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Polar Wandering on Mars?

Abstract. *Polar wandering during the past 10^8 years may be recorded by unique quasi-circular structures in the polar regions of Mars. Polar wandering on Mars is likely if deep convection is involved in the origin of the very large constructional volcanic features located near the equator. The magnitude of the nonhydrostatic low order components of the gravity field and their correlation with the equatorial volcanic features may be additional evidence of deep convection and associated polar wandering.*

Mariner 9 has revealed a variety of unexpected aspects of Mars. We speculate here that three of the most surprising may be related to the wandering of the spin axis of the planet.

To our knowledge, polar wandering has not been seriously anticipated on Mars, although the subject has been considered extensively for the earth (*1*). Goldreich and Toomre (*2*) have reinterpreted certain features of the earth's gravity field as indicative of internal conditions suitable for polar wandering. They argue that polar wandering may have come about as a result of the gradual redistribution of density inhomogeneities associated with the convective processes in the earth's mantle responsible for continental drift. In the case of Mars, internal heating just now may be reaching the point where convection processes are being initiated. Such a possibility was hinted at by Urey (*3*), and was suggested by the thermal models of Anderson and Phinney (*4*) and by more recent models of Anderson (*5*). Limited occurrences of "chaotic terrain" seen in the pictures returned by Mariner 6 and Mariner 7 were recognized as possible indications of recent internal activity (*6*).

Most conclusively, Mariner 9 has returned abundant and unambiguous evidence of extensive volcanic and tectonic activity over portions of the surface of Mars (*7, 8*). Thus, martian mantle convection now can be regarded as at least a reasonable possibility (*9*).

To us, the most suggestive evidence of polar wandering on Mars is found in the polar regions. There, peculiar quasi-circular topographic features are observed (Fig. 1). Such structures in the south polar area have been described by Murray *et al.* (*10*) and are believed to be roughly circular plates with outward sloping edges. The plates are composed of thin laminae of light and dark material (about 20 to 80 m thick) (*11*) and exhibit a profile at the edges which is convex outward, suggestive of ablation. The plates exhibit a surprising uniformity in width and the amount of progressive offset from one another. The laminated terrain and the associated quasi-circular topographic features are restricted to the area surrounding both poles, where carbon dioxide frost formation and disappearance take place on an annual basis. For this reason, the laminated terrain is believed to be genetically coupled to volatiles, perhaps still retaining a high percentage of volatiles mixed with eolian dust.

The concentric pattern of the topographic steps suggests to us an origin and evolution symmetrical to the past location of the spin axis of the planet. If volatiles act only as a collecting agent for atmospheric dust and are later lost by sublimation, the symmetrical orientation relative to the spin axis may reflect the annual stability boundaries of the volatile carbon dioxide. On the other hand, if the laminated terrain still contains large amounts of permanent carbon dioxide, such an orientation would be expected on the basis of equal average solar insolation (*12*). Either way, the former position of Mars' spin axis may be recorded by the centers of curvature of the displaced circular topographic features of the laminated terrain. The positions of the circular arcs and of their apparent centers of curvature are shown in Fig. 1, c and d. A maximum polar wandering of about 15° would be indicated by the plates clearly discernible. In addition, it appears that a vertical sequence of concentric plates is discernible at some places. There, an apparent time progression of the pole seems to be recorded as well. Figure 1, c and d, suggests a correspondence between the apparent fossil locations of the north and south poles, although differences in visibility and perhaps tectonic response may complicate the correlation.

