RUSSIAN JOURNAL of EARTH SCIENCES

REVERSALS AND LARGE-SCALE VARIATIONS OF THE GEOMAGNETIC FIELD: SIMILARITIES AND DIFFERENCES

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Abstract: It is shown that during reversals in geodynamo models the minimum amplitudes of the dipole, quadrupole and octupole coincide. Since the characteristic time of the reversal is close to the oscillations of the large-scale geomagnetic field, a similar analysis was carried out for the minima of the amplitude of the dipole magnetic field over the past 100 thousand years. It turned out that in this case such synchronization also occurs. It can be assumed that reversals and large scale variations of the geomagnetic field between the reversals have a lot in common. The wavelet analysis carried out indicates that the concept of the main geodynamo cycle is very arbitrary: the period of oscillation can vary from 8–10 thousand years to 20–30 thousand for a dipole. Analysis of the evolution of the Mauersberger spectrum allows us to conclude that magnetic field fluctuations observed at the Earth's surface are associated with the transfer of the magnetic field to the surface of the liquid core and can hardly be described by functions periodic in time.

Keywords: geodynamo, core-mantle boundary, magnetic field modes synchronization.

Citation: M. Yu. Reshetnyak (2024), Reversals and Large-Scale Variations of the Geomagnetic Field: Similarities and Differences, *Russian Journal of Earth Sciences*, 24, ES2003, EDN: OUNMDD, https://doi.org/10.2205/2024es000903

RESEARCH ARTICLE

Received: 20 October 2023
Accepted: 29 December 2023
Published: 22 April 2023

Introduction

Variations of the geomagnetic field penetrating to the Earth's surface from the surface of the liquid core cover a wide time range: from decades to hundreds of million of years [*Valet et al.*, 2005]. It is assumed that variations up to 100 thousand years are directly related to processes in the Earth's core, in which the magnetic field is generated. Variations with longer times correspond to processes in the Earth's mantle that changes the magnitude of the heat flow at the core-mantle boundary.

According to observations, the magnetic field on the Earth's surface is 90% dipole. The axis of the magnetic dipole at times greater than several tens of thousands of years coincides with the geographic axis. As follows from archeo- and paleomagnetic observations, the amplitude of the magnetic dipole can change with a characteristic time of 8–12 thousand years (the so-called main period of the geodynamo).

However situation in the liquid core is different. Firstly, note that from a mathematical point of view, the dipole component is not distinguished in any way in relation to neighboring modes, which also oscillate due to the turbulent motions and change its sign. In the core itself, the dipole component is only slightly larger in amplitude than the dipole and octupole, hardly standing out against neighbor harmonics in the spectrum.

The other point, is that as follows from the three-dimensional geodynamo modeling, there is a transition from oscillations of an axisymmetric dipole g_1^0 with a non-zero average to appearance of geomagnetic field excursions and then reversals with increase of the energy sources available to geomagnetic field generation [*Christensen and Aubert*, 2006]. he similar situation takes place in the mean-field dynamo models adopted to the Earth [*Reshetnyak*, 2017]. We emphasize, that characteristic duration of reversals is of the same order of magnitude as the main cycle $\sim 10^4$ years [*Valet*, 2003].

It can be assumed that, by their nature, reversals are not much different from magnetic field oscillations with a non-zero mean level, i.e. between reversals. Below we consider behavior of the first modes in expansion in spherical functions in observations over the last 100 thousand years that do not contain reversals, and the sequence of the reversals in dynamo models, in order to identify common behavior as the amplitude of the modes decrease.

Dynamo Predictions

As was mentioned in Introduction, the magnetic field reversals start with an increase in the intensity of the energy sources [*Christensen and Aubert*, 2006; *Reshetnyak*, 2021]. Depending on the model, this can be either an increase in the heat flux in the liquid core in the case of thermal convection, or due to change in the growth rate of the solid core in the case of compositional convection. In the both cases, there is a transition from quasi-periodic oscillations of the magnetic dipole with the period of the main cycle of geodynamo without sign alternation to the regime with the reversals, in which the polarity of the axi-symmetric magnetic dipole g_1^0 changes.

