Mercury's internal structure and core thermal evolution

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1. Abstract

Measurements of Mercury's spin state and gravitational field supplemented by the assumption that the planet's core is made of iron and sulfur give strong constraints on its interior structure. In particular, they allow a precise determination of Mercury's core size and average mantle density (Rivoldini et al. 2013). However, those data provide only a weak constraint on thermal state of the planet and core.

Additional information about the thermal state and the presence of an inner core can be obtained by modeling the crystallization regime of iron in Mercury's core and its relation to the presence of its internally generated magnetic field (Dumberry et al. 2015). But, the conclusions of those studies depend strongly on the thermodynamic properties of iron and alloying candidate light elements. For instance, depending on the thermodynamic data of Fe used, only top-down inner core formation by iron-snow is possible, therefore a power source responsible for generating a major part of the buoyancy flux driving compositional convection is not available.

Here, we first show how the recently determined tidal Love number k_2 and the radial contraction of Mercury together with previous geodesy data can further constrain models of its internal structure and thermal state. Then we use a coupled thermal evolution model of the core and the mantle to assess whether those models allow for past and present day magnetic field generation.

2. Thermal evolution model

- coupled core-mantle thermal evolution model (core: Davies 2015, mantle: Morschhauser et al. 2011 and Tosi et al. 2013)
- assume core radius of 1965 km and 2045 km (marginal dynamo), and 2000 km (global model)
- neglect gravitational power produced by iron-snow ($<$ 0.1 TW)
- radioactive heating in the mantle
- assess occurence of past and present-day marginal dynamo in the core (zero entropy production)

Thermal evolution of the core and the mantle deduced from global energy and entropy balance.

3. Structure models

- crust: density 2900 kg/m^3 and thickness 40 km
- mantle: olivine (60%wt)-orthopyroxene (40wt%) with Mg# = 1 non-elastic (Jackson and Faul 2010)
- core:
  - Fe-S ideal solution with thermodynamic data of Fe from Komabayashi (2014) and liquidus from Anzellini et al. (2013)
  - core isentrope is steeper than liquids everywhere $\rightarrow$ only top-down crystallization of Fe
  - Fe snow formation when $T(r) \leq T_{\text{melt}}(r)$
  - inner core formation by Fe precipitation when core snowfield extends to the core center
  - thermal conductivity depends on sulfur concentration, temperature, and pressure (Secco et al. 1989 and Konôpková et al. 2016)
- thermal state constraints:
  - present day core-mantle temperature below lower mantle solidus ($\sim$ 1850 K)
  - our mantle thermal evolution studies indicate that the core cooled by not much more than 250 K and that the present day core-mantle boundary heat flux is likely below 10 mW/m^2

4. Geophysical constraints

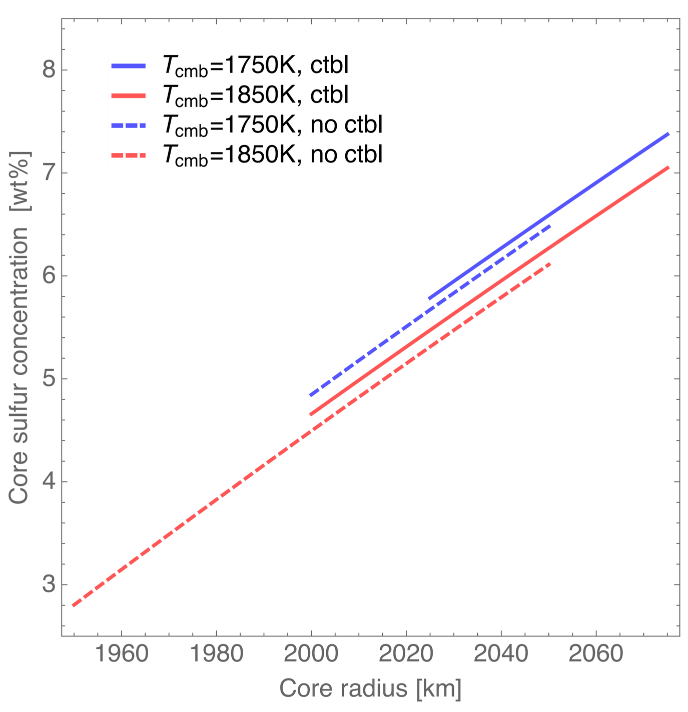

Fig. 1: Core sulfur concentration as a function of core radius for models with (full) and without (dashed) a core thermal boundary layer (ctbl) for a core-mantle temperature (T_{cmb}) of 1750 K (blue) and 1850 K (red). Models with a ctbl do not allow for much smaller core radii since the core temperature would be below the core liquidus everywhere.

