SF2A 2006
D. Barret, F. Casoli, T. Contini, G. Lagache, A. Lecavelier, and L. Pagani (eds)

LIBRATIONS OF MERCURY DUE TO CORE-MANTLE COUPLINGS

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Abstract. Mercury is an extreme of our planetary system. It is the closest planet to the Sun and has the highest uncompressed density of all planets, indicating the existence of a large core. The detection of a magnetic field suggests that at least an upper layer of the core is still liquid and generates a magnetic field by dynamo action. These properties are major challenges for scenarios of Mercury's formation and play an important role in constraining and testing dynamical and compositional theories of planetary formation. Measurements of librations of Mercury, which depend on solar and planetary torques as well as on Mercury's shape and internal structure, will provide crucial information on geophysical parameters such as the size of the core and sulfur concentration of the core.

We investigate the librational response of the planet with particular emphasis on the influence of core-mantle coupling mechanisms. We use the $SONYR$ model of the Solar System in order to reach a very accurate rotational motion of Mercury, and we introduce various core-mantle couplings (inertial, electromagnetic, viscous) to study their effects on libration, and to isolate the signature of the relevant geophysical parameters. Notably, we find that the amplitude of the 88-day libration presents a strong dependence on the radius of the core or, equivalently, on the concentration of sulfur in the core, and the range of amplitude values is larger than the observational accuracy of NASA MESSENGER and ESA BepiColombo missions, indicating the possibility to discriminate between models of internal structure by using accurate libration measurements.

1 Introduction

The internal structure of Mercury is enigmatic and studies suggest that its core is at least partially liquid (Margot et al. 2004; Peale et al. 2002). Inner and outer core properties depend critically on core sulfur concentration and temperature, which are determined by conditions at formation and by the evolution over geological timescales of the planet. Consequently, the accurate determination of the present state of the core will provide crucial constraints on the history of the Solar System.

We investigate the librational response of the planet, which depend on solar and planetary torques as well as on Mercury's shape and internal structure, in a realistic model of the dynamics of the Solar System, called SONYR. We introduce various core-mantle couplings (inertial, electromagnetic, viscous) to study their effects on libration, and to isolate the signature of the relevant geophysical parameters.

2 SONYR model

A relativistic spin-orbit model of the Solar System has been gradually elaborated from a post-newtonian formulation of a system of N arbitrarily extended, weakly self-gravitating, rotating and deformable bodies in mutual interactions (firstly, BJV model for planets translational motion and Moon's spin-orbit motion; then SONYR for its extension to spin-orbit couplings and core-mantle couplings of terrestrial planets (Bois 2000; Bois & Girard 1999; Bois & Vockrouhlicky 1995; Rambaux & Bois 2004). The SONYR model is used here as it performs an accurate simultaneous integration of the spin-orbit motion of Mercury. We introduce various core-mantle couplings. (i) Inertial coupling that results from the dynamical motion of the fluid core, which exerts pressure on the triaxial ellipsoidal shape of the core-mantle boundary. In this case, fluid's motion essentially corresponds to a rotation of the core as if it where a solid. (ii) Magnetic coupling acts when the solid mantle and ! the liquid

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core of the body are conducting layers, which is likely the case for Mercury. Magnetic coupling is a dissipative coupling. (iii) Viscous coupling is created by the existence of fluid motions in a viscous core and damps the relative motions of the core and mantle. The existence of turbulence may enhance the effective viscosity of the fluid.

3 Internal structure models

Mercury presents a large core consisting mainly of iron (Fe). The detection of a magnetic field (Ness et al. 1975) suggests that at least an upper layer of the core is still liquid and generates a magnetic field by dynamo action. A small amount of sulfur (S) is sufficient to depress the freezing temperature of the core alloy and keep the core liquid (Schuber et al. 1988). A series of models of internal structure of Mercury (mantle, core and inner core) has been developed in order to study the effect of the core of Mercury on its librations. We use models with a range of mean sulfur concentration in the core between 0.1 and 14 wt% (weight percentage; see Van Hoolst & Jacobs (2003) for more details on the interior models). For each model (uniquely defined by S and the inner core radius R_{ic}) we calculated the mean moment of inertia I_c of the core plus inner core, and the whole planet moment of inertia I that are the dynamical parameters acting on the rotational motion of the planet. We defined a reference model composed of three layers of radius 635.00, 1858.13, and 2439 km and 0.1 wt% of sulfur in the outer core.

