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Reversals of the Geomagnetic Field: Constraint on Convection Intensity in the Earth's Core

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Abstract—Modern geodynamo models allow the generation of a magnetic field without reversals and with frequent reversals. The transition from one regime to another is associated with a relatively small change in the intensity of the generation sources. From this, it is usually concluded that the geodynamo system is located near such a transition, which, generally speaking, requires a more detailed justification. Such a transition leads to other changes in the behavior of the geomagnetic field, which are analyzed in this paper based on modern geodynamo models, in particular, the degree to which the dipole of the magnetic field is violated, the change in its strength, and the ratio of the decay time and growth of the dipole during the reversal.

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1. INTRODUCTION

According to the geodynamo theory, the geomagnetic field observed on the Earth's surface is generated by the flows of a conducting fluid in the core (Kono, 2009). According to paleomagnetologists' estimates, the magnetic field has existed for at least 3.6 billion years (see (Reshetnyak and Pavlov, 2016) for details), which is comparable to the age of the Earth—4.5 billion years. It can be argued with less confidence that the magnetic field was dipole for most of that time and only occasionally underwent a reversal of the polarity of the magnetic dipole (reversal of the geomagnetic field), during which the amplitude of the dipole decreased several times. Over the history of the Earth, there have been several hundred reversals, which, together with the field dipole, is a good test for verification of the performance of geodynamo models.

In geodynamo models that include convection equations, there are two threshold phenomena associated with the appearance of convection and a magnetic field. Both processes begin with the exceedance of the threshold values of the energy sources causing convection and, in fact, the intensity of the arising convection, which, in turn, generate the magnetic field. The thermal convection in the liquid core is turbulent, and the hydrodynamic Reynolds number is $\mathrm{Re} \sim 10^8$. Such a high Re value indicates that turbulence has developed, a large number of convective modes are excited, and the behavior of the velocity field on large scales no longer depends on the change in the intensity of thermal convection sources. The situation with the magnetic field is different: a magnetic Reynolds number of $\mathrm{Rm} \sim 10^2$–10^3 is not so large and exceeds its critical value only by one to two orders of magnitude. Because of this, the change in the magnetic field on large scales during convective fluctuations can be very significant due to the small number of excited magnetic modes in the induction equation. It is assumed that a change in the generation regime without reversals to a regime with frequent reversals is associated with such fluctuations. As a rule, it is not discussed exactly why the system is located near this transition throughout the entire history of the Earth.

The concept of how the reversal frequency is related to the amplitude of energy sources has evolved with the development of geodynamo models. According to the first models of the mean field geodynamo (Jones, 1995), including the Z-model (Anufriev et al., 1997), the transition from a regime without reversals to frequent reversals near the generation threshold was associated with a decrease in the amplitude of energy sources (dynamo numbers). With the emergence of three-dimensional (3D), non-axisymmetric geodynamo models that made it possible to simulate cyclonic convection, the point of view changed to the opposite: it turned out that such a transition requires an increase in the amplitude of energy sources (Christensen et al., 1999). Later, a similar result was obtained in mean-field models with the use of the geostrophic currents obtained in 3D models of thermal convection (Reshetnyak, 2017). The transition to frequent reversals is associated with a relative decrease in the reversals of rotation, which, in turn, leads to an increase in the fluctuations of the magnetic poles relative to the geographic ones (see Reshetnyak and Hejda, 2013 for details).

Since Rm is small, we can reasonably expect that the behavior of the magnetic field can change dramatically with a change in Rm and is not limited only by the frequency of reversals. Such changes are indeed observed both in 3D models (Christensen et al., 1999) and mean-field models (Reshetnyak, 2017). However, it is difficult to say to what extent this fact is confirmed by paleomagnetic observations, since the accuracy of the determination of the frequency of reversals of the geomagnetic field significantly exceeds the accuracy of the determinaiton of other characteristics of the field in the past. Further, using the mean-field models and the 3D dynamo model with thermal convection as an example, we will consider the other changes that occur in the magnetic field during the transition from a regime without reversals to frequent polarity changes and the extent to which we can compare the simulation results with observations.

