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Thermal and compositional stratification of the inner core

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ABSTRACT

The improvements of the knowledge of the seismic structure of the inner core and the complexities thereby revealed ask for a dynamical origin. Sub-solidus convection was one of the early suggestions to explain the seismic anisotropy, but it requires an unstable density gradient either from thermal or compositional origin, or from both. Temperature and composition profiles in the inner core are computed using a unidimensional model of core evolution including diffusion in the inner core and fractional crystallisation at the inner core boundary (ICB). The thermal conductivity of the core has been recently revised upwardly and, moreover, found to increase with depth. Values of the heat flow across the core mantle boundary (CMB) sufficient to maintain convection in the whole outer core are not sufficient to make the temperature in the inner core super-isentropic and therefore prone to thermal instability. An unreasonably high CMB heat flow is necessary to this end. The compositional stratification results from a competition of the increase of the concentration of light elements in the outer core with inner core growth, which makes the inner core concentration also increase, and of the decrease of the liquidus, which makes the partition coefficient decrease as well as the concentration of light elements in the solid. While the latter (destabilizing) effect dominates at small inner core sizes, the former takes over for a large inner core. The turnover point is encountered for an inner core about half its current size in the case of S, but much larger for the case of O. The combined thermal and compositional buoyancy is stabilizing and solid-state convection in the inner core appears unlikely, unless an early double-diffusive instability can set in.

1. Introduction

Since the discovery of the inner core anisotropy (Morelli et al., 1986; Poupinet et al., 1983; Woodhouse et al., 1986), many different mechanisms have been proposed to explain this observation (Deguen, 2012). It is not clear at present if any of these models is in fact able to quantitatively explain the observations and it is necessary to test systematically all the scenarios. This paper deals with one of the first proposed scenario: convection in the inner core (Buffett, 2009; Cottaar and Buffett, 2012; Deguen and Cardin, 2011; Deguen et al., 2013; Jeanloz and Wenk, 1988; Mizzon and Monnereau, 2013; Weber and Machetel, 1992).

Convection in the solid inner core is possible, like in the solid mantle, provided a sufficient source of buoyancy is available. For thermal convection to occur, the buoyancy source must come from a combination of radiogenic heating (Jeanloz and Wenk, 1988; Weber and Machetel, 1992), secular cooling (Buffett, 2009; Cottaar and Buffett, 2012; Deguen and Cardin, 2011; Deguen et al., 2013; Mizzon and Monnereau, 2013) or even Joule heating (Takehiro, 2011). The amount of potassium in the core is likely very limited (Hirose et al., 2013) and will not be considered further. Joule heating in the inner core (Takehiro, 2011) depends on the strength and pattern of the magnetic field at the bottom of the outer core and will

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also be omitted here. Secular cooling can provide enough buoyancy to drive thermal convection in the inner core if cooling is fast enough compared to the time required to cool the inner core by diffusion. This question was investigated in great details in a few recent papers (Buffett, 2009; Deguen and Cardin, 2011; Deguen et al., 2013; Yukutake, 1998). In particular, Deguen and Cardin (2011) proposed an approximate criterion for the possibility of thermal instability involving the age of the inner core and the thermal conductivity of the inner core. Recent results on the thermal conductivity of the core (Gomi et al., 2013; de Koker et al., 2012; Pozzo et al., 2012, 2014) favor a value much larger than previously thought, which makes the case for inner core thermal convection harder to defend. This will be discussed in section 3.

Compositional convection is also possible if the metal that crystallizes at the inner core boundary (ICB) gets depleted in light elements as the inner core grows. The concentration in light element X in the solid, C_X^s, is related to that of the liquid C_X^l by

$$C_X^s = P_X^{sl} C_X^l, \tag{1}$$

P_X^{sl} being the partition coefficient, generally lower than 1. As discussed by Deguen and Cardin (2011), C_X^s can vary because of the variation of P_X^{sl} and C_X^l. Assuming that the outer core is compositionally well mixed, C_X^l increases with the inner core growth due to the expulsion from the inner core with $P_X^{sl} < 1$. This effect tends to create a stably stratified inner core and must be compensated by a decrease of P_X^{sl} for compositional convection to occur. Gubbins et al. (2013) proposed that the decrease of the liquidus temperature with inner core growth is able to provide such variation. This effect will be discussed in section 4. The combined thermal and compositional buoyancy will then be discussed in section 5.

