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Generation of Magnetic Fields in Cosmic Objects: Electrokinetic Model

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Abstract
Based on the assumption of separation of the charges in matter of cosmic bodies the possibility of obtaining the magnetic moment by these bodies is proved. The magnitude of the magnetic field appears proportional to the angular velocity of the body's rotation and to the radius of convective layer. The periods of change of polarity of magnetic field of the Earth and the Sun are calculated by means of the size the convective layer and the convection speed. The solar activity appears the consequence of periodic transformation of the thermal energy into the electromagnetic form of energy.

Keywords: electrokinetic model, stellar magnetic fields, geomagnetism

1. Introduction

One of the most popular theories on the ways of generation of the magnetic field of cosmic bodies is the theory of hydromagnetic dynamo (HD). In 1919 the English physicist J. Larmor first suggested this idea to explain the solar magnetic field (Larmor 1919). For the theory of HD it is essential that the ionized fluid was moving in a special, rather complicated way under the action of internal pressure, the buoyancy force, gravitation and magnetic forces. For example, the existing magnetic field "frozen into the fluid " due to the effect of induction, together with the fluid should turn with the formation and superposition of loops of the magnetic field (Vainshtein and Zel'dovich 1972). Then the addition of the magnetic fields of the adjacent matter units and increase of the total magnetic field are possible. There are a number of solutions of equations of magnetohydrodynamics for HD and geodynamo simulations, when with the given matter fluxes increasing and maintaining of the magnetic field takes place (Kono and Roberts 2002). But so far there is no evidence that the actual motion of electroconductive and magnetized matter in cosmic bodies could correspond to the motions required for the effect of HD (Tobias 2002). Recent developments include numerical models of the solar convection zone and outer radiative interior that capture the convective motions and rotation and begin to show cycling dynamo behaviour, though they do not yet succeed in producing solar-like behavior: either they need a rotation rate that is far greater than that of the Sun, or they produce cycle periods that are longer than the Sun's (Thompson 2014).
We shall now point out the scales of the energy required for the effect of HD in the Earth interior. Measurements of the Earth's magnetic field show that its main sources are hidden in the core, and the magnitude of the field changes slowly with the time. To characterize the sizes of the Earth we shall use the following approximate data: the average radius is 6371 km, the equatorial radius – 6378 km, the polar radius – 6356 km. In 2005, at the north magnetic pole of the Earth (near the coast of the Canadian Archipelago), the magnetic field induction was about $B_p = 5.698 \cdot 10^{-5}$ T according to the World Magnetic Model of the Earth (British Geological Survey 2005). Assuming that this field is generated by the magnetic dipole moment, using the polar radius r_p of the Earth, we can estimate the magnetic moment of the Earth: $P_E = \frac{2\pi B_p r_p^3}{\mu_0} = 7.3 \cdot 10^{22}$ J/T, where μ_0 is the vacuum permeability.

The inner crystalline core of the Earth has the radius of the order of $r_1 = 1220$ km, and the outer liquid core of molten iron can be presented as part of the ball between the radius r_1 and the radius $r_2 = 3485$ km, with the mass of about $M_2 = 1.97 \cdot 10^{24}$ kg (Жарков 1978). In the outer core the currents should presumably flow, maintaining the magnetic field due to the effect of HD. The magnetic moment of the Earth can be modeled by the product of the electric current and the area of the contour of the outer core (the core section). Hence, the required electric current should be of the order of $I \approx 10^{10}$ A. The conductivity of the core fluid, with the value of up to $\sigma = 3 \cdot 10^5$ S/m according to (Жарков 1978), allows to estimate the electrical resistance of the fluid, which is proportional to the length of the circumference of the core and inversely proportional to half of its section: $R \approx \frac{1}{\sigma} \frac{2\pi r_2}{\pi r_2^2 / 2} = \frac{4}{\sigma r_2}$. Then the power of electrical losses due to the current flow should reach $W = I^2 R \approx 10^8$ W. As we have mentioned in (Fedosin 2014), the total heat flow from the Earth's surface is equal to $3.2 \cdot 10^{13}$ W, the contribution into the thermal energy of the Earth from lunar tides can be up to $3.45 \cdot 10^{12}$ W, and the average power of seismicity of the Earth is about $3 \cdot 10^{10}$ W. Thus, the thermal energy would be sufficient to start the HD mechanism.

But apparently, the theory of HD may not be the general theory to explain the magnetic field of all cosmic bodies, since in white dwarfs and neutron stars, convection is almost absent, while the magnetic fields of these stars are extremely high. There is no significant motion of matter in the solar interior, where the main energy transfer from the core to the outside occurs due to emission, and for photons it takes several million years. Only in the solar shell convection is so large that it leads to the periodic removal of the magnetic field tubes to the surface, which produce sunspots there. However, the observed changes in the polarity of the magnetic field of the Sun (with a period of about 22 years) and the Earth (with periods from 20,000 years up to a million years or more) contradict the theory of HD. Indeed, the effect of HD requires initial magnetic field, which can then be amplified and further be maintained by the motion of fluid of the same type. In the change of the polarity the magnetic field should be systematically reduced to zero, thereby eliminating the initial magnetic field, which is necessary for the occurrence of HD.

In this regard, we present further electrokinetic model of the origin of the magnetic field in space objects, as some additional mechanism which is independent on the hydrodynamic dynamo.

2. The electrokinetic model

According to the results in (Fedosin 2012, 2014), the magnetic moment of the proton can be obtained from the condition that the electric charge of the proton is almost uniformly distributed over its volume. Then the rapid rotation of the proton with its volume electric charge is able to generate the required magnetic moment. In addition, the highly magnetized matter of the proton is also involved in the creation of the magnetic moment of the proton. The analogy here is the neutron stars-magnetars, the magnetic moment of which is made up of the magnetic moments of the neutrons, which form the basis of the stellar matter. In order the proton and the magnetar could obtain the corresponding electrical charges and the magnetic moments with almost total magnetization of their matter, appropriate conditions are necessary. In particular, the proton can occur from the neutron in beta decay, when the negative charge is removed from the neutron due to emission of the electron. As the model of the neutron in (Fedosin 2014) the neutron star was considered, in which due to the process of charge separation the core becomes positively charged and the shell obtains the negative charge. It allowed explaining the neutrality of the neutron and its negative magnetic moment. The neutron star can obtain a sufficiently large magnetic field already at its formation in the collapse of the supernova core, as the star rotates rapidly and also accumulates the magnetic flux of the original star.

