Mars' Ancient Dynamo and Crustal Remanent Magnetism

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Primary author:

R. J. Lillis	University of California Berkeley (510-642-6211, rlillis@ssl.Berkeley.edu)

Co-authors:	(no particular order)
Arkani-Hamed, J.	University of Toronto
Ravat, D.	University of Kentucky
Fuller, M.	University of Hawaii at Manoa
Whaler, K.	University of Edinburgh, Scotland
Milbury, C.	University of California Los Angeles
Russell, C.T.	University of California Los Angeles
Delory, G.	University of California Berkeley/NASA Ames Research Center
Brain, D.	University of California Berkeley
Halekas, J. S.	University of California Berkeley
Lin, R. P.	University of California Berkeley
Manga, M.	University of California Berkeley
Johnson, C. L.	University of British Columbia
Hood, L. L.	University of Arizona
Purucker, M.	Raytheon at NASA Goddard Space Flight Center
Jurdy, D.	Northwestern University
Smrekar, S.	NASA Jet Propulsion Laboratory
Connerney, J. E. P.	NASA Goddard Space Flight Center
Espley, J.	NASA Goddard Space Flight Center
Kletetschka, G.	NASA Goddard Space Flight Center
Weiss, B. P.	Massachusetts Institute of Technology
Roberts, J. H.	Johns Hopkins University Applied Physics Laboratory
Louzada, K. L.	Harvard University
Stewart, S. T.	Harvard University
Cain, J. C.	Florida State University
Mozzoni, D.	Florida State University
Vennerstrom, S.	Denmark Technical University, Denmark
Langlais, B.	CNRS/University of Nantes, France
Gattecceca, J.	CNRS/Université d'Aix Marseille, France
Rochette, P.	CNRS/Université d'Aix Marseille, France

Executive Summary

At present, Mars has no global magnetic field and therefore no active dynamo. The strong crustal remanent magnetic fields imply that a dynamo once existed, likely ceasing ~4 Gyr ago. The cessation of the dynamo exposed the atmosphere to stripping by the solar wind and quite possibly altered the course of climate evolution. The pattern of crustal magnetic fields (and hence subsurface magnetization) has been modified by impact, fluvial, hydrothermal, tectonic and volcanic processes over the planet's history. The Martian meteorite suite and observations from the Mars Global Surveyor (MGS) Magnetometer/ Electron Reflectometer (MAG/ER) have provided great insight into Mars' evolution and the magnetic record imprinted on the Mars crust. However, we have little context for the former and the latter were gathered from orbit, at great distance from the source. Hence, many questions remain about the spatial distribution, direction, strength, depth and mineral carrier(s) of the crustal magnetization and the strength, nature and duration of the ancient core dynamo. **To address these questions, we recommend to the 2011 Decadal Survey that NASA:**

- **Support an extended MAVEN mission with a low periapsis altitude (150 km), to map the magnetic signatures of smaller geologic features (e.g. craters, rifts, volcanoes) with improved spatial resolution.**
- **Investigate placing a magnetometer investigation on a rover sent to a region of known strong magnetic sources. The field strength in such regions is so large in magnitude that rover-generated fields can be easily mitigated.**
- **Investigate placing a magnetometer on an aerial platform (aircraft or long-lived balloon) to obtain low-altitude magnetic measurements over tens or hundreds of kilometers.**
- **Begin planning for the return to Earth of oriented Noachian bedrock samples in magnetically-shielded containers for magnetic and radioisotope analysis in terrestrial laboratories.**

Value

Determining the nature and origin of Mars' crustal remanent magnetization will provide valuable knowledge pertinent to three major questions in Mars science:

1) The formation and evolution of the crust, including its mineralogy and modification, during the past ~4.5 Gyr, by tectonic, impact, fluvial, hydrothermal and magmatic processes.
2) The evolution of the interior, including early global heat flow, mantle dynamics, plate tectonics and the history and lifespan of convection within the core (i.e. by studying the history of the dynamo).
3) The evolution of climate and habitability, particularly the stability of surface water, which are constrained by the lifespan of the global magnetic field (and the shielding it provided against solar wind stripping of the atmosphere).

