Constraining the interior structure of Mercury by geodesy data

Marie-Hélène Deproost[1,2], Attilio Rivoldini[2], Tim Van Hoolst[1,2]
1. KU Leuven, 2. Royal Observatory of Belgium (marie-helene.deproost@oma.be)

1. Abstract

Geodetic properties of planets are strongly related to their interior structure and can be used to infer their deep structure. In this study we combine the 88-day libration amplitude, the obliquity, the gravitationnal field, and the tidal Love number k_2 in order to constrain Mercury's interior structure, and in particular its core and inner core sizes.

2. Interior model

Thermal evolution of the core and the mantle based on global energy balance and assessment of core dynamo by entropy balance.

Core:

- core thermal evolution model based on Davies (2015) and Gubbins et al. (2003, 2004)
- Fe-S-Si ideal solution (Dumberry and Rivoldini 2015); liquidus Fe-S from Dumberry and Rivoldini (2015); Fe liquidus from Anzellini et al. (2013)
- thermal conductivity depends on sulfur concentration, temperature, and pressure (Secco et al. 1989 and Konôpková et al. 2016)

Silicate shell:

- mantle: olivine (60%wt)-orthopyroxene (40wt%) with Mg# = 1 non-elastic (Jackson and Faul 2010)
- thermal evolution model of the mantle based on Morschhauser et al. (2011) and Grott et al. (2011)
- radioactive element concentrations from Peplowski (2011); factor of enrichment in radiogenic elements with respect to the mantle from Tosi et al. (2013)

3. Geodetic constraints

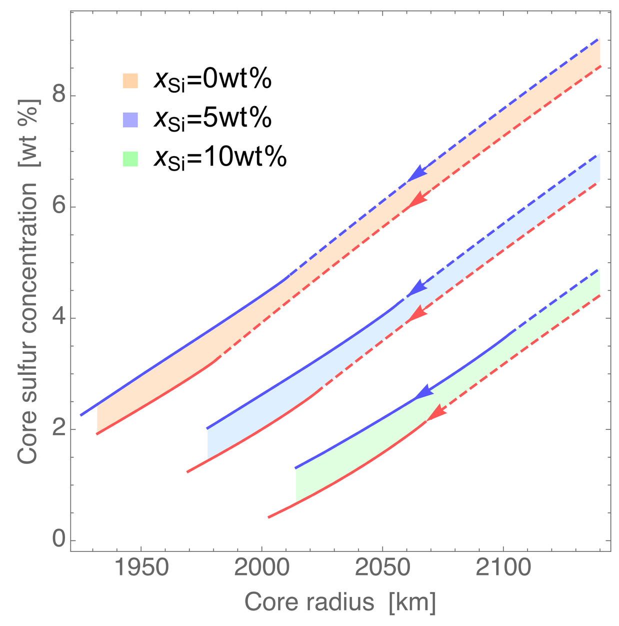

Fig. 1: Core radius-sulfur relation assuming a core-mantle boundary temperature range of 1850 K (blue)-2000 K (red). Solid lines represent models with an inner core and dashed lines are for liquid core models. Models that agree at 3 σ with the moment of inertia and 88 day libration amplitude are located to the left of the arrow-head.

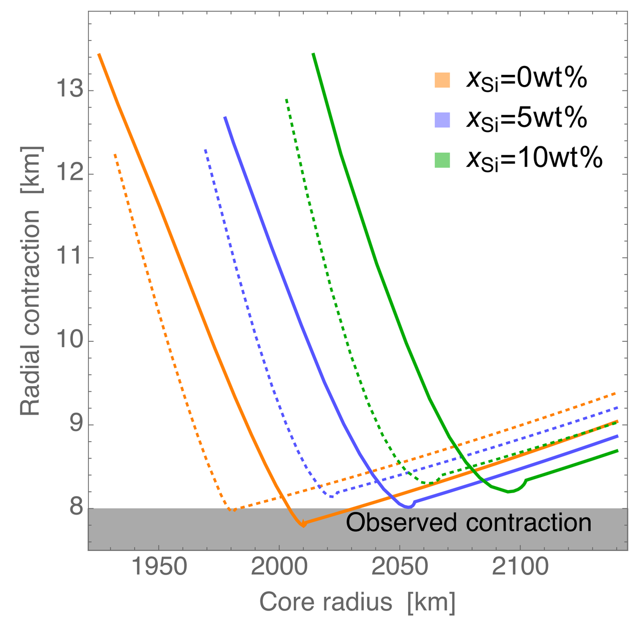

Fig. 2: Radial contraction since the end of the late heavy bombardment event assuming a core-mantle boundary temperature range of 1850 K (blue)-2000 K (red). Solid lines represent models with an inner core and dashed lines are for liquid core models. A temperature drop of 150 K at the core-mantle boundary is assumed. The shaded area represents the estimated radial contraction of Mercury since LHB (Byrne 2014).