Is there any other evidence about Mars suggestive of polar wandering? One of the greatest surprises presented by the Mariner 9 pictures was the discovery of extremely large constructional volcanic features near the equator in the longitude region 90° to 150°W (Fig. 2). These are similar in general morphology to shield volcanoes on the earth except that they are of considerably larger extent. The largest is identified with the classic albedo feature Nix Olympica and has been designated by that name. The three next largest lie along a northeast-southwest line centered near the equator, and were first seen as dark spots on the dust-shrouded planet in Mariner 9 preorbital photographs. They acquired the temporary descriptive names North, Middle, and South Spots, due to their appearance at that time. They are about 400 to 550 km in diameter and have heights of the order of 10 km. In addition, there are other less dramatic evidences of vulcanism scattered over the planet, but not over the whole surface nor in a uniform way. The existence of these constructional volcanic features raises an immediate question concerning polar wandering. Has the observed extensive extrusion of the surface mass introduced a rigid body nutation? For example, the Nix Olympica shield volcano (Table 1) represents a mass of perhaps 4×10^{-6} the mass of Mars. If this mass were supported by an entirely rigid planet, then a rigid body nutation of angle δ could be produced, described approximately by:

$$\frac{\tan\delta}{\sin\Phi\cos\Phi} = \frac{m}{M}\frac{MR^2}{C-A} = \frac{m}{M}\frac{3}{2J_2} = \frac{3}{2}\frac{4\times10^{-6}}{J_2} \quad (1)$$

where Φ is the latitude, m the mass of Nix Olympica, M the mass of Mars, R the radius of Mars, C and A principal moments of inertia, and J_2 the primary coefficient of the low order harmonics of the martian gravity field (*13*). If we assume that J_2 is about 2×10^{-3} (*14*)

$$\delta \sim 10^{-3} \sin 2\Phi \sim 0.04^\circ \quad (2)$$

Thus, rigid body nutation resulting solely from the uncompensated mass of all four large shield volcanoes would appear to be two orders of magnitude too small to account for the maximum polar wandering suggested by the quasi-circular features of the polar regions —if Mars is an entirely rigid planet.

Table 1. Data for some martian shield volcanoes. The mass of Mars is 6.4×10^{26} g. North latitude is positive and south latitude negative.

Volcano	Approximate diameter (km)	Latitude (deg)	West longitude (deg)	Approximate mass (g)
Nix Olympica	520	17.3	132.9	2.4×10^{21}
North Spot	375	11.6	104.6	1.3×10^{21}
Middle Spot	425	0.8	112.9	2.0×10^{21}
South Spot	400	−9.3	119.8	1.6×10^{21}

