Polar Wander of Mars: Evidence from Magnetic Anomalies

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Introduction: The polar wander of Mars has been suggested by many investigators. The quasi-circular surface morphology of the deposits in the polar region detected by Mariner 9 mission led Murray and Malin [1973] to suggest that the Martian rotation axis has wandered by 10-20 degrees in the last ~100 Myr. Melosh [1980] gradually removed the mass of Tharsis bulge while diagonalizing the moment of inertia tensor of Mars, and showed that the Martian rotation axis has displaced by about 25 degrees due to the formation of the bulge. The similarity between the deposits on Mesogaea, south of Olympus, and those in the polar region led Schultz and Lutz [1988] to suggest a polar path with a total of 120 degree wandering. Long-term rotational dynamics of Mars was theoretically investigated by Spada et al. [1996] through modeling Olympus mountain as a point mass, initially located at 45 degree latitude on the surface, and allowing the mass to reach the equator. They considered a comprehensive suit of internal structure models of Mars with mantle viscosity ranging from 10^{21} to 10^{23} and imposed the Murray and Malin's constraint of 10-20 degree polar wander in the last 100 MYr. The authors concluded that the mass will reach the equator within less than 2 Gyr., in a much shorter time for low viscosity mantle models. It is also shown that a thick elastic lithosphere atop a viscous mantle increases polar wander because of elastically supporting the surface mass and allowing its greater influence on the rotational dynamics of Mars [Willmann, 1984; Stiefelhagen, 2002].

The Mars Global Surveyor magnetic data have provided new evidence for the polar wander of Mars. Arkani-Hamed (2001a) estimated the paleomagnetic pole positions of Mars through modeling 10 small and isolated magnetic anomalies. Seven out of the 10 poles clustered within a radius of 30 degrees centered at 25N, 225E. Hood and Zakharian (2001) modeled the source bodies of two magnetic anomalies near the north pole. One of the anomalies was included in the 10 anomalies modeled by Arkani-Hamed, and the pole positions of this anomaly determined by the authors were very close. Assuming that the dipole core field axis coincided with the rotation axis, the clustering of the poles suggests that the rotation axis has wandered by about 65 degrees since the magnetic source bodies were magnetized. This critical assumption that links the dipole core field axis to the rotation axis presently holds for both terrestrial planets with active core dynamo, Earth and Mercury, and possibly for Earth throughout its history. We make the same assumption in this paper.

We present the paleomagnetic pole positions of Mars determined through modeling 16 small magnetic anomalies. The previous 10 anomalies were extracted from a 50-degree spherical harmonic model of the magnetic potential of Mars (Arkani-Hamed, 2001b) that was derived on the basis of the low-altitude (~100-200 km) data. The original data had many wide gaps parallel to the satellite tracks and the number of original tracks passing over each anomaly was limited. The track data used by Hood and Zakharian (2001) were also extracted from the low-altitude data and suffered from the same limited coverage. The vast amount of high-altitude magnetic data now available provides a good opportunity to verify the previous results and also identify and model additional isolated anomalies. Hood and Richmond (2003) used the new data to model two new anomalies in the low latitudes. The pole position determined from one of the anomalies fall within the 30 degree cluster mentioned above. The present study not only includes 6 additional magnetic anomalies and uses a huge amount of the high-altitude data available, but also employs a new space domain algorithm that incorporates all three components of the magnetic data.

