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ON THE FIBROUS STRUCTURE OF CURRENTS IN THE MAGNETOSPHERE

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SUMMARY

The hypothesis on fibrous small-scale structure of current systems in the Earth's magnetosphere is expressed on the basis of estimates of the magnitude and characteristic dimensions of longitudinal currents in the magnetosphere, closed through the lower inonosphere, and also and the data of the coherence of magnetic disturbances in conjugate regions. By way of consequence conclusion is derived on cellular structure of current systems in the ionosphere. The longitudinal currents are probably equivalent to fluxes of electrons with energies of 1 to 10 kev and the number of particles to ~ $10^7 - 10^9$ $cm^{-2} \cdot sec^{-1}$.

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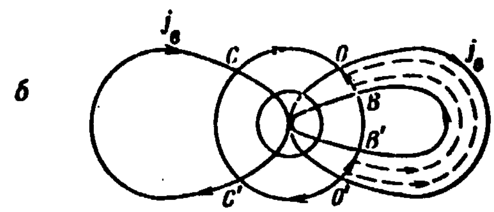
The classical representations on the source of magnetic variations in the form of surface current systems, closed in the lower ionosphere, introduced by Chapman and Bartels [1] continue to develop at the present time also ([2 - 7] and others). Alongside with this well known also are the works started by Birkeland and Alfven [9, 10], in which the systems of currents equivalent to magnetic disturbances on the Earth's surface, include, besides the horizontal currents in the lower ionosphere, currents along the geomagnetic field lines [11 - 21]. These currents were recently investigated also as one of the basic factors determining S_q-variations, i.e. the variations of the geomagnetic field in a quiet magnetosphere.[22, 23].

The aim of the current work is to note that the longitudinal currents in the magnetosphere have apparently a fibrous structure and can be responsible for aurorae and the conjugate disturbances of the ionosphere. This paper is in fact a development of the works [22, 24].

(*) O VOLOKNISTOY STRUKTURE TOKOV V MAGNITOSFERE

Assume that a current of density j_B (Fig.1,a) flows into the ionosphere along the tube of field lines. The current will close along contours represented in Fig.1,б. Those are contours OO'B'BO, OO'C'CO, the contours shown by dashed lines and others. Shown in Fig.1 are the contour's OO'B'BO involute (в) and the conjunction of parallel contours. (г). Here OB and O'B', and also OC and O'C' are the ionosphere portions of the contours; OO', BB', CC' and KK' are the geomagnetic lines of force.

Let us consider the morphology of currents spreading out at entering the ionosphere in the vicinity of a certain point O' (Fig.1(г)), of radius r_0 in the assumption of stationary state of spread



