Abstract. We discuss the question as to how the magnetospheric energy source feeds the ionospheric current system. It is shown that a consistent application and further development of Kennel’s ideas makes it possible to successfully solve the magnetosphere-ionosphere coupling problem in regard to the formation of auroral electrojets by steady volume currents generated in the magnetosphere by the magnetospheric MHD generator in the case of a simple model which, nevertheless, retains the essential features of the reality. It is concluded that the whole of the complicated magnetospheric "design" only acts to redistribute, in space and time, currents and energy fluxes which must be supplied by external sources to feed the dissipative processes in the ionosphere.

1 INTRODUCTION

The resumes of the last two international conferences [Kamide, 1998; Lui, 2000] distinctly voiced a faint note of dissatisfaction with the lack of progress toward an understanding of the physical essence of magnetospheric processes and, above all, the magnetospheric
substorm. In our opinion, to speak in plain terms, things are reaching a conceptual crisis. Four decades ago, two concepts of solar wind (SW)-magnetosphere coupling were formulated: the concept of quasi-viscous interaction [Axford and Hines, 1961], and the concept of magnetic field line reconnection [Dungey, 1961]. The concepts are both based on the assumption that in the region of SW-magnetosphere interaction there exist meaningful transport coefficients: a certain effective viscosity and effective conductivity in the former and latter cases, respectively. These coefficients are both proportional to a certain length having the meaning of the free path length of particles in the case of paired collisions. Since the free path length of particles in the magnetosphere at paired collisions involving Coulomb interaction is far in excess of the dimensions of the magnetosphere, magnetospheric plasma is said to be collisionless. However, plasma can sustain collective processes leading to exchanges of momentum and energy between particles. The exchange proceeds through waves which must have a spectral energy density large enough for a sufficient exchange rate to be ensured (quasi-collisional mode). Thus the validity of both concepts boils down to the problem of finding out such plasma instabilities which would be capable of ensuring the quasi-collisional regime. This problem has not been solved yet, and hence groundwork is lacking for both concepts of energy transfer from the solar wind to the magnetosphere. Still this does not seem to be the main reason behind the crisis. The required instabilities may well be found. Moreover, recently V.V.Mishin [Mishin, 2001] was able to demonstrate that when supersonic magnetosheeth plasma flows round the magnetopause, the shear flow generates oblique magnetosonic waves penetrating deep into the magnetosphere and carrying their momentum along. This process proved to be sufficiently effective, so it must be taken into account in the energy budget of the magnetosphere. The chief reason, however, is that neither of the two concepts failed to serve as an appropriate foundation for constructing a sequence of physical mechanisms which would lead us from the processes in the bow shock to the processes of auroral electrojet formation. To find a way out of the impasse implies adopting a new concept based on the well-known Kennel’s paper entitled ”Consequences of magnetospheric plasma” [Kennel, 1969]. The essentials of this concept may be summarized as follows. The combined action of convection and pitch-angle diffusion leads to the formation in the magnetosphere of a spatial distribution of gas pressure, that is, steady volume currents. The divergence of this volume currents brings about a spatial distribution of field-aligned currents, i.e. magnetospheric sources of ionospheric current systems. Such approach offers, among other things, a ”totally gratuitous” explanation (and adequate description!) of the substorm ”breakup” [Ponomarev, 1981]. We now consider this issue in slightly greater detail. It is known [Ponomarev, 1985] that the contents of the magnetic flux tube (MFT) to be referred to as the plasma tube (PT) throughout the text, transfers from one MFT to another in the
convection process without surplus and deficiency in the case where the field lines of the magnetic flux tube are equipotential ones. This idealization is quite realistic everywhere apart from polar auroras.