Based on these data, we shall construct the electrokinetic model of emerging of the magnetic field of the Earth. The name of the model implies that a significant role in it is played by the distribution of electric charges and their motion as the sources of the magnetic field. It is known that the closer we get to the center of the Earth, the higher is the temperature of the matter. At the Earth's surface the temperature gradient is about 20 degrees per 1 km, in the depth the gradient decreases. The average temperature of the Earth core is in the range of 5000 – 6000º K, and on the outer core radius r_2 the expected change in the temperature reaches 2000º K. Thus, the temperature gradient can lead to diffusion of free electrons to the outer shell of the outer core, where the temperature is lowered. This effect can be caused by the pressure gradient in the matter ionized by the high temperature, which pushes the electrons out faster than the ions.

We shall suppose that for the matter the formula for the pressure of the ideal gas is valid: $p = nkT$, where n is the concentration of particles, k is the Boltzmann constant, T is temperature. According to (Жарков 1978), the pressure in the center of the Earth reaches 3600 kb, and at the periphery of the outer core it is 1350 kb, with the corresponding temperatures of 6300º K and 4300º K. From these data and the formula for the pressure it follows that the ratio of the concentration of the particles of matter at the border of the outer core to the concentration in the center of the Earth can be in the range 0.55 – 0.75 (the latter figure is closer to the standard physical models of the Earth structure). The presence of gradients of concentration, pressure and temperature (as well as the centripetal force due to the Earth's rotation and chemical separation which changes the buoyancy of fluid) leads to emerging of radial flows of matter, including the currents of ions and electrons. The thermal velocities of electrons are much higher than the ion velocities, so the electron diffusion can occur faster.

It seems that if in the matter the separation of the charges takes place under action of different factors, then the electric force between the positive and the negative ions should counteract this separation, and at some point stop it. However, in the case of complete spherical symmetry, this occurs in a special way. We shall suppose, for definiteness, that in the center of the sphere there is a positive charge, and a negative charge equal to it by the value is dispersed throughout the sphere. It turns out that near the surface of the sphere, the electrons are in equilibrium, since the action of the internal positive charge will be compensated by the action of the total negative charge. In moving inside of the sphere the relative equilibrium of the electrons can be maintained up to the radius at which the electric and gravitational forces of attraction to the center are compensated by the force of repulsion of the electrons from each other and by the gradients of temperature and pressure. We can notice that a similar structure of separated charges is realized in the electron-ion model of ball lightning, in which the lightning consists almost entirely of the positively charged ionized hot air with a thin shell of electrons. The stability of the electrons is provided by their rapid rotation and the electrical forces, and the electron shell shields the lightning from the surrounding atmosphere (Fedosin 2001, 2002).

We shall assume in our simple idealized model, that under the influence of several factors the separation of charges took place in the Earth's core. This could occur even at the time of formation of the Earth, when it had high temperature and was nearly all melted. We shall use the linear formula for the distribution of the total charge density: $\eta = \eta_1 + hr$, where η_1 is the charge density in the center, h is some coefficient, r is the current radius from the center to the arbitrary point in the core. The coefficient h can be determined from the condition of the electroneutrality of the core as a whole. To do this, we must integrate the charge density over the entire volume of the core and equate the result to zero. After finding h through η_1 and the radius of the outer core r_2, we obtain the following formula for the charge density:

$$\eta = \eta_1 \left(1 - \frac{4r}{3r_2} \right). \qquad (1)$$

At low r the charge density η is positive, with $r > \frac{3r_2}{4}$ the final charge density becomes negative. The charge, distributed in the core according to the relation (1) is fixed relative to the Earth and rotates with it at the angular velocity $\omega = 7.29 \cdot 10^{-5}$ rad/s. This creates the magnetic field of the Earth with the magnetic moment P_E . In (Fedosin 2014) we integrated the charge density distribution of the form (1) in order to find the magnetic moment. Similarly, for the magnetic moment of the Earth we find:

$$P_E = -\frac{V_2 \eta_1 \omega r_2^2}{45} = -\frac{4\pi \eta_1 \omega r_2^5}{135}, \qquad (2)$$

where $V_2 = \frac{4\pi r_2^3}{3}$ is the volume of the outer core of the Earth,

and the minus sign in (2) shows that the total magnetic moment of the Earth is directed opposite to the angular velocity of its rotation ω, if the main contribution to the magnetic moment is made by the electrons at the core periphery.

From (2) by the known values $|P_E| = 7.3 \cdot 10^{22}$ J/T, ω and r_2 it is possible to estimate the charge density in the center of the Earth: $\eta_1 = 2.1 \cdot 10^{-5}$ C/m^3. The charge density distribution (1) allows us to find the magnetic field in the center of the Earth. For each elementary circular current, which arises due to rotation of the charge dq at the angular velocity ω, in spherical coordinates we can write down:

$$di = \frac{dq}{dt} = \frac{\omega dq}{2\pi} = \frac{\omega \eta r^2 dr \sin Q \, dQ}{2\pi} \int_0^{2\pi} d\varphi = \omega \eta r^2 dr \sin Q \, dQ.$$

The elementary circular currents are differently shifted along the axis OZ relative to the center of the sphere with the radius r_2 of the outer core. Their contribution to the total magnetic field in the center of the sphere can be taken into account with the help of the angle Q, under which each elementary circular current from the center of the sphere relative to the axis OZ is seen:

$$dB = \frac{\mu_0 di \sin^2 Q}{2r}.$$

This formula is obtained from the standard expression for the magnetic field on the axis of the elementary circular current inside the sphere $dB = \frac{\mu_0 di\, r'^2}{2(r'^2 + z^2)^{3/2}}$, where $r' = r \sin Q$ is the radius of the circular current, $z = r \cos Q$ is the distance from the center of the sphere to the center of the elementary circular current, $r'^2 + z^2 = r^2$, the angle Q is the angular coordinate of the spherical coordinates.

Substituting the current di into the expression for dB and expressing η in it with the help of (1) and the values η_1 from (2), after integration over the volume of the core we obtain the magnetic field induction at the center of the Earth:

$$B_1 = \frac{\mu_0 \eta_1 \omega}{2} \int_0^{r_2} r \left(1 - \frac{4r}{3r_2}\right) dr \int_0^{\pi} \sin^3 Q \, dQ = \frac{\mu_0 \eta_1 \omega r_2^2}{27} = -\frac{5\mu_0 P_E}{4\pi r_2^3} = 8.6 \cdot 10^{-4} \text{ T}, \qquad (3)$$

where P_E from (2) was also used.