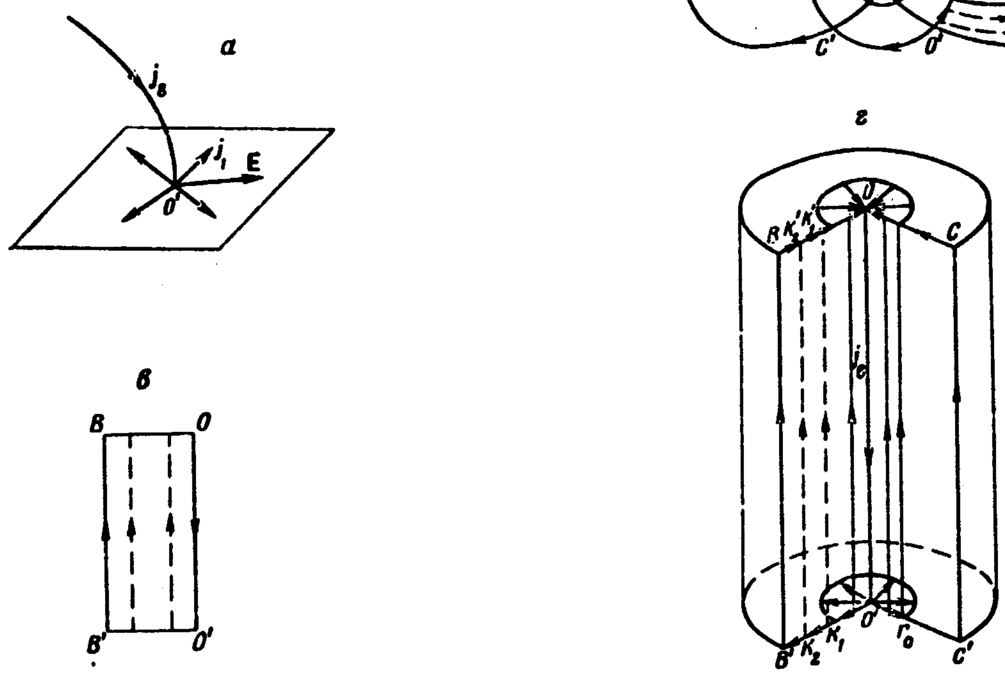


Fig.1

At the same time we leave aside the question of magnitude and spatial distribution of the electromotive force acting between the neighborhoods of the points O and O' of ionosphere's conjugate points. We only assume that such an emf exists and induces a current of total magnitude I_0. Then, for the value of the horizontal spreading current $I = I(r)$, flowing across the boundary representing a circle of radius r, it is not difficult to obtain the equation in the assumption of unoform conductance of the lower ionosphere

$$\frac{d^2I}{dr^2} - \frac{1}{r}\frac{dI}{dr} - \frac{2\sigma_0}{\Sigma_1 l} I = 0. \quad (1)$$

The solution of Eq.(1) for $r > r_0$ may be written in the form

$$I(r) = I_0 \frac{r}{r_0} \frac{K_1\left(\frac{r}{L}\right)}{K_1\left(\frac{r_0}{L}\right)}, \quad (2)$$

where I_0 is the total vertical current flowing into the ionosphere in the neighborhood θ_0 of the point O', K_1 is a Kelvin function of the order 1, and

$$L^2 = \frac{\Sigma_1 l}{2\sigma_0}. \quad (3)$$

In the last expression

$$\Sigma_1 = \int_{h_1}^{h_2} \sigma_1 dh;$$

σ_1 is the Pedersen conductance, is the length of the line of force between conjugate points; σ_0 is the specific conductance along the line of force of the magentic field. When obtaining (2), the condition $I(r_0) = I_0$ was utilized.

Entering in expression (2) are L, which is the characteristic length of the transverse inhomogeneity of vertical currents, and also the characteristic dimension of spreading currents and of electric fields connected with them.

Assuming

$$l = 10^{10} \text{ cm},$$
$$\Sigma_1 = 2\cdot 10^{12} \text{ units CGS},$$

and postulating on the basis of [17, 25] (and also on the basis of a private communication of K. G. Ivanov), taking into account the series of laboratory experiments of [26 - 28] whereby $\sigma_0 \sim 10^7$ units CGS, we find