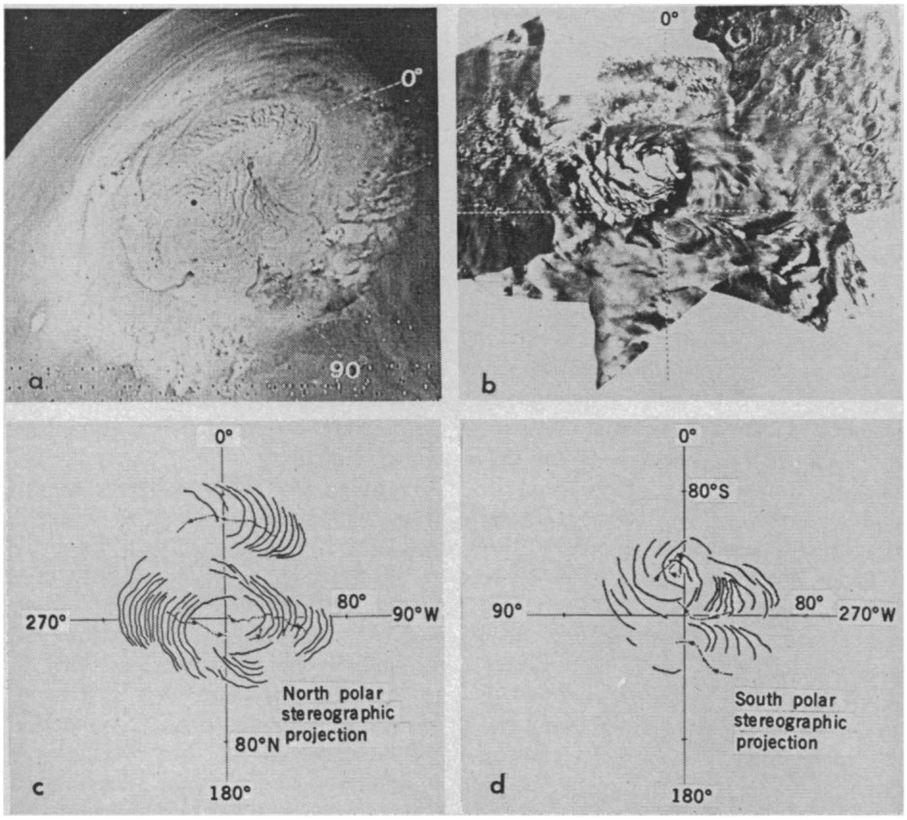

Fig. 1. The polar regions of Mars. (a) Oblique view of the martian north polar region, taken by Mariner 9 on 7 August 1972, from an altitude of 13,126 km. This photograph shows the shrinking frost cap at some 2000 km in diameter. Interior to the edge of the cap is a region of curved features which are the frosted laminated terrain plates. Individual laminae are too small to be seen on this scale. (b) Polar stereographic projection of the south polar region of Mars. The bright white residual polar cap is some 300 km long and offset from the present spin axis. The dark bands within the polar cap are believed to be the defrosted outward-facing edges of the plates. A comparison with (a) shows that the visibility of the laminated plates is a strong function of frost cover. (Rectification and scaling by the Image Processing Laboratory of the Jet Propulsion Laboratory.) (c) Polar stereographic line drawing of curvilinear features in the north polar region. (Solid lines) Edges of laminated terrain plates seen in the wide-angle camera coverage. (Dashed lines) Loci of centers of curvatures. (Arrows) Hypothetical motion of the spin axis if the curves are axially symmetric and associated with polar wandering. Note that the parallel motion in the quadrant 0° to 90°W gives rise to a valley-like structure. (d) Polar stereographic line drawing of south polar curvilinear features. (Solid lines) Plate edges seen in the wide-angle camera coverage; (dashed lines) loci of centers of curvature. If polar wandering is associated with plate locations, a valley would be predicted in the quadrant 180° to 270°W. Although exact correspondence is poor, some symmetry with the northern plates is apparent.

However, Mars is probably not entirely rigid. The close correspondence of the observed J_2 term with that expected from a rotating Mars in hydrostatic equilibrium, as well as the results of almost any assumptions in thermal history modeling, indicate that while Mars exhibits rigidity at its surface, much of the interior may be hot enough to respond viscously rather than rigidly to an exterior torque. Under such circumstances, the nutation angle δ is limited only by the truly rigid component of J_2, which is probably much smaller than the total value used in Eq. 1. Hence, nutation induced from the production of shield volcanoes might have produced a significant nutation on Mars.

Furthermore, massive as these volcanic features are, they may be only the surface expression of a much grander phenomenon: mantle convection. A very much larger mass may be in motion than that represented by the visible surface extrusions. A viscous interior would damp polar wobble arising from mass displacements, and in the long run lead to a shift of the principal axis relative to the lithosphere, that is, polar wandering. As outlined for the earth by Goldreich and Toomre (*2*), the pole may be driven sequentially to different quasi-stationary positions in response to evolving density differences, rather than exhibiting a "spinning top" oscillatory motion. In this way, a relatively small mass shift in the mantle can induce a change which will then be compensated for by the shift of more mantle material. Hence, we conclude that to the extent that mantle convection on Mars is now a reasonable possibility, it is likely that a limited amount of polar wandering is taking place.