For comparison, we shall give the magnitude of the magnetic field induction at the equator outside the outer core, calculated by the standard dipole formula through the magnetic moment of the Earth P_E for the case if the magnetic moment was at the center of the Earth:

$$B_2 = -\frac{\mu_0 P_E}{4\pi r_2^3} = 1.7 \cdot 10^{-4} \quad \text{T}, \tag{4}$$

here P_E is considered negative.

The value of the field (4) is not entirely accurate, since the magnetic moment is actually dispersed throughout the core in a nonuniform way. Therefore, as a first approximation, we shall assume that the magnetic field at the equator of the core is twice larger than (4), and is equal to $2B_2$.

We can assume that the magnetic fields at the center of the core and near the surface have opposite directions (this is the consequence of the change in the sign of the charge density (1) when moving along the radius from the center to the surface of the core). Then in the motion in the equatorial plane along the radius from the center

to the edge of the outer core the magnetic field induction will change from B_1 to $(-2B_2)$. This can be reflected by the following linear formula:

$$B = B_1\left(1 - \frac{7r}{5r_2}\right). \tag{5}$$

According to (5), the magnetic field changes its sign inside the core. In accordance with these considerations Figure 1 shows a simplified picture of the magnetic field in the Earth's core. We shall remind that this structure of the field is the consequence of rotation of the electric charge distributed along the radius of the core.

We shall now estimate the average velocity of matter motion V in the Earth's core. We shall suppose that under the influence of the temperature gradient, the pressure force (the buoyancy force), the gravitational and centripetal forces, the matter moves approximately along the radius. The first three forces can be considered symmetrical relative to the center of the core, whereas the centripetal force is symmetrical relative to the axis of rotation of the Earth. We can therefore expect an increased speed of matter motion in the equatorial plane of the core.

During the motion of the conducting fluid in the magnetic field, currents are induced in this fluid due to the Lorentz force. If the magnetic field is directed along the axis OZ, and the fluid is moving perpendicular to the axis OZ, the current density would obtain rotation around the axis OZ:

$$\boldsymbol{j}_\varphi = \sigma[\boldsymbol{V} \times \boldsymbol{B}]. \tag{6}$$

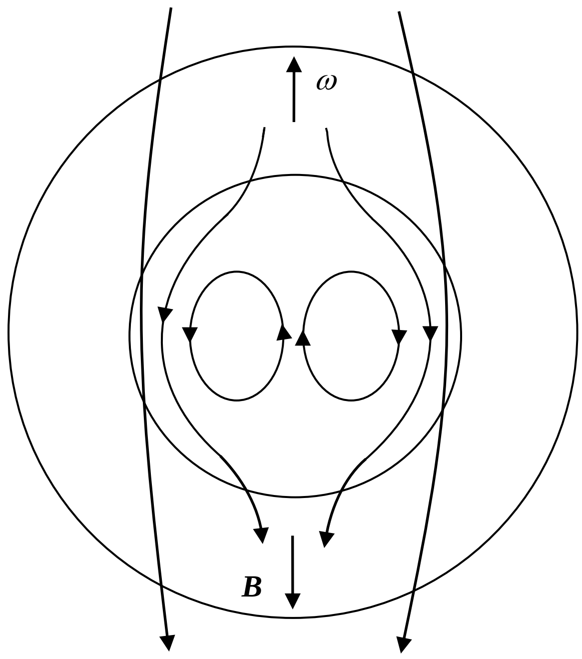

Figure 1. The assumed configuration of the magnetic field of the Earth with induction $\boldsymbol{B}$ in the plane passing through the polar axis. The angular velocity of the earth's rotation ω. The magnetic lines in the center of the core and at the edge have opposite directions.

In our simplified approach, we shall assume the velocity of the fluid to be constant, and as the magnetic field induction we shall take the mean value $\overline{B}$. The maximum induced current can be estimated as the product of the current density and the half-section of the core: $\bar{I} \approx k_1 \bar{j}_\varphi \cdot \frac{\pi r_2^2}{2} = \frac{k_1 \sigma V \overline{B} \pi r_2^2}{2}$, where the coefficient $k_1 < 1$ takes into account that the hot fluid is not only removed from the axis OZ, but returns after cooling, reducing the induced current. This current generates in the core the magnetic moment with the value:

$$\overline{P} \approx \bar{I} \pi r_2^2 = \frac{k_1 \sigma V \overline{B} \pi^2 r_2^4}{2}. \tag{7}$$

It is obvious that the magnetic moment $\overline{P}$ must be less than the magnetic moment of the Earth: $\overline{P} = k_2 P_E$, where $k_2 < 1$. Substituting here the absolute value P_E from (3) in the assumption that $\overline{B} \approx \frac{B_1}{2}$ we find:

$$\overline{P} = \frac{8\pi k_2 r_2^3 \overline{B}}{5\mu_0}. \tag{8}$$

From (7) and (8) for the velocity of the fluid we obtain:

$$V \approx \frac{16 k_2}{5\pi \mu_0 \sigma r_2 k_1} = 8 \cdot 10^{-7} \cdot \frac{k_2}{k_1} \text{ m/s.} \tag{9}$$

The velocity of the fluid (9) is small enough. Using it we can estimate the Reynolds number $\mathrm{Re} = \frac{V r_2 \rho_2}{\nu}$, the magnetic Reynolds number $\mathrm{Rm} = V r_2 \sigma \mu_0$, the magnetic Prandtl number $\mathrm{Pm} = \frac{\mathrm{Rm}}{\mathrm{Re}}$, here $\nu \le 100$ Pa·s is the dynamic viscosity (internal friction) in the core, according to (Жарков 1978), $\sigma = 3 \cdot 10^5$ S/m is the conductivity of the core fluid, $\rho_2 = 1.43 \cdot 10^4$ kg/m^3 is the average fluid density in the core. Based on (15) further it will be shown that $k_1 \approx k_2$ in (9). Substituting the values of all quantities, we find $\mathrm{Re} = 380$, $\mathrm{Rm} = 1$, $\mathrm{Pm} = 3 \cdot 10^{-3}$. The Reynolds number is inversely proportional to the adhesive force of the particles of gas or liquid, which affects the free motion of the body or separate elements of the fluid. The magnetic Reynolds number is directly proportional to the force of magnetic friction in the fluid that prevents from the slippage of the magnetic lines through the fluid. The magnetic Prandtl number is an additional characteristic that takes into account the contributions of the magnetic and ordinary friction and increases with increasing of viscosity and conductivity of the fluid.