The time interval between reversals decreases as convection intensity increases. The characteristic time of the reversal itself is close to the main period $\sim 10^4$ years. Based on this, it can be assumed that reversals are in some sense close in nature to the main cycle. The difference between reversals and the main period of the geodynamo stands in existence of a non-zero mean level in the oscillations of the main period, which is two times larger for the last 10 thousand years than the amplitude of the oscillations.

The phenomenon of reversal can be easily predicted from the symmetry properties of the geodynamo equations. Due to quadratic form of the Lorentz force, dynamo equations are symmetric to the sign alternation of the magnetic field: $\mathbf{B} \to -\mathbf{B}$. Generally speaking, realization of such a change of the sign of the total magnetic field $\mathbf{B}$ assumes simultaneous change of the sign of the magnetic field at all the scales in the multipole decomposition. The more realistic suggestion is that reversal happens when the majority of the modes change the sign. The number of these modes depends on the spectrum of the magnetic field and the energy contained in the modes.

Following this scenario and provided that the modes are not correlated in time [*Hulot and Le Mouël*, 1994], we can suggest that reversals occur randomly, interval between the reversals depends on the amplitude of mode oscillations, and duration of reversal is of the same order of the oscillation's time scale.

In this sense, dipole and its reversals are not something extraordinary: the magnetic dipole fluctuates as well as the higher harmonics. Note that this statement does not contradict with the mean-field dynamo theory [*Krause and Rädler*, 1980], which makes a distinction between large-scale fields and turbulence, since the core does not exhibit the separation of fields by scale used in the theory. As follows from the three-dimensional models, continuous spectrum of the magnetic field is observed [*Christensen et al.*, 1999].

Depending on the model parameters, the dipole poloidal magnetic field observed at the Earth's surface is slightly larger or smaller than the quadrupole one, which generally does not change the conclusion about similarity of the modes. Let us also note the fact that exceed of the dipole component of the field at the Earth's surface is caused with two circumstances: the more rapid decrease in high modes in the mantle and the absence of the toroidal component of the magnetic field, which does not penetrate beyond the core. Taking into account the toroidal component of the magnetic field leads to decrease in the relative fraction of the dipole magnetic field in the core.

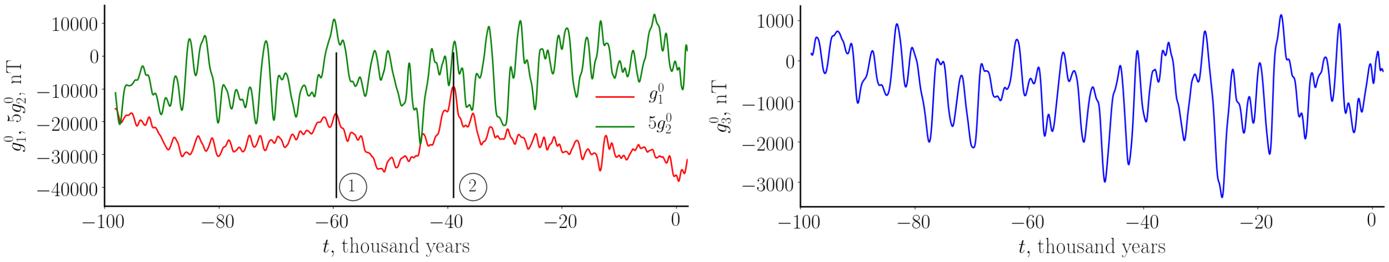
To prove the statement of similarity of reversals and geomagnetic field oscillations between the reversals, including the geodynamo main cycle, the analysis of some general properties of magnetic field oscillations between the reversals and the reversals itself is performed below. For the first case, data from the spherical-harmonic analysis of GGF100k model [*Panovska et al.*, 2018] for the last 100 thousand years were used. To analyze the behavior of the magnetic field during reversals, MAGIC geodynamo model was used [*Wicht*, 2002] In particular, we check below whether there is similarity (synchronization) in the behavior of the first modes (dipole, quadrupole and octupole) during reversals and during periods of a quiet magnetic field between reversals. The latter is not limited to the study of the main cycle of the magnetic dipole and includes the analysis of long-term variations in the magnetic field.