Current knowledge of Mars crustal magnetism & ancient Dynamo

Unexpectedly strong crustal fields: The era of Mars crustal magnetism began in 1997, when intense, localized magnetic fields (up to 1500 nT at 100 km) were discovered by the MGS MAG/ER experiment (figure 1). These fields are several orders of magnitude stronger than lunar crustal fields and at least one order of magnitude stronger than terrestrial crustal fields. They require large volumes (up to ~10^6 km^3) of coherently magnetized crust, with remanent magnetizations of at least tens of A/m [Acuña et al., 1999], that are the crustal remains of a past strong Martian global field and core dynamo.

Magnetic mapping and global distribution of magnetic fields: 9 years of crustal magnetic field measurements from the MGS MAG (vector measurements sparsely down as low as 90 km, but mostly at 400 km) and MGS ER (remote measurements of total field magnitude at 185 km) have been used extensively for geophysical interpretation of impact, fluvial, tectonic and volcanic features, whose formation processes modified the crustal magnetization pattern [e.g. Acuña et al., 1999; Connerney et al., 1999; Arkani-Hamed, 2004; Lillis et al., 2006, 2008a; Johnson and Phillips, 2005; Whaler and Purucker, 2005; Mitchell et al., 2007, Shahnas and Arkani-Hamed, 2007; Hood et al., 2003; Langlais et al., 2004; McEnroe et al., 2004, Milbury et al., 2007; Nimmo and Gilmore, 2001; Voorhees, 2008].

To first order, the global crustal field pattern follows the dichotomy boundary, with the older, heavily-cratered Noachian surface south of the boundary displaying much stronger crustal fields than the less-cratered northern lowlands. This pattern may be due to hemispheric differences in crustal thickness [Neumann et al., 2004], resurfacing and crustal heating [Connerney et al., 2005], core dynamo field strength [Stanley et al., 2008] and/or serpentinization [Quesnel et al., 2009]. The true cause is unclear.

Modification of magnetization by tectonic, magmatic and impact processes: The linear pattern of the radial crustal magnetic fields in Terra Cimmeria and Terra Sirenum (lower middle of the map in figure 2) has been interpreted as being the product of plate tectonic activity early in Mars' history [Connerney et al., 1999; 2005], though this suggestion remains debatable since compact sources of magnetization, rather than elongated ones, can also account for this linear pattern [Hood et al., 2007; Jurdy and Stefanick, 2004].

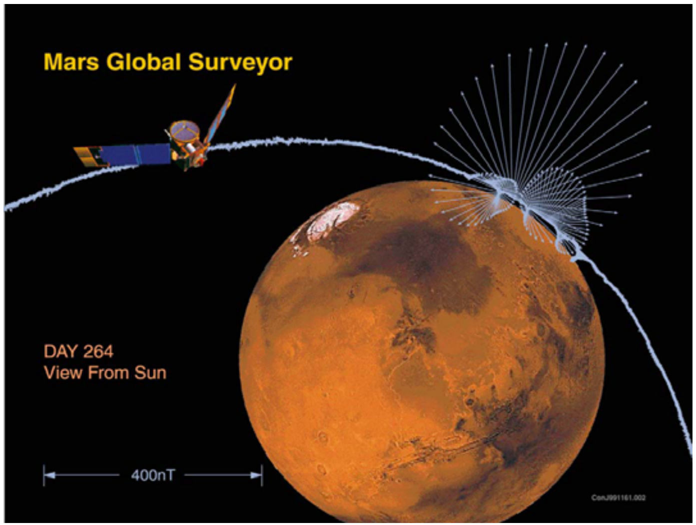

Figure 1: MGS aerobraking pass with magnetic field vectors emanating from spacecraft position, demonstrating the crustal origin of the strong magnetic fields.