2. MODELING RESULTS

The geodynamo model must satisfy at least two requirements: the use of parameters (transfer coefficients, amplitudes of energy sources, angular velocity of the planet's rotation) based on a physical model of the Earth and the reproduction of evolutionary series of the magnetic field that are close to observed values. Currently, none of the models satisfies the first criterion, since modeling convection at $\mathrm{Re} \sim 10^8$ without the use of turbulent convection models is impossible. The application of the known models of turbulence is also impossible, since they do not take into account the fast rotation and the associated anisotropy of convection. As a result, the following compromise is adopted in terms of parameters: the transfer coefficients are taken to be several orders of magnitude higher, so that the Reynolds numbers are of the order of 10^2–10^3. It is obvious that such an approach increases the fluctuations of the large-scale velocity with an increase in the amplitudes of the energy sources, and, as a consequence, the large-scale magnetic field.

Another important parameter, the period of the planet's daily rotation, is usually assumed to be less than a day in order to reduce the gap between days and the characteristic time of variations in the dipole magnetic field, which is $\sim 10^3$ years or more. In practice, the rotation is chosen such that at least the geostrophic balance of forces is fulfilled (Pedlosky, 1987). In this case, scaling estimates that describe the relationship between dimensionless numbers provide hope (Christensen and Aubert, 2006) that the solutions can be recalculated for the kernel parameters.

Modern 3D geodynamo models register two important boundaries: the beginning of the generation of a dipole magnetic field without reversals (I) and, as the amplitude of energy sources (Rayleigh numbers in thermal and compositional convection) increases, the transition of the magnetic field to a multipole configuration with frequent reversals (II). The presence of boundary II qualitatively reflects the fact that an increase in the amplitude of centrally symmetric buoyancy forces decreases the relative role of rotational forces with axial symmetry (Reshetnyak and Hejda, 2013). This was shown for the first time in 3D geodynamo models (Glatzmaier et al., 1999), and the result was then formulated in terms of the critical Rossby number $\mathrm{Ro}^{\mathrm{cr}}$ (Christensen and Aubert, 2006). When $\mathrm{Ro} < \mathrm{Ro}^{\mathrm{cr}}$, the magnetic poles are close to the geographic ones; reversals appear upon an increase in Ro. It is important that rotation also affects the generation of the magnetic field during frequent reversals. This follows both from the fact that the duration of the reversals (10^3–10^4 years) is much shorter than the time between reversals, which is millions of years or more, and the more fundamental property of the generation of large-scale magnetic fields is associated with the need for such rotation.

Let us illustrate this in Fig. 1, which shows the behavior of the kinetic E_k and magnetic E_m energy, as well as the magnetic energy of the dipole E_m^d in a 3D model in Geodynamo Magic (see the detailed description of the model in Annex). As we can see, the position of the highs for the three charts is different. If the kinetic energy continues to grow with an increase in the Rayleigh number Ra, then the magnetic dipole begins to decrease much faster than the total magnetic energy. By the time the reversals appear, ($\mathrm{Ra} \sim 4 \times 10^5$) becomes quite small. This result is well known and is supported by numerous numerical experiments (Christensen and Aubert, 2006). In other words, it is difficult in 3D models to obtain simultaneously a strong dipole magnetic field and reversals. The comparison of boundary II with observations should be made with extreme caution, since, according to observations (see (Reshetnyak and Pavlov, 2016) for details), the magnetic field at geological times in the past most likely (i) was dipole and (ii) had tensions comparable to current tensions. It should be taken into account that the sought geodynamo model should reproduce fields that are close to the currently observed properties against the background of sufficiently large changes in parameters associated with the evolution of liquid and solid cores (Reshetnyak, 2019), i.e., it should not show high sensitivity to changes in parameters.

In this situation, it is interesting to refer to the accumulated experience in the modeling of the mean-field dynamo. When fast rotation is disregarded, standard models of the mean field at the lasing threshold give periodic reversals of the magnetic field (Jones, 1995). A similar picture was observed in the Braginsky Z-model (Anufriev et al., 1997). If we take geostrophic flows from 3D convection models, calculate the hydrodynamic helicity, α-effect, and differential rotation from them, and substitute this into the αω-dynamo model (mean-field model) with algebraic quenching for the α-effect, then the result qualitatively resembles the results described above with 3D modeling. First, a dipole magnetic field is generated without reversals; then, as the velocities increase, there is a transition to frequent reversals of the magnetic field with the loss of dipole (Reshetnyak, 2017). It is interesting that the Rossby number does not appear explicitly in the mean-field models, and the solution for the magnetic field depends only on the amplitude of the current velocities. In terms of linear analysis, this corresponds to a change in the growth rate of the magnetic-field modes and the appearance of new modes with an increase in the current velocity, i.e., Rm. From this point of view, the result obtained by Christensen and Aubert (2006) could receive a new interpretation, not as a dependence of the dipole on Ro but on Rm.

