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SOME QUESTIONS OF GEOEFFECTIVENESS OF SOLAR CORPUSCULAR STREAMS

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SUMMARY

It is noted that the magnetic field of solar corpuscular streams plays an intervening role in the interaction of the fluxes with the Earth's magnetosphere, thus leading to the increase of the effective interaction cross section, determining the possibility of solar plasma injection into the Earth's magnetosphere, modifying the degree of frictional effect at interaction and so forth.

Considered are the questions of magnetic flux conservation, of the impossibility of the stream's field penetration into the Earth's magnetosphere and of the thereby connected requirement of magnetohydrodynamic treatment of the theory of geomagnetic disturbances. Discussed also are the possible mechanisms of energy transfer to Earth's magnetosphere.

* * *

1.- Serious attention has been lately given to the questions of solar corpuscular streams' interaction with the geomagnetic field. When analyzing these questions, the knowledge of the structure and of various parameters of solar corpuscular streams (s.c.s.) has a great significance.

The quantitative computations of interaction have been conducted only for a uniform stationary solar plasma flow without magnetic field [1]; the attempt to account for the effect of the interplanetary field [2] is reduced to the particular case of a uniform field. Meanwhile, from the standpoint of geoeffectiveness of s.c.s, the nonstationary case is precisely the one required for a nonuniform flow, inasmuch as the energy transfer from a uniform stationary flux of solar plasma to the Earth's magnetosphere is impossible [3].- Note also that the variations of flux's kinetic pressure

* NEKOTORYYE VOPROSY GEOEFFEKTIVNOSTI SOLNECHNYKH KORPUSKULYARNYKH POTOKOV.

cannot yet be estimated sufficiently convincing in themselves to impart to them the role of mechanism of energy introduction into the Earth's magnetosphere. From this viewpoint, a comparative analysis of the development of various geomagnetic storms [4], showing that even a sharp variation of flux's kinetic pressure still does not determine the subsequent character of storm development, offers interest. In connection with this the search for an explanation of the different degree of geoeffectiveness of s.c.s. in the influence of their magnetic field is entirely founded.

At the same time it is apparently possible to speak of a corpuscular stream as a sequence of plasma clouds with proper magnetic field; the emission duration of such a sequence is determined by the development of electromagnetic fields above the corresponding active region on the Sun. Aside from considerations relative to generation and emergence of fluxes [5], the analysis [6] of the magnetohydrodynamic instability of models of fluxes, in which either the solar plasma shifts freely along the quasiradial magnetic field, or there exists a plasma-intruded magnetic field, whose lines of force are linked with the Sun [7], speaks also in favor of such a representation. The sporadic character and the brevity of polar geomagnetic disturbances DP [8] are also evidence of the presence of irregularities in the corpuscular flux, which we identify with plasma clouds having their proper magnetic field. Taking into account the high conductance of the plasma, the proper magnetic field of plasma clusters must be frozen-in. Thus, the magnetic field hinders the rapid diffusion of the plasma cloud and serves as the cause of the fact that the fluxes behave as a fluid (the linear dimensions of the flux exceed the Larmor radius $L_i \sim 900$ km for a proton with energy ~ 1 kev in the magnetic field of the stream of $\sim 5\gamma$).

2.- It should be noted that the intensity of the magnetic field of the flux is not high to the point that a direct dynamic effect ought to be expected from the field's magnetic pressure. Indeed, at $B \sim 5\gamma$ the magnetic pressure would constitute only ~ 0.01 of the kinetic pressure of a flux with concentration $\sim 10\ cm^{-3}$ and velocity $\sim 5 \cdot 10^7$ cm/sec. The increase of field pressure at compression in the process of incident flow upon the magnetosphere could not increase this estimate by more than 5 — 10 times; this would not affect the correlation between the kinetic and magne-

