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Review

Asymmetric dynamics of the inner core and impact on the outer core

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ABSTRACT

The history and present state of knowledge of the dynamics of the inner core are outlined in this paper. The observations that motivated ideas on the dynamical processes are introduced, but the main objective is really to concentrate on the diverse dynamical models that have been and are currently proposed for the formation and evolution of the inner core. A deliberate choice has been made of reproducing key figures from the literature in a didactic attempt to provide clear and quick identification for these models. This review looses impartiality concerning recent models, notably those aiming at explaining the hemispherical asymmetry. A preference for an intrinsic dynamic mode of the inner core is expressed, as opposed to the distant influence of the dynamics of the mantle through heat-flux heterogeneities. Meanwhile, the opinion is conveyed that the dynamics of the inner core is largely not understood yet and that every model must be considered with a critical eye.

Contents

1. Introduction

The inner core of the Earth is only 5000 km away but will remain out of reach for ever. We depend on indirect information gleaned from magnetic, gravity and most importantly seismic measurements on the surface of the planet. We may just consider one other type of measurements that might become very interesting in the future: detection of neutrinos (Borexino Collaboration et al., 2010; KamLand Collaboration et al., 2011). Since the discovery of the inner core by seismology (Lehmann, 1936), some basic features of its structure have been revealed (Souriau., 2007; Tkalcic and Kennett, 2008), prompting attempts to provide an explanation in terms of dynamics of the inner core.

The question of the dynamics of the inner core has been in constant evolution since the discovery of this central object (see Sumita and Bergman, 2007; Deguen, 2012, for previous reviews of inner-core dynamics). First, the question of its solid nature had to be

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sorted out. Then came the question of the origin of the solid phase: crystallization on the ICB or a rain of crystals coming from the outer core above. That question is associated with that of the relative slopes of the adiabat in the outer core and the Clapeyron curve. Later, the internal dynamics of the inner core was examined, under the pressing need to explain the newly discovered seismic properties of the inner core. We are now still struggling with incomplete seismic information and ignorance of very fundamental thermophysical data: what is the thermal conductivity of the inner and outer cores? What is the secular cooling rate in the inner core?

There has been growing evidence for the anisotropy of the inner core from the 80s. Seismic waves travel faster along the polar direction than they do along an equatorial path. Several dynamic models have been proposed, but there is still no definitive answer to this puzzle. The hemispherically asymmetric (East–West) structure of the inner core is the next remarkable feature. We shall focus more particularly on this one, because it has been explained by radically different models, involving the dynamics of the entire core and even that of the mantle. In a few words, one model holds that the heterogeneous heat flux at the base of the mantle has a long term influence on the outer core circulation which is responsible for differential crystallization growth on the surface of the inner core. The other argues that an intrinsic buoyancy mode of the inner core can lead to its hemispherical asymmetry with profound implications on the dynamics of the outer core. In addition, in this last model, the aspherical mass distribution in the mantle would play a role in selecting the hemispherical orientation. In any case, a dynamic coupling within the whole core is present. A third feature must be mentioned: an anomalous layer has been detected at the base of the outer core which could be a stratified region of a thickness of about 250 km. This has been formally related to the dynamics explaining the hemispherical asymmetry according to the second model mentioned above.

Section 2 will be devoted to the historical development of dynamic and thermodynamic models relative to the inner core. In Section 3, we shall focus on models explaining the hemispherical asymmetry. In the next Section 4, hints of structures of degree 1 within the outer core will be listed and Section 5 will bring us the opportunity to discuss what consequences on the inner core or on the outer core can be inferred from the observed asymmetry. Finally a discussion in Section 6 will present directions of promising investigations.

2. Historic development of inner core models

2.1. Discovery of the inner core

The existence of the Earth's core, which already had quantitative supports at the end of the nineteenth century (Wiechert, 1897), was confirmed from seismology by Oldham (1906) and Gutenberg (1913). The core was initially widely thought to be solid, mostly because of the requirement from tides amplitude measurements that the interior of the Earth must, as stated by Kelvin, be "as rigid as steel". The failure to observe S-waves travelling in the core was not considered at that time as a compelling evidence for the core fluidity (Brush, 1980). Indeed, the core fluid state hasn't been accepted before Jeffreys (1926) showed the mantle's rigidity to be significantly higher than the mean rigidity of the Earth, thus requiring the core to have a low rigidity. The primary seismological evidence for the Earth's core is the core 'shadow zone' – a range of epicentral distance, between 103° and 143°, in which no P-waves arrival are expected. The shadow zone results from the fact that P-waves, being slower in the core than in the mantle, are refracted downward at the core–mantle boundary. Before 1936, some detections of faint direct arrivals of P-waves had been made in the shadow

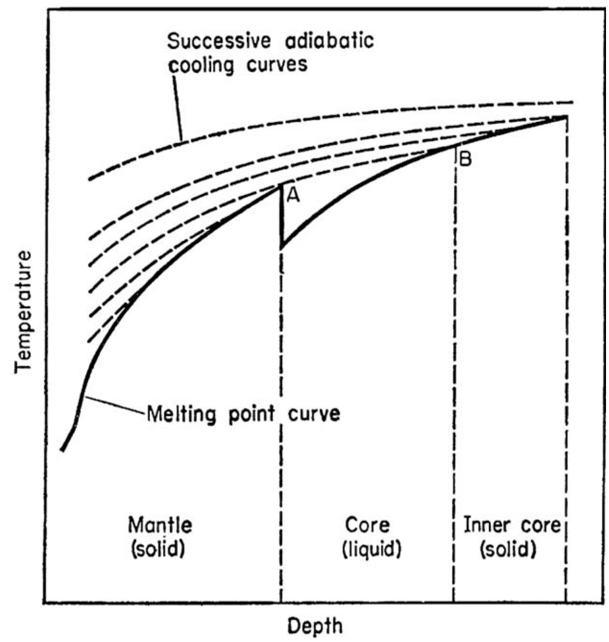

Fig. 1. Interpretation of the solid inner core as the product of crystallization of the liquid outer core driven by secular cooling (copy of the original figure from Jacobs (1953)). Reprinted by permission from Macmillan Publishers Ltd: Nature, copyright 1953.

zone (PKP waves, also called P′), but their existence was attributed to wave scattering at the CMB, as a general consensus. In 1936, Inge Lehmann formulated the assumption of a new discontinuity – the inner core boundary (Lehmann, 1936) – which better explained the observations and was quickly accepted as a new consensus (Gutenberg and Richter, 1938; Jeffreys, 1939).

