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Abstract

Full Text

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ON THE INFLUENCE OF EXTERNAL DRIFT CURRENTS ON THE MAGNETOHYDRODYNAMIC SELF-EXCITATION OF THE EARTH' S MAGNETIC FIELD

(Presented by Academician M. A. Leontovich, 30 XII 1960)

1. Studies using space rockets and satellites ([1]) show that the Earth is surrounded by a powerful belt of radiation consisting of electrons with energies of tens and hundreds of kiloelectronvolts. Drifting in a nonuniform magnetic field, these electrons create a ring current of the same sign as the currents inside the Earth. The maximum field intensity of the ring current may reach 400 gamma ([2]).

As a result of the disturbance of the external radiation zone during magnetic storms, external currents also arise in the same direction as the internal terrestrial currents. These currents exist for several days and create, in the region of the Earth, a field with intensity ~ 60 gamma.

Finally, let us note that the existence of external currents of this direction was established by some investigators on the basis of a spherical analysis of magnetic-survey data. According to these data, the intensity of the external field near the Earth is ~ 1000 gamma. The indicated results were called into question; however, in light of the new data ([1,2]), the existence of external currents may be regarded as proven. As for the numerical value of the external field (1000 gamma), it appears to be overestimated. (For a detailed review of the spherical analysis of the geomagnetic field, see ([3]).)

From the data presented above one may conclude that the Earth is surrounded by a drift current whose field near the Earth is parallel to its dipole moment and may be regarded as uniform. The average value of this field at the Earth is apparently ~ 100 gamma.

It seems probable that the drift current is maintained by the filling of the Earth' s magnetic trap with fast electrons during magnetic storms. The course of magnetic storms and their energy are determined by solar activity and by the magnitude of the Earth' s dipole moment. If we assume that solar activity is, on average, constant, then it may be asserted that the time-averaged field intensity of the drift currents near the Earth is determined by a relation of the form

$$H_0 = \frac{M}{R^3} K(M), \tag{1}$$

where M is the Earth' s dipole moment; K is a dimensionless function of M (the factor $R = 3000$ km is the radius of the Earth' s core, introduced for considerations of dimensionality). Since, as M increases, the energy of a magnetic storm—defined as the difference between the energies of the disturbed and undisturbed fields—must increase, the energy transferred in this process to particles in the external radiation belt must also increase. Furthermore, for large M, confinement of particles in a larger volume becomes possible. These factors should lead to an increase in the current and, consequently, H_0, since the density of the drift current is proportional to the energy of the particles, while the total current strength is proportional to their

integer. On the other hand, as M increases, the drift current on average moves away from the Earth, since its density is inversely proportional to the external field.

A complete accounting of all these factors is possible only in a detailed theory of the external radiation zone. In the present work some consequences of relation (1) are considered, with the assumption that, as a result of the current' s moving away from the Earth, H_0 grows more slowly than M.

2. With time, the field H_0 penetrates into the Earth' s core. Interacting with the convective motions of the conducting masses, the external field may, under certain conditions, induce an additional dipole moment M', strengthening the total field, which in turn may increase H_0, and so on. In this case self-excitation occurs.

If one uses the common analogy with a dynamo machine, one may say that the external radiation zone plays the role of the stator, and the convective core that of the rotor. Feedback is effected by magnetic storms, which pump particles into the magnetic trap.

For each type of convective flow (neglecting the reverse influence of the field on the motion), there exists a linear dependence between the components of the external field and the induced dipole moment:

$$M'_i = q_{ik} R^3 H_{0k}. \quad (2)$$

In particular, if the flow is axially symmetric with respect to H_0, then

$$M' = q R^3 H_0. \quad (3)$$

The coefficient q, depending on the character of the flow, may take all possible values, beginning with -2 (in the case of developed isotropic turbulence, when the external field is expelled from the liquid) and up to arbitrarily large positive numbers.

Depending on q and k, an initially weak field will either decay (for small q) or grow. These regions of values of k and q are separated from one another by a certain curve $k = k(q)$, corresponding to conservation of a stationary field.