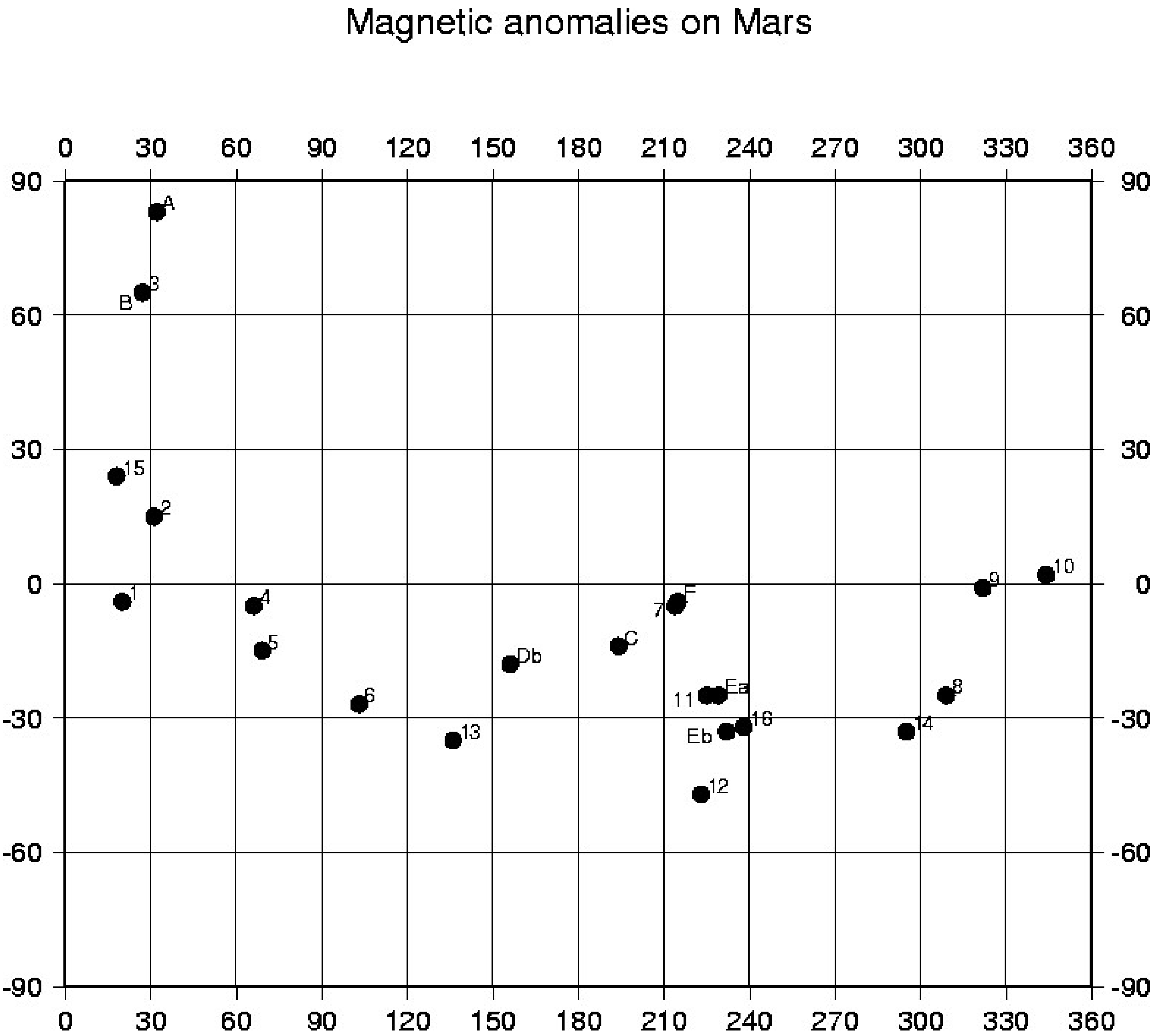

Figure 1 : Position on the surface of Mars of the magnetic anomalies modeled in this study. Anomalies 1 to 10 are the anomalies modeled by Arkani-Hamed (2001A). Anomalies 11 to 16 are the new anomalies added in this study. The other anomalies are from Hood and Richmond (2003) . Note also that anomaly A and B of Hood and Richmond (2003) are the same as the north and south anomalies modeled by Hood and Zacharian (2001).

Paleomagnetic Poles of Mars: The paleomagnetic pole position of Earth is usually determined using in situ measurements of the direction of rock magnetization (e.g., Butler, 1992). At present such measurements are not possible on Mars. However, a rough estimate of the magnetic pole positions of Mars can be made on the basis of modeling magnetic anomalies. We have modeled 16 isolated small magnetic anomalies. For a given anomaly, the three components of the magnetic data are extracted from both low- and high-altitude data sets and transferred to a local rectangular coordinate system centered on the anomaly. The coordinate origin is on a spheroid with a polar radius of 3375 km and an equatorial radius of 3397 km. The model source body is a vertical prism of elliptical cross section with uniform magnetization. Adopting an elliptical prism, rather than circular, provides an opportunity to change the aspect ratio (major axis/minor axis) as well as the orientation of the body and minimized the misfit between the observed and calculated anomalies.

