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Concerning the Generation of Plasma Inhomogeneities in the Magnetosphere

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Abstract

This paper is devoted to developing of the mechanism for convecting inhomogeneities generation in the geomagnetosphere. In previous papers it has been shown that all attributes of substorm break-up can be described if we admit that convecting plasma flow directed from the tail to the Earth has non-uniform structure in the form of the "bunches" moving towards the Earth along with plasma convection. In this paper, it is shown that the existence of spatial inhomogeneity of convection velocity and its sudden change in time can create in combine action the spatial - temporal formation which looks like inhomogeneity of plasma density (pressure), moving at convection speed (in the direction of the Earth) or at Alfven speed towards the magnetotail. I show that the structure appears on the magnetosphere night side at the distance of 10-20 Earth radii, because of peculiarities of the electric field of convection.

Most likely, plasmoids, observed during geomagnetic disturbances moving towards the magnetospheric tail, approximately at Alfven speed, are Alfven resonances. Even though mechanisms of generation of both plasma convecting, and Alfven wave perturbations are similar, conditions of excitation of the latter are harder. Therefore, not all substorms will be accompanied by generation of plasmoids. And may be intensive, but short pulses of south IMF Bz-component can generate plasmoids, but not create auroral break up of a substorm. The electric field theory forecasts electric field peculiarity along the magnetotail axis with the minimum at L ~ 18, in the magnetic field depression region. This anomaly is associated with the negative anomaly of the convection velocity, positive anomalies of the density and the plasma pressure. The latter should result in the magnetic field depression observed in the magnetospheric magnetic model exactly in this region. The most important is that interaction between the spatial inhomogeneity of density and the temporal oscillation of the same density results in the plasma pressure inhomogeneity moving at the convection velocity towards the Earth. Thus an important modulus for the substorm formation mechanism is made. According to this mechanism, the convectional inhomogeneity represents a necessary and sufficient condition for the substorm break-up.

Introduction

All attributes of substorm break-up can be described if we admit that convecting plasma flow directed from the tail to the Earth has non-uniform structure in the form of the "bunches" moving towards the Earth along with plasma convection.

M.I. Pudovkin [5, 6] called the time of the plasma tube passage from the boundary L_∞ to the observation point L as “transport time”. Obviously it is not longer than the period between the reversal of the Bz-component sign of the interplanetary magnetic field (IMF) and the substorm commencement (45-60 min). During this time, the plasma tube covers the distance of L_∞-L with average velocity of $(cE/4B_0)L_\infty^4/(L_\infty - L) \sim (cE/4B_0)\ L_\infty^3$ while drifting; the time of this process is $T = 4B_0R_0(L_\infty-L)^2/cEL_\infty^4$. Given T = 3000 s, $B_0 = 0.5$, $R_0 = 6.37 \cdot 10^8$ cm, $E = 3 \cdot 10^{-8}$ CGSE, we derive L_∞ value ≥ 10.86, if $L \leq 5.43$. Thus the plasma tube should start from the L-shell 10-12 to be found on the L-shell of the auroral oval midposition. M.I. Pudovkin considers reconnection region to be situated on the L-shell 10-12 [6]. There were many unsuccessful attempts to find physical processes (microscopic processes) accompanying the reconnection (i.e. existence of strong plasma turbulence implying quasi-collisional regime) in this region. What is there at these distances on the night side of the geomagnetosphere? The magnetic field empirical model of Mead-Fairfield [1] is based only on generalization results of observations and does not contain artificial corrections of hypothetical character. Fig. 16 shows significant depression of the magnetic field on the magnetosphere night side at L ~ 12-15. All figures demonstrating the magnetic field distribution in [1] distinctly show this effect, though authors consider it to be an artifact.

There should be balance between the magnetic and gas pressure; consequently, the region of the magnetic depression should coincide with that of the increased gas pressure. Region of the gas pressure increase in one-dimensional flow under study is also the region of an increased plasma density and low convection velocity.

Mechanism for forming plasma inhomogeneities in the magnetosphere

As pressure and density in the magnetosphere are related by the adiabatic equation, we will interpret the equation:

$$n'(x,t) = n_\infty(x-V_0t)\ (x_\infty/x)^4 \exp(-\int dx/V_x\tau). \qquad (1)$$

Hereafter, x is the distance along the axis X in Earth radii R_e, V is the convection velocity in R_e/s.