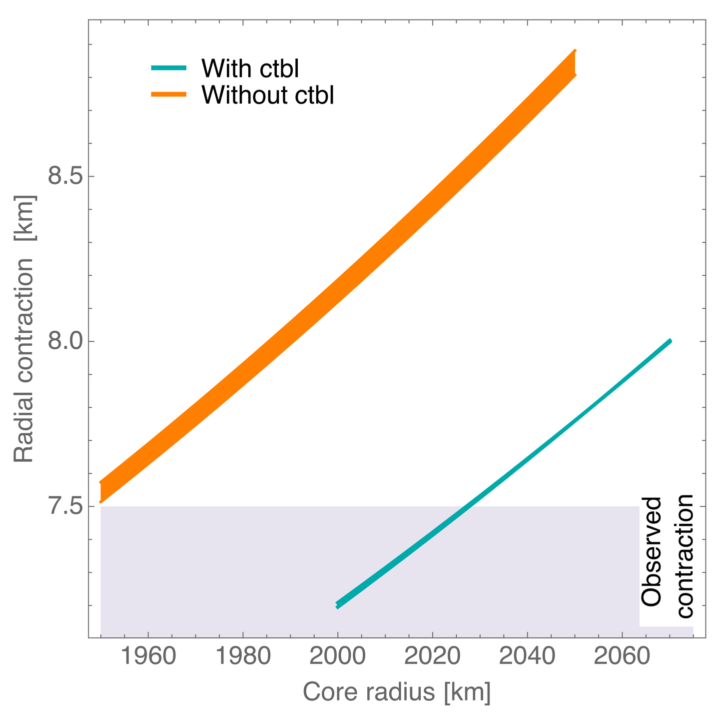

Fig. 2: Radial contraction as a function of core radius for models with (cyan) and without (orange) a core thermal boundary layer (ctbl) since the end of the late heavy bombardment event for a core cooling rate of 50 K/Gyr. The spread of the the curves results from the considered temperature range at the core mantle boundary (1750-1850 K). The shaded area delimits the observed radial contraction of Mercury since the end of the late heavy bombardment event (Byrne et al. 2014).

