Formation and Dynamics of a Stably Stratified Layer below the Core-Mantle Boundary (Ref IAP-17-98)

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In partnership with University of Glasgow, School of Mathematics and Statistics

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Overview

A stratified layer at the top of the outer core?
Motions of liquid iron in the outer core are driven by thermal and compositional convection due to the cooling of the planet. These convective motions are the main source for the generation and sustenance of the geomagnetic field. An on-going debate in the deep Earth interior community is whether the whole outer core is convecting or whether a region near the core-mantle boundary (CMB) is stably stratified (e.g. Gubbins 2007). This issue has important implications for the interpretation of the geomagnetic data measured at the Earth's surface (Buffett 2014) and the thermal evolution of the core (Labrosse 2015). In this project, we propose to study the mechanisms by which a stratified layer could form at the top of Earth’s core, the nature of the motions in this layer, and the layer thickness.

Double-diffusive convection in the core
There are two sources of buoyancy in the core: (i) a thermal source due to the secular cooling, the latent heat release during the solidification of iron at the inner core boundary (ICB), and possibly, radiogenic heat sources; (ii) a compositional source due to the release of light elements during the solidification of the inner core. This second source is thought to be a major contribution to the buoyancy driving (estimates suggest that the light element flux coming from the ICB supplies 50 to 80% of the total buoyancy flux). Temperature and composition have very different molecular diffusivities and this difference greatly influences their effect on the flows. This difference is particularly important for the formation and dynamics of a stable layer below the CMB.

![Figure 1: Schematic of the Earth’s interior. Fluid motions in the liquid core generate the Earth’s magnetic field and convect heat from the deep interior to the mantle.](image)

A possible scenario for the formation of this layer is that the lighter fluid released at the ICB forms plumes that do not fully mix in the outer core and deposit light elements in a layer when reaching the CMB. In this scenario, the layer would be stably stratified due to composition, but potentially unstable to thermal perturbations. Another plausible scenario is that a
thermally stably-stratified layer forms if the mantle imposes a low heat flux at the CMB, but it might be unstable to compositional perturbations. In these two different scenarios, the stratified layer could be prone to double-diffusive instabilities. These instabilities are well known in oceanography and astrophysics (Turner 1974), but, surprisingly, they have received little attention in the context of the core so far. Yet, if present, they would have a significant effect on the efficiency of transport of chemicals and heat towards the CMB.

Scientific challenge and aim of the project
Little is actually known about the flows inside the core due to the lack of direct observations. We can devise estimates of the flow near the CMB from measurements of the changes of the geomagnetic field. This gives a flow speed of about 10-20 km/yr, which is sufficient to change the field significantly over hundreds of years. However, we cannot observe the flow in the interior of the core directly, and this has motivated the development of numerical models that aim to describe the main features of these flows (e.g. Christensen & Wicht 2015). The core flow is expected to be very turbulent, meaning that a wide range of lengthscales (from 1000 km to 1 mm) and timescales (from millions of years to days) are involved in the dynamics. Resolving this vast spectrum of scales is extremely challenging numerically, so current models cannot use the true parameters of the core and some approximations are necessary to make progress in our understanding of the dynamics of the core flows.

In most numerical models of the Earth’s core, the distinction between compositional buoyancy and thermal buoyancy is ignored, and these two components are combined into a single co-density variable. This approach, used for simplicity, is poorly justified because these buoyancy sources have different diffusivities and boundary conditions. The ratio of the diffusivities of temperature to composition is called the Lewis number (Le), and is estimated to about 1000 in the core. Numerical simulations are extremely costly to run in three dimensions, so the study of thermo-compositional convection with double diffusion has been very limited so far. Only a few numerical studies have explored Lewis numbers greater than 1 (typically, Le≈10 in these studies) (Manglik et al 2010, Simitev 2011, Trüper et al 2012, Takakashi 2014). They all report results that differ significantly from the results obtained with the traditional models using the co-density approach.

