Convection in rocky planets: how well can the mantle be stirred?

3D Convective Mixing in Planetary Interiors with Strongly Variable Rheological Properties

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In Short

- The rocky mantles of the Earth and terrestrial planets undergo vigorous solid-state convection
- Isotopic analyses of surface rocks and meteorites suggest the existence of large-scale compositional reservoirs in the deep interior of terrestrial planets that survived convective stirring and mixing for billions of years
- The characterization of mixing is computationally challenging and so far the problem has been addressed at realistic conditions only with 2D simulations
- The only 3D mixing simulations available rely on the assumption of constant viscosity
- We will perform large-scale 3D simulations of thermal convection in planetary interiors to quantify the mixing properties of planetary mantles at realistic conditions using strongly variable viscosity

The interior of the terrestrial bodies of the Solar System (Mercury, Venus, Mars, the Earth and the Moon) consists of a layered structure composed by a central metallic core (solid or liquid) overlain by a rocky silicate mantle and a thin crust of volcanic origin. Although the mantle and crust are solid, at the extreme pressure and temperature conditions present in planetary interiors, rocks become ductile and flow over geological time scales like extremely viscous liquids. After planetary formation solid mantles accumulate a vast amount of heat, which is then transported via solid-state thermal convection from the interior to the surface over billions of years of evolution [1].

With the exception of the Earth's mantle and core, which can be probed through the analysis of seismic waves, planetary interiors remain largely inaccessible to direct inspection. However, the study of surface rocks and meteorites carried out by spectrometers on board of orbiting spacecrafts and, if possible, in the laboratory provide important information about processes taking place in the deep interior. In particular, isotopic analyses indicate that planetary mantles are far from being chemically homogeneous. These analyses suggest that large-scale compositional reservoirs that have been able to survive long-term convective mixing and stirring must be present in the deep mantle of terrestrial bodies [2].

While it is well established that chemically-distinct reservoirs must exist in planetary mantles, it is less clear whether and how such reservoirs can be preserved over billions of years of evolution during which mantle convection has been acting to homogenize them.

Using different Lagrangian techniques based on tracking the evolution of the trajectories of passive tracers, convective mixing of compositional reservoirs has been investigated with numerical models under a variety of conditions and in the presence of complex flows in 2D geometry [e.g., 3]. Only a handful of studies have been dedicated to the analysis of compositional mixing in 3D mantle convection, all of which relied on the assumption of constant viscosity. However, the viscosity of mantle rocks is a strong function of temperature [3]. It increases (decreases) exponentially as the temperature decreases (increases) according to an Arrhenius relationship. Such a strong temperature dependence is responsible for the formation of the so-called "stagnant lid", an immobile upper layer that is too stiff to participate in mantle convection. This situation is the most common in the Solar System. Mercury, Mars, the Moon and, at least at present, Venus, are all characterized by a stagnant lid forming an immobile plate. Convection can only take place at depth beneath this single plate where temperatures are high enough for ductile flow to be possible (Figure 1a). The Earth is the only known planetary body operating in a mobile lid regime with a surface split into tectonic plates that are an active part of the mantle convection system (Figure 1b).

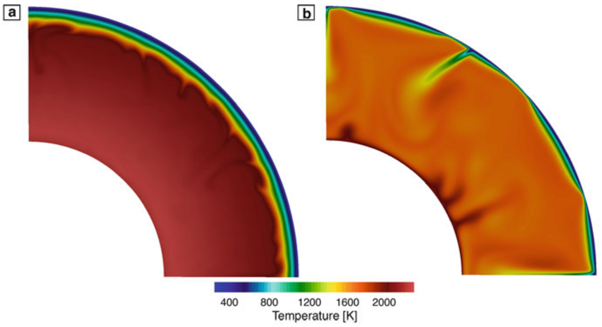

Figure 1: *Mantle temperature field from a simulation of convection in the stagnant-lid regime characteristic of the terrestrial planets (a) and in the mobile lid or plate tectonics regime characteristic of the Earth (b).*

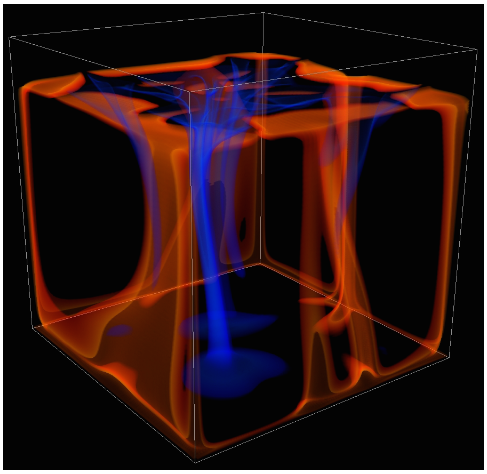

Figure 2: *Isothermal surfaces marking up- and downwellings (orange and blue) flowing beneath the stagnant lid in a 3D simulation of thermal convection with variable viscosity. The stagnant, high-viscosity lid is not shown and occupies the upper part of the box.*

In this project we aim at performing large-scale simulations of 3D thermal convection with variable viscosity in order to characterize for the first time the mixing properties of planetary mantles operating operating in the stagnant lid regime (Figure 2) as well as in the mobile lid or plate tectonics regime.

To this end, we will employ our mantle convection code Gaia. Gaia is a fluid solver based on the finite volume method which can solve the conservation equations of thermal convection in several geometries in the presence of strongly variable viscosity [4]. The code is parallelized with MPI using domain decomposition. Its performance and scalability have been tested on the HLRN III system using up to 54000 cores and a mesh of 54×10^6 grid points.

As a first study, we will keep the complexity of the convection model at a low level in order to identify the fundamental features that distinguish the properties of mixing of isoviscous systems from those of systems with temperature-dependent viscosity. In follow-up projects we plan to investigate additional important rheological effects such as the pressure dependence of the viscosity and non-linear, power low rheologies with variable grain size.

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More Information

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Funding

Helmholtz Gemeinschaft (project VH-NG-1017)