As we have already noted, a necessary condition for the break-up formation is the presence of plasma inhomogeneities that drift from the geomagnetic tail region to the Earth. It is evident that there are plasma density (pressure) inhomogeneities in the near magnetotail. How make them move at the electric drift velocity? The main problem here is to "get" inhomogeneity into the stream of convection.

Consider one-dimensional case. Let us suppose spatial density inhomogeneity:

$$n'(x,t.) = n_0 A(t) R(x) \quad (2)$$

where A (t) is the time function, R(x) is the x-coordinate function. Let A(t) and R(x) be a(ω) and r(k), respectively: $A(t) = (1/2\pi)\int a(\omega)\exp(-i\omega t)d\omega$ and $R(x) = (1/2\pi)\int r(k)\exp(-ikx)dk$. It is necessary that $\omega = kV_0$ for frequency and spatial oscillations form the wave moving at V_0 phase velocity. Then:

$$n'/n_0 = (x_0/2\pi)\ \{\int a(kV_0)r(k)\exp(-ik(V_0t + x))\,dk\}. \quad (3)$$

Thus "resonance" adjoint oscillations with $\omega=kV_0$ (waves moving at the convection velocity) "get" into the convection stream. The product $a(kV_0)r(k)$ should not be small inside the integration interval (i.e., curves $a(kV_0)$ and r(k) should coincide) for the generation process of such oscillations to be effective.

According to the "resonance" $\omega = kV_0$, spatial inhomogeneity dimension is l; consequently, the adjoint period of temporal oscillations should be l/V_0. The period of temporal oscillations is $3 \cdot 10^3$ s (about an hour) at $l \sim 6 \cdot 10^9$ cm (i.e., 10 Earth radii) and the convection velocity $2 \cdot 10^6$ cm/s.

Resonance can appear at the convection velocity as well as at the Alfven velocity V_A. The Earth-directed higher inhomogeneity of the magnetic field results in certain excitement conditions of the Alfven wave moving towards the Earth. These conditions are harder than those of the wave moving towards the magnetotail. Besides, the Alfven velocity is higher than the convection one; therefore frequency range is higher. If "convective waves" resonate with variations of IMF Bz-component with the period of about an hour, Alfven waves resonate with Bz-component (IMF) variations (period of 5-10 min), i.e. with steep fronts.

Plasmoids moving towards the magnetotail at the Alfven velocity during the geomagnetic disturbance are most probably Alfven resonances. Generation mechanisms of both convective and Alfven wave disturbances are similar, but excitement conditions of the latter are harder. That is why just some substorms involve plasmoid generation. Probably, these are intensive narrow (short) pulses of the south IMF Bz-component that may generate only plasmoids, but not create auroral break up of substorm. If the plasma inhomogeneity did not "get" into the stream of convection towards the Earth (there is no "resonance") when Bz<0, then there will not be auroral breakup. Such situation according to observations is known.

The A(t) certain form is specified by variation of the Bz-component and solar wind velocity. Though this dependence is variable, it can be characterized by a rapid increase (modulo) and more gradual decrease. Let us approximate it by the function:

$$A(t) = t_0 (t + t_0) /(t^2 + t_0^2), \quad t \geq 0. \quad (4)$$

The R(x) function describing the "bunch" of plasma density (of plasma pressure) in the region of the magnetic field decrease can also be approximated by a simple function:

$$R(x) = x_0 [(x^* - x) + x_0]/[(x^* - x)^2 + x_0^2]\ . \quad (5)$$

Functions (4) and (5) present disturbances of a certain initial state; density variations should be considered in reference to it $n_\infty = n_g + n'(x,t)$.

Certain form of approximating functions is an arbitrarily chosen (to make the Fourier transform operation easier). Parameters of approximating functions are deduced from generalized observation data.

