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Dynamo tests for stratification below the core-mantle boundary

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ABSTRACT

Evidence from seismology, mineral physics, and core dynamics suggests a layer with an overall stable stratification in the Earth's outer core, possibly thermal in origin, extending below the core-mantle boundary (CMB) for several hundred kilometers. Yet vigorous deep mantle convection with locally elevated heat flux implies locally unstable thermal stratification below the CMB, consistent with interpretations of non-dipole geomagnetic field behavior that favor upwelling flows in places below the CMB. To resolve this apparent inconsistency, we investigate the structure of convection and magnetic fields in the core using numerical dynamos with laterally heterogeneous boundary heat flux. Strongly heterogeneous boundary heat flux generates localized convection beneath the CMB that coexists with an overall stable stratification there. Our partially stratified dynamos are distinguished by their time average magnetic field structures. Without stratification or with stratification confined to a thin layer, the octupole component is small and the CMB magnetic field structure includes polar intensity minima. With more extensive stratification, the octupole component is large and the magnetic field structure includes intense patches or high intensity lobes in the polar regions. Comparisons with the time-averaged geomagnetic field are generally favorable for partial stratification in a thin (<400 km) layer but unfavorable for stratification in a thick ($\sim$1000 km) layer beneath the CMB.

1. Introduction

The possibility of a distinct layer below Earth's core-mantle boundary (CMB), Braginsky's (1993) so-called *hidden ocean*, has been the subject of numerous studies using a variety of seismic, geomagnetic, and mineral physics approaches, with the twin objectives of resolving the properties of this layer and understanding its dynamical significance. The majority of these studies conclude that the layer extends one to two hundred kilometers below the CMB (Whaler, 1980; Lay and Young, 1990; Garnero et al., 1993; Gubbins, 2007; Tanaka, 2007; Buffett, 2014) although some claim it extends to far greater depths, perhaps three hundred kilometers (Helffrich and Kaneshima, 2010) or more (Gomi et al., 2013; Tang et al., 2015; Kaneshima, 2017). Interpretations include stable (subadiabatic) thermal stratification (Gomi et al., 2013; Buffett, 2014) as well as stable compositional stratification due to excess light element concentrations in the layer (Helffrich and Kaneshima, 2013; Gubbins and Davies, 2013).

It is important to point out, however, that not every study supports the existence of such a layer, or at least, there are reasons to doubt that the region below the CMB is uniformly stable to all convective motions. Interpretations of the geomagnetic secular variation are most easily accommodated by core flows including upwelling and downwelling motions that extend to within 100 km below the CMB or shallower (Gubbins, 2007; Amit, 2014; Lesur et al., 2015). Likewise, the proliferation and rapid evolution of reverse flux spots in the present-day geomagnetic field on the CMB (Olsen et al., 2014) argue for flux expulsion related to upwellings and downwellings (Olson and Amit, 2006).

In addition, it is necessary to consider the effects of the mantle circulation on the geodynamo. Mantle global circulation models (Zhong and Rudolph, 2015; Nakagawa and Tackley, 2013; Nakagawa and Tackley, 2015) predict vigorous deep mantle convection with locally elevated heat flux that is large enough to sustain unstable thermal stratification in some regions beneath the CMB (Olson et al., 2015), even if recent estimates of high thermal conductivity in the core (Ohta et al., 2016) apply. Alternatively, with lower thermal conductivity (Konopkova et al., 2016), thermal conditions may be unstable everywhere, but in that case a small accumulation of light elements at the top of the core (Buffett and Seagle, 2010) could provide the stable stratification.

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These issues raise the question of whether it is possible to reconcile seemingly contradictory inferences: a layer providing overall stable stratification on the one hand, with radial motions in the fluid outer core below the CMB on the other. In this paper we address this apparent incongruity using numerical dynamos with a particular suite of boundary conditions that (1) model inner core boundary buoyancy release as the source of the main convection, (2) produce an overall (i.e., spherically-averaged) stable thermal stratification below the outer boundary, and (3) generate strong lateral heterogeneity in the stratification, including localized convection. We find that this combination of boundary conditions implies a style of convection in the outer core that dynamically maintains stably stratified conditions in limited regions below the CMB, yet allows for radial motions in places as well as generating a dipole-dominant magnetic field. We call these *partially stratified dynamos*. In addition, we demonstrate that partially stratified dynamos have distinctive high latitude magnetic field structures, allowing the strength of the stratification below the CMB to be inferred remotely, using the geomagnetic field on the CMB.

Our study is limited to the types of stratification that are produced when the destabilizing effects of inner core boundary buoyancy release are comparable in the stratified region to the stabilizing effects of subadiabatic CMB heat flux. This regime has been explored previously using numerical dynamos with homogeneous outer boundary conditions (Christensen and Wicht, 2008; Nakagawa, 2011, 2015) and magnetoconvection models (Takehiro and Sasaki, 2017). It has been shown that stable stratification tends to filter the non-axisymmetric non-dipolar fields, and if the stratified layer is thick, also reduces the intensity of the axial dipole field (Christensen and Wicht, 2008; Nakagawa, 2011, 2015). Christensen (2016) used combinations of subadiabatic mean boundary heat flux plus lateral boundary variations to produce dynamos with stratification extending below the CMB to 20–40% of the outer core depth. Under these conditions he finds thin horizontal circulations that mediate the boundary heat flux heterogeneity, but little mixing of the stratification. In contrast, stratified magnetoconvection calculations by Takehiro and Sasaki (2017) produce strong flows capable of penetrating most of the stable region.

