Compatibility of Two System of Field-Aligned Currents

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Abstract The combined action of convection and pitch-angle diffusion of electrons and protons is responsible for the formation of gas pressure distribution in the magnetosphere. Plasma pressure, in turn, determines - within the framework of a given magnetic field model - the density of bulk currents in the magnetosphere. With knowledge of the bulk currents as a function of coordinates, we can calculate the field-aligned currents as a divergence of bulk currents. On the other hand, specifying the convection model is equivalent to specifying the electric field model. Since within the approximation of equipotential field lines the electric field is common to the magnetosphere and ionosphere, bulk currents and field-aligned currents in the ionosphere can be formally calculated subject to the condition that ionospheric conductivity is wholly determined by electron precipitation from the magnetosphere. Sun illumination is important for dayside region. The precipitation intensity is readily inferred from our structurally adequate model of the geomagnetosphere. Thus, we have two systems of field-aligned currents. One system is calculated from the model of plasma pressure distribution in the magnetosphere, and the other is inferred from a given model of the electric field and the electroconductivity model calculated from electron precipitation. This brings up the question: How can these two systems of field-aligned currents be reconciled? From previous studies it is known that magnetospheric convection "adjusts itself" to the level of energy losses in the ionosphere. Based on this, an attempt can be made to achieve a compatibility of the aforementioned two systems of field-aligned currents. This paper is devoted to analyzing such an attempt.

1. Introduction

The problem of magnetosphere-ionosphere coupling is very interesting. Magnetospheric Alfvén waves are reflected by the ionosphere. According to (Ellis, Southwood, 1983), the field-aligned currents (FACs) in the subsidiary Alfvén waves serve to close divergent horizontal currents resulting from the non-uniform ionospheric conductivity.

According to [Zhu, et al., 1993), the inhomogeneity of ionospheric conductivity can lead to FACs, which originate in the ionosphere. Increasing the conductivity gradient (in the direction which is perpendicular to the incident wave field), can increase the ratio of the Hall and Pedersen conductivities, and lowering the conductivity all lead to a larger rotation of the reflected wave field (in the range of from a few up to 40°).

According to (Yoshikawa, et al., 2013a), the polarization charge produced by the Pedersen current divergence has a role to cancel and intensify the ambient background electric field inside and outside the high-conductivity band, respectively. The polarization charge produced by the Hall current divergence has a role to rotate the electric field from the background electric field, which causes a meandering of ionospheric convection flow along the boundary of a high-conductivity band are always perpendicular to each other. The Hall and Pedersen currents never close each other when conductances are homogeneous, but they can do that at the conductivity gradient region.

Authors of (Yoshikawa et al., 2013b) presented the formulation of the coupling between the ionospheric horizontal currents and FACs via shear Alfven waves, which can describe the formation of a Cowling channel without any a prior parameterization of the secondary (Hall polarization) electric field strength. They showed that the reflected wave can carry FACs that connect to divergent Hall currents. They identified how large the secondary electric field becomes, how efficiently the divergent Hall current is closed within the ionosphere, and how much of the Hall current continues out to the magnetosphere as FACs. Authors concluded that only a small fraction of FACs is connected to Hall currents at conductance gradients.

The ionosphere is an ohmic environment, where the electric field and the current are related by the Ohm's law. If the ionospheric current were purely Hall currents, this would not be a dangerous phenomenon since the Hall current is nondivergent and does not deliver a work. In fact, the ionospheric current is combined and always includes the Pedersen component, and the ionosphere is a real energy consumer (sink). It is known that the contents of the magnetic flux tube to be referred to as the plasma tube throughout the text, transfers from one magnetic flux tube 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 plasma tube 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 $\sim L^{20/3}$. However, the process of adiabatic compression is attended by the processes of plasma tube depletion due to pitch-angle diffusion into the loss cone. This process is described by the factor $\sim \exp(-\int dt/\tau) = \exp(-\int dr/V_r \tau) = \exp(-\int r d\upsilon/V_\upsilon \tau)$ (Ponomarev, 1985). Thus gas pressure has a maximum on each line of convection. In accordance with the equation for p_g (Ponomarev, 1985; Ponomarev, Sedykh, 2006), we have:

$$p_g = p_g^0 \left(\frac{L_\infty}{L} \right)^{\frac{20}{3}} \exp\left(-\frac{5}{3} \int \frac{dr}{V_r \tau} \right) \qquad (1.1)$$