tic pressures. Alongside with the transverse (relative to flux's direction of motion) pressure component of thermal flow the flux's magnetic pressure plays a direct role only in processes of locking the train of the magnetosphere, that is, at remote distances from the Earth [9]. An important role may be played by the flux's field in nonadiabatic processes at magnetosphere boundary (plasma heating at the expense of the magnetic energy liberated at annihilation of the magnetic field of the flux and of the geomagnetic field . However, the latter process, particularly important for the problem of solar flares [10], and also for the closing of the train of the magnetosphere and the acceleration of particles inside it [11], cannot serve as a direct mechanism of energy introduction inside the magnetosphere in the course of direct interaction of the flux with the Earth's magnetosphere, acting only at its boundary. This is precisely the reason why it is plausible to search for an explanation of a different character for the development of various storms outside the direct influence of the magnetic field of the plasma cloud.

3.- The field of the flux may play a substantially greater role as an intermediary, changing the character of flux's plasma interaction with the magnetosphere of the Earth. Here we should note first of all the increase of the effective interaction cross section of the flux with the Earth's magnetosphere and the possibility of transfer of greater energy to it. Indeed, the hydrodynamic treatment of the interaction is quite justified in the presence of a magnetic field in the plasma flow. Its supersonic character (which means that the directed velocity of plasma flow is greater than the Alfvén velocity) leads to the formation of a standing shock wave ahead of the magnetosphere*, in connection with which the effective interaction cross section is determined by the aperture angle of the Mach cone, and is found to be greater than the cross section of the encounter cylinder, determined by the incident subsonic flow of plasma without field, or of a flux of interacting particles.

It should be noted that after the closest rapprochement of the Earth's magnetosphere with the axial line of the flow, the sources of the flux's proper field are found to be within the bounds of the Mach cone, which also allows to speak of the possibility of greater energy transfer

* see infrapagimal note next page.

to the magnetosphere (by comparison with the motion of the Earth's magnetosphere in a flux of plasma with magnetic field, of which the sources are on the Sun). At the same time, as the magnetosphere draws nearer the axial line of the flow, the increase of the magnetic field leads to the rise of the Alfvén velocity and may lead to transition to subsonic character of the flow. In this case, the particles of the flux, directly interacting with the magnetosphere, will induce a deceleration (and a corresponding reconstruction) of the magnetic field of the flux, which should in its turn include in the interaction the more remote particles, trapped (retained) by the magnetic field of the flux and not participating in the direct interaction with the Earth's magnetosphere. On the whole, the increase in the effective interaction cross section may result quite substantial (by a factor of 5 to 10).

The influence of the magnetic field of the flux may also result to be decisive in relation to the possibility of particle injection from the corpuscular stream into the Earth's magnetosphere [13]. The field of the flux may play an intervening role in the injection of solar plasma particles at reconnection of the lines of force of the flux's field with the lines of force of the geomagnetic field [14]. The latter process is also important when analyzing the motions in the magnetosphere.

Finally, let us note the influence of the magnetic field of the flux on the degree of the frictional effect at flux's interaction with the magnetosphere. Without recourse to frictional effect and of corresponding motions in the magnetosphere, it is difficult to explain the data of magnetic storm morphology, these being instrumental in the rapid changes in the pattern of polar disturbances DP [15]. It is quite possible that dependent upon the friction mechanism is also the mechanism responsible for the main phase of the storm (formation of the ring current). The Kelvin-Helmholtz instability at the boundary of two plasma regions with independent magnetic fields depends on the angle between the direction of the fields. The magnetic field dimimishes the state of friction (stabilizes the boundary) if the field is not parallel (or not antiparallel). In the opposite case the "friction" with energy transfer from one region to the other is inescapable.

At interaction of corpuscular streams with the Earth's magnetosphere the direction of the magnetic field of the flux is not, generally related to the more or less fixed in space geomagnetic field. According to satellite data it varies in time and space to a sufficiently marked extent [16]. (Note that this fact may be viewed as still another argument in favor of the representation about the irregularities in solar corpuscular streams). Thus, it is natural to expect that in specific cases the magnetic fields of the flux and of the terrestrial magnetosphere may either result to be parallel or antiparallel, which would be manifest in the appearance of a notable frictional effect and energy introduction into the Earth's magnetosphere, linked with it, that is, in the geoeffectiveness of the solar corpuscular stream.