2.2. Towards a solid inner core

The solid or liquid nature of the newly discovered inner core was debated very early after its discovery. In 1940, Birch (1940) wrote that "…it is not inconceivable that the outer part of the core might be molten, while an inner core remained frozen." His study was related to the dependence of temperature of iron phase transitions on pressure. It contained speculations on which iron phase might exist under pressures prevailing in the core and by extension on the temperature dependence of the melting point of iron. In a short paper published 6 years later (Bullen, 1946), Bullen was more specific and proposed a reasoning in favour of a solid inner core. He wrote "…it follows with a high degree of probability that the inner part of the central core …is solid, that is, possesses significant rigidity (μ)". The reasoning is based on the observation that the incompressibility k is a smooth function of pressure, the most striking example is that it shows very little change across the CMB. If that is true on the ICB, then the observed increase in P-wave velocity v_P in the inner core must be due to a substantial value of the shear modulus μ, since $v_P = \sqrt{(k + 4\mu/3)/\rho}$. The idea proved essentially correct even though it has since been determined that there exists a discontinuity for density and incompressibility (to a lesser extent) across the ICB (Bolt and Qamar, 1970).

In 1953, Jacobs (1953) suggested for the first time that the inner core was the result of crystallization of the outer core (see Fig. 1), made of iron and lighter elements, as a result of the secular cooling of the Earth. To explain why crystallization occurs deep in the core rather than at the CMB, Jacobs (1953) speculated that the melting temperature increases with pressure faster than the geotherm, assumed to be adiabatic. As the core cooled from an initially molten state, solidification began at the center of the Earth where the adiabatic geotherm first intersected the melting temperature profile. Further cooling results in the outward growth of the inner core (Fig. 1). The release of light incompatible elements resulting from inner core crystallization provides a significant energy source for outer core convection and dynamo action. Although the idea proved to be indeed correct, this scenario was challenged in the early 70s by Higgins and Kennedy (1971) and Kennedy and Higgins (1973), who predicted that the core adiabat was steeper than the melting temperature profile, from extrapolations to the core conditions of low pressure experimental results. In this case, solidification would be expected to start at the CMB rather than at the center of the Earth. Busse (1972), Malkus (1972), and Elsasser (1972) suggested that the core would evolve toward a state where the whole outer core consists of a slurry with small solid iron particles in suspension, with the inner core resulting from the slow sedimentation of this slurry. Later studies showed that the slope of the melting curve is in fact likely to be greater than that of the adiabat (Jamieson et al., 1978; Stevenson, 1980), giving strong support for Jacob's model, which is the currently accepted model for core thermal state and crystallization. Interestingly, the situation envisaged by Higgins and Kennedy, and the resulting slurry core scenario, may be relevant for smaller terrestrial planets and satellites, including the Moon, Mars, Mercury, Ganymede, and iron meteorites parent bodies (Kennedy and Higgins, 1975; Haack and Scott, 1992; Hauck et al., 2006; Chen et al., 2008; Williams, 2009). The primary reason for this rests on the expected dependence of the thermal expansion coefficient of liquid iron α with pressure (or density ρ). The slope of the adiabat is proportional to $\rho^{-1/2}$ for a constant temperature and exceeds the Clapeyron slope below 8 GPa. An additional effect is expected from the possible large sulphur content of small terrestrial bodies as indicated by meteorite composition. Sulphur lowers both the adiabat and Clapeyron slopes but the latter is found to be more strongly reduced.

There was a discussion on the nature of the seismic transition between the outer and inner cores: smooth or sharp. The sharp transition suggested by Lehmann was definitely confirmed much later in 1970 with the observation of PKiKP (Engdahl et al., 1970) indicating direct reflection on the ICB.

2.3. The F-layer

Meanwhile, between 1939 and 1973, took place the chaotic story of the F-layer. In order to best account for the P wave arrival times, Jeffreys (1939) introduced a layer of thickness 200 km around the inner core, with a lower velocity. There was no discontinuity of P-wave velocity at the top of this layer, and Jeffreys set the maximal decrease of velocity with depth such that there could still be a lowest turning point of seismic rays within that region. That corresponded to a reduction of 10 percent in P-wave velocity within the layer. Bullen (1940) attributed the letter "F" to this region in his A to G nomenclature, from the crust to the inner core. Bullen (1949) then realized that other velocity distributions would explain the P arrivals, and suggested that there could be a velocity discontinuity at the top of the layer and a smaller decrease in P-velocity with depth than originally proposed. More and more complex versions were imagined, with two discontinuities of very small amplitude (0.02 km/s) between 100 and 200 km above the inner core (Bolt, 1964). Most of these sophisticated models were due to the need to explain early precursors to the PKIKP waves. The history of the F-layer, or rather its first part, ended when Haddon (1972) and Cleary and Haddon (1972) suggested the early precursors could be due to wave-scattering on the CMB (or rather within D″), an assumption that was definitely validated by King et al. (1973) in 1973. However, before it was abandoned, the F-layer received a supporting dynamical model by Braginsky (1963). In this model, the F-layer is

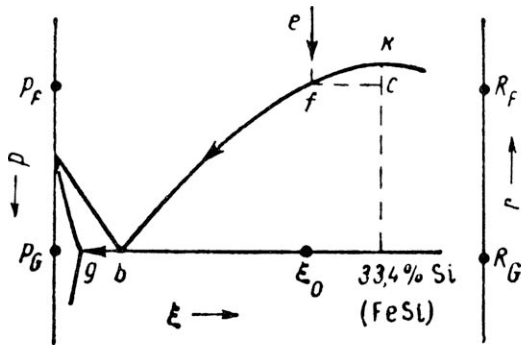

Fig. 2. Eutectic crystallization model of the Earth's inner core after Braginsky (1963). This concept provides a natural explanation for the F-layer. Copy of the original Fig. 1 from Braginsky (1963). Reprinted by permission of the American Geosciences Institute, Translation of the Doklady Akademii Nauk SSSR, copyright 1963.

a region of thermodynamical equilibrium between rising light solid crystals and the liquid outer core. The composition of the core was assumed to be beyond eutectic in silicon, while the ICB was supposed to coincide with the eutectic point where dense iron-rich crystals contribute to the growth of the inner core and light FeSi crystals rise and melt within the F-layer. The net excess of silicon in the liquid phase was held responsible for convection in the outer core (see Fig. 2). When the seismologic evidence of the F-layer vanished, Braginsky's model lost a lot of its interest for the inner core. Moreover, the current state of knowledge in mineralogy does not favour such a high content in silicon, in any case not beyond the eutectic point (Vočadlo, 2007).

2.4. Mush or slurry

Even after the original F-layer was dismissed, questions remained on the mode of crystallization of the inner core, with basically two opposite point of views: the slurry and the mush. Proponents of the slurry (*e.g.* Morse, 1986) assume that solid crystals form ahead of the ICB and settle by gravity. The growth of the inner core is thus a consequence of the accumulation of these crystals. On the contrary, supporters of the mush (*e.g.* Fearn et al., 1981) favour the dendritic growth of the inner core from the ICB itself. Most recent studies (Shimizu et al., 2005; Deguen et al., 2007) favour the mush hypothesis, as it seems unlikely that the level and extent of undercooling in the liquid ahead of the ICB can produce enough solid grains to account for the estimated growth rate of the inner core. Basic features of the mush remain unknown, like the interdendritic primary spacing, liquid fraction, crystal phase and orientation.

