Mars' Magnetic Field:

Crustal Magnetization as Evidence for an Ancient Dynamo

Solomon Granor
12/8/02
Astronomy 330

Since the earliest Martian exploration, Mars' magnetic field has perplexed much of the scientific community. It has challenged theories of planetary magnetism and inspired much unjustified assumption and speculation in scientific papers. Overall, the worst setback arose from a near total lack of data. While over a dozen successful probe missions have visited Mars, only six of these carried magnetometers.

The first human probe to visit Mars, Mariner 4, also made the first measurements of Mars' magnetic field. These measurements are significantly limited by the flyby nature of the Mariner 4 mission; however, they are enough to limit any inherent Martian dipole to 3*10^-4 times the strength of that of Earth's. The most relevant aspect of the Mariner 4 data is a fluctuation of ~5*10^-5 Gauss, lasting for approximately 3 hours. This has both been interpreted as the probe entering Mars' bow shock and as a totally random fluctuation in the stellar magnetic field of the sort that the probe had encountered en route.[1]

Much great controversy has arisen over the data from the Russian Mars 2, 3, and 5 probes – the next probes to carry magnetometers to Mars. These data were heavily studied and modeled in the late 1970's and the 1980's, as no other Martian magnetic data would be taken until 1989.[2] The data from the Mars series probes are far from ideal due to the eccentricity of the probes' orbits and their distance from the planet. Worse, the probes' magnetometers were not correctly calibrated, and could, thus, only return data on the relative field strength at different locations. Nevertheless, each of these probes returned at least one set of data magnetic data that has been interpreted as a disturbance in some way due to Mars. Data from Mars 2 were suggestive to some of a weak dipole moment having its axis in the equatorial plane. A series of data from Mars 3 showed evidence of entry into a magnetosphere or magnetosheath. Finally, Mars 5 repeatedly returned data suggestive of passage through a magnetic tail on the night side of the planet. It is worthwhile to note that only the first of these cannot be explained by effects arising from changes in the interplanetary magnetic field due to the very presence of the planet.[3]

While much analysis and modeling were performed with the Mars 2, 3, and 5 data, they alone never led to a coherent picture of Mars' field, as the inferences from the different data sets were always incompatible. Some of this confusion was resolved in 1989 with data from the Russian Phobos 2 probe. During the two months before it was lost, Phobos 2 collected magnetic data, coming as close to Mars as 800 km in its 8-hour circular orbit. This data strengthened the case for the effects seen being the result of the planet's interaction with the interplanetary magnetic field. The most compelling evidence for this strongly correlated the direction of Mars' magnetic tail with the interplanetary magnetic medium.[2]

Finally, in 1997, with the arrival of Mars Global Surveyor into orbit, sufficient data to fully characterize the Martian magnetic field began to arrive. Even the earliest data received alone would have been enough to revolutionize the study of Mars' magnetic field, when, on September 15, MGS passed through and unequivocally detected Mars' bow shock. Within a month, MGS had detected substantial enough evidence for the Global Surveyor team to announce publicly that not only does Mars have a magnetic field, but that it is at least dominated by the magnetization of the planet's crust.[4]

Now, with several years' more data, maps of Mars' magnetic field 400 km above the surface (the altitude at which MGS orbits) have been created. As a sphere of uniformly magnetized crust will give off no field, these maps are related to the relative magnetizations of different areas of the crust, rather than to the actual magnetization. Comments here about such maps will be related specifically to the map in Connerney et. al. [2001] unless specifically noted otherwise. This map was created by taking the median value from 18 mapping cycles for every block on the Martian surface; where a length of 1 degree of longitude defines a block. Only values taken on the night side of the planet during the 18 cycles were used in the process, in order to reduce the influence of external fields.[5]

The map shows Mars' magnetization to be largely uniform with the vast majority of deviations being along the equator and in the Terra Cimmeria/Terra Sirenum region of the southern hemisphere. In this later region, both the radial and colatitude components of the field show a striated pattern evocative of seafloor spreading on Earth. The maximum variation in field strength over the striations is ~400 nT. This region could very well be what Mars 2 detected as evidence of a dipole moment.

Except along the Tharsis bulge, where any magnetization seems to have been erased, the northern boundary of the equatorial magnetic strip coincides strongly with the boundary between the southern highlands and the northern lowlands. This suggests that the magnetization is older than the northern surface, as the northern surface is known to be younger than the southern.