A third new discovery about Mars

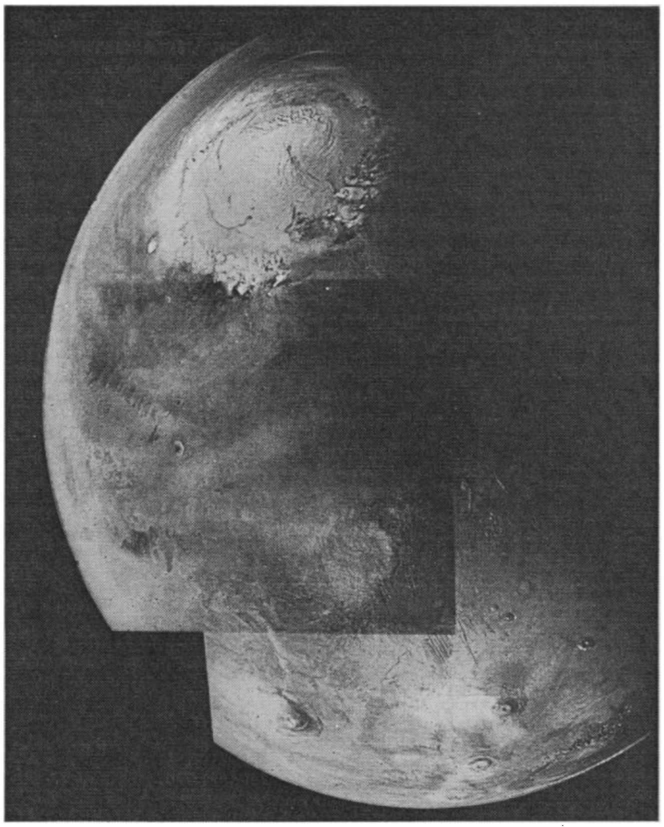

Fig. 2. Hemispheric view of Mars. The north polar cap is in the upper left; the equator runs just north of the canyon region at the lower right. The volcanoes are Nix Olympica (farthest left) and North, Middle, and South Spots (large features in the lower right; South Spot is very near the limb). Other volcanic features are clearly visible in the mosaic (prepared by the Image Processing Laboratory of the Jet Propulsion Laboratory).

is that the planet is gravitationally "rougher" than either the moon or the earth. The low-degree spherical harmonic coefficients of its gravitational field are considerably larger (in the sense of stress implication) than those of either the moon or the earth *(14)*. Significantly, it has been the existence of these and other low-order gravitational harmonics (which cannot be produced by the mass distribution within a rotating body in hydrostatic equilibrium) that fuel the debate over polar wandering on the earth *(15, 16)*.

The same kind of debate over internal constitution may develop for Mars, although not complicated by the large-scale plate tectonic motions recognized on the earth. There is, however, an important difference in the nonhydrostatic gravitational terms of Mars and the earth. Whereas on the earth, there is little correlation of low-order gravitational harmonics with surface topography and geology, on Mars a significant correlation is found *(17)*. In particular, the apex of the equatorial bulge, in both the physical surface and the gravitational field, corresponds closely to the location of the four shield volcanoes. Once again, the same observational data may be regarded as evidence of very different interior conditions. On the one hand, it may be argued that both the mantle and the crust of Mars are very strong and that even the largest crustal features are rigidly supported to a significant extent. Convection could not be present under such conditions, and the equatorial bulge would have to be regarded either as an accidental result of many local anomalies, or as reflecting earlier dynamical conditions. On the other hand, the correlation of such low-order harmonics with a unique and extensive volcanic province on Mars can be argued as evidence of a connection between large-scale vulcanism and deep density differences, precisely as might be expected at the initiation of large-scale mantle convection. Furthermore, if the equatorial gravitational bulge were merely a remnant of an earlier dynamical episode in Mars' history, why is it now correlated with the location of the large volcanic features?

A further intriguing and possibly related aspect of the gravity anomalies is the apparent symmetry with respect to the equator of the higher-order features. Presumably, internal density irregularities could form at almost any latitude. However, a property of polar wandering is that the spin axis will always be located along the major axis of inertia. As a result, polar wandering will tend to rotate the equatorial plane over time in such a way as to balance anomalies in the northern and southern hemispheres. Thus, the gravity data are at least consistent with the idea that anomalies originate in part from deep density differences whose change would be required for polar wandering.