2.5. Anisotropy

The next challenge from seismology arose when it was noticed that polar paths across the inner core were faster than equatorial paths (Poupinet et al., 1983). The inner core appears to be globally anisotropic with a fast axis parallel to the rotation axis from body waves (Morelli et al., 1986) and free oscillations (Woodhouse et al., 1986). Karato (1993) suggested that iron crystals may align with the magnetic field during solidification. He argues that iron is expected to be paramagnetic at inner core conditions and that small crystals nucleated ahead of the ICB would align with the ambient magnetic field during sedimentation because of their induced magnetic moment. Bergman (1997) pointed out that such an anisotropy might have been acquired during the process of crystallization itself, under a heat flux with cylindrical symmetry. He suggested using analogue experiments that the columnar structure of the flow in the outer core – owing to the influence of Coriolis forces – should

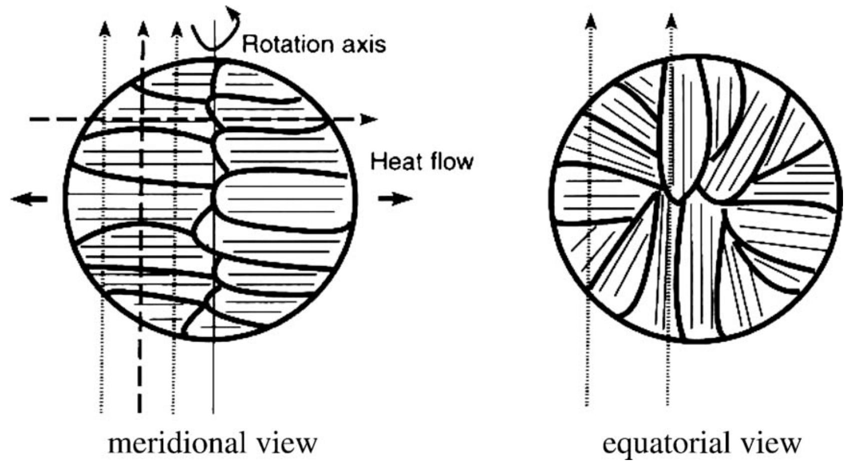

Fig. 3. Crystallization with preferred cylindrical radial direction along the most efficient heat flux direction. Copy of the original Fig. 2 from Bergman (1997). Reprinted by permission from Macmillan Publishers Ltd: Nature, copyright 1997.

favour a cylindrical radial heat flux out of the ICB, which leads to a preferred cylindrically radial crystallographic structure (see Fig. 3) and finally to the observed anisotropy. However, anisotropy is found only more than a 100 km under the ICB, below a so-called isotropic layer. It seems then difficult to imagine that anisotropy is acquired when crystallization takes place. It can be acquired deeper within the inner core under the effect of internal shear when a process of lattice preferred orientation (LPO in short) is at work. If the shear possesses a South–North axial symmetry, so is expected the preferred crystallographic orientation. Different causes have been put forward: thermal convection (Jeanloz and Wenk, 1988; Weber and Machetel, 1992; Wenk et al., 2000; Buffett, 2009; Deguen and Cardin, 2011; Cottaar and Buffett, 2012), equatorial preferential crystallization growth (Yoshida et al., 1996), shear flow due to Lorentz forces (Karato, 1999; Buffett and Wenk, 2001), or differential Joule heating within the inner core (Takehiro, 2010). In the magnetic scenario (Karato, 1999), it is anticipated that Lorentz forces remain axisymmetrical on average over a billion year timescale. The toroidal magnetic field (blue lines on Fig. 4) is expected to be strong and anti-symmetrical with respect to the equator. Hence Maxwell stresses drive an axisymmetric shear flow within the core, with an inward component near the poles and outward near the equator. The scenario based on differential growth rate (Yoshida et al., 1996) starts from similar premises as that of Bergman (1997): the heat flux driven by the outer core is mainly cylindrically radial. Moreover, this heat transfer is assumed to be much more efficient near the equator than it should be at higher latitudes. This should be accompanied by a similar heterogeneity in growth rate of the inner core, building up a positive equatorial topography and a negative polar topography. Gravitational equilibrium (hydrostatic at first order) tends to restore the spherical shape of the inner core, through an axisymmetrical shear flow, inward on the equator, outward on the poles, just the opposite of the magnetically driven flow (Karato, 1999) (Fig. 5).

2.6. An anomalous layer above the ICB

New observations (Souriau and Poupinet, 1991) came in support of an anomalous slow (P-wave) layer of thickness 200–250 km just above the ICB. This is also visible in the most recent 1D models

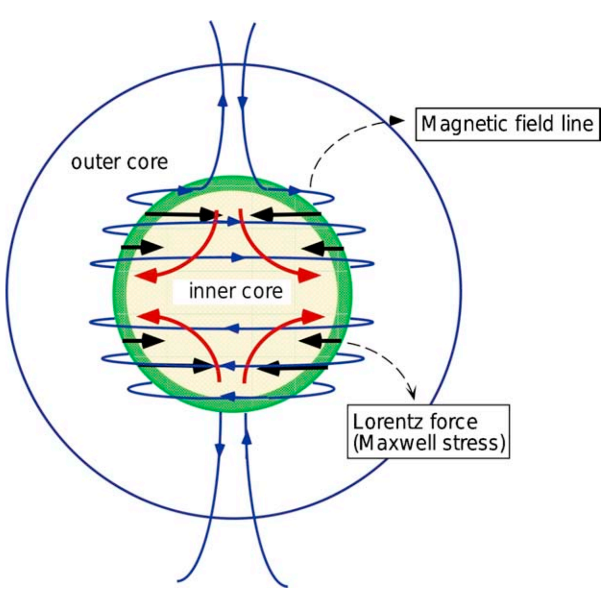

Fig. 4. Shear flow induced by Lorentz forces in the inner core. Copy of the original Fig. 1 from Karato (1999). Reprinted by permission from Macmillan Publishers Ltd: Nature, copyright 1999.

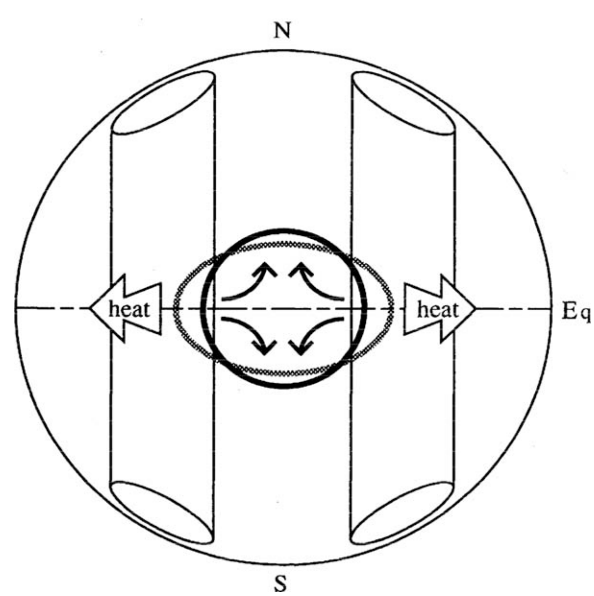

Fig. 5. Enhanced equatorial crystallization rate and subsequent deformation. Copy of the original Fig. 1 from Yoshida et al. (1996). Reproduced by permission of American Geophysical Union: Journal of Geophysical Research. Copyright 1996.

