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A Simple Mechanism for Generating a Geomagnetic Field

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Abstract

On the basis of the ideal gas model, the polarization of charges in the mantle was obtained, a physical and mathematical model was constructed, and estimated calculations of the dipole mode of the Earth's magnetic field were performed, taking into account the speed of its angular rotation, the parameters of density and temperature, the chemical composition, the ionization potential, the dielectric constant and the percentage of the main chemical compounds of the mantle substance.

Keywords

Physical Parameters of the Earth's Mantle, Maxwell-Boltzmann Statistics, Phonon Gas, Thermal Ionization, Electron-Hole Polarization, Electron-Hole Recombination, Earth's Magnetic Field, Dipole Mode of the Magnetic Field

1. Introduction

Currently, great progress has been made in studying the mechanism of the evolution of the Earth's magnetic field based on the model of a hydromagnetic dynamo [1], presumably operating in the Earth's liquid core. An experimental setup [2] and a simple mathematical model [3] have been constructed to demonstrate the process of magnetic field inversion against the background of its stationary dipole component, which allows us to consider the Earth's rotation speed as one of the parameters of the magnetic field generation mechanism. There are also works that consider additional mechanisms of magnetic field generation, for example [4]. In this work, based on the ideal gas model, a simple mechanism for generating the geomagnetic field, presumably operating in the Earth's mantle, is proposed. The obtained results, based on the physical parameters of the mantle and the Earth's rotation speed, demonstrate a high degree of agreement between the calculated and measured values of the magnetic moment and partially confirm the

Sutherland-Einstein hypothesis on the origin of magnetic fields of astrophysical objects [5].

2. The Basic Physical Parameters of the Earth

2.1. Characterization of the Earth's Magnetic Field

In the first approximation, the Earth's magnet seems to be a dipole inclined to the rotation axis at an angle of 11˚ and having a strength of 0.3 G at the magnetic equator. To date, the amplitudes of more than a dozen harmonics following the dipole have been measured, which decrease according to the power law with a break at the eighth harmonic. The dipole mode accounts for about 90% of the intensity. The residual field (full minus dipole) has the form of a finite number of anomalies occupying areas with sizes from hundreds to two thousand kilometers. Chaotic fluctuations of the direction of the dipole moment with characteristic time periods of 10^3 - 10^4 years have been observed. When averaging over these fluctuations, the average Earth dipole will be oriented along the rotation axis. Consequently, rotation must have a strong influence on the evolution of the magnetic field. After a characteristic time period of about 10^5 years reversals (inversions) of the magnetic dipole direction take place. The process is random ([1], pp. 266-267).

Modes those are higher than the dipole mode result from turbulent fluctuations of currents of electrically conducting liquid in the Earth's outer core. Mathematical modeling shows that if they are considered as white noise acting on the dipole mode, then model states occur that explain the inversion of the Earth's magnetic field [3].

2.2. Physical Parameters of the Earth

Figure 1 shows a simplified scheme of the Earth's structure with an indication of the names of the regions and the distances from the surface to the boundaries of characteristic states of matter ([6], V2, p. 79).

Inner and Outer Core		Lower and Upper Mantle		Crust
6371 km	5120 km	2885 km	1000 km	40 km

Figure 1. Diagram of the earth's structure.

The depth distribution of pressure, temperature and density according to the model "Earth-2" by V. N. Zharkov, V. P. Trubitsyn and P. V. Samsonenko is given in **Table 1** in ([7], pp. 26-27). An interpolation by parabolic splines was performed on the tabular data for the temperature and the density of matter in the Earth's interior. The range of density values (5.56 - 10.08) g/cm³ at a depth of 2920 km was replaced by the average value of 7.82 g/cm³. The depth parameter was recalculated as the distance from the center. The density parameter was normalized to the Earth mass. All parameters were converted to the international measurement system SI.

Table 1. Pressure, density, and temperature in the earth's interior.