$$L \sim 3.2\cdot 10^7 \text{ cm}.$$

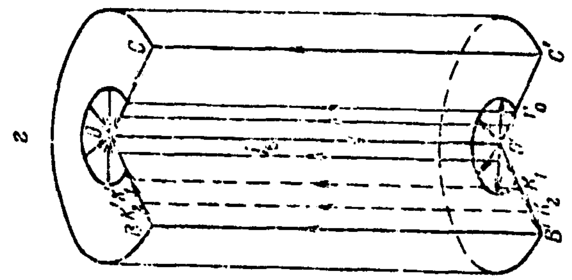


Fig.1

Г

The magnetospheric current which flow along the geomagnetic field lines form tubes similar to that represented in Fig.1(Г), with characteristic transverse dimension of ~ 300 km. The quantity L determines the charcteristic dimensions of inhomogeneities of currents j_B and magnetic fields induced by them. The available experimental data confirm our estimate of the characteristic length of the transverse inhomogeneity of vertical currents. Thus, according to [29, 30], variable magnetic fields are characteristic for heights ~ 1100 km, provided they are transverse relative to the main geomagnetic field, with magnitude 30 - 300γ; the greatest dimension of the region in which such fields were observed constitutes ~ 400 km. According to data of [6] the characteristic dimension of the region of true conjugate state of magnetic variations is of 200 to 300 km. According to data on simultaneous measurements on stratoballoon and rocket, analogous estimate was also obtained for the dimension of the coherence region of X-ray radiation outbursts caused by precipitation of energetic electrons [31]. The dimension of the region of coherent geomagnetic oscillations with period $T \sim 10^3$ sec at high latitudes also constitutes 200 - 400 km and less [2, 32]. At middle latitudes a cellular structure is noted in ionospheric currents determining the three-hour K-indices of magnetic activity; the characteristic dimension of the cells is less than 300 km [33].

It seems to us that the above data allow us to venture the hypothesis on the fibrous small-scale structure of current systems in the magnetosphere and, by way of consequence, on a small-scale cellular-type structure of current systems in the ionosphere. Such a representation corresponds to fibrous structure phenomenon in cosmic plasma (radial shapes in the Sun's corona, filaments in interplanetary magnetic fields [34], aurora rays, whistler propagation channels [35] and so forth), and also to data on laboratory experiments on fibrous structure of plasma (plasma column breaking up in pinches [36, 37], strata in a flowing discharge [38]). All these phenomena allow us to assume that the fibrous structure is a general property of a plasma with current, placed in a magnetic field .

So far we considered the stationary process of flow in and relaxation of a certain current I_0, generated by some emf, as connected between the points 0 and 0', or, to be more precise, as the potential difference between conjugate points. Such a potential difference may be (or much rather actually is) a function of time. Then, the form of equations describing the temporal and spatial behavior of vertical currents and of horizontal spreading currents connected with them, will become more complex; the process will assume a wave character, and the inductance and capacitance of ionospheric and magnetospheric portions of the contours will begin to play a specific role. In this case, still one more parameter will appear: this parameter will characterize the spatial periodicity of the inhomogeneity in case of its wave character, whereupon it will be $\lambda < L$ and dependent on the period of variations. This process, as well as the means of formation of large-scale current systems and their tubes, similar to that considered above, are discussed in the work [39].

We shall estimate the magnitude of the verical current j_B. To that effect let us note that the linear density of the horizontal spreading current, taking into account the expression (2), is

$$j(r)=\frac{I(r)}{2\pi r}=\frac{I_0}{2\pi r_0}\frac{K_1(r/L)}{K_1(r_0/L)} \quad (4)$$

where $E_i(r)$ is the strength of the horizontal electric field linked with the spreading currents.

Assuming $I_0=\pi r_0^2\langle j_B\rangle$, where $\langle j_B\rangle$ is the mean density of inflowing vertical currents, we obtain for $\langle j_B\rangle$

$$\langle j_B\rangle=\frac{2\Sigma_1 E_i(r)}{r_0}\frac{K_1(r_0/L)}{K_1(r/L)}. \quad (5)$$

We shall obtain the expression for vertical return currents j_B from the equality $dI/dr=-2\pi r j_B$, i.e., $j_B=\frac{1}{2\pi r}dI/dr$, which, after rather simple transformations and utilizing (2) and (5), acquires the form

$$j_B = \frac{\Sigma_1 E_i(r)}{r} + \frac{\Sigma_1 E_i(r)}{L} \frac{K_0(r/L) - K_2(r/L)}{K_1(r/L)}. \quad (6)$$

For the estimate of vertical currents by order of magnitude we may assume the expression

$$j_B \sim \frac{\Sigma_1 E_i}{l}, \quad (7)$$

where E_i is a certain "mean" electric field in the ionosphere.

