The Global Magnetic Field of Mars and Implications for Crustal Evolution

J. E. P. Connerney, M. H. Acuña, P. J. Wasilewski, G. Kletetschka
NASA Goddard Space Flight Center, Greenbelt, Maryland

N. F. Ness
Bartol Research Institute, University of Delaware, Newark, Delaware

H. Rème
Centre d'Etude Spatiale des Rayonnements, Toulouse, France

R. P. Lin, and D. L. Mitchell
Space Sciences Laboratory, University of California, Berkeley, California

Abstract. The Mars Global Surveyor spacecraft obtained globally-distributed vector magnetic field measurements approximately 400 km above the surface of Mars. These have been compiled to produce the first complete global magnetic field maps of Mars. Crustal magnetization appears dichotomized, with intense magnetization mainly confined to the ancient, heavily cratered highlands in the south. The global distribution of sources is consistent with a reversing dynamo that halted early in Mars evolution. Intense crustal magnetization requires an increased oxidation state relative to mantle-derived rock, consistent with assimilation of an aqueous component at crustal depths.

1. Introduction

The Mars Global Surveyor (MGS) magnetometer experiment [*Acuña et al.*, 1992] acquires vector magnetic field measurements up to 32 samples/s throughout the mission [*Albee et al.*, 1998]. The spacecraft has been in a nearly polar, circular orbit ("mapping phase") since March, 1999, following 18 months of operation in a highly elliptical orbit ("aerobraking phase") designed to lower spacecraft apoapsis using atmospheric drag. Observations obtained during aerobraking [*Acuña et al.*, 1998, 1999] provided globally distributed but sparse coverage of the planet at altitudes in excess of 85 km. Mapping phase provides nearly uniform global coverage at orbit altitude (370 - 438 km) every 28 days (one "mapping cycle") with track to track separation of $\sim 1^\circ$ (59 km) at the equator. The orbit plane is fixed in local time (2 am - 2 pm). The data used in this report span 18 mapping cycles, from March, 1999 through August, 2000.

Mars lacks an appreciable global magnetic field at present (<0.5 nT equatorial surface field) but must have had one in the distant past [*Acuña et al.*, 2001]. The field measured at mapping orbit altitude is dominated by sources in the Mars crust (remanent magnetism) and external fields arising from the interaction of the solar wind with Mars' atmosphere. This external field is highly variable, ranging from a few nT in magnitude to as much as (rarely) $\sim$100 nT. The magnetic field due to crustal remanence reaches a maximum of $\sim$220 nT at mapping altitude.

2. Data Reduction

Maps of the crustal magnetic field at mapping orbit altitude (Figure 1) were constructed by data selection, averaging, binning, and sorting, to produce an estimate of the vector field for each 1 degree by 1 degree bin. The vector measurements were first averaged along track and decimated in time to produce an averaged value of each component of the magnetic field for every degree of latitude. These averages were sorted into 360 x 180 bins, extending 1 degree in the north-south direction ($\sim$59 km) and an equal length in the east-west direction (1° longitude at the equator). The median bin contained 14 such samples. These are largely statistically independent, because the time between subsequent samples in each bin is large compared to variations in the external field. These data are available in digital form on the MGS MAG-ER web site: http://mgs-mager.gsfc.nasa.gov/.

The influence of external fields was minimized by using only those observations obtained over the darkened hemisphere and by selection of the median value, rather than the average, for each bin. The 18 mapping cycles of data used span a period of 504 days or 0.73 of a Mars year (687 days), beginning during northern summer and continuing through winter and spring. The seasonal coverage, combined with selection of night time data, resulted in more samples at high northern latitudes relative to high southern latitudes. Accuracy of the crustal field (few nT) is limited primarily by residual external fields.