Depth, in km	Pressure, in Megabar	Density, in g/cm³	Temperature, in ˚C
30	0.0084	3.32	700
100	0.031	3.38	1500
200	0.065	3.46	1950
413	0.130	3.64	2400
1047	0.399	4.58	2800
2060	0.889	5.12	3600
2920	1.386	5.56 - 10.08	4300
3955	2.445	11.46	5250
4991	3.239	12.28	6050
6371	3.657	12.68	6300

The obtained dependences of the absolute temperature $T_z(r)$ and density $\rho_n(r)$ of matter in the Earth's interior, which are further used in the calculation of ionization and polarization of free electrons in the Earth's mantle, are shown in **Figure 2**.

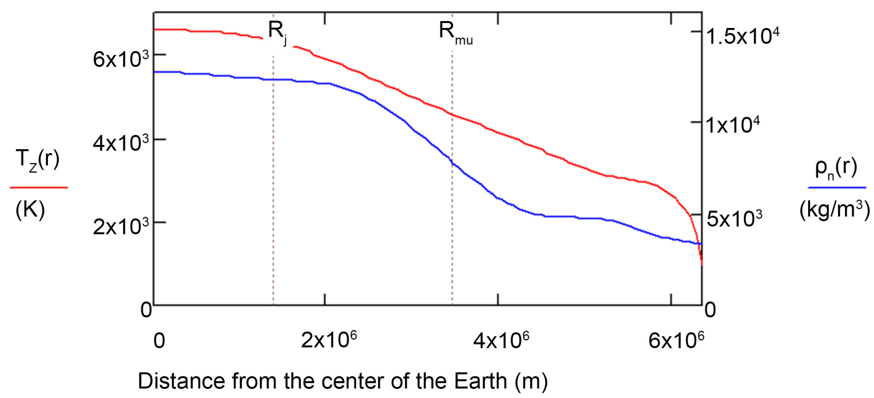

Figure 2. Temperature and density in the Earth's Interior.

Vertical markers indicate the radius of the inner core $R_j = 1.25 \times 10^6$ m and the inner radius of the mantle $R_{mu} = 4.35 \times 10^6$ m. The largest radius value corresponds to the boundary of the upper mantle $R_{mo} = 6.34 \times 10^6$ m.

2.3. Ionization in the Earth's Mantle

Table 2 shows the concentration of oxides of the main elements of the Earth's mantle in mass percent (according to Ringwood A. E.) ([8], p. 12), their molecular weight, number of atoms in a molecule, density, and relative dielectric permittivity [9], as well as the first ionization potential (energy) of the molecules [10] [11] and [12]. Oxides, the content of which in the Earth's mantle is less than 1%, are excluded from the calculation. These data were used in the further calculation of the ionization and polarization of charges in the Earth's mantle.

Table 2. Physical parameters of the oxides of the main elements of the mantle.

Oxide	SiO_2	MgO	FeO	Al_2O_3	CaO
Mass Fraction, in % (8, p. 12)	45.1	38.1	7.6	4.6	3.1
Molecular weight, in atomic mass units (9, V. 2)	60.8 (p.104)	40.31 (p.114)	71.84 [p. 60]	101.96 (p. 20)	56.08 (p. 92)
Number of Atoms	3	2	2	5	2
Density, in г/см³ [9, V. 2]	2.3 (p. 104)	3.58 (p. 114)	5.7 (p. 60)	3.97 (p. 20)	3.37 (p. 92)
Dielectric Permittivity [9, V. 1, p. 960]	3.9	9.65	100	8.8	4
Ionization Potential (Energy), in (eV)	11.7 (10)	8.5 (10)	8.5 (12)	9.9 (11)	6.5 (10)

Temperature fluctuations of atoms in the Earth's mantle can be considered as a phonon gas, subject to Boltzmann statistics. The number of molecules with an energy value greater than a given w_0, at $w_0 \gg k_b T$, can be represented by the expression ([13], p. 207):

$$N(w_0) = 2N\sqrt{\frac{w_0}{\pi k_b T}} e^{-\frac{w_0}{k_b T}}$$

where: N is the total number of molecules in the considered volume;

k_b is the Boltzmann constant;

T is the temperature of the substance.