In the presence in the ionosphere of the field $\vec{E}$ Pedersen currents arise

$$\mathbf{j}_1 = \Sigma_1 \cdot \mathbf{E} \quad (8)$$

and also the Hall currents

$$\mathbf{j}_2 = \Sigma_2 \cdot [\mathbf{E} \times \mathbf{h}], \quad (9)$$

where $\vec{h}$ is the unitary vector of the geomagnetic field. Σ_2 is the Hall's integral conductance. Assume for simplicity that $\vec{h} = \vec{n}$, where $\vec{n}$ is the unitary vector of the normal to the horizontal surface of the ionosphere. Then we may write

$$\mathbf{j}_2 = [\nabla \mathbf{R}_1 \times \mathbf{n}]; \quad \mathbf{j}_1 = \frac{\Sigma_1}{\Sigma_2} \nabla \mathbf{R}_1, \quad (10)$$

where $R_1(\theta,\lambda)$ is a current function [1]. Expressions (10) signify that the currents j_1 and j_2 are horizontal and that the current j_2 is closed on the horizontal surface.

Besides the currents j_1 and j_2 there may exist horizontal currents j_3 which are not connected with j_B. Assuming that they are closed, we shall have

$$j_3 = [\nabla \mathbf{R}_2 \times \mathbf{n}], \quad (11)$$

where $R_2(\theta,\lambda)$ is still another current function.

Currents j_1 on one side and currents j_2 and j_3 on the other differ in their contribution to the magnetic potential $V(\theta,\lambda)$ measured on the Earth's surface. As was noted in [40], ground magnetic effects of currents j_1 and j_B tend to compenaate one another. At $\vec{n} = \vec{h}$ and $\sigma(\theta,\lambda) = \text{const}$, this compensation is complete and the ground magnetic field is induced by currents j_2 and j_3, whose sum may be represented in the form

$$\mathbf{j}' = [\nabla \mathbf{R} \times \mathbf{n}], \quad (12)$$

where $R(\theta,\lambda) = R_1(\theta,\lambda) + R_2(\theta,\lambda)$.

The density of the current $\vec{j}'$ may be found by the ground magnetic data with the aid of the relations

$$V(\theta,\lambda)=\sum_n\sum_m (a_n{}^m\cos m\lambda+b_n{}^m\sin m\lambda)P_n{}^m(\cos\theta),$$

$$R(\theta,\lambda)=-\frac{R}{4\pi}\sum_n\sum_m\frac{2n+1}{n+1}\left(\frac{r}{R}\right)(a_n{}^m\cos m\lambda+b_n{}^m\sin m\lambda)P_n{}^m(\cos\theta). \quad (13)$$

If $(\theta,\lambda)\neq$ const, then currents j_2, j_3 as well j_1 will contribute to the potential $V(\theta,\lambda)$. Moreover, in the presence of sharp inhomogeneities σ the contribution of j_1 may be fundamental.

Thus, in the general case, the quantity j', determined by ground data with the aid of (13) is the sum

$$j' = j_2 + j_3 + kj_1, \quad (14)$$

where $k \leqslant 1$. As is shown in [23], in order to explain the daily and annual variations of the systems of currents equivalent to fields S_q and S_D, it is necessary to admit

$$[\nabla R\times n]\approx j_2+j_3, \quad (15)$$

where $|j_2| \approx |j_3|$. Consequently, the estimate of the magnitude of j_2 and of the field $E = j_2/\Sigma_2$ may be found from ground data.

The total current in the mid-latitude S_q-eddy is about $2.5\cdot10^5$ a for a 2 by 35° latitude dimension of the eddy, and this is why the mean value of the linear density of S_q-currents is equal to $6\cdot10^{-4}$ a/cm. Assuming the thickness of the current-carrying layer to be 20 km, we find the current density to be $3\cdot10^{-10}$ a/cm^2. At $\sigma_2 = 6\cdot10^6$ un.CGS, this corresponds to an average electric field $E_i \approx 4.5\cdot10^{-5}$ v/cm.