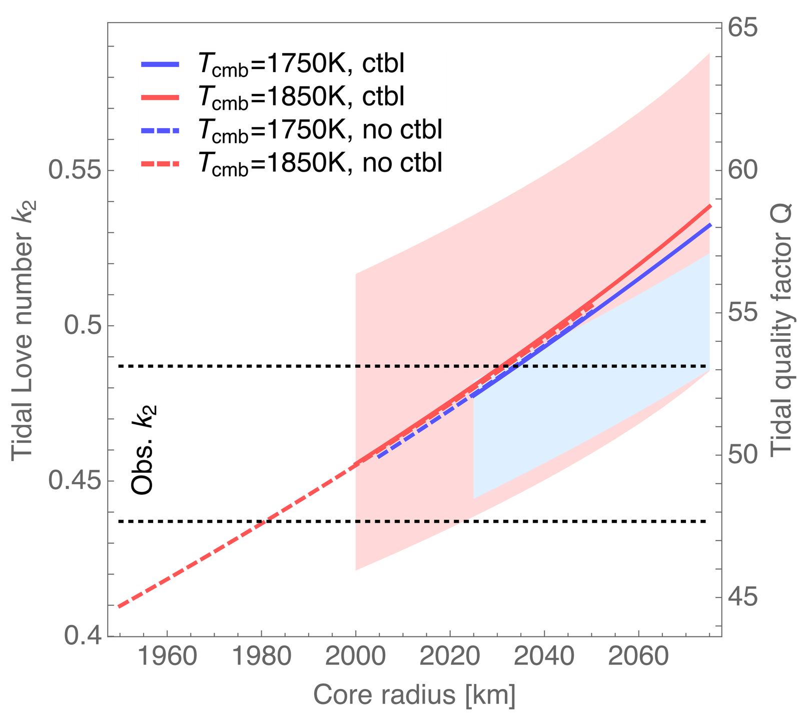

Fig. 3: Tidal Love number k_2 and quality factor Q as a function of core radius for models with (full) and without (dashed) a core thermal boundary layer. The surface delimited by the black dashed line represent the observed k_2 value (Mazarico et al. 2014 and Verma et al. 2016). Q is only shown for models with a ctbl. The spread of Q results from the considered grain size range (1-10 mm) of olivine in the mantle.

- Past and present mantle controlled core-mantle boundary heat flow implies substantial thermal boundary layer in the upper core ($>$ 300 km).
- For a given core-mantle temperature, models with a core thermal boundary layer are colder than those without such a layer and thus require more sulfur to stay molten and therefore, because of mass conservation, have a larger core.
- Models with and without a core thermal boundary layer agree with k_2 and the internal structure constraints are compatible with previous estimates based on geodesy data alone. Additionally, Q values agree with R.-M. Baland et al. 2016 (this meeting)
- Upon cooling and for a given core radius, models with a core thermal boundary layer contract less then models without a thermal boundary.

5. Marginal dynamo

- To power a marginal thermal dynamo during the whole evolution of Mercury requires a cooling rate of about 110 K/Gyr and results in a core cooling of more than 500 K, in contradiction with the observed radial contraction.
- Such a large cooling rate and resulting large core temperature imply a molten lower mantle for a significant part of Mercury's evolution, in contradiction with the early cessation of major effusive volcanism and crust formation episode ($\sim$ end of LHB)
- Assuming a non-molten lower mantle after the LHB event implies a present day core temperature below 1500 K
- Marginal dynamos require a core-mantle boundary heat flow that is significantly larger than that predicted by mantle thermal evolution studies
- Assuming a core cooling of about 250 K over the whole evolution ($\sim$ 55 K/Gyr), an additional energy source producing at least 0.8 TW is required to power entire core convection and allow for a dynamo during the whole history of the planet. Our preliminary result indicate the power generated by the formation of iron-snow in the core is not sufficient since it is likely not much larger than 0.2 TW.

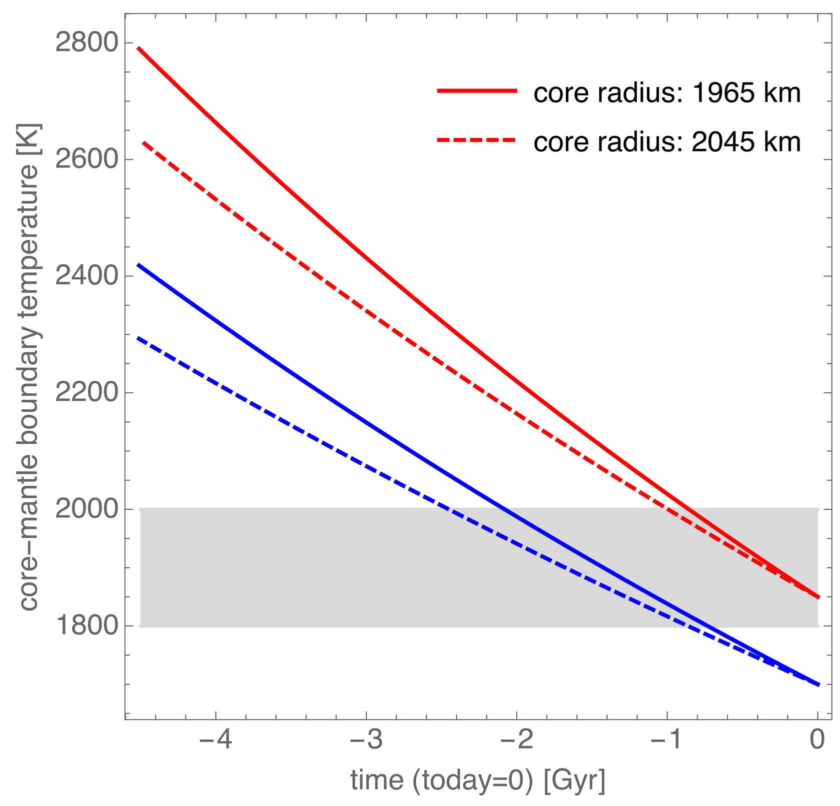

Fig. 4: Core-mantle boundary (CMB) temperature through time for a marginal dynamo and a fixed CMB temperature today. The light gray zone represents the lower mantle solidus (Namur et al., 2016).