The other regions of significant interest on the map are the Hellas and Argyre impact basins. Neither of these shows deviation from the background magnetization, but there is net magnetization in some of the ejecta from Hellas. These patterns suggest that both of these impacts occurred after the crustal magnetization was formed. Since either of these impacts was large enough to raise the impacted surface past its Curie temperature, erasing any pre-existing magnetization, these impacts could not have occurred while the magnetization was forming, as the presence of a magnetic field strong enough to create the magnetizations seen in Terra Cimmeria and Terra Sirenum would have left these impact basins as magnetic anomalies as well. Further, it is unlikely that the impacts occurred before the magnetization, as the ejecta from Hellas would not have been magnetized in that case. Thus, the lack of a magnetic signature in Hellas or Argyre suggests that the impacts occurred after the cessation of the strong magnetic field that created the crustal magnetization.[6]

The source of the magnetization is much more difficult to determine than its implications for the Martian timeline. Modeling performed by Sprenke and Baker [2000] on preliminary data from MGS attempted to address several possibilities for the Terra Cimmeria/Terra Sirenum striations. The first set of models attempt to explain these as the result of seafloor spreading in a Martian dipole field, while the second set model the crust cooling in place in an axial dipole field. The seafloor spreading models could not be made to fit the actual striation data to better than 68%; although, Sprenke and Baker were able to conclude that the most likely spreading center for such a process would have been quite distant from the remaining anomalies, lying somewhere in the northern hemisphere. The static models, which assumed the region started out at uniform magnetization and was subsequently broken, fared better, fitting up to 86%.[7]

The successful introduction of an axial dipole field into Sprenke and Baker's models suggests a core dynamo at least superficially similar to Earth's. Earth's dynamo is generally assumed to be composed of convection currents in the outer core, driven by the gradual cooling of the inner core. The field itself will then be a solution of the magnetohydrodynamic equations, which are an amalgam of mechanics, thermodynamics, and electrodynamics. Earth's field has been modeled in this context with a great deal of success.

The magnetohydrodynamic equations are:

$$\frac{\partial \rho}{\partial t} = -\vec{\nabla} \cdot \left(\rho \vec{V}\right) \tag{1}$$

$$\rho \frac{d\vec{V}}{dt} = -\vec{\nabla} \cdot P + \rho \vec{g} - 2\rho \vec{\Omega} \times \vec{V} + \rho \vec{F}^{B} + \rho \vec{F}^{v} \tag{2}$$

$$\rho \frac{dS}{dt} = -\vec{\nabla} \cdot \vec{I}^{S} + \sigma^{S} \tag{3}$$

$$\rho \frac{d\xi}{dt} = -\vec{\nabla} \cdot \vec{I}^{\xi} \tag{4}$$

$$\vec{\nabla} \cdot \vec{B} = 0 \tag{5}$$

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times \left(\vec{V} \times \vec{B}\right) - \vec{\nabla} \times \left(\eta \vec{\nabla} \times \vec{B}\right) \tag{6}$$

Equation (1) is a mass continuity equation, (3) is an entropy continuity equation allowing for the creation, but not loss, of additional entropy, and (4) demands the continuity of the mass component of the core other than iron. Equation (2) describes the forces in the system, including those due only to planetary rotation. Equations (5) and (6) define the magnetic field arising from all of the present effects. It should be noted that the only interaction between the first four equations and the last two occurs in the terms $\vec{V}$ (the velocity field) and $\vec{F}^{B}$, where $\rho \vec{F}^{B} = \vec{J} \times \vec{B}$, $\vec{J}$ being the current density. The interpretation of this is that the relevance of the first four equations to the last two is to define the velocity field, and that of the last two to the first four is to provide a component of force.[8]

Application of magnetohydrodynamics to Mars could explain the magnetization of the crust; but it introduces the new question of why the dynamo stopped. These considerations are also intricately bound with the discussion of the timing of the dynamo. From the considerations noted above – the Hellas and Argyre impacts, the lack of magnetization in the northern lowlands, and the areas of background magnetization in the southern hemisphere – the best estimates for the timing of the dynamo point to a period of no more than a few hundred million years, ending ~4 to 4.2 billion years ago.

Three possible scenarios have been proposed to account for the cessation of the Martian dynamo. The first and simplest suggests that Mars interior cooled so fast during its early history that no solid inner core ever formed. To prevent freezing, the core must have high sulphur content. If this were the case, the liquid core, though starting with a convection-based dynamo, could quickly cool to the point that the heat flow out could be accommodated by conduction alone. This transition could occur in as short a time as a few thousand years. The possibility is left open that a solid inner core could begin to form and set up new convection currents.