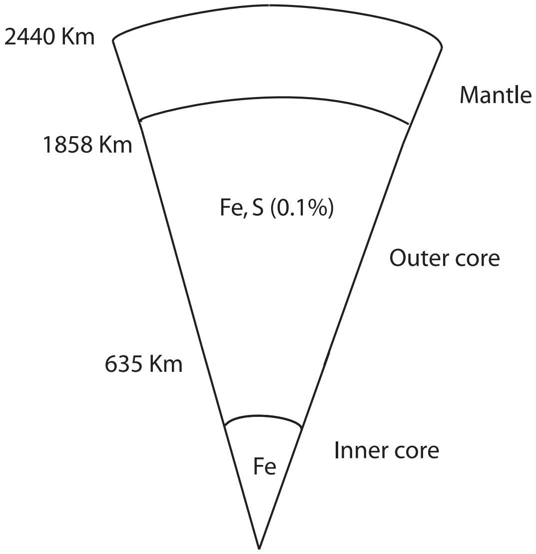

Fig. 1. Reference model of the interior of Mercury.

4 Centrifugal librations

We calculated the dynamical behavior of the rotational motion of Mercury considered as a solid homogeneous body and as a body with two layers, a liquid core (composed of inner plus outer core) and a solid mantle. We determined the Mercury's libration for a large set of interior structure models defined in previous Section. We find a relationship between the relative amplitude librations ΔA_φ (with respect to the reference model defined in Figure 1) and the mean core sulfur concentration expressed as:

$$0.0 \text{ as} < \Delta A_\varphi < 20 \text{ as} \quad \text{for} \quad 0.1 < S < 14 \text{ wt\%}$$

The range amplitude is larger than the observational accuracy of NASA MESSENGER and ESA Bepi-Colombo missions (3.2 as) (Solomon et al. 2001; Milani et al. 2001), indicating the possibility to discriminate between models of internal structure by using accurate libration measurements.

For a correct interpretation of libration data, all possible effects on libration must be included. In this theoretical study, we investigate the possible effects of inertial core-mantle coupling on the libration of Mercury.

We use several values for the CMB flattening (some of them large) to explore different possibilities and to obtain an upper limit for the effect of inertial coupling on libration (Table 1). The signature are faint with respect to the 20 as.

Inertial coupling	ΔA_φ (mas)
$\alpha_c = 10^{-3}, \beta_c = 0$	7.5
$\alpha_c = 10^{-4}, \beta_c = 0$	1.125

Table 1. Signature of the core-mantle boundary triaxiality on librations. α_c and β_c polar and equatorial core flattenings.

In addition to the inertial coupling, which is a conservative coupling, we have introduced the viscomagnetic coupling, which is a dissipative one. The magnetic field of Mercury is of the order of $B_0 = 400$ nT and acts when the solid mantle and liquid core are conducting layers. Following the formulation for the Earth (Buffett 1992; Greff & Legros 1999), we have calculated the signature of the magnetic coupling on libration. We also took into account the viscous coupling coming from the turbulent motion in the core fluid (with an Eckman number of 10^{-15}). The signature on the 88-day libration is negligible (Table 2).

Viscomagnetic coupling Frictional constants	ΔA_φ (mas)
$K_{mc} = 2.37 \times 10^{-7}$ $K_{vc} = 9.1 \times 10^{-8}$	~ 0.0050
$K_{mc} = 1.26 \times 10^{-7}$ $K_{vc} = 5.31 \times 10^{-8}$	~ 0.0025

Table 2. Signature of the viscomagnetic coupling on librations for frictional constants (K_{mc} and K_{vc}, see Greff & Legros 1999) for two extremes interior models. In the calculation of K_{mc} and K_{vc}, we taken $B_0 = 400$ nT, magnetic field measured at the surface of Mercury. $E = 10^{-15}$ Eckman number similar for the Earth.