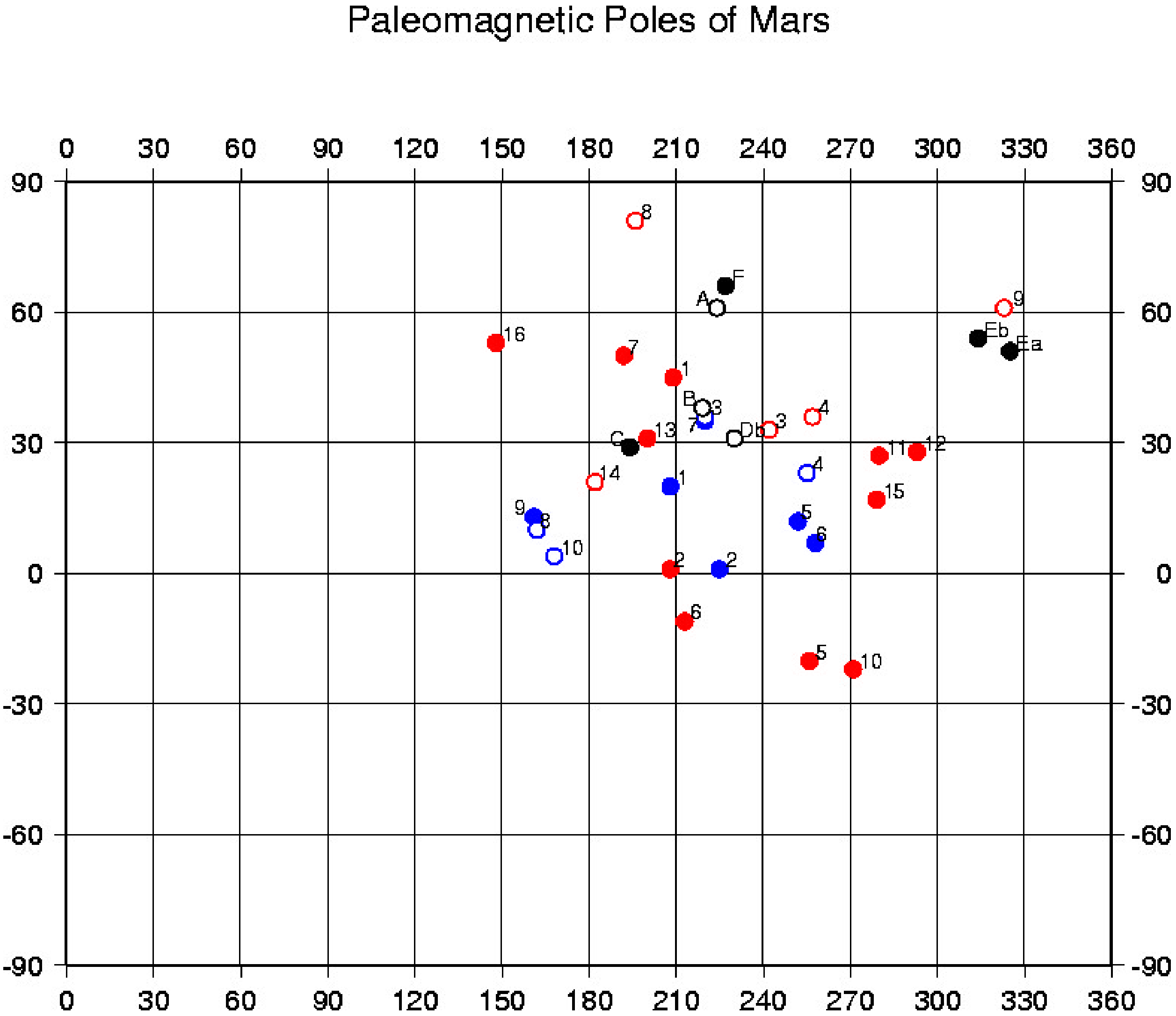

Figure 2 : Paleopole positions on Mars. Open circles are south poles , filled circles are north poles. Blue circles are the 1 to 10 anomalies results by Arkani-Hamed (2001A). Red circles are the new results obtained in this study. Black circles represent pole positions obtained by Hood and Richmond (2003). Results of Hood and Zacharian (2001) are identicals to results obtained for anomaly A and B of Hood and Richmond (2003).

Figure 2 shows the paleomagnetic pole positions determined from the magnetization of the source bodies, each is assumed to be magnetized by a dipole core field. We only present one of the poles. The core field is upward at the north pole and downward at the south pole. Included in the figure are the paleomagnetic pole positions determined by Arkani-Hamed (2001A) , Hood and Richmond (2003) and Hood & Zacharian (2001) for comparison. The figure shows appreciable clustering of the poles. Although slightly more scattered, the cluster overlaps the previous 30 degree cluster. The scatter is partly because of the noise in the high-altitude data.