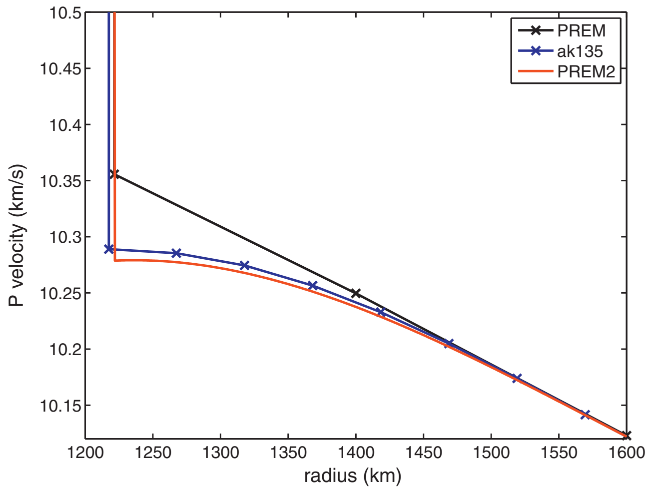

Fig. 6. P-wave velocity profile above the inner core, according to models PREM (Dziewonski and Anderson, 1981), ak135 (Kennett et al., 1995) and PREM2 (Song and Helmberger, 1995).

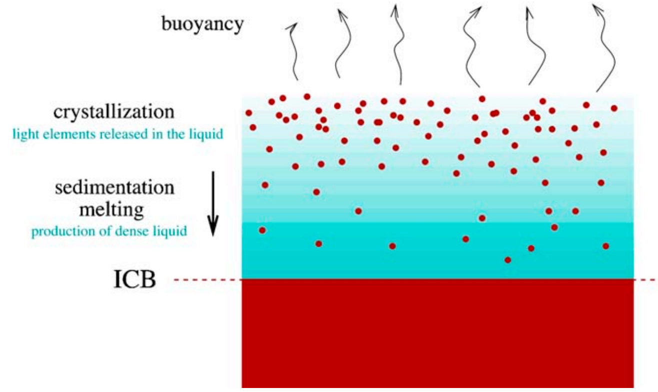

Fig. 7. Production and melting of crystals after the scenario developed in Gubbins et al. (2008).

of P-velocity ak135 (Kennett et al., 1995) and PREM2 (Song and Helmberger, 1995). Compared to the adiabatic profile assumed in PREM (Dziewonski and Anderson, 1981), there is a velocity deficit of 0.7–0.8 percent (see Fig. 6). This is just causing a smooth bending of the velocity profile: the velocity increases with depth less than predicted for an adiabatic outer core, but does not actually diminish. In a way, this is a pale version of the dramatic original F-layer. Gubbins et al. (2008) have attempted to provide a dynamical model for this anomalous layer. First they show that it is likely that the low velocity in the layer is related to an increase in density, making it a stably stratified layer. Then, along the lines of Braginsky's model, they propose that the layer is an equilibrium region between solid crystals and the liquid outer core. Crystallization (below the eutectic point in a phase diagram with iron and a light element) would occur near the top of the 200 km thick layer – releasing light elements in the outer core – and grains would sink and melt, thus maintaining an iron-rich liquid composition in the layer. It is however far from obvious how such a layer can be initiated and sustained (Fig. 7).

An alternative suggestion has been made by us (Alboussière et al., 2010), whereby melting on part of the ICB and crystallization on another part has been shown to generate a stratified dense layer in an analogue experiment. With a small (<1) partition ratio of light elements, crystallization produces a light liquid, melting produces a dense liquid (see Fig. 8). While the melting rate has to be less than the crystallization rate to ensure the net growth of the inner core, it is necessary that the melting rate exceeds 80% of the crystallization rate for the dense layer to develop in the analogue experiments. While in our study, melting is generated by a mode of convection of the inner core (Alboussière et al., 2010), another study (Gubbins et al., 2011) indicates that melting on the ICB might be due to heat flux heterogeneity on the CMB (see Section 3).

2.7. Rotation of the inner core

The idea that the inner core is rather free to rotate differentially with respect to the mantle (Gubbins, 1981) was supported by an early numerical model of the geodynamo (Glatzmaier et al., 1996). The torque is provided by the Lorentz forces associated with dynamo action. A series of seismological analyses provided contrasted results (Song and Richards, 1996; Su et al., 1996; Creager, 2007; Vidale et al., 2000; Poupinet et al., 2000; Song and Poupinet, 2007). Some studies have found a rotation rate of up to 1 or 2 degrees per year, while others have shown little or no rotation (Poupinet et al., 2000; Makinen and Deuss, 2011). The observations seem to fail to identify a steady rotation over decades. Gravitational coupling with the mantle is certainly an obstacle to such a permanent differential rotation, which might be overcome only if the inner core can deform quickly enough or restore a new equilibrium shape by fast processes of crystallization and melting (Buffett, 1997; Buffett and Glatzmaier, 2000). This issue will be discussed further in Section 3. Another way to reconcile fast differential rotation (typically 1 degree per year) and gravitational locking with the mantle, is to allow oscillations about a fixed (or slowly drifting, 1 degree per My) angular position (Dumberry and Mound, 2010; Aubert and Dumberry, 2011).

2.8. An innermost inner core

It has been suggested that the inner core has a distinct innermost part, of radius between 300 and 600 km, based on anisotropy (Ishii and Dziewonski, 2002) or attenuation properties (Li and Cormier, 2002; Cormier and Li, 2002). The observation of such a innermost structure is model dependent and can be due to a lack of spatial resolution. If however its existence is confirmed it could be due to a phase change (Kuwayama et al., 2008) within the narrow ranges of pressure and temperature of the inner core. It could also be the signature of ancient distinct structures when the inner core was younger (Deguen and Cardin, 2009, 2011; Buffett, 2009).

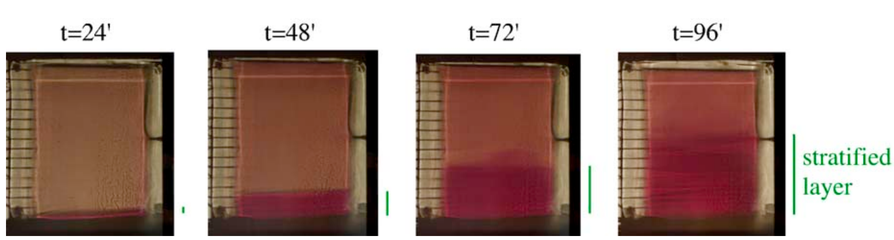

Fig. 8. A stratified layer produced by the simultaneous release from the bottom of dense and light liquid (Alboussière et al., 2010).

