Slichter modes of Mercury: period and possible observation

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Introduction

- Slichter modes of a terrestrial planet are the translational modes of the inner core of a planet within the outer core.
- Slichter modes of the Earth have been theoretically introduced – but not observed – by Louis B. Slichter in 1961 after the earthquake in Chile in 1960.
- The Slichter modes of the Earth are yet to be detected (e.g. Jensen et al. (1995); Hinderer et al. (1995); Kroner et al. (2004); Sun et al. (2006); Rosat et al. (2007)) even though some scientists already claimed their detection (e.g. Smylie (1992); Courtier et al. (2000); Xu et al. (2010)).
- Due to its high mean density compared to the other terrestrial planets, the core of Mercury is thought to be relatively much larger than the core of the other terrestrial planets of the solar system.
- Many factors also seem to indicate the presence of an inner core :
  - Observations of periodic changes in Mercury's spin rate have shown that at least the outer part of Mercury's core is liquid (Margot et al. 2007);
  - The global magnetic field observed by Mariner 10 in 1974 and confirmed by MESSENGER (Anderson et al. 2008), if due to a hydrodynamo, can be considered as evidence of the presence of a growing inner core;
  - An inner core is also consistent with thermal evolution models of Mercury although they cannot rule out a fully liquid core (Breuer et al. 2007; Hauck II et al. 2004), and with the lobate scarps on the surface of Mercury (e.g. Melosh & McKinnon (1988); Watters et al. (2004, 2009)), which are thought to be created by the contraction of the planet and may partly be caused by the formation of a solid inner core.
- Our motivation for this study is that, thanks to its possibly larger inner core (due to its larger core), the Slichter modes of Mercury could be easier to detect than the Slichter modes of the Earth. Therefore, we study the possibility of observation by probes like MESSENGER now in orbit about Mercury since March 18, 2011 or BepiColombo, probably in orbit about Mercury in 2022.
- The internal structure of Mercury being still unknown, we first develop a set of three-layer models of Mercury and use them in order to calculate the Slichter mode period of Mercury.

1. Models of Mercury

- We construct interior structure models of Mercury following the growth of its inner core (Van Hoolst & Jacobs, 2003). We start initially with a two-layer model in which Mercury's core is entirely liquid, and follow the growth of the inner core until the entire core has become solid.
- The different interior structure models for Mercury are constructed taking into account the global mass of Mercury, its radius and the densities of solid Fe and an alloy of liquid Fe and FeS at core pressure and temperature, respectively for the inner core and the outer core.
- When the outer core reaches the eutectic composition, new solid deposited on the inner core has the same composition as the liquid. Mercury is then divided into four homogeneous layers.

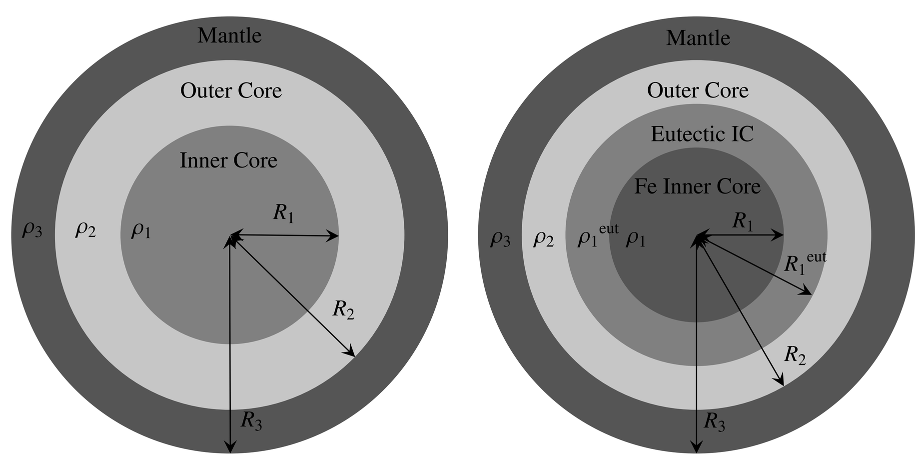

Figure 1: *Interior structure of Mercury consisting of a solid inner core, a liquid outer core and a solid mantle (left) and once the eutectic point is reached (right). The inner core is then divided into two parts: a central iron part and an external part with eutectic composition.*

2. Slichter modes of Mercury

- The Slichter mode period of Mercury is calculated following the method developed by Grinfeld & Wisdom (2005) which takes into account the motion of the mantle associated with the Slichter modes. This method is extended to interiors consisting of more than three layers.
- The Slichter mode period is obtained from the equation of conservation of momentum of the planet and from Newton's second law for the inner core. Mercury is assumed to be spherical and not rotating.
- For a three-layer planet, the Slichter mode frequency is then (Grinfeld & Wisdom, 2005)

$$\omega = \sqrt{\frac{4\pi}{3} G \rho_2 \frac{DM}{\frac{3}{2}EM + D(M-m)}} \qquad (1)$$

with M the mass of Mercury, m the difference between the mass of the inner core and the mass of a body with the volume of the inner core and density of the outer core ($m = 4\pi/3 R_1^3(\rho_1-\rho_2)$), $D = (\rho_1-\rho_2)(R_2^3-R_1^3)$ and $E = \rho_2 R_2^3$.