3. Interpretation

Crustal magnetization appears dichotomized: strongly magnetized crust appears near and southward of the transition from relatively low northern elevations to high southern

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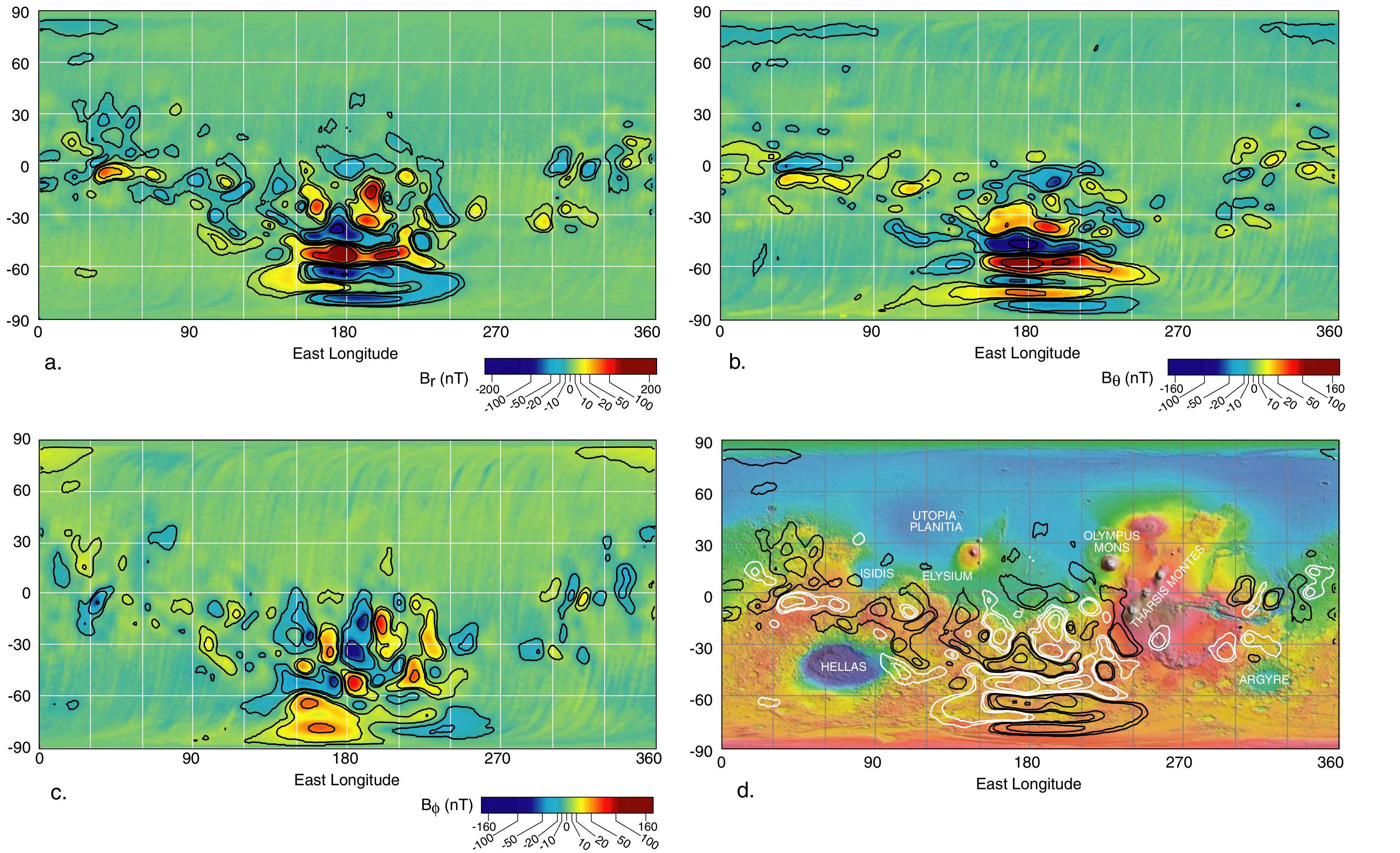

Figure 1. Maps of the magnetic field of Mars at 400(+/- 30) km altitude. The radial (a) component of the field is shown with a colorbar scaled to +/- 220 nT; the theta (b) and phi (c) components share a colorbar with reduced scale (180 nT). Comparison of radial field contours with MOLA topography (d). Isomagnetic contours are drawn for B = +/- 10, 20, 50, 100, 200 nT.