Since boundary II in mean-field models is as sharp as in 3D models and it is almost impossible to obtain a strong magnetic dipole with frequent reversals, a modification of the αω-dynamo model was undertaken. The idea was to take into account the fluctuations of the generation source, the α-effect (Hoyng, 1993), associated with turbulence. The latter can be done both near boundary I and II. For boundary I, this issue was considered earlier (Reshetnyak, 2019). The choice of this particular boundary was due to the slow decay of the dipole observed by paleomagnetologists during the last five reversals and its rapid recovery after the reversals (Valet, 2005). The authors suggested that the decrease in the dipole amplitude is associated with the damping of the magnetic field caused by the failure of the dynamo process. In terms of the model (Hoyng, 1993), damping can be associated with fluctuations in α. In the αω-model of the mean field with geostrophic velocities (Reshetnyak, 2019), it is possible to obtain the observed ratio of times 4 : 1. Note that the dipole magnetic field is very stable near boundary I, and "additional" measures are required to obtain reversals. In a similar way, reversals can be reproduced near boundary II. However, from general considerations, one should expect that an increase in the amplitude of the energy sources will lead to a decrease in the characteristic time of the magnetic field variation and a time ratio that is less than unity.

Within the framework of 3D modeling, fluctuations of energy sources near boundary I were implemented in the form of the following numerical experiment. Since not every fluctuation leads to an reversal of the magnetic dipole and 3D modeling itself requires time-consuming calculations, it was decided to restrict ourselves to the estimation of the response time of a particular quantity to a parameter change. In this case, the reversals themselves, if any, were not taken into account. In the 3D model of the dynamo, a stepwise

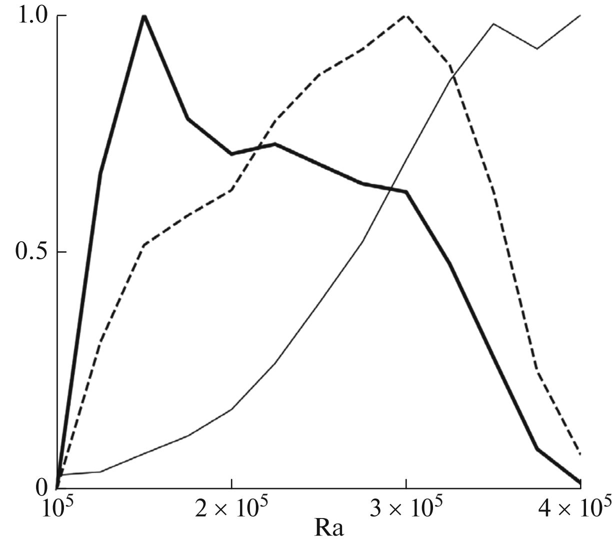

Fig. 1. Dependence of the kinetic energy E_k (thin line), magnetic energy (dashed line), and magnetic dipole energy E_m^d (thick line) on the Rayleigh number Ra for Pr = 1, Pm = 5, E = 10^{-3}. Graphs are normalized to 5.7 values × 10^8, 1.0 × 10^9, 1.2 × 10^8, respectively.

change in the Rayleigh number Ra over a time interval was introduced $\tilde{T}$:

$$Ra(t) = \begin{cases} R_1, & i - \text{четное}, \\ R_2, & i - \text{нечетное}, \end{cases} \quad (1)$$

$i\tilde{T} \le t < (i+1)\tilde{T}, \quad i = 0...N$. The period $\tilde{T} = 20$ was selected such that the solution had time to reach the quasi-stationary level. The characteristic calculation time for $N = 20$ took one day.

The tested values were the energies averaged over the number of realizations E_k, E_m and E_m^d. Of the total N of Ra changes, two sequences were identified: the first included the transition $R_1 \to R_2$ in the middle of the interval $\tilde{T}$ (curve C_1), and the second included the reverse transition, $R_2 \to R_1$ (curve C_2). For C_2, time t was counted in the opposite direction from $\tilde{T}$ to 0. If the process is reversible, then the ends of curves C_1 and C_2 match for a sufficiently large $\tilde{T}$. The behavior of the curves C_1 and C_2 near $\tilde{T}/2$ may differ, and a hysteresis loop occurs. The presence of hysteresis is associated with the inertia (memory) of the process.