The stratification analyzed in this study refers to radial density gradients that deviate from adiabatic (i.e., uniform entropy) thermal conditions. Temperature gradients resulting from self-compression of the fluid are therefore excluded from our dynamo calculations, and must be factored in before comparing our results to Earth's core. Dynamos that explicitly include adiabatic density and thermal gradients due to compressibility of the fluid also show stratification effects, particularly when the adiabatic density variation is large across the fluid (Jones et al., 2011; Gastine et al., 2012; Yadav et al., 2013). Because the density scale height of the outer core is greater than its depth, the direct effects of compressibility are not included in our dynamos. In addition, our study does not consider the situation in which the stabilizing effects of stratification vastly outweigh the destabilizing effects of inner core growth, as would be the case for strong, pre-existing compositional stratification (Landeau et al., 2016) or compositional stratification that develops over time through rapid chemical diffusion (Nakagawa, 2017). With such strong stratification, lateral variations in heat flux at the CMB would likely play a more limited role in determining the global structure of the outer core and its overall dynamical behavior.

2. Partially stratified dynamos

To model dynamo action with thermal and compositional buoyancy originating at the inner core boundary (ICB) due to inner core growth plus dynamically-regulated thermal stratification below the CMB, all within the context of the Boussinesq approximation, we follow standard procedures (Jones, 2007), defining the codensity perturbation C in the outer core as the sum of densities due to temperature and light element concentration variations:

$$C = \rho_o(\alpha T + \beta\chi), \tag{1}$$

where ρ_o is outer core average density, T is temperature relative to the core adiabat, χ is the outer core light element concentration relative to its mean, and α and β are volumetric expansion coefficients for T and χ, respectively. We let $\dot{\chi}_o$ and $\dot{T}_o$ denote the time rate-of-change of the background (volume-averaged) light element concentration and temperature of the outer core, each assumed to be constant over the time span of a single dynamo simulation, so that $\dot{C}_o = \rho_o(\alpha\dot{T}_o + \beta\dot{\chi}_o)$ is the volume-averaged rate-of-change of the background codensity, also assumed constant over a simulation. Further, let Ω denote angular velocity of Earth's rotation, g gravity at the CMB, $D = r_{cmb} - r_{icb}$ the depth of the outer core fluid, r_{cmb} and r_{icb} being the radii of the CMB and the ICB, respectively, and let ν and κ denote outer core kinematic viscosity and codensity diffusivity, respectively.

With these definitions, the Boussinesq equations for conservation of momentum including rotation, conservation of mass, and codensity transport in a rotating spherical shell (see Appendix) include the following dimensionless control parameters:

$$E = \frac{\nu}{\Omega D^2}; \quad Pr = \frac{\nu}{\kappa}; \quad Ra = \frac{\beta g D^5 \dot{\chi}_o}{\nu^2 \kappa}. \tag{2}$$

Here E is the Ekman number, Pr is the Prandtl number, and Ra is the Rayleigh number, and the factors D, D^2/ν and $D^2\rho_o\beta\dot{\chi}_o/\nu$ scale length, time, and codensity variations, respectively. Two additional control parameters appearing in the magnetic induction equation and the codensity equation are the magnetic Prandtl number Pm and the dimensionless volumetric codensity source/sink ε that quantifies the rate of buoyancy absorbed in the outer core from the mixing of light elements, secular cooling of the outer core, and radioactive heat sources. Our dynamos are driven by the combination of light element release at r_{icb} and secular cooling without radioactive heating, so that

$$\varepsilon = -\left(1 + \frac{\alpha\dot{T}_o}{\beta\dot{\chi}_o}\right). \tag{3}$$

The magnetic Prandtl number Pm is defined by

$$Pm = \frac{\nu}{\eta}, \tag{4}$$

where η is the magnetic diffusivity of the outer core. Magnetic fields are scaled by $\sqrt{\rho_o\Omega/\sigma}$, where σ is electrical conductivity.

Additional control parameters arise in defining the boundary conditions. At the ICB we assume no-slip velocity conditions and a uniform codensity, C_{icb}. At the CMB also assume no-slip velocity conditions, zero compositional flux, and we specify the heat flux there to be the sum of a spherical mean part (denoted by an overbar) and a deviation from the spherical mean (denoted by a prime):

$$q = \bar{q} + q'(\phi, \theta), \tag{5}$$

where ϕ and θ are longitude and co-latitude, respectively, and $\bar{q}$ is measured relative to the heat flux down the core adiabat, with $\bar{q} > 0$ being superadiabatic heat flux and $\bar{q} < 0$ being subadiabatic heat flux. The variable q' in (5) specifies the pattern and the amplitude of the CMB heat flux heterogeneity. In the same way we can write the codensity as the sum of a spherical mean part $\bar{C}$ and a laterally varying part C'. Then using (1) and (5) and assuming Fourier's