Chapter 15
Thermo–Chemical Convection in Planetary Mantles:
Advection Methods and Magma Ocean Overturn Simulations

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ABSTRACT

Thermo-chemical convection is the primary process that controls the large-scale dynamics of the mantle of the Earth and terrestrial planets. Its numerical simulation is one the principal tools for exploiting the constraints posed by geological and geochemical surface observations performed by planetary spacecrafts. In the present work, the authors discuss the modeling of active compositional fields in the framework of solid-state mantle convection using the cylindrical/spherical code Gaia. They compare an Eulerian method based on double-diffusive convection against a Lagrangian, particle-based method. Through a series of increasingly complex benchmark tests, the authors show the superiority of the particle method when it comes to model the advection of compositional interfaces with sharp density and viscosity contrasts. They finally apply this technique to simulate the Rayleigh-Taylor overturn of the Mars' and Mercury's primordial magma oceans.

INTRODUCTION

Our knowledge about planetary systems and bodies has significantly improved over the last 50 years thanks to the vast amount of information provided by Earth-based and space telescopes, orbiter and lander missions made possible by the efforts of national space agencies such as NASA, ESA, JAXA, etc. However, most data available have been derived from surface observations which offer an indirect and limited view of the deep interior and can thus provide only relatively poor constraints on the dynamics and thermal history of planetary bodies. Our main understanding

of the fluid dynamics of planetary mantles stems from laboratory experiments of convection and, in particular, from computer simulations. On the one hand, convection experiments are restricted to a small parameter range, not always relevant for planetary evolution. On the other hand, with the remarkable increase of computational power over the past years, numerical simulations have become the most powerful tool to model the temporal evolution of mantle flow with complex rheologies.

At the extreme conditions of planetary interiors, pressure- and temperature-activated deformation processes occurring at atomic level (e.g. Karato, 2008) allow rocks to flow like highly viscous fluids over geological time-scales ($\sim 10^6$ years and longer). The slow creep of the silicate materials that make up the mantle of terrestrial planets (i.e. Mercury, Venus, the Earth and Mars) is driven by a combination of thermal and compositional buoyancy. On the one hand, the primordial heat accumulated after accretion and core formation and the heat released by the decay of radiogenic isotopes are transported from the interior to the surface by thermal convection. This process involves the transfer of heat both via diffusion, which occurs mainly across thermal boundary layers, and advection due to fluid motion in the bulk of the mantle. On the other hand, density anomalies of non-thermal origin associated with chemical (i.e. compositional) heterogeneities provide an additional source of buoyancy that actively contributes to the transport of energy and mass.

Compositional heterogeneity in the mantle occurs at all spatial scales. It is an important factor in controlling the dynamics of regional- to medium-scale processes such as the flow in magma chambers (Verhoeven & Schmalzl, 2009), the rise of salt diapirs in sedimentary basins (Chemia et al., 2008), the dynamics of partial melt in the upper mantle (Fraeman & Korenaga, 2010), the subduction of lithospheric plates (Schmeling et al., 2008) or the dynamics of multi-component plumes (Samuel & Farnetani, 2003). It can also

contribute to the first order to shape the global-scale mantle circulation. Atop the core-mantle boundary (CMB) of the Earth, for example, seismic evidence indicates the existence of two broad antipodal regions characterized by higher than average density (Ishii & Tromp, 2004), which are interpreted as ascending thermo-chemical plumes (Tan & Gurnis, 2007) that represent a plausible source for hot-spots volcanism (Dechamps et al., 2011). Aside Earth, chemical heterogeneities are believed to play an essential role also in the evolution of other terrestrial bodies. Geochemical analysis of the so-called SNC meteorites suggests the existence of separate chemical reservoirs in the mantle of Mars, which have been preserved over the entire planetary evolution (Papike et al., 2009). The composition of some glasses on the Moon also suggests the migration of melt through a chemically heterogeneous mantle (Elkins-Tanton et al., 2011). On Mercury, the poor-iron oxide surface silicates and the high metallic iron fraction of the bulk planet hint at a complex thermo-chemical history of the mantle (Brown & Elkins-Tanton, 2009). Also, the fractional crystallization of a so-called magma ocean (see Section "Magma ocean cumulate overturn simulations"), which may take place early in the evolution of a terrestrial planet (e.g. Solomatov, 2007), produces a gravitationally unstable density stratification that can lead to a rapid overturn of the whole mantle and influence the onset and evolution of thermal convection (e.g. Elkins-Tanton et al., 2005; Brown & Elkins-Tanton, 2009).

In its simplest form, modeling of compositional heterogeneities requires the solution of the transport equation for a scalar, non-reactive field C:

$$\frac{\partial C}{\partial t} + \boldsymbol{v} \cdot \nabla C = 0 \tag{1}$$

where t is the time and $\boldsymbol{v}$ a given velocity field. The accurate solution of Equation (1) is of primary importance especially if C is associated with buoyancy and/or rheological (i.e. viscosity)

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