elevations, as noted by *Acuña et al.* [1999; 2001]. A hemispheric dichotomy is also reflected in crustal thickness [*Zuber et al.*, 2000] and surface geology, with younger, smooth and flat, and lightly cratered terrain in the northern lowlands indicating sedimentary or volcanic resurfacing in the Late Hesperian and Amazonian ages [*Smith et al.*, 1999]. The hemispheric dichotomy may have an impact or tectonic origin and is one of the most important unanswered questions of Mars geology [*Pepin and Carr*, 1992].

These maps, acquired at nearly constant altitude, are a more reliable indication of the global distribution of magnetization than those deduced from aerobraking phase observations. *Acuña et al.* [1999; 2001] appealed to the absence of magnetization near the Hellas and Argyre impact basins to argue for cessation of the dynamo during the early Noachian period, prior to the end of late heavy bombardment. Our new maps strengthen this chronology and remove objections [*Schubert et al.*, 2000] that arise if one uses Purucker's model [*Purucker et al.*, 2000] to infer the distribution of magnetization. This model used 11,550 radial dipoles, uniformly distributed in the crust, to compute the field on a constant altitude surface. Spurious crustal fields may result where dipoles are poorly constrained by (sparse) observations or where large external fields were encountered.

The most prominent crustal sources are the extensive, east-west trending features in Terra Cimmeria and Terra Sirenum and centered on the 180 meridian. These have been attributed to quasi-parallel bands of intensely magnetized crustal rock [*Connerney et al.*, 1999] like those associated with sea floor spreading on Earth. They may have formed by an early era of crustal genesis and spreading in the presence of a reversing dipole [*Connerney et al.*, 1999; *Sprenke and Baker*, 2000; *Nimmo*, 2000], fragmentation and separation of a uniformly magnetized crust [*Sprenke and Baker*, 2000], or by a moving locus of dike intrusion [*Nimmo*, 2000]. The magnitude and polarity of the mapping orbit observations are consistent with earlier results [*Connerney et al.*, 1999] if one takes into account the upward continuation of the potential field.

It is not possible to uniquely determine the intensity or direction of magnetization in the crust from observations of the vector magnetic field above the source [*Blakely*, 1995]. Since the magnetic field above a uniformly magnetized crust is zero, it is the variation of magnetization with location that is apparent in maps of this kind. The spatial resolution afforded by these maps is comparable to the altitude of observation, some 400 km. It would be quite remarkable if the Mars crust contained sources of these dimensions with uniform magnetizations. More likely we observe the average magnetization over these dimensions, which are not simply related to in situ magnetizations.

A number of features with predominately circular geometry appear in the radial field map. The simplest features are the relatively isolated, unipolar features (e.g., -35°, 295°E). This feature resembles that of an isolated source with average magnetization within a few tens of degrees of the radial direction; the positive radial flux just above the source is readily apparent, while the negative return flux, distributed over a much larger area, is nearly undetectable.

This feature *could be* produced by a dipole source with moment of 2.8 x 10^{16} A-m^2 at a depth of 106 km beneath the surface, oriented within 9 degrees of vertical. The inferred depth is most likely an indication that the source is distributed spatially and closer to the surface. Alternative models with very different source characteristics fit the data equally well; without a constraint on the source location and dimensions, the direction of magnetization of such a source is indeterminable.

Some of the circular features (e.g., -45°, 224°E; -11°, 110°E) may be associated with an impact process that creates a central basin surrounded by uplifted crust. The central basin, filled from below by post-impact intrusion and extrusion of iron-rich magma, may acquire thermoremanent magnetization (TRM) if it cools in the presence of an early dynamo-generated field. Subsequent flooding of magma external to the uplifted rim, followed by cooling in a normal or reversed field, can produce a surrounding ring of either polarity. A large volume of magnetic material (moment ~6 x 10^{15} A-m^2) is required to produce a 20 nT feature at 400 km altitude. A 200 km diameter disc, only 3 km thick, of intensely and uniformly magnetized rock (60 A/m) would suffice. The lack of an association between these features and visible craters suggests an extensively reworked surface.

