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Numerical modelling of dense material distribution on the core-mantle boundaries in terrestrial planets

A. Płonka (1), L. Czechowski (1)
(1) Institute of Geophysics, Faculty of Physics, University of Warsaw, Poland

Abstract

Our main interest lies within the properties of the lower thermal boundary layer of the mantle convection. We assume whole-mantle convection for smaller planetary bodies like Westa, for the Earth our model corresponds to two-layered convection with only the strongest currents reaching the lowermost mantle. For certain densities of the accumulates on the core we calculate their distribution, stream function and temperature. The Rayleigh number is kept relatively low. We search over accumulate densities reaching from 1 to 2.5 of the mantle density – in this way we want to determine for which densities the accumulates start to form distinct domes on the core-mantle boundary. For the Earth, formation of high and sharp domes is visible for high densities after 700 million years. Another question, addressing also the problem of the accumulate genesis, is the ratio of radiogenic heat production in the dense material.

1. Introduction

The core-mantle boundary (CMB) is a reservoir of material of density between the density of rocky mantle and outer core. We assume this material is flowing on the CMB analogously to the continents on the astenosphere. For the Earth this assumption matches recent tomographic models of the mantle at 2800 km depth, in which we may distinguish two regions of considerably lower S wave velocity (Large Low Shear Velocity Provinces, LLSVPs), located antipodally beneath Africa and Central Pacific. They most probably correspond to regions of different chemical composition, denser and enriched in iron, and are referred as core-continents (c-continents) or BAM (basal mélange) [1,2]. Such bodies may be originated in the earliest days of the Earth's history. The Earth's CMB is an interface between geodynamo and mantle convection, so their presence plays a crucial role in the dynamics of the planet as a whole.

In our research we consider the role of in the evolution of mantle convection. We use Rayleigh numbers of values from 100 000 to 750 000, illustrating not only convection in the Earth's lower mantle, but also whole-mantle convection in smaller planetary bodies.

2. The model

We are working on two-dimensional numerical model based on the following equations:

$$\rho(T, Z_a, Z_b) = \rho_0 - \alpha\rho_0 T - \gamma_a Z_a + \gamma_b Z_b \qquad (1)$$

$$\frac{DT}{Dt} = \nabla^2 T + f(Z_a, Z_b) \qquad (2)$$

$$f(Z_a, Z_b) = (1 - Z_a - Z_b)Q_m + Z_a Q_a + Z_b Q_b \qquad (3)$$

$$\nabla^2(\eta\nabla^2 S) = R_T \frac{\partial T}{\partial x} + R_{Z_a}\frac{\partial Z_a}{\partial x} + R_{Z_b}\frac{\partial Z_b}{\partial x} \qquad (4)$$

$$\frac{DZ_{(a,b)}}{Dt} = C_{(a,b)}\left[\frac{\partial^2}{\partial x^2} + \frac{\partial}{\partial y}\left(\frac{\partial}{\partial y} - B_{(a,b)}\right)\right] Z_{(a,b)} \qquad (5)$$

where $\frac{D}{Dt}$ denotes substantial derivative, η is viscosity, R_T corresponds to Rayleigh number in the case of internal heating and R_{Z_a}, R_{Z_b}, $C_{(a,b)}$ and $B_{(a,b)}$ are non-dimensional parameters characterizing gravitational differentiation. We use two different fractions of material: the crust, referred as Z_a, and c-continents, referred as Z_b. Assuming whole-mantle convection and given initial density distribution and initial temperature, we calculate temperature T, stream function S and distribution of both fractions. The function f in the temperature equation (2) describes radioactive heat production in each of the fractions considered (3), where Q_m and Q_a denote the concentration of heat sources in the mantle and in the crust respectively.

Used were four different values of Rayleigh number R_T, densities ranging from 0,0 (same as the mantle density) to 2,5 (same as the core density) with the step of 0,1, and different radiogenic heat production ratios (from the same as in the mantle to 100 times higher or lower than in the mantle).

3. Preliminary results for fraction distribution

Our goal is to determine for which density value the convection remains stable and the dense accumulates on the core form distinct piles. We see changes in the stream function for densities around 1,4 of the mantle density, then they are growing. For higher densities we obtained two antipodal, sharp and high piles of the dense material, which can be compared with what we know about the Earth's core-mantle boundary. Time used was 700 million years for the Earth.

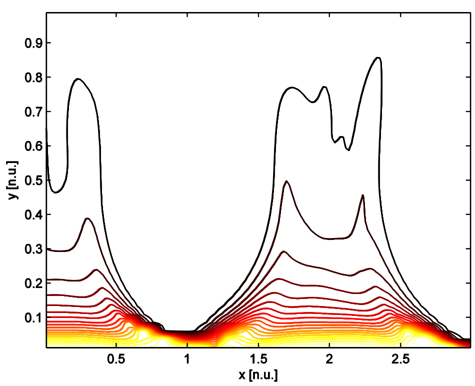

Figure 1: Spatial distribution of the dense material on the core-mantle boundary, Rayleigh number of 500 000, accumulate density 2,5 times higher than the mantle density. Visible are two separate, high and sharp-edged piles, much resembling the ones we know for the Earth

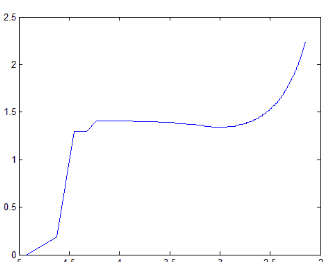

Figure 2: Convection velocity as a function of logarithm of the time unit. Parameters as in Figure 1. We see that for certain time the convection remains stable. The flat part of the graph is smaller for lower densities of the material.

4. Questions concerning radiogenic heat production

Another value worth looking closer at is radiogenic heating ratio in the dense accumulates. We see slight changes in the isotherms even for times as short as 7 million years for the Earth (Figure 3), so we expect larger differences for longer times. Investigation of this parameter may help answering the question of the genesis of c-continents: if they originated from the primeval mantle, radiogenic heating in them is probably much higher than in the mantle.

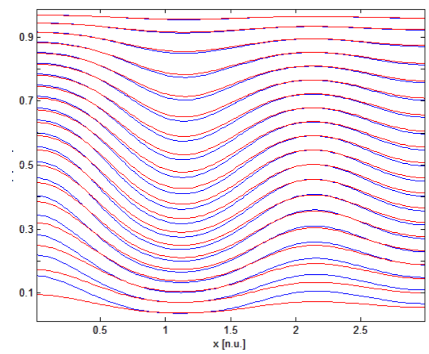

Figure 3: Isotherms for different ratios of radiogenic heating (spatial distribution) in the lowermost mantle. Red is 100 times higher than blue. Time unit is 7 million years for the Earth.

5. Summary and Conclusions

In the presented model we obtain similar distribution of the dense material on the CMB as we know for the Earth. Investigated are small Rayleigh numbers corresponding to two-layered convection in the Earth or to convection in small planetary bodies.

References

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