Thermal evolution and core stratification of Mercury

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1. Scope

The thermal evolution of Mercury is strongly related to its interior structure and therefore can be used to put constraints on it, in particular on the inner core. Compressional deformation features on Mercury's surface indicate that Mercury has contracted during its evolution by as much as 7 km. Contraction is mainly due to secular cooling and resulting inner core growth; therefore it provides insight on the existence, formation and size of an inner core.

Recent measurements of Mercury's rotation and gravitational field strongly constrain the size and density of the core, but provide little information about a solid inner core. Both an entirely liquid core and a large solid inner core surrounded by a liquid outer part are consistent with those observations. The present-day global magnetic field is likely driven by thermo-chemical convection in the liquid outer core mainly resulting from the crystallization of an iron rich alloy.

The thermal evolution of the core is controlled by the amount of heat extracted by the mantle from the core. We therefore use a coupled core-mantle model to study the interior structure of Mercury. The thermal evolution of the planet is modeled by studying the energy balance of the core and the mantle and the presence of an internally generated magnetic field is deduced from the entropy balance of the core. We assess which interior structure models that agree with geodesy data, contraction measurements, tides, and crust formation timing allow for dynamo action in the core.

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 Wicht et al. (2007) and Christensen and Wicht (2008)
- assume core radius of 1950 km and 2050 km, in agreement with moment of inertia and libration amplitude
- initial core-mantle boundary temperature between 1900 K and 2200 K
- 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)
- neglect gravitational power produced by iron snow

Silicate shell:

- 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)
- 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)
- initial thickness of stagnant lid: 50 km

3. Geodetic constraints

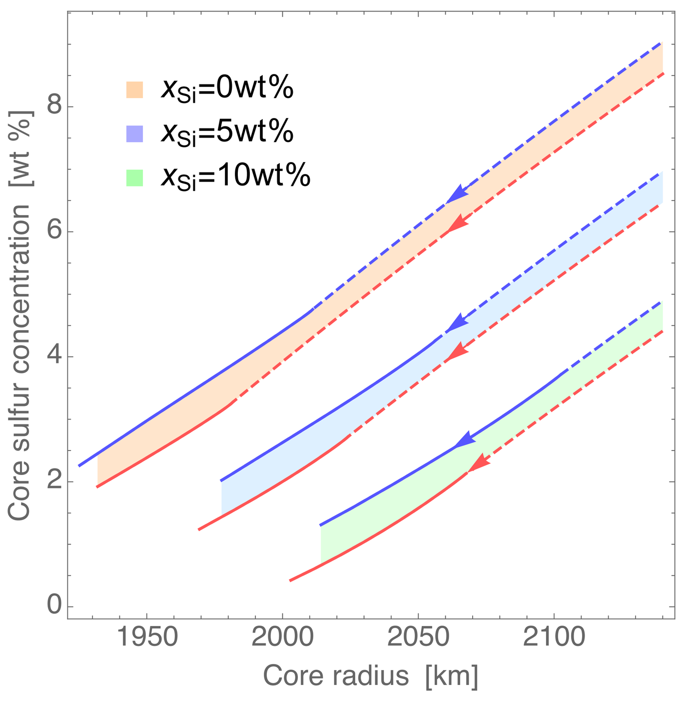

Fig. 1: Core radius-sulfur relation assuming a core-mantle boundary temperature range of 1850 K (blue)-2000 K (red). Solid lines represent models with an inner core and dashed lines are for liquid core models. Models that agree at 3 σ with the moment of inertia and 88 day libration amplitude are located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