We can compare the obtained numbers with the corresponding numbers, with which the hydromagnetic dynamo (HD) can occur. For example, in the Ponomarenko dynamo (Ponomarenko 1973) it is required that $\mathrm{Rm} \ge 18$. In (Schekochihin et al 2007) it is proved that the diffusion dynamo is possible when $\mathrm{Rm} >> 1$ and $\mathrm{Pm} << 1$, and also when $\mathrm{Pm} \ge 1$ and $\mathrm{Rm} > 60$, $\mathrm{Re} >> 1$. If the formula (8) and our calculations of the numbers are valid, it turns out that the conditions for the occurrence of HD in the Earth's core are not favorable.

We shall now consider the issue of the relationship between the magnetic force and the Coriolis force acting on the unit of the conductive core fluid. From the value $\mathrm{Rm} = 1$ it follows that the adhesion of the magnetic field lines to the fluid is small in the core scale. The obtained above estimate of the value of the magnetic field in the core is almost one order of magnitude greater than the value of the magnetic field on the Earth's surface and in general has little effect on the motion of the fluid. The density of the magnetic force can be written as follows:

$$\boldsymbol{f}_m = [\boldsymbol{j} \times \boldsymbol{B}], \tag{10}$$

where $\boldsymbol{j} \approx \eta \boldsymbol{V}$ is the current density, transferred by the fluid unit in the core, mainly in the radial direction, η is the charge density (1).

For the density of the Coriolis force, we have:

$$\boldsymbol{f}_C = -2\rho_2 [\boldsymbol{V} \times \boldsymbol{\omega}]. \tag{11}$$

The forces (10) and (11) have opposite directions and both depend in the same way on the velocity $\boldsymbol{V}$ of the fluid motion, and the magnetic field and the angular velocity are approximately parallel. The inertial force (11) is substantially greater than the magnetic force (10) since the core fluid is not an ideal conductor. We shall suppose now that for all the planets, in which the magnetic field is generated in the core, there is the same dependence between the forces (10) and (11). Namely, we shall assume that for the magnitudes of the densities of forces, the relation $f_m = k_3 f_C$ is satisfied, where $k_3 << 1$. From (10) and (11) we obtain:

$$\eta B = 2 k_3 \rho_2 \omega . \tag{12}$$

The fluid density ρ_2 in the right side of (12) within the core does not change so significantly as the values η and B in the left side. We shall substitute instead of η and B some average values, which make the greatest contribution. We shall assume $\eta = \frac{2\eta_1}{3}$ as the absolute value of the double charge density from (1) with $r = r_2$. Instead of B, we shall use $\overline{B} \approx \frac{B_1}{2}$ which is equal to half of the magnitude of the magnetic field induction at the center of the core from (3). The equation (12) after excluding the value η_1 with the help of (2) takes the following form:

$$\eta B = \frac{\eta_1 B_1}{3} = \frac{225\mu_0 P_E^2}{16\pi^2 \omega r_2^8} = 2k_3 \rho_2 \omega ,$$

$$P_E = \omega r_2^4 \sqrt{\rho_2} \sqrt{\frac{32\pi^2 k_3}{225\mu_0}} . \qquad (13)$$

If the coefficient k_3 is approximately equal for all planets, then (13) gives the formula for determining the magnetic moments of the planets through their known angular velocities of rotation ω, the radii of the cores r_2 and the densities of the fluid ρ_2 in these cores. The dependence of the form (13) was constructed in (Fedosin 1999) and it was noted that it approximates the magnetic moments of the planets as well as the dependence of the magnetic moments from the spins of the cores of the planets. Even the magnetic moment of the Sun satisfies the formula (13). We shall note that the dependence of the magnetic moment of the planet in the form $P_p \sim \omega r_2^4 \sqrt{\rho_2}$ was also found in (Busse 1976).

We shall estimate the magnitude of the maximum magnetic field induction at the center of the planet, substituting P_E from (13) into (3):

$$B_c = \omega r_2 \sqrt{\rho_2} \sqrt{\frac{2k_3 \mu_0}{9}} . \qquad (14)$$

From (14) it follows that the magnetic field in the core is determined by the angular velocity of rotation, the radius of the core and the fluid density. The expression (14) can be transformed, taking into account the relation for the magnetic energy density in the center of the core $U_c = \frac{B_c^2}{2\mu_0}$ and the relation for the kinetic energy density at the equator of the core $\varepsilon = \frac{\rho_2 V_\varphi^2}{2} = \frac{\rho_2 \omega^2 r_2^2}{2}$. This gives the following equation: $U_c = \frac{2k_3 \varepsilon}{9}$. Therefore, approximately equal coefficient k_3 for all the planets follows from the fact that the density of the magnetic energy contained in the cores of the planets is proportional to the rotational kinetic energy of the cores. In our opinion this indicates that the magnetic field is generated rather by the rotation of the charge, which has some gradient of distribution in the core due to the difference of temperatures and pressures than due to the mechanism of HD. The estimate of k_3 can be obtained from (13). Substituting the data for the Earth, we find $k_3 \approx 3 \cdot 10^{-9}$.

3. The Earth's magnetic field reversals

The magnetic field induction of our planet is not constant; it fluctuates with the difference of minimum and maximum amplitudes almost by a factor of 2, with the period of about 7500 years (the fundamental frequency in the spectrum). There are also variations with characteristic periods from 550 to 1800 years (Жарков 1978), explained by magnetohydrodynamic waves in the Earth's core. In particular, the drift of isoclines of the nondipole part of the magnetic field to the west occurs at the speed of 0.2º per year, making a complete rotation every 1800 years. At the equator of the outer core it would correspond to the velocity of the fluid motion $v_2 = 4 \cdot 10^{-4}$ m/s.

In the spectrum of the geomagnetic field there are fluctuations with a period of 60 years, coinciding in time with variations in the rotational speed of the Earth. If we assume that the fluid in 60 years should pass a circle with the radius equal to the radius r_1 of the inner core, then we obtain the velocity $v_1 = 4 \cdot 10^{-3}$ m/s. This velocity is too high for the flow of fluid. But v_1 coincides with the velocity of the Alfven magnetohydrodynamic wave which is equal to $u_1 = \frac{B}{\sqrt{\mu_0 \rho_2}}$. If we substitute here instead of B the magnetic field induction from (5) for $r = r_1$, that is magnitude of about $0.5 B_1$, then taking into account (3) we find $u_1 = 3 \cdot 10^{-3}$ m/s. Thus, the transverse magnetohydrodynamic waves near the inner core can influence its rotation, the change of the Earth's rotational speed and the total magnetic field, which is proportional to the angular velocity of rotation according to (13).

