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Dynamos driven by weak thermal convection and heterogeneous outer boundary heat flux

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ABSTRACT

We use numerical dynamo models with heterogeneous core–mantle boundary (CMB) heat flux to show that lower mantle lateral thermal variability may help support a dynamo under weak thermal convection. In our reference models with homogeneous CMB heat flux, convection is either marginally supercritical or absent, always below the threshold for dynamo onset. We find that lateral CMB heat flux variations organize the flow in the core into patterns that favour the growth of an early magnetic field. Heat flux patterns symmetric about the equator produce non-reversing magnetic fields, whereas anti-symmetric patterns produce polarity reversals. Our results may explain the existence of the geodynamo prior to inner core nucleation under a tight energy budget. Furthermore, in order to sustain a strong geomagnetic field, the lower mantle thermal distribution was likely dominantly symmetric about the equator.

1. Introduction

The geodynamo is powered by thermochemical convection of an electrically conducting fluid in the outer core. Thermal convection originates from secular cooling due to the loss of heat through the core–mantle boundary (CMB), latent heat release at the inner-core boundary (ICB) and possibly radiogenic heating within the shell volume. Chemical convection originates from the release of light elements at the ICB as the core freezes.

Evidence for the existence of a geomagnetic field goes back to the Hadean period (Tarduno et al., 2015). Estimates of the age of the inner core are less than 1 Gyr (Nakagawa and Tackley, 2013). It is therefore likely that the geodynamo has operated in its early stages, that is, prior to inner core nucleation, on purely thermal convection. However, large estimates of the thermal conductivity of the outer core (de Koker et al., 2012; Pozzo et al., 2012, 2013; Hirose et al., 2013) suggest that the thermal gradient in the core is near, or even below the adiabat. At present the geodynamo is predominantly powered by the release of light elements due to inner core freezing (Olson, 2007); however, before inner core nucleation, it is not clear how the early geodynamo was sustained under such tight energetic constraints.

Convection in the core may be affected by buoyancy flux heterogeneities at its outer boundary. It has been shown that heterogeneous CMB heat flux may determine the long-term pattern of the geomagnetic field on the CMB (Bloxham, 2002; Olson and Christensen, 2002; Gubbins et al., 2007; Willis et al., 2007; Amit et al., 2010), the flow at the top of the core (Aubert et al., 2007), and the ICB buoyancy flux (Aubert et al., 2008; Amit and Choblet, 2009; Gubbins et al., 2011). Core–mantle boundary heterogeneity may also affect the dynamo onset. While it has been proposed that thermal winds driven by the lower mantle heterogeneity can enhance dynamo action (Sreenivasan, 2009; Aurnou and Aubert, 2011; Dietrich and Wicht, 2013), the applicability of these models for early Earth is debatable because of the large lateral variations in heat flux required to obtain a significant magnetic energy (Aurnou and Aubert, 2011) or because convection in these studies is not purely thermal as in early Earth's core (Sreenivasan, 2009; Aurnou and Aubert, 2011). In addition, in these studies a large inner core consistent with present-day core geometry is used.

In this paper we analyze numerical dynamo models powered by purely thermal convection with moderate heat flux variations imposed on the outer boundary. The size of the inner core is kept very small. We examine the impact of different CMB heat flux patterns and amplitudes on the dynamo onset. Finally, possible application to early Earth conditions is discussed.

