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Mars magnetic field intensity: Relationship to core-mantle boundary thermal variability

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Abstract

The high intensity of the martian crustal magnetic field has implications for the crustal magnetic carriers and thickness of the magnetized crust. The magnetization of crustal rocks depends on the strength of the dynamo-generated magnetizing field. Here we use numerical dynamo models to demonstrate that the magnetic field strength can depend on lateral core-mantle boundary (CMB) thermal variations. Specifically, if Mars' crust was magnetized by a hemispheric dynamo resulting from a zonal degree-one CMB heat flux variation, then the magnetic energy increases with the magnitude of thermal variability.

1. Introduction

The crustal magnetic field of Mars was most likely generated by a dynamo that was operational for a short time early in Mars' history [1]. The crustal magnetic field is more intense in the southern hemisphere than the northern hemisphere, with the intensity in certain regions very high (about 20 times more intense than fields found on Earth) [2].

Various explanations have been put forth to explain the spatial distribution of the martian crustal fields. Post-dynamo explanations for the lack of strong fields in the northern hemisphere include hydrothermal alteration [3] or impact demagnetization [4]. Alternatively, the correlation of the magnetic field with the hemispheric crustal dichotomy led Stanley et al. [5] to propose that the formation of the crustal dichotomy could have resulted in lateral heat flux variations at the CMB of Mars. They showed that degree-one heat flux variations could result in a single-hemisphere dynamo with strong magnetic fields only generated in the southern hemisphere. This provided a possible explanation for the concentration of intense fields in the southern hemisphere without relying on post-dynamo mechanisms.

In order to explain the strongest magnetic anomalies on Mars, strongly magnetizable minerals and/or thick layers of magnetized crust are invoked. However, in order to constrain these processes, the intensity of the magnetizing field must be assumed [6].

Typically, scaling laws such as magnetostrophic balance are used to estimate the strength of Mars' ancient dynamo. However, if lateral heat flux variations at the CMB significantly affected the dynamo, it is possible that other force balances determined the strength of the martian dynamo-generated field.

Here we use dynamo models to investigate the sensitivity of the magnetic field intensity to CMB variable heat flux (VHF) patterns. We consider a range of VHF patterns and magnitudes.

2. Methods

We use the numerical dynamo model of Kuang & Bloxham [7, 8] with the parameter values given in Table 1. We impose various simple spherical harmonic VHF patterns on the core mantle boundary (CMB). We consider both zonal and sectoral VHF patterns of low degree L and order m and compare them to a model with homogeneous heat flux.

Table 1: Dynamo Model Parameters. The first four non-dimensional numbers are defined in [8]. Δq_σ is the r.m.s. of the imposed heat flux variations on the CMB and q_0 is the average super-adiabatic heat flux on the CMB. L is spherical harmonic degree and m is spherical harmonic order. The range of values in the $\Delta q_\sigma/q_0$ and L, m rows describe the range of models we consider.

Parameter	Value
Rayleigh #	5000
Prandtl #	1
Magnetic Rossby #	2×10^{-5}
Ekman #	2×10^{-5}
$\Delta q_\sigma/q_0$	$0 \rightarrow 13.5$
L, m	0,1,2

3. Results

In Figure 1 we show the relationship between magnetic energy and CMB heat flux variation for the models in Table 1. The zonal VHF pattern models have larger magnetic energy than the sectoral patterns for a given $\Delta q_\sigma / q_0$. In addition, the zonal VHF patterns result in increasing magnetic energy with $\Delta q_\sigma / q_0$ whereas the sectoral harmonics models display a slight decrease.

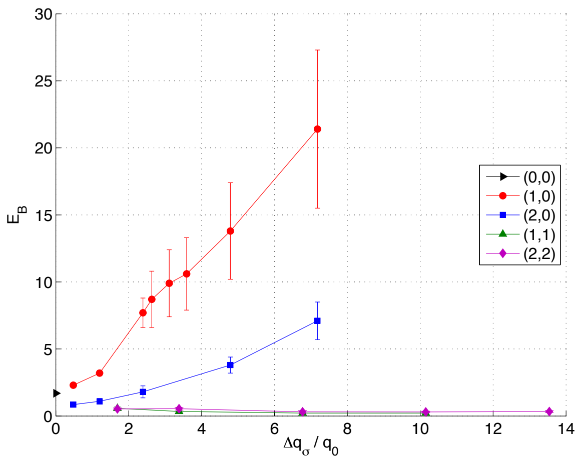

Figure 1: Magnetic energy as a function of r.m.s. heat flux variation for the models in Table 1. The $L = 1, m = 1$ curve (green) is very similar to the $L = 2, m = 2$ curve (magenta) and therefore hidden beneath it.

4. Discussion and Conclusions

Our results demonstrate that the dynamo can be very sensitive to the CMB VHF pattern. Zonal patterns appear to promote magnetic field energy whereas sectoral patterns do not. This is likely due to the fact that in the absence of VHF patterns, the dynamo produces a dominantly axisymmetric field. Zonal VHF patterns are axisymmetric and hence don't disturb the dynamo's natural inclination to axisymmetry whereas sectoral harmonics are completely non-axisymmetric and hence may work against the natural state of the dynamo.

If Mars' crustal dichotomy formed in its present orientation, and a hemispheric dynamo explains the magnetic field spatial distribution, these results imply that the dynamo-generated field may have been more intense than standard magnestrophic balance estimates would predict. This more intense magnetizing field would relax some of the constraints placed on the required magnetic minerals or magnetized layer thickness assumed for the martian crust.

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