/\text{yr}$. This value is very close to the opposite of a small term due to the perturbations of Jupiter and Saturn $s_6 - g_6 + g_5 = -50.3021\ ''/\text{yr}$. Indeed, the passage through resonance can occur during an ice age, and can lead to an increase of 0.5 degree in the variations of the obliquity[5]. Nevertheless, the Earth is far from the main planetary resonances, the closest being $s_6 = -26.3302\ ''/\text{yr}$. With the current value of α, we can estimate that this resonance is reached for an obliquity of about 60°.

In order to investigate the stability of the obliquity of the Earth, we have integrated the equations of precession over 18 Myr for all values of the initial obliquity ε_0, every 0.1°, from 0° to 170°. The perturbation effect of the solar system is taken into account by using the secular La90 solution for the Earth. We used the frequency analysis method developped by Laskar[6,11,12] for the analysis of the obliquity and precession. Briefly speaking, this method consists to define for each orbit a frequency vector by a refined Fourier analysis over a finite time span. The regularity of the orbits can then be analyzed in a very precise way by the study of the regularity of the frequency application which goes from the action like variables to the frequency space. In Fig.2a, the precession frequency p is plotted against the initial obliquity ε_0, for a fixed value of the initial precession ψ_0. From $\varepsilon_0 = 0$ to $\varepsilon_0 = 60°$, the frequency curve is very regular, and reflects the regular behavior of the solution. Then, a large chaotic zone extends from 60° to 90°. For higher values of the obliquity, the precession frequency becomes negative: the possible resonances are much smaller, and the motion is again very regular. On Fig.2b, for each integration, the minimum, maximum, and mean values of the obliquity reached during the 18 Myr of the integration are given. Thus, if the obliquity goes to 60°, then in a few million years, it can reach 90°, only due to the planetary secular perturbations.

In a recent work[5], we have suppressed the Moon, keeping the present values for the Earth parameters. Due to the reduction of the torque exerted on the Earth ($C_1 = C_2 = C_3 = 0$), the precession frequency goes down to about 15.6 $''$/yr, which becomes very close to the opposite value of the leading frequencies of $\mathbf{A}(t) + i\mathbf{B}(t)$. As was forecasted by Ward[13], this led to large variations of the obliquity (from 15° to 32° in 1Myr).

Now we want to understand the possible dynamics of the very early stages of the Earth, in the hypothesis that the Moon was not present at the time. In this case, due to tidal dissipation, the rotation of the Earth was faster, as can attest the geological records[14] which give $\nu \approx 1.22\ \nu_0$ for -2.5 Gyr. We analyzed the variations of the obliquity for this value of the Earth rotation (Fig.3). In this case, the chaotic region becomes very large, and extends from 0° to about 80°. Even if the initial obliquity is very small, then in a few millions years, it can reach more than 50°. Even more, the frequency analysis shows the possibility of diffusion up to about 80°, although this diffusion may be slow.

For a higher rotation speed of $\nu = 1.6\ \nu_0$, which may have existed at -4.5 Gyr, a large resonant zone appears, corresponding to the node secular mean rate of Jupiter and Saturn ($s_6 = -26.3302\ ''/yr$) (Fig.4). For zero initial obliquity, we found variations, of about 10°, but as soon as the initial obliquity reaches 4°, the motion can enter in the chaotic zone surrounding the resonant island, and show variations of more than 30° in a few millions years, with the possibility of further diffusion up to more than 85°.

Several important issues can be briefly summarized:

Even if the initial obliquity of the Earth, at the early stage of its formation was very small, resonances or chaotic behavior of the obliquity of the Earth can raise it up to 50° in a few millions years, with mean value from 20° to 30°. Then, if the Moon is captured, the precession frequency will suddenly increase, and the motion will become very regular. The value of the obliquity will be freezed to its current value and will then suffer only small oscillations, until tidal dissipation[13] ultimately drives the Earth into the large chaotic zone.

Contrary to Ward[13], it can be claimed that the Moon is a climate regulator for the Earth: If it were not present, the Earth obliquity would be chaotic and would reach values of more than 50° in a few millions years and may even, in a longer time, reach more than 85°. This would have changed drastically the climate on the Earth, and would have probably prevented the appearance of organized live.

The application to other planets in the solar system may give some explanation of their obliquity, involving only secular planetary perturbations.