One of the reasons for the occurrence of magnetohydrodynamic waves in the Earth's core can be the phenomena similar to the solar and lunar tides observed on the water in the oceans and the seas. The tidal energy at their beating at large inhomogeneities of fluid can increase the energy of the waves. If the magnetohydrodynamic waves propagate near the surface of the outer core, then at low magnetic fields the velocities of the waves become less. Perhaps this leads to the drift of the isoclines with periods of about 1000 years or more, with the corresponding wave velocities, equivalent to the fluid velocities which close to the value v_2.

The discrepancy between the directions of motion of magnetohydrodynamic waves near the inner core and at the periphery of the outer core with each other and the direction of rotation of the Earth, the existence of possible inhomogeneities in the core, the fluctuations of the position of the inner core relative to the center of the Earth and other similar factors lead to the shift of convective flows and can cause the observed deflection of the magnetic dipole axis from the Earth's rotation axis by about 11º, and the shift of the dipole center at some distance from the center of the Earth. The magnetic pole is turning near the north geographic pole: in 1580 in London the compass needle deviated from the geographic pole to the east almost by 11º, and in 1960 – by 10º but in the west. The opposite magnetic poles of the Earth can also be not at the same dipole axis, but have a certain shift relative to it.

We shall now consider the possible causes of slow oscillations of the magnetic field. Using the relation (9) and dividing the radius of the outer core by the velocity of the fluid, we can find the characteristic period of circulation of the fluid in the core:

$$T \approx \frac{r_2}{V} = 1.4 \cdot 10^5 \cdot \frac{k_1}{k_2} \text{ years.} \qquad (15)$$

This value is close to the duration of the magnetic field of the one polarity observed in recent historic time (about $2 \cdot 10^5$ years). Consequently, in (15) and (9) $k_1 \approx k_2$. In the past, longer periods of one polarity often occurred, up to a million years or more. Thus, not each circulation of the core fluid leads to the change in the sign of the magnetic field, but rather in

case of one polarity the observed variations of the amplitude of the field take place with the average period of about 7500 years.
From the perspective of electrokinetic model, the initial charge separation (the positive charge in the center, the negative charge at the periphery of the core) is periodically violated due to the fluid convection. This occurs as follows. We shall suppose that the charge is distributed in the core according to the law (1). A certain configuration of the electric field corresponds to this charge distribution.

By solving the Poisson equations $\nabla^2\varphi = -\frac{\eta}{\varepsilon_0}$ by the known dependence (1) of the charge density η on the current radius we can find distribution of the potential and the electric field strength inside the Earth core:

$$\varphi = \frac{\eta_1 r_2^2}{18\varepsilon_0} - \frac{\eta_1 r^2}{6\varepsilon_0} + \frac{\eta_1 r^3}{9 r_2 \varepsilon_0}, \qquad E = -\nabla\varphi = \frac{\eta_1 r}{3\varepsilon_0} - \frac{\eta_1 r^2}{3 r_2 \varepsilon_0}, \tag{16}$$

provided that at the radius r_2 of outer core the electric potential is zero, and $\eta_1 = 2.1\cdot 10^{-5}$ C/m^3 is the charge density in the center of the Earth.

With small radii, and also with $r = r_2$, the electric field (16) tends to zero. The maximum electric field is reached at $r = \frac{r_2}{2}$, that is in the middle of the outer core: $E_{\max} = \frac{\eta_1 r_2}{12\varepsilon_0} = 7\cdot 10^{11}$ V/m. Such a large electric field, even with its partial neutralization can cause constant ionization of the fluid. For comparison, in the hydrogen atom at the Bohr radius the electric field of the nucleus is equal to $E_B = \frac{e}{4\pi\varepsilon_0 r_B^2} = 5\cdot 10^{11}$ V/m. Therefore, when the maximum initial charge separation in the Earth's core is achieved, due to ionization in the center of the core, part of the fluid becomes positively charged and begins to move toward the periphery of the core, mainly due to convection. At the same time the negatively charged part of the fluid has the ability to be transferred to the center of the core, wherein the paths of movement of the positively and negatively charged parts of the fluid do not coincide. During the time, close to the time (15), the charge distribution in the core according to the law (1) is violated, there is partial or complete compensation of the electric charge. To change the polarity of the magnetic field it is necessary that such excess compensation of the electric charge would occur, with which the new charge, which came with the fluid, took the position close to the periphery of the core. Then the contribution of this charge in the magnetic moment would be decisive for the sign of the magnetic field on the surface of the Earth. As it was mentioned above, not for each time period (15) the change of the polarity of the magnetic field takes place, it can take seven or more such periods.
It is also possible to explain approximately in the same way the periods of variations of the amplitude of the magnetic field with a period of 7,500 years. In this case, if we use (15), the fluid passes a characteristic way, which is equal $\approx 0.05 r_2$, that is 20 times less than the radius of the outer core. The hot charged fluid, circulating near the periphery of the core, comes up, and after cooling goes back to the depth of the core, periodically changing the total charge and the value of the magnetic field almost two times. The charge of this fluid is not enough to change the sign of the charge of the fluid at the periphery of the core and to change the polarity of the magnetic field since it is taken from a limited volume. Only large-scale radial motion of the charged fluid leads to the polarity reversal of the magnetic field of the Earth.
We can estimate the maximum energy of the electric field in the Earth's core, integrating over the volume and taking into account (16) we have:

$$W = \int_{r_1}^{r_2} \frac{\varepsilon_0 E^2}{2} dV = \frac{2\pi \eta_1^2 (r_2^5 - r_1^5)}{945\varepsilon_0} \approx 10^{32} \text{ J}.$$

The thermal energy and pressure energy of the Earth's core are close to the calculated energy of the electric field. Thus, in the core of the Earth is in principle possible charge separation and thus the generation of the magnetic field due to the rotation of these charges, in combination with hydromagnetic dynamo.

4. The magnetic field of the Sun and other stars

Modern technique of measurement of the magnetic fields allows to discover in stars relatively small details of the field and to make medium-and large-scale magnetic topology maps. This makes it possible to separate the poloidal (meridional) field from the toroidal field which is directed along the parallels. The study of the magnetic configurations of young low-mass fully convective stars in (Donati at al 2008) showed that the faster the star is rotating, the more visible in it is the total dipole component of field on the background of magnetic spots on the surface. For example, the dwarf V374 Peg of the spectral class M4.5 (with the rotation period of about 12 hours, almost 60 times less than the period of proper rotation of the Sun), has a very strong axisymmetric magnetic field near the poles. Young newly formed stars such as T Tauri demonstrate at the pole the magnetic induction of about tenths of Tesla, so that such axisymmetric fields effectively regulate the flows of accretion matter from the massive discs near these stars, as well as the jets near the poles. This picture contradicts most theories of HD, which predict for fully convective stars the predominance of the toroidal field component over the poloidal. At the same time the proportionality of the magnetic field to the angular velocity of rotation in general corresponds to our expression (14). In solar-type stars the change of the polarity of the magnetic field, the spotted magnetic field structure, as well as stable states with low magnetic activity (such as the Maunder minimum for the Sun) are often observed. Many researchers note that the magnetic field distribution is very similar in the magnetic A and B-stars, white dwarfs and neutron stars, which suggests a common mechanism of its formation in the stars at the stage of the main sequence, or even earlier (Reisenegger 2009).