Magnetic Field Minima in Observations and Models

To synthesize the geomagnetic field over the last 100 thousand years GGF100k database [*Panovska et al.*, 2018] was used, presented as a set of Gaussian coefficients g_l^m, h_l^m. The model allows one to calculate the components of the magnetic field $\mathbf{B} = -\nabla U$, where the scalar potential U is given as an expansion in spherical harmonics:

$$U = \sum_{l=1}^{l_0} \frac{R_e^{l+2}}{r^{l+1}} \sum_{m=0}^{l} \Big(g_l^m \cos m\varphi + h_l^m \sin m\varphi \Big) P_l^m(\cos\theta),$$

$(r,\, \theta,\, \varphi)$ – spherical coordinates, $R_e = 6381$ km is the Earth's radius, P_l^m – associated Legendre polynomials, l_0 is the maximum harmonic number. Using the bispline interpolation allows one to calculate the magnetic field at an arbitrary moment in time.

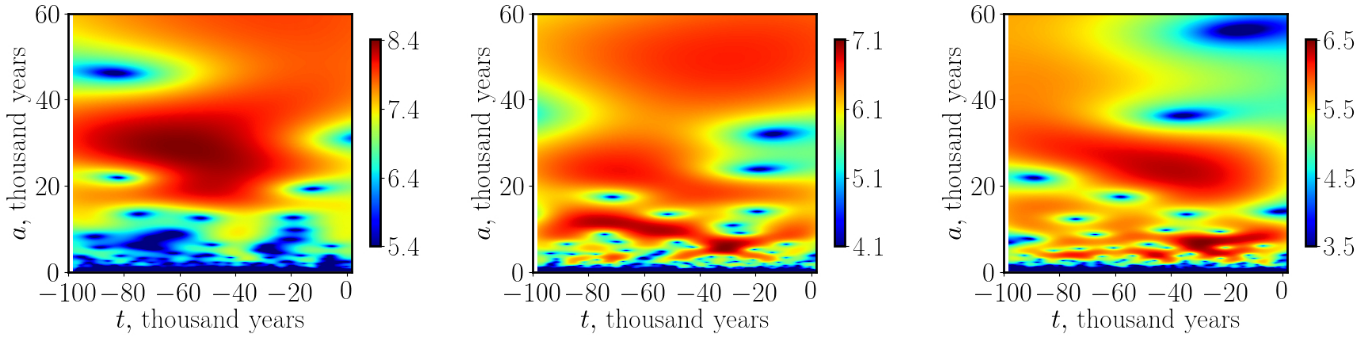


(a) **(b)**

Figure 1. Evolution of the axisymmetric dipole g_1^0 and quadrupole g_2^0 (a) and octupole g_3^0 (b) over the last 100 thousand years according to observations. For convenience, the quadrupole values are increased by 5 times, and the octupole values by 10 times. Zero time value corresponds to the beginning of a new era. The numbers in circles denote the positions of $|g_1^0|$ minima.

The evolution of the first three axisymmetric harmonics g_1^0 (dipole), g_2^0 (quadrupole) and g_3^0 (octupole) from GGF100k model are presented in Figure 1. Firstly, the above-mentioned main geodynamo cycle (for g_1^0) is weakly expressed: it is observed only in the last 10 thousand years. The latter is clearly visible in Figure 2, with the decimal logarithm of the Morlet wavelet spectrum in the Fourier normalization. The choice of wavelet analysis is associated with its lower tendency to appearance of false peaks in the spectrum and ability to detect evolution of the spectrum over the time. The abscissa axis represents time t, and the ordinate axis represents the time scale a of the process. If there was a constant in time periodicity, a horizontal band would be observed in the spectrum. Instead, for g_1^0 only recently the existence of a periodicity of the order of 10–15 thousand years has been observed, the duration of this event is comparable to the value of a. A more pronounced periodicity is the 30 thousand years oscillation. With that, the quadrupole's curve demonstrates traces of 10 thousand years periodicity with exception of the time interval $[-40, -30]$ thousand years, when the 5 thousand years periodicity dominated. During this period of time in the spectrum of the octupole a set of waves with periods from 4 to 8 thousand years was observed as well. The rest of the time there was quasi-periodicity with a characteristic time of about 7 thousand years. For the last two harmonics an oscillation with a characteristic time of 25 thousand years is observed. All considered oscillations demonstrate non-constancy of the periodicities. In many cases the lifetime of the process is comparable to the characteristic oscillation time.

