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Thermo-chemical evolution and global contraction of Mercury

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Abstract

We present revised thermo-chemical evolution models to explain the observed small global contraction of Mercury. Our results confirm earlier findings of Hauck et al. [4] showing that only a dry, olivine rich mantle heated mainly by thorium can explain the observations. However, in addition to the result of [4], which further requires an initial sulfur content in the core of greater than 6.5 wt.% S and suggests a small present-day solid inner core, we show that also a low initial sulfur content ($\sim$1 wt.% S) is consistent with the small contraction. This latter model further suggests the rapid formation of a large solid inner core and a present-day crustal thickness of several tens of kilometers.

1. Introduction

After its three fly-bys, MESSENGER confirmed so far the 1 to 2 km global contraction since the end of the late heavy bombardment [6] and the weak, active magnetic field [5], both already suggested from Mariner 10 data. These findings are strongly related to the thermal evolution of the planet and previous studies using paramterized convection models [4] found that only a dry, olivine rich mantle heated mainly by thorium and a sulfur-rich core (>6.5 wt.%) can explain the observations. Here, we extend the model in contrast to [4] by further considering the influence of crustal growth as well as the thermal conductivity in the crust on the global contraction.

2. Model of thermo-chemical evolution and global contraction

The thermo-chemical evolution is calculated using a parameterization for stagnant lid convection [3] and including solid inner core growth. We further account for the crust formation and the associated depletion of radioactive elements in the mantle. The global contraction is caused by the cooling of the interior and by phase changes associated with the growth of the solid inner core and the formation of crust. For the contraction by cooling we consider the temperature and pressure dependent thermal expansivity of the different materials. The variation in the planetary radius by phase changes is obtained by the conservation of mass. As the growing solid inner core is denser than the liquid outer core, freezing of an inner core is associated with contraction. The formation of a less dense crust, however, results in expansion.

We have varied the following parameters as these are directly linked to the efficiency of cooling during Mercury's history: the initial thermal profile (T_m, ΔT_{cm}), the reference viscosity of the mantle (η_0), the bulk sulfur content of the core, the thermal conductivity of the crust (k_c) and the bulk abundance of radioactive elements (see table 1). The latter depends on the formation scenario [1],[2], [7].

model	**U (ppb)**	**Th (ppb)**	**K (ppm)**
Condensation	30	120	0
Vaporization	0	400	0
CI chondrite	8	30	550

Table 1: Radioactive elements in formation models

3. Results

We find - consistent to [4] - that the heat production rate in the mantle is of major importance. Only the vaporization model that suggests thorium as the main heat source explains the small contraction. This is due to the 14 Gyr half-life of this element that accounts for an almost constant heating rate throughout history. Models assuming also uranium and potassium show a much faster planetary cooling, leading to a much larger contraction.

Similar, the influence of the mantle viscosity is significant. Only models with reference viscosity of 10^{21} Pa.s, corresponding to a dry, olivine rich rheology are consistent with the observed contraction. A smaller reference viscosity representing a weaker mantle leads to a more efficient cooling and thus to larger contraction.

The influence of the crust on global contraction is more complex. The crust can insulate the interior assuming a thermal conductivity smaller than the conductivity of the mantle. Thus, the smaller the thermal conductivity of the crust the stronger is the reduction of planetary cooling and contraction. Furthermore, crust formation contributes to the expansion of the planet due to its lower density. However, an increase in thickness of the insulating crust does not necessarily account for even smaller contraction. These effects can be compensated by the depletion in radioactive elements of the mantle. The latter will result in a more efficient cooling and counterbalance the thermal insulation. As a consequence, a thick insulating and enriched crust can even enhance the contraction.

Our study shows that only a small parameter range can fit the observed contraction. Interestingly for this parameter set (i.e., $T_m = 1750$K, $\Delta T_{cm} = 350$K, $k_c = 1\mathrm{Wm}^{-1}\mathrm{K}^{-1}$, $\eta_0 = 10^{21}$ Pa.s and vaporization formation scenario), a model with an initial sulfur content of $\sim$7 wt.-% S but also of $\sim$1 wt.-% S can explain the small contraction. The high initial sulfur content results in an inner core growth very late in the evolution and a thin present-day crust. The low sulfur content will lead to an early rapid inner core growth and a reduced growth rate after a few hundred Ma (Figure 1). The energy relased by this early core formation also heats up the mantle and thus enhances crust formation in contrast to the 'high' sulfur model.

4. Discussion

In addition to the results presented by [4] that suggest a late inner core growth we find that also models with a low sulfur content are compatible with the small planetary contraction. It is interesting to note, however, that the model with late inner core growth has difficulties in explaining the contractional timing. For this model, contraction is almost neglectable for about 1 Ga after heavy bombardement, which appears to be in disagreement with observations. The model with S = 1 wt.-%, on the other hand, is consistent with old contractional features - 20% of the contraction occured during the first 500 Myr (Fig. 2).

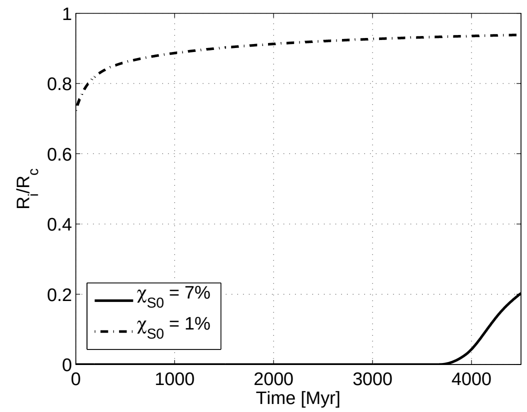

Figure 1: Normalized inner core growth as a function of time for sulfur contents of 1 wt.% and 7 wt.-% S.

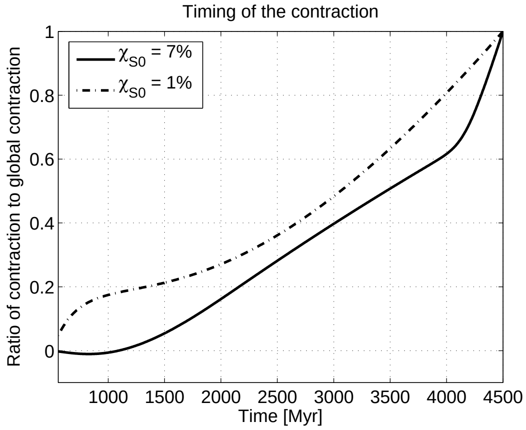
Timing of the contraction

Figure 2: Time evolution of global contraction. Both models correspond to 3 km contraction in the last 4Ga.

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