This expression is also valid for the density of molecules if we take the derivative with respect to volume of both parts of the equation and if the number of molecules per unit volume is statistically significant:

$$\delta_i(r) = 2n_i\sqrt{\frac{w_i}{\pi k_b T_z(r)}} e^{-\frac{w_i}{k_b T_z(r)}}$$

where: $n_i(r) = \frac{\rho_n(r) m_i}{AMU \cdot M_i}$ is the number of molecules of the i-th oxide per unit volume;

$m_i = \frac{pr_i}{\Sigma pr_i}$ is the fraction of the *i*-th oxide in the mixture;

pr_i is the percentage content of the i-th oxide (Table 2);

AMU is the atomic mass unit constant;

M_i is the molar mass of a molecule of the i-th oxide;

w_i is the first ionization potential of the molecule;

r is the distance from the center of the Earth.

The resulting density is obtained by summing over all components of the mixture:

$$\delta_{is}(r) = \Sigma\delta_i(r) \tag{1}$$

The logarithm of the relative ion density $\delta_{is}(r)$ in the Earth's mantle is shown in **Figure 3**. Vertical markers indicate the conventional limits of polarization $R_p = 5.9\times10^6$ m and ionization $R_i = 6.2\times10^6$ m obtained below.

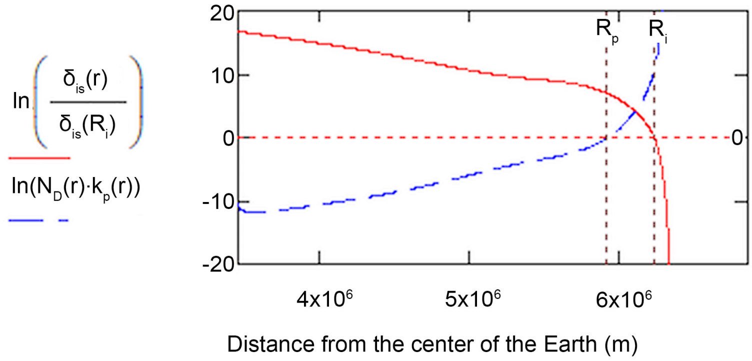

Figure 3. Ionization of the mantle and polarization criterion.

As can be seen from the figure, the lower part of the mantle is strongly ionized. The ion density decreases exponentially and reaches a critical value in the region of the conditional ionization boundary R_i. The ratio of the number of ions to the number of atoms per unit volume at characteristic points was:

$$k_i(R_{mu}) = \delta_{is}(R_{mu})/n_a(R_{mu}) = 6\times10^{-9}$$

$$k_i(R_p) = \delta_{is}(R_p)/n_a(R_p) = 7\times10^{-13}$$

$$k_i(R_i) = \delta_{is}(R_i)/n_a(R_i) = 7\times10^{-16}$$

There are at least 10^8 neutral atoms per ion. This is also true for free electrons, whose partial pressure can be neglected compared to the partial pressure of the phonon gas. Thus, the matter of the mantle is in the state of a semiconductor, the "holes" of which are "frozen" in the basic matter, and the free electrons are in the state of an electron gas. In other words, the polarization of free electrons in the mantle matter is possible.

2.4. Polarization of Charges in the Earth's Mantle

Under the influence of the radial component of the phonon gas pressure gradient, free electrons are displaced in the direction of the Earth's surface (polarized), and the equilibrium state is described by the equation of the equilibrium of forces acting on an elementary volume of electron gas in an electric field created by holes:

$$E_p(r)\cdot\Delta q_e + \nabla_r p(r)\cdot\Delta V \tag{2}$$

where: $E_p(r) = \frac{q_p}{\varepsilon\varepsilon_o S_n(r)}$ is the strength of the electrostatic field created by the positive charge of holes;

ε_o is the permittivity of vacuum;

ε is the relative permittivity of the mantle;

$\Delta q_e(r)$ is a change in the charge of free electrons in a volume ΔV;

$\Delta V = S_n(r)\cdot\Delta r$ is the volume increment;

$S_n(r) = 4\pi r^2$ is the spherical surface area;

Δr is the increment of the radius;

$\nabla_r p(r) = p(r)\cdot\psi(r)$ is the pressure gradient in the radial direction;

$p(r) = n_a(r)\cdot k_b\cdot T_z(r)$ is the pressure of the phonon gas;

$n_a(r) = \Sigma na_i(r)$ is the number of atoms in a unit volume;

$na_i(r) = N_i\cdot m_i(r)$ is the density of the atoms of the *i*-th oxide;

N_i is the number of atoms in an oxide molecule;

$\psi(r) = \frac{\nabla_r n_a(r)}{n_a(r)} + \frac{\nabla_r T_z(r)}{T_z(r)}$ is the gradient function (a function equal to the sum of the relative values of the radial gradients of atomic density and temperature in the mantle).