It is evident that $dt = dR/V_R = R_0 d\lambda/V_\lambda$, $\Delta t = \int dt$ is the transport time, i.e., the time over which the flux tube will move from the boundary to the given point on the flux line; and V_R and V_λ are the radial and azimuthal components of convection velocity; L is the McIlwain parameter. Thus (1.1) indicates how gas pressure changes when plasma moves along the convection line at a velocity $V = (V_R^2 + V_\lambda^2)^{1/2}$; τ - is a time over which the plasma tube loses 1/e part or the initial number of particles $\tau = \tau_0 L^4$ ($\tau_0 = 1$s for electrons, $\tau_0 = 12$-18 s for protons). The radial components of convection velocity is $V_r = V_0 L^{9/2} \cos\lambda$. The azimuthal components of convection velocity is $V_\lambda = -2.5 V_0 L^{9/2} \sin\lambda + V_1 L$; V_1 – is a function of initial values of energy of electrons and protons; $V_0 = c[E \times B]/B^2$; γ is the adiabatic exponent; p_g^0 is an initial pressure at the boundary $L = L_\infty$ for particles with the corresponding energy.
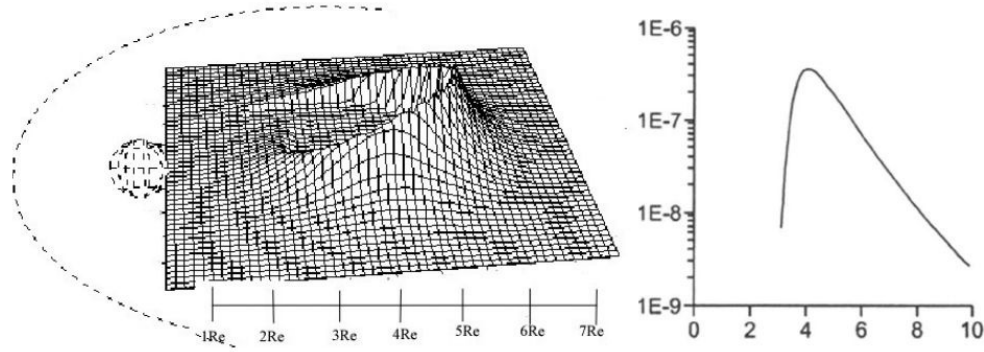
Fig. 1. Results of modeling. Plasma pressure distribution for steady-state boundary conditions. The profile (calculated values) of plasma pressure: P, [dyn/cm^2] / $L(R_E)$

The pitch-angle diffusion of particles into the loss cone, together with adiabatic compression of plasma during the convection into the magnetosphere determines the behavior of the contents of the magnetic flux tube, the plasma tube. Gas pressure builds up under the action of an adiabatic compression of plasma drifting in a magnetic field with increasing strength and precipitation-induced losses.

In this case the magnetosphere develops a plasma pressure distribution, such as shown in Fig. 1.

A gas pressure pattern 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.

In these calculations, boundary conditions are time-independent, that is, the supply of plasma through the boundary remains uniform, and only the convection velocity changes. The pressure peak increases with the increasing electric field. Noteworthy are the relatively gentle backward slope of the relief and a very steep forward slope. If the boundary conditions are unsteady and pressure increases for a certain time on the boundary of the region, from which plasma starts, the resulting plasma "bunch" drifts downstream of the convection.

Partially, these results were obtained in the classical work by C.F. Kennel (1969), who studied in detail the process of pitch-angle diffusion of electrons into the loss cone and estimated the actual value of τ_e. Kennel did not estimate the time of pitch-angle diffusion of protons (τ_p), but he proposed a simple principle for determining this time. In an ultimate case, which was called pitch-angle diffusion by Kennel, the loss cone should be filled during one bounce period of a particle with an average energy.

The situation changes principally when the boundary conditions are dependent on time. The soltion structure is so that $p_0(t)$ can be considered as an input signal multiplied by the transfer function A.

Input parameters for modeling are the electric field of magnetospheric convection and the magnetic field in the magnetosphere. The function for the electric field variation can be applied from our paper (Ponomarev et al., 2006), taking into account the well-known paper (Volland, 1975). Our obtained result is also standard. The character of electric field distribution over the dawn–dusk meridian (Ponomarev et al., 2006) quite corresponds to the classical distribution obtained in (Heppner, 1977). We applied the dipole like magnetic field model, but with special additional parameters for stretching magnetotail. For illustration of results of modeling, we applied the following expressions. The expression (1.1) can be written in the form (Sedykh, Ponomarev, 2012):

$$p(t`) = G(t)\,A(L) \qquad (1.2)$$

$$E_0 = E_{00} \begin{cases} 1; & t < -900s \\ 2t/1800 + 2; & -900s \le t \le 900s \\ 1; & t > 5400s \end{cases}$$

$$G = G_0^a \begin{cases} 1; & t^{/} < 0s \\ 2t^{/}/500 + 1; & 0s \le t^{/} \le 500s \\ -t^{/}/500 + 4; & 500s < t^{/} \le 1500s \\ 1; & t^{/} > 1500s \end{cases} \qquad (1.3)$$

The expressions (1.3) are simple, and represent plasma pressure inhomogeneity in the magnetosphere during periods of magnetospheric disturbance development.

