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Magnetic reversal frequency scaling in dynamos with thermochemical convection

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ABSTRACT

Scaling relationships are derived for the frequency of magnetic polarity reversals in numerical dynamos powered by thermochemical convection. We show that the average number of reversals per unit of time scales with the local Rossby number Ro_ℓ of the convection. With uniform core–mantle boundary (CMB) heat flux, polarity reversals are absent below a critical value $Ro_{\ell crit} \simeq 0.05$, beyond which reversal frequency increases approximately linearly with Ro_ℓ. The relative standard deviation of the dipole intensity fluctuations increases with reversal frequency and Ro_ℓ. With heterogeneous CMB heat flux that models the large-scale seismic heterogeneity in Earth's lower mantle, reversal frequency also exhibits linear dependence on Ro_ℓ, and increases approximately as the square root of the amplitude of the CMB heterogeneity. Applied to the history of the geodynamo, these results imply lower CMB heat flux with $Ro_\ell \leqslant Ro_{\ell crit}$ during magnetic superchrons and higher, more heterogeneous CMB heat flux with $Ro_\ell > Ro_{\ell crit}$ when geomagnetic reversals were frequent. They also suggest that polarity reversals may have been commonplace in the early history of other terrestrial planets. We find that zonal heterogeneity in CMB heat flux produces special effects. Close to $Ro_{\ell crit}$ enhanced equatorial cooling at the CMB increases reversal frequency by concentrating magnetic flux at low latitudes, whereas far beyond $Ro_{\ell crit}$ enhanced polar cooling at the CMB increases reversal frequency by amplifying outer core convection.

1. Introduction

Many of the larger objects in the solar system have experienced dynamo action at some time in their history, but among the planets, only the Earth has a record of magnetic polarity reversals. Paleomagnetic data shows that polarity reversals have occurred throughout Earth's history since the Archean (Layer et al., 1996; Strik et al., 2003), with the length of time between reversals having varied by nearly three orders of magnitude, from 40 Myr long superchrons to short subchrons lasting under 40 kyr (Cande and Kent, 1995; Merrill et al., 1998). It remains an open question as to whether the histories of other planetary dynamos include polarity transitions.

The general criteria that determine under what conditions and how often a self-sustaining planetary dynamo undergoes spontaneous polarity reversals remain obscure, but the reversal behavior of numerical dynamos (Kutzner and Christensen, 2000; Kutzner and Christensen, 2002; Christensen and Aubert, 2006; Olson and Christensen, 2006; Aubert et al., 2009; Wicht et al., 2009), laboratory dynamos (Berhanu et al., 2007) and idealized theoretical models (Pétrélis et al., 2009; Gissinger et al., 2010) point to some of the conditions under which polarity transitions are favored. Numerical dynamo studies in particular have identified several factors that control the likelihood of reversals. On average, reversals are more likely as the dynamo forcing is increased (Heimpel and Evans, 2013), and conversely, they become less likely as the planetary rotation is increased (Kutzner and Christensen, 2002). The timing of the individual reversals appears to be largely stochastic (Olson et al., 2009; Wicht et al., 2009). Using low resolution dynamos that produce large sets of reversals, Driscoll and Olson (2009a) delineated the transition from stable to reversing dynamos in terms of the relative strengths of convection and rotation, and confirmed that increasing the vigor of convection or decreasing the rate of rotation tends to destabilize the polarity. Driscoll and Olson (2009a) also found that the frequency of reversals generally increases with the vigor of convection in dynamos with fixed rotation, and reversal frequency generally decreases when the rotation is increased but the convection is fixed. In addition, for dynamos with uniform boundary conditions, it has been found that the mean boundary heat flux is inversely proportional to dipole strength, so reversal frequency may be anti-correlated

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to dipole strength (Driscoll and Olson, 2009b; Driscoll and Olson, 2011).

Based on numerical dynamos with heterogeneous core–mantle boundary (CMB) heat flux, it was proposed that the relationship between the background dynamo convection mode and the boundary pattern may influence dipole stability (Glatzmaier et al., 1999), and in particular, the latitudinal distribution of CMB heat flux can affect reversal frequency. Enhanced CMB heat flux inside the tangent cylinder promotes dipole stability (Glatzmaier and Roberts, 1997; Glatzmaier et al., 1999), enhanced equatorial heat flux increases reversal frequency (Glatzmaier et al., 1999; Kutzner and Christensen, 2004; Olson et al., 2010), whereas reduced equatorial heat flux decreases reversal frequency and may even prevent reversals (Glatzmaier et al., 1999; Kutzner and Christensen, 2004), although this latter result is not always replicated (Olson et al., 2010). Kutzner and Christensen (2004) found with a spherical harmonic degree Y_2^2 CMB heat flux pattern that reversal frequency varies linearly with convection vigor and nearly linearly with the amplitude of the boundary anomaly, but for tomographic conditions they found no variation of reversal frequency with convection strength or boundary heterogeneity amplitude. In contrast, Olson et al. (2010) and Heimpel and Evans (2013) found that increasing the boundary heterogeneity amplitude nearly always increases reversal frequency. Another important factor is the level of equatorial symmetry of the CMB heat flux, specifically, the possibility that high equatorial symmetry promotes dipole stability (Pétrélis et al., 2009; Pétrélis et al., 2011). In particular, laboratory reversing dynamos (Berhanu et al., 2007) point to the importance of symmetry breaking of the fluid motion in precipitating reversal onset.

