MAGNETIC FIELD AT MERCURY: EFFECTS OF EXTERNAL SOURCES ON PLANETARY DYNAMOS

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Introduction: Intrinsic magnetic fields in celestial bodies may be attributed to planetary dynamo processes. On Earth, the molten iron core convects, generating a magnetic field. Such a field causes secular variations as well as polarity reversals that may depend on the thermal and chemical equilibrium of the core. Numerical models of Earth's dynamo have been successful in reproducing such features, despite the use of non-realistic physical parameters – energy diffusion is assumed to be large compared to that expected in planetary interiors [e.g., 1]. Dynamo theory is consistent with magnetic fields measured at Earth, the Sun, the gas giants, and the ice giants but it is hard to reconcile with the magnetic field found at Mercury [e.g., 2]. In general, planetary dynamos show a balance between Coriolis and magnetic forces [3]. Under special conditions, dynamos may have a weak magnetic field where the Coriolis force is greater than the magnetic force (i.e., the Elsasser number $\Lambda < 1$). Taking into account the rotation rate and the size of the planet, Mercury's Coriolis force may be up to four orders of magnitude stronger than the magnetic force at the core–mantle boundary (CMB). Some authors have argued that the weak magnetic field may be caused by crustal remanent magnetization as opposed to present dynamo action [e.g., 4]. Recent measurements, however, have found no evidence of a correlation between surface topography and magnetic field magnitude [5]. If a dynamo is present in Mercury's core, it needs to be understood how such a weak dynamo is possible. Christensen [6] and Wicht et al. [7] have argued that the liquid core in Mercury may be stably stratified at its top, and a deep dynamo generates a magnetic field that has a significant Lorentz force. The magnetic field diffuses then through the current-free, stagnant, liquid iron and is significantly weakened farther from the source, i.e., at the CMB and at spacecraft altitude.

Here we study yet another possible mechanism that may affect magnetic field generation in Mercury. In Mercury, the currents in the magnetosphere are so strong that the field induced by them is estimated to be of the order of 4% of the total field measured at the CMB [8, 9]. The influence of external fields on dynamo field generation has been marginally studied in the context of the Jovian moons [10, 11], and it was found that the effect of the strong magnetospheric currents may have a defining effect on the character of the dynamo. A "feedback dynamo" has been proposed [9], but the effect of such feedback in three-dimensional dynamos has not been studied. We present a systematic study where the influence from an external field that opposes the internal dipole direction affects internal field generation and changes the reversal frequency and the total magnetic energy of the dynamo.

Planetary dynamos and external fields: For this study we used an existing numerical solution of the equations of motion of an electrically conductive liquid in a rotating spherical shell of internal and external radii r_i and r_o, [12]. The solution is found by the time evolution of the magnetic field induction and velocity vector fields ($\mathbf{B}$ and $\mathbf{u}$, respectively) in addition to the temperature scalar, T. They follow from:

$$\begin{aligned} E &\left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u} - \nabla^2\mathbf{u}\right) + 2\hat{\mathbf{z}}\times\mathbf{u} \\ = &-\nabla P + \frac{R_a E}{P_r}\frac{g}{g_o}\hat{\mathbf{r}}T + \frac{1}{P_m}(\nabla\times\mathbf{B})\times\mathbf{B}, \quad (1) \end{aligned}$$

$$\nabla\cdot\mathbf{u} = 0, \qquad \nabla\cdot\mathbf{B} = 0, \qquad (2)$$

$$\frac{\partial T}{\partial t} + \mathbf{u}\cdot\nabla T = \frac{1}{P_r}\nabla^2 T, \qquad (3)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla\times(\mathbf{u}\times\mathbf{B}) - \frac{1}{P_m}\nabla^2\mathbf{B}, \qquad (4)$$

where t is time scaled as the viscous diffusion time, $\tau_\nu = D^2\nu^{-1}$, $D = r_o - r_i$, and ν is the viscous diffusivity. g and g_o are the radially varying acceleration of gravity and its value at $r = r_o$, respectively. The fluid is defined by the non-dimensional parameters: R_a, the Rayleigh number defining the ratio between convective and conductive heat transfer; E, the Ekman number, the ratio between the viscous and Coriolis forces; P_r, the Prandtl number, the ratio of viscous to thermal diffusivities; and P_m, the magnetic Prandtl number, the ratio of magnetic to thermal diffusivities.

In order to introduce the external field, the top boundary condition is expressed as a combination of internal (dynamo-induced field) and external (induced from the magnetosphere) parts. We explore three sets with identical physical parameters and boundary conditions with the exception of the Rayleigh number, which is $13R_{a_c}$ in set A, $20R_{a_c}$ in set B, and $30R_{a_c}$ in set C; R_{a_c} is the critical Rayleigh number for the onset of convection.

The external field is homogeneous in space and constant in time. It is chosen to have a magnitude B_o for time $t > 0$, and it is aligned with the axis of rotation. In order to simulate a Mercury-like environment, the direction of the external field is chosen to oppose the internal dipole of the control solution (that with $B_o = 0$).

Results: Since the three regimes studied differ in the resultant magnetic field strength, we use the time-averaged field at the CMB for each set, to compare the strength of the external field, B_o, to that of the non-disturbed solution. Thus, when referring to an $x\%$ external field the reader may understand that $x = B_o/B_{rms}^{CMB} \times 100\%$, where B_{rms}^{CMB} refers to the solution with the external field equal to zero.

The most stable dynamo regime studied, set A, is greatly affected by external fields greater than 3% of the original CMB field. Sets B and C, with stronger convection, result in control cases with less dipolar solutions and are affected by relatively weaker (1% or 2%) external fields.

The total magnetic energy is lessened by the diffusing external field while the internal and external dipole polarities are opposed and increases right after the internal dipole polarity is reversed. The most dramatic effect in the total energy is found for set A (where the original dipole is dominant). The geometry of the flow changes when the magnetic energy is at its minimum, and it is restored back to that of the control case when the internal and external dipole are parallel and the Lorentz force is restored. In contrast, set C does not need a strong external field to stabilize the dipole polarity and inhibit the natural dipole reversal. The flow does not change significantly, and the kinetic energy dominates the dynamics of the system.

We find that the influence of an external field is great when the internal dynamics yields a stable dipole and that it affects significantly the energy balance (the Elsasser number). Chaotic reversing dynamos may also be affected by the external field, but it is likely that the destabilization of the dipole may be too fast; the external field does not penetrate far into the liquid core, resulting in very weak dipole (weaker than the undisturbed solution).

The magnetic field at Mercury is very likely to be affected by the external field, and the extent of this influence may be dramatically affected by the time stability of its own dipolar component. In any case, the influence of the magnetospheric fields is very likely to depress the dipolar component at the CMB when compared with an undisturbed system and may serve as an explanation for the weak magnetic field of Mercury.

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