On the role of the bow shock in power of magnetospheric disturbances

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Abstract. Bow shock is a powerful transformer of the solar wind kinetic energy into the gas dynamic and electromagnetic energy. Indeed, the magnetic field tangential component and magnetic energy density increase by factors of almost 4 and approximately 15, respectively, at the bow point when the front is crossed. A jump of the magnetic field tangential component at front crossing means that the front carries an electric current. The solar wind kinetic energy partly transforms to gas kinetic and electromagnetic energy when passage through the bow shock front. The transition layer (magnetosheath) can use the part of this energy for accelerating of plasma, but can conversely spend the part its kinetic energy on the electric power generation, which afterwards may be used by the magnetosphere. Thereby, transition layer can be both consumer and generator of electric power depending upon special conditions. The direction of current behind the bow shock front depends on the sign of the IMF Bz-component. It is this current which sets plasma convection in motion. Energetically, this external current is necessary for maintaining convection of plasma in the inhomogeneous system (magnetosphere). The generator at the bow shock front can be a sufficient source of power for supplying energy to substorm processes in the geomagnetosphere.

Keywords: Solar wind, bow shock, plasma, magnetosphere

Introduction

It was clear that the primary source of energy is the solar wind, in essence, it was necessary to ask two questions. The first question was: what type of energy is used. The Perreault-Akasofu formula [1], which adequately described the relation between the solar wind parameters and geomagnetic disturbance, evidently indicated that the electromagnetic part of the total solar wind energy is used. However, this conclusion has become doubtful at once. First, only very small part of the solar wind energy is presented in the electromagnetic form. Therefore, it was necessary to assume that the efficiency of the transfer and transformation mechanisms should be about 100% in order to feed a substorm process. However, the main question was: how this energy penetrates into the magnetosphere and is subsequently realized in this region.

However, the Perreault-Akasofu formula is still successfully used (although is criticized) as a convenient empirical block in practical calculations. In this case many researchers ignored the fact that the bow shock is a powerful transformer of the solar wind kinetic energy into the gas dynamic and electromagnetic energy.

When the solar wind flows round the magnetosphere, its flow structure and interplanetary magnetic field (IMF) lines are affected. This indicates the appearance of an electric current system in near-Earth space. the magnetized solar wind plasma moving at the solar wind velocity in the coordinate system of near-earth bow shock (BS) induces an electric field in this system. When crossing the bow shock front at the nose point, the tangential magnetic field component increases nearly four times, and the magnetic field density – 15 times. The physics of the phenomenon implies that the Earth in the solar wind stream disturbs the stream supersonic for the Earth. this suggests that a BS front is formed above which along the stream the solar wind plasma is undisturbed, and below new scales of value variations (minimal is the front thickness) appear. it is clear that the primary energy source for magnetospheric processes is the solar wind, but the process of energy transfer from the solar wind into the magnetosphere, or rather, to convecting magnetospheric plasma, appears to be rather complicated. It is necessary to note, that interest to research processes in BS has strongly increased recently (research within the framework of projects GEOTAIL and CLUSTER-II), and what is especially important, now BS is being considered not only as a characteristic of the solar wind, but also as a characteristic of the near-Earth space.

Basic equations

the Poynting vector (for the case of the solar wind-magnetosphere interaction) is defined as:

$$S = c\,[E\mathrm{x}B]/4\pi$$

where E, B are intensities of the electric and magnetic fields, respectively.

1. $S = c\,[E\mathrm{x}B]/4\pi = VB^2/4\pi$, where $v = \dfrac{c[E\times B]}{B^2}$;
2. $S = c\,[E\mathrm{x}B]/4\pi = VB^2/4\pi = 2VP_B$, because P_B is a magnetic pressure ($P_B = B^2/8\pi$).
3. $S = \dfrac{c[E\times B]}{4\pi} = -\dfrac{c[\nabla\phi\times B]}{4\pi}$, (in the stationary case E=-**grad**(Φ)); **curl**(ΦB)=Φ**curl**(B)+[∇Φ×B];

j=(c/4π)**curl**(B), **div**(S)=**div**(Φj), because it is well known **div**(**curl**)=0.