Secondly, two local minima are observed for the dipole intensity, separated by 20 thousand years and denoted in the Figure 1 by number in circles. The greatest decrease in the magnetic dipole strength was observed at time $t_2 = -38{,}950$ years indicated by the num-



(**a**) (**b**) (**c**)

Figure 2. Wavelet spectra with Fourier norma: g_1^0 (a), g_2^0 (b) and g_3^0 (c).

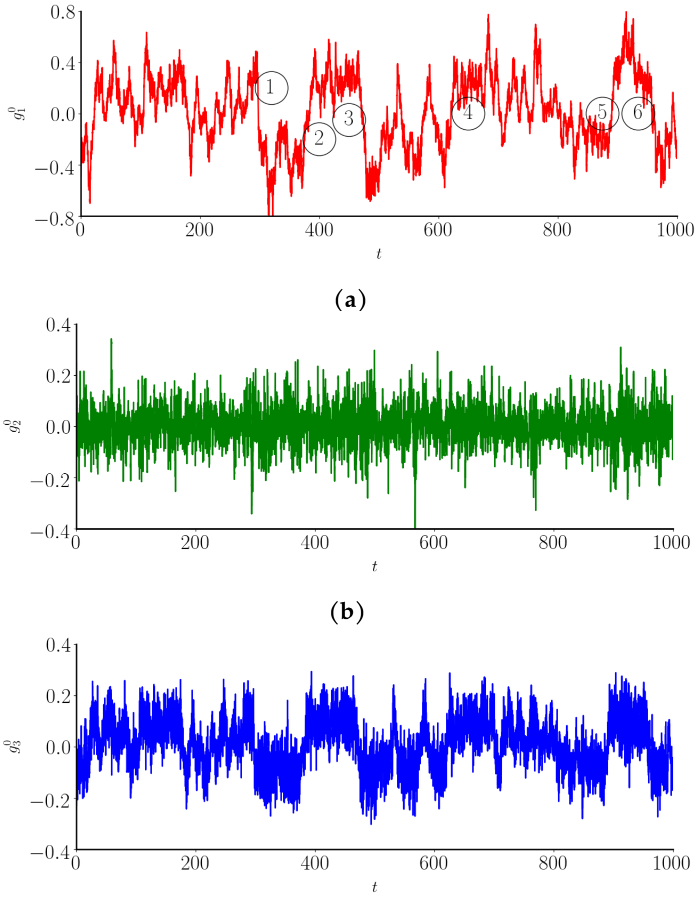
ber 2. This minimum corresponds to the Leschamps excursion [*Bonhommet and Zähringer*, 1969]. At this moment, the other two harmonics g_2^0, g_3^0 had small absolute values as well. To estimate decrease of Gauss coefficients at the minimum, it is convenient to normalize each curve at Figure 1 at its maximal absolute value. Then values of g_1^0, g_2^0, and g_3^0 at $t = t_2$ are -0.25, 0.12, and -0.24, correspondingly. Such a decrease of g_1^0 is of the same order of magnitude as the decrease of the dipole during the reversal or excursion due to the pure resolution of common observations. These minima correspond to the short-period processes in Figure 2.

Such a coincidence of minima reminds situation in the three-dimensional geodynamo model during reversals, Figure 3, see for details Appendix A. The behavior of g_1^0 and g_3^0 modes, which are antisymmetric relative to the equator plane, is similar: both modes change sign simultaneously. Additionally, in g_3^0 mode the high-frequency component is observed.

The evolution of the g_2^0 quadrupole differs from antisymmetric modes in that the oscillations occur at a zero average level. However, even for this harmonic, at the moment when $g_1^0 = 0$ the amplitude of g_2^0 is small as well. The analysis shows that all the magnetic field energy in the model on the Earth's surface also has a minimum during the reversal. It can be concluded that reversals occur when all the minima of the modes coincide. At the moment of reversal, synchronization of the different modes is observed. Such a behavior of the magnetic field could be expected for the dynamo regime in vicinity of the generation threshold, where the break of generation of the dipole field during the reversal means decay of the total magnetic field in the core. In this case correlation of the different modes between the reversals is provided by the non-linear interaction between the modes. For the larger energy sources it is the coincidence of the minima of the energy of the modes during the reversals is important. So far, the time scales decrease with increase of heat sources, time interval between the reversals decreases as well.

