Reports

Mars: Change in Axial Tilt Due to Climate?

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The average tilt of Mars' equator with respect to its orbital plane may have increased significantly over the age of the solar system. Obliquity oscillations might have induced changes in the climate, which altered the mass distribution and hence the solar torque on the planet. Viscous deformation attributable to loading by the large polar caps expected at low obliquity may have induced secular changes in the axial tilt. Earth-like effective viscosities can account for virtually the entire present obliquity of 24.4 degrees. Thus the present average tilt of Mars may not be primordial.

Ward and co-workers (*1–4*) have shown that the obliquity of Mars, the angle between its orbital and equatorial planes, oscillates on a hundred thousand–year time scale. The amplitude of the Ward oscillations can reach ±13° about a mean value of 24.4° (*3*). There are also mechanisms that can change the mean value (*4–6*). One example is the rise of the Tharsis bulge, which could have decreased the average obliquity by 7° (*4*). Another is "seasonal friction," analogous to tidal friction, caused by the waxing and waning of the polar caps (*6*). The caps are out of phase with the sun, causing a net solar gravitational torque on the planet when averaged over one Martian year. The effect on the obliquity is small, amounting to a probable increase of only 1° or 2° over the age of the solar system.

The purpose of the present investigation is to explore what might be called "climate friction," which is similar to seasonal friction but operative over the hundred thousand–year time scale. The basic idea is that the Ward oscillations induce climatic changes on Mars, which alter its mass distribution. The solar torque on the rearranged mass then secularly shifts the tilt of the planet. This mechanism may be capable of changing Mars' obliquity by an amount on the order of the obliquity itself, depending on the internal structure of the planet.

Let Θ be the obliquity and φ the precession angle; then (*2*):

$$\dot{\varphi} = -\alpha \cos\Theta - \dot{\Omega} (\cos I - \sin I \cot\Theta \sin\varphi) + \dot{I}(\cot\Theta \cos\varphi) \quad (1)$$

$$\dot{\Theta} = -\dot{\Omega}(\sin I \cos\varphi) + \dot{I}(\sin\varphi) \quad (2)$$

where I is the inclination of Mars' orbit with respect to the invariable plane, Ω is the ascending node, and the dot denotes the time derivative. Also,

$$\alpha = 3J_2 n^2/(2\lambda\dot{\theta}) = 8.3 \text{ arc sec year}^{-1} \quad (3)$$

where the usual spherical harmonic coefficient $J_2 = (C - A)/(MR^2) = 1.955 \times 10^{-3}$ is a measure of the flattening of the planet, caused mostly by rotation. Here $M = 6.4 \times 10^{23}$ kg is the mass and $R = 3390$ km is the radius of Mars, with C and A being the polar and equatorial moments of inertia, respectively. Also, $\dot{\theta} = 7.09 \times 10^{-5}\ s^{-1}$ is the angular speed of Mars about its axis, $n = 1.06 \times 10^{-7}\ s^{-1}$ is the mean motion about the sun, and $\lambda = C/(MR^2) = 0.365$.

I investigate a simple solution to Eqs. 1 and 2 by assuming that $I = 3.6°$ and $\dot{\Omega} = -17.8$ arc sec year^{-1}, since these values dominate the celestial mechanics at the present time (*3*). Thus I can write

$$\dot{\varphi} = -[\alpha \cos\Theta + \dot{\Omega} (\cos I - \sin I \cot\Theta \sin\varphi)] \quad (4)$$

$$\frac{d\Theta}{d\varphi} = \frac{\dot{\Omega} (\sin I \cos\varphi)}{(\alpha \cos\Theta + \dot{\Omega} \cos I) + \dot{\Omega} \sin I \cot\Theta \sin\varphi} \quad (5)$$

where I have divided Eq. 2 by Eq. 1 to get Eq. 5. If I now set $\omega = -(\alpha \cos\Theta^* + \dot{\Omega} \cos I) = 10.3$ arc sec year^{-1} (where Θ^* is the mean obliquity) and integrate Eqs. 4 and 5, I obtain $\varphi \cong \omega t$ and $\Theta \cong \Delta\Theta + \Theta^*$, where $\Delta\Theta \propto \sin\varphi$ is the principal term of the Ward oscillation (*3*).