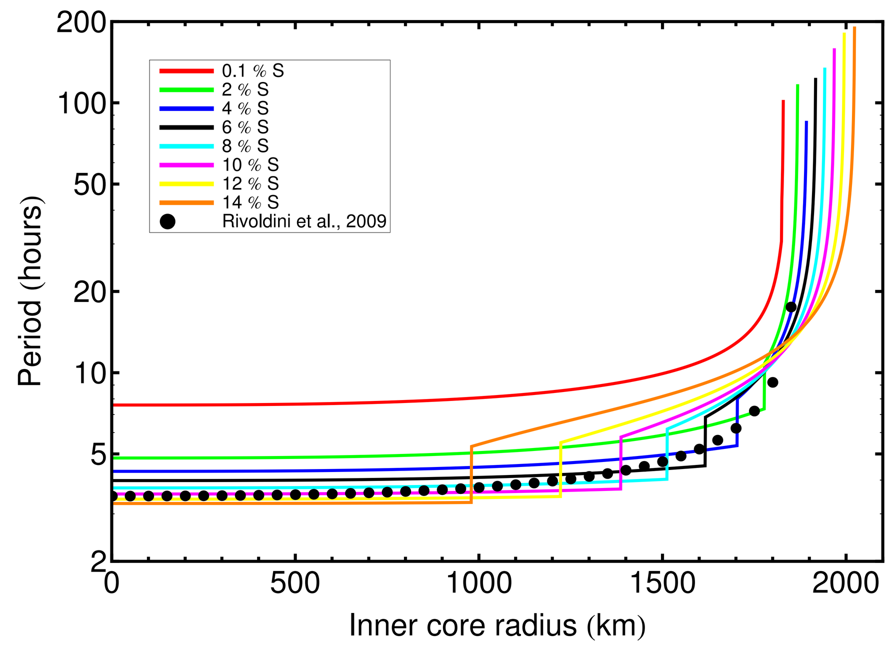

Figure 2: *Slichter mode periods for the different models of Mercury. Different colors represent different sulfur contents of the core, from 0.1 wt% to 14 wt%. Values for full internal structure models of Mercury (Rivoldini et al., 2009) are represented with big bullets.*

- Periods obtained (Figure 2) are of the order of a few hours and increase with increasing inner core radius to infinite period (no more oscillations) when the whole core is solid. The increase of the Slichter mode period with increasing inner core radius can be explained by the larger inertia of the inner core.
- Figure 2 shows that the period of the Slichter mode increases with increasing inner core radius and decreasing bulk sulfur concentration in the core. This behaviour is due to the increase of the period with decreasing density jump at the inner core boundary, which also explains the jump in period when the outer core reaches the eutectic composition.

3. Slichter modes detection

- As the center of mass of Mercury remains fixed during a Slichter mode oscillation, gravity anomalies due to this mode cannot be measured from orbit.
- However, Slichter modes of Mercury could be detected from orbit by measuring the motion of the mantle of Mercury.
- The precision of the surface position due to altimeter and orbit errors of MESSENGER and BepiColombo is respectively 10 m (Solomon et al. 2001) and smaller than 1 m (Iess et al. 2009).