Therefore, either the presence or the absence of geoeffectiveness of the solar corpuscular stream are apparently determined by the orientation of the stream's field relative to the geomagnetic field in the process of the interaction of the flux (stream) with the Earth's magnetosphere.

4.- In connection with the role of the magnetic field of the stream (flux) in energy transfer to the Earth's magnetosphere [17], it is necessary to stress the impossibility of stream's filed penetration into the magnetosphere (contrary, for example, to [3]), that is, the impossibility of variation of magnetosphere's magnetic flux Φ_M directly at the expense of the magnetic field of the corpuscular stream. In other words, it is important to note the necessity of transforming the energy of the magnetic field of the corpuscular stream even if it does not play a substantial role in the explanation of geomagnetic disturbances. It should be borne in mind that the magnetic field of the stream is an external field relative to the Earth's magnetosphere, which constitutes, at least at distances from 3-4 to 10-15 R_E, a highly-conducting plasma. In order to confirm this position, let us bring forth the estimate of certain parameters characterizing the magnetosphere plasma, basing ourselves on the formulas obtained in [18]. At the same time, in accord with the experimental data, we shall assume

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TABLE

Gyrofrequency for the ions Ω_i rad/sec	~ 20
period T_i sec	~ 0.3
Larmor radius L_i, cm	$\sim 5 \cdot 10^4$
Gyrofrequency for the electrons Ω_e rad/sec	$\sim 4 \cdot 10^4$
period T_e, sec	$\sim 1.8 \cdot 10^{-4}$
Larmor radius L_e, cm	$\sim 1.6 \cdot 10^3$
Debye radius D, cm	~ 100
Thermal velocity of ions V_T^i, cm/sec	$\sim 10^6$
Thermal velocity of electrons V_T^e cm/sec	$\sim 10^7$
Plasma frequency ω_p, rad/sec.	$\sim 4 \cdot 10^5$
period T_p, sec.	$\sim 1.5 \cdot 10^{-5}$
Pressure p_{gas} erg/cm^3	$\sim 7.4 \cdot 10^{-11}$
Magnetic pressure, p_{magn} erg/cm^3	$\sim 4 \cdot 10^{-8}$

The conductivity σ is determined by the effective number of collisions

$$\nu^{e}_{эфф} = \nu^{ei}_{эфф} + \nu^{ee}_{эфф} + \nu^{em}_{эфф} \approx \nu^{ei}_{эфф} + \nu^{em}_{эфф}$$

(the indices e, i, m correspond to electrons, ions and neutral particles; [the index эфф means "eff"]; an analogous expression should also be written for $\nu^{i}_{эфф}$). For the applicability of the kinetic approach [18], it is necessary that $\omega_p^2 \gg \omega^2$. By the same token we limit the validity of our discussions to the region of sufficiently low frequencies (see Table). But if above all $\omega \gg \nu_{эфф}$, then during the estimates of conductivity σ it may be estimated that $\nu_{эфф}$ depends only on the velocity v, neglecting the dependence on the frequency ω. In this case

$$\nu^{ei}_{эфф} = \frac{2\pi}{3} \frac{e^4}{k^2T^4} \bar{v}_e N_i \ln\left(\frac{2kTD}{1{,}78\, e^2}\right),$$

where

$$\bar{v}_e = (8kT / \pi m)^{1/2},$$

or (after substitution of numerical values)

$$\nu^{ei}_{эфф} = \frac{5{,}5\, N_i}{T^{3/2}} \ln(220T/N^{1/3}) \approx 2 \cdot 10^{-3} \text{ sec}^{-1}.$$

In case of collisions with molecules the Coulomb forces are not taken into account at great distances and the transverse cross section

depends little on v and on the scattering angle θ; This is why, considering the molecule to be hard sphere of radius $a \sim 10^{-8}$ cm, we have

$$\nu_{\text{эфф}}^{em} = \frac{4\pi}{3} a^2 N_m \bar{v}_e \approx 10^{-6} \text{ sec}^{-1}.$$