By integrating (2), we obtain the distribution of the charge of holes in the mantle. At negative values of the gradient function, it has a real value and characterizes the displacement of free electrons from the center to the Earth's surface.

$$q_o(r) = \sqrt{-2\varepsilon\varepsilon_o\int_{R_{mu}}^{r} S_n(r)^2\, p(r)\psi(r)\,\mathrm{d}r}$$

Integrating by parts, we obtain an expression that is more convenient for calculations:

$$q_o(r) = \sqrt{2\varepsilon\varepsilon_o\left(p(R_{mu})S_n(R_{mu})^2 - p(r)S_n(r)^2 - 16\pi\int_{R_{mu}}^{r} r\cdot S_n(r)^2\, p(r)\,\mathrm{d}r\right)} \quad (3)$$

Expression (3) is used to calculate the magnetic moment and the integral of forces acting on free electrons beyond the polarization boundary. Below R_{mu} there is a conducting liquid core, the polarization of whose charges is not considered within the framework of the proposed mechanism.

The relative dielectric permittivity of the medium for a homogeneous mixture is estimated with the Landau-Lifshitz equation ([14], p. 69):

$$\varepsilon = \left(\frac{\sum_i^n mt_i\cdot\sqrt[3]{\varepsilon_i}}{\sum_i^n mt_i}\right)^3 = 8.4$$

where: $mt_i = m_i/M_i$ is the fraction of molecules of the *i*-th oxide;

ε_i is the relative dielectric permittivity of the *i*-th oxide;

$n = 5$ is the number of oxides taken into account.

If the density of the free electrons is low, Equation (2) loses its physical meaning. Each atom must experience on average at least one collision per second with free electrons distributed in the volume:

$$u_s(r)\sqrt[3]{n_a(r)}\cdot kp_{ea}(r) \geq 1\cdot\mathrm{s}^{-1} \quad (3.1)$$

where: $u_s(r) = \sqrt{\frac{8k_bT_z(r)}{\pi m_e}}$ Is the arithmetic mean velocity of the free electrons ([13], p. 207);

m_e is the mass of an electron;

$kp_{ea}(r) = \delta_i(r)/n_a(r)$ is the ratio of the number of ions (or free electrons) to the number of atoms in a unit volume.

Inequality (3.1) is a physical condition for the application of expression (3). Its solution gives the value of the ionization boundary R_i (**Figure 3**). The following expression is to be considered as a criterion for the polarization boundary of free electrons:

$$\ln\left(N_d(r)k_p(r)\right) \le 0 \tag{3.2}$$

where: $N_d(r) = \frac{4}{3}\pi R_D(r)^3 \delta_i(r)$ is the Debye number of the plasma (number of charge particles of one sign within the region bounded by the Debye length:

$R_D(r) = \sqrt{\frac{\varepsilon\varepsilon_o k_b T_z(r)}{\delta_i(r) q_e^2}}$;

$k_p = \delta_p(r)/\delta_i(r)$ is the polarization coefficient;

$\delta_p(r) = \frac{\mathrm{d}q_p(r)}{q_e \mathrm{d}V}$ is the number of holes per unit volume;

$\mathrm{d}V = S_n(r)\mathrm{d}r$ is the change in volume;

$\mathrm{d}r$ is the change in radius;

q_e is the elementary charge.

From a physical point of view, expression (3.2) means that the average number of free electrons leaving the Debye screening region as a result of polarization does not exceed one. The mantle substance remains quasi-neutral. The solution of expression (3.2) gives the magnitude of the polarization boundary as $R_p = 5.64 \times 10^6\ \mathrm{m} < R_i$. Its value is located in the region of pronounced ionization (**Figure 3**).