2. Method

We consider an electrically conducting fluid confined between two concentric, co-rotating spherical surfaces. For numerical sta-

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bility, we retain a small conducting inner sphere of radius 0.1 times the outer sphere radius. The principal body forces acting on the fluid core are the thermal buoyancy force modulated by the lateral thermal variations at the outer boundary, the Coriolis force originating from the background rotation of the system and the Lorentz force arising from the interaction between the induced electric currents and the magnetic fields. The governing equations are in the Boussinesq approximation (Kono and Roberts, 2002). Lengths are scaled by the thickness of the spherical shell L, and time is scaled by the magnetic diffusion time, L^2/η, where η is the magnetic diffusivity. The temperature is scaled by βL^2, where β is a constant proportional to the uniform volumetric heat source S (see below), the velocity field $\mathbf{u}$ is scaled by η/L and the magnetic field $\mathbf{B}$ is scaled by $(2\Omega\rho\mu\eta)^{1/2}$ where Ω is the rotation rate, ρ is the fluid density and μ is the free space magnetic permeability. The scaled magnetic field, known as the Elsasser number Λ, is an output derived from the volume-averaged magnetic energy in our dynamo simulations. The role of CMB heterogeneity in dynamo action is studied by imposing prescribed heat flux patterns on the outer boundary. Purely thermal convection is modelled by imposing zero heat flux on the inner boundary, so although the inner core size is non-zero, it is passive in terms of core convection. Previous systematic parametric studies of numerical dynamos find that a small and passive inner core has little effect on dynamo models (Aubert et al., 2009; Hori et al., 2010) even with the no-slip condition on the ICB. Although a small inner core might prevent equator-crossing meridional flow which can exist in highly supercritical convection (Landeau and Aubert, 2011), our models operate in a distinctive parameter regime close to convective onset, where rotational effects are dominant and the flow avoids crossing the equatorial plane.

The non-dimensional magnetohydrodynamic (MHD) equations for the velocity $\mathbf{u}$, magnetic field $\mathbf{B}$ and temperature T are

$$EPm^{-1}\left(\frac{\partial \mathbf{u}}{\partial t}+(\nabla\times\mathbf{u})\times\mathbf{u}\right)+\hat{\mathbf{z}}\times\mathbf{u}=-\nabla p^{\star}+RaPmPr^{-1}T\mathbf{r}+(\nabla\times\mathbf{B})\times\mathbf{B}+E\nabla^2\mathbf{u}, \quad (1)$$

$$\frac{\partial \mathbf{B}}{\partial t}=\nabla\times(\mathbf{u}\times\mathbf{B})+\nabla^2\mathbf{B}, \quad (2)$$

$$\frac{\partial T}{\partial t}+(\mathbf{u}\cdot\nabla)T=PmPr^{-1}\nabla^2T+S, \quad (3)$$

$$\nabla\cdot\mathbf{u}=\nabla\cdot\mathbf{B}=0, \quad (4)$$

The modified pressure $p^{\star}$ in Eq. (1) is given by $p+\frac{1}{2}EPm^{-1}|\mathbf{u}|^2$, where p is the fluid pressure. The velocity satisfies the no-slip condition at the boundaries and the magnetic field matches a potential field at the outer boundary. The dimensionless parameters in Eqs. (1)–(3) are the Ekman number $E=\nu/2\Omega L^2$ which measures the ratio of viscous to rotational forces, the Prandtl number $Pr=\nu/\kappa$ which is the ratio of viscous to thermal diffusivities, the magnetic Prandtl number $Pm=\nu/\eta$ which is the ratio of viscous to magnetic diffusivities, and a modified Rayleigh number Ra which is the product of the classical Rayleigh number and the Ekman number given by $g\gamma\beta L^3/2\Omega\kappa$, where g is the gravitational acceleration acting radially inward, γ is the coefficient of thermal expansion, β is the scaling constant for temperature and κ is the thermal diffusivity. The last control parameter is the amplitude of the outer boundary heat flux heterogeneity defined by its peak-to-peak difference normalized by the mean:

$$q^*=\frac{q_{max}-q_{min}}{q_0}\times 100\%. \quad (5)$$

Note that defined this way, locally inward superadiabatic heat flux would occur for $q^*>200\%$.