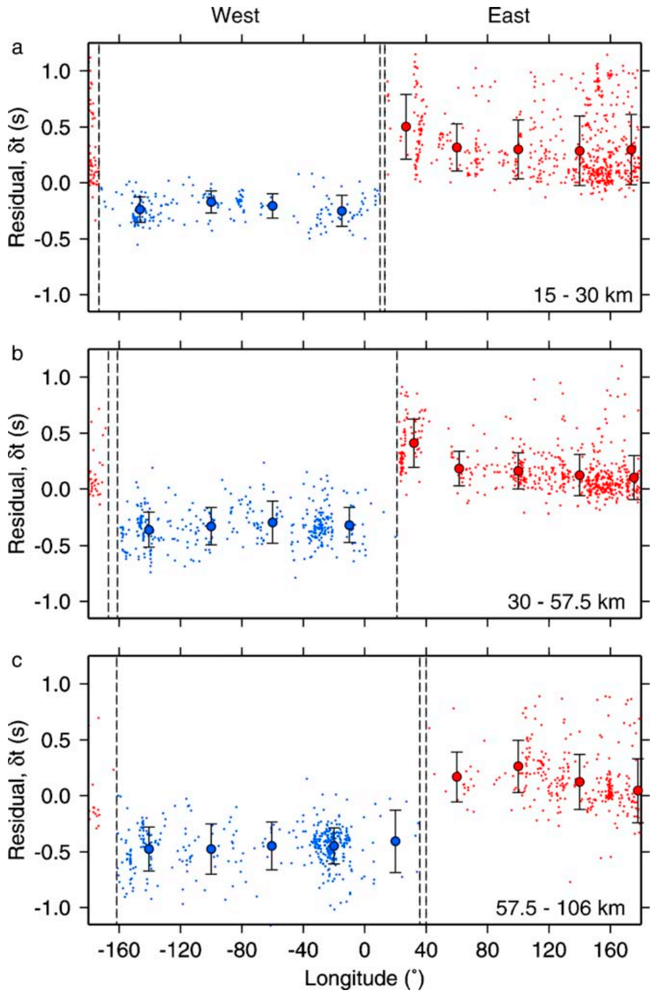

Fig. 9. PKIKP-PKiKP residuals, depending on longitude and depth. Copy of the original Fig. 3 from Waszek and Deuss (2011). Reproduced by permission of American Geophysical Union: Journal of Geophysical Research. Copyright 2011.

2.9. Hemispherical asymmetry

Since 1997, an asymmetry of seismic P-wave velocity near the surface of the ICB has been observed (Tanaka and Hamaguchi, 1997). This concerns the 70–100 km or so below the ICB, with a fast eastern hemisphere and a slow western hemisphere. It turns out that the two regions correspond nearly to the western and eastern hemispheres defined in respect to the Greenwich meridian and that the boundary between them seems to be very sharp (see Fig. 9 from Waszek and Deuss (2011)). A mild eastward shift of the boundary is detected as depth is increased (dashed lines on Fig. 9) *i.e.* the longitudes corresponding to the boundary between seismically distinct hemispheres are found to move slightly towards the East at larger depth.

3. Modelling the hemispheric asymmetry

Among the diverse features of the inner core, the hemispheric asymmetry is the most surprising. For instance, although the question of the anisotropy of the inner core is largely not yet understood, one can think of good potential reasons why the direction of the Earth's rotation axis is being singled out: Coriolis forces and the geomagnetic field possess a similar symmetry. On the contrary, the hemispherical asymmetry does not refer to a known symmetry property of the Earth. Moreover, it is not seen as a vague contribution of degree 1, but rather as a nearly perfect dichotomy between two hemispheres separated by the rotation axis.

There have been two approaches to this puzzle, with radically opposite views on the dynamics of the core. The first one was suggested by Sumita and Olson (1999, 2002) and Aubert et al. (2008) and investigates the long-term influence of heat flux heterogeneities on the CMB imposed by the slow dynamics of the mantle. Although the short-term dynamics of the liquid core is highly nonlinear and complex, the authors argue that its long-term dynamics conserves the memory of the heterogeneity of the driving force. Through the analysis of numerical calculations,[1] it is found in particular that the CMB heat flux heterogeneities – mainly of degree 2 – induces a heat flux pattern on the ICB with a predominant degree 1 contribution (see Fig. 10). The authors of the paper then conclude that the heat flux heterogeneity on the ICB leads to an heterogeneity of the local growth rate (10% variations) which is in turn responsible for the hemispherical seismic asymmetry of the superficial inner core.

The other approach (Alboussière et al., 2010) has been formulated by the authors of this present review paper. We argue that thermal convection of the inner core is possible, with the available data on thermal conductivity and estimates of the secular cooling, and that convection takes the form of a translation (with minor deformation) when the effective viscosity of the inner core is large enough[2] (see Fig. 11). This mode results from the interaction of three ingredients of the inner core: superadiabaticity, gravitational equilibrium and exchange of latent heat with the outer core. The inner core is superadiabatic when its secular cooling exceeds conduction down the adiabat. Gravitational equilibrium manifests itself as a shift of the inner core compared to its exact central position when a density gradient exists across the inner core. Heat exchange of latent heat implies that the ICB should be below or above the equilibrium position dictated by the phase diagram where crystallization or melting takes place. From these ingredients, a positive feed-back loop can be envisaged. Given a small temperature gradient across the inner core (in addition to the adiabatic profile) generating a density gradient, the equilibrium position of the inner core is shifted in the direction of the temperature gradient. Positive topography is then melted at the rate allowed by heat transfer in the outer core, while negative topography experiences crystallization. This induces a global velocity field in the inner core that reinforces the initially assumed temperature gradient, under the hypothesis of a superadiabatic state. According to this model, one hemisphere is crystallizing at a rate as large as one hundred times the growth rate of the radius of the inner core, while the other hemisphere is melting at nearly the same rate. Such an asymmetry must have consequences on the outer core. Crystallization is associated with release of fluid enriched in light elements, while melting results in a depleted dense liquid. We have examined one consequence of this type of buoyancy forcing in the same paper (Alboussière et al., 2010), which is the formation of a dense stratified region above the ICB compatible with the seismically observed anomalous slow layer (see Section 2.6).

In a more recent paper (Gubbins et al., 2011), the "CMB approach" was further investigated and it was concluded that the long term flow could even generate regions of melting on the ICB

[1] These calculations correspond to the present state of the art in terms of numerical simulations, but one should remain aware of the fact that the accessible range of key dimensionless parameters (Ekman number, magnetic Prandtl number, magnetic Lehnert number...) is still a long way to the realistic estimates.

[2] In the translation mode, density differences develop along gravitational isopotentials. When the effective viscosity is less than around 10^{18} Pa s, the rate of deformation of the inner core is comparable to the rate of translation and annihilates the density gradients required for the translation (Alboussière et al., 2010).