Utilizing analogous operations for the number of collisions of ions, we shall obtain

$$\nu_{\text{эфф}}^{ii} = 10{,}4 \cdot 10^{-8} N_i \ln [2.3 \cdot 10^5 (T/N_i^{1/3})^{3/2}] \approx 10^{-5}$$

$$\nu_{\text{эфф}}^{im} = 8 \cdot 10^{-18} T^{1/2} N_m \approx 10^{-8}$$

$$\nu_{\text{эфф}}^{ie} = N_e \nu_{\text{эфф}}^{ei} / N_i = \nu_{\text{эфф}}^{ei} \approx 2 \cdot 10^{-3}$$

The estimate of conductivity of partially ionized medium is a rather complex problem. However, in the outer parts of the magnetosphere we may neglect the influence of neutral ions, that is, we may estimate the bond of ion-electron plasma with neutral atoms as very weak. In accord with [19] the weak bond condition is

$$\omega (\nu_{\text{эфф}}^{im} + m_e \nu_{\text{эфф}}^{em} / m_i)^{-1} \gg 1.$$

Inasmuch as the region under consideration is that of sufficiently low frequencies (see above), this condition is fulfilled. Indeed, for frequencies $\omega \sim 10^{-2}$ ($T \sim 10^2$ sec)

$$\omega (\nu_{\text{эфф}}^{im} + m_e \nu_{\text{эфф}}^{em} / m_i)^{-1} \approx 10^6 \gg 1.$$

Noting, by the way, that in the considered case the mean free path $l \sim 10^{10}$ cm, is comparable with the characteristic dimension ($\sim 8 R_E$) of the region $L \sim 5 \cdot 10^9$ cm, which, according to the classification of [20], corresponds to average density plasma with all the ensuing consequences relative to high conductivity and the validity of plasma definition as a fluid.

In the outer magnetosphere the medium is anisotropic, inasmuch as in the given case the isotropy condition is not fulfilled [18]

$$\Omega_e \Omega_i \ll \nu_{\text{эфф}}^{ei} \nu_{\text{эфф}}^{im}.$$

In connection with the generalized Ohm law for an anisotropic medium

$$\mathbf{j} = \sigma_0 E_{\parallel} + \sigma_1 E_{\perp} + \sigma_2 \frac{\mathbf{B} \times \mathbf{E}}{|\mathbf{B}|},$$

where, neglecting the contribution of ions,

$$\sigma_0 \approx \sigma_0^e = \frac{e^2 N_e}{m_e \nu^{ei}_{\text{эфф}}} = 6{,}4 \cdot 10^{12}\ \text{сек}^{-1} = 7{,}1 \cdot 10^2 (\text{ом} \cdot \text{м})^{-1}$$

$$\sigma_1 \approx \sigma_1^e = \frac{e^2 N_e \nu^{ei}_{\text{эфф}}}{m_e [\Omega_e^2 + (\nu^{ei}_{\text{эфф}})^2]} = 1{,}6 \cdot 10^{-2}\ \text{сек}^{-1} = 1{,}7 \cdot 10^{-12} (\text{ом} \cdot \text{м})^{-1}.$$

In the expression for the Hall conductivity

$$\sigma_2 = \sigma_2^e - \sigma_2^i = e^2 N_e \left\{ \frac{\Omega_e}{m_e [\Omega_e^2 + (\nu^{ei}_{\text{эфф}})^2]} - \frac{\Omega_i}{m_i [\Omega_i^2 + (\nu^{im}_{\text{эфф}})^2]} \right\} \approx 0,$$

$$\sigma_2^e \approx \sigma_2^i = 3{,}2 \cdot 10^5\ \text{сек}^{-1} = 3{,}5 \cdot 10^{-5}\ (\text{ом} \cdot \text{м})^{-1}.$$