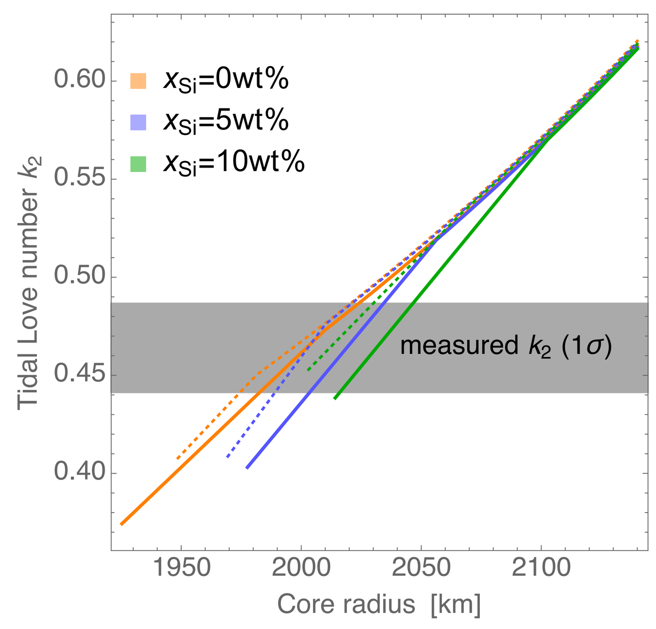

Fig. 3: Tidal Love number k_2 as a function of core radius. The shaded surface represents the measured k2 value (Mazarico 2014 and Verma 2016). The tidal quality factor of all models is between 50 and 110 for mantle grain sizes of 1 and 10 mm.

- The planet radial contraction is about 7 km: it requires an inner core radius $\leq$ 300 km and a cooling $\leq$150 K, since the end of the Late Heavy Bombardment episode. The core radius is $\leq$ 2060 km and the core silicon concentration is $\leq$ 5 wt%.
- The tides (tidal Love number k_2) requires a core radius between 1970 km and 2050 km.
- Combination of rotation and gravity field (88-day libration and moment of inertia) requires a core radius $\leq$ 2080 km and, if the silicon concentration is larger than 10 wt%, only models with solid inner core agree with data.

4. Coupled models

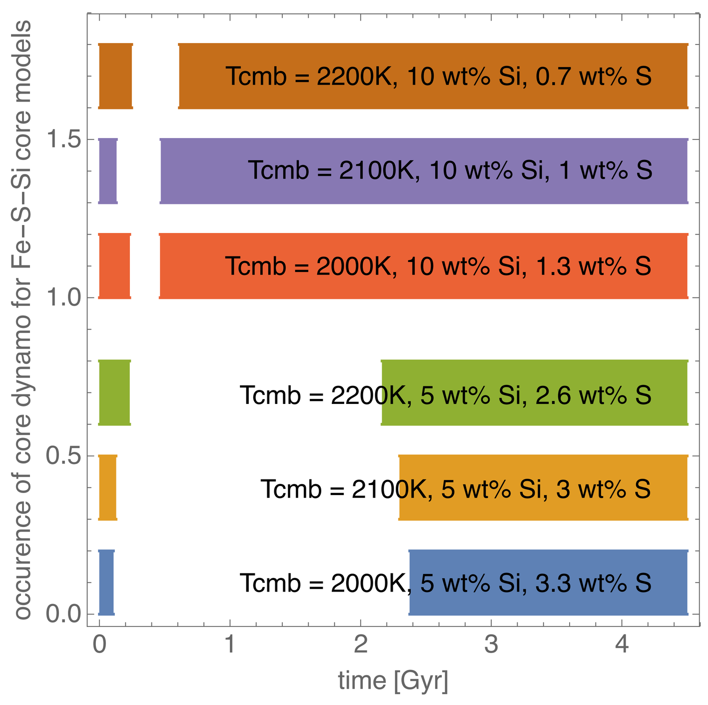

Fig. 4: Fe-S-Si models allow for a present-day dynamo. Entropy generated by core cooling (in the first Myrs) and by inner core formation (later), is sufficient to drive a dynamo during a large part of the evolution. Models with initial core-mantle boundary temperature of 2000 K, 2100 K and 2200 K are presented.