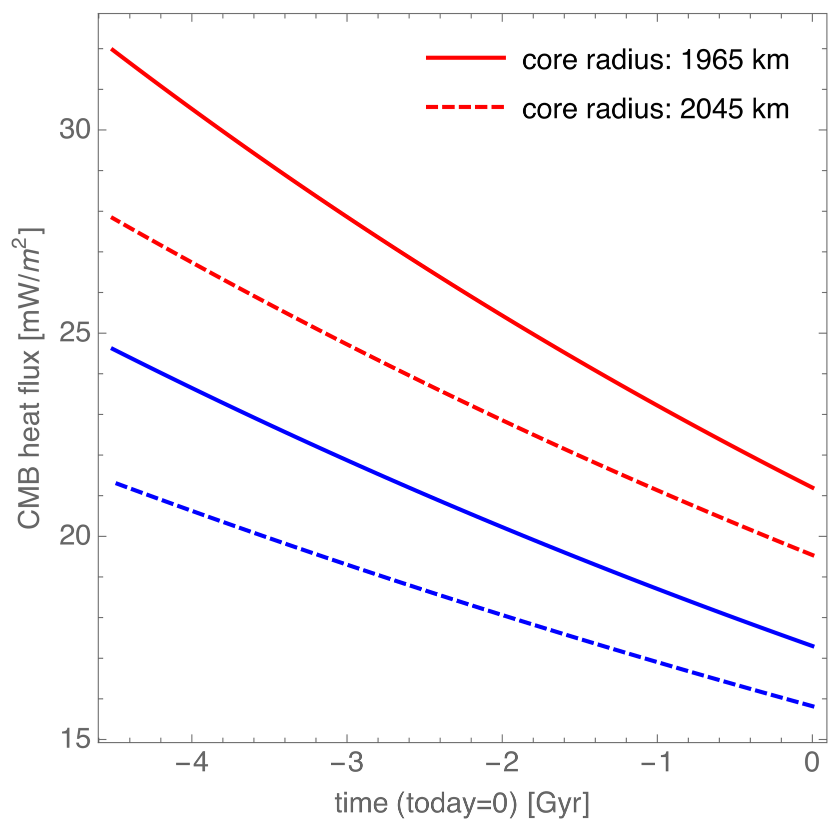

Fig. 5: Core-mantle boundary heat flux through time for a marginal dynamo and a fixed CMB temperature today (see Fig.4).

Two end-members for the CMB temperature are presented: a cold end-member with a temperature of 1700 K (blue) today and a hot end-member with a temperature of 1850 K (red) today. In both cases, two core radii are considered: 1965 km (full) and 2045 km (dashed).

6. Global model

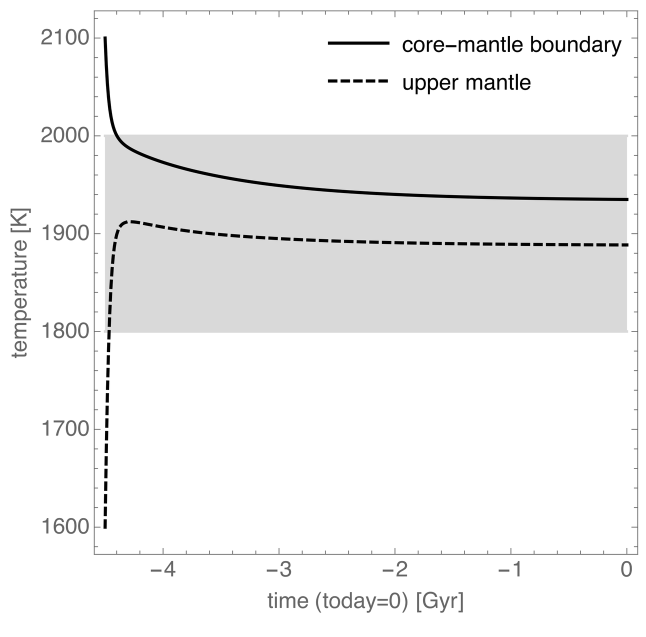

Fig. 6: Core-mantle boundary and upper mantle average temperature evolution, for initial temperatures respectively of 2100 K and 1600 K. The light gray zone represents the lower mantle solidus (Namur et al.).