The gas kinetic energy flux will be:

$$S = V(\gamma \cdot P_g + \frac{1}{2}\rho V^2),$$

Pg – is a gas pressure, V – is a mass velocity of plasma, ρ – is a density of plasma; γ – is the adiabatic exponent.

We restrict ourselves to the stationary case. In the stationary case, the terms with partial derivatives (∂E/∂t) and (∂B/∂t) are zero, whereas the electric field is potential: E=-**grad**Φ; Φ is the electric potential. It is known that [**grad**Φ×B]=**curl**(ΦB) – Φ**curl**(B).

So S=Φj–(c/4π)**curl**(ΦB). The integral over the entire magnetosphere surface (s) is:

$\oint$ Sds= $\oint$ [Φj– (c/4π)**curl**(ΦB)]ds = $\oint$ Φjds. The integral $\oint$ Φjds≠0, if Φ≠const.

The energy flow within the closed surface is defined by the electric current normal component and potential distribution along the surface. the density of the electric current component normal to the surface is expressed in terms of surface current divergence.

The bow shock

A jump of the magnetic field tangential component when crossing the BS front indicates the presence of a current at this front. We use three coordinate systems. The first coordinate system is earth-centered solar-terrestrial orthogonal. Its X-axis is directed to the Sun, Z-axis is perpendicular to the plane of the ecliptic, Y-axis is also in the plane of the ecliptic and is dawn-dusk directed. The second one is orthogonal l,n,τ with the center at the BS front at the tangency point of the axis 1 to the front. Here the n-axis is directed along the outward normal, and the τ-axis supplements the coordinate system to the right one. The third system starts at the Earth center, the distance to a point, whose coordinates are given, is defined by the position vector r, angular φ between the position vector and the X-axis, and angular ψ between the XZ and Xr planes (see fig. 1).

The bow shock front surface is given by the paraboloid of rotation. the BS front is in fact very close in form to hyperboloid, but we make here a simplification that we consider non-essential. So the equation for the BS front is

$$r = y_g/\cos(\varphi/2) \quad (1)$$

each point on the surface of the front is given by two coordinates: φ,ψ. The IMF components in the coordinate system (l,n,τ) on the BS front surface are as follows [2, 3]:

$$B_{l0}=B_0[b_{x0}\sin(\varphi/2) + (b_{y0}\sin\psi - b_{z0}\cos\psi)\cos(\varphi/2)] \quad (2)$$

$$B_{n0} = B_0[b_{x0}\cos(\varphi/2) - (b_{y0}\sin\psi - b_{z0}\cos\psi)\sin(\varphi/2)] \quad (3)$$

$$B_{\tau 0} = B_0[b_{y0}\cos\psi + b_{z0}\sin\psi] \quad (4)$$

The corresponding surface current density at the BS front [2] is defined as:

$$J_{l;1} = -c(\sigma - 1)B_{\tau 0}/4\pi \quad (5)$$

$$J_{\tau 1} = c(\sigma - 1)B_{l0}/4\pi \quad (6)$$

where σ = (B_{l1}/B_{l0}) = ($B_{\tau 1}/B_{\tau 0}$), i.e., the ratio between magnetic field tangential components in front of and behind the BS front(fig.2). The expression for σ in the function of medium parameters is given in [4]:

$$F(\sigma) = \sigma^3 + d_2\sigma^2 + d_1\sigma + d_0 = 0 \quad (7)$$

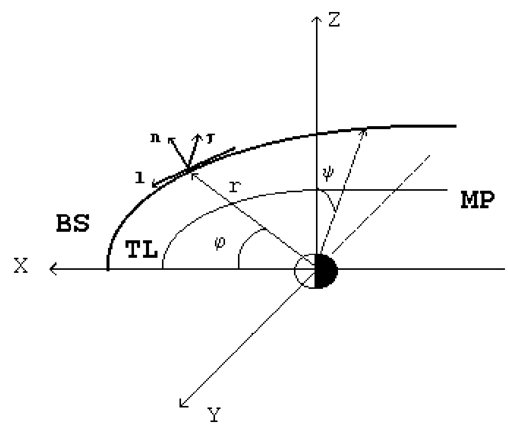

Fig. 1. The fragment of the Bow Shock (BS), of the Transition Layer (TL) or magnetosheath, magnetopause (MP). The location of the orthogonal coordinate system with the origin in the Earth's center (axis x is directed towards the sun, axis y is directed from dawn to dusk and axis z is directed towards the geographic north) and the location of auxiliary coordinate system (r, φ, ψ) and the local coordinate system (l, n, τ).

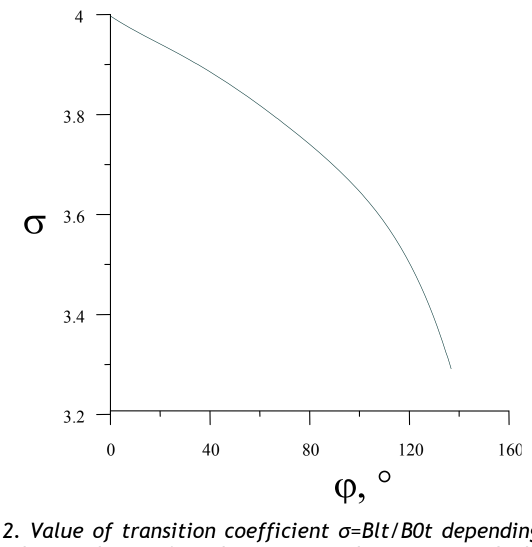

Fig.2. Value of transition coefficient σ=Blt/B0t depending on the angle φ for the equatorial section (calculated

Coefficients of (7) are specified by the following relations in [4]:

$$d_2 = [1 + (2-\gamma)(A^2 - 1)] \quad (8)$$

$$d_1 = [\gamma - 2k + (\gamma - 1)(A^2 - 1)k](A^2-1) \quad (9)$$

$$d_0 = - (\gamma + 1)(A^2 - 1)^2 k \quad (10)$$

where $k = (B_{n0}/B_{\tau 1})^2$, $A^2 = A_0^2 \cos^2(\varphi/2)/(B_{n0})^2$, $A_0^2 = 4\pi\rho_o V_0^2/B_0^2$, ρ_o is the density, V0 is the solar wind velocity, B_0 is the IMF intensity magnitude. It is evident that given $A\rightarrow\infty$, for the monatomic gas: $\sigma\rightarrow(\gamma+1)/(\gamma-1)=\sigma_0 = 4$.

Using the Newton method for clarifying rough approximations $F(\sigma_1)=\sigma_0 - F(\sigma_0)/F'(\sigma_0)$ we can obtain from the expression (7):

$$\sigma_1 = \sigma_0(1- d_2\sigma_0/d_1)=\sigma_0[1- \sigma_0^3 (b_{\tau 0})^2/ 2A_0^2\cos^2(\varphi/2)] \quad (11)$$

Require (11) to be applied up to $X^* = -10R_E$. then
$\cos^2(\varphi^*/2) = 0.5/(1- X^*/y_g) = 0.353$
at $y_g = 24R_E$. as a correction to σ_1 is to be small $\sigma_1 = \sigma_0(1-\xi)$, $\xi<<1$, $A_0^2 = 90.25\ (b_{\tau 0})^2/\xi$.

Assuming that the IMF contribution to all components is the same, i.e., that $(b_{\tau 0})^2=1/3$ and an accuracy $\xi = 0.2$ is enough for us, we find that the minimum value A_0^2 is ~150, which allows us to make estimates over the distance range along the midday-midnight meridian ($y_g/2 > X > -10R_E$). the value corresponds to disturbed conditions A_0^2 is 70 for the quiet solar wind.

