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Mantle convection and phase transitions on Mars

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Abstract

The influence of phase transitions in the Martian mantle has been studied with an axisymmetric spherical shell model. An extended Boussinesq model with a temperature and depth dependant viscosity, including the decay of radioactive elements and the cooling of the core has been used with two different sizes of the Martian core. In the case of a small core, the endothermic phase transition tends to inhibit the convective flow. Decreasing in depth with the core cooling, that phase transition can disappear after few millions years, inducing a sudden increase of the heat flux out of the core who could explain a core dynamo reactivation [1]. Our results demonstrate that it is difficult to rejuvenate a dynamo for both core sizes but the endothermic phase in the small core case reheats the core and allows melt generation in hot plumes. On the contrary, the exothermic phase tends to accelerate the convective flow and with a large core, no melt zones are obtained. The importance to consider a viscosity layering in the mantle is confirmed as it involves degree-1 convection for both core sizes [2].

1. Numerical Simulation

Decreasing in depth with the core cooling, the spinel to perovskite phase can disappear involving a sudden increase of the heat flow out of the core. If the heat flow exceeds a critical value where a dynamo can be sustained, a core reactivation is conceivable after the shutdown of an initial global magnetic field.

As we do not know exactly the size of the Martian core, we studied two cases with two different core sizes, depending on sulfur content in that core [3, 4]. We used the axisymmetric spherical-shell from CITCOM2D, using a finite-element resolution method [5, 6]. The convection is described by the equations of conservation of mass, momentum and energy, assuming incompressibility and the extended Boussinesq approximation [7]. Isothermal and free-slip boundary conditions are applied at the top and the bottom of the model. The temperature at the top of the model is 220 K and the temperature at the bottom is decreasing with time as we modified the code to take into account the cooling of the core. The initial bottom temperature is 2500 K for a small core and 2000 K for a larger core.

We consider three different models and two different core radii of 1360 km (SC model) and 1700 km (LC models). The small core case includes the endothermic spinel to perovskite phase transition close to the core-mantle boundary (CMB) and an exothermic phase transition. For the case with a large core, the LC2 model includes two exothermic phase transitions with a thickness of 35 km each and the model LC1 includes only the olivine to γ-spinel phase transition with a thickness of 170 km as the Martian mantle is supposed to have an higher iron content than the Earth's mantle, according the isothermal phase relations in the binary system Mg_2SiO_4–Fe_2SiO_4 from Bertka and Fei (1997) [8]. We added to theses models the decay of radioactive elements from an initial heat production of 8.3 10^{-8} $W.m^{-3}$ [9] and a viscosity contrast between the bottom and the top of the model $\Delta\eta = 10^7$ with a jump in viscosity of a factor of 25 at the depth of the olivine to spinel phase transition [2].

2. Results

On figure 1 we compare the evolution of the CMB heat flux with time for the studied models. We add to this plot a SCold case from a previous study without viscosity layering and for which the initial mantle temperature is lower (0.4 dimensionless) than the other cases (0.8). In this SCold model, the heat flux decreases at the beginning as the core cools and then a large increase is observed, above the critical heat flux, allowing a dynamo reactivation. However, this increase happens when the convection initiates and is not linked to the motion of the endothermic phase transition. In the other models (SC, LC1 and LC2), the heat flux decreases more rapidly at the beginning and no reactivation is possible. Moreover, in the SC model, the endothermic phase does not decrease in depth and is still present at 4.5 Ga. This phase transition reheats the core as it tends to inhibit the convective flow, and allows melt generation until about 3 billions years.

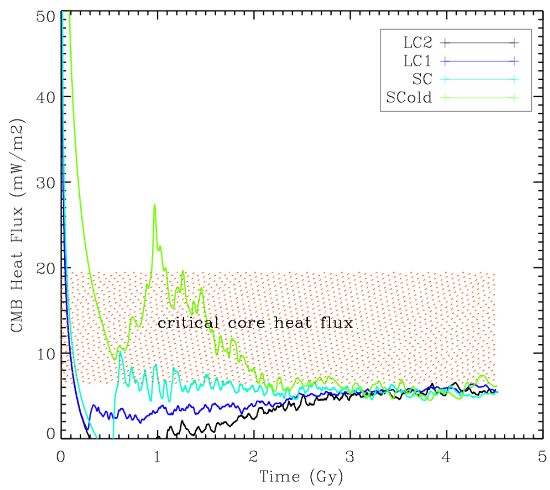

Figure 1: Evolution of the CMB heat flux from 0 to 4.5 billions years, for small core (SC, SCold) and large core (LC1, LC2) models. The critical core heat flux, below which a dynamo cannot be active anymore, is indicated on this figure.

In the large core models, as temperatures are lower, they do not exceed the solidus and no melt generation is identified. The presence of one or two exothermic phases in the mantle accelerates the convective flow in the same way and no differences are observed except that the core cools more rapidly in the LC1 model.

As the mantle is thinner in large core models, it is not possible to obtain degree one convection without the consideration of a viscosity layering. Including a jump in viscosity of a factor of 25 in the mantle allows the presence of one or two convective cells for the LC1 and LC2 models, as well as in the small core model.

3. Conclusions

These results demonstrate that, when the core is cooling, no dynamo reactivation is possible, even in the presence of an endothermic phase transition close to the CMB. However, phase transitions effects are significant. The endothermic phase is still present at 4.5 billions years and tends to reheat the core. The viscosity jump allows degree-1 convection in the three models, in agreement with results of Roberts and Zhong (2006) [2].

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