One of the important characteristics of the pole positions is their appreciable clustering. If the average magnetic pole position coincided with the rotation axis of Mars, the cluster center indicates an appreciable true polar wander of Mars, likely induced by the formation of the Tharsis bulge, the large shield volcanoes such as Olympus and Tharsis mountains, and giant impacts such as Hellas, Utopia, Argyre and Isidis.

Discussion: Hood and Zakharian (2001) and Hood and Richmond (2003) used circular prisms to model isolated magnetic anomalies. Arkani-Hamed (2001A) adopted elliptical prisms. To what extent a paleopole position determined by an elliptical model differs from that determined by a circular model? We address this question theoretically by calculating the magnetic field of a uniformly magnetized elliptical prism, with a semi-major axis 400 km and a semi-minor axis 200 km, and modeling the field by a circular prism. The magnetic field is calculated at 150 km and 400 km altitudes, the mean elevations of the low- and high-altitude data. If the elliptical body is magnetized vertically, or horizontally but along either the major or the minor axis, the paleomagnetic pole position determined by the circular prism model coincides with that of the elliptical prism. However, when the elliptical body is magnetized at some angle with respect to either of its axes, the two palemagnetic pole positions differ, by as much as 15 degrees. The difference is more pronounced at 150 km altitude than at 400 km, because the short-wavelength components of the magnetic field strongly attenuate with altitude and the field of the elliptical body becomes similar to that of the circular model. The difference is large enough to favor the elliptical prism modeling technique. The freedom of varying the aspect ratio and the orientation of the ellipse, none of which are required for a circular prism, allows the results of elliptical modeling to better fit the observation.

Despite determined efforts made by several investigators, the pole positions determined by modeling the isolated magnetic anomalies must be regarded as preliminary. The high-altitude data densely covers almost the entire globe but its resolution suffers from the high elevation, wavelengths shorted that ~400 km are not accurately reflected in the data (Connerney et al., 2001). Moreover, because of proximity to the ionosphere (Mitchell et al., 2001), and strong attenuation of the magnetic field of the crust with altitude of the short wavelength components, the signal to noise ratio of the high-altitude data is low. The difference between the pole position inferred from anomaly M3 in this study and those determined from the low-altitude data alone (Arkani-Hamed, 2001A; Hood and Zakharian, 2001) is a good indication of the effects of the limited resolution of the high-altitude data. At the present, the accuracy of a given paleopole position must be decided upon agreement of the results obtained by different authors using different methods.

References

Arkani-Hamed J., Paleomagnetic pole positions and pole reversals of Mars, Geophysical Research Letters , 17 , 3409-3412 , 2001A.

Arkani-Hamed J., A 50 deg spherical harmonic model of the magnetic field of Mars, J. Geophys. Res., 106, 23197-23208, 2001B.

Butler, R. F., Paleomagnetism: Magnetic Domains to Geological Terrains, 319 pp, Blackwell Sci., Malden , Mass., 1992.

Connerney et al. The Glonal magnetic field of Mars and Implications for Crustal Evolution, Geophysical Research Letters, 28, 4015-4018,2001.

Hood L. L. and Zacharian A., Mapping and modeling of magnetic anomalies in the northen polar region of Mars, J. Geophys. Res., 106 , 14601-14619 , 2001.

Hood, L.L., and N. Richmond , LPSC , XXXIII, abstracts 1721, LPI, Houston, 2003.

Melosh H.J., Tectonic patterns on a reoriented planet: Mars, Icarus,44,745-751, 1980.

Mitchell, D. L., et al., Probing Mars crustal magnetic field and ionosphere with the MGS Electron Reflectometer, J. Geophys. Res., 106, 23,418-23,427, 2001.

Murray B.C. , and Malin M.C. Polar Wandering on Mars, Science, 179 , 997-1000 , 1973

Schultz, P.H., and A.B. Lutz, Polar wandering of Mars, Icarus, 73, 91-141,1988.

Spada, G., R. Sabadini, and E. Boschi, Long-term rotation and mantle dynamics of the Earth, Mars, and Venus, J. Geophys. Res., 101 , 2253-2266 , 1996.

Stiefelhagen, M, A comparative study of long-term polar motion of terrestial planets, MSc thesis, Delft University of technology, Netherland, 2002.

Willeman, R. J., Reorientation of planets with elastic lithosphepres, Icarus, 60 , 701-709, 1984.