

SEARCH AND DISCOVERY

New Data from Mars Hint at a Dynamic Past

As the Mars Global Surveyor orbits the Red Planet, magnetometers aboard the spacecraft have been sending home some astounding data.^{1,2} The instruments have confirmed indications from earlier missions that, if Mars has a global magnetic dipole at all, it is more than 10 000 times weaker than Earth's.³ Nevertheless, the magnetometers find, Mars's surface is dotted with local regions where the magnetic fields are over ten times greater than any perturbations in Earth's global field. Most likely, the local fields stem from an early time when the planet's core was still molten and a magnetic dynamo imprinted its field in the rocks. But the most intriguing discovery by far is the large, linear magnetic structure evident in Mars's southern hemisphere: Along a band extending nearly 2000 km from east to west, the crustal magnetic moments are aligned in one direction; those in adjacent bands appear to be magnetized in the reverse direction, and so forth—for five or six flips of the magnetic field.

These data remind mission scientists of the alternating patterns of crustal magnetization that flank the mid-oceanic ridges on Earth. Observations of such magnetic bands helped clinch the theory of plate tectonics, according to which Earth's surface consists of several independent plates moving relative to one another. The midocean ridges are boundaries between major plates, where partially melted mantle wells up to form new crust. As the melt cools into crust, the magnetization within minerals becomes frozen in the direction of Earth's magnetic field. When the field reverses, as it does a few times every million years, the new crust bears the imprint of the reversed field. As successive crust forms and moves out from the ridge, it carries an alternating pattern of magnetization. The magnetic stripes now seen on Mars suggest that some similar type of plate movement once operated there.

Magnetic measurements

The new data were reported by a team of researchers from NASA Goddard Space Flight Center, the University of Delaware, the University of California at Berkeley, Rice University, and the Centre d'Etude Spatiale des Rayonnements in Toulouse, France. Mario Acuña of Goddard leads the team.

The magnetic stripes recorded by

Magnetic measurements suggest that a process akin to Earth's seafloor spreading once operated on Mars.

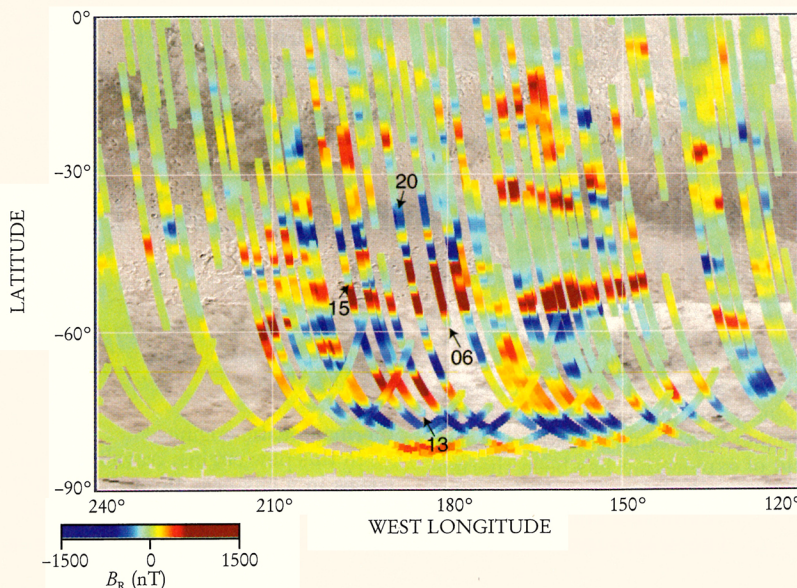
the Mars Global Surveyor (MGS) are shown in the figure. There, each green ribbon traces the path of the spacecraft above the surface while the color code indicates the intensity of the radial (z) component of the magnetic field sensed along these paths. Such alternating peaks and valleys in the magnetic field intensity were seen in the x -component (directed north-south) as well. Magnetometer team member Jack Connerney of NASA Goddard notes that the y (east-west) component was considerably weaker, as expected from a simple model of a series of parallel, infinitely long magnets.

The magnetic bands occur only in Mars's southern hemisphere, where most of the terrain lies above the planet's average elevation. The researchers saw some scattered sources of magnetization in the northern lowlands, but the intensities there were roughly 40 times weaker, the sources were more sparse, and they were not organized into any linear features. The magnetic sources appear to be roughly

correlated with topography; they are stronger and more numerous south of the dichotomy boundary, the rough dividing line between the heavily cratered, old crust to the south and the smooth, relatively young crust to the north. (Young crust is that which has been resurfaced, either by the lava from volcanic eruptions or by sediments carried by wind, water, or ice.) Perhaps, some conjecture, the heat from lava spewed by the enormous volcanoes in the north erased most traces of the magnetism imparted there earlier by an active dynamo.

The magnetic slate may also have been wiped clean in places by the heat of meteoroid impacts; no magnetic sources are seen in the vicinities of the largest impact craters. From this observation, Acuña and his colleagues estimate that Mars's dynamo turned off before these large craters formed, some four billion years ago; otherwise, the ambient field would have left its imprint as the molten material refroze. Mars itself formed about 4.5 billion years ago, so the dynamo may have operated only during the planet's first half-billion years.