For the majority of our simulations, we choose $E=1.2\times10^{-4}$, $Pr=1$, $Pm=50$ and $Ra=1.2Ra_c$, where Ra_c is the critical Rayleigh number for onset of non-magnetic convection (with homogeneous outer boundary heat flux). A few runs are performed at $E=1.2\times10^{-5}$, $Pr=1$, $Pm=10$ and $Ra=1.8Ra_c$. Finally, we explore a parameter regime with $Ra=0.94Ra_c$ at $E=1.2\times10^{-4}$ and $Pm=50$ to study dynamo onset when there is no convection with homogeneous outer boundary heat flux. Approaching dynamo onset at low Rayleigh numbers and numerically accessible Ekman numbers necessitates a large electrical conductivity, which is why Pm is set to a high value. This problem is common to practically all dynamo models, which operate with $Pm\sim1-10$ values (e.g. Christensen and Aubert, 2006), much larger than the core value of $Pm\sim10^{-6}$ (Olson, 2007). It is, however, possible that $Pm\sim1$ can be eventually reached in calculations at progressively lower E, which are computationally far more expensive. Despite the artificial enhancement of viscous diffusion due to our choice of internal parameters, our model may effectively capture the dynamics of the rapidly rotating core affected by lateral CMB heat flux variations.

The basic state buoyancy profile is obtained by solving the energy Eq. (3) under steady state and no flow conditions:

$$PmPr^{-1}\nabla^2T+S=0, \quad (6)$$

where the uniform volumetric heat source S, assumed to be $3PmPr^{-1}$ in this study, mimics secular cooling and radiogenic heat sources. Eq. (6) is then solved for the non-dimensional basic state heat flux $\partial T/\partial r$, using the zero flux condition at the inner boundary.

The dynamo calculations at $E=1.2\times10^{-4}$ and $Pm=50$ are performed with 108 Chebyshev collocation points in radius and a spherical harmonic degree cut-off value of $l=108$. For $E=1.2\times10^{-5}$ and $Pm=10$, 144 radial grid points and a spectral

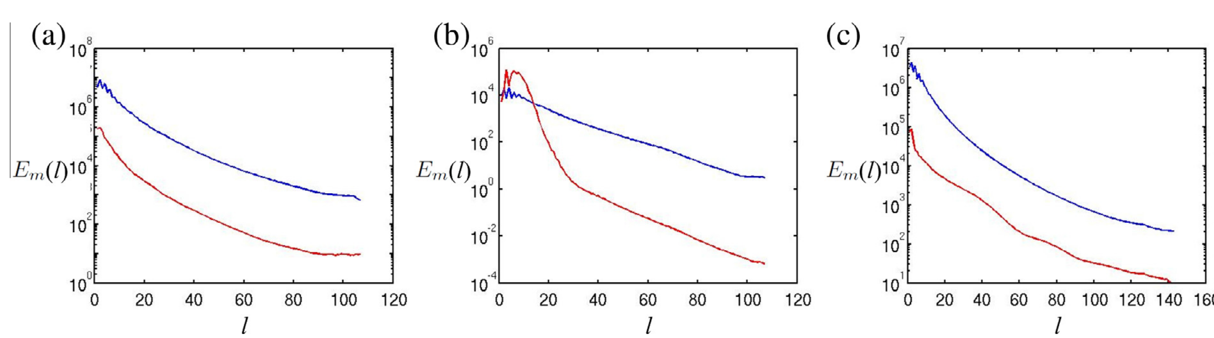

Fig. 1. Time-averaged kinetic (red) and magnetic (blue) energy versus spherical harmonic degree l. (a) and (b): Dynamos at $E=1.2\times10^{-4}$, $Pr=1$, $Pm=50$ and $Ra/Ra_c=1.2$ with Y_1^1 ($q^*=60\%$) and Y_2^1 ($q^*=60\%$) boundary heat flux patterns respectively. (c) Dynamo at $E=1.2\times10^{-5}$, $Pr=1$, $Pm=10$ and $Ra/Ra_c=1.8$ with Y_1^1 ($q^*=60\%$) heat flux pattern respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)