Then, as the PT drifting toward the Earth in a dipole field, its volume decreases in proportion to $L^{-4}$, and the situation is the reverse for density, while pressure increases in proportion to $\sim L^{\frac{20}{3}}$. However, the process of adiabatic compression is attended by the processes of PT depletion due to pitch-angle diffusion into the loss cone. This process is described by the factor $\sim \exp(-\int \frac{dv}{v^2}) = \exp(-\frac{1}{2} \int \frac{dr}{v_r^2}) = \exp(-\frac{5}{3} \int \frac{dv}{v_r \tau})$. Thus gas pressure has a maximum on each line of convection. In accordance with the equation for $p_g$ [Ponomarev, 1985], we have:

$$p_g = p_{g0} \left(\frac{L_{\infty}}{L}\right)^{\frac{20}{3}} \exp\left(-\frac{5}{3} \int \frac{dr}{v_r \tau}\right)$$

(1)

Here $p_g$ is gas pressure, $L$ is the L-coordinate, $r = LR_e$ is the distance to the Earth ($R_e$ being the Earth’s radius), $V_r$ and $V_{\vartheta}$ are the radial and azimuthal components of the convection velocity of the equatorial trace of the plasma tube, respectively, and $\tau$ is the characteristic time of PT depletion due to pitch-angle diffusion. The initial pressure at a certain boundary $L_{\infty}$ was considered time-independent in [Kennel, 1969]. For reasons unknown, Kennel did not extended his model to the unsteady-state case. This was done by one of us in [Ponomarev, 1981; Ponomarev, 1985; Anistratenko and Ponomarev, 1981].

A typical gas pressure pattern that results through the combined action of convection and losses, is depicted in Fig. 1a. It has the form of an amphitheater with a clearly pronounced maximum near the midnight meridian, and with a sharp earthward "break". This "break" received the name "Inner Edge of the Plasma Sheet", IEPS.

The projection of the "amphitheater" onto the ground corresponds to the form and position of the auroral oval. This projection, like the real oval, executes a motion with a change of the convection electric field, and expands with an enhancement of the field. In this process the amplitude at a maximum increases as the IEPS approaches the Earth. Next we consider the case where the boundary conditions in (1) are time-dependent. Let the pressure on the boundary be increased by, say, a factor of two. This "impulse" will start to drift downstream with the convection velocity, with a region of double amplitude remaining everywhere in its wake. If the "impulse" is of short duration, then a region "multiplied by two" of a limited size will travel downstream. The effect of multiplication of two spatially narrow signals is always small apart from the time when their maximal coincide. An amplitude "flare" will occur then. Just this is the explanation for the "substorm breakup", a simple, logical corollary of the inhomogeneity of the system and
motion [Ponomarev, 2000].

Fig. 1b illustrates the second phase of development of the pressure pattern in the process of a model substorm.

Based on the spatial distribution of pressure as a function of coordinates and time, we can calculate the spatial distribution of volume currents:

\[ j = \frac{c[B \times \nabla P_g]}{B^2} \]  (2)

The divergence (2) under steady-state conditions gives an expression for field-aligned current densities:

\[ j_\parallel = cB_1 \int_0^l \frac{[\nabla P_g \times \nabla P_B]B}{p_B B^3} dl \]  (3)

We perform the integration along a magnetic field line of the Earth’s dipole field from the equator (0) to the ionosphere (l). Noteworthy is the following property of the expression under the integral sign. It depends on the angle of intersection of magnetic and gas pressure contours. Within the dipole approximation \( p_B = const \) are merely circles. On the contrary, \( p_g = const \) have a complex configuration. The sign of current \( j_\parallel \) depends, ultimately, on the sine sign of the angle between the normals to pressure contours. This factor eases qualitatively analysis of the current situation.

2 STATEMENT OF THE PROBLEM.

Above we have outlined the prerequisites for the solution of the magnetosphere-ionosphere coupling (MIC) problem in the part of it concerning their relations as the source and consumer of electric current and electric energy.

The complexity of the MIC problem implies that currents in the ionosphere are governed by the electric field (with conductivity specified as a parameter), and in the magnetosphere they are determined by gas pressure gradient. There does exist a connection between the pressure distribution and convection, albeit relatively complicated. Our intention is to understand (by analyzing a maximum possible simple model that at the same time retains the most important traits of reality) how consistently current is established in the overall ionosphere-magnetosphere chain, how the magnetospheric generator of ionospheric currents operates, and what sources of power (including those of non electromagnetic origin) this generator uses to be at work. A partial answer to the last question has been given to date. We have demonstrated [Ponomarev, 1981; Ponomarev, 1985] that magnetospheric
regions that operate like an MHD compressor where plasma is compressed under the action of Ampere's force $\frac{j \times B}{c}$, satisfy the condition $\nabla \cdot \mathbf{p}_g > 0$, and regions where gas dynamic forces acts on electromagnetic forces, i.e. regions of MHD generators, satisfy the condition $\nabla \cdot \mathbf{p}_g < 0$ Conversion of energy from one kind to another may be written by a straightforward formula:

$$\nabla \cdot \mathbf{p}_g = j \mathbf{E}$$

(4)