In the above derivation, it is assumed that J_2 is fixed. I now examine the case where it is not and write $J_2 = J_2^0 + \Delta J_2$, where J_2^0 is constant and

$$\Delta J_2 = \Delta J_2^0 \sin(\varphi - \xi) \quad (6)$$

is the change in J_2 induced by the climatic changes. ΔJ_2^0 is also a constant. This equation assumes that ΔJ_2 is proportional to $\Delta\Theta$, lagged by an angle ξ. Substituting Eq. 6 into Eq. 5 and assuming $\Delta J_2 << J_2$ gives, by a binomial expansion, a secular rate of change in Θ:

$$\frac{d\Theta}{d\varphi} \cong \left(\frac{3n^2}{4\lambda\dot{\theta}}\right) \frac{(\dot{\Omega} \sin I \cos\Theta^*)}{\omega^2} \Delta J_2^0 \sin\xi \quad (7)$$

Remembering $d\varphi \cong \omega dt$ and integrating gives

$$\delta\Theta \cong -267 \times 10^6 \Delta J_2^0 \sin\xi \quad (8)$$

as the change in the obliquity (in degrees) after 4.55×10^9 years, the age of the solar system. The integration assumes that the right side of Eq. 7 is constant and evaluated for the current values of the parameters. A Runge-Kutta integration of Eqs. 1 and 2 with artificially large values of ΔJ_2^0 and ξ confirms the existence of the secular term derived above.

I will concentrate here on only one mechanism for changing the obliquity, namely, "postglacial rebound" on Mars. The idea is that at low obliquity the poles get very cold; CO_2 is desorbed from the Martian regolith and deposited onto gigantic polar caps (*7*). At high obliquity the reverse occurs; thus there is a cyclic process of growth and decay. The polar regions depress under the weight of the caps, squeezing out an excess equatorial bulge and increasing the J_2 of the solid planet; but the deformation is delayed because of the effective viscosity of Mars' mantle. Likewise, when the caps disappear, the excess bulge takes a finite time to collapse. Hence there is a phase lag in the solid part of the planet associated with the cap cycle.

I will limit the discussion to the simple case of a homogeneous planet with an effective viscosity η. The CO_2 ice will be modeled as a single spherical cap of radius Ψ centered on one of the poles. I will further assume that its mass fluctuates according to $-M_i \sin\varphi$, where M_i is a positive constant, so that the cap is largest at low obliquity. Any phase lag associated with the formation of the cap is presumed to be small (*8*), so that the cap itself plays no direct role in the obliquity change; its own ΔJ_2 need not be considered.

The solid planet, however, will lag in phase by

$$\tan\xi = 19\ \eta\omega/(2Rg\rho) \quad (9)$$

where $g = 3.73\ m\ s^{-2}$ is the gravitational acceleration at the surface and $\rho = 3933$ kg m^{-3} is the average density of Mars (*9*). This phase lag can be considerable, depending on the effective viscosity. Also for the solid

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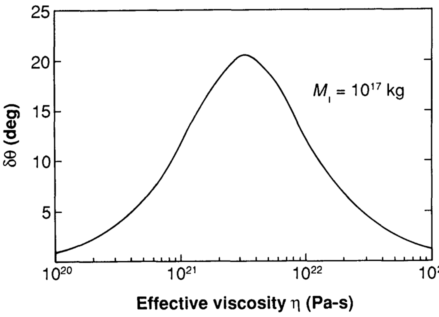

Fig. 1. Change in obliquity $\delta\Theta$ as a function of effective viscosity η for a cap radius of 10° and $M_i = 10^{17}$ kg. The total change in cap mass over one cycle is $2M_i$. Larger or smaller changes in mass shift the curve proportionally up or down. The instantaneous obliquity today is 25.2°, which is coincidentally near the present average of 24.4°.