Making use of expression (7), we obtain an estimate of the order of magnitude of vertical currents

$$(j_B)_q \sim 3\cdot10^{-12}\ \text{a/cm}^2. \quad (16)$$

For high latitudes and in perturbed days the magnitude of the electric field exceeds by about one order the mid-latitude values. In this case

$$(j_B)_D \sim 3\ 10^{-11}\ \text{a/cm}^2.$$

In the region of flow of currents $j_B \sim 3\ 10^{-11}$ a/cm^2 a transverse magnetic field $H \sim 4\pi j^2 L \approx 100\ \gamma$ must be observed. As noted above, such magnetic fields were indeed oberved at 1100 km heights [30].

nowing the expression for j_B, it is possible to estimate the magnitude of the mean longitudinal field $\langle E_\parallel \rangle \sim j_B / \sigma_0$. At the same time the question what form is assumed by the energy liberated, which is dissipated by the passing current. We shall then take into account that in our case $\langle E_\parallel \rangle \sim (3 \cdot 10^{-7} - 3 \cdot 10^{-6}$ v/cm, which is much more than the critical ('Dreisser') field $E_{Dr} \sim 10^{-9}$ v/cm, whose estimate was conducted according to [10]. Usually for $E \sim E_{Dr}$ all the energy picked up from the source of emf is expended not for heating the medium, but for the acceleration of electrons, and it is transferred alongside with them along the current's circuit to the place of electron deceleration.

However, in our case there takes place interaction of particles with the fluctuations of the electromagnetic field, which precisely explains the low value of σ_0. In other words, formulas for E_{Dr} according to [10] are not quite valid. Nevertheless, we may note that the mechanism of particle acceleration acquires rather complex a character; the liberated power $j_B^2 L / \sigma_0$ is expended at the outset on the creation of some oscillations $\tilde{H}^2/4\pi$, and from them the energy already passes to plasma particles, accelerating a part of them. It is evident that such an acceleration in the presence of the external magnetic field H is basically collinear to vector $\vec{H}_0/H$ and may be classified as a seepage of electrons in the presence of turbulence. Qualitatively, such a process may be interpreted as follows: in the time $\tau = \lambda_{wave}/v_{particle}$ of motion, the "resonance" particle acquires an energy sufficient to allow its emergence from the fluctuation well (pit) and becoming nonresonance. In case of turbulent plasma the value of E_{Dr}, that is, a certain 'Dreisser' field, may be found only by way of the solution of the nonlinear problem.

However, assuming that such a situation is possible for our case (since $E_\parallel$ is rather great), one still may attempt to estimate the energy contributed by accelerated particles as $Q \sim j^2 L/\sigma_0$ $(k \lesssim 1)$. On the basis of quasilinear theory it was shown in [41] that such a seepage of electrons is also possible for such a $E_{Dr}^* \sim E_{Dr}$. The electrons then acquire an energy of the order of the potencial difference between conjugate points. Laboratory experiments of

[42] also speak in favor of the above-proposed mechanism; it was noted in the course of these experiments that for $E \sim E_{Dr}$, ~ 0.1 of all plasma particles go to seepage and then the electron acquires an energy $T_{kin} \sim 5$ kev.

For the above considered values of electric field strength the kinetic energy of precipitating electrons $T_{kin} \sim 3$ kev and the energy transferred by them is $Q \sim 0.1$ erg/cm^2·sec (for middle latitudes). At polar latitudes $T_{kin} \sim 30$ kev, $Q \sim 10$ ergs/cm^2·sec. These values characterize also the experimentally observed fluxes of particles at middle and high latitudes [43].

Taking the above facts into account, which mainly refer to the coherence of magnetic disturbances in conjugate regions, clearly demonstrating the significant role of longitudinal magnetospheric currents, it may be assumed that a substantial part of the observed particle fluxes originate precisely in these currents, namely that a regime is realized of electron acceleration in the turbulized tube of force of the magnetosphere. At the same time, the energy liberated in the ionosphere in the course of the deceleration process of charged particles, is refilled at the expense of the energy of emf sources between the conjugate regions.

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