It seems appropriate to employ in the analysis the region of the "cleft" which is produced when a plasma disturbance flows against the undisturbed pressure pattern (as a result of the unsteady-state character of boundary conditions as mentioned above). This detail of the pattern is clearly seen in Fig. 1b. Fig. 2 shows a schematic representation of a section of this pattern. The section of the cleft is represented by "corridors". One can see that the walls of "corridors" serve as the sources of two bands of field-aligned currents which direction is opposite on different walls. On the whole, a current configuration forms, which corresponds to the Iijima-Potemra scheme [Iijima and Potemra, 1976]. Importantly, the stream convection lines run virtually along the axis of the "corridor", the "corridor" itself is extended with respect to the contours at a small angle, and hence the magnetic field inside it is nearly homogeneous. For that reason, the precipitation parameter $\tau$ can be considered a constant quantity.

In the model of our interest, we replace the "corridor" itself by a rectangular channel with perfectly conducting walls overlaid by a conducting "cover", the ionosphere. We compensate for the difference in spatial scales, which is caused by the convergence of field lines, by a correction of parameters. The channel with a homogeneous magnetic field includes a steady flow of ideal plasma with a corresponding pressure gradient. All this is portrayed in detail in Fig. 3.

3 MODEL OF THE SECONDARY MAGNETOSPHERIC GENERATOR.

Let us consider the phenomena occurring in the plasma "corridor" on the basis of a simple model. As is evident from Fig. 2, the orientation of the "corridor" is such that plasma flows nearly along its axis. The corridor is extended in a longitudinal direction; therefore, the magnetic field changes little within it. All these factors allow us to replace the "corridor" by a channel (extended along the axis Y) of width $2D$, length $L$, and height $H$. The axis Y will be oriented across the channel, and the axis Z along its height, as shown in Fig. 3. The
channel is filled with ideal plasma with pressure $p^0$ at the inlet and $p^1$ at the outlet. The magnetic field $B = (0, 0, B_z)$ will be considered homogeneous. Plasma with the velocity $V = V(x)$ flows along the axis $X$ in a positive direction. The walls of the channel possess infinite conductivity. The ionosphere is modeled by the upper cover of thickness $h$ with Pedersen conductivity $\sigma$. As a consequence of the existence of a pressure gradient along the channel, the following current flows across it:

$$j_y = \frac{c}{B} \left( \frac{\partial p}{\partial x} \right)$$

To this volume density of current there corresponds the surface density and a total current:

$$I_G(x) = \int j_y \, dz = H j_y, \quad J_G = \int I_G \, dx$$

Accordingly, a total current of ionospheric load is:

$$J_\sigma = \int \int \sigma E_1 \, dx \, dz = \sigma h \int E \, dx = \sigma h \frac{B c}{c} \int V \, dx$$

The primes on the differentials signify that the integration is performed over the space of the ionosphere. Furthermore, because of the equipotentiality of magnetic field lines, the electric field in the ionosphere $E_I$ is related to the electric field in the magnetosphere by the relation: $E_I dx = E dx$ In these formulas, $c$ is the velocity of light.

In addition to the current that closes through the ionosphere, a part of the MHD generator’s current can close through the magnetosphere, as is the case with the corridor’s current in Fig. 2. We designate this current by index 1. Then:

$$J_1 = \int \int j_{y1} \, dx \, dz = \int I_1 \, dx$$

From the condition of continuity of currents we find:

$$\frac{dp}{dx} = -\frac{\sigma^* B^2 V}{c^2} + \frac{I_1 B}{cH}$$

where $\sigma^* = \sigma \left( \frac{h}{H} \right)$. The balance equation of gas kinetic energy in a steady-state one-dimensional case has the form:

$$V \frac{dp}{dx} + \gamma p \frac{dV}{dx} = -\frac{\gamma p}{\tau}$$

(7)
Whence:

\[ p = p^0 \left( \frac{V_0}{V} \right)^\gamma \exp \left( -\gamma \int \frac{dx}{V \tau} \right) \]  