Recall that x<0 on the night side. Position of the magnetic field depression region indicates that the inhomogeneity formation region (hereafter we will call it "wedge") is at the distance of 10-15 R_E. It means that the "tip" of this wedge is displaced at the distance of 10-12 R_E on the night side. Let us arrange that the wedge tip has coordinate x* at the instant of time t=0. The R(x) function has extremum at:

$$x_r^{1,2}=x^*-x_0(1\pm\sqrt{2}). \quad (6)$$

Fourier transforms (4) and (5) are:

$$a(\omega) = 1/2\ \exp(-\omega t_0) \quad \text{and} \quad r(k) = \exp(kx_0)\sin(kx^*). \quad (7)$$

If we substitute a(ω) and r(k) in (6), considering that $\omega = kV_0$, we obtain the following equation after the inverse Fourier transform:

$$n'/n_0 = x_0\ (V_0t - x + x^*)]/[(V_0t_0 + x_0)^2 + (V_0t - x + x^*)^2]. \quad (8)$$

This is a wave disturbance that results from interaction of two oscillatory motions. Thus (8) presents a dynamic wedge form (unlike the static one described by (5)). We will call the new physical object (plasma inhomogeneity described by the dynamic wedge) as "plasma packet" to avoid confusion. The stable phase point $\boldsymbol{\varphi = (V_0t - x + x^*) = \mathrm{const}}$ probably moves at V_0. As for values of relations, it is an instantaneous velocity of plasma electric drift in the equatorial region (drift velocity of the plasma tube trace, see [8]) for V_0. We can specify the tube average velocity at the segment between the L-shell 1 and L-shell 2 for the stable electric and dipole geomagnetic field:

$$\langle V \rangle = cE/B_0 L^3_{ef}, \text{ где } L^3_{ef} = L_1^2 L_2^2/(L_1 + L_2)$$

If the segment is not long, substitution of L_{ef} for the least value from $\{L_1L_2\}$ will not result in mistake. Thus the convection velocity will be considered coordinate-independent in the region of the wedge formation. Equation (8) consists of four parameters V_0, t_0, x_0 and x^*. Let us determine them using problem situation.

From (4)-(5) it follows that $t_m = t_0$, where t_m is the moment of the time-disturbance maximum. Hereafter we will consider t to be $t = 1.8{\cdot}10^3$ s (half of an hour), V_0 to be constant value equal to $1.8 \cdot 10^{-3}$ R_E/s or $1.15{\cdot}10^6$ cm·s^{-1} This magnitude corresponds to the electric field of ~25 mV/m in the ionosphere in latitude of ~ 68°, i.e. to a typical electric-field value in the medium-disturbed auroral ionosphere. Given transport time of 45 minutes (time between the change of the Bz-component sign and the break up), let us determine distance from L=5 to the start point, where the wedge motion of about 5 Earth radii started 40-45 minutes before. The distance L=5 corresponds to the geomagnetic latitude of 64°, where we can observe the extreme equatorial point of the auroral oval night side at moderate disturbances. In this case the start-point coordinate, where the plasma packet "tip" started its motion, is $x^* = -10$. Finally, from (6): $x_0 = (x^*-x_r^{(2)})/(\sqrt{2}-1)$. Given $x^* = -10$, $x_r^{(2)} = -13$, x_0 is -7.25.

The said arguments explain formation of the space-time traveling disturbance, which results from interaction of spatial and temporal oscillations. There are many such disturbances, but significant are those with the phase velocity close to the convection one ("resonance" disturbances). Such plasma packet is a necessary and sufficient condition for the substorm "break up" appearance [2, 8]. The proposed phenomenological model is based on the observation-data interpretation and does not describe the cause of the plasma pressure bunch and magnetic depression. We think the cause is the anomaly of hydrodynamical flow. If it decelerates, the plasma pressure bunch appears. In this case the only one cause of negative anomaly is that of the electric convection field.

The magnetospheric electric field depends on the solar wind parameters. The bow shock (BS) front is the main transducer of the kinetic energy of the solar wind into the electromagnetic and gas-kinetic energy of the transition layer and magnetospheric processes [2-4, 7]. Potential of the BS front can be defined from the electric field integration at the front using continuity of a normal component of the solar wind velocity and the IMF tangential component [2-4, 7]:

$$U_b = -(VsB_0/c)\ y_b(b_y^2+b_z^2)^{1/2}\ \mathrm{tg}\varphi/2\ \sin(\psi-\psi_0),$$

where V_S is the solar wind velocity, B_0 is the IMF intensity modulus, c is the velocity of light, b_x and b_y are unit vectors of the solar-magnetospheric coordinate system, φ is the angle between the axis X and the vector directed from the coordinate origin to this front point. The front is approximated by the paraboloid of rotation with y_b parameter ($y_b/2$ is the distance from the coordinate origin to the "nose" ("head") BS-front point). Finally, $\mathrm{tg}\psi = y/z$, $\mathrm{tg}\psi_0 = b_y/b_z$.