We shall apply the electrokinetic model for substantiation of emerging and maintaining of the solar magnetic field. With some variations approximately 9 times per every 100 years, the field polarity of the Sun at the poles is reversed, at the same time the 11-year cycles of solar activity take place. Thus, every 22 years the polarity of the field is the same, which is the full period of change in the magnetic field. The magnetic dipole of the Sun at the maximum is estimated by the value $P_s = 3.4 \cdot 10^{29}$ J/T, according to (Аллен 1977). With the average radius of the Sun $s = 6.96 \cdot 10^8$ m we find for this case the field induction at the pole: $B_{ps} = \frac{\mu_0 P_s}{2\pi s^3} = 2 \cdot 10^{-4}$ T.

The modern model of the Sun includes the following main zones: 1) the core with the radius of about $s_1 = 1.5 \cdot 10^8$ m ($s_1 \approx 0.2s$), where thermonuclear reactions take place. 2) the area of radiation energy transfer with the radius from s_1 up to $s_2 = 4.9 \cdot 10^8$ m ($s_2 \approx 0.7s$), which consists of ionized fluid. 3) the convective zone with the radius from s_2 and up to the visible solar surface, i.e. up to the photosphere with a typical zone width of about $s - s_2 = 2 \cdot 10^8$ m. The fluid in this zone consists mainly of atoms absorbing emission, therefore convection here is the predominant way of heat transfer to the surface.

The feature of the Sun is the differential, not solid-state rotation of its surface – at the equator the rotation period is 25.05 days, and at the poles the rotation period increases up to 34.3 days. For further calculations we shall use the period of 25.38 days at the latitude of 16º, where the maximum frequency of appearance of sunspots is observed. This gives the angular velocity of rotation $\Omega = 2.86 \cdot 10^{-6}$ rad/s as a certain characteristic of the average solar rotation.

We shall now estimate the average magnetic field inside the Sun, based on the fact that the charge separation takes place throughout the radial distance according to the linear approximation (1). From (2) we find the charge density in the center in the form $\eta_{1S} = \frac{135P_s}{4\pi s^5 \Omega} = 8\cdot 10^{-9}$ C/m^3. Similarly, from (3) for the magnetic field in the center of the Sun, we have:

$$B_{1S} = \frac{\mu_0 \eta_{1S} s^2 \Omega}{27} = 5\cdot 10^{-4} \text{ T.} \qquad (17)$$

Really, if there was the constant poloidal field it cannot be stronger than a few gauss at the top of the radiative zone, otherwise it would penetrate in the convective zone and cause a polarity asymmetry between the two halves of the magnetic cycle (Boruta 1996, Friedland and Gruzinov 2004).

It turns out that the average poloidal magnetic fields inside the Sun are as small, as in the Earth's core. The total magnetic fluxes on the solar surface in the small-scale details are also approximately equal to the total magnetic fluxes in the large-scale structures, giving the effective average field with the induction $(1-2)\cdot 10^{-4}$ T. The peak of the field induction, discovered in separate fibers in the dark spots on the solar surface, can be almost a thousand times greater than the magnitude of the field (17). However, the magnetic field averaged over the entire area of a typical sunspot, is of the order of $\pm 2\cdot 10^{-3}$ T and significantly less than the peak values.

From observations of sunspots it follows that they move faster than the surrounding plasma on the solar surface. In addition, the newly emerging spots have an increased speed relative to the old spots. This can be explained by the fact that in the depths the plasma rotates faster than on the surface. The spots are connected with the deep layers by the magnetic field, and therefore move faster, and the young spots on the average are deeper than of the old spots. There is the profile of rotation frequency of the fluid in the solar interior (Thompson, Christensen-Dalsgaard, Miesch and Toomre 2003), from which it follows that the rotation frequency at the bottom of the convective zone is about 450 nHz.

In the fluid interaction during the convection between the different layers the exchange of the angular momentum must take place. In equilibrium, the specific angular momentum (the angular momentum of unit mass) will tend to a constant: $\Omega(r,Q)r^2 \sin^2 Q = const$. This shows that the angular velocity of rotation $\Omega(r,Q)$ must be inversely proportional to the square of the radius r and the square of the sine of the polar angle Q associated with the latitude θ by the expression $Q = \frac{\pi}{2} - \theta$. But according to the profile of rotation frequency of the fluid in the solar interior, at the equator with the latitude 0º the fluid rotates faster when approaching the surface of the Sun, while at the surface the rotation frequency again reduces.

Why does the acceleration of rotation in the convective zone take place? One of the explanations is the action of magnetic field. From a simple linear dependence for the magnetic field of the form (5) it follows that somewhere near the radius $r \approx \frac{5s}{7} \approx 0.7s$ the magnetic field should be minimal and should change the sign. In the convective zone the magnetic field increases and has more significant impact on the fluid. The total magnetic field of the Sun rotates at some average speed, specified by all the matter in general. In its turn, the fluid tends to rotate at the same average speed, due to the effect of partial freezing of the magnetic field lines in the fluid. The action of the field will be more revealed where the magnitude of the field is greater, the connection of the field with the fluid is more and the friction of fluid layers is less. Apparently, these conditions are best met in the equatorial area of the convective zone, which make the largest contribution into the magnetic field and at the same time rotate faster. According to (Rüdiger and Hollerbach 2004), a small magnetic field with induction of the order of $1\cdot 10^{-4}$ T would be sufficient to maintain the observed almost solid-state rotation of