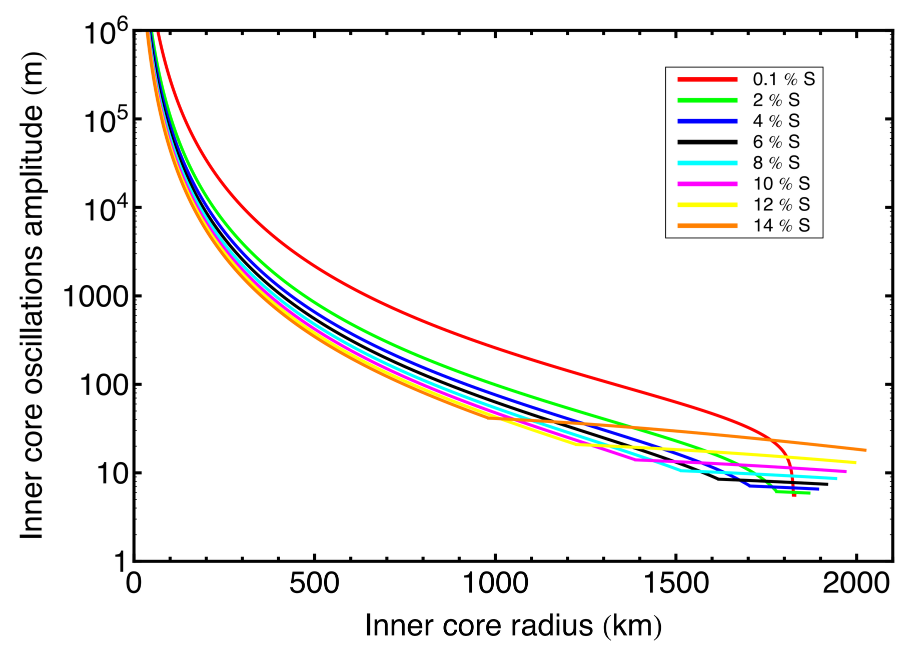

Figure 3: *Amplitude of the inner core oscillations that could be detected by BepiColombo (i.e. with a surface motion amplitude of 1 m). Legend used is the same as in Figure 2.*

- For inner core radii smaller than a few hundred km, displacements of the order of one km or more are needed in order to allow observation of the Slichter mode (Figure 3). For the largest inner cores, the displacement can be as small as ten meters and still allows detection.

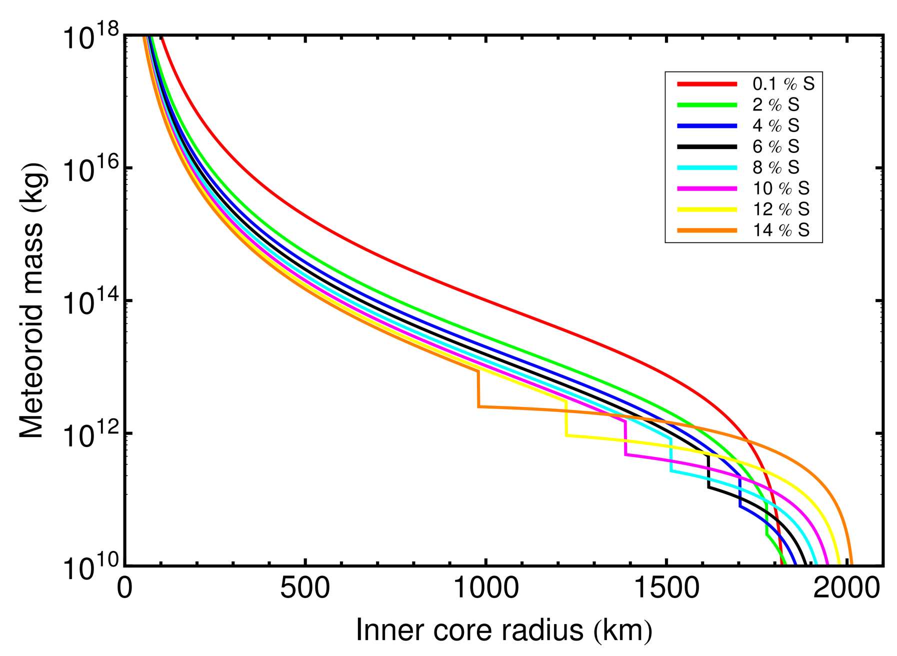

Figure 4: *Mass of the meteoroid that will lead to a detection of the Slichter mode by BepiColombo assuming that all the remaining energy is transfered to the Slichter mode. Legend used is the same as in Figure 2.*

- We study the possible excitation of Slichter modes by a colllision with a meteoroid and estimate the minimal size of the meteoroid that could lead to a detection of these modes by BepiColombo, assuming that the Slichter mode is the only excited mode (Figure 4).
- For a small inner core, the Slichter mode could be detected by BepiColombo if the mass of the meteoroid is at least of the order of 10^{16} kg (meteoroid of about 10 km radius) (Figure 4). The rate of impact of Jupiter family comets of radius greater than 1 km on Mercury is about 8.6 10^{-10} meteoroids per year (Levison & Duncan 1997), so that the Slichter mode excitation of Mercury would only occur in average one time over a billion years.
- For a large inner core, the Slichter mode could be detected by BepiColombo if the mass of the meteoroid is at least of 10^{10} kg (meteoroid of about 100 m radius) (Figure 4). The average interval between two impacts of meteoroids of that size is 140 My (Marchi et al. 2005).