Below the polarization boundary, intense electron-hole recombination with the release of thermal energy should occur. Most likely, this is due to a sharp decrease in the density of the phonon gas, which leads to a loss of free electron energy (**Figure 4**). The maximum energy release corresponds to the radius $R_r = 5.46 \times 10^6\ \mathrm{m} < R_p$, obtained from the solution of the equation:

$$\frac{\mathrm{d}}{\mathrm{d}r}\left(\frac{\nabla_r T_z(r)}{T_z(r)}\right) = 0$$

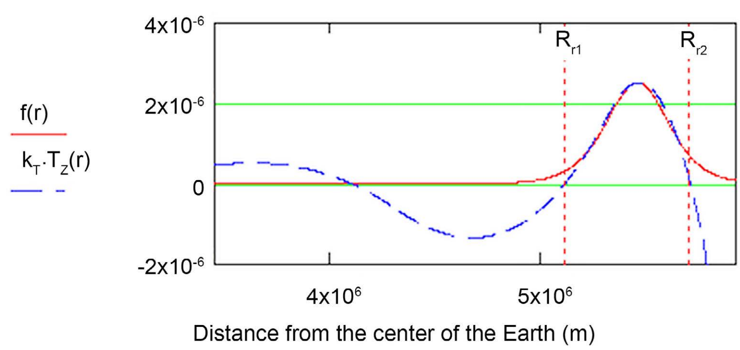

Figure 4. Functions of the temperature gradient and probability density.

By analogy with the Maxwell distribution, we apply the Fermi-Dirac distribution to the region of electron-hole recombination, the center of which is the R_r, analogue of the chemical potential. The probability of polarization of a free electron will be equal to:

$$p(r) = \left(1 + \mathrm{e}^{\frac{r - R_r}{\Delta_r}}\right)^{-1}$$

where: $\Delta_r = \frac{R_{r2} - R_{r1}}{6} = 99\ \text{km}$ is a length constant that characterizes the decrease in the charge of holes by e times on a given segment (e is the constant of the natural logarithm);

$R_{r1} = 5.1 \times 10^6\ \text{m}$ and $R_{r2} = 5.7 \times 10^6\ \text{m}$ are the lower and upper limits of the region of recombination, which are obtained as a result of solving the equation: $T_z'(r) = 0$ ranging from R_{mu} to R_p, where $T_z'(r) = \Delta_T(r) - median(\Delta_T(r))$;

$\Delta_T(r) = \frac{\nabla_r T_z(r)}{T_z(r)}$ is a function of the temperature gradient.

This probability corresponds to the probability density of electron-hole recombination:

$$f(r) = \frac{1}{4\Delta_r \cosh^2\left(\frac{R_r - r}{2\Delta_r}\right)}$$

Figure 4 shows the functions of the temperature gradient and probability density of electron-hole recombination normalized at point R_r, where $k_T = \frac{f(R_r)}{T_z(R_r)}$ is the normalization coefficient.

The distribution of the positive charge of holes in the earth's mantle can be represented by the expression:

$$q_p(r) = \frac{q_o(r)}{1 + \mathrm{e}^{\frac{r - R_r}{\Delta_r}}} \tag{3.3}$$

Figure 5 shows the distribution of the positive charge of holes in the earth's mantle and the terms of the gradient function. The horizontal marker marks the median value of the temperature gradient function. Vertical markers mark the recombination center and polarization boundary.

The change in the force acting in the center of the recombination region on the total charge of free electrons located in the elementary volume, due to the change in charge, has the form:

$$\Delta F(r) = E(r)\Delta q_{pe} \tag{4}$$

where: $E(r) = \frac{q_o(r) + q_{pe}}{\varepsilon\varepsilon_o S_n(r)}$ is the electrostatic field strength;

$q_o(r) + q_{pe}$ is the charge near the polarization boundary;

q_{pe} is the charge of the free electrons;

Δq_{pe} is the change in the charge of free electrons.