The density of the electric field component normal to the bow shock is represented by surface current divergence:

$$j_{n1}= [\ \partial(\rho J_l)/\partial l + \partial J_\tau/\partial\psi]/\rho \quad (12)$$

substituting surface current values from (5) and (6) in (12) and using field components from (2) and (4) and ratios $dl/d\varphi = r/\cos(\varphi/2)$ and $d\tau/d\psi = \rho = r\cdot\sin\varphi$, we can obtain:

$$j_{nl} = c/4\pi\rho[\ - B_{\tau 0}\cdot\sin\varphi\cdot\cos(\varphi/2)\ \partial\sigma/\partial\varphi + B_{l0}\partial\sigma/\partial\psi] \quad (13)$$

if we restrict ourselves to the first approximation $\sigma= \sigma_1$,

$$\partial\sigma_1/\partial\varphi = - \sigma_0^4 (b_{\tau 0})^2 \sin(\varphi/2)/2A_0^2\cos^3(\varphi/2), \quad (14)$$

For the derivative with ψ in general case we should use the following formula:
$\partial\sigma/\partial\psi = \partial[\sigma(\varphi,\psi)-\sigma(0,\psi)]/\partial\psi$.
for the first approximation:

$$\partial\sigma_1/\partial\psi = - \sigma_0^4\cdot \mathrm{tg}^2 (\varphi/2)\cdot b_{\tau 0}\ (\partial b_{\tau 0}/\partial\psi)/A_0^2 \quad (15)$$

Substituting derivatives from (14), (15) and field values from (2)-(4) in (13), we can obtain the expression for j_{n1}:

$$j_{n1} = j_\infty R^3\sin(\varphi/2)\cdot\sin(\psi+\psi_0)[1-(b_{x0}/R)\cdot\mathrm{tg}(\varphi/2)\cdot\cos(\psi+\psi_0)] \quad (16)$$

here $j_\infty=cB_0\sigma_0^4/4\pi y_g A_0^2$, $R=[(b_{y0})^2 + (b_{z0})^2]^{1/2}$, $\mathrm{tg}\psi_0 = b_{y0}/b_{z0}$.

Let us now turn to the question on the electrical potential distribution over the BS surface (see fig.3). Here we will use results from [2]. In those works, an expression for the potential without restraint except a priori forming of the BS front was derived:

$$\Phi = \Phi_0 R\sin(\psi+\psi_0)\mathrm{tg}(\varphi/2) \quad (17)$$

where $\Phi_0 = (-V_0B_0/c)\cdot y_g$

the energy flux density consists of two parts – a divergent part and a vortical part (a curl): $S = S_D + S_R$. obviously the curl part $S_R=-(c/4\pi)$**curl**(ΦB) does not contribute to the consumable power and therefore may be disregarded. As **div(curl)**=0, using divergence from both parts we obtain:

$$\mathbf{div}\ S = \mathbf{div}\ S_D=-E\cdot j \quad (18)$$

$$S_{nD}=S_0\ R^4\mathrm{tg}(\varphi/2)\sin(\varphi/2)\sin^2(\psi+\psi_0)[1-b_{x0}/R)\mathrm{tg}(\varphi/2)\cos(\psi+\psi_0)] \quad (19)$$

where $S_0 = (-\sigma_0^4/M_A)\cdot(V_AB_0^2/4\pi)$, V_A - the Alfvén velocity, M_A - the Mach-Alfvén number.

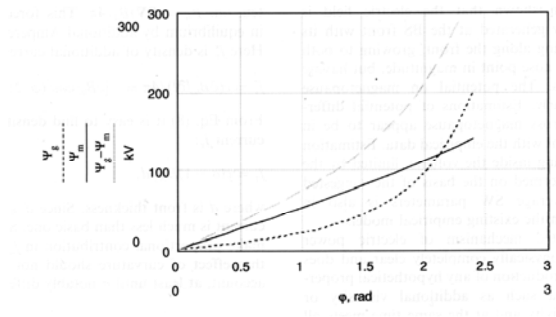

Fig. 3. Results of calculation of change of electric potential Ψg(φ) - at the bow shock front, Ψm(φ) - on the magnetopause and the differences Ψg - Ψm (when IMF Bz=-2nT); φ -in rad.