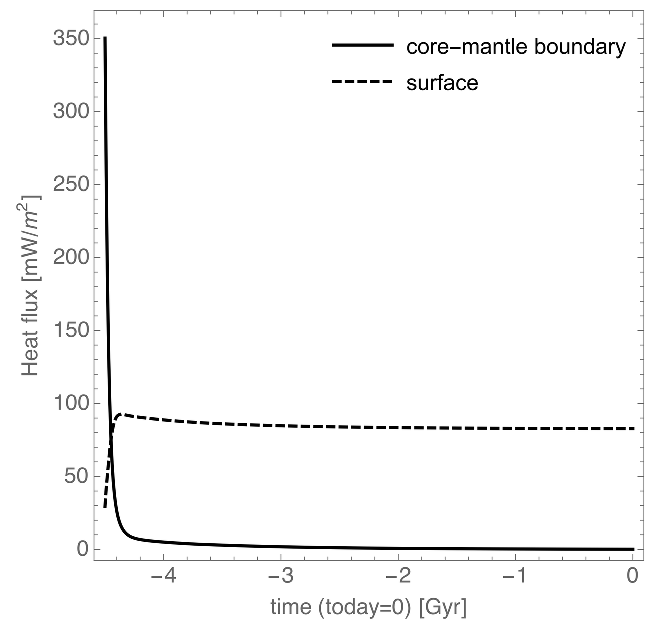

Fig. 7: Core-mantle boundary and surface heat flux evolution, for the temperature evolution presented in Fig.6.

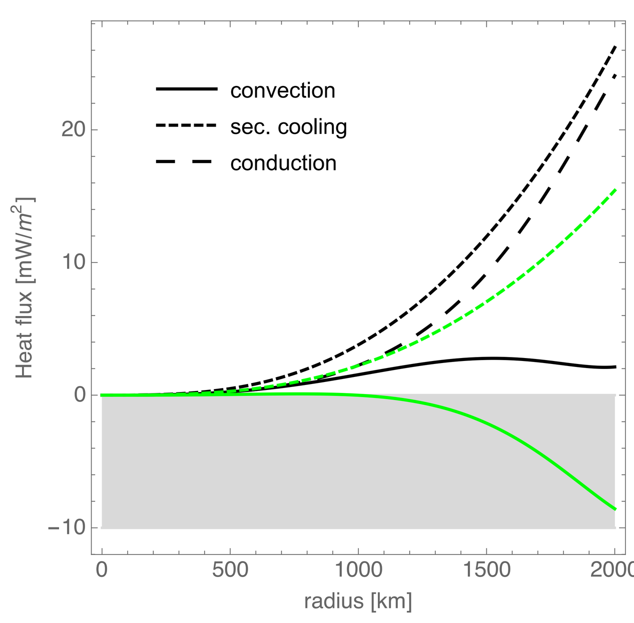

Fig. 8: Radial profiles of contributions to the convective heat flux at time $t = -4.4$ Gyr (black) and $t = -4.37$ Gyr (green), for the temperature evolution presented in Fig.6.

7. Conclusion

- With a core cooling in agreement with contraction ($\sim$170 K), a thermally driven dynamo is only possible until the end of the LHB. We need another buoyancy source than secular cooling to explain the present-day magnetic field.
- The small core cooling and the subsequent core temperature allow to avoid melting of the lower mantle during the whole evolution.
- The heat flux conducted along the adiabat across the core-mantle boundary is about 23 mW/m^2, much higher than the heat taken from the core by the mantle: it means a sub-adiabatic core heat flux and a thermal stratification of the upper part of the core during the larger part of the core evolution. The core is entirely thermally stratified after 150 Myr.

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