5. - Let us now turn back to the question of magnetic field of the stream penetration into the Earth's magnetosphere (sec. 4). In the presence of highly conducting plasma in the magnetosphere there takes place the conservation of the magnetic flux. The lines of force of the stream's field behave as if, somehow, they would "flow" past the Earth's magnetosphere, without penetrating into it (see Fig. 1). In the presence in the field of a component, perpendicular to the motion direction of the flow, field contraction takes place ahead of the magnetosphere (with a corresponding decrease of stream's plasma compressibility at the expense of magnetic pressure rise) with slipping sidewise. The representation of the magnetosphere as a highly conducting fluid compels us to seek a magnetohydrodynamic treatment of the problem of geomagnetic storms (see for example [21, 22]. The discovery of radiation belts allowed to propose a concrete physical mechanism of geomagnetic storm development, admitting both, the magnetohydrodynamic as well as the classical treatment (the former with representation of magnetosphere compression and expansion [23], and the latter with ring current representation during the main phase of the storm [24]).

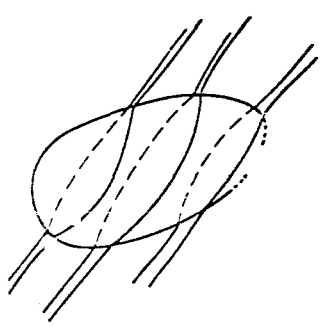

Fig. 1

The frozen-in state of the magnetic field in the plasma leads to field increase at plasma compression and its attenuation at expansion. At the same time the increase and the decrease of the field (that is, the appearance of is not connected with the real change of the magnetic flux, and consequently, it has nothing in common with the increase or decrease of the field on account of stream's field superimposition.

6. - Correspondingly with these representations, any general planetary negative perturbation must be linked with magnetosphere expansion at the expense of the emergence of an additional number of charged particles inside the magnetosphere or heating (acceleration) of previously existing particles or on account of part of the lines of force of the geomagnetic field being carried away by the corpuscular stream (formation of magnetosphere train); action by both mechanisms is quite possible. Any increase of external, either kinetic or magnetic pressure of the corpuscular stream may lead only to positive general planetary perturbations. Indeed, any line of force of a magentic field, external relative to the magnetosphere, and identified by charged particles twisted near it, does not penetrate the magnetosphere plasma, but "pushes" it. In the last resort the external field might diffuse through the magnetosphere and induce the field attenuation at the Earth's surface; however, the characteristic time of diffusion is very great.

Analogous representations should be borne in mind also when analyzing the question of energetic losses. Being left on its own, the geomagnetic field is very inertial only under influence of inner sources of losses. Indeed, in the presence of frozen-in state of the magnetic field in the magnetosphere plasma the characteristic attenuation time is $t \sim 4\pi\sigma L^2 / c^2$, where σ is the conductance, L is the characteristic dimension, c is the speed of light. At $\sigma \sim 10^{12}$ sec^{-1} it is sufficient to shift the line of force by 10 km, so that $\sim 10^4$ sec be required for the return to initial state; for lesser line of force displacements (less than the variations of the geomagnetic field) the characteristic attenuation time decreases.

Taking into account the above expounded considerations, the rate of energetic losses at general planetary perturbations is determined by the rate of magnetosphere "cooling". In other words, if the source of the storm,

assuring the energy ingress into the geomagnetic field, is disposed of, the speed of field restoration to the normal (initial) state is determined by the velocity of removal of geomagnetic field-trapped energetic particles bearing the responsibility for the perturbation. The charge exchange reaction between radiation belt protons and atmosphere's (geocorona's) neutral hydrogen atoms ([23], including the infrapaginal notes) is in this regard effective. As a result of this reaction, the proton loses a significant part of its energy, and therefore does not contribute substantially to the geomagnetic effects. The concentrations of atomic hydrogen at distances $\sim 4R_E$ is $\sim 10^2$ cm^{-3}, and the lifetime of energetic protons constitutes $\sim 10^5$ sec [23, 25]. During major storms the contraction of the magnetosphere is greater, the ring current forms nearer the Earth; accordingly, the lifetime of protons is lesser. The charge exchange process accelerates also as a result of magnetosphere heating by magnetohydrodynamic waves, which too leads to the curtailment of the lifetime of protons.