The transition layer (magnetosheath)

The correspondences of the parameters in front of and behind (in TL) the bow shock are in the Tab.1.

In this case, numbers 1, 2 correspond to the solar wind and magnetosheath, respectively; γ – is the adiabatic index; α – is the angle between the tangent to the bow shock and the axis X; β – is the angle between the direction of the solar wind velocity and the projection of the magnetic field onto the equatorial plane B_{1q}.

TABLE 1

THE PLASMA DENSITY	$\rho_2 = \rho_1\cdot\delta;\ \delta = \frac{\gamma+1}{\gamma-1};$
THE GAS PRESSURE	$p_{2g} = 2\rho_1 v_1^2 \frac{\sin^2(\alpha)}{\gamma+1}$
THE TANGENTIAL VELOCITY COMPONENT	$v_{2l} = v_{1l} = v_1\cos(\alpha)$
THE NORMAL VELOCITY COMPONENT	$v_{2h} = \frac{v_{1h}}{\delta} = v_1\frac{\sin(\alpha)}{\delta}$
THE VERTICAL COMPONENT OF THE MAGNETIC FIELD	$B_{2z} = B_{1z}\cdot\delta$
THE TANGENTAIL COMPONENT OF THE MAGNETIC FIELD	$B_{2l} = B_{1l}\cdot\delta = B_{1q}\cdot\delta\cos(\alpha+\beta)$
THE NORMAL COMPONENT OF THE MAGNETIC FIELD	$B_{2h} = B_{1h} = B_{1q}\sin(\alpha+\beta)$

From these expressions one may obtain the expression for the gas pressure gradient and the inertial force behind the bow shock front (i.e. in the transitional layer) [2, 3]:

$$\frac{dP_{2g}}{dl} = \frac{2\rho_1 v_1^2}{\gamma + 1}\frac{d}{dl}\sin^2\alpha \, ;$$

$$\frac{\rho_2}{2}\frac{dv_2^2}{dl} = -\frac{\rho_1 v_1^2\left(\delta^2 - 1\right)}{\delta}\frac{d}{dl}\sin^2\alpha$$

Next, substituting these expressions into the formula for current density one may obtain:

$$j = \frac{c}{B_2^2}\left[B \times \left(\nabla p_g + \rho\frac{\nabla v^2}{2}\right)\right]; \quad j_{2h} = c\left(\frac{dP_{2g}}{dl} + \rho\frac{dv_{2l}^2}{dl}\right)\frac{B_{2z}}{B_2^2};$$

or

$$j_{2h} = -\frac{2B_{1z}}{\left(\gamma^2 - 1\right)B_2^2}c\delta\rho_1 v_1^2\frac{d}{dl}\sin^2\alpha \, ,$$

where $\mathbf{j_{2h}}$ - is an electric current flowing across the transition layer;

$$B_2^2 = B_{1z}^2\delta^2 + B_{1g}^2\left(\left(\delta^2 + 1\right) - 2\left(\delta^2 - 1\right)\sin\alpha\cdot\cos\alpha\right);$$

The surface density of the current flowing in the transitive layer along it, will be integral from jl across the layer from magnetopause up to bow shock: $J_l = cB_{1z}\delta\frac{P_g(a) - P_g(b)}{B_2^2}$, where $\mathbf{P_g(a)}$ and $\mathbf{P_g(b)}$ - gas pressure under the bow shock and on the magnetopause, respectively. The TL may only conditionally be classed as a “consumer”, because in a certain mode the TL can act as a generator. Let's estimate density of the current, and also density of energy flux which would be brought by this current into the magnetosphere:

If B_{1z}=-5 nT, $B_2=B_3$=20 nT, $\rho_1 v_1^2$~30 ergs/cm^3 and l~10^{10}cm then maximum value of j_{3h}~10^{-4} CGSE, and when electric field E~$5\cdot 10^{-9}$ CGSE, volume of the region of the magnetosphere ~$4\cdot 10^{30}$ cm^3, maximum total power will be ~10^{18} ergs/s (10^{11} W). Similar estimations show, that transition layer as a consumer can consume the maximum power no more ~ 10^{11} Watt. The hydrodynamic and electrodynamic quantities are in the right and left sides of the equation, respectively [5]:

$$Ej = -j\frac{[v \times B]}{c} = -\frac{[j \times v]B}{c} = -\frac{[B \times j]v}{c} = v\frac{[j \times B]}{c} = v\nabla p_g$$

The physical sense of this expression is clear. If gas moves toward increasing pressure, then Ej >0. We have an electric power consumer. If $V\cdot\nabla P_g<0$, we have an electric power generator.

$$j_{3h} = \frac{dJ_l}{dl} = -\frac{cB_{1z}\delta}{B_2^2}\left(\frac{2\rho_1 v_1^2}{\gamma^2 - 1}\frac{d}{dl}\sin^2\alpha - \frac{d}{dl}\left(\frac{B_3^2}{8\pi}\right)\right).$$

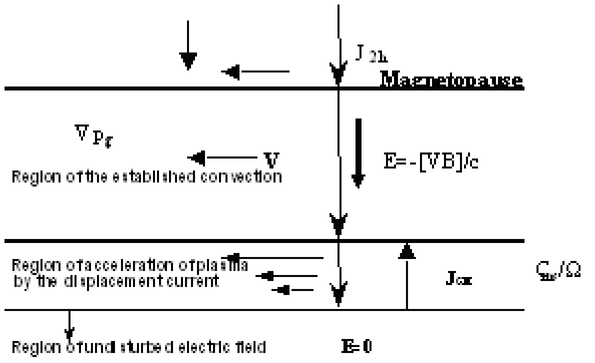

Fig. 4. The schematic illustrating the penetration of the external current into plasma, and excitation of magnetospheric convection. The process of penetration of current into plasma is a two-stage one. Initially, the polarization field is produced, which penetrates into plasma “layer by layer”. Or, more exactly, the momentum corresponding to this field penetrates into plasma. Here, if the system is inhomogeneous, the flow can redistribute pressure in such a manner that an electric current arises in plasma because of the appearance of gradients. Energetically, this current is necessary for maintaining convection in the inhomogeneous system.

The problem of the penetration of external electric field and current into the geomagnetosphere.

The process of external current penetration into the magnetosphere is not simple as opposed to the penetration into the ohmic medium, where the electric field is functionally connected with the current due to the Ohm low. Let us consider this process using the interaction between the dawn-dusk current and the magnetosphere as an example. Assume that the dawn-dusk current with the density j_{0n} flows through the magnetosphere. It is the current that deforms the dipole magnetic field, stretching it in the anti-solar direction. The plasma pressure gradient $\mathbf{grad}(p_0)=[j_{0n}xB]/c$ corresponds to this current. Suppose that the current increased, the fixed plasma pressure gradient would impede this in the magnetosphere. This may give rise only to a polarization field on the magnetospheric flanks. This field starts penetrating into the magnetosphere as the Alfvén wave front with a displacement current and corresponding Ampère force. This force accelerates the plasma so that behind the Alfvén wave front a new convection velocity and a new field appear. The new convection velocity results in a new plasma pressure gradient and thus in a new current. The external current is properly the extra current that is necessary for the magnetosphere to do work on plasma; i.e., in order the pressure maximum to be nearer the Earth and its amplitude to increase (fig.4).

Energetically, the external electric current is necessary for maintaining plasma convection in the inhomogeneous system. Any change in external current through the magnetosphere causes a convection restructuring within a time on the order of the travel time of the magnetosonic wave from the magnetopause to the center of the system, because the restructuring wave comes from both flanks. Until a new distribution of gas pressure is established, the role of the force counteracting the Ampere force is played by the inertial force. This corresponds to the acceleration of plasma and hence to a change of the electric field. The energy flux into the magnetosphere is closely related to the current through the magnetosphere by the well-known expression. The establishment time of the electric field in a system here is about te=L/V, and the time of the current establishment – of about ti =L/Vc, where L – the system size, V – phase velocity of the electromagnetic signal propagation across the system, Vc – plasma convection velocity. An approximate estimate used to magnetosphere gives the time of electric field establishment – hundreds of seconds, the electric current establishment time – of about an hour.