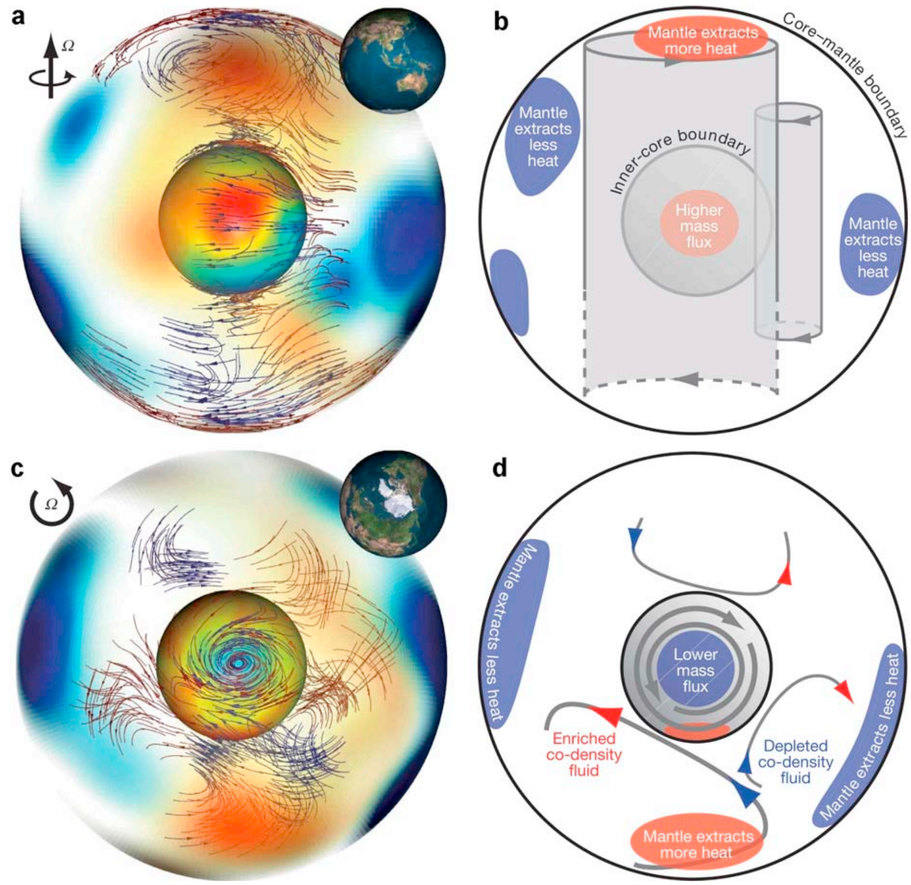

Fig. 10. Long-term dynamics of the outer core generate a heat-flux asymmetry on the ICB from the degree two pattern of the CMB heat flux. Copy of the original Fig. 1 from Aubert et al. (2008). Reprinted by permission from Macmillan Publishers Ltd: Nature, copyright 2008.

and not just regions of reduced crystallization rate as in Aubert et al. (2008).

For us, the best argument in favour of the inner core translation dynamics is provided by recent seismic data (see Fig. 9). These results were actually only available after the two models have been published. The nearly perfect division in two hemispheres is a strong indication in favour of translation. This is a signature of a qualitative change. It would be extremely difficult to imagine that the long-term convection in the outer core could lead to such a precise geometry of heat flux on the ICB. On the contrary, if one hemisphere is melting while the other is crystallizing, there is such a qualitative change. We can envisage that the structure of a melting mush is qualitatively different from that of a crystallizing mush. Key parameters, such as solutal diffusivities are vastly different in the solid and in the liquid phases: interface stability and morphology is related to compositional diffusion in the liquid phase for crystallization, while that in the solid phase is relevant for melting. One can reasonably speculate that the seismic velocity is mostly dependent on the melting or crystallizing nature of the medium, with a much weaker sensitivity to the actual rate of the melting or crystallization. This is consistent with the sharp seismic distinction between western and eastern hemispheres seen on Fig. 9, even though crystallization/melting rate is a smooth function of longitude. Another seismic study (Cormier et al., 2011) reveals distinct properties on each hemisphere.

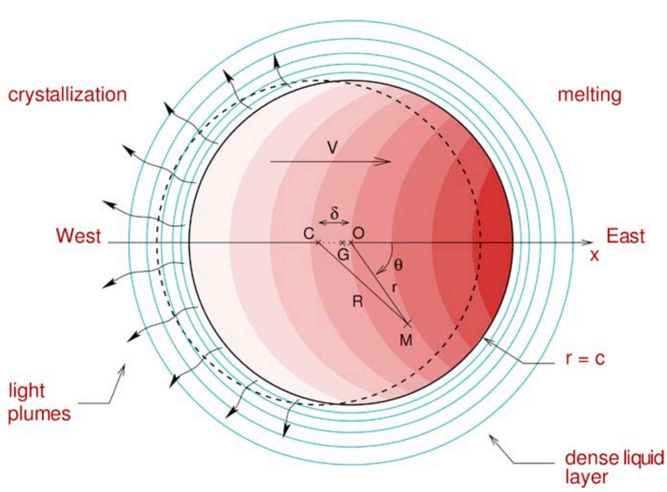

Fig. 11. Translation of the inner core as a convective mode with large effective viscosity (Alboussière et al., 2010).

Other arguments are consistent with a convective translation of the inner core. We have shown that this mode of convection develops preferentially along the longest axis of the ellipsoid fitting the inner core (Alboussière et al., 2010). Owing to the flattening of the rotating Earth, that mode of convection can only be along an equatorial direction. This in turn is only compatible with an hemispheric asymmetry, such as that observed, in which the axis of rotation of the Earth lies just between the asymmetric hemispheres.

It is worth mentioning that laboratory experiments (Bergman et al., 2010) have shown that anisotropy acquired during crystallization can be progressively lost during annealing. This would fit with the idea that anisotropy in the inner core is generated on the western side and would decay during its translation towards

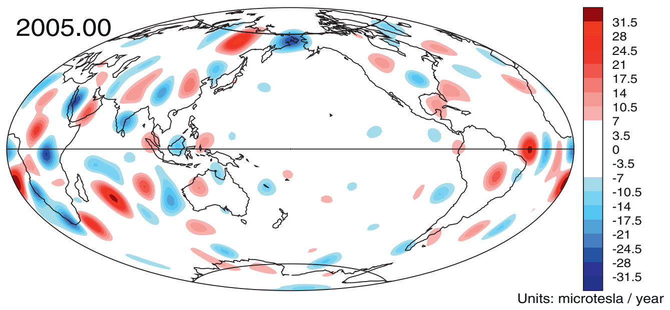

Fig. 12. Geomagnetic secular variation of the vertical component (courtesy of Andy Jackson).

the eastern side, leading to the observed spatial distribution of anisotropy (Tanaka and Hamaguchi, 1997; Deuss et al., 2010).

Within the framework of the translation of the inner core, let us investigate the general consequences of this model on the dynamics of the outer core in the next section.