The time scale of the hypothetical pole wandering is difficult to assess. There are two very approximate means of estimating the ages of the surface features that may be related to pole wandering. First, the volcanic terrains in the equatorial area exhibit few small bowl-shaped impact craters. Even surrounding terrain, possibly as old as the beginning of the construction of the volcanoes, is only sparsely cratered *(8, 18)*. As a result, one can conservatively estimate a limit for the maximum age of the volcanic features as not greater than a few hundred million years *(19)*. If each individual lamina of the laminated terrain corresponds to the 50,000-year period in the polar climate of Mars postulated by Leighton and Murray *(20)*, then an estimate can be made of the age of a single plate by noting the number of such laminae visible *(21)*. This was done by Murray *et al.* *(10)* and they estimated that the laminated terrain under observation at the south pole probably represented a few million years of accumulated deposits. In the north as many as 20 or 30 plates can be recognized. Therefore, perhaps 5×10^7 years may be represented in the clearly discernible plates, and a somewhat longer interval and greater wandering evidenced by more eroded areas of laminated terrain offset from the present axis by as much as 20° in latitude. Thus, we are led by these arguments to suppose that polar wandering of 10° to 20° has occurred over the last 10^8 years or so, with a rate of about 5×10^{-9} radians per year (about 20 arc minutes per million years) over portions of that time interval.

BRUCE C. MURRAY
MICHAEL C. MALIN
Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena 91109

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9. The notion of deep convection on Mars has been independently developed in some detail by our Mariner 9 colleague, W. K. Hartmann (in preparation).
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11. We are aware of the conventional restriction in geological terminology of the term "lamina" to layers less than 2 cm thick. These finely banded polar deposits are quite distinct from other layered deposits on Mars, and the term "laminated" remains the best characteristically descriptive term so far proposed for them. Hence, we feel there is little value in introducing another descriptive name at this early stage of martian geological studies.
12. A number of papers dealing with the nature and origin of laminated terrains are being prepared by Mariner 9 television investigators and alternative concepts to those expressed here may well be developed, along with elaboration of those referred to in this paper.
13. This problem can be treated as an exercise in classical rigid body dynamics. An oblate spheroid with principal moments of inertia C, A, A (where C is greater than A and along the spin axis) is perturbed by a point mass m instantaneously added at latitude Φ in a plane containing C' and one of the other moments. The problem then reduces to determination of the new principal moments (C', A', A') by diagonalization of the inertia tensor. The ratio of the components of either eigenvector is thus equal to the tangent of the angle between the new and old principal axes.
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17. On the earth, the correlation turns positive at the sixth degree (*16*). On Mars, it appears to be positive from the second degree on.
18. Even the greatest concentrations of small craters on Mars are less abundant than those of the lunar mare. An age of about 10^9 years would be estimated for a portion of the moon exhibiting the abundance of small craters observed on Mars, and it would probably be closer to 300 million years on the average. Since it is generally believed that Mars experiences a much higher impact flux than the moon, the actual age represented by the presently observed martian small craters is likely to be less than 10^9 years; hence, we choose a few times 10^8 years as a conservative estimate.
19. For more complete studies of the ages of various martian geological units see the "Mariner Mars 1971 project science report," *J. Geophys. Res.*, in press.
20. R. B. Leighton and B. C. Murray, *Science* **153**, 136 (1966).
21. In more recent work a 95,000-year period is assigned to each lamina (B. C. Murray, W. Ward, S. C. Yeung, *Science*, in press). A more complete discussion of the relationship between climatic fluctuations and the martian laminated terrain is presented in B. C. Murray, W. R. Ward, S. C. Yeung (in preparation).
22. We have benefited from discussions with W. R. Ward, R. B. Leighton, J. A. J. Cutts, and J. A. Burns. P. Goldreich and W. M. Kaula have been especially generous in aiding our understanding of the theory of polar wandering and how it might apply to Mars. Supported by the National Aeronautics and Space Administration. Contribution No. 2199 of the Division of Geological and Planetary Sciences, California Institute of Technology.