4. Discussion

These maps are unlike those of the Earth's crust, obtained at comparable altitude [*Langel et al.*, 1982]. The Earth's crustal field is difficult to measure in the presence of a much larger background field due to the dynamo. Anomalies measured at comparable altitude are an order of magnitude weaker than Mars crustal sources and subject to relatively large estimation errors. Terrestrial anomalies are observed in the presence of a large inducing field, so it is not possible to distinguish between induced and remanent magnetism.

The magnetic minerals responsible for crustal magnetic remanence at Mars are likely to be among those magnetizing the Earth's crust. The magnetic properties of crustal rocks depend critically upon the mineralogical form of the iron, which is diagnostic of the composition and conditions prevalent in the crust at the time of formation or alteration. The intensely magnetized crust must contain iron in a form that can acquire and preserve, over aeons, a large remanent field.

Magnetic minerals with high remanence include forms of titanomagnetite (solid solution of Fe_3O_4 - Fe_2TiO_4), pyrrhotite (Fe_7S_8), and titanohematite (solid solution of Fe_2O_3 - $FeTiO_3$). Magnetite and pyrrhotite in effective single domain (SD) size can acquire very large TRM upon cooling in an Earth-like inducing field. These minerals have the high coercivity characteristic of the Shergotty, Nakhlite, and Chassigny (SNC) meteorites [*Cisowski*, 1986] and long term stability. In contrast, homogeneous multidomain-sized (MD) magnetite and pyrrhotite are less efficient in acquisition of TRM and have low coercivity and low long term stability. MD hematite is an attractive candidate because it acquires TRM very efficiently and it is very stable [*Kletetschka et al.*, 2000]. Production of hematite requires high levels of oxidation. It is not found in SNC meteorites but was identified in IR spectra of the surface [*Christensen et al.*, 2000]. Pyrrhotite is a less suitable candidate because it is easily demagnetized by the high pressures [*Vaughan and Tossell*, 1973] associated with large meteorite impacts. Evidently, only the very largest of impacts, e.g., those associated with the Hellas and Argyre basins, have erased crustal remanence (presumably by heating above the Curie point).

The magnetic mineralogy of the Mars crust may reflect an oxidation state that is more oxidizing than that of the Mars mantle. Studies of Shergottite meteorites [*Wadhwa*, 2000; *McSween et al.*, 2001] suggest that the different samples in this group derive from magmas that have been modified by assimilation of crustal material with an oxidized (aqueous) component. The sample (QUE94201) most representative of mantle conditions contains ilmenite and ulvospinel, appropriate oxide compositions for crystallization of basaltic material near the iron-wustite buffer. Rocks crystallizing under these relatively reducing conditions would be non-magnetic in the Mars crust. At the other extreme is Shergotty, more oxidized than the quartz-fayalite-magnetite buffer. Intense crustal remanence indicates that large portions of the Mars crust formed from mantle-derived material modified by assimilation of an aqueous component at crustal depths. This may lead to a magnetic boundary at depth in the crust dictated by the transition to an oxidation state appropriate for crystallization of magnetic iron oxides, e.g., titanomagnetite or titanohematite.

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J. E. P. Connerney and M. H. Acuña, Code 695, NASA Goddard Space Flight Center, Greenbelt, MD, 20771. (e-mail: connerney@gsfc.nasa.gov)

P. J. Wasilewski and G. Kletetschka, Code 691, NASA Goddard Space Flight Center, Greenbelt, MD, 20771.

N. F. Ness, Bartol Research Institute, University of Delaware, Newark, DE, 19716.

H. Rème, Centre d'Etude Spatiale des Rayonnements, 31028 Toulouse Cedex 4, France.

R. P. Lin and D. Mitchell, Space Sciences Laboratory, University of California, Berkeley, CA, 94720.

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