4. Degree one structures in the outer core

With intense melting on one hemisphere of the ICB and intense crystallization on the other one, we expect an excessively asymmetric buoyancy forcing of the outer core. Does one observe any signature of this asymmetry on the dynamics of the outer core? An easier question is: does one observe structures of degree one? The answer to that last question is positive. There are features of degree one in the geomagnetic field of the Earth. However, it is not straightforward to understand how they could be a consequence of the asymmetric buoyancy flux on the ICB.

First, a look at the secular variations of the magnetic field on the CMB (see Jackson et al., 2007; Holme et al., 2011 for instance) reveals that the level is not homogeneous with a very quiet region corresponding to the pacific ocean (see Fig. 12). This is indeed a degree 1 (order 1) pattern, like the hemispherical seismic asymmetry of the inner core, although one cannot easily make a connection with a West to East translation of the inner core.

Second, geomagnetic field asymmetry is also apparent from the analysis of the "best-fitting dipole" – the magnetic dipole that best fits the observed geomagnetic field. Numerical dynamos with an hemispherical ICB forcing predict persistent asymmetry of the magnetic field, with the best-fitting dipole offset in the direction of fast inner core crystallization (Olson and Deguen, submitted for publication). In archeomagnetic models for the last 10 ky (Korte et al., 2011), the center of the eccentric dipole has remained in the western hemisphere during the last 10 ky, consistent with faster crystallization in the western hemisphere. However, models of the time-averaged field over the last 5 My (Johnson and Constable, 1997; Hatakeyama and Kono, 2002) shows an offset in the eastern hemisphere.

Third, recent models of velocity inversion on the CMB, under the assumption of quasi-geostrophy, has shown evidence of a large non-axisymmetric circulation (Pais and Jault, 2008; Gillet et al., 2009). This giant gyre circles around the tangent cylinder, but while it comes close to the CMB near the Greenwich meridian, it is stuck to the tangent cylinder at 180 degrees (see Fig. 13). Again, it is not clear how to relate this gyre to an heterogeneous buoyancy flux on the ICB. In fact, it seems to be more compatible with a translation in the opposite direction: the combination of the resulting buoyancy and Coriolis forces would indeed generate the observed gyre (Davies et al., 2012)

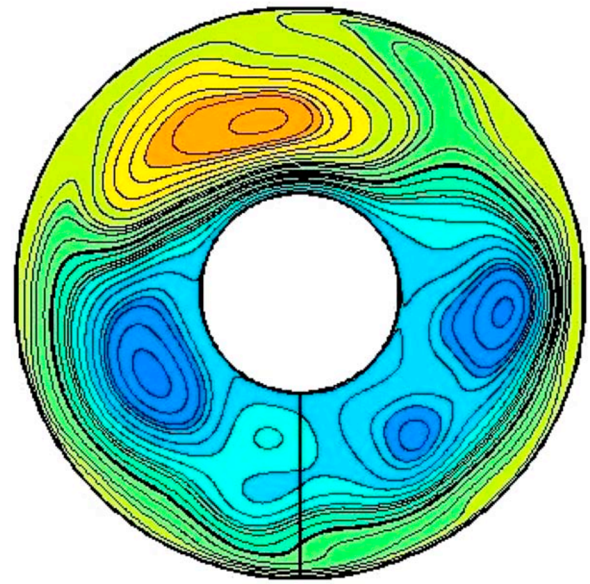

Fig. 13. Velocity inversion with quasi-geostrophy assumed. The lines are contours of constant value of the streamfunction for the quasi-two-dimensional core flow, while the colour corresponds to the streamfunction's value (blue for cyclones, orange for anti-cyclones). The radial line marks the Greenwich's meridian. Copy of the original Fig. 12 (year 2000) from Gillet et al. (2009). Reproduced by permission of American Geophysical Union: Geochemistry, Geophysics, Geosystems. Copyright 2009.

5. Interactions between the mantle, inner and outer cores

It is sometimes difficult to separate the causes and the consequences when the dynamics is closely inter-related. We can perhaps start with a firm basis in stating that the mantle is responsible for setting the heat flux going out of the CMB. The heat flux then dictates the cooling of the core which governs the growth of the inner core. Crystallization of the inner core releases light elements, a process which is perhaps responsible for two thirds of the mechanical energy input to drive convection (compositional buoyancy) in the outer core presently while cooling from the CMB accounts for the last third (thermal buoyancy) (Braginsky and Roberts, 1995; Lister and Buffett, 1995; Lister, 2003). It is now difficult to decide whether the outer core has more impact on the inner core or the opposite. When heterogeneities of heat flux on the CMB are considered, one alters the way thermal convection acts on the outer core and possibly on the growth of the inner core. When one considers asymmetric crystallization of the inner core, one changes the pattern of the main source of buoyancy for the outer core.

At first, it may seem that a difference into the two approaches explaining the hemispherical asymmetry of the inner core should be related to the rotation of the inner core. If heat flux heterogeneities on the CMB are to be responsible for the long-term surface structure of the inner core, a consistent rotation of the inner core is precluded (on a time-scale of 10^4 years or less). Inversely, the translation convection mode is attached to the inner core and could be independent of a fast rotation of the inner core. However, we have shown (Alboussière et al., 2010) that the translation mode of convection can only exist for a large value of effective viscosity of the inner core. In that case, a consistent rotation of the inner core is not possible as its shape would not adapt quickly enough. The inner core is locked to the mantle by gravitational coupling. Moreover, the aspherical distribution of mass in the Earth (Masters et al., 1982) and models of CMB topography (Sze and van der Hilst, 2003) indicate that the longest axis of the ellipsoid approximation for the core (hence inner core) lies roughly in the direction of the expected translation (see Fig. 14 and compare with Fig. 9). This is again compatible with the translation mode that develops

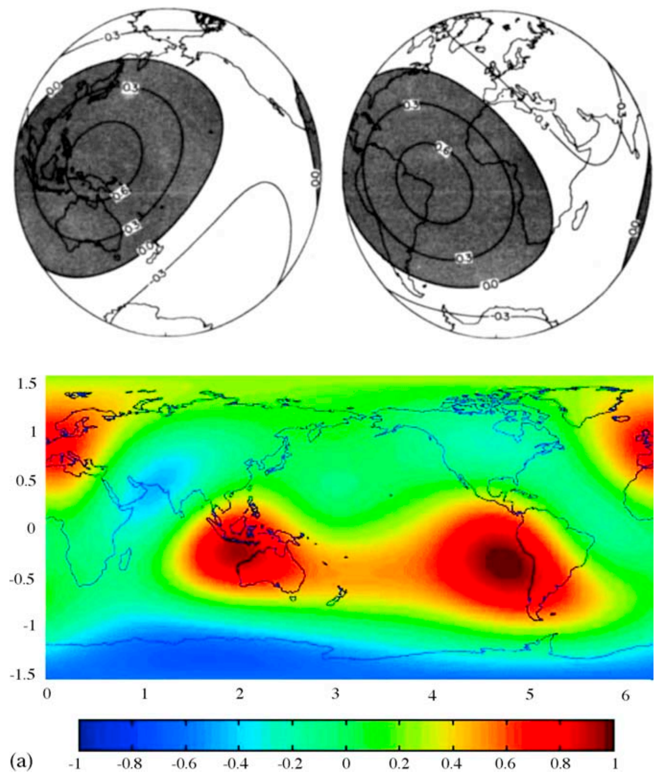

Fig. 14. Aspherical mass distribution of the Earth (isolines of normalized transition-zone mass anomalies), copy of the original Fig. 5 from Masters et al. (1982) (Reprinted by permission from Macmillan Publishers Ltd: Nature, copyright 1982.) (top) and topography of the CMB (in km), copy of the original Fig. 13(a) from Sze and van der Hilst (2003) (Reprinted with permission from Elsevier. Physics of the Earth and Planetary Interiors. Copyright 2003) (bottom).

fastest and strongest along the longest axis of an ellipsoid. This also makes it more difficult to discriminate between the models for hemispherical asymmetry, because topography and mass anomalies are related to the accumulation of subducted slabs which also corresponds to regions of large heat flux on the CMB.