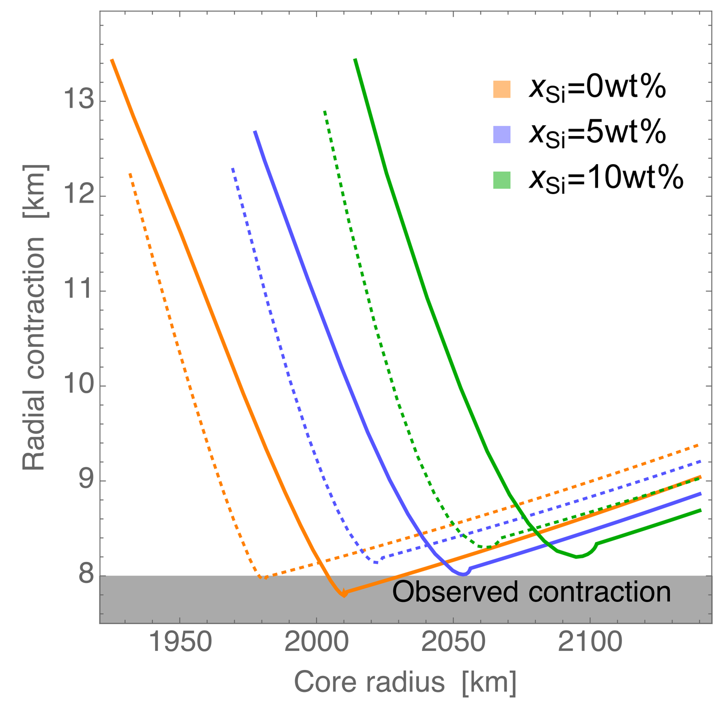

Fig. 2: Radial contraction since the end of the late heavy bombardment event assuming a core-mantle boundary temperature range of 1850 K (blue)-2000 K (red). Solid lines represent models with an inner core and dashed lines are for liquid core models. A temperature drop of 150 K at the core-mantle boundary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

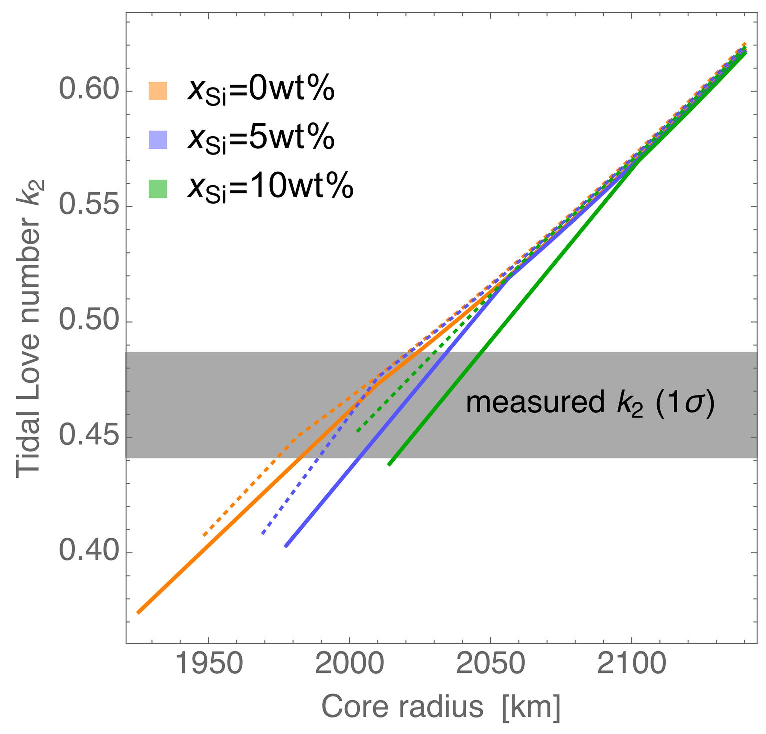

Fig. 3: Tidal Love number k2 as a function of core radius. The shaded surface represents the measured k2 value (Mazarico 2014 and Verma 2016). The tidal quality factor of all models is between 50 and 110 for mantle grain sizes of 1 and 10 mm.

- 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 k2) 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. Energy and entropy budgets: coupled models

- 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, latent heat contribution is larger than in Fe-S cores (25% for energy and 30% for entropy), but 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): sufficient entropy to drive a dynamo in the first 200 Myrs, later dynamo possible for hot initial core temperature (2200 K) when inner core formation starts. Convection stops when iron snow layer reaches the inner core (after about 3.5 Gyr).
- Fe-S-Si cores with 5-10 wt% Si (core radius: 2050 km): a dynamo is possible during a large part of the evolution until today. With 5 wt% Si - 3 wt% S, late dynamo at odds with early magnetization. Models with 10 wt% Si - 1 wt% S in disagreement with contraction constraints.