Returning to the observational data, we note that for the time moment 1 (in circle), $t_1 = -59{,}500$ years, which is close to the Norwegian-Greenland Sea excursion [*Liu et al.*, 2020], there is no correlation between $|g_1^0|$ and $|g_2^0|$ in Figure 1. The corresponding normalized values of coefficients g_1^0, g_2^0, g_3^0 at $t = t_1$ are -0.46, 0.35, and -0.14, correspondingly. It is possible that this difference is due to the fact that the decrease in magnetic field strength at time moment 1 in GGF100k model is less than at the moment 2. Nevertheless, the minimum g_1^0 coincides with decrease in the amplitude g_3^0. Let us recall that the asymmetry of the spectrum of a modern magnetic field is well known: the spectrum has a sawtooth structure, so that antisymmetric harmonics are slightly larger in amplitude than neighboring symmetric ones [*Lowes*, 1974]. According to the considered scenario, the lack of synchronization between g_1^0 and g_2^0 makes reversal impossible.

The extent to which different modes are correlated was studied over timescales of several hundred years [*Christensen and Aubert*, 2006; *Hulot and Le Mouël*, 1994]. The answer was negative: for different l and m modes are statistically independent. Formally, we also



(a)

(b)

(c)

Figure 3. Evolution of the axisymmetric dipole g_1^0 (a), quadrupole g_2^0 (b) and octupole g_3^0 (c) in geodynamo model. The numbers denote the reversals under consideration.

prove this result for GGF100k: the Pearson linear correlation coefficients for $(g_1^0,\, g_2^0)$, $(g_1^0,\, g_3^0)$, $(g_2^0,\, g_3^0)$ are too small: $r_{12} = -0.10$, $r_{13} = 0.18$, $r_{23} = 0.16$. Then, conclusion about absence of correlation remains valid, although for now the characteristic times of variations are much longer than that ones in [*Christensen and Aubert*, 2006]: $\tau_l = 535/l$ years.

For the model time serries in Figure 3 the following Pearson coefficients are estimated: $r_{12} = -0.02$, $r_{13} = 0.84$, $r_{23} = 0.01$. Such a large coefficient r_{13} is associated with the appearance of reversals. The more pronounced correlation of g_1^0 and g_3^0 is demonstrated using the scatter diagram, see Figure 4. Between the reversals, r is less than 0.5. This value, although higher than those observed in the GGF100k model, is still too small to say about correlation of g_1^0 and g_3^0 between the reversals. We remind that r can be interpreted as the cosine of the angle between two vectors in n-dimensional space. A complete lack of correlation with $r = 0$ corresponds to an angle of 90°, and a value of $r = 0.5$ corresponds to an angle of 60°, that corresponds to the negligible correalation.

Therefore, it can be assumed that the observed coincidence of the decrease in harmonic amplitudes during reversals, Figure 3, and in the observations for the stable field (between reversals) in Figure 1, may indicate the similarity of the processes occurring. In any case, such a point of view can be stated by an observer on the Earth's surface who knows nothing about the properties of the magnetic field in the Earth's core, where this field is generated by dynamo processes. The difference lies in the existence of a non-zero dipole field between the reversals, against the mean-level of which the magnetic dipole oscillates.