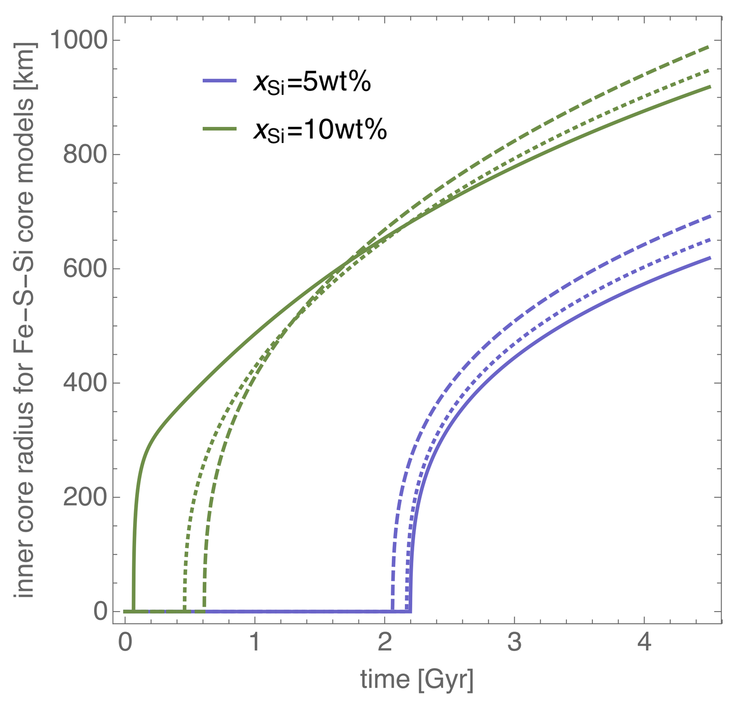

Fig. 5: Fe-S-Si models form a solid inner core. Inner core appears later for models with 5 wt% Si because of their larger S concentration (3 wt% S). Solid, dotted and dashed lines are for an initial core-mantle temperature of respectively 2000 K, 2100 K and 2200 K.

- Fe-Si cores must be too warm to have a molten core: S is required together with Si to lower the liquidus. But addition of Si allows to decrease S concentration and therefore to form more easily a solid inner core.
- Main contribution to both energy and entropy budgets is latent heat. In Fe-S-Si cores, gravitational energy and entropy contributions are small as a result of equipartition in solid and liquid phase of Fe-Si alloys.
- Fe-S large core models (2050 km): only early dynamo (first 200 Myrs); no inner core because of large sulfur concentrations (4.6 - 5.7 wt%).
- Fe-S small core models (1950 km) form a solid inner core that reaches a present-day radius of about 1200-1400 km, in contradiction with contraction observations.
- Fe-S-Si models with 5 wt% Si - 3 wt% S only allow for a late dynamo, in disagreement with early magnetization. Fe-S-Si models with 10 wt% Si - 1 wt% S allow for a dynamo during a large part of the evolution until today but are in disagreement with contraction constraints. All the Fe-S-Si models form a solid inner too large compared with contraction observations.