We now designate the initial level of gas pressure that is necessary and sufficient for supplying the ionosphere with electric current, by \( p^{01} \) so that \( p^0 = p^{01} + p^{02} \), where \( p^{02} \) is the initial level of gas pressure that produces a current \( J_1 \).

\[ \gamma \left[ p^0 \left( \frac{V_0}{V} \right)^\gamma \right]^{\gamma+1} \exp \left( -\gamma \int \frac{dx}{V \tau} \right) \left[ \frac{dV}{dx} + \frac{1}{\tau} \right] = \sigma^* \left( \frac{B}{c} \right)^2 V V_0 \]  

The solution of this system of equations that satisfies the conditions of our problem, is:

\[ V = V_0 - \frac{\gamma x}{(\gamma + 2)\tau} \]  

From (9) we obtain the condition:

\[ p^{01} = \frac{(\gamma + 2)}{2\gamma} \left( \frac{B}{c} \right)^2 \sigma^* \tau V_0^2 \]  

And from (10) we get:

\[ I_1 = \left[ p^0 - \left( \frac{\gamma + 2}{2\gamma} \right) \left( \frac{B}{c} \right)^2 \sigma^* \tau V_0^2 \right] \frac{V}{B \tau V_0^2} \]  

It is evident from (13) that the current \( I_1 \) is "organized" by the "principle of balance": all the necessary expenses of the ionosphere in current (power) are covered first, and what remains leaves for the geomagnetic tail region. As is evident from the figures, the current \( I_1 \) (\( J_1 \)) there becomes part of the dawn-dusk current. Only a part because there exists also the dawn-dusk current \( J_B \) of a different origin. It is an external current with respect to the magnetosphere itself. As was shown by Ponomarev et al. [2000], it is produce at the Bow Shock (BS) front through a partial deceleration of solar wind plasma by Ampere’s force with the involvement of this current. If the \( B_z \)-component of the Interplanetary Magnetic Field (IMF) is less than zero, the direction of this current is such that, by closing through the magnetospheric body, it produces there Ampere’s force capable of acting to pushing
magnetospheric plasma earthward, toward an increase of magnetic and gas pressure. Thus the MHD compressor lie in this region (located mostly at $5 < L < 10$ on the nightside, i.e. before the gas pressure maximum, see the figures; for details see in a book by Ponomarev [1985]. It is the gas compressed by the generator that is supplied to the MHD channel, the operation of which we are discussing here. Unlike the channel’s region, the region of the MHD compressor lies in the area where the plasma is driven by magnetospheric convection to travel nearly radially to the Earth. From the balance of the gas pressure force and Ampere’s force we have:

$$J_1 + J_B = cH \int B^{-1} \left( \frac{dp}{dL} \right) dL$$

(14)

where $B = \frac{B_0}{L}$. Whence:

$$p^0 = q \left( \frac{B_c}{cH} \right) [J_1 + J_B],\text{where}: q = \frac{(4\gamma - 1)}{4\gamma} \left( \frac{L_c}{L_T} \right)^{4\gamma} L_c^2$$

(15)

$L_c$ and $L_T$ are the coordinates of the end and beginning of the area of plasma compression, and $B_c$ is the magnetic field strength at the compressor output. Further it will be assumed that $B_c = B$, that is, the MHD compressor output territorially coincides with the MHD generator input. Since plasma requires some time to travel the distance from the compressor input to output:

$$\Delta T = \int_{L_T}^{L_c} \frac{R_e}{V_R} dL$$

then pressure at the MHD generator input will correspond to the earlier value of the compressor current.