Extremely weak fields are measured over the large volcanic provinces Elysium and Tharsis, suggesting post-dynamo thermal demagnetization by long-lived pervasive magmatism [Johnson and Phillips, 2005; Lillis et al., 2009] while somewhat stronger fields have been measured over the older and smaller highland volcanoes [Lillis et al., 2006; Langlais and Purucker, 2007].

Very weak or nonexistent crustal fields

are measured within the 5 youngest large (>1000 km) impact basins, implying shock and thermal demagnetization by impact processes [Hood et al., 2003; Mohit and Arkani-Hamed, 2004; Lillis et al., 2008b]. In contrast, the 14 oldest identified large impact basins all have moderate-to-strong magnetic fields within. Analysis of basin ages and magnetic signatures suggests a rapid decrease in post-impact crustal magnetization within these basins around a model age of ~4.1 Gyr [Lillis et al., 2008b].

The Martian dynamo: The most straightforward explanation of the sudden decrease in crustal magnetization is that turbulent core convection became insufficiently vigorous to sustain a global magnetic field [Acuña et al., 1999; Arkani-Hamed, 2004, Lillis et al., 2008a,b], thereafter exposing the upper atmosphere to being stripped away by the solar wind [Jakosky et al., 1994]. This rapid cessation is consistent with Mars core dynamo simulations [Kuang and Jiang, 2008].

Evidence from Martian meteorites: Martian meteorites provide direct sampling of Martian magnetization, for which magnetic fields are a (sometimes rough) proxy [Rochette et al., 2005]. Analysis of the oldest known meteorite from Mars, ALH 84001, indic were ates that the meteorite's remanence is carried primarily by magnetite and pyrrhotite, and that the paleofield on Mars ~4 Ga was likely similar to that on the Earth presently [e.g., Weiss et al., 2008], which is consistent (within errors) with the aforementioned giant basin magnetic field signatures.

Candidate magnetic minerals: There are 4 candidates for the mineralogical carrier of Martian crustal magnetization. Titanohematite, which is very stable for slow cooling and high lithostatic pressures, is an attractive candidate particularly if the crustal sources are deep-seated. Titanomagnetite, the main ferromagnetic mineral in nakhlites, has lower saturation magnetization and Curie temperature and therefore is a less favorable candidate except in the case of anisotropic stresses or nanoscale exsolution. Pyrrhotite is an important magnetic carrier in the basaltic shergottite meteorites [e.g., Rochette et al., 2005], but has a low blocking temperature (320°C), requiring sources to be shallow and intense [Dunlop and Arkani-Hamed, 2005]. Lamellar hematite-ilmenite has also been proposed based its role in intense terrestrial anomalies [McEnroe et al., 2004].