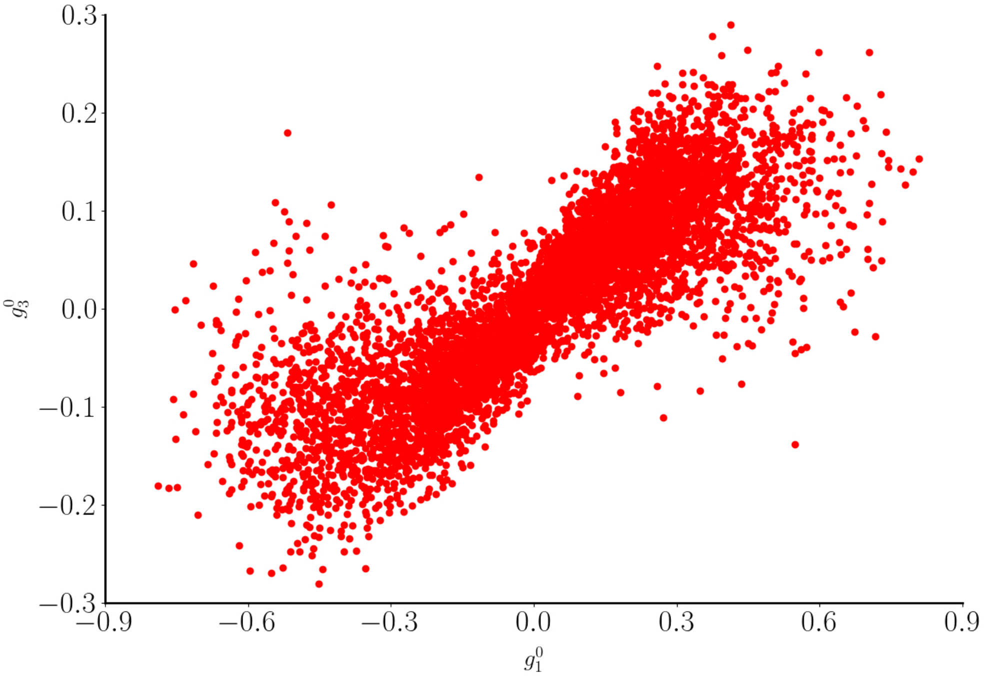
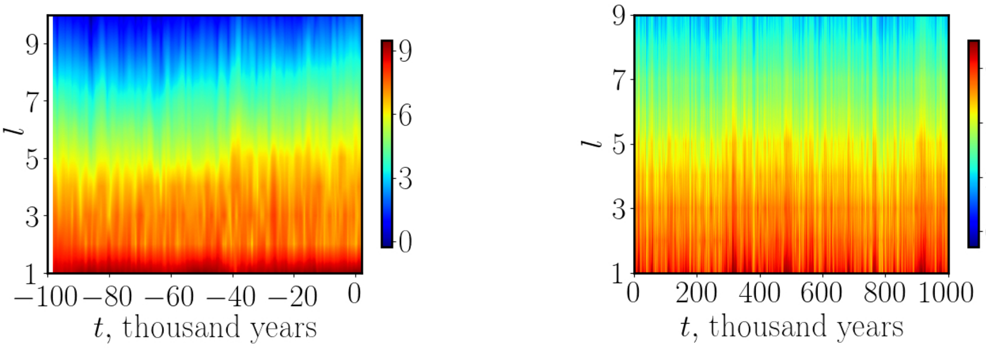


Figure 4. The scatter diagram for the model g_1^0 and g_3^0 time series.



(**a**) (**b**)

Figure 5. Evolution in time of the decimal logarithm of the magnetic field spectrum, $\lg S_l$ at the Earth's surface. GGF100k model (a) geodynamo simulations (b) presented in Figure 3.

It is instructive to compare the change in the spatial Mauersberger spectrum

$$S_l = (l+1)\sum_{m=0}^{l}\left((g_l^m)^2 + (h_l^m)^2\right) \tag{1}$$

over the time for observations GGF100k and dynamo model, discussed above, see Figure 5. The spectra have a band structure. The stripes are located not along the time axis, as if periodic processes with a fixed spatial scale $\sim 1/l$ were observed, but perpendicular to the time axis. From a physical point of view, this means that there were magnetic field fluctuations that contributed to all l. Obviously, this picture has nothing to do with the wave propagation, but corresponds to the ascent/sinking of hot/cold regions of the liquid core, carrying with them a magnetic field. This information, in common with the analysis of the pure potential field at the surface of the Earth, let us assume some new knowledge about convection at the surface of the liquid core. The model case corresponds to the magnetic Reynolds number $\mathrm{R_m} = 350$ and $\mathrm{Pm} = 20$, and hardly can be considered as the well-developed turbulence regime from the strict point of view. However the behaviour of the Gauss coefficients is already very similar to the well-known turbulent noise scenario. The additional analysis of the total kinetic and magnetic energy fluctuations in the liquid core, which are quite large and not regular in time, supports this statement. The more realistic point of view that such flows can be classified as the boundary turbulence. The analysis of the Mauersberger spectrum of the secular variation, in the definition of which in (1) instead of g and h there are their time derivatives, demonstrates no essential changes.[1]

Conclusions

Similarity of the characteristic times of geomagnetic field reversals and large-scale magnetic field variations between reversals suggests existence of the deeper connection between these processes. According to calculations, a simultaneous decrease in the amplitude of the first modes in the expansion in spherical functions of the potential field outside the core is observed. With that, the correlation of these modes at long times is close to zero. It can be concluded that the reversal occurs as a result of the coincidence of the amplitude minima of the first few modes at least. In the absence of such a coincidence, quasiperiodic variations of the large-scale magnetic field are observed at the same time scales $\sim 10^4$ years at a non-zero level for an axisymmetric dipole g_1^0. Such variations, according to observations, are characterized by partial coincidences of minima, for example, dipole and octupole.