planet

$$\Delta J_2^0 = -M_i(\cos\xi \cos\Psi)/M \qquad (10)$$

Viking spacecraft measurements indicate that $\sim 3 \times 10^{17}$ kg of CO_2 is flushed every 10^5 years from the megaregolith (*7, 10*). Such a vast reservoir of oxygen is needed to explain the lack of enrichment of ^{18}O relative to ^{16}O, as would be expected from exospheric escape. I will adopt an estimate of $M_i = 10^{17}$ kg, with $\Psi = 10°$ (*7*).

The effective viscosity of Mars' mantle is not known; the change in obliquity for various viscosities based on Eqs. 8 through 10 is shown in Fig. 1. For comparison, the effective viscosity of Earth's upper mantle is about 10^{21} Pa-s (*11*). Values only slightly higher than Earth's account for nearly the entire obliquity of the red planet.

Mars is less active tectonically than Earth, so that one might expect a cooler interior and a higher viscosity. On the other hand, experimental studies (*12*) indicate that the effective viscosity of Mars may be 4×10^{20} Pa-s or less (for tectonic loads on the order of 100 bars, rather than the more modest $\sim$1 bar for the massive caps). Thus the range of viscosities shown in Fig. 1 does not appear to be unreasonable, and the axial tilt of Mars may have changed significantly over the age of the solar system. This could have important implications for the paleoclimate of this planet.

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13. I thank S. Blackwell for programming support and two anonymous referees for their corrections and criticisms. T. Clark's suggestion of looking for seasonal changes in J_2 with the Mars Observer ultimately led to the present investigation.

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Spatial Variation of Ozone Depletion Rates in the Springtime Antarctic Polar Vortex

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An area-mapping technique, designed to filter out synoptic perturbations of the Antarctic polar vortex such as distortion or displacement away from the pole, was applied to the Nimbus-7 TOMS (Total Ozone Mapping Spectrometer) data. This procedure reveals the detailed morphology of the temporal evolution of column O_3. The results for the austral spring of 1987 suggest the existence of a relatively stable collar region enclosing an interior that is undergoing large variations. There is tentative evidence for quasi-periodic (15 to 20 days) O_3 fluctuations in the collar and for upwelling of tropospheric air in late spring. A simplified photochemical model of O_3 loss and the temporal evolution of the area-mapped polar O_3 are used to constrain the chlorine monoxide (ClO) concentrations in the springtime Antarctic vortex. The concentrations required to account for the observed loss of O_3 are higher than those previously reported by Anderson *et al.* but are comparable to their recently revised values. However, the O_3 loss rates could be larger than deduced here because of underestimates of total O_3 by TOMS near the terminator. This uncertainty, together with the uncertainties associated with measurements acquired during the Airborne Antarctic Ozone Experiment, suggests that in early spring, closer to the vortex center, there may be even larger ClO concentrations than have yet been detected.

MAN-MADE HALOCARBONS HAVE been generally recognized as the cause of enhanced springtime O_3 depletion in the Antarctic stratosphere (*1–7*). However, the detailed description of O_3 loss rates in the "O_3 hole" needed for testing the theories quantitatively is not known. The most comprehensive global and temporal O_3 data set is the TOMS data obtained by the Nimbus-7 spacecraft since 1978 (*2, 8*). This instrument derives high-quality total column O_3 (precision ~1%) from backscattered sunlight in several ultraviolet channels. Daily data sets are available for 1979 through 1989 with latitude and longitude resolutions of 2° and 5°, respectively, covering the whole globe except for the unilluminated winter poles, where data collection is impossible. It is difficult to extract from these data information on the spatial dependence of the O_3 loss rate in spring within the polar vortex for two reasons. First, the center of the O_3 hole (as defined by the minimum O_3 isopleth) does not stay fixed at the South Pole. It may wander off the pole by as much as 10° in a few days. Second, the

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