the zone of radiation transfer.
Various estimates show that the velocities of the fluid units in the solar convective zone are much higher than the velocities in the Earth's core. According to (Прохоров, Абашидзе 1986), the convection velocity at the bottom of the convective zone is of about 1 m/s, and on the surface of the photosphere of the Sun the velocity can reach 3 km/s. Quite a large sunspot with the size of tens of thousands km can appear on the surface of the Sun in two or three days. If the width of the spot is approximately equal to the path passed by the fluid, then the average velocity of the fluid must be of the order of 100 m/s.
We can estimate the characteristic numbers describing the motion of the fluid in the magnetic field. The quantity $\sigma\mu_0$ called the coefficient of the magnetic diffusion at the bottom of the convective zone is not known exactly, and presumably has the value from $5\cdot 10^{-9}$ up to $5\cdot 10^{-7}$ m^2/s (Jiang and Wang 2007). Substituting this value in (9) with $k_1 \approx k_2$, and substituting there r_2 with $s - s_2 = 2\cdot 10^8$ m, we find the speed range of the fluid: $V_c \approx \frac{16}{5\pi\mu_0\sigma(s-s_2)}$, or the value from 10^{-2} to 1 m/s. The magnetic Reynolds number at the bottom of the convective zone is equal to $\mathrm{Rm} = V_c\,\mu_0\sigma(s-s_2) \approx 1$. According to (Brandenburg 2007), the magnetic Prandtl number Pm is in the range from 10^{-7} up to 10^{-4} for the top and the bottom of the convective zone, respectively. Then at the bottom of the convective zone the Reynolds number is of the order of $\mathrm{Re} = \frac{\mathrm{Rm}}{\mathrm{Pm}} \approx 10^4$.
Based on the velocity of the fluid motion along the radius in the convective zone, we can estimate the characteristic period of the circulation of fluid:

$$T_s \approx \frac{s-s_2}{V_c}, \text{ or the value from } 6 \text{ to } 600 \text{ years.} \tag{18}$$

The observed 11-year cycle of solar activity falls in the interval (18), which is accompanied by the change in the polarity of the magnetic field. If we proceed from (16) and the electrokinetic model, then in the center of the Sun should the electric field arise from time to time with the magnitude up to $E_{\max} = \frac{\eta_{1S}\, s}{12\varepsilon_0} = 5\cdot 10^{10}$ V/m. Some part of the field, generated by the maximum charge separation inside the whole Sun, acts in the convective zone. Under the influence of this electric field in the convective zone the conditions appear from time to time for the transfer of the charged fluid with the corresponding sign to the upper layers, with further compensation of the electric field. Thus not only the compensation of the electric field takes place, but also charge exchange in the upper layers of the convective zone. This leads to the inversion of the solar magnetic field, the creation of the electric field of opposite polarity in the Sun volume and then to repeating of the cycle.
The described picture is confirmed by the following circumstances. It is known that the change in the polarity of the magnetic field at the poles occurs after the sunspot maximum, somewhat later than the middle of 11-year cycle. The appearance of the sunspots is associated with the beginning of coming of the charged and magnetized fluid from the bottom of the convective zone. By the time of maximum coming of the fluid and the maximum solar activity the internal electric field disappears and also the poloidal axisymmetric magnetic field. The subsequent coming of the fluid leads to the electric charge exchange in the fluid, the inversion of the dipole magnetic field and the emergence of new, properly charged portions of fluid in the solar interior. The discovered correlation of the total rotation of the Sun with the solar cycle (Donahue and Keil 1995) can be explained by changing the angular momentum of the Sun due to the periodic displacement of the charged and magnetized fluid from the bottom to the outer layers and vice versa.

It is known that the maximum angular velocity of the motion of the sunspots on the solar surface is almost equal to the maximum angular velocity of the fluid rotation, which is reached at the depth of $0.05s = 3.5 \cdot 10^7$ m. When the size of the spots is about tens of thousands km, they are deeply immersed in the matter of the Sun, and are well connected with the rapidly rotating underlying layers.

According to (Thompson, Christensen-Dalsgaard, Miesch and Toomre 2003), in the layer from $r = 0.95s$ up to the surface of the Sun the negative gradient of the angular velocity is observed. This layer is sometimes called the supergranulation layer, since the sizes of supergranules on the surface of the Sun are of the order of $3 \cdot 10^7$ m. Like the granules with the size of about 10^6 m, the supergranules are the reflection of stationary convection at the solar surface. Indeed, the supergranules are angular and are similar to polygons, resembling hexagonal Bénard cells in the thin layer of fluid heated from below. Plasma streams in supergranules flow from the center to the borders of supergranules, where they sink into the depths along the magnetic force lines (the magnetic field on the borders is in tens or hundreds of times, and in the corners of the borders – in thousands of times greater than the average solar magnetic field). If we divide the thickness of the supergranulation layer $0.05s$ by the average velocity of the plasma convection 250 m/s, then we obtain about 40 hours – the average lifetime of supergranules.

We can also assume that the sizes of supergranules are associated among other things with magnetic ordering. We shall use the formula for the supergranules and the borders between them as for magnetic domains with opposite signs of the magnetic field. In the theory of ferromagnetism there is a formula that relates the domain size d, width of interdomain wall δ and the characteristic size of the sample ℓ (Landau and Lifshitz 1935): $d^2 = \delta \ell$. Taking instead of d the size of the supergranule, instead of ℓ – the circumference of the Sun, and instead of δ – the width of the border between the supergranules, for the latter we find $\delta \approx 200$ km. Consequently, the ratio of the area of the supergranule to the area of its border equals $\frac{d}{4\delta} \approx 75$. If the magnetic fluxes through the supergranule and its border are equal and opposite, then the magnetic field at the border of the supergranule should be approximately 75 times greater than the average solar magnetic field, as it is observed.

From observations of the spots it follows that they represent cross sections of long magnetic flux tubes of large size, coming to the surface. If the initially axisymmetrically magnetized fluid under the influence of convection is moving radially inside the Sun in the form of expanding separate spherical layers, then under the influence of differential rotation in the convective zone the equatorial currents draw the tubes out of the layers in the direction of the parallels. When the first magnetic flux tubes reach the surface after another minimum of solar activity, they are concentrated mainly in the high latitudes, at 35º – 45º. Certainly, there are rising tube also at low latitudes, but they meet the descending tubes of the previous cycle, annihilate with them, and therefore almost never reveal. As the solar activity cycle develops the tubes and the sunspots associated with them appear closer to the equator, being located in the latitude zone between 15º to 20º at the time of inversion of the magnetic field. By the end of the cycle the spots are concentrated mainly at latitudes ± (5º – 10º).

