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Mercury's Weak Magnetic Field: Result of Magnetospheric Feedback?

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1 Introduction

The magnetic field of Mercury has been a topic of study since its discovery by the Mariner 10 spacecraft. The internal field is weak when compared to other solar system dynamos (e.g., the surface field is about one order of magnitude weaker than that of Ganymede), and there have been a variety of suggestions for how such a weak field may originate. A few models bypass the need for a conventional dynamo in a convective core, by invoking core-mantle boundary (CMB) topography [1] or crustal magnetization [2]. The confirmation that Mercury has a liquid outer core [3] has given support to the possibility of a dynamo. However, scaling laws for dynamos cannot yet account readily for the weak field. It has been proposed that the outer core of Mercury may not be fully convective but rather is stably stratified at its top with a convective layer at its base [4]. If this is the case, the magnetic field at the surface would be strongly damped by the skin-depth effect of diffusion through the non-convective layer at the top of the core, which would suppress preferentially the field's small-scale and high-frequency components.

At Mercury, the combination of the weak internal field and comparatively strong solar wind suggests that the magnetic field induced by magnetospheric currents may exert an important influence on the dynamics of the core dynamo [5]. Here we utilize dynamo simulations to propose that such magnetospheric feedback may have maintained Mercury's dynamo in a weak-field state for most if not all of the history of the planet's internal magnetic field.

2 Methodology

We integrate the Navier-Stokes equation for an incompressible, electrically conductive fluid in a spherical shell of internal radius r_i and external radius r_o rotating with an angular velocity $\mathbf{\Omega} = \Omega\,\hat{\mathbf{z}}$. The magnetic field induced by the magnetosphere, $\mathbf{B_m}$, is modeled as an axial field that is spatially homogeneous: $\mathbf{B_m} = s\,B_i\,\hat{\mathbf{z}}$ [6], where $s = |g_1^0|/g_1^0$ indicates the direction of the dynamo-generated axial dipole $\mathbf{B_{dip}}(r,\theta,\phi) = (r_o/r)^3\,g_1^0[\cos\theta\,\hat{\mathbf{r}} + \sin\theta\,\hat{\theta}]$, and B_i is the magnitude of the magnetospheric-induced field.

We studied the effects of various values of B_i on self-sustained dynamos for which the undisturbed field is non-reversing and dominated by the dipolar component (and for which $r_i/r_o = 0.35$). We studied the time development of the dynamo under two different conditions, a weak initial condition (WIC) and a strong initial condition (SIC), where weak and strong denote the magnitude of the dipolar field at the beginning of the simulations, i.e., g_1^0 at time $t = 0$.

3 Results

As a measure of the magnetic energy in the system we use the the ratio of Lorentz to Coriolis forces, i.e., the Elsasser number, $\Lambda = \langle B^2 \rangle\,(\rho\,\mu_0\,\lambda\,\Omega)^{-1}$, where μ_o is the magnetic permeability of vacuum, ρ is the bulk density of the fluid core, and the angle brackets indicate space and time averages. Here we use two different time-averaged quantities: the volumetric and time average per unit volume, i.e., Λ, and the CMB surface and time average per unit area, Λ_o. In Figure 1 we show Λ and Λ_o as functions of the imposed field magnitude, B_i.

We find that the WIC models result in solutions for which the observable magnetic field is weak (low Λ_o). Such solutions are found for values of $B_i \geq 0.01$. In contrast, the SIC models result in weak solutions only when $B_i \geq 0.5$, and those are highly variable in time. This result implies that magnetopheric-induced feedback is not likely to modify the dynamo-generated solution for SIC models unless the magnetospheric-induced field is unrealistically large. However, given an originally weak dynamo-generated field (e.g., WIC models), magnetospheric feedback can provide a mechanism for a sustained weak field that displays observable secular variation

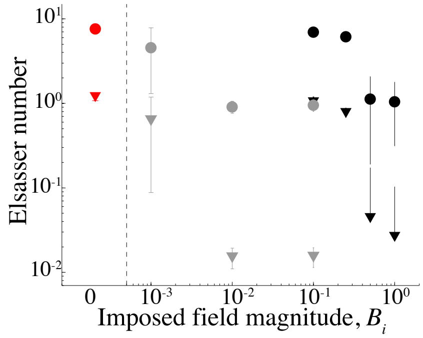

Figure 1. Elsasser numbers averaged for two magnetic diffusion times for the entire shell (circles) and the core-mantle boundary (triangles) as functions of imposed field intensity. Black symbols correspond to SIC, and gray to WIC. For comparison, we include on the left the control model for which $B_i = 0$ (red).

(see standard deviation in time shown by error bars).

From snapshots of the models we can extrapolate the observable radial magnetic field to spacecraft altitudes. In Figure 2, we show the radial field for a model without feedback and for a WIC model with $B_i = 10^{-2}$ (a value comparable to that expected at Mercury). The magnitude of the observable field

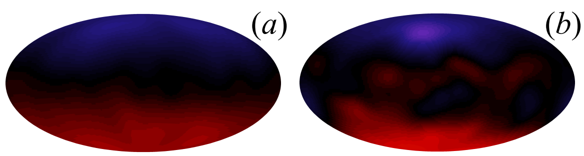

Figure 2. Radial component of the magnetic field for (a) a model without feedback, and (b) a WIC model with $B_i = 10^{-2}$. The field has been upward continued to a spacecraft altitude of 200 km. The core radius is $0.8R_\mathrm{M}$, where R_M is Mercury's radius. Color scales are -10^3 to 10^3 nT in (a) and -10^2 to 10^2 nT in (b).

is comparable to that seen at Mercury [7] and is weak when compared to the solution without magnetospheric feedback.

A high solar wind pressure at Mercury's orbit plays an important role in the size of the magnetosphere. The magnetopause is located at the point where the dynamo-generated magnetic field pressure balances the solar wind pressure. In the early solar system, the solar wind density was higher, possibly by a factor of up to 1000 [8]. The present solar wind pressure at Mercury's orbit would then have been found at $\sqrt[3]{1000}R_{orb} \sim 3.5$ AU. This result implies that magnetospheric feedback was more important in the early solar system, and it may have affected other terrestrial planets.

What was the origin of the weak initial field in Mercury? One possibility is that the initial seed field of the dynamo had a very weak dipolar component. This condition is not unlikely if the seed field was the relatively weak and highly variable interplanetary magnetic field. Alternatively, a weak self-sustained dynamo may have been present at a later time in the history of the planet. Such a scenario may have been the result of a dipole polarity reversal [9], core geometry [10], or a sufficiently strong convective forcing to result in a multipolar dynamo [11].

4 Conclusion

We have found that magnetospheric feedback is an efficient mechanism for stabilizing weak dynamos. If the magnetic field of Mercury is being generated in a fully convective outer core and stabilized by magnetospheric feedback, secular variation of the field is predicted. However, it may prove difficult to separate the variability of the magnetospheric fields from that of the interior field. Magnetic field measurements during periods longer than the nominal MESSENGER mission, as well as later measurements from other spacecraft (e.g., BepiColombo), will serve to test the feedback hypothesis.

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