Although moderate variations in reversal frequency are attributable to the stochastic nature of dynamo action (Jonkers, 2003; Ryan and Sarson, 2007; Wicht et al., 2009), the existence of superchrons in the paleomagnetic record and the fact that they are spaced about 200 Myr apart, similar to the overturn time of mantle convection, suggests that changing mantle conditions play some role (Glatzmaier et al., 1999; Kutzner and Christensen, 2004). Driscoll and Olson (2009b) proposed that the initiation and termination of a superchron requires an anomalous perturbation of the convective and rotational mean state of the core. Driscoll and Olson (2011) found that the CMB heat flux magnitude is positively correlated with reversal frequency, and argued on this basis that the superchron cycle is caused by slow variations in the magnitude of the CMB heat flux magnitude, as would result from time dependent mantle convection.

In this paper we measure reversal frequency in a set of low-resolution numerical dynamos in which the distribution of convective forcing is similar to what is inferred for the present-day geodynamo. In these numerical dynamos, the primary driving force is the flux of co-density at the inner core boundary (ICB), representing buoyancy produced by solidification of the inner core. In contrast, the heat flux at the CMB is comparable to the heat conducted along the core adiabat, so the contribution from thermal buoyancy to the convection is smaller than from compositional buoyancy. For purposes of generality, we consider dynamos with both uniform CMB heat flux, the basic model for terrestrial planets, plus dynamos with boundary heat flux heterogeneity. In one set of cases representing the present-day Earth, the CMB heterogeneity is proportional to the long wavelength seismic heterogeneity in the lower mantle, and in another set of cases representing hypothetical past conditions, the heterogeneity is proportional to a single spherical harmonic degree. We then derive scaling laws that link the reversal frequency in these types of dynamos to the local Rossby number of the convection and to the fluctuations of the dipole moment. Previous numerical dynamos studies have established that the onset of reversals have some connection with these parameters (Christensen and Aubert, 2006; Olson and Christensen, 2006; Sreenivasan and Jones, 2006; Aubert et al., 2009; Driscoll and Olson, 2009b; Wicht et al., 2009; Olson et al., 2010; Biggin et al., 2012; Gastine et al., 2012; Duarte et al., 2013) but did not provide a quantitative relationship between reversal frequency and these parameters.

2. Methods

We focus on numerical dynamos with dominantly compositional driving, and make use of the co-density formulation (Braginsky and Roberts, 1995) in which $C = \rho(\alpha T + \beta\chi)$ where ρ is mean density, T is temperature, χ is the light element concentration (mixing ratio) in the outer core, and α and β are their respective expansivities. Control parameters for these dynamos include the Ekman number E, the Prandtl number Pr and the magnetic Prandtl number Pm defined respectively by

$$E = \frac{\nu}{\Omega D^2} \tag{1}$$

$$Pr = \frac{\nu}{\kappa} \tag{2}$$

$$Pm = \frac{\nu}{\eta} \tag{3}$$

where ν is kinematic viscosity, Ω is the angular velocity of rotation, $D = r_o - r_i$ is the outer core shell thickness, κ is the diffusivity of the co-density and η is magnetic diffusivity. Buoyancy is parameterized in terms of the Rayleigh number Ra, which can be defined for thermochemical dynamos as

$$Ra = \frac{\beta g D^5 \dot{\chi}}{\kappa \nu^2} \tag{4}$$

where g is gravity at the CMB and $\dot{\chi}$ is the time rate of change of the light element concentration (mixing ratio) in the outer core due to inner core growth. Here we have used D and D^2/ν to scale length and time, respectively, and $\rho\beta D^2\dot{\chi}/\nu$ to scale co-density.

Boundary conditions lead to additional control parameters. At the ICB we set $C = C_i$. At the CMB we specify the heat flux as the sum of a global mean part $\bar{q}$ and a laterally varying part q':

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

where ϕ and θ are longitude and co-latitude, respectively, and $\bar{q}$ is measured relative to the heat flux down the core adiabat, such that $\bar{q} > 0$ corresponds to superadiabatic heat flux. The function q' in (5) specifies the amplitude and the planform of the CMB heat flux heterogeneity.

In terms of the dimensionless radial coordinate r^* and the scaled global mean and laterally varying co-density $\bar{C}^* + C'^*(\phi, \theta)$, we write the flux conditions on the CMB as

$$\frac{\partial \bar{C}^*}{\partial r^*} = -\bar{q}^* \tag{6}$$

and

$$\frac{\partial C'^*}{\partial r^*} = -q'^* \tag{7}$$

where $\bar{q}^* = \alpha\nu\bar{q}/\beta k D\dot{\chi}$ is the dimensionless global mean CMB heat flux, $q'^* = \alpha\nu q'/\beta k D\dot{\chi}$ is its dimensionless lateral heterogeneity, and k is the thermal conductivity.

The dimensionless amplitude of the CMB heat flux heterogeneity is often expressed as one-half of the peak-to-peak boundary heat flux variation normalized by the mean (Olson and Christensen, 2002):

$$\delta q^* = \frac{q'_{max} - q'_{min}}{2\bar{q}} \tag{8}$$