Nutation measurements can also provide information on the structure of the Earth and on the coupling between the mantle, core and inner core. Part of the attenuation of nutations can be attributed to the deformation of the inner core, leading to an estimate around 10^{14} Pa s for its viscosity (Greff-Lefftz et al., 2000; Koot and Dumberry, 2011). It should be noted first that this concerns viscous properties on the diurnal timescale and secondly that this should rather be considered as a lower bound for viscosity, as other attenuating effects may have been underestimated (magnetic damping, topography coupling, inertial wave or tidal (Buffett, 2010) dissipation in the liquid core,. . .) or overlooked.

6. Discussion

Given the relatively recent discovery of the inner core, rich and valuable knowledge has been accumulated already on its structure and history. Given the current efforts devoted to the subject, it is obvious that much progress can be expected in the near future. However, there is still a distinct possibility that a radically different new idea might supersede the current ideas (one cannot speak of a consensus) on the dynamics of the inner core. Future progress can be expected from different sources and we shall now outline some of them. Seismology will certainly continue to provide sharper and sharper representations of the inner core and this will guide future work. Conversely, as we have seen from past history, seismic data are often interpreted within a certain frame which rests on preconceptions. For instance, the PKP precursors have been interpreted as a consequence of a stratified layer at the bottom of the outer core, and then as scattering from the D″ layer. There is a need to have pre-conceived ideas in order to best extract information from seismic data, but one must always be ready to question those pre-conceived ideas. Many scenarios are based on seismic observations and they are not all compatible. For instance, it seems difficult to reconcile a translation of the inner core with the existence of an innermost inner core, unless it is due to phase change: the translation scenario requires a large effective viscosity of the inner core, and would thus entrain an innermost structure even if the latter is stably stratified.

There are still pending questions, of general interest for the dynamics of the core, regarding thermal history. Although the current heat flux going out of the Earth is known with a good accuracy (47 TW ± 2 TW Jaupart et al., 2007; Davies and Davies, 2010), the part of that heat flux crossing the core–mantle boundary is much less constrained (10 TW ± 4 TW, according to Nimmo, 2007, and even more from the last estimates of core thermal conductivity). We may hope that better knowledge on the Earth's secular cooling, hence on the heat flux through the CMB, will be provided by measurements of geoneutrinos (Fiorentini et al., 2007; Borexino Collaboration et al., 2010; KamLand Collaboration et al., 2011). An objective is to determine radioactive sources throughout the Earth: secular cooling is then obtained as the complement part to the total heat flux out of the Earth. The other major uncertainty concerns thermal conductivity in the core. Until a couple of years ago, the published result provided a rather low value 36 $W\,m^{-1}K^{-1}$ (Stacey and Davis, 2008) but some new results suggest it might be larger by a factor around three (Sha and Cohen, 2011; de Koker et al., 2012; Pozzo et al., 2012) from first-principle computations. A large value of thermal conductivity leads to questions as to how a magnetic field can have been sustained before the inner core was formed. Was secular cooling large enough to maintain a superadiabatic thermally driven convection? Similarly, if the inner core is not presently superadiabatic, what are the other possibilities for a translation convection mode of the inner core? For the latter question, compositional buoyancy has been invoked as a substitute for thermal buoyancy in (Alboussière et al., 2010; Deguen and Cardin, 2011) when the partition coefficient evolves as the radius of the inner core increases. What matters is how much of the core light elements are incorporated in the solid inner core and whether this quantity increases or decreases as time elapses. The amount of light elements in the liquid core is likely to increase because of solute rejection during crystallization, however this relative increase cannot exceed 4% since the formation of the inner core, given its present volume. Meanwhile, the stratified layer at the bottom of the outer core could correspond to a 10% relative depletion in light elements near the ICB. However, the fraction of light elements found in the inner core with respect to that in the liquid core is dependent on the thermodynamic partition coefficient (possibly dependent on pressure) and on the physical parameters of crystallization, among them gravity increasing on the ICB as the radius of the inner core increases. Then two cases are possible. If the fraction of light elements increases as new material is progressively crystallized, compositional buoyancy has a stabilizing effect on convection in the inner core, with stratification. In this case, deformation induced for instance by heterogeneous crystallization rate on the ICB is contrived to form shallow convection cells stretched horizontally (Deguen and Cardin, 2009). Otherwise, if the fraction of light elements decreases, compositional buoyancy plays an active role and can reinforce or even replace thermal buoyancy to drive convection and possibly a convective mode of translation (Alboussière et al., 2010).

There is actually a need to investigate in more details the actual process of crystallization on the ICB. Gravity-dependent phenomena such as compaction and convection must govern the rejection of light elements segregated during phase change. This determines the effective partition ratio of light constituents between solid and liquid phases, with possible consequences on the global dynamics of the inner core, through compositional buoyancy forces. The primary spacing of dendrites, the typical size of crystal grains (Venet et al., 2009; Deguen et al., 2007; Calvet and Margerin, 2008) also have important consequences on the rheology of the whole inner core.

Geomagnetic studies have also made much progress recently. First, geomagnetic data enable a better description of the magnetic field on the CMB and the derivation of the surface velocity in the outer core are improving. In this field, data assimilation is now being tested (Fournier et al., 2007) and the velocity inferred might then be incorporated within three-dimensional numerical models. Nowadays, computations of numerical dynamos is common and it is possible to investigate the influence of external parameters such as heat flux heterogeneity at the CMB (Aubert et al., 2008). We hope that this approach can be used with different scenarios for the dynamics of the inner core. More generally, our opinion is that it is time for a more integrated approach in the numerical computation of inner core and outer core dynamics. Heat transfer, topography, phase change result from the state on both sides. So far, simplified boundary conditions have been imposed for each of these objects when the dynamics of the other was being investigated. Unfortunately, this puts strong restrictions on the possible coupled dynamical regimes. There are technical difficulties and it may be difficult to deal with the very different time-scales between inner and outer cores, but this approach is worth the effort.

Within the next decades, it will be very interesting to observe whether the puzzle of the inner core will get more puzzling or whether some pieces will eventually match.

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