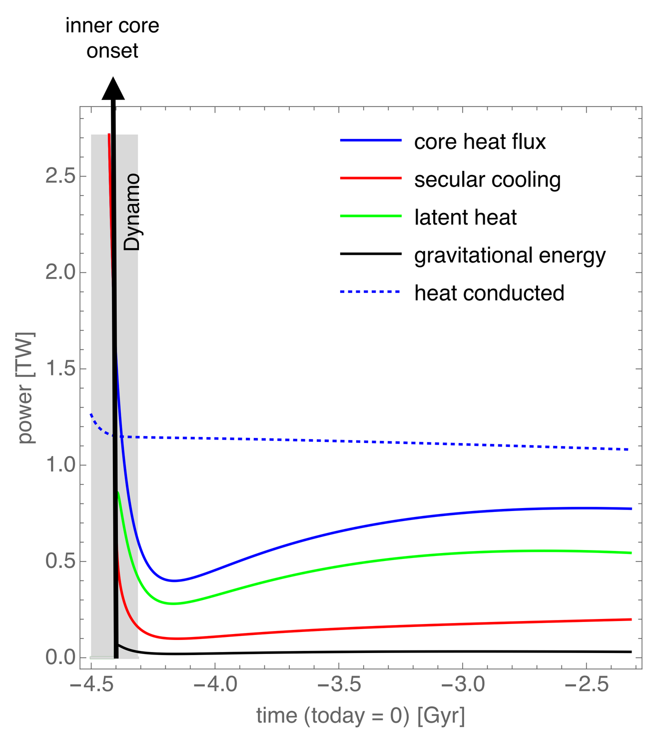

Fig. 4: Core energy budget for a model with core radius 1950 km and initial core-mantle boundary temperature of 2100 K. The heat flux taken from the core by the mantle is generated by three sources: secular cooling of the core, latent heat generated by freezing of iron-rich alloy at the inner core boundary and gravitational energy released at the inner core boundary by the segregation of sulfur in the liquid core. Convection stops when the iron snow layer reaches the inner core. Entropy is available to drive a dynamo during the first Myrs. Core heat flux becomes subadiabatic after 100 Myrs.

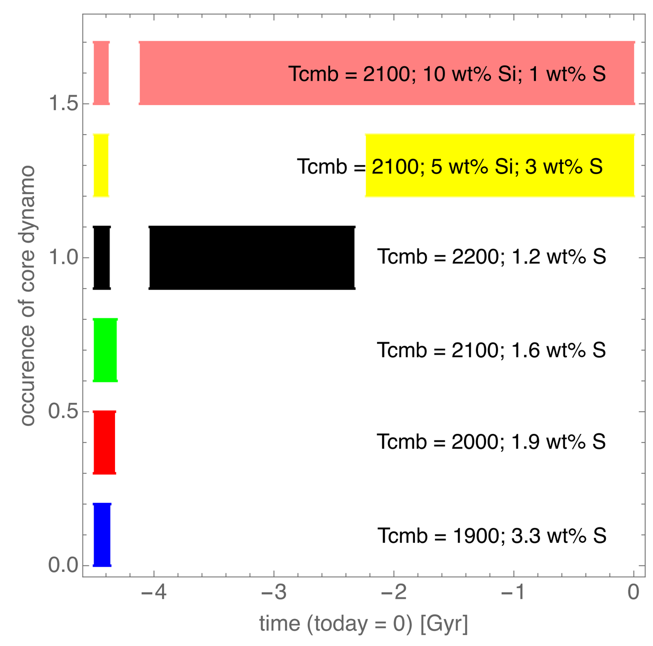

Fig. 5: Periods of time during which entropy is sufficient to drive a core dynamo for different initial core-mantle boundary temperatures. All models form a solid inner core: Fe-S models (core radius: 1950 km), Fe-S-Si models (core radius: 2050 km). Only a hot Fe-S core allows for a dynamo after the first Myrs. A present-day dynamo is only possible for Fe-S-Si core models, but 5 wt% Si only allows for a late dynamo, in disagreement with early magnetization.

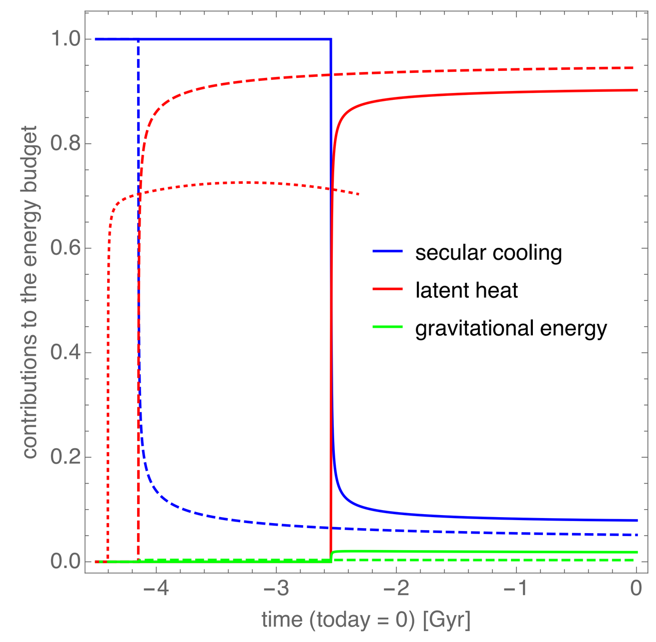

Fig. 6: Fe-S-Si core contributions to the energy budget for an initial temperature of 2100 K at the core-mantle boundary and a large core (r_{cmb} = 2050 km). Solid lines are for the model with 5 wt% Si - 3 wt% S, dashed lines are for the model with 10 wt% Si - 1 wt% S. For comparison, the red dotted line represents the latent heat contribution of the Fe-S core model with r_{cmb} = 1950 km (1.6 wt% S).

