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F-layer formation in the outer core with asymmetric inner core growth

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ABSTRACT

Numerical calculations of thermochemical convection in a rotating, electrically conducting fluid sphere with heterogeneous boundary conditions are used to model effects of asymmetric inner core growth. With heterogeneous inner core growth but no melting, outer core flow consists of intense convection where inner core buoyancy release is high, weak convection where inner core buoyancy release is low, and large scale, mostly westward flow in the form of spiraling gyres. With localized inner core melting, outer core flow includes a gravity current of dense fluid that spreads over the inner core boundary, analogous to the seismic F-layer. An analytical model for gravity currents on a sphere connects the structure of the dense layer to the distribution of inner core melting and solidification. Predictions for F-layer formation by asymmetric inner core growth include large-scale asymmetric gyres below the core-mantle boundary and eccentricity of the geomagnetic field.

1. Introduction

The seismic F-layer is defined by a decrease in the compression wave (P wave) velocity gradient in an approximately 150–200 km-thick layer in Earth's outer core located just above the inner core boundary (ICB). The anomalous gradient in this region is large enough that it has recently been incorporated into a number of global seismic models, as shown in Fig. 1. Most observations indicate that the F-layer is global, that is, it surrounds the entire inner core (Cormier, 2009; Cormier et al., 2011; Souriau and Poupinet, 1991; Zou et al., 2008), although lateral variations in its properties remain an open possibility (Yu et al., 2005).

Interpretations of the F-layer attribute its anomalous seismic velocity gradient to an approximately monotonic increase in the heavy element concentration (Fe and Ni) with depth, or equivalently, a corresponding decrease in the light element concentration (O, Si, S...) with depth at the base of the liquid outer core (Gubbins et al., 2008). An increase in iron content relative to light elements that accounts for the reduced P wave velocity gradient there has the opposite effect on outer core density (Badro et al., 2007), producing a density increase with depth, i.e., a stable compositional stratification.

The possibility of stable density stratification at the base of the outer core raises important questions about energy transfer and dynamics in the core. According to the standard model of core energetics (Labrosse, 2003), as the core cools, solidification at the ICB partitions heavy elements into the solid and lighter elements into the liquid, providing the primary source of buoyancy for driving convection in the liquid outer core. Under these conditions, the region above the ICB would be expected to have neutral or slightly unstable density stratification due to its elevated light element concentration. Adding a layer

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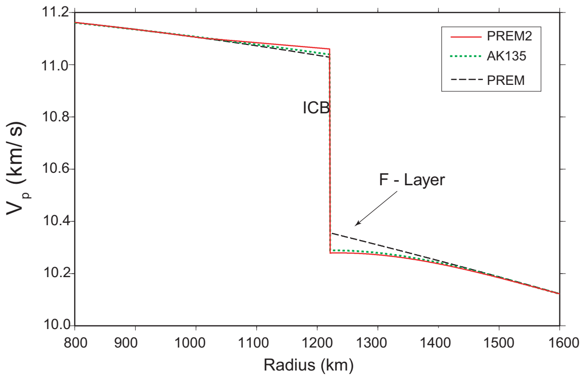

Fig. 1. (Color online). Variation of compression wave velocity V_p versus radius through the core showing the anomalous F-layer at the base of the outer core, according to seismic models PREM (Dziewonski and Anderson, 1981), AK135 (Kennett et al., 1995), and PREM2 (Song and Helmberger, 1995); after Zhou et al. (2008). ICB denotes the inner core boundary.

with stable stratification complicates this picture in several ways. First, it begs the question of how the F-layer formed. Second, it appears to limit the downward transport of light elements from the outer core to the ICB, thereby inhibiting compositional convection in the outer core.