In this project, we propose to push the Lewis number towards Earth-like values using a simplified numerical model. The model assumes that the velocity, temperature and compositional fields are invariant along the rotation axis due to the rapid rotation of the system (see figure 2). This approximation allows the reduction of the problem from three dimensions to two dimensions, and thus, alleviates part of the computational limitations (Guervilly & Cardin 2016). This simplified numerical model will allow us to study dynamical regimes that have never been explored before. By carrying out an extensive exploration of the parameter space, we will determine the necessary conditions for the formation of a stratified layer.

Figure 2: Numerical simulation of thermal convection during the early history of Earth’s core (before the formation of the inner core) (credits: N. Schaeffer). The simulation shows that the flow takes the form of columns aligned with the rotation axis.

Project outline and objectives
Due to the limited number of simulations that have been able to study the regime relevant for the Earth’s core (Le>>1), little is known about the formation and properties of any stratified layer below the CMB. For instance, the nature of the stratification (thermal and/or compositional) possible in Earth’s core remains undetermined. In addition, the dynamics of the stratified layer (i.e. whether it is prone to double-diffusive instabilities) is poorly known. Using a simplified 2D numerical model, we will be able to vary three of the important elements of the problem: the Lewis number (over several orders of magnitude), the ratio between the compositional and thermal buoyancy fluxes, and different boundary conditions for the temperature and concentration fields.

The main objectives of the project are:

1. to determine the necessary conditions for the formation of a stably stratified layer in double-diffusive thermo-compositional convection,
2. to understand the mechanisms of formation,
3. to study double-diffusive instabilities within the layer and their effect on the transport of heat towards the CMB,
4. to investigate the thickness of the layer as a function of the model parameters and extrapolate the results to Earth’s core conditions,
(5) to study the effect of heterogeneous boundary conditions at the CMB (i.e. longitudinal variations imposed by the mantle) and its effect on the thickness of the layer.

**Methodology**

We will use an existing numerical code of rapidly-rotating thermal convection in a spherical shell (Guervilly & Cardin 2016). The student will modify the code by adding the compositional field and by implementing heterogeneous boundary conditions. Simulations using the thermo-compositional convection code will be run on the high performance computing facilities available at Newcastle and Glasgow Universities. An exploration of the parameter space will be carried out to study the effect of the Lewis number and the buoyancy ratio on the formation and dynamics of the stable layer.

**Timeline**

Year 1: Literature survey on the dynamics of the deep Earth’s interior, rotating convection and double diffusion. Develop familiarity with the numerical model to be used in the research and high performance computing. Modify the numerical model to include thermo-compositional convection. Perform the first simulations with homogeneous boundary conditions.

Year 2: Determine the scaling laws for the thickness of the stable layer. Present results at international conferences. Publish the first results with homogeneous boundary conditions.

Year 3: Investigate double-diffusive instabilities. Investigate the effect of heterogeneous boundary conditions. Present results at international conferences. Write paper on the double-diffusive instabilities results.

Year 4 (6 months): Write paper on heterogeneous boundary conditions results. Write and defend thesis.

**Training & Skills**

The student will develop a multi-disciplinary expertise in deep Earth research and applied mathematics. In particular, the project provides specialist training in mathematical and numerical aspects of geophysics and fluid dynamics, with a strong emphasis on high performance computing. The student will have the opportunity to attend training workshops in computational modelling. Training in a wide range of generic skills (e.g. presentation skills, scientific writing skills) is provided by the Faculty of Science, Agriculture and Engineering at Newcastle University via the Postgraduate Researcher Development Programme (PGRDP) and additional accredited researcher-development courses are available at Glasgow. The School of Mathematics and Statistics at Glasgow provides year-long taught PhD modules in core topics of Applied Mathematics as a part of the Scottish Mathematical Sciences Training Centre (SMSTC). These SMSTC courses are available via video-conferencing and can be attended remotely. The student will also benefit from cross-disciplinary training provided as part of IAPETUS. The student will participate in weekly meetings of the astrophysical and geophysical fluid dynamics research group of the Schools of Mathematics at Newcastle and at Glasgow. The student will be encouraged to attend and present their work at national and international conferences and to develop collaborations in and outside Newcastle and Glasgow.

**References & Further Reading**


**Further Information**

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