5. Stratification

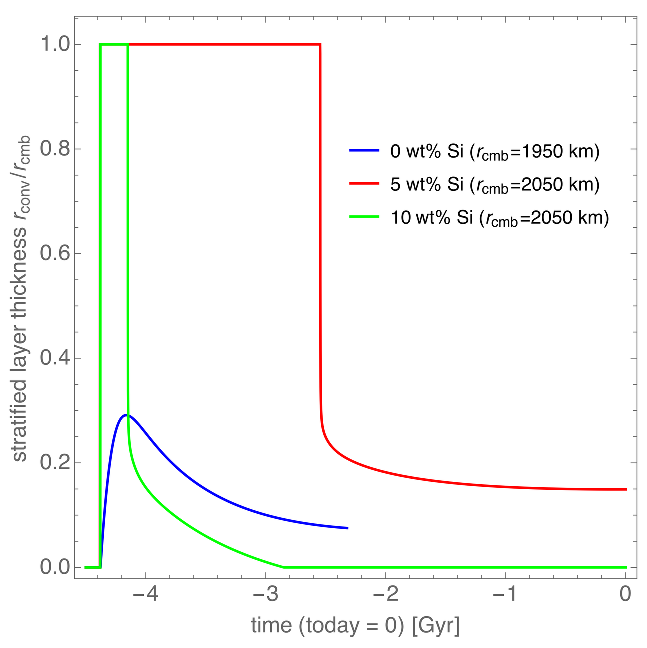

Fig. 7: Relative thickness of the stratified layer for three models (solid line: r_{cmb} = 2050 km, 5 wt% Si - 3 wt% S; dashed line: r_{cmb} = 2050 km, 10 wt% Si - 1 wt% S; dotted line: r_{cmb} = 1950 km, 0 wt% Si - 1.6 wt% S). The initial temperature at the core-mantle boundary is 2100 K for the three models. Fe-S-Si cores are entirely stratified before inner core onset. Buoyancy flux generated by the inner core growth reduces the size of the stratified layer. With 10 wt% Si, the core is entirely convective today. Cores with 5 wt% Si are still partially stratified today with a stratified layer of about 300 km. During entirely stratified periods, convection stops and no internal core dynamo is possible.

6. Conclusions

- Fe-S core:
  - no model without core heating that has sufficient entropy to drive a dynamo today but a dynamo action is possible during the first Myrs of the evolution:
    - small core models: power generated by the inner core growth not sufficient to drive a dynamo; convection likely stops after at most 3.5 Gyr because of iron-rich snow reaching the inner core boundary
    - large core models: no solid inner core because of large sulfur concentration; only early dynamo
  - inner core size in small core models much larger than 300 km: in contradiction with contraction constraints
  - core cooling below 150 K during the last 4 Gyrs: in agreement with contraction constraints
  - lower mantle likely melted during a substantial part of the evolution: in contradiction with old major volcanism
  - radioactivity: addition of 5% (small core models) - 10% (large core models) of the crustal concentration in radioactive elements in the core allows for a partly convective core today
- Fe-S-Si core: addition of 5 wt% Si (with 3 wt% S) is sufficient for a solid inner core and a liquid outer core today with a present-day dynamo. But dynamo begins late, at odds with early magnetization. Models with 10 wt% Si are in contradiction with contraction constraints. Even with the addition of Si, the lower mantle is melted during a large part of the evolution.
- Stratification:
  - growth of a solid inner core generates buoyancy flux acting against stratification
  - Fe-S large core models: early entirely stratified core (200 Myrs): no convection, and therefore no core dynamo, are possible. In Fe-S small core models: core at least partly stratified during the largest part of the evolution, but the buoyancy forces are not sufficient to drive a dynamo
  - Fe-S-Si cores with 5 wt%Si - 3 wt% S: still partially stratified today, after a long episode ($\sim$1.5 Gyr) without convection. Fe-S-Si cores with 10 wt%Si - 1 wt% S: entirely convective today: smaller S concentration allows for an earlier inner core, but the core experiences an entirely stratified episode during $\sim$100 Myrs
  - possible for a dynamo to restart after an episode without convection due to core stratification? If not, models with 5-10 wt% Si are likely ruled out