The spacecraft magnetometers cannot determine separately the magneti-



ALTERNATING BANDS OF MAGNETIC POLARITY suggest that plate tectonics may once have operated on Mars. Superposed on the topography of part of Mars's southern hemisphere are the paths (green) of the orbiting Mars Global Surveyor and color-coded values of the radial magnetic fields B_R measured by the spacecraft. The stripes of outward-pointing (red) and inward-pointing (blue) fields extend as far as 2000 km. (Adapted from ref. 2.)

zation per unit volume or the depth of material that is magnetized—only the product of those two parameters. When mission scientists make a reasonable—though admittedly arbitrary—estimate of the magnetization, such as 20 amperes per meter (within the range of the most intensely magnetized rocks in Earth's crust), they find that the crust must be magnetized to a depth of 30 km, far exceeding the 1-km thickness of Earth's crust. Ron Merrill of the University of Washington points out that the Martian field may well have changed or even reversed during the cooling of such a thick layer, imparting different magnetizations throughout; he believes that, if plate tectonics did operate on Mars, it had quite a different character from what we see on Earth.

Possible explanations

The magnetic stripes seen on Mars are not as definitive as those extending out from the midocean ridges on Earth. Of course, terrestrial researchers can make measurements more easily than can those experimenters trying to gather data on our planetary neighbor. On Earth, researchers have found that the width of a seafloor region with a given magnetic orientation is on the order of tens of kilometers. On Mars, the bands were found to be 200 km wide—the limit of the spatial resolution from an instrument that can get no closer to the surface than 100 km. The measurements can't resolve any structure finer than this. Also, on Earth researchers have been able to date the seafloor around Earth's midocean ridges, thereby confirming the plate tectonics predictions that the crust is older farther from the ridge. If

one could similarly determine the dates of the Martian crust, it would certainly help to test the conjecture about plate tectonics, but such measurements seem out of the question.

What else besides plate tectonics could explain the extensive magnetic pattern that has been seen on Mars? One possibility described by Acuña is that the Martian surface began as a thin, uniformly magnetized crust that was cracked by the same internal rises that gave birth to some of the planet's large volcanoes. With the pressure from below, the surface may have cracked, much like "a muffin in the oven." (Such aligned cracks, called *graves*, have been seen on Mars's surface.) The crustal bar magnets would have broken in half, giving rise to bipolar fields. Later processes may have spread the fissures apart and filled in the gaps. With this scenario, however, it's hard to explain the enormous extent of the observed features. Another possible explanation for the magnetic bands is that the crust was uniformly magnetized at some point and acquired apparent flips in the field direction as a result of crustal folding, but then one must ask, What could cause folding on such a large and regular scale? A third explanation is that the magnetization stems from chemical rather than physical processes.

The hypothesis of plate tectonics on Mars is not entirely new. Back in 1994, before the MGS flew, Norman Sleep of Stanford University proposed that plate tectonics in the northern hemisphere might account for the formation of the lowlands there.⁴ He speculated that a subduction zone might once have paralleled the line of three large volcanoes there.

Serendipity

The very existence of the recent data that revealed intriguing patterns of magnetization on Mars is an unexpected boon: They were taken during a so-called aerobraking maneuver designed to use the friction of Mars's atmosphere to slow the MGS and change its orbit from highly elliptical to circular. While the MGS was still in its elliptical orbit, it passed about 100 km above Mars's surface once in each circuit. By contrast, in its circular orbit, the spacecraft orbits 400 km above the planet's surface. While at the lower altitude, the MGS instruments picked up the magnetic field intensity with 16 times the sensitivity and four times better spatial resolution than is possible in the 400-km orbit. The aerobraking lasted longer than expected so that researchers accumulated ten times more data in this mode than they had counted on. Unfortunately, the aerobraking phase did not allow complete surface coverage nor measurements at a constant altitude, so the measurements at 400 km, now under way, will be a useful complement.

BARBARA GOSS LEVI

References

1. M. H. Acuña, J. E. P. Connerney, N. F. Ness, R. P. Lin, D. L. Mitchell, C. W. Carlson, J. McFadden, K. A. Anderson, H. Rème, C. Mazelle, D. Vignes, P. Wasilewski, P. Cloutier, *Science* **284**, 790 (1999).
2. J. E. P. Connerney, M. H. Acuña, P. Wasilewski, N. F. Ness, H. Rème, C. Mazelle, D. Vignes, R. P. Lin, D. L. Mitchell, P. Cloutier, *Science* **284**, 794 (1999).
3. M. H. Acuña *et al.*, *Science* **279**, 1676 (1998).
4. N. H. Sleep, *J. Geophys. Res.* **99**, 5699 (1994).

Traveling-Wave Thermoacoustic Heat Engines Attain High Efficiency

With continued concerns about greenhouse gases and ozone-depleting refrigerants, the quest for efficient and environmentally benign engines, heat pumps, and refrigerators remains important. For 20 years, one field of exploration has been thermoacoustics, which involves the interplay between thermodynamics and sound waves. Thermoacoustic engine research has focused almost exclusively on standing-wave engines. Now Scott Backhaus and Greg Swift of Los Alamos National Laboratory have reported a new implementation of a *traveling-wave* thermoacoustic engine—a pistonless Stirling engine that's almost twice as efficient as standing-wave

 A new design efficiently converts heat into useful work without any moving parts.

thermoacoustic engines.¹

In this new engine, traveling sound waves in a gas pass through a tightly packed porous medium called a regenerator. One end of the regenerator is kept at ambient temperature, while the other end is heated, thereby establishing a temperature gradient along the regenerator. Gas molecules are kept at the local regenerator temperature as they oscillate back and forth. As a result, parcels of gas expand as they move toward the hotter end of the

regenerator and contract as they move toward the colder end. This cyclic heat transfer, combined with the alternating compression and expansion of the gas produced by the acoustic waves, produces a net increase in the acoustic energy of the sound wave.

A question of phasing

The pressure and velocity of acoustic waves in a gas have rough analogies in AC electric circuits: The pressure resembles the voltage, and the velocity the current. To get any work out of an AC circuit, the voltage and current must not be 90° out of phase. But in a standing-wave thermoacoustic engine (described by Swift in *PHYSICS*