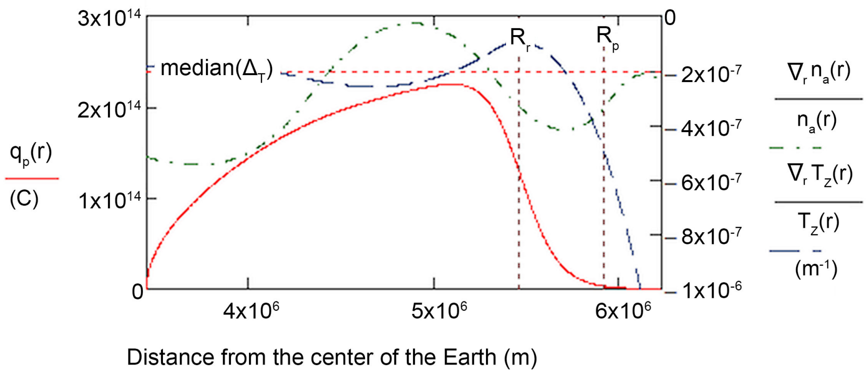

Figure 5. Distribution of charge and terms of the gradient function.

$$F(r)=\int_0^{-q_o(r)}\frac{(q_o(r)+q_{pe})dq_{pe}}{\varepsilon\varepsilon_o S_n(r)}=-\frac{q_o(r)^2}{2\varepsilon\varepsilon_o S_n(r)}$$

By integrating (4) taking into account the equality of charges of different signs, we obtain the integral of the attractive forces directed toward the center of the Earth and acting on free electrons outside the recombination region.

$$F_g(R_{r1})=-\frac{q_o(R_{r1})^2}{2\varepsilon\varepsilon_o S_n(R_{r1})}=-1.1\times10^{24}\ \text{N}$$

The integral of the gradient pressure forces directed away from the center and acting on the free electrons distributed in the Earth's mantle:

$$F_m(R_{r1})=\int_{R_{mu}}^{R_{r1}}S_n(r)p(r)\psi(r)\text{d}r=-1.5F_g(R_{r1})$$

This value exceeds the integral of the attraction forces by 50% and confirms the possibility of keeping the charges in the polarized state.

3. Comparison of the Obtained Result with Measurement Data

The dipole mode of the Earth's magnetic moment as of 2010 was $M_{2010}=-7.746\times10^{22}\ \text{A}\cdot\text{m}^2$ (IGRF-11, 2010). The minus sign indicates that the magnetic moment is directed in the direction opposite to its mechanical moment. It follows that the north magnetic pole of the Earth coincides with the south geographic pole. The change in the magnetic moment arising from the rotation of a charged ball due to a change in current has the form:

$$\Delta M_d=S_d\cdot\Delta I \quad (5)$$

where: $S_d=\pi\cdot(r\cdot\cos(\theta))^2$ is the area bounded by the current loop;

$\Delta I=\nu\cdot q_e\cdot\delta_p(r)\cdot\Delta V$ is the change in current;

ν is the rotational frequency;

$\Delta V=2\pi r\cdot\cos(\theta)\cdot r\cdot\Delta\theta\cdot\Delta r$ is the change in volume;

θ is the latitude;

$\Delta\theta$ is the increment of latitude.

Integration of the differential equation by parts gives the following solution:

$$M_{dh}(r) = \frac{\Omega}{3}\left\{r^2\left[q_o(r) - q_o(R_{mu})\right] - 2\int_{R_{mu}}^{r} r \cdot q_o(r) \cdot \mathrm{d}r\right\} \quad (5.1)$$

where: Ω is the angular velocity of rotation of the ball;

$q_o(r)$ is the charge distributed in the volume (3).

Since the proposed model only takes into account the polarization of charges, the total charge outside the polarization boundary is zero. This implies an expression for the magnetic moment created by the rotation of a polarized ball (let's call it a rotational magnetic dipole to distinguish it from the dipole mode of the Earth's magnetic field, inclined to the axis of its rotation at an angle of 11˚):

$$M_{ds}(r) = \frac{-2\Omega_z}{3}\int_{R_{mu}}^{r} r \cdot q_p(r) \cdot \mathrm{d}r \quad (5.2)$$

where: $\Omega_z = 7.3 \times 10^{-5}\ \mathrm{s}^{-1}$ is the angular velocity of the Earth's rotation,

$q_p(r)$ is the positive charge of the holes in the mantle (3.3).