Figure 2 shows the solution near boundary I. An increase in Ra on curves $C_1(C_2)$ leads to an increase in E_k and E_m^d, and a decrease in Ra causes them to decrease. Since the convective time during fast rotation is less than the magnetic time, the jump for E_k is sharper. For a magnetic dipole, a hysteresis loop is

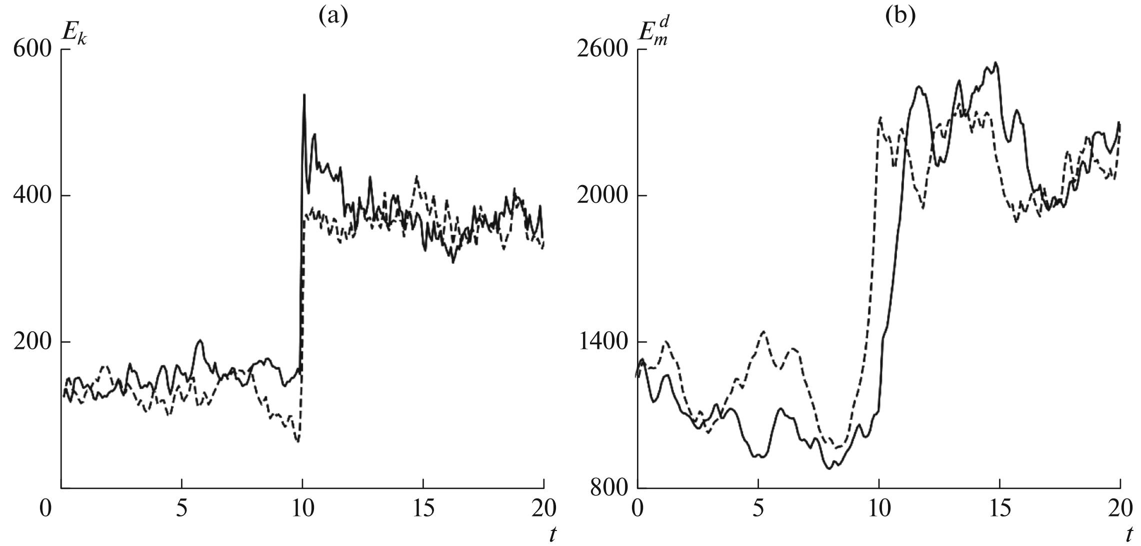

Fig. 2. Hysteresis loops for kinetic energy E_k (a) and the magnetic energy of the dipole E_m^d (b) in dimensionless units (details in the Appendix) for Pr = 1, Pm = 20, E = 10^{-3}, $R_1 = 8 \times 10^4$, $R_2 = 1.05 \times 10^5$. Solid line, C_1; dashed line, C_2.

observed (a slight shift of the curves near $t = \tilde{T}/2 = 10$), because the characteristic time of E_m^d is higher than that for E_k (and at E_m). Note that in the liquid core Pm ~ 10^{-5} and that the difference in the characteristic times of convection and magnetic field is even greater, but, on the whole, the model correctly reproduces the ratio of convective and magnetic time. In the model, bursts of kinetic energy are observed at the moment of the jump: later, as the magnetic field changes, the kinetic energy decreases (increases) for the curves $C_1(C_2)$.

Since the slopes of the curves in Fig. 2b near $t = 10$ are close, the characteristic decay and rise times of the magnetic dipole coincide (the ratio of the times is of the order of unity). None of the experiments carried out in the 3D model near boundary I allowed a significant change in the time ratios. The ability to obtain a nonunity time ratio in 3D models was also not discussed in the available literature.

3. DISCUSSION

If we exclude from consideration the reliability of observations (and the author does not know of analogs of the work of Valet (2005)) and try to explain why the mean-field models and 3D models give different results, then the following assumption can be made. In contrast to the mean-field model, in which convection is specified as a time-constant profile of differential rotation and the distribution of the α-effect with a simple form of feedback over the magnetic field, both the generation process and the dissipation process are associated with cyclonic convection in the 3D model. Convection in the core is non-axisymmetric and represents rotating columnar vortices elongated along the rotational axis, the horizontal scale of which is much smaller than the vertical scale. In the case of damping of the magnetic field when Rm is small, the vortices destroy the large-scale, axisymmetric magnetic field in a short period of time, on the order of the vortex-turnover time. In mean-field models, there are only characteristic times for the magnetic field itself, which is considered to be axisymmetric. The damping slows and lasts longer as the damping-mode Ra approaches the boundary I. Thus, the mean-field and 3D models give different ratios of the growth and decay times of the magnetic field.