By integrating (13) over the entire length of the channel and assuming that the plasma velocity at the output is much smaller than that at the input of the MHD generator, we find:

$$J_1 = \left( \frac{cH}{B} \right) \left[ p^0 - \frac{(\gamma + 2)}{2\gamma} \left( \frac{B}{c} \right)^2 \sigma^* \tau V_0^2 \right]$$

(16)

Upon substituting (15) into (16), in view of what has been said about the delay, we obtain an important relation:

$$J_1(t) - qJ_1(t - \Delta T) = qJ_B(t - \Delta T) - J_2(t)$$

(17)
In a steady state where there is no explicit time-dependence and \( q = 1 \):

\[
J_B = J_\sigma
\]  

(18)

This means that actually dissipative processes can take place in the magnetosphere only at the expense of an external source of current (and energy). The whole of the complicated magnetospheric "design" only redistributes currents and energy fluxes in space and time. Overall, though, this is an obvious inference as it is expectable. The integrity of (18) in this case implies that this is not merely a declaration now. We can point out the limits of applicability of (18) as well as the particular processes behind the notions "steady state" and "unsteady state".

We now turn our attention to the "cross-tail currents". Let \( J_1 + J_B \) be designated by \( I_s \). Then from (17) it follows that:

\[
J_s(t) = qJ_s(t - \Delta T) + [J_B(t) - J_\sigma(t)]
\]  

(19)

Obviously, the control of the tail current \( I_s \) proceeds both at the expense of a variation of \( J_B \) and at the expense of the variation of the current of ionospheric load \( J_\sigma \). In a quasi-steady situation where \( J^{-1} \frac{dJ_s}{dt} \ll 1, q = 1 \) we have:

\[
\frac{dJ_s}{dt} \sim \frac{[J_B - J_\sigma]}{\Delta T}
\]  

(20)

Obviously, when \( J_B > J_\sigma \), the cross-tail current increases, and the magnetospheric magnetic field is observed to extend into the tail. Otherwise when the ionospheric load current exceeds the external current, \( dJ_s/dt < 0 \) and the tail current decreases, a "dipolization" of the magnetic field occurs. The physical reason behind this is the increase in ionospheric consumption of current because of the increase in conductivity caused by an enhancement of auroral particle precipitation.

Thus between the consumer of current and energy, on the one hand, and their "general supplier", the external current, there exists a flexible connection via a "depot" represented by current \( J_1 \). Fig. 4 presents the scheme of time response of currents to a change in integral ionospheric conductivity.

4 CONCLUSION

We have shown that the consistent application of the idea put forward by Kennel [Kennel, 1969] which we further developed in [Ponomarev, 1981; Ponomarev et al., 2000], makes it
possible to successfully solve the magnetosphere-ionosphere coupling problem as regards the formation of auroral electrojets by volume currents generated in the magnetosphere by a corresponding distribution of plasma pressure. It was demonstrated that magnetosphere-ionosphere coupling mechanisms, along with the mechanisms of interaction between the magnetospheric MHD compressor and the MHD generator, only act to effect the redistribution of energy and electric current which must be supplied by external sources to feed the dissipative processes in the ionosphere Ponomarev et al. [2000] suggested a generation mechanism for this external current at the expense of a deceleration of solar wind plasma on the bow shock.

We have been able, for the first time, to solve the problem of conjugacy of magnetospheric "gradient" current (dependent on plasma pressure gradient but independent on the electric field) with "resistive" ionospheric current dependent on the electric field (but independent of gas pressure). We pioneered the analysis of the combined operation of the magnetospheric MHD compressor and MHD generator which, in essence, represent a materialization of Kennel’s idea of simultaneous existence of convection and precipitation in magnetospheric plasma.

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Figure 1. Gas pressure pattern resulting from a combined action of plasma convection and losses as a consequence of particle precipitation into the ionosphere. Fig. 1b shows something like a “cleft” which forms when a plasma disturbance flows against the undisturbed pressure pattern (as a result of the unsteady-state character of boundary conditions).
Figure 2. Schematic representation of a cut of the gas pressure pattern. A cut of the “cleft” is represented by “corridors”, on the walls of which field-aligned currents are generated.
Figure 3. Schematic representation of the channel of the magnetospheric MHD generator with perfectly conducting walls overlaid by a conducting “cover”, the ionosphere. The dashed line shows the gas pressure pattern \( P_g \), and the thick lines show the direction of currents (for designations see the text).
**Figure 4.** Plots of time response of currents to a change in integral ionospheric conductivity.