It is easy to see that if $kq = 1$, then from (1) and (3) it follows that $M = M'$, and the processes considered above can maintain a magnetic field constant in time. Consequently, the condition for self-excitation reduces to the inequality

$$kq > 1. \tag{4}$$

Under the assumptions made above concerning the dependence of k on M, there always exists a region of sufficiently small values of M for which inequality (4) is satisfied. Self-excitation continues until M assumes such a value M_0 that

$$k(M_0) = \frac{1}{q}.$$

3. If we take $H_0 = 100$ gauss and assume that M has by the present time assumed the value M_0, then we obtain that $k(M_0) \sim 10^{-4}$, while $q \sim 10^4 \gg 1$. Below, the simplest example of a flow is considered for which q can be a very large positive number.

Let there occur, in the interior of a gravitating sphere homogeneous in composition and under great pressure, a phase transition of matter into a metallized state (let us note that the compression energy at the center of the Earth, per atom, is ~ 20 eV, which is sufficient for the ionization of most elements). In the presence of a negative temperature gradient, convective motions may arise that encompass the whole sphere. However, magnetohydrodynamic effects play a role only in the core, because of the low conductivity of the matter in the shell.

If the convective currents have quadrupole symmetry, and the dimensions of the core are small, then the motion in it in cylindrical coordinates has the form:

$$V_z = 2V_0\frac{z}{R}, \qquad V_r = -V_0\frac{r}{R}, \qquad V_\varphi = 0. \tag{5}$$

It is obvious that the dipole moment induced by such a flow can be estimated by considering the flow with potential (5) not in a sphere, but in a cylinder, and then calculating the dipole moment of the corresponding section of the cylinder near the origin.

Passing to the problem of a cylinder, let us suppose that where $\sigma \neq 0$ (for $0 \leq r \leq R$), the velocity distribution is given by formula (5), and that at infinity there exists a homogeneous magnetic field $H_z = H_0$. The solution of the equations

$$\operatorname{rot}\mathbf{H} = \begin{cases} \dfrac{4\pi\sigma}{c^2}[\mathbf{VH}] & (0 \leq r \leq R), \\ 0 & (r > R); \end{cases} \tag{6}$$

$$\operatorname{div} \mathbf{H} = 0, \tag{7}$$

finite at zero, continuous at the boundary, and tending at infinity to H_0, has the form:

$$H_r = H_\varphi = 0;$$

$$H_z = \begin{cases} H_0 e^{\lambda(1-r^2/R^2)} & (0 \le r \le R), \\ H_0 & (r > R), \end{cases} \tag{8}$$

where $\lambda = 2\pi\sigma V_0 R/c^2$.

The dipole moment of a unit length of the cylinder is determined by integrating the quantity $\frac{1}{8\pi}[\mathbf{r} \operatorname{rot} \mathbf{H}]$ over the cross-section,

$$M_1 = \frac{R^2}{4} H_0 \left(e^\lambda - 1\right). \tag{9}$$

Hence it is seen that for sufficiently large λ the core will induce a dipole moment $M' \sim H_0 R^3 e^\lambda$, i.e.,

$$q \sim e^\lambda. \tag{10}$$

The conductivity of a metal with a limiting Fermi energy ~ 20 eV at a temperature of 3000° will be $\sim 10^{17}$. The flow velocity $V_0 \ge 10$ cm/sec (in this case the field ~ 10 gauss ceases to influence the motion). If one takes $R \sim 1000$ km, then $q \sim 10^{100000}$, which, of course, is more than sufficient for self-excitation.

It is not excluded that the real currents in the Earth's core are also characterized by $q \gg 1$. If this is so, the proposed mechanism is capable of explaining a number of characteristic features of the Earth' s magnetic field, including its high degree of symmetry.

In conclusion I take this opportunity to express my deep gratitude to Academician M. A. Leontovich and Prof. D. A. Frank-Kamenetskii for their interest in the work and for fruitful discussion of the results.

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Note: Figure translations are in progress. See original paper for figures.