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Internal forcing of Mercury's long period free librations

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Abstract

Observations of Mercury's spin rate suggest that, in addition to the forced 88-day mantle libration induced by solar torques, a decadal timescale libration may also be present. It has been proposed that this signal represents an amplified forced libration caused by the periodic 11.86 yr perturbation on Mercury's orbit by Jupiter. Here, we investigate the possibility that a decadal libration may be produced by a forcing internal to the planet. Our mechanism is based on the presence of time-dependent zonal flows generated by convective dynamics in Mercury's fluid core. Through electromagnetic coupling, these flows entrain longitudinal displacements of the inner core, which then entrain mantle librations by gravitational coupling. We construct a simple model to capture this exchange of angular momentum and we show that when the period of the zonal core flows approaches a free libration mode, amplification occurs. Our results suggest that for plausible values of Mercury's internal magnetic field, if the inner core of Mercury is large ($\geq$ 1000 km), decadal mantle libration amplitudes of the order of 10 arcsec can be generated by zonal flows of the order of 1 km yr^{-1}.

1. Introduction

The period of the free mantle libration about the Mercury-Sun line is predicted to be 12.07 yr [3]. Through gravitational coupling with the mantle, the presence of an inner core can lengthen this period (the free mantle-inner core (MIC) libration) up to 19 yr [2]. A second free libration exists, the out-of-phase free gravitational oscillation between the mantle and inner core (MICG mode) which can vary between 4 - 16 yr depending on model parameters [2].

In the absence of an ongoing excitation mechanism, free librations are expected to be completely attenuated. However, if a forcing acts on a timescale close to the period of a free mode, resonant amplification can occur. Here, we investigate whether this forcing can be of internal origin. The basic scenario we propose is inspired from turbulent MHD convective dynamics in spherical shells which naturally produce time-dependent zonal flows. If Mercury's fluid core include such temporally varying zonal flows, they will entrain longitudinal displacements of the inner core by electromagnetic (EM) coupling, and the latter will entrain mantle librations by gravitational coupling. We expect zonal flows to have a white spectrum in frequency, but amplification by resonance will occur at periods close to MIC and MICG modes. Our goal is to establish whether such a mechanism can generate a potentially observable libration amplitude.

2. Model

We consider a three-layer model of Mercury, where the solid inner core, fluid outer core, and mantle each have a uniform density. All asymmetrical densities are modelled in terms of the equatorial ellipticities of the external surface, the core-mantle boundary (CMB) and the inner-core boundary (ICB). Interior models of Mercury are constructed by following the approach of ref. [5]. Tthe ellipticities at each boundary are uniquely determined by the requirement that the ratio of moment of inertia $\Delta I_m = (B_m - A_m)/C_m$ and gravity coefficient C_{22} are consistent with observations: $\Delta I_m = (2.03 \pm 0.12) \times 10^{-4}$ [3] and $C_{22} = (0.81 \pm 0.08) \times 10^{-5}$ [4]. This allows us to calculate, for every internal model, the strength of gravitational coupling between the mantle and inner core [5].

The internal forcing mechanism we propose is based on the presence of time-dependent zonal flows in Mercury's fluid core. Differential motion at the ICB shears radial magnetic field (B_r) lines crossing the boundary, producing a periodic EM torque on the inner core. The strength of this torque depends on the geometry and amplitude of the radial magnetic field. Here, we use a simple dipolar geometry, with 2 different choices of field strength: case 1) the amplitude at the ICB is equal to that at the CMB as derived from MESSENGER observations (e.g. $g_1^0 = 195$ nT, [1]); and case 2) the ICB field is 10 times larger than at the

CMB.

We build a system of angular momentum exchange between the mantle, fluid core, and inner core that includes the solar gravitational torque acting on the asymmetric figures of the mantle and inner core, their mutual gravitational interaction, and the EM torque at the ICB. We also include viscous deformation of the inner core (in a characteristic time τ); since the viscosity of Mercury's inner core is unknown, we leave it as a free parameter. The forcing in our system takes the form of periodic longitudinal displacements in the FOC, representing convection-induced time-dependent zonal flows. Analytical solutions for the forced librations of the mantle and inner core are found as a function of the frequency and amplitude of the forcing.

3. Results

Fig. 1 shows the flow amplitude at the ICB required to produce a mantle libration of 35 arcsec, for different choices of τ, for our two choices of ICB B_r-field strength, and when the period of the forcing is close to the MICG and MIC free modes. For case 1, at large τ, flow amplitudes of 100 km yr^{-1} are required to produce a mantle libration of 35 arcsec. (These results can be scaled linearly for different libration amplitudes; a 3.5 arcsec mantle libration requires flows of the order of 10 km yr^{-1}.) For case 2, at large τ, typical flow amplitudes of 1 km yr^{-1} produce a mantle libration amplitude of approximately 10 arcsec. In all these cases, the inner core radius must be larger than 1000 km.

4. Discussion and Conclusion

The results of our simple model suggest that, if the inner core of Mercury is large ($\geq$ 1000 km) and its viscous relaxation timescale exceeds 10 yr, mantle libration amplitudes of the order of a few 10's of arcsec can be generated by an internal forcing. Turbulent convective dynamics in a spherical shell naturally produce zonal flows with temporal fluctuations over a broad frequency spectrum. Our mechanism requires that the zonal flows at decadal timescale in Mercury's core have an amplitudes of the order of 1 km yr^{-1}. Whether the convective dynamics of Mercury can generate such flows is unknown. Future magnetic field observations may detect a secular variation from which typical core flow velocities can be reconstructed. Ongoing observations from Earth-based radar techniques [3] and satellite missions may eventually cover a sufficiently long time interval and be of sufficiently good quality to robustly reconstruct the libration of Mercury at decadal timescale, or the lack thereof. Since an inner core larger than 1000 km significantly affects the long-period librations, constraints on the size of Mercury's inner core may then be obtained on the basis of these observations.

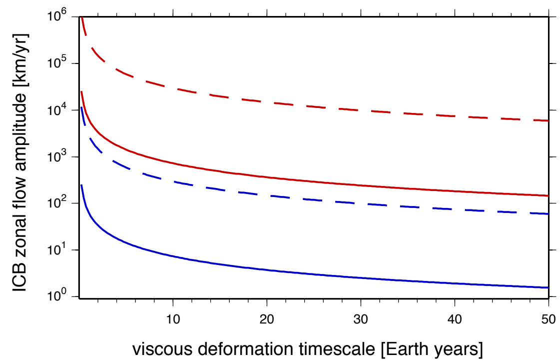

Figure 1: Amplitude of mean zonal flow at the ICB required to generate a mantle libration of 35 arcsec, as a function of τ. Red lines correspond to case 1 ($B_r^{ICB} = B_r^{CMB}$); blue lines to case 2 ($B_r^{ICB} = 10 \cdot B_r^{CMB}$). Solid (dashed) lines correspond to the peak resonance amplitude at the period of the MIC (MICG) mode.

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