Compared to the previous work cited above, this paper differs in several ways. I do not attempt to solve the full convection problem as done by Deguen and Cardin (2011) and Deguen et al. (2013), because I merely want to study the conditions under which the basic stratification in a diffusion regime can become unstable, conditions that are found hard to meet with the large thermal conductivity implied by the recent studies. On the other hand, I solve the full thermal diffusion problem including the moving inner core boundary, coupled to the outer core evolution, which was not done by the previous workers on the topic, except Yukutake (1998), who did not consider compositional effects. The compositional evolution follows from the thermodynamics relations of Alfè et al. (2002) and Gubbins et al. (2013), but is treated in a more self-consistent way than the latter study, as discussed below.

2. Model for the evolution of the inner core

Following Alfè et al. (2002) and Gubbins et al. (2013), I assume a ternary composition for the core with Fe, O, and S. An alternative ternary composition with Fe, O and Si will be briefly discussed in section 6 for completeness. Following Gubbins et al. (2013), two compositional models are considered, one matching the ICB density jump of PREM (Dziewonski and Anderson, 1981) (thereafter termed PREM model) and the other one matching the ICB jump proposed by Masters and Gubbins (2003) (M & G model), which is larger. Because only O significantly fractionates at the ICB, the larger the density jump, the more O is needed in the core. Considering these two models allows us to investigate the implications this has on the stratification of the inner core.

O is highly incompatible in the inner core ($P_O^{sl} \ll 1$), while S has a partition coefficient only slightly lower than 1, which means that both are not very promising to create an unstable stratification in the inner core. Indeed, the limit $P = 0$ allows no solute in the inner core and $P = 1$ forbids its change in the outer core and therefore in the inner core. In both end-member cases, no concentration stratification is possible in the inner core and the optimum value for such a stratification is $P = 0.5$ (Deguen and Cardin, 2011).

The evolution of concentrations of O and S in the outer core from inner core growth follows from their conservation equations. These are most readily written using their mass fraction, ξ_X^i, i being either “s” for solid or “l” for liquid and X any of the two light elements considered, S or O. In the following, an omitted X means that it applies to either of the two. The relations between mass and molar fractions in the ternary system are given in Appendix A. In terms of mass fraction, the partition between liquid and solid is expressed by the factor K_X^{sl} defined as the ratio of the mass fraction in the solid to that in the liquid:

$$K_X^{sl} = \frac{\xi_X^s}{\xi_X^l}. \tag{2}$$

The conservation of light element X can simply be stated as

$$\frac{d}{dt}\left(\xi^l M_{OC}\right) = -K^{sl}\xi^l \frac{dM_{IC}}{dt} \tag{3}$$

which expresses that the total mass of the light element in the outer core, $\xi^l M_{OC}$, M_{OC} being the outer core mass, decreases because of the flux of solute going in the growing inner core. For an infinitesimal duration δt, the inner core mass increases by δM_{IC} and incorporates a total mass of solute equal to $\xi^s \delta M_{IC} = K^{sl}\xi^l \delta M_{IC}$. The total mass of the core $M_{tot} = M_{IC} + M_{OC}$ being constant, equation (3) can be recast as

$$\frac{d\xi^l}{dt} = \xi^l \frac{1 - K^{sl}}{M_{OC}} 4\pi r_{IC}^2 \rho(r_{IC}) \frac{dr_{IC}}{dt}, \tag{4}$$

where all terms on the right-hand side vary with time, or more precisely with the growth of the inner core (radius r_{IC}, r_{OC} for the outer core). Because of the very small value of the partition coefficient for O, very little is incorporated in the inner core and I assume $K_O^{sl} = 0$ to compute the evolution of the concentration in the outer core. The solution to equation (3) is then

$$\xi_O^l = \xi_{O0}^l \frac{M_{tot}}{M_{OC}} \tag{5}$$

ξ_{O0}^l being the initial mass fraction of O in the core. The variation of ξ_O^l with the inner core growth comes only from