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Figures Captions

Fig. 1 Fourier spectrum of $\mathbf{A}(t) + i\mathbf{B}(t)$ over 17 Myr. Only the main secular frequencies of the solar system can be identified, as well as the small isolated term $s_6 - g_6 + g_5$.

Fig. 2 The frequency analysis over 18 Myr of the precession of the Earth under lunar and solar torque for all values of the initial obliquity (ε_0) (a) shows the existence of a large chaotic zone from about 60° to 90°. (b) Maximum, mean, and minimum obliquity reached during 18 Myr .

Fig.3 If the Moon were not present, the chaotic zone revealed by the frequency analysis over 18Myr (a) extends from 0° to about 85°, for a rotation velocity of the Earth $\nu = 1.22\nu_0$, where ν_0 is the present rotation velocity of the Earth. (b) Maximum, mean, and minimum obliquity reached during 18 Myr.

Fig. 4 For $\nu = 1.6\nu_0$, the large chaotic zone extends from nearly 0° to about 85°. In the region of low obliquity, there exist a large island corresponding to resonances with the secular frequency $s_6 = -26.3302$ ″/yr of the node of Jupiter and Saturn (a), which is also visible on (b).

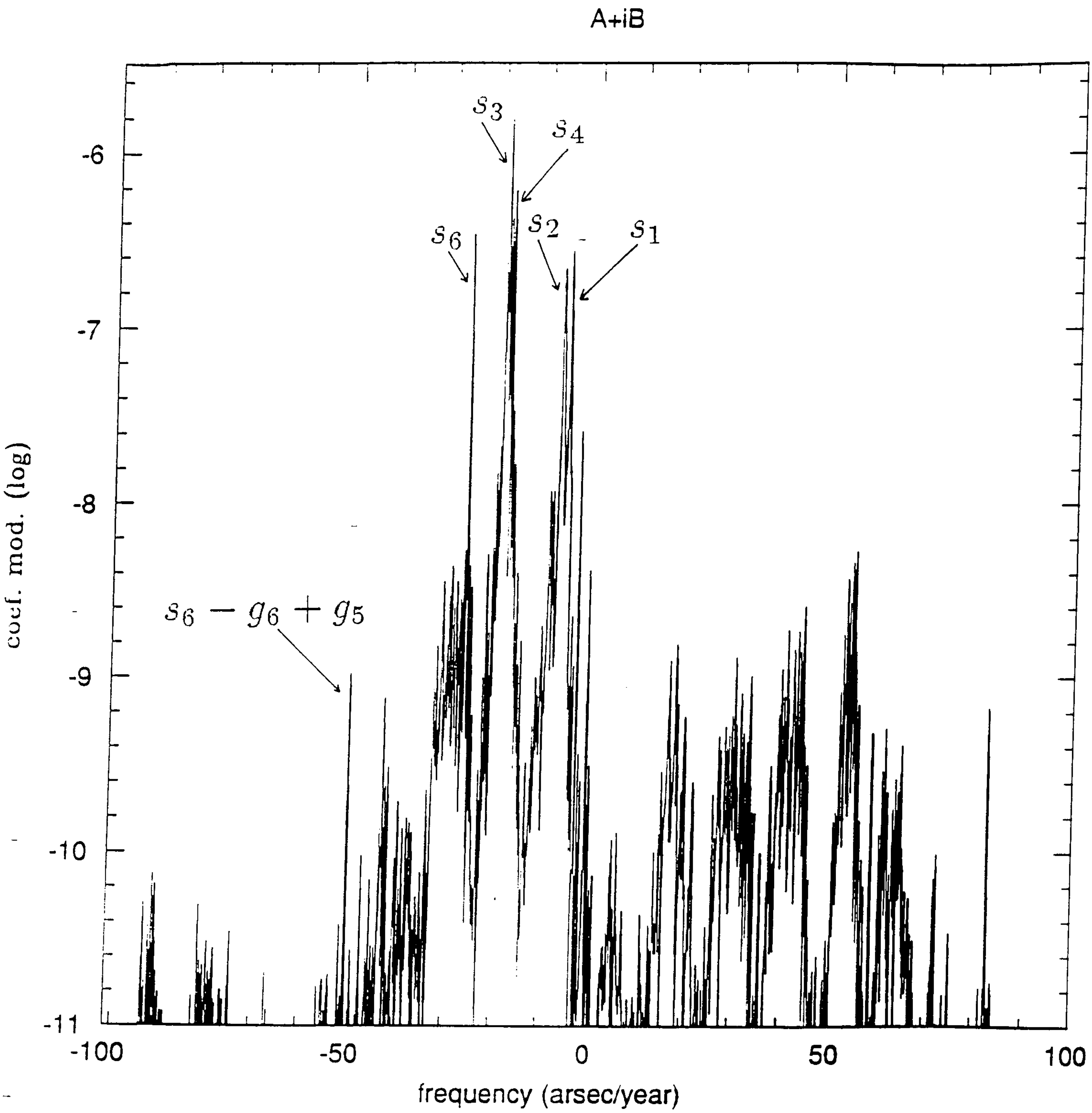
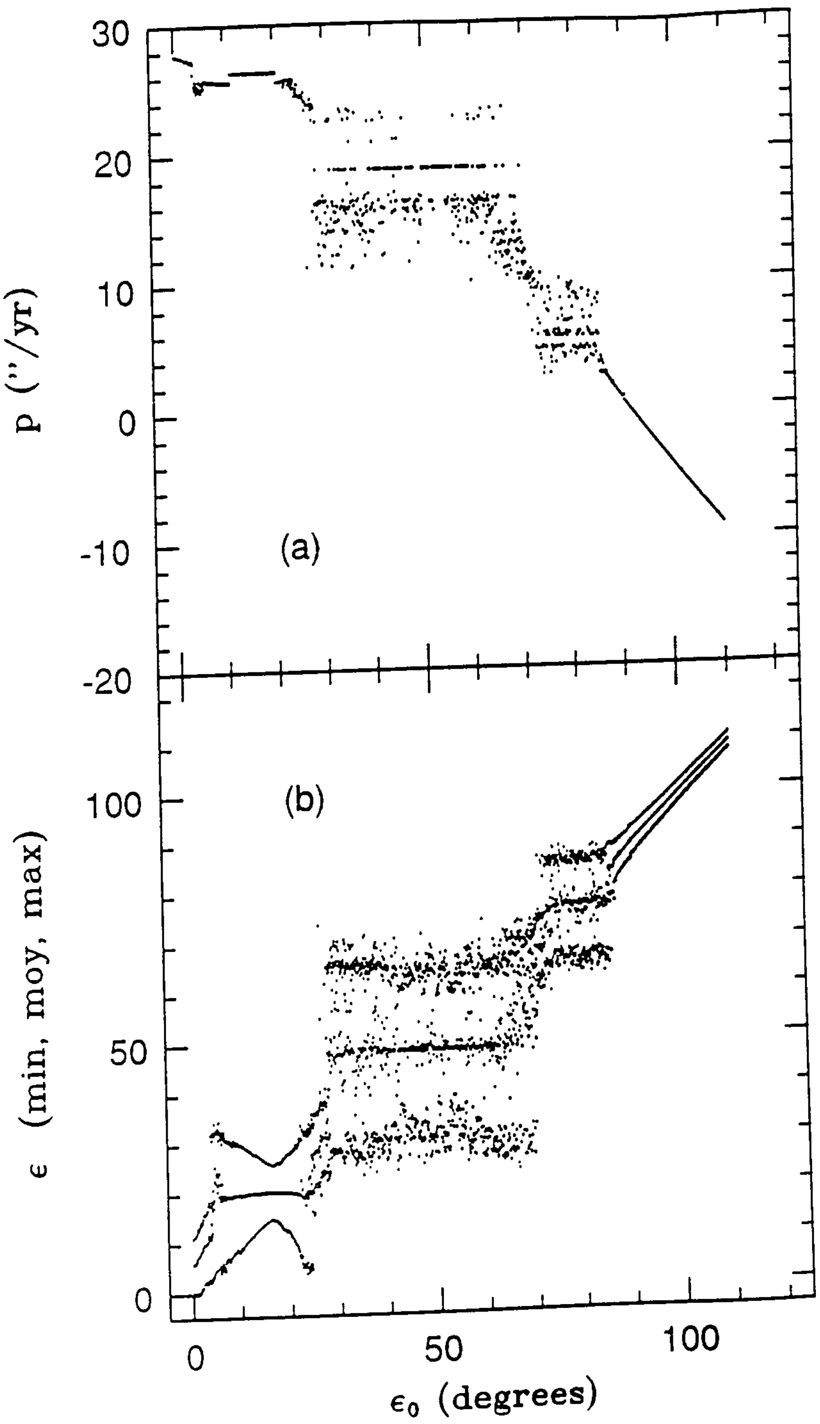