This can be explained in another way: upon a decrease in energy sources, the solution in the limit in mean-field models tends to be a freely decaying axisymmetric solution without turbulent convection. This decay process is relatively slow. In 3D models, convection is also present during decay. This effect can be formulated both in the language of anisotropic turbulent diffusion and, in the first approximation, via estimation of the dissipation time from the time of the revolution of the convective vortex. In any case, the solution during decay will differ significantly from a freely decaying solution with a uniform diffusion coefficient.

CONCLUSIONS

If these results are extrapolated to the reversal process, it can be assumed that there will be no temporal asymmetry in the 3D model, even during reversals. As we can see, comparison of the results of simulations of various models and observations improves our understanding of the physics of processes in the liquid core of the Earth. The emergence of 3D dynamo models required a revision of the previously obtained simulation results in mean-field models. Comparison of the results of modeling with observations requires both further refinement of the observations themselves, in particular, on the fine structure of reversals, and an answer to the question as to why evolutionary processes in the Earth's core have little effect on the behavior of the magnetic field. Further study of the spectral properties of the induction equation near boundaries I and II seems to be a completely logical step for further research.

APPENDIX

Let us consider the dynamo equations in a spherical layer $r_i \le r \le r_0$, where (r, θ, φ) is a spherical coordinate system, $r_0 = 1$, and $r_i = 0.35$. Entering the following units for speed **V**, time t, pressure P and magnetic field **B**, ν/d, d^2/ν, $\varrho\nu^2/d^2$, and $\sqrt{2\Omega\varrho\nu\mu}$, where $d = r_0 - r_i$ is the unit of length, ν is the coefficient of kinematic viscosity, ϱ is the density of matter, and μ is the magnetic permeability, we write the system of dynamo equations in the form

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla\times(\mathbf{V}\times\mathbf{B}) + \mathrm{Pm}^{-1}\Delta\mathbf{B}, \quad \nabla\cdot\mathbf{V} = 0, \quad \nabla\cdot\mathbf{B} = 0,$$
$$\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V}\cdot\nabla)\mathbf{V} = -\nabla P - \frac{2}{\mathrm{E}}\mathbf{1}_z\times\mathbf{V} + \frac{\mathrm{Ra}}{\mathrm{Pr}}T\mathbf{1}_r$$
$$+ \Delta\mathbf{V} + \frac{1}{\mathrm{EPm}}(\nabla\times\mathbf{B})\times\mathbf{B},$$
$$\frac{\partial T}{\partial t} + (\mathbf{V}\cdot\nabla)(T + T_0) = \mathrm{Pr}^{-1}\Delta T. \quad \text{(A.1)}$$

The dimensionless Prandtl, Ekman, Rayleigh, and magnetic Prandtl numbers are given in the form $\mathrm{Pr} = \frac{\nu}{\kappa}$, $\mathrm{E} = \frac{\nu}{2\Omega L^2}$, $\mathrm{Ra} = \frac{\alpha g_o \delta T d^3}{\nu\kappa}$ and $\mathrm{Pm} = \frac{\nu}{\eta}$, where κ is the coefficient of molecular thermal conductivity, α is the coefficient of volumetric expansion, $\mathbf{g}_o$ is the acceleration of gravity, δT is the unit of temperature perturbation T relative to the "diffusion" (nonconvective) temperature distribution $T_0 = \frac{r_i(r-1)}{r(r_i-1)}$, and η is the coefficient of magnetic diffusion.

System (A.1) is closed by vacuum boundary conditions for the magnetic field at r_0, r_i and by zero boundary conditions for the velocity field and temperature perturbations. The work uses the pseudo-spectral, MPI-code Magic adapted for the Gentoo operating system. For expansions in 65 Chebyshev polynomials and 128 spherical functions, 16 cores were used on Intel (R) Xeon (R) CPU E5-2640 computers. The used code is an amazing example of how, thanks to the enormous efforts of German scientists (Wicht, 2002; Gastine and Wicht, 2012), the pioneering prototype code developed at Los Alamos by Harry Glatzmaier (Glatzmaier and Roberts, 1995), was made publicly available on GitHub.

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