Conclusions

The bow shock front is the main converter of solar wind kinetic energy into electromagnetic energy. When passing through the bow shock front the intensity of the tangential component of the SW magnetic field and the plasma density increase several fold. Therefore, among other things, the BS front is a current sheet. The current is diverging in this layer, that is the front is the generator of the electric current. Since plasma with magnetic field passes through the front, electric field arises in the front reference system. Thus, the BS front is a source of electric power. This electric power is distributed between two consumers - the Transition Layer (TL, or magnetosheath) and the magnetosphere. The TL may only conditionally be classed as a 'consumer', because in a certain mode the TL can act as a generator. There is a potential difference between the BS front and the magnetosphere, unequivocally (since the TL magnetic field is determined by the SW magnetic field) associated with the velocity of the transition layer plasma flow. Thus, the magnetopause potential is functionally related to SW parameters. The power consumed by the magnetosphere is spent on the magnetospheric MHD compressor work and consists of active and reactive power [5, 6]. The active part covers losses in the ionosphere (ohmic losses, primarily), the reactive part returns to the magnetospheric MHD-compressor [6]. The power produced by the generator at the BS front does not appear to depend on power consumed by the magnetosphere, but then a necessity arises for a "power depot", in which the power produced by the BS, but not consumed by the magnetosphere, can be dumped. The transition layer is a viable candidate for this role.

The process of current penetration into the magnetosphere is two-step. First forms a polarization field that penetrates layer-by-layer into the magnetosphere. More exactly, a pulse corresponding to this field penetrates into the plasma. Then, if the system is inhomogeneous, the flow may redistribute the pressure so that gradients appearing in the plasma induce an electric current. In energy terms, this current is required to maintain convection in the inhomogeneous system. Any change in the external current through the magnetosphere causes a convection restructuring within a time on the order of travel time of the magnetosonic wave from the magnetopause to the center of the system, because the restructuring wave comes from both flanks. Here the energy conditions become inefficient for the processes in the magnetosphere and those of the magnetosphere-ionosphere coupling. As long as the new distribution of gas pressure does not set, the role of the force opposed to the Ampère force is played by the inertial force. This corresponds to a plasma acceleration and thus to a change in the electric field. It is worthwhile trying to observe and examine the restructuring wave in high latitudes using radar systems SuperDARN or television systems with a wide angle of vision.

We can propose the following way of testing the suggested approach. Satellite measurements (multisatellite missions) of the flow of substances brought into the magnetosphere are necessary. Using the expressions obtained in this paper for normal components of the electric current, the flow of substance brought into the magnetosphere can be estimated. A normal component of convection velocity on border is equal to zero; hence, the flow of the number of particles, transferable by the electric current, will be $j_{3h}/2e$ ≈10^5÷$5\cdot10^5$ $cm^{-2}\cdot s^{-1}$, where j_{3h}~10^{-4} CGSE (~$3{,}3\cdot10^{-10}$ A/m^2), e – is the charge of electron. Through the surface of the geomagnetosphere (~10^{20} cm^2) the total flow of the number of particles would be ~$5\cdot10^{25}$ s^{-1}.

According to the reconnection concept [7] at IMF B_z southern component the magnetosphere becomes open, and this implies the flow of substance from the solar wind into the magnetosphere too. Besides, according to the reconnection concept, the electric field of the solar wind E_{sw}=-(1/c)[VB] must penetrate completely into the magnetosphere, since conductivity along magnetic field lines is very high. According to the above-mentioned scheme of penetration of the external current and electric field into the magnetosphere, only a part (about 1/5 part of E_{sw}) of the electric field of the solar wind will penetrate into the Earth's magnetosphere. Such satellite measurement data on the electric field in the solar wind and magnetosphere would be useful as well as simultaneous measurements of the flow of the number of particles into the magnetosphere.

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