Often there are configurations where one tube produces four sunspots at the same time, located at the corners of a trapezoid. For example, there is the first trailing spot in the northern hemisphere, which moves after the leading spot, usually located closer to the equator; the second leading spot, but in the southern hemisphere, and the trailing spot in the southern hemisphere. The signs of the magnetic field in the spots alternate in the way, as if the spots were cross sections of one magnetic flux tube, highly elongated along the equator, and the magnetic field moves from one spot to the next spot either over the surface of the photosphere, or inside it. In the group of spots the leading spot usually has the same direction of the field as the field at the corresponding pole of the Sun. This suggests that besides the inversion of the magnetic field at the poles there is a corresponding inversion of the magnetic field inside the ascending tubes. The fact that the complete cycle of the change of the magnetic field at the poles is 22 years is supplemented by the inequality field amplitudes of different polarity with a period of 22 years (apparently as the consequence of the nonequivalence of flows of positively and negatively charged fluid, occasionally coming from the solar interior).

During the cycle of inversion of the Sun magnetic field and 11-year cycle of solar activity, the meeting takes place of heated magnetic flux tubes, which rise up under the influence of convection, and of the sinking cold magnetic flux tubes. The magnetic fields in these tubes have opposite directions, and opposite charges, which are concentrated in the tubes. Besides the electrical forces arising from the fluid charges and magnetic forces, in the tubes there are longitudinal currents, which give additional forces of attraction or repulsion. In the replacing of one generation of the tubes by another, the annihilation of part the tubes takes place, some of them connect with each other, and their electromagnetic energy is converted into the sound and magnetohydrodynamic waves. On the Sun subsonic sound oscillations are discovered with periods ranging from 200 to 10^4 s, which modulate the solar wind and as a result affect many terrestrial phenomena. For example, the similar oscillation frequencies are acquired by the magnetic field, the atmosphere, and the geological structures of the Earth, and even the voltage of transoceanic cables. The release of a significant amount of energy of the tube brings in motion the large masses of the solar plasma from the photosphere to the corona, which is observed in the form of solar prominences, solar flares and solar wind variations.

Besides the 11-year solar activity cycle (sometimes it is called the Schwabe cycle), and the 22-year cycle of double polarity reversal of the dipole magnetic field or the Hale cycle, longer periods are discovered at the Sun (by means of isotopic analysis of the rings in the tree cuts and of the samples of Greenland ice). These periods include the 88-year Gleissberg cycle, 205-year de Vries or Suess cycle, 2100 or 2300-year Hallstatt cycle. The cycles with periods of 88 and 205 years are revealed in particular in the long declines of solar activity. The declines occurred in 1010 – 1050 at the Oort minimum, in 1280 – 1340 at the Wolf minimum, in 1450 – 1550 at the Spörer minimum, in 1645 – 1715 at the Maunder minimum. At the Maunder minimum the 15-year cycle of activity took place, and after the minimum the sunspots appeared mostly in the northern hemisphere of the Sun. It is possible that shifts of the duration of cycles and the long periods are associated with changes in gravitation from the planets of the Solar system, occasionally influencing the processes occurring inside the Sun.

5. Conclusion

Our goal was to show the existence of a special mechanism that in addition to hydromagnetic dynamo leads to the periodic transformation of thermal energy of cosmic bodies (planets and stars) into the electromagnetic energy, particularly into the magnetic energy. The feature of the electrokinetic model is the minimization of losses due to electric currents required to generate the magnetic field. This makes the model independent on the well-known problem of attenuation of the magnetic field. After another charge separation due to convection and the temperature and pressure gradients, the charged matter rotates synchronously with the cosmic body, creating the volume electric currents in the convective zone. Due to these currents the body acquires the magnetic moment proportional to the angular velocity of rotation.

Due to spherical symmetry, the volume charges in the center of the core and in the shell of the body are relatively stable. However, within the body approximately in the middle of the radius a large electric field emerges. This creates the conditions for the oscillatory mode, which leads eventually to the periodic changes of the polarity of the magnetic field. As the charge separation takes place and the charge gradient increases along the radius of the body, the internal electric field also increases. It leads to the fact that inside the body the fluid rising under the influence of convection has mainly the sign of the charge, which is trying to compensate the volume charge in the shell of the body. After emerging of sufficient amount of the charged fluid in the shell, the volume charge, the electric and magnetic axisymmetric fields on the average disappear. If the charged fluid continues to emerge, the shell of the body is recharged and during the rotation of the body the dipole magnetic field of the opposite sign is created. The amplitude of the obtained magnetic field depends on the rotation frequency and on the radius at which the convection takes place (the more fluid is charged in the interior of the body, the greater is the extent to which this fluid can recharge the shell). The period of the magnetic field change is directly proportional to the radius of convection and inversely proportional to the velocity of convection. Due to the high speed of convection and the fluid motion the period of change in the solar magnetic field is much shorter than the period of change in the Earth's magnetic field.

It should be noted that the strong electric field inside the space objects that arise due to charge separation may not manifest itself to the outside observer. This is due to the spherical symmetry of the field and the overall electrical neutrality of space objects.

In (Davis at all 1989) it is indicated that the counting rate of the solar neutrinos by the perchloroethylene detector in the Davis experiment has a clear anticorrelation with the solar cycle. The exact reasons of this phenomenon have not yet been found. We can assume now that the reason of this phenomenon is associated with the strong electric field in the solar convective shell, arising as a result of charge separation and reaching the maximum at the maximum of solar activity. The strong electric field affects the formation and propagation of the neutrinos produced in thermonuclear reactions in the solar core, changing conditions of weak interaction. On the other hand, there is also the Mikheyev–Smirnov–Wolfenstein effect which connects neutrino oscillations with electrons of matter as a result of scattering of the electron neutrinos.

In the Sun the differential rotation of fluid in the convective zone is discovered, which depends both on the radius and the polar angle. Besides, there is also the meridional motion of the fluid. Consequently, the poloidal magnetic fields associated with the fluid, are able to stretch out in the toroidal fields and be concentrated in the magnetic flux tubes with a significant increase in the total magnetic field induction. The ascending magnetic flux tubes of a new generation bearing the electric charge, meet the descending magnetic flux tubes of previous generations with the opposite electric charge and the opposite magnetic field direction. Therefore, near the maximum of solar activity the energy released in the annihilation of the magnetic flux tubes feeds such large-scale phenomena as solar prominences and solar flares by means of magnetic and sound waves. Apparently, the extremely high temperature of the corona (over million degrees) is due to the transfer of electromagnetic energy by waves from the fluid to the highest layers of the solar atmosphere. The form of the corona obtains the largest volume near the maximum of solar activity.

From the stated above it follows that on the Earth during the reversal of the magnetic field we should also expect the release of magnetic energy and some increase in the geological activity, increase in the frequency of earthquakes, climate changes, anomalies in the ocean and the atmosphere, the increased influence of cosmic rays on living organisms, etc.

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