The lower boundary of integration corresponds to the lower mantle boundary R_{mu}, and the upper boundary to the polarization boundary R_p. The negative value obtained as a result of integration by parts indicates that the vector of the rotational magnetic moment of the rotating polarized ball is directed opposite to the vector of its mechanical moment.

The values of the rotational magnetic moment were $M_{ds}(R_{mo}) = 1.04 M_{2010}$ (at the polarization boundary and to the Earth's surface), which convincingly confirms the reality of the proposed mechanism for generating the Earth's magnetic field. The relative error was $\frac{M_{ds}(R_{mo}) - M_{2010}}{M_{2010}} = 4\%$.

4. Discussion of the Result

The magnetic moment $M_{de} = -q_o(R_r) \cdot R_r^2 \cdot \frac{\Omega_z}{3} = 2.4 M_{2010}$ created by the negative charge of free electrons in the center of the recombination zone corresponds to the ring current $I_e = M_{de} / \pi R_r^2 = -2 \times 10^9\ \mathrm{A}$

The magnetic moment $M_{dh}(R_r) = -1.4 M_{2010}$ created by the positive charge of the holes (the minus sign indicates that it is directed opposite to the magnetic moment of the Earth) corresponds to the ring current $I_h = \frac{M_{dh}(R_r)}{\pi R_s^2} = 1.6 \times 10^9\ \mathrm{A}$

where $R_s = \frac{\int_{R_{mu}}^{R_r} r \cdot q_p(r)\mathrm{d}r}{\int_{R_{mu}}^{R_r} q_p(r)\mathrm{d}r} = 4.6 \times 10^6\ \mathrm{m}$ is a weighted mean of the radius corresponding to the distribution of the positive charge of holes in the Earth's mantle. The resulting magnetic moment is equal to the sum of these moments $M_{de} + M_{dh} = M_{ds}$.

Schematically, the rotational magnetic dipole can be represented as the difference between the magnetic dipoles created by two ring currents flowing in the equatorial plane in different directions at a distance from the center (with the value clockwise) and (with the value counterclockwise, if observed from the southern geographic pole), which partially confirms the SUTHERLAND-EINSTEIN hypothesis, but gives a different idea of the mechanism of generation of the Earth's magnetic field. The proposed mechanism describes well the magnitude of the dipole mode of the Earth's magnetic field, and calculations convincingly show the possibility of charge polarization in its mantle.

5. Conclusions

1) Thermal ionization, the polarization of free electrons in response to density and temperature gradients, and the rate of angular rotation of the Earth are the main physical factors for the formation of the dipole mode of the magnetic field.

2) The Earth's magnetic moment is formed outside the core in the mantle and, consequently, the liquid part of the core is penetrated by magnetic field lines. The ion density in the liquid core is at least $\delta_i\left(R_j\right)=10^{23}\ \mathrm{m}^{-3}$. Convective flows of conducting matter arising in the liquid core can cause local changes in the magnetic field near the Earth's surface, and their asymmetry can be the cause of shifting the magnetic moment axis. In other words, modes that are higher than the dipole mode arise as a result of partial dissipation of the magnetic field energy by turbulent flows arising in the liquid core, and the vector of the magnetic axis shift is caused by the asymmetry of convective flows relative to the Earth's rotation axis.

3) The proposed mechanism does not reject the theory of the hydromagnetic dynamo, but supplements it, in the author's opinion, with a missing stationary component. The hydromagnetic dynamo is not an isolated mechanism of magnetic field generation and does not claim in this sense to be completely universal ([1], p. 265).

Note

The calculations were performed using the MathCAD program with a standard accuracy of 4 significant digits. The values used for the fundamental constants values correspond to those recommended by the National Institute of Standards and Technology of the USA ([15], p. 94). The basic physical parameters of the Earth correspond to the values given in the manual ([6], V2, pp. 78-79).

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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