The second model assumes low sulphur content, leading to rapid inner core development. With a rapidly growing inner core, the outer core quickly becomes too thin to sustain convection currents of the scale needed for the dynamo. Since the freezing process partly purifies the material condensing into the inner core, the outer core is left with residue sulphur. Thus, after a point, the outer core will no longer freeze, due to the increased sulphur; therefore, there will always be a liquid layer between the solid inner core and the mantle.

In the final model, a change in mantle convection stifles the core dynamo. All of the convection models assume a process of recycling the lithosphere to release the convection energy from the mantle. The assumption here is that some change in the mantle or lithosphere stopped this process, ended both plate tectonics and core convection, as the energy from the convection would now have nowhere to which to escape. Since the elimination of heat from the mantle will now be less efficient, this cessation requires that the mantle's average temperature rise, leading to the conclusion that its coldest point occurred early in its history. This temperature increase, in effect, prevents the core dynamo, even if the inner core continues to form. This model suffers from the lack of a know mechanism for the cessation of plate tectonics and bears the implication that Mars could become volcanically active at any time.[6]

Some of the most surprising results from the study of Martian magnetism arise from the investigation of Mars' paleomagnetic poles – the places where the Martian magnetic field once had poles. The Sprenke and Baker modeling results in the surprising conclusion that the most likely locations for the magnetic pole of a field with the correct characteristics to create the Terra Cimmeria/Terra Sirenum striation are along the equator, not at the current Martian poles. Due to the involvement of the planet's angular momentum ($\vec{\Omega}$) in the magnetohydrodynamic equations, it is extraordinarily unlikely that a dynamo could remain stable at an orientation so far off from the axial. This implies that either apparent or true polar wander has occurred on Mars.

Apparent polar wander is an effect of plate tectonics that appears in the geologic record on Earth, and is used to trace continental drift. The movement of a plate changes its position and orientation with respect to the position at which the magnetic pole had been when the local rock was magnetized. When this rock is later examined, it will appear to indicate a different pole direction than actually occurred. The application of this to Mars would suggest that, assuming Mars' rotation axis has not changed, the Terra Cimmeria/Terra Sirenum region has rotated ~90º from its initial orientation. This could have been accomplished were the northern lowlands formed by sea-floor spreading.

True polar wander, alternatively, implies that the geologic record is accurate – the Martian poles were, in fact, along the equator. For the magnetic poles to have had this orientation, it is almost necessary that the spin poles did as well. For the spin poles to have changed so drastically would require a significant change in the planet's inertia tensor, most likely due to a redistribution of mass. It has been suggested that the rise of Tharsis could produce an inertia effect of this magnitude, although that is not the only possibility.

Martian polar wander has been studied with methods totally unrelated to magnetism, including the studies of grazing impacts and geomorphologies. Using knowledge about the current Martian poles, these studies have been used to suggest a possible wander path for the Martian south pole. Almost this entire path falls inside the most probable region for the paleomagnetic pole in the Sprenke and Baker study, adding weight to case for true polar wander, and leading to suggestions of specific regions, such as the chaotic terrains of the eastern Valles Marineris, as former poles sites.[7]

---

[1] Smith, Edward J., Leverett Davis, Jr., Paul J. Coleman, Jr., and Douglas E. Jones, "Magnetic Field Measurements near Mars", Science 149 (1965): 1241-2.

---

[2] Russell, C. T., “Magnetic Fields of the Terrestrial Planets”, Journal of Geophysical Research 98 (1993): 18,681-95.

[3] Russell, C. T., J. G. Luhmann, J. R. Spreiter, and S. S. Stahara, “The Magnetic Field of Mars: Implications from Gas Dynamic Modeling”, Journal of Geophysical Research 89 (1984): 2997-3003.

[4] Showstack, Randy, “Mars Has Crustal, Complex Magnetic Field”, Eos, Transactions, American Geophysical Union, 78 (1997): 429.

[5] Connerney, J. E. P., M. H. Acuña, P. J. Wasilewski, G. Kletetschka, N. F. Ness, H. Rème, R. P. Lin, and D. L. Mitchell, “The Global Magnetic Field of Mars and Implications for Crustal Evolution”, Geophysical Research Letters 28 (2001): 4015-8.

[6] Stevenson, David J., “Mars’ Core and Magnetism”, Nature 412: 214.

[7] Sprenke, Kenneth L. and Leslie L. Baker, “Magnetization, Paleomagnetic Poles, and Polar Wander on Mars”, Icarus 147 (2000): 26-34.

[8] Roberts, Paul S. and Gary A. Glatzmaier, “Geodynamo Theory and Simulations”, Reviews of Modern Physics 72 (2000): 1081-1123.