FORMATION OF THARSIS AND THE OBLIQUITY HISTORY OF MARS

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It has been suggested (1) that, prior to formation of Tharsis, the obliquity of Mars may have undergone very large periodic variations due to a resonance between the axial and orbital precession rates. This hypothesis has remained largely unchallenged and has recently been invoked as a major factor in the climatic evolution of Mars (2,3,4). While the secular resonance idea remains an attractive possibility, an attempt to assess the likelihood that the appropriate conditions were actually satisfied seems warranted.

The primary basis for the secular spin orbit resonance idea consists of two simple observations. The first is that an estimate of the present axial precession rate 7.47 arcsec/yr lies between two of the eigenfrequencies for orbital precession (5); 6.77 and 7.75 arcsec/yr. The second observation is that estimates (6,7) of the contribution Tharsis makes to the gravitational oblateness of Mars, taken at face value, suggest that prior to the formation of Tharsis the axial precession rate might have been in exact resonance with the slower of the two orbital terms.

In order to assess the plausibility of this notion, we need to examine each of its elements in turn. The axial precession rate is simply $\alpha \cos(\theta)$, where θ is the obliquity and

$$\alpha = \frac{3}{2} \frac{GM_S}{\omega a^3} \frac{J_2}{\lambda}$$

where a is the orbital semimajor axis, M_S is the solar mass, G is the gravitational constant, ω is the spin rate, $J_2 = [C - (A+B)/2]/MR^2$ is the gravitational oblateness, M and R are the mass and radius of Mars, $A < B < C$ are the principal moments of inertia, and $\lambda = C/MR^2$. The specific resonance scenario proposed in (1) depends on three basic premises, all three of which appear at least somewhat suspect. The premises are: the orbital precession frequencies have not changed appreciably (~1%) since the formation of Tharsis (probably 3-4 billion years), whereas the growth of Tharsis changed the axial precession rate via a 6% increase in J_2, while λ stayed fixed at what is presumed to be its present value.

Of the quantities determining the present axial precession rate, the least well known is λ. For bodies in hydrostatic equilibrium, there is a unique relationship between J_2 and λ. To lowest order (8),

$$\frac{3\lambda}{2} = 1 - \frac{2}{5}\left\{\frac{4m - 3J_2}{m + 3J_2}\right\}^{1/2}$$

where $m = \omega^2 R^3/GM$ is the ratio of centifugal to gravitational acceleration. For a body as oblate as Mars, the higher order terms are quite negligible. The real difficulty is that Mars is clearly not in hydrostatic equilibrium. If it were, the two equatorial moments would be equal. Thus, as a first approximation, we may assume that B-A is a good estimate of the nonhydrostatic component of C-(A+B)/2. This, indeed is the basic assumption required to obtain the currently accepted estimate of $\lambda = 0.365$ (6,7). However, B-A actually serves better as a lower bound to the nonhydrostatic component. For both the Moon (9) and Venus (10) where the moment differences are well known and clearly nonhydrostatic, the intermediate principal moment B is approximately midway between A and C. If the same is true of Mars, the nonhydrostatic correction is closer to 1.5(B-A), and this yields $\lambda = 0.360$. For the Earth, the nonhydrostatic part of the oblateness is even larger compared to the equatorial moment difference (11); 2.4(B-A). Using that as a guide to Mars, we would obtain $\lambda = 0.350$. This would imply a present axial precession rate of 7.79 arcsec/yr, which is faster that either of the putative resonant rates. The main point here is that uncertainty in the present value of α due to uncertainty in λ is nearly as large as the putative effect of the formation of Tharsis via a change in J_2.

The notion that the oblateness of Mars changed during the formation of Tharsis seems reasonable enough, but quantification of the effect is rather difficult. A wide range of models for the present structure and formation processes have been proposed (12,13,14,15) and their effects on oblateness are likely to be quite different. At the very least, it seems unlikely that Mars was in perfect hydrostatic balance before Tharsis formed. Thus the nonhydrostatic component of J_2 (if it were known) might be a rather poor estimate of the Tharsis contribution. A further complication arises in scenarios where differentiation of the planet (which will mainly effect λ) overlaps in time with the formation of Tharsis (which will mainly effect J_2). Recall that it is the ratio of these two parameters which determines the axial precession rate.

While analytic secular variation models for the orbital elements give quite reasonable approximations to planetary motion for periods as long as 10^6 years (16), recent work suggests that even on time scales of 10^7 years (17) and certainly on time scales of 10^8 years (18), even the outer planets exhibit behaviors not well approximated by the secular theories. Thus the supposition that the orbital precession frequency spectrum of Mars has changed by less than 1% over several 10^9 years seems entirely unwarranted.

The Mars Observer mission will allow determination of the second degree harmonics of the gravity field with sufficient accuracy that the orientation of the axis of greatest inertia will be resolved to ~1 arcsec accuracy each time the subspacecraft position makes a complete circuit in longitude (on average, every 41 days). This will allow detection of the axial precession, but will only produce an estimate of the precession rate with useful accuracy (~2%) if the observations are continued for ~5 years.

References

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