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Compaction during the evolution of planetary inner cores

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Abstract

Growth of the solid inner core is generally considered to drive the Earth's present geodynamo. Here we estimate the compaction of planetary cores for different scenarios of growth and size of inner core. Our main results indicate that small inner cores are unlikely to compact efficiently the liquid trapped during the first steps of the growth. The light elements are thus released on Myear or Gyear time scales, essentially decoupling the latent heat and the light element effects for driving the geodynamo. This could have implications for the dynamo evolution in bodies such as the Moon or Ganymede.

Introduction

Growth of the solid inner core is generally considered to drive the Earth's present geodynamo, providing the major source of energy for convection in the liquid outer core by releasing light elements and latent heat at the bottom of the liquid core. Similarly, the crystallization of a liquid core has been proposed for some rocky bodies of the solar system, such as the Moon[1], Mercury[2] and Ganymede[3], to explain the presence of a past and/or present magnetic field.

Most of the models for the evolution of planetary magnetic fields are based on the Earth's example, with modifications for taking into account the changes in pressure, temperature, composition. It is the only planet for which we have seismic observations of a solid inner core, providing constrains for its size, density and elastic properties. For the other planetary bodies, the existence of a solid fraction in the core is inferred from the evidence of a magnetic field and our current knowledge of the phase diagrams of iron alloys.

Considering a simple model of a binary alloy with a eutectic-type phase diagram for the outer core alloy, the inner core freezes through fractional crystallization and the light-element enriched liquid is extracted by compaction from the solid matrix. The eutectic temperature is never reached, and the extraction of the liquid by gravity is here a key ingredient to the release of light elements in the liquid outer core.

The compaction of the inner core has been studied previously for the Earth, but it is still unclear if this compaction would be efficient for planetary bodies. Here, we propose to investigate the problem of compaction for a large range of bodies and the implications for the studies of planetary magnetic field.

Model

Following [4], we model the compaction of the matrix of the inner core as a two-phase flow system where the dynamics is driven by the density difference between liquid and solid. Both phases are treated as viscous fluids, with a liquid viscosity several orders of magnitude larger than the solid one. We do not consider the effects of melting or freezing in the system.

In this project, we solve the porosity evolution in 1D for several scenarios of growth. We obtain compaction profiles and calculate the average fraction of liquid trapped in the volume and the typical size of the upper mushy layer.

Results

For a typical core with a density jump of 500 kg.m^{-3} and $g_0 = 4.4$ m.s^{-2}, the Darcy velocity and the compaction length can be estimated as $\delta \sim 10^{-2} - 10^{2}$ km and $V_D \sim 10^{-12}$ m/s.

Small growth rates

As the estimations of growth rates for planetary inner cores are usually of the same magnitude than the crystallization rate of the present inner core ($\sim 10^{-10}$ m/s), we focus first on the case where the growth rate is small compared to V_D.

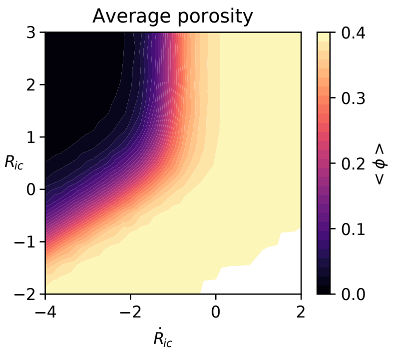

Figure 1: Average porosity as function of the radius of the inner core R_{ic}/δ and the growth rate $\dot{R}_{ic}/V_D$.

For sizes of inner core larger than the compaction length, a mushy layer of thickness similar to the reduced compaction length $\delta_r = \delta\sqrt{\dot{r}_{ic}/V_D}$ is observed and compaction is very efficient. For smaller inner core, the compaction is inefficient. Even where a mushy layer develops at the top of the inner core, the inefficient compaction prevents the bulk to fully compact, and liquid can be trapped in depth.

Initial very fast growth

An initial step of very fast growth has been proposed for some planetary cores. [1] considered growth scenarios of the inner core of the Moon where most of the crystallization occurs in the first few 100 Myears, to be able to explain an initial strong magnetic field for the Moon. [5] proposed also a scenario with an episode of very fast growth at the early times of a planetary inner cores, as the crystallization may be delayed due to the supercooling effect.

In both cases, the very fast growth may prevent the extraction of liquid to the outer core and modify the evolution of the dynamo. We estimate the typical time to extract half of the volume of liquid trapped in an initially mushy and homogeneous sphere. This time scales as $t_{\text{comp}} \sim R_{\text{ic}}/V_D$ for small inner cores and as $t_{\text{comp}} \sim \delta^2/(R_{\text{ic}}V_D)$ for large inner cores.

Implications for planetary cores

Seismic observations of the Earth's inner core shows no evidence for liquid trapped in depth due to inefficient compaction. However, we cannot observe other planetary inner cores and we don't know their physical state and properties. Here we estimated the compaction of planetary cores for different scenarios of growth and size of inner core.

We obtained that small inner cores are unlikely to compact efficiently, and that the release of the trapped liquid is done on Myear or Gyear time scales, decoupling the latent heat and the light element release for driving the geodynamo. This could have implications for inner core in bodies such as the Moon or Ganymede.

For large inner core, such as the one observed for the Earth or the one inferred for Mercury, the compaction is efficient. An episode of super fast growth at the beginning of the growth, such the one proposed by [5] is still unlikely to trap a significant amount of liquids in depth. However, we observed the propagation of solitary waves in the system, which would likely be destabilized in real 3D system and may explain some of the intriguing observations of the Earth's inner core.

References

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