The magnetosphere is also approximated by the paraboloid of rotation with y_g parameter. Solution of the Laplace equation in parabolic coordinates yields potential [37-39]:

$$U_g = [(au + b/u)(cv+d/v) + U_{02}\, J_1(ku)\, I_1(kv)\}\sin(\psi - \psi_0)]. \tag{9}$$

where u and v are parabolic coordinates, J_1 and J_2 are Bessel functions,

$u = (r+x)^{1/2} = (2r)^{1/2}\cos\varphi/2$, $v = (r-x)^{1/2} = (2r)^{1/2}\sin\varphi/2$, $r = (x^2+y^2+z^2)^{1/2}$. Hereafter distances will be measured in Earth-radius units in the Cartesian coordinate system (unless otherwise specified). The k value is chosen in such a way that the second summand of the potential (9) is nil in the magnetopause [3, 7].

In this case $k = 3.83(y_g)^{-1/2}$, where y_g is the magnetosphere half-width (with the guess value of 20 Earth radii) along the Dawn-Dusk meridian. Note that the distance from the Earth to the subsolar magnetosphere point is $y_g/2$.

Electric potential for the magnetosphere in the XY plain at $b_y = 0$ (without considering the corotation field) can be written as:

$$U_g = [-A(VsB_0z/c)y + U_{02}\, J_1(ku)\, I_1(kv)]_{z=0}\ , \tag{10}$$

where A is a certain numerical coefficient calculated from conditions of the substance balance (substance coming through the bow shock front and going along the transition layer). It is the constant magnitude under steady conditions [3].

Y-differentiation of (10) yields y-component E_y^D of the electric field for the Dawn-Dusk meridian:

$$E_y^D = E_{01} + E_{02}[J_1(S_x)/S_x]\ , \tag{11}$$

where $E_{01} = -AVsB_0z/c$, $E_{02} = -U_{02}k^2$, $S_x = k(2x)^{1/2}$, V_0 is velocity, Bz is a vertical component of the interplanetary magnetic field; U_{02} is found using boundary conditions.

Time dependence of the electric field is expressed by time-dependent solar wind parameters V_0 and B_0z of the component E_{01}. Time dependence of the E_{02} electric field is unknown. Let us suppose that it is equal for E_{01} and E_{02}. Then:

$$E_y^D = E_{01}\ [1 + G\, J_1(1.21\sqrt{x})/\sqrt{x}]. \tag{12}$$

Here $G = E_{02}/1.21E_{01}$=const, E_{01} depends only on time. In the case of one-dimensional steady flow for $y_g = 20$:

$$n' = \langle nV \rangle/V = n_0V_0/V = D/[1 + GJ_1(1.21\sqrt{x})/\sqrt{x}] \tag{13}$$

where n' is the density disturbed value, n_0 is an undisturbed value of the plasma density, <nV> is a time- and space-averaged value of the particle flux under undisturbed conditions, D is the function of t.

Equation (13) corresponds to (1) and (3) from the physical point of view. Structure of these expressions is similar to that of (1): it is a product of two functions, one of which is time-dependent, while the second is X coordinate-dependent. Value x_m^0 for (7) is -18, and the (5) maximum coincides with that of (13). Parameters of D and G for (13) are 0.981 and 2.43, respectively. In this case both curves correlate well.

Conclusions

Physical meaning of this coincidence is that the electric field theory [3, 4, 7] forecasts electric field peculiarity along the magnetotail axis with the minimum at L ~ 18, in the magnetic field depression region. This anomaly is associated with the negative anomaly of the convection velocity, positive anomalies of the density and the gas pressure. The latter should result in the magnetic field depression observed in the model MF-75 [1] exactly in this region. The most important is that interaction between the spatial inhomogeneity of density and the temporal oscillation of the same density results in the plasma pressure inhomogeneity moving at the convection velocity towards the Earth. Thus an important modulus for the substorm formation mechanism [2, 8] is made. According to this mechanism, the convectional inhomogeneity represents a necessary and sufficient condition for the substorm break-up.

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