Several mechanisms have been offered to explain the formation of the F-layer, each with far-reaching implications for the dynamics in the core. One possibility is that the F-layer is a relic of the core formation process. This mechanism is based on the idea that the light element abundances in core-forming metals evolved with time as the Earth accreted in such a way that the core was built with an initial radial stratification consisting of progressively less dense alloys (Hernlund et al., 2013). According to this scenario, the F-layer consists of the remnants of the initial stratification. Another proposal is that the F-layer is maintained by iron solidifying at the top of the layer then re-melting as it precipitates through the layer (Gubbins et al., 2008).

By far the most provocative mechanism, and the one we focus on in this study, assumes that the F-layer is maintained through the interaction of separated melting and solidifying regions distributed over the ICB (Alboussière et al., 2010). Because the ICB is a phase change boundary, substantial lateral variations in temperature must be present there for melting and freezing to occur simultaneously. The core-mantle boundary (CMB) is one possible source of these lateral temperature variations. Experiments (Sumita and Olson, 1999, 2002) and numerical simulations (Aubert et al., 2008) have shown that temperature anomalies generated by strongly heterogeneous CMB heat flux can be transmitted from the CMB to the ICB by outer core convection. Gubbins et al. (2011) demonstrated that, under proper conditions, these CMB-generated temperature anomalies can produce a pattern of simultaneous melting and freezing on the ICB.

The other possibility is convection in the solid inner core. The simplest form of inner core convection consists of melting and solidification in separate hemispheres, leading to a lateral translation of the solid material in the inner core from the freezing hemisphere to the melting one, the so-called inner core translation mode (Alboussière et al., 2010; Monnereau et al., 2010). In addition to the substantial interest in its energetics and dynamics, inner core translation offers a plausible explanation for the observed east–west variations in seismic anisotropy in the inner core (Bergman et al., 2010; Deuss et al., 2010; Niu and Wen, 2001; Sun and Song, 2008; Tanaka and Hamaguchi, 1997), thereby linking its seismic structure to its growth.

The onset of subsolidus convective instabilities in the inner core, including the translational mode, has been examined using several approaches (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). The main requirement for convective instability in the inner core is an adverse radial density gradient. Inner core translation is the preferred mode of instability at high viscosity, as it involves little or no solid-state deformation. Cellular (i.e., higher mode) convection favored at viscosities less than about $3 10^{18}$ Pa.s can also produce localized melting and solidification, but less efficiently than the translation mode (Deguen et al., 2013; Mizzon and Monnereau, 2013).

A systematic investigation of the influence of inner core translation on the outer core by Davies et al. (2013) examined thermal convection driven by a spherical harmonic degree and order one pattern of heat flux applied at the ICB. They found that the flow transitions from the usual columnar-style convection when the ICB is homogeneous (Sumita and Olson, 2000) to a pattern dominated by larger-scale mostly prograde (eastward) spiraling jets when the ICB heterogeneity is strong. In cases where the ICB heterogeneity was large enough to simulate melting (corresponding to negative ICB heat flux in their model) the spiral jets found by Davies et al. (2013) resulted in large hemispherical differences in azimuthal velocity everywhere in the outer core, including below the CMB.

Several previous studies have examined dynamo action with spherical harmonic degree one ICB heterogeneity. Results of these studies include dipole eccentricity (Olson and Deguen, 2012) as well as east-west asymmetry in the secular variation of the magnetic field (Aubert, 2013; Aubert et al., 2013). Aubert et al. (2013) have shown that the differences in the geomagnetic secular variation observed between Atlantic and Pacific hemispheres can be produced by a relatively small amount of hemispherically asymmetric inner core buoyancy flux, provided it is properly oriented. In particular, they found that the observed asymmetry of the geomagnetic secular variation is best explained if the buoyancy flux is maximum in the eastern hemisphere, implying westward inner core translation, which is the opposite direction from the original interpretations of the inner core anisotropy (Bergman et al., 2010; Geballe et al., 2013; Monnereau et al., 2010), though in agreement with other interpretations of the observed seismic properties of the inner core (Cormier and Attanayake, 2013; Cormier et al., 2011).

In this study we consider the effects of asymmetric inner core growth including translation in the context of thermochemical convection and dynamo action, using