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"BAROMAGNETISM" OF PLANETS AND STARS

V. I. Grigor'ev

Physical mechanism of formation of magnetic fields of planets and stars associated with differential motions of electric charges in their interior acquired due to the baroelectric effect is considered. This polarization-kinetic mechanism, not discussed previously, allows an understanding, in particular, of how tidal effects cause the noncoincidence of the geographic and magnetic axes of celestial bodies.

The idea of magneto-hydrodynamic nature of magnetism of stars and planets received wide recognition after the publication of Larmor's work in 1910 [1]. It is usually referred to as a "dynamo model", whose physical essence is that the kinetic energy of differential motions in the bulk of the conductor may convert into the magnetic field energy due to an electromagnetic induction phenomenon. The dynamo-mechanism of magnetic field generation (to be more precise, of the amplification) in celestial bodies is treated in numerous theoretical investigations, among which a prominent place was held by the investigations of Ya. I. Frenkel [2]. At present there is much speculations that this mechanism is the dominant if not the sole.

Meanwhile, seven years before the publication of Larmor's investigations, the first of the two Sutherlend's papers appeared [3], in which a hypothesis was advanced of a different, "polarization" mechanism of origination of stars and planets magnetism, of the Sun and the Earth primarily. According to Sutherlend's hypothesis, under the effect of gravity there takes place a redistribution of charges: part of the electrons from the internal areas of the bodies are displaced to their surface; the rotation of the planet or star, into which the redistributed charges are also involved, sets up a magnetic field.

Sutherlend's hypothesis had no reliable theoretical substantiation; moreover, first attempts of experimental verification of this hypothesis [4, 5] did not give positive results (not due to the absence of the effect as such, but because of insufficient sensitivity of experimental apparatus, which, however, was only shown considerably later [6]). Therefore, scientists were sceptical of the "polarization mechanism" of formation of magnetic fields of celestial bodies, and after the advent of the idea of "hydromagnetic dynamo", the "polarization mechanism" was forgotten almost altogether.

BAROELECTRIC AND BAROMAGNETIC FIELDS

According to Sutherlend's hypothesis, electric polarization of a substance is brought about directly under the effect of a gravitation field. Actually, however, gravitation causes only the appearance of pressure gradients (for the sake of simplicity, only the pressure field rather than the stress tensor may be considered, because this will not change the order of estimates). Baroelectric redistribution of charges occurs in the presence of pressure differentials irrespective of the physical mechanism of their origination.

It is useful to note a far-reaching analogy between baroelectric and "contact" electric fields, which arise in the presence of chemical heterogeneities. In the case of mechanical contact of various metals, electrons escape from metals with a smaller work function to those in which it is greater; such redistribution of charges generates contact potential differences to maintain which, as is known, no power supply is required. However, the work function of the conductor depends not only on its chemical composition, but also on its physical properties. In the presence of gradients of these parameters, the charges are also redistributed, and, hence, electric fields are set up. The dependence of the work function on pressure (more generally, on internal stresses) leads to the fact that electrons are displaced from the areas where the internal stresses are greater into the areas where they are smaller. This is exactly the physical idea of the baroelectric effect.

Craig's experiments [7] can be regarded as a direct experimental verification of the work function pressure dependence.

Just as constant contact potential differences cannot set up electric current in the conductor ("Volta's theorem"), so baroelectric fields, which do not vary with time, do not set up currents either. In particular, although pressure differentials in the interior of celestial bodies set up baroelectric fields, whose intensities may reach considerable values, these fields set up currents if only a variable part exists in them, i. e., when the internal stresses prove to be nonstationary. Such nonstationarity may arise because of the intraplanetary processes (in particular, those connected with seismic events), and due to time-dependent external effects. Among the latter, tidal effects are of considerable interest, and their role deserves special discussion.

If the conductor, in which baroelectric redistribution of charges has taken place, is moving, then, generally speaking, a magnetic field should originate as well; for the sake of brevity we shall call this field "baromagnetic". In previous publications (see, e. g., [8]) theoretical methods of calculating these fields and the results of particular estimations related both to baroelectric and to baromagnetic fields of some planets and stars were described. It will be appropriate to recall some of these results.

As the simplest model of a planet, we consider a massive chemically homogeneous, electrically neutral, cold ball of radius R that rotates making an integral with constant angular velocity ω and we assume that the pressure built up in it by gravity is distributed according to the "hydrostatic" law

$$p(x) = p_0(1 - x^2),$$

where $x = r/R$, r is the distance from the ball center, $p_0 = p(0)$. The radial (the only) component of the baroelectric field intensity $E(x)$ at $x < 1$ for such a model of the planet has the form

$$E(x) = Tx\sqrt{(1-x^2)}, \quad T = \frac{3GM^2}{4R^4\sqrt{\pi K}}. \tag{1}$$

Here G is the gravitational constant, M is the mass of the planet, K is the mean value of its compression modulus.