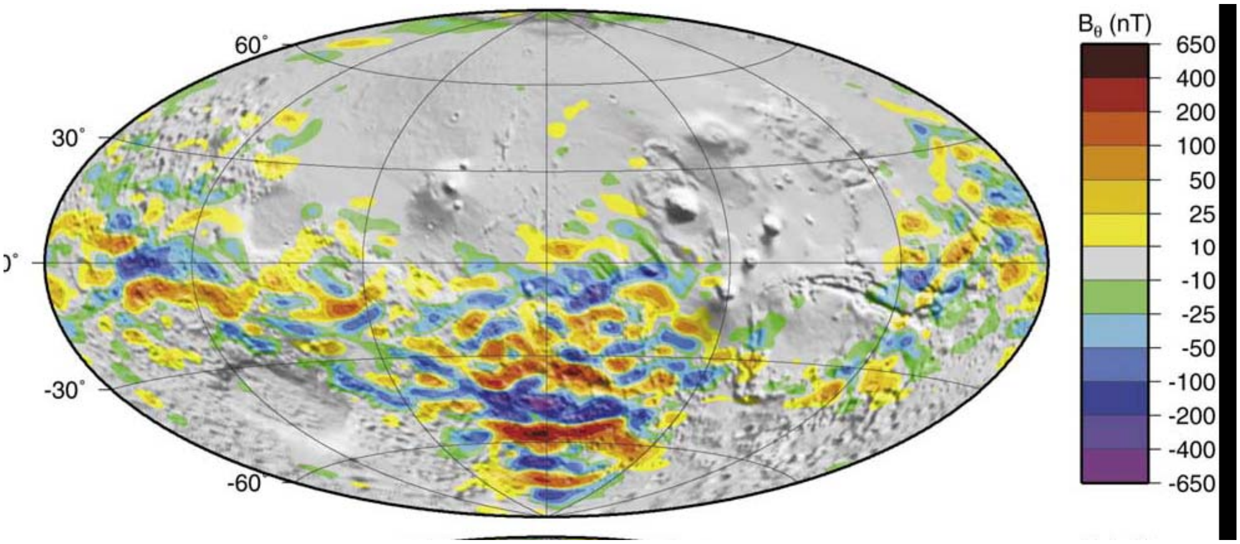

Figure 2: map of the radial component of Mars' crustal magnetic field at 200 km altitude from the equivalent source dipole model of Langlais et al. [2004], which is based on 5 years of MGS magnetometer data.

Outstanding questions

Despite all that we have learned thus far about Mars' crustal remanent magnetism and ancient dynamo, we have been mostly limited to remote observations of magnetic fields; whose interpretation suffers from inherent non-uniqueness (which worsens with distance). **Much of the evidence for what we believe is circumstantial because we lack 'ground truth' for crustal magnetization, in terms of its strength, direction, age or mineral carrier.** The three major outstanding questions are:

1) What is/are the major carrier(s) of Martian crustal magnetization?
    a. What are their domain states?
    b. When, in what type of environment and through what processes did they form?
2) What are the properties of the sources responsible for Mars' remarkable crustal magnetic fields?
    a. What is the lateral scale of these sources and what does this tell us about their formation processes?
    b. What is the maximum depth of magnetization and what does this tell us about the thermal gradient in the crust when they formed and subsequently?
    c. What are their formation ages?
3) What were the characteristics of Martian dynamo?
    a. How soon after accretion did it start?
    b. Did it ever stop and restart?
    c. When did it cease permanently and how quickly did this happen?
    d. What was the average surface field strength and did it vary over time?
    e. Was the field aligned with the rotation axis?
    f. Was it dominantly dipolar or did it have substantial higher order terms?
    g. Did it reverse polarity and if so, how frequently and what were the characteristics of the reversals (duration, global field weakening)?

Currently planned measurements

The MAVEN Mars Scout's 365-day nominal mission consists of ~2000 orbits with periapsis at 150 km, plus 125 orbits at 120 km. Its orbit is due to precess naturally so that a mission extension of 2-4 years could provide effectively global vector magnetic field coverage at ~150 km. While measurements from the nominal mission will be useful in improving models of the Martian crustal magnetic field, a significant extended mission would enable a comprehensive study of the magnetic field signatures of significantly smaller geological features (e.g. impact craters, volcanoes) than is currently possible. **However, magnetic field measurements taken from orbit will not by themselves enable us to solve the outstanding questions about Mars' crustal remanent magnetism and the ancient dynamo.**

Recommendations for future measurements

***Recommendation #1**: extend MAVENs mission with as low a periapsis as possible*

- Because any orbiter with a periapsis much below ~150 km requires constant DSN coverage (which is expensive and impractical over a long mission), the most cost-effective way to achieve the best possible global knowledge of Mars' crustal magnetic fields is for NASA to extend the MAVEN mission well beyond the currently planned 365 days. Such global coverage will provide further constraints on crustal evolution and history of the ancient dynamo.
- Simultaneous interplanetary magnetic field measurements from the Chinese Yinghuo-1 will help to better characterize crustal fields by providing an outer boundary condition.

