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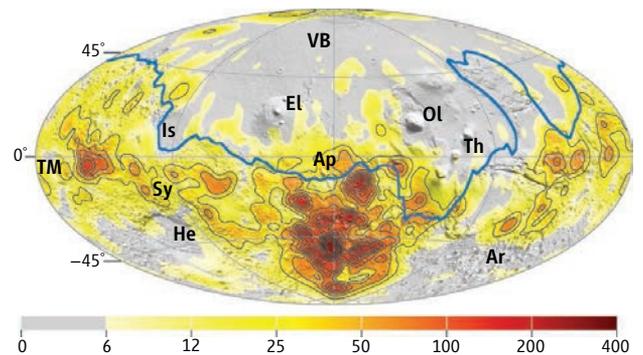
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The Past Martian Dynamo

Benoit Langlais¹ and Hagay Amit²

Measurements by Mars Global Surveyor (MGS) have revealed intense magnetic anomalies mostly located south of the crustal dichotomy, the topographic boundary separating the southern cratered highlands and the northern smooth lowlands. Assuming the dynamo of Mars was similar to that of Earth—dipolar, axial, and centered, the magnetic dichotomy implies that the magnetization of the northern hemisphere was erased at some time, and thus that the dynamo stopped operating very early in its history (1). On page 1822 of this issue, Stanley *et al.* propose an alternative model in which the dynamo is driven by a hemisphere-scale heat flux pattern at the core-mantle boundary (CMB) (2). The proposed thermal constraint is compatible with martian mantle convection models (3) and can also explain the crustal dichotomy (4). In this new scenario, the much weaker crustal magnetization in the northern hemisphere is

A magnetic dichotomy. Predicted magnetic field intensity (nT) at 300 km altitude (from (17), iso-contours are 25 nT), on top of a shaded relief of the martian surface. Northern hemisphere magnetic field anomalies are of the same order of magnitude as terrestrial magnetic field anomalies at similar altitude, and approximately one-tenth of what is measured in the southern hemisphere. The large impact craters, as well as the large volcanic provinces, show no appreciable magnetic fields at high altitude. Blue line represents the crustal dichotomy. VB, Vastitas Borealis; EL, Elysium; OL, Olympus; IS, Isidis; TH, Tharsis; AP, Apollinaris Patera; TM, Terra Meridiani; SY, Syrtis Major; HE, Hellas; AR, Argyre.



Numerical dynamo modeling studies may explain the observation that strong magnetic fields are only found in Mars's southern hemisphere.

not a result of a post-dynamo process such as a giant impact (5), but rather, it was never magnetized in the first place.

Thermal core-mantle coupling can explain some features related to Earth's dynamo. Evidence suggests that the heterogeneous lower mantle affects convection and dynamo action in Earth's outer core. Paleomagnetic field models time-averaged over the past 5 million years show deviations from axial sym-

metry (6). Core flow models time-averaged over the past 150 years show persistent non-axisymmetric features (7), and the seismic properties of the upper part of Earth's inner core also exhibit an east-west hemispheric dichotomy (8).

Dynamo simulations with heterogeneous heat flux boundary conditions have been used to study the possible impact of the mantle on Earth's dynamo (9). The models successfully

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explain some of the observed non-axisymmetric features, such as the locations of the high-latitude intense geomagnetic flux patches in the modern era (10). A recent study recovered large parts of the time-averaged patterns of the paleomagnetic field, historical core flow, and inner-core buoyancy flux hemispheric dichotomy (11). In these models, core convection is primarily driven from below, whereas the variable boundary heat flux controls its long-term pattern. An upper bound for dynamo action was reported for this type of moderate heat flux anomaly amplitude (9).

Stanley *et al.* assume much stronger heat flux heterogeneities at the martian CMB, with convection driven from above maintaining the dynamo. Other aspects that differ from most geodynamo models (9–11) include stress-free boundary conditions and hyperdiffusivities. Two additional modeling issues concern the state of the martian core and the heat flux pattern. First, it is thought that the martian core was completely liquid during the first 500 million years (the Noachian era) (12). The effect of absence of an inner core therefore has to be evaluated. Second, the proposed dynamo model concentrates its field lines where the heat flux is the largest, i.e., below a cold downwelling mantle, whereas others (4) suggest that the thickened crust of the southern hemisphere is related to upwelling. The hemisphere-scale convection pattern in the mantle and its relationship with surface features clearly need to be better understood. Recovery of the single-hemisphere dynamo using different dynamo modeling methods and assumptions may strengthen the robustness of the proposed scenario.

Very little is known about the weak magnetic field signature of the northern lowlands. At 400 km altitude, where MGS spent most of its time, it is indeed very low, with a maximum of 20 nT above Vastitas Borealis. The absence of magnetization in the northern hemisphere (see the figure) may well be due to the single-hemisphere dynamo proposed by Stanley *et al.*, but one can invoke other hypotheses. For example, serpentinization of the southern hemisphere lithosphere, associated with magnetite crystallization and crustal material density decrease (13), could also explain the magnetic and topographic patterns on Mars, as could rapidly varying magnetization directions resulting in null to weak fields at spacecraft altitudes.

The proposed model of Stanley *et al.* resolves a number of apparent discrepancies on Mars. The existence of such thermal wind dynamos may open a new avenue for dynamo modeling, for Earth but also for other planets, such as Mercury (14). As with Uranus and Neptune, and as opposed to Earth, Jupiter, and Saturn (15), the current model shows that the

past martian magnetic field was possibly non-dipolar and non-axisymmetric. Additional computations and observations are required to validate or dismiss their model. The next breakthrough will come from new observations, first when low-altitude measurements of the magnetic field are made (16) and when surface geophysical (seismic, magnetic, and heat flow) measurements are taken as planned by the European Space Agency's forthcoming Exomars rover and associated lander mission. These measurements will give some hints on the current lithosphere thickness, its origin, its relationship with possible hemisphere-scale convection, and the existence of a solid inner core. Combined with thermal evolution models, it will be possible to estimate the thermodynamic conditions on Mars during its early days. These inferences will introduce new geodynamic constraints on models of the past martian dynamo and may shed light on the reasons for its demise. The martian magnetic history is not yet over.

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