At $x > 1$, i. e., above the surface of the planet, $E(x) = 0$; the jump δE on the surface $x = 1$ corresponds to the presence of a negative surface charge. The surface density of this charge is

$$\sigma = \delta E/4\pi. \tag{2}$$

The density of space charges $\rho = \rho(x)$ is determined from the Maxwell equation $\operatorname{curl} \mathbf{E} = 4\pi\rho$ or, in a spherical system of coordinates, in view of spherical symmetry

$$\rho(x) = \frac{1}{4\pi R x^2}\frac{d}{dx}\Big[x^2 E(x)\Big]. \tag{3}$$

The barometric field above the surface of the planet with such a choice of the model will be purely a dipole one. The dipole magnetic moment of the planet consists of two parts. One of them is caused by the rotation of positive space charges

$$\mathbf{M}_v = \frac{1}{2c}\int_0^R dV\rho(\mathbf{r})[\mathbf{r}[\omega\mathbf{r}]],$$

where c is the velocity of light.

If the distribution of charges is centrosymmetric, i. e., $\rho = \rho(\mathbf{r})$, then this part is directed along the angular velocity vector. The other part directed oppositely and exceeding the first part in magnitude, owes its origin to the rotation of negative surface charges. It is

$$\mathbf{M}_s = -\frac{4\pi}{3c}R^4\sigma\boldsymbol{\omega} = -\boldsymbol{\omega}\frac{R^4E(R)}{3c}.$$

It is easy to show (see, e. g., [8]) that the total "baromagnetic" moment proves to be opposite in direction to the moment of momentum and is equal to

$$\mathbf{M} = -\frac{2\omega R^4}{3c}\int_0^R dx \cdot x^3 E(x). \tag{4}$$

The "barometric field", in contrast to the baroelectric one, with the indicated choice of the planet model, is present in the external area as well.

The results of numerical estimations produce an impression that the proportion of "baromagnetic" fields in planets is rather essential. For instance, for the Earth this proportion is about 10%, for some other planets of the Earth group it is probably even higher. But one should not overestimate the importance of the proximity in the numerical values of empirical and "baromagnetic" moments, because sometimes they differ appreciably even in direction. However, all the differences are quite natural: in real objects the superposition of magnetic fields of magnetohydrodynamic and polarization nature takes place. This superposition manifests itself most sharply in stars, in the Sun in particular: an instantaneous observed picture of magnetic field distribution falls far short of looking a dipole one, which is a reflection of vigorous and whimsical intrastellar differential flows and, as has already been stated, is connected with dynamo-generation (to be more precise, with intensification) of magnetic fields. The part of the magnetic field, which is of a polarization nature, is comparatively more stable, so that the magnetic field pattern averaged over a sufficiently long time interval appears to be close to the dipole one.

We would like to note that in the model of the planet used above, if we additionally confine our consideration to usually realizable cases of slow rotation (i. e., when the parameter $\omega R/c$ is small and its consideration can be restricted to a linear approximation), the magnetic field in the intrinsic reference system of the planet (i. e., in the system rotating together with it) and that in the inertial center-of-mass system prove to be the same.

In the same approximation the baroelectric field inside the planet appears to be purely Coulombian and "insensitive" to rotation.

No work is required to maintain the baroelectric redistribution of charges, owing to which baromagnetic fields have no need for (in contrast to magnetohydrodynamic fields) a continuous power supply. Therefore, such a field is suited well for the role of a "primer", without which the "dynamo-mechanism" would not have the ability of functioning.

From the above-said it follows that isobars in the conductor are at once the surfaces of constant baroelectric potential; therefore, the surfaces of real celestial bodies, in particular, which owing to rotation are not precisely spherical, are equipotential, so that this nonsphericity does not lead to the penetration of the baroelectric field into the external area.

ONCE AGAIN ABOUT THE ROLE OF DIFFERENTIAL MOTIONS

When considering the dynamo-mechanism of formation of the magnetic field of planets and stars, we usually assumed that their interior can be regarded as electrically neutral, i. e., that the bulk density of the charge is zero. Taking into account the polarization mechanism, it is necessary to reconsider this assumption.

Positively charged volumes of substance prove to be involved into those differential flows, which are responsible for the magnetohydrodynamic "pumping-over" of kinetic energy into magnetic field energy. The motion of charges is an electric current, which generates an additional magnetic field. Such a "direct" generation of a magnetic field by the current was not, apparently, discussed earlier in geo- and astrophysics. At the same time, differential internal motions obviously exist not only in stars, but also in planets, and, hence, the above-mentioned mechanism of their influence on magnetic fields should be taken into account.

