Thermo-compositional convection in magma oceans

Master/PhD project proposed by Stéphane Labrosse,
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The formation of terrestrial planets and satellites (Earth, Mars, Venus, Mercury, the Moon) ended with a phase of giant impacts between planetary embryos. In the case of the Earth, the last such giant impact is generally thought to have resulted in the formation of the Moon. The huge kinetic energy involved in such impacts is enough to melt or even vaporize a large part of the planets and their subsequent thermal and chemical evolution starts with the condensation and crystallisation of their silicate part to form their currently solid mantle. It is then thought that the silicate Earth went through a period in which it was mostly molten, hence forming what is called a *magma ocean*. The dynamics, thermal evolution and crystallisation of this magma ocean are responsible for early differentiation events in the mantle, which sets the initial condition for solid state convection in the mantle. For a few years now, several studies have uncovered evidences of these early events in the form of tiny isotopic anomalies for several elements. On the other hand, models developed so far for the dynamics and evolution of magma oceans are extremely simplistic, mostly based on scaling laws whose relevance to the problem are not demonstrated. In particular, all these models assume that magma oceans are always well mixed by turbulent convection. However, crystallisation of a magma with a complex composition generally leads to differences in composition between the solid and the liquid (fractional crystallisation), the liquid being generally richer in FeO than the coexisting solid. The liquid gets therefore enriched in FeO over time. Owing to a great increase of the liquidus with pressure, crystallisation is thought to proceed from the bottom upward, and the melt at the bottom of the magma ocean becoming reacher in FeO over time can stabilise against entrainment by thermal convection (Labrosse, Hernlund, and Hirose, 2015). The goal of this project is to explore the different dynamical regimes of thermo-compositional convection in a rotating spherical shell as a function of the relative importance of the destabilising thermal gradient at the top and the stabilising compositional gradient at the bottom. This will allow the development of new scaling laws for the dynamics and evolution of magma oceans and to revise our understanding of the early dynamics of the Earth.

For this study, we will use the thermo-compositional convection code developed by Mathieu Bouffard during his PhD (defence on september 20^{th}, 2017). This code was written for application to core dynamics and dynamo calculations (Bouffard et al., 2017) (fig. 1) but was successfully tested for applications to the setup of this study, showing indeed the formation of a stably stratified layer at the bottom of the shell.

This project is well suited as a master internship subject and/or a PhD project. It comprises a first period of training to master the code and small developments, followed by a large amount of exploration of the parameter space to develop scalings before their application to magma oceans.

References

Bouffard, M., S. Labrosse, G. Choblet, A. Fournier, J. Aubert, and P. J. Tackley (2017). A particle-in-cell method for studying double-diffusive convection in the liquid layers of planetary interiors. *J. Comput. Phys.* **346**, 552–571.

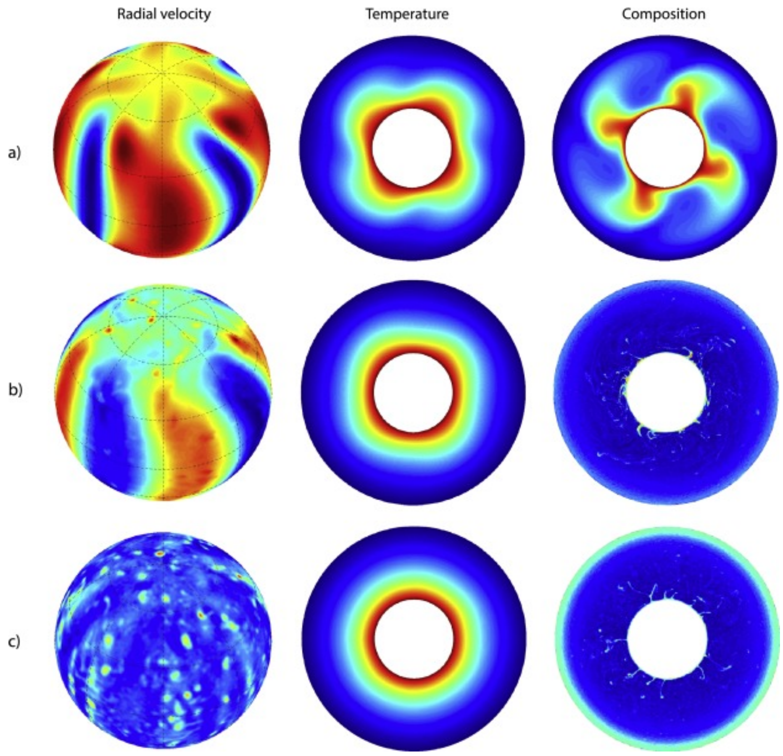

Figure 1: Snapshots of radial velocity, temperature and composition in a model of thermo-compositional convection in a rotating spherical shell. Each line is for a different set of input parameters. The last row, neglecting all solute composition, is driven mostly by composition differences (80%). It shows the development of a stably stratified layer at the top of the domain. See Bouffard et al. (2017) for details.

Labrosse, S., J. W. Hernlund, and K. Hirose (2015). "Fractional melting and freezing in the deep mantle and implications for the formation of a basal magma ocean". *The Early Earth: Accretion and Differentiation*. Ed. by J. Badro and M. J. Walter. Vol. 212. AGU Geophysical Monograph. Wiley, pp. 123–142.