Note that the last circumstances agree well with the observation data. Firstly, the duration of the restoration phase decreases indeed with the rise of storm intensity [26]. Secondly, this phase varies with the course of the solar activity cycle [27]. The last case should have been expected from the following considerations. According to [28], the intensity of solar radiation, responsible for the formation of atomic hydrogen (λ 2000 Å), varies little with the course of the cycle, while radiation with λ 1000 Å, determining the temperature of the exosphere, is less intense in the cycle minimum. In connection with this the geocorona must be denser in the minimum years, inasmuch as the correlation between the rate of atomic hydrogen formation and its escape varies. This is why the phase of restoration of the storm must also be shorter in the cycle minimum.

Besides protons, electrons may also be responsible for the ring current (or for line of force shift, which is equivalent) [29]. The interaction between the electrons themselves (as a result of pitch-angle chaotization and the ensuing decrease in the number of electrons with small pitch-angles) may lead to electron annihilation in the dense layers of the atmosphere. According to [30], the time required for the direction of particles moving in a gas of identical particles, to change by 90° is $\sim 2 \cdot 10^6$ sec (for a concentration of 200 cm^{-3}, which is evidently, overrated and energy of 1 kev).

For electron-proton collisions this rate decreases by 10 days. Inelastic collisions of electrons with energies ~ 1 kev with hydrogen atoms correspond to a time of $\sim 3 \cdot 10^6$ sec. Therefore, the death of electrons, surviving longer than protons, can hardly determine the rate of energetic losses.

It is clear that the drift away velocity of particles is not great. All particles (total return to normal state) may be removed in about 10^5 - 10^4 sec. A smaller fraction of particles may, evidently, drift away in a lesser time (incomplete return to normal state).

The above discussions refer to geomagnetic disturbances of general planetary character, that is, to perturbations linked with the extra-ionospheric part of the magnetosphere, The disturbances linked with the ionosphere have a substantially lesser attenuation time (on account of lesser conductivity σ, as well as smaller characteristic dimensions). However, the disturbances of the ionospheric origin cannot have in the general planetary plan a higher energy than that of perturbations of extra-ionospheric origin (and this on the basis of representations on causality). The energetic estimates [31, 32] also refer to that. Note that the irregular D_i- disturbances may reflect not only the irregular character of energy ingress in the magnetosphere, linked with the influence of the magnetic field of the stream on its interaction with the Earth's magnetosphere, but also the nonuniform and nonstationary character of distribution of geocorona's atomic hydrogen.

7. - Obviously, the most important question of the introduction mechanism of energy into the Earth's magnetosphere is not resolved by our discussions and reasonings. It is most probable of all, that effective in this regard are not one, but several mechanisms, complementing one another:

1) at the expense of boundary turbulization small plasma clusters may reach inside the magnetosphere and be trapped by the geomagnetic field; the clusters' proper field, taking into account the smallness of their dimensions, must rapidly attenuate;

2) the magnetohydrodynamic waves, emerging at magnetosphere boundary at irregular action of the stream (taking into account the field), may become shock waves at magnetosphere penetration, with a corresponding energy dissipation and magnetosphere plasma heating (this is close to the idea of the magnetic "piston", developed in [3]);

3) there is in the transitional region between the magnetopause and standing shock wave a turbulent region, which may be considered as an isotropic set of acoustic waves. Taking into account the relative motion of the plasma in this region and in the outer part of the magnetosphere, the refraction of waves at magnetosphere boundary allows to explain the transfer inside the magnetosphere up to 10^{19} erg/sec [33], which apparently is sufficient for the explanation of storm's energy;

4) the mechanism of nonlinear reaction of electrons and of possible acoustic waves in the unsteady transitional region of solar wind interaction with the Earth's magnetosphere, which is linked with the resonance events on electron gyrofrequency and suggests the modified mechanism of cyclotron instability [34].

*** THE END ***

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