***Recommendation #2:** surface and/or aerial magnetometer survey*

We recommend that a **magnetometer be mounted on a mobile surface and/or low altitude platform** to allow spatially continuous measurements of crustal magnetic fields.

- One straightforward idea would involve a boom-mounted dual magnetometer system on a (preferably magnetically clean) rover.
- **The recently-canceled stationary magnetometer (MSMO) on the ESA ExoMars mission (launch in 2016) should be replaced by magnetometers placed on both the rover and the stationary lander, in order to separate spatial and temporal signals.**
- From a rover platform, there are various ways of determining the magnetization vector of surface outcrops and rock samples [see Rochette et al., 2006]. Our preferred method involves making field gradient measurements (using a dual system or a moving magnetometer) or having the sample rotated in front of the magnetometer. Normalizing to laboratory-measured magnetization can allow us to determine the type of magnetization and field intensity in which it was acquired, thus helping to shed light on the timing of the ancient dynamo. Though not nearly as scientifically fruitful as sample return, this magnetometer-plus-robotic arm surface package would help answer several of the outstanding questions about Mars crustal magnetism for relatively modest cost.
- Beyond a rover, for increased spatial coverage of tens or hundreds of kilometers, we recommend a magnetometer mounted on a mobile platform such as an aircraft (figure 3) or balloon.

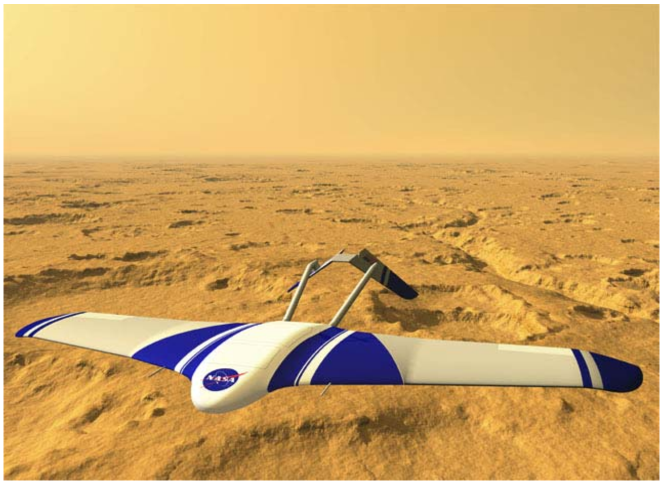

Figure 3: ARES concept for a low altitude Mars aircraft that could carry a magnetometer over a substantial distance of tens of kilometers.

- For either of the above, terrestrial experience in magnetic surveys will enable us to:
  a) Characterize contrasts in Mars' crustal magnetization down to kilometer scales.
  b) Much more accurately estimate the depth and thickness of the magnetized crust.
  c) Accurately judge the potential of strong field regions for shielding the surface (and hence life and human explorers) from cosmic rays and solar energetic particles.

Recommendation #3: *sample return of Noachian crust*

We recommend direct magnetic and radioisotope analysis of oriented Martian bedrock samples (i.e. samples whose original orientation is known), preferably in areas of Noachian crust, in terrestrial laboratories. We recognize that this will require sample return from the surface of Mars, an expensive and technologically challenging undertaking. However, the wealth of experience in radioisotope dating and paleomagnetism will enable us to determine or at least estimate:

- The strength and direction of the sample's magnetization and hence the strength and (with caveats) the paleopole location of the global magnetic field that magnetized it.
- The rate of geomagnetic reversals and secular variation.
- Whether Mars experienced plate tectonics and/or true polar wander (by comparing the orientation of the paleopoles with respect to past and present spin poles).
- The mineral carrier of the remanence and its domain state (e.g. single domain magnetite, multi-domain hematite etc.).
- The type of magnetic remanence (e.g. shock, chemical, thermal, lightning) and hence conditions under which it formed.
- The age of the magnetic inclusions and hence the time at which the magnetization was acquired.

It should also be stressed that the return of even non-oriented samples would enable us to address the latter three issues and would be of enormous scientific value.

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