A+iB
s_3
s_4
s_6
s_2
s_1
$s_6 - g_6 + g_5$
coef. mod. (log)
-6
-7
-8
-9
-10
-11
-100
-50
0
50
100
frequency (arsec/year)

Fig 1



p (''/yr)
30
20
10
0
-10
-20
(a)
ε (min, moy, max)
100
50
0
(b)
0
50
100
ϵ_0 (degrees)

Fig 4

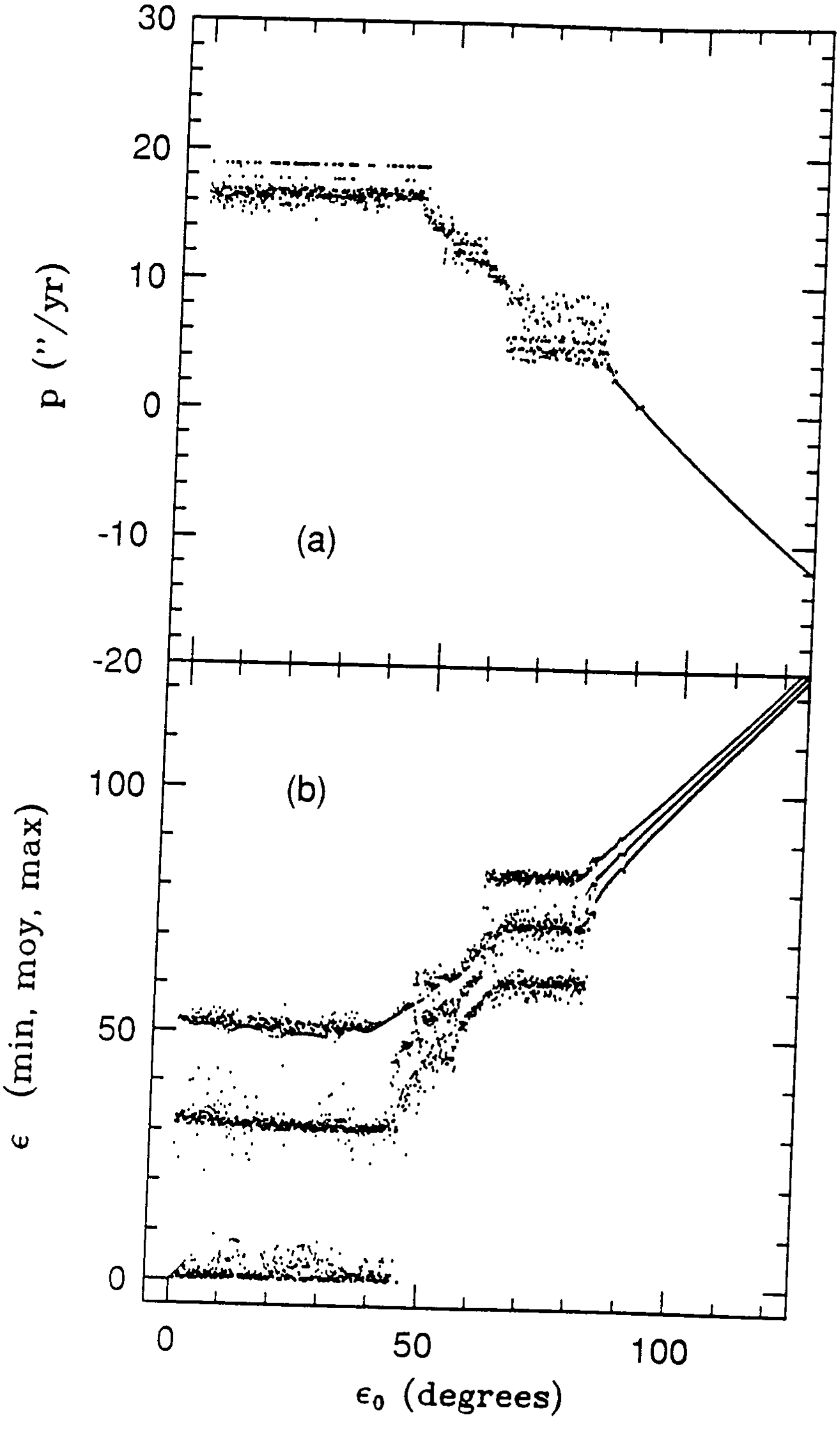


Fig 3
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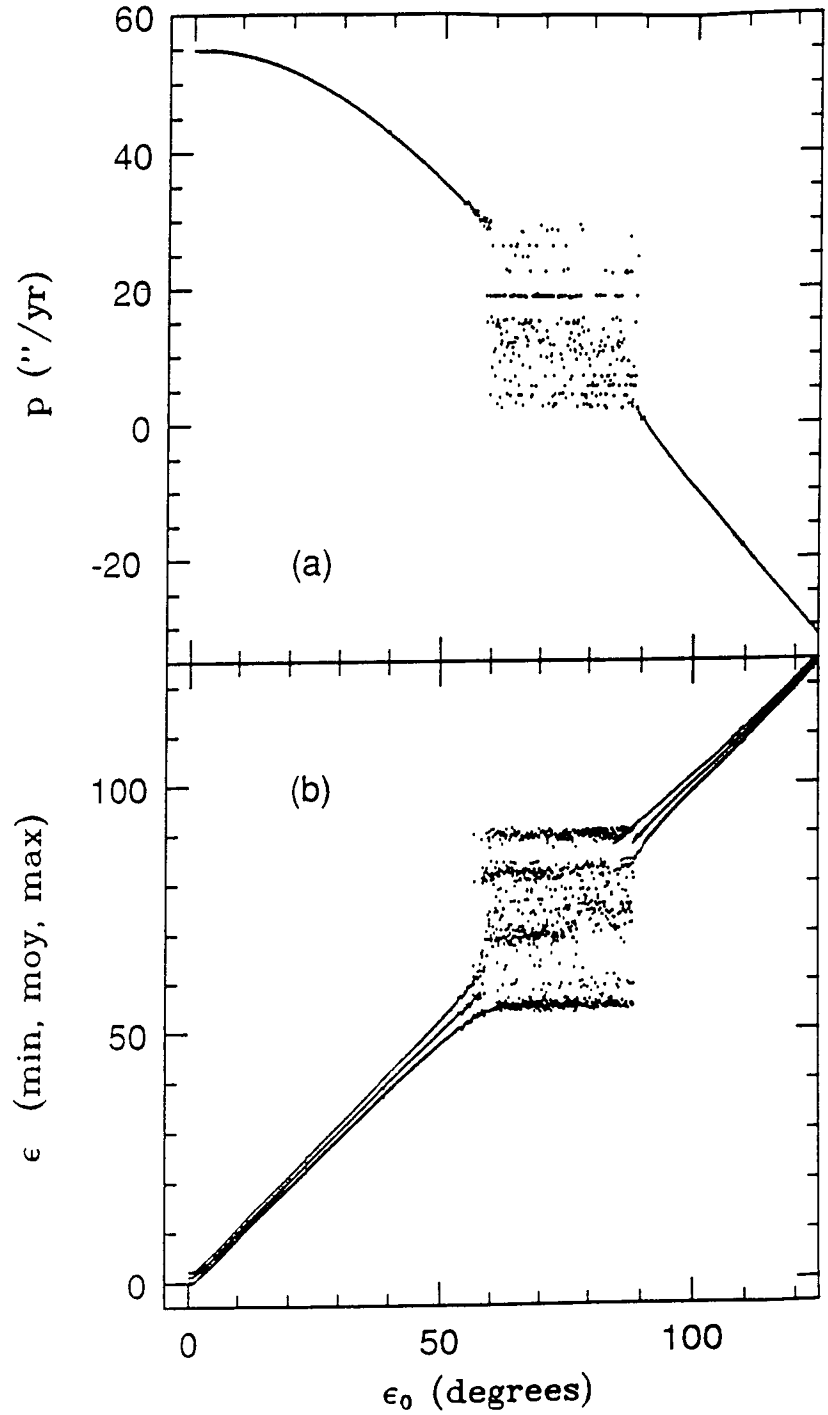

Fig 2