5 Characteristics time

The combination of ground-based radar measurements, MESSENGER and BepiColombo may allow to detect the impact of the core on longer time scales up to 20 years (BepiColombo is scheduled for arrival in 2019). The 3:2 spin-orbit resonance of the hermean motion generates a resonant period of 15.8 years for a solid homogeneous case (Rambaux & Bois 2004). For the model with a liquid core, this period varies between 10.61 and 11.82 years. If the long-term libration will be observed by accumulating observations, its period could be used as an additional constraint on the interior of Mercury.

We also calculated the impact of the interior structure for the Free Core Nutation (FCN) period and for the damping time τ due to dissipative couplings (see Figure 2). We found periods of 600 to 850 years for the FCN and from 50,000 to 90,000 years for the damping time.

6 Conclusion

We have analyzed and identified the different families of rotational librations resulting from core-mantle couplings. Notably, we find that the amplitude of the 88-day libration presents a strong dependence on the radius of the core or, equivalently, on the concentration of sulfur in the core. The range of amplitude values is larger than the observational accuracy of NASA MESSENGER and ESA BepiColombo missions, indicating the possibility to discriminate between models of internal structure by using accurate libration measurements. In addition, we calculate the impact of the inertial coupling and viscomagnetic coupling. The inertial coupling is largely dominant for the 88-day libration amplitude. The determination of the interior structure parameters plays an important role in constraining and testing dynamical and compositional theories of planetary formation.

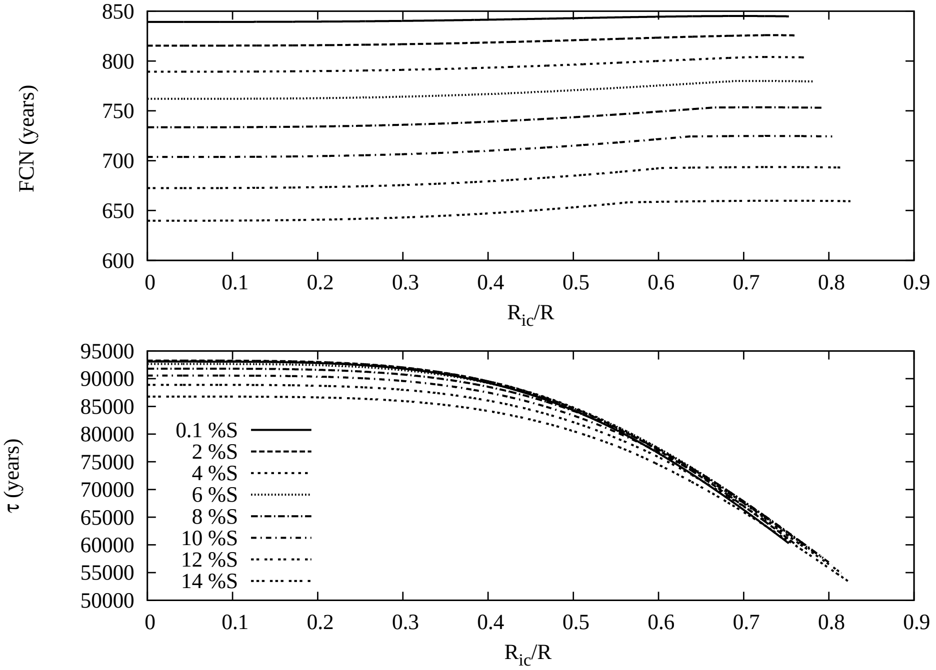

Fig. 2. Impact of the inner core radius and core sulfur concentration (where each color is associated with one value of the sulfur concentration) for the Free Core Nutation (FCN) period and for the damping time τ.

NR acknowledges the support of Prodex/ESA contract at FUNDP.

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