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Conversion of Thyroxine to Triiodothyronine by Cultured Human Cells

Abstract. *Human liver and kidney cells convert 6 to 10 percent of added thyroxine to triiodothyronine in vitro at 37°C. This extent of conversion is ten times greater than that in control studies with killed cells. Conversion is evident within 10 minutes and appears to be maximal within 1 hour. Greater net triiodothyronine formation results if greater amounts of exogenous thyroxine are added to the system, with no plateau evident even at very high thyroxine concentrations. The addition of high concentrations of nonradioactive triiodothyronine resulted in no evident inhibition of the conversion.*

Only part of the triiodothyronine (T_3) in the human circulation is secreted by the thyroid gland. The remainder must originate elsewhere. Peripheral conversion of thyroxine (T_4) to T_3 was demonstrated in athyreotic human subjects by Braverman *et al.* (*1*). Soon after Sterling *et al.* (*2*) and Pittman *et al.* (*3*) showed that T_3 may arise from ^{14}C-labeled T_4 administered to normal volunteers. Oppenheimer's group subsequently confirmed these results in the experimental rat (*4*). This prompted investigation of the possible sites and extent of such conversion in the tissues.

Conversion of T_4 to T_3 was demonstrated in vitro in rat kidney slices (*5*) and in human kidney slices obtained at operation (*6*). Slices of liver and skeletal muscle failed to show this conversion, and results for cardiac muscle were equivocal.

Refetoff *et al.* (*7*) showed conversion of T_4 to T_3 in skin fibroblast cultures. They concluded that intracellular T_4 concentration and the rate of T_3 formation depend on the availability of extracellular free T_4, and also demonstrated that T_3 does not inhibit the conversion of T_4 to T_3. Rabinowitz and Hercker (*8*), using isolated surviving rat hearts perfused with T_4 labeled with ^{14}C and ^{125}I, found significant conversion to T_3 after 5 minutes of perfusion; the amount of T_3 formed increased only slightly during the remaining 90 minutes.

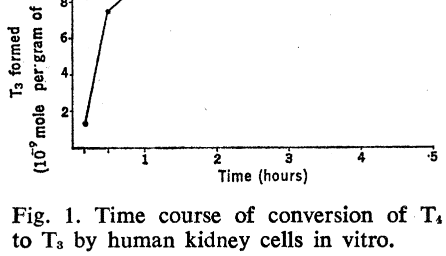

Fig. 1. Time course of conversion of T_4 to T_3 by human kidney cells in vitro.

The present studies were undertaken (i) to determine the conversion of T_4 to T_3 by human cell cultures and (ii) to determine the effect of increasing amounts of T_4 and T_3 on this conversion. Human kidney and liver cells in monolayer cultures were used, as well as suspensions of kidney cells from stillborn infants. The cultures were obtained from Microbiological Associates, Bethesda, Maryland. Cells were shipped in Eagle's basal medium containing 10 percent calf serum. Upon arrival the cells were incubated overnight at 37°C for temperature equilibration and resumption of growth. The next morning or after 2 or 3 days of further incubation with fresh medium, the cells were dispersed from the monolayer culture with a rubber policeman, the suspensions were then centrifuged, the supernatant fluid was discarded, and the cells were washed twice with Eagle's minimum essential medium for suspension cultures (SMEM). This was done to remove fetal calf serum. Finally, the cells were resuspended in a measured volume of SMEM, and 1 ml was distributed to each of a series of sterile plastic centrifuge tubes for the experiments. The small button of cells at the bottom of each tube occupied a volume of less than 0.1 ml. The cell protein content per tube was usually more than 200 μg but varied considerably, ranging from 55 to 3470 μg in different studies. Removal of calf serum, which contains T_4 binding proteins, was essential for adequate uptake of thyroid hormone into the cells. The viability of cells was evident by acid production, shown by phenol red indicator in the medium.

Tracer amounts of [^{125}I]T_4 (Abbott Laboratories, North Chicago, Illinois) were added to cell incubation medium (SMEM). Tracer amounts of [^{131}I]T_3 were also added for localization on chromatographic strips and for calculating recovery of newly formed [^{125}I]T_3 (range, 20 to 45 percent). This also