Since the actual pattern of differential internal motions is usually unknown, we shall turn to simple models which make it possible to establish some qualitative facts. For the sake of brevity, we shall only recite the results, the detailed exposition of which can be found in [9].

Let there be a ball, throughout whose bulk a charge Q is uniformly distributed and over the surface of which a charge $-Q$ is uniformly distributed, so that on the whole the ball is electrically neutral. (Note that such a charge distribution is rather close to that considered earlier: in the internal area of the planet the intensity of the electric field grows almost linearly which means that the charge bulk density is almost constant. If the velocities of differential motions are not too great, the influence of these motions on pressure distribution, and, hence, on charge distribution, can be neglected).

But if earlier we assumed that the planet rotates as a single unit, we shall now assume that the internal area I of radius R_1 rotates with the angular velocity $\mathbf{\Omega}$, in relation to area II surrounding it, in which $R_1 \le r \le R_2$, and area II itself rotates in relation to the inertial frame of reference of the center of mass of the planet with angular velocity $\boldsymbol{\omega}$. Area III lies outside the planet.

As is shown in the publications cited above, particularly in [9], the intensity of the magnetic field above the surface of such a "model planet", i. e., in area III, has the form

$$\mathbf{H}_3 = \frac{8\pi}{45cr^3}\rho R_2^5\boldsymbol{\omega} - \frac{24\pi}{45cr^5}\rho R_2^5\mathbf{r}(\boldsymbol{\omega}\mathbf{r}) - \frac{4\pi}{15cr^3}\rho R_1\mathbf{\Omega} + \frac{12\pi}{15cr^5}\rho\mathbf{r}(\mathbf{\Omega}\mathbf{r}), \tag{5}$$

where $\rho = 3Q/4\pi R_2^3$ is the bulk density of the charge.

The field in area III proves to be purely dipole. The total magnetic moment is

$$\mathbf{M} = -\frac{8\pi}{45c}\rho R_2^5\boldsymbol{\omega} + \frac{4\pi}{15c}\rho R_1^5\mathbf{\Omega}. \tag{6}$$

The position of magnetic poles, i. e., of points near the surface of the ball, at which the magnetic field has only a vertical component, can be found from the following relation:

$$[\mathbf{H}_3 \times \mathbf{n}] = 0.$$

From this relation and from (6) it follows that the radius-vector $\mathbf{R}_p$ indicating the position of poles is defined by the relation

$$[(q\boldsymbol{\omega} - \mathbf{\Omega})\mathbf{R}_p] = 0; \quad q = \frac{2R_2^5}{3R_1^5}. \tag{7}$$

Therefore, only when $\boldsymbol{\omega}$ and $\mathbf{\Omega}$ are directed along the same straight line, the position of geographic and that of magnetic poles can be the same.

In conclusion, one more remark of a qualitative character concerning also probable reasons for the noncoincidence of the geographic and that of magnetic axes of planets can be demonstrated.

If we only confine our consideration to that part of the magnetic field of the celestial bodies, which is caused by the baroelectric effect, then, as long as the factors breaking the spherical symmetry of the problem are not taken into account, these axes will coincide. Such distortions are caused, in particular, by gravitational interactions of all celestial bodies, to be more precise, by those parts of these effects, which are called tidal and are brought about by spatial inhomogeneities of gravitational fields generated by any celestial bodies. (If one uses an approximation in which these inhomogeneities are not considered, i. e., confines the approximation to the terms of zero order expansion with respect to a small parameter equal to the ratio of the planet size to the distance from the center of the external source of gravitational effect, then in the intrinsic frame of reference the planet will be in the state of weightlessness, which cannot, naturally, break the axial symmetry).

In all other orders of expansion in terms of this small parameter, including the first order (which usually makes the main contribution and to which, therefore, the investigations are usually confined), those symmetry distortions manifest themselves, owing to which a number of important observed effects originate. One of such effects — penetration of baroelectric field into the area above the surface of the planet — is treated in a number of publications (see, e. g., [10]). The problem of tidal effects influence on the baroelectric field was also discussed, but then the subject for study were only its "tidal variations", whereas the effect of a considerably larger scale still remained unnoticed.

Much has already been said about the influence of differential flows in the interior of celestial bodies on the magnetic fields of celestial bodies. One of the main factors responsible for the origination of these flows are temperature gradients. Ascending flows from more hot central areas (as well as the descending motion of a cooled substance) also generate flows in the latitudinal direction owing to the planet rotation. But all this on the average (with respect to time) does not lead to disturbances of the axial symmetry. It is precisely the tidal forces, that generally generate such disturbances, and this may lead to a deviation of the magnetic axis from the geographic one.

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Department of Quantum Theory and High-Energy Physics