5. Core models: stratification (preliminary results)

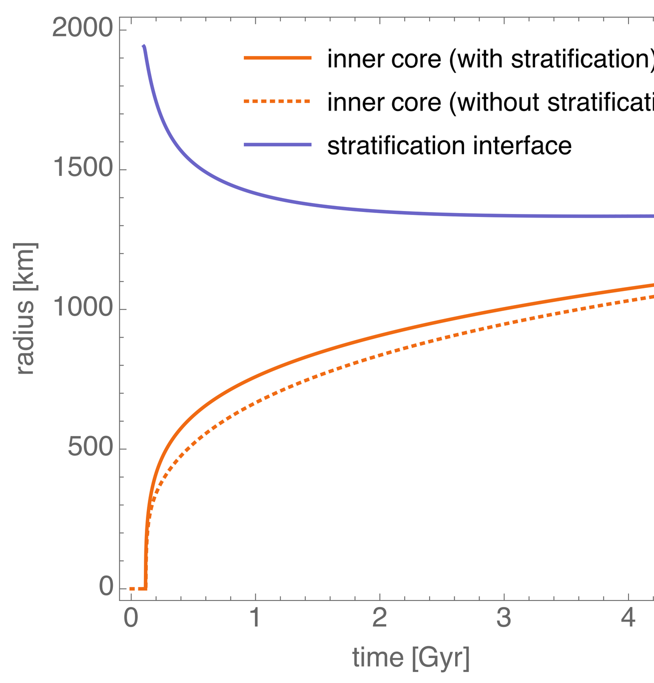

Fig. 6: The presence of a stratified layer do not have a large effect on the inner core evolution. The solid lines present the inner core radius and the position of the interface between the convective and the conductive parts through time, with stratification taken into account during evolution. The inner core evolution without a thermal boundary layer for the same model is shown by the dotted line.

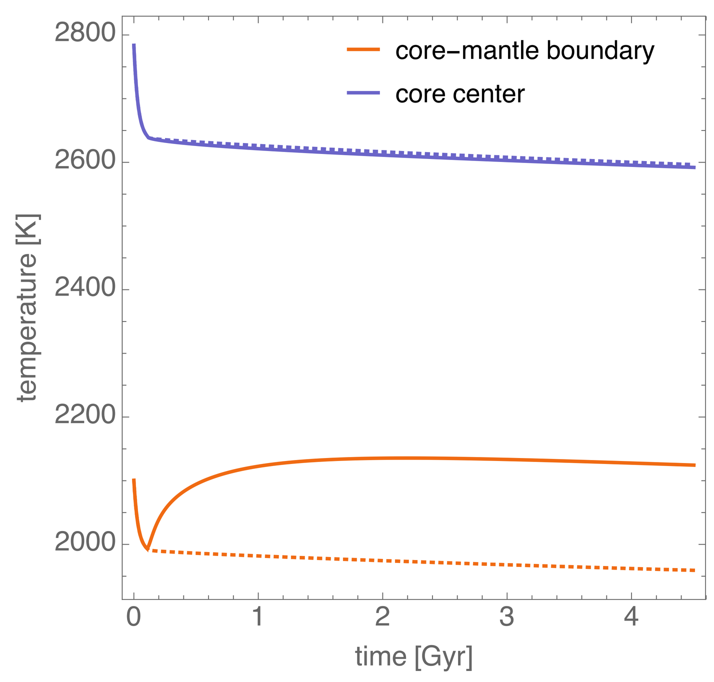

Fig. 7: The presence of a thermal boundary layer at the top of the core mainly affects the core-mantle boundary temperature. The impact on the convective lower core, and the core center temperature, is small. Solid and dotted lines are for evolution respectively with and without a thermal boundary layer.

- When the core-mantle boundary heat flux becomes subadiabatic, a thermal stratified layer forms at the top of the core. A compositionnal stratification of the core due to chemical interactions between the core and the mantle is also possible but not considered here.
- The results presented above are for an Fe-S small core (1950 km) with an initial core-mantle temperature of 2100 K. The core-mantle boundary heat flow is modelised by an exponential law of the form: $Q_{cmb}(t) = A\mathrm{e}^{Bt} + C$ where A, B and C are constants.
- Stratification occurs a few Myrs before inner core onset but mainly affect the evolution of the top of the core. The evolution of the convective lower part of the core is little impacted.

6. Conclusions

- Fe-S models with small cores (1950 km) and Fe-S-Si models have a present-day solid inner core but are in contradiction with contraction observations
- Fe-S-Si models with 5 wt% Si - 3 wt% S have a late dynamo at odds with early magnetization. Fe-S-Si models with 10 wt% Si - 1 wt% S allow for a dynamo during a large part of the evolution until today but are in disagreement with contraction constraints.
- Fe-S models with large cores (2050 km) do not form a solid inner core. Core cooling is only sufficient to drive a dynamo during the first Myrs.
- Prelimlinary results show that a thermal boundary layer at the top of core appears early, after a few Myrs and before inner core onset, but mainly impacts the evolution of the top of the core. The convective lower core (core center temperature and inner core evolution) is little affected.

LaTeX TikZposter