Apparently, the amplitude of the variation itself is also important: when a certain threshold value is reached, the reversal occurs. In its turn amplitude of variation depends on the energy sources of dynamo in the core. The above leads to the conclusion that reversals are a fairly ordinary coincidence of circumstances from the point of view of magnetohydrodynamics. This phenomenon is the intrinsic nature of the dynamo mechanism and no other external trigger is needed. It is worth to note, that this scenario assumes, that temporal spectra of the magnetic field before and after the reversal is the same. Than follows that the start and the end of, e.g., superchrone is the same from spectral point of view and no prediction of the superchrone is possible at the times larger than $\sim 10^4$ years.

Acknowledgements. The geodynamo modelling part of the work was supported by the Russian Science Foundation grant # 23-17-00112 and analysis of observational data was performed within the framework of a State Assignment of the Institute of Physics of the Earth of Russian Academy of Sciences.

Appendix A

Let us consider the dynamo equations in a spherical layer $r_1 \le r \le r_0$, rotating with the angular velocity Ω around axis $\mathbf{z}$, where $(r,\ \theta,\ \varphi)$ is a spherical coordinates, $r_0 = 1$ and $r_i = 0.35$. Entering the following units for velocity $\mathbf{V}$, time t, pressure P and magnetic field $\mathbf{B}$, ν/d, d^2/ν, $\rho\nu\Omega$ and $\sqrt{\Omega\rho\eta\mu}$, where $d = r_0 - r_i$ is the unit of length, ν is the coefficient of kinematic viscosity, ρ is the density of matter, μ is the magnetic permeability, and η is the coefficient of magnetic diffusion, we write the system of dynamo equations in the form

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}) + \mathrm{Pm}^{-1}\,\Delta\mathbf{B}$$
$$\left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V}\cdot\nabla\right)\mathbf{V} = -\frac{1}{\mathrm{E}}\nabla P - \frac{2}{\mathrm{E}}\,\mathbf{1_z} \times \mathbf{V} + \frac{\mathrm{Ra}}{\mathrm{Pr}}\,T\,\mathbf{1_r} + \frac{1}{\mathrm{E\,Pm}}\mathrm{rot}\,\mathbf{B} \times \mathbf{B} + \Delta\mathbf{V} \qquad \text{(A1)}$$
$$\frac{\partial T}{\partial t} + (\mathbf{V}\cdot\nabla)(T + T_0) = \mathrm{Pr}^{-1}\Delta T.$$

The dimensionless Prandtl, Ekman, Rayleigh, and magnetic Prandtl numbers are given in the form $\mathrm{Pr} = \dfrac{\nu}{\kappa}$, $\mathrm{E} = \dfrac{\nu}{\omega d^2}$, $\mathrm{Ra} = \dfrac{\alpha g_0 \delta T d^3}{\nu^2}$ and $\mathrm{Pm} = \dfrac{\nu}{\eta}$, where κ is the coefficient

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[1] The secular variation spectrum is used to filter a large-scale magnetic field that has long characteristic times.

of molecular thermal conductivity, α is the coefficient of volumetric expansion, $g_\circ$ is the acceleration of gravity, δT is the unit of temperature perturbation T relative to the "diffusion" (non-convective) temperature distribution $T_0 = \dfrac{r_i(r-1)}{r(r_i-1)}$.

System (A1) 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. We used the pseudo-spectral, MPI-code Magic [*Wicht*, 2002] adapted for the Gentoo operating system. For expansions in 65 Chebyshev polynomials and 128 spherical functions, 16 cores were used on Intel® Xeon® CPU E5-2640 computers.

For simulations presented in Figure 3 the following values of parameters were used: $\mathrm{Pr} = 1$, $\mathrm{Pm} = 20$, $\mathrm{E} = 6.5 \times 10^{-3}$, $\mathrm{Ra} = 5 \times 10^{5}$.

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