4. Discussion

- If we neglect the deformation of the inner core during Slichter mode oscillations, the damping of the Slichter mode is principaly due to magnetic and viscous stresses in the outer core (Buffett & Goertz 1995; Rieutord 2002). As the viscosity in the outer core of Mercury is still unknown, we consider here only dissipation due to a magnetic field.
- The correction to the Slichter mode frequency due to magnetic stresses is given by Buffett & Goertz 1995 :

$$\frac{\delta\omega}{\omega} = \frac{3}{4}\Lambda \frac{L}{R_1}\frac{\rho_2}{\rho_1}\frac{(1+i)\sqrt{1-i\Lambda}}{1-i\Lambda+\sqrt{1-i\Lambda}} \qquad (2)$$

where $\Lambda \approx B_r^2/(L^2\omega^2\mu\rho_2)$ is the ratio of the magnetic force to the inertial force and $L = \sqrt{2\eta/\omega}$ is the depth of the magnetic boundary layer at the ICB (skin depth).
- The e-folding time τ is then given by $\tau = [\Im(\delta\omega)]^{-1}$ (Figure 5).

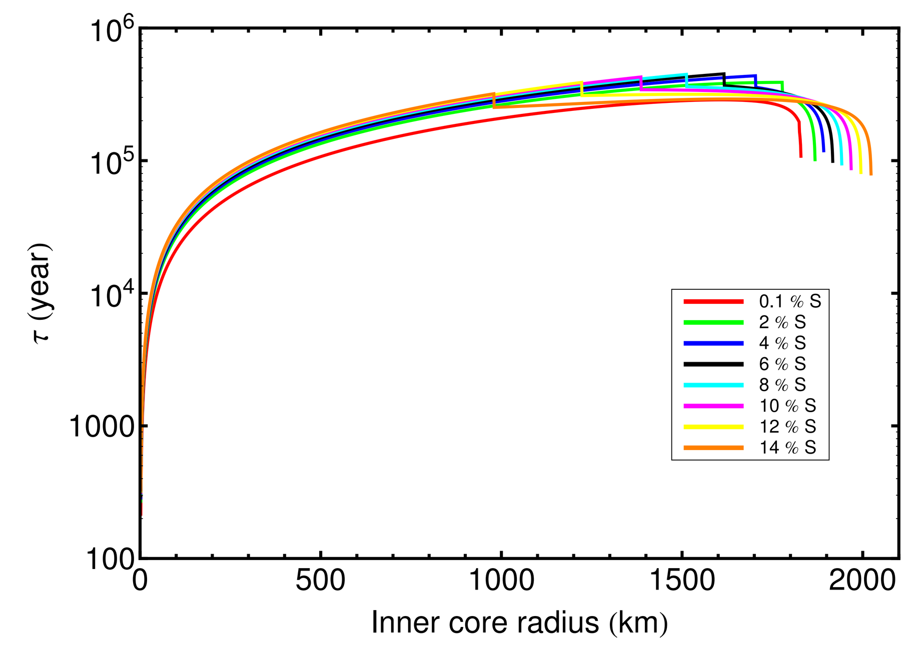

Figure 5: *Magnetic damping time of the Slichter mode of Mercury. Legend used is the same as in Figure 2.*

- When the inner core is very large, the damping time is about 0.5 My, still below the average time between impacts of 100 m radius meteoroid.
- Moreover, as we have considered here only dissipation due to the magnetic field of Mercury, the effective damping time will be smaller than 0.5 My.
- Hence, the observation of the Slichter mode of Mercury, if excited by meteoroid impacts, would require a fortunate recent impact (less than 0.5 My ago).

Conclusion

- Observation of the Slichter modes of Mercury would constrain the size of its inner core: e.g. if Mercury has a Slichter mode period longer than ten hours, the radius of the inner core would be at least 1700 km.
- Observation of the Slichter mode of Mercury is possible if the inner core is very large and is excited to an amplitude of the order or greater than ten meters.
- If the Slichter mode of Mercury is assumed to be excited by a collision with a meteoroid, the mass of the meteoroid must be at least of the order of 10^{10} kg (for a large inner core) in order to allow observation by BepiColombo. On average, such a collision occurs once every 100 My, which is much larger than the dissipation time of the Slichter mode, therefore requiring a recent impact (less than 0.5 My ago).

For more information, see: Coyette A., Van Hoolst, T. and Dehant, V. 2012, A&A, 543, A40, doi: 10.1051/0004-6361/201218891.

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EPSC2012–185