Since the relationship between the coordinate and time (L = $\int V_R dt$) exists for the drifting plasma tube, the p_0 disturbance can be represented as a disturbance moving with convection stream, the amplitude of which increases by a factor of A depending on L. If p_0 and A(L) are narrow functions, their product is always close to zero except the instant when these functions coincide.

Since the resulting pressure amplitude is the product of the undisturbed signal amplitude by the magnitude of the disturbance, there emerges the picture shown in Fig. 2. The sequence in Fig.2 illustrates the pressure relief time history as a function of the convection electric field and nonstationary boundary conditions. One can see that at the time when the plasma bunch reaches the region of maximum steady-state pressure, there occurs a powerful short-duration outlier of plasma pressure (density and, accordingly, intensity of particle precipitation). We interpret it as break-up substorms (Sedykh, Ponomarev, 2012).

Since in plasma with isotropic pressure (within 3.5 < L < 7, where L is the McIlwain parameter) the plasma pressure relief wholly determines the density of bulk currents for particles with the energy less than 15 keV, then:

$$\mathbf{j}_\perp = c\,[\mathbf{B} \times \nabla p_g]/B^2, \qquad (1.4)$$

where **B** is the magnetic field strength, p_g is gas pressure, and **c** is the velocity of light.

2. Formulation of the problem and computational technique

The flux density of precipitating particles is rather sharply localized in the space and produces in the ionosphere a clearly pronounced precipitation oval (Fig. 3).

Sharp spatially localized regions of increased conductivity in the ionosphere also correspond to such a distribution of precipitation. In the energy range 1-20 keV in which auroral electrons exist, about 30 electron-volt of the flux energy supplied to the ionosphere are expended in producing an electron-ion pair.
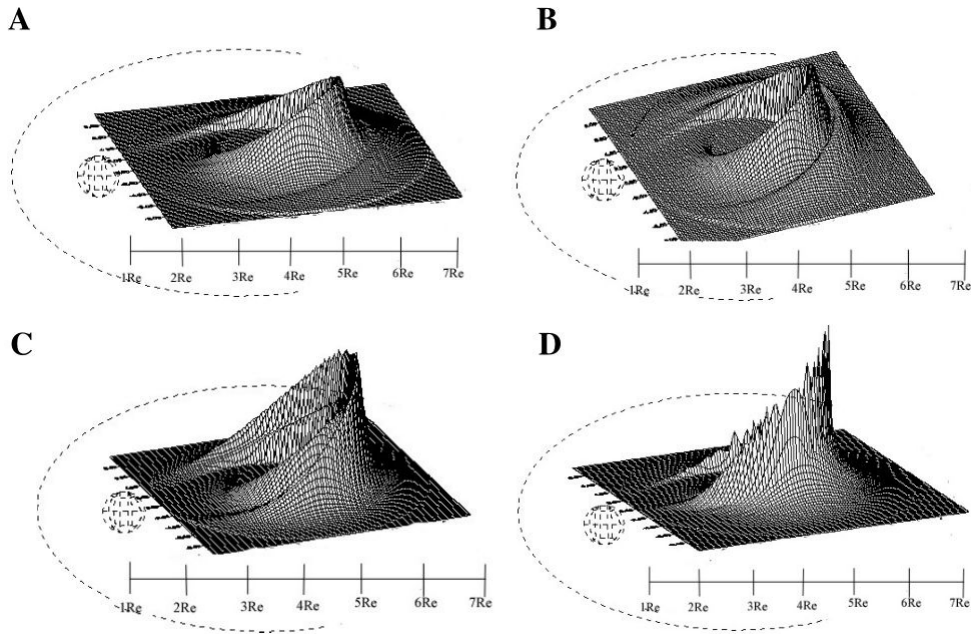
Fig. 2. The plasma pressure relief (results of modeling) under the nonstationary boundary conditions, and with the electric field which is variable in time (periods of magnetospheric disturbances): (a) t = 0 s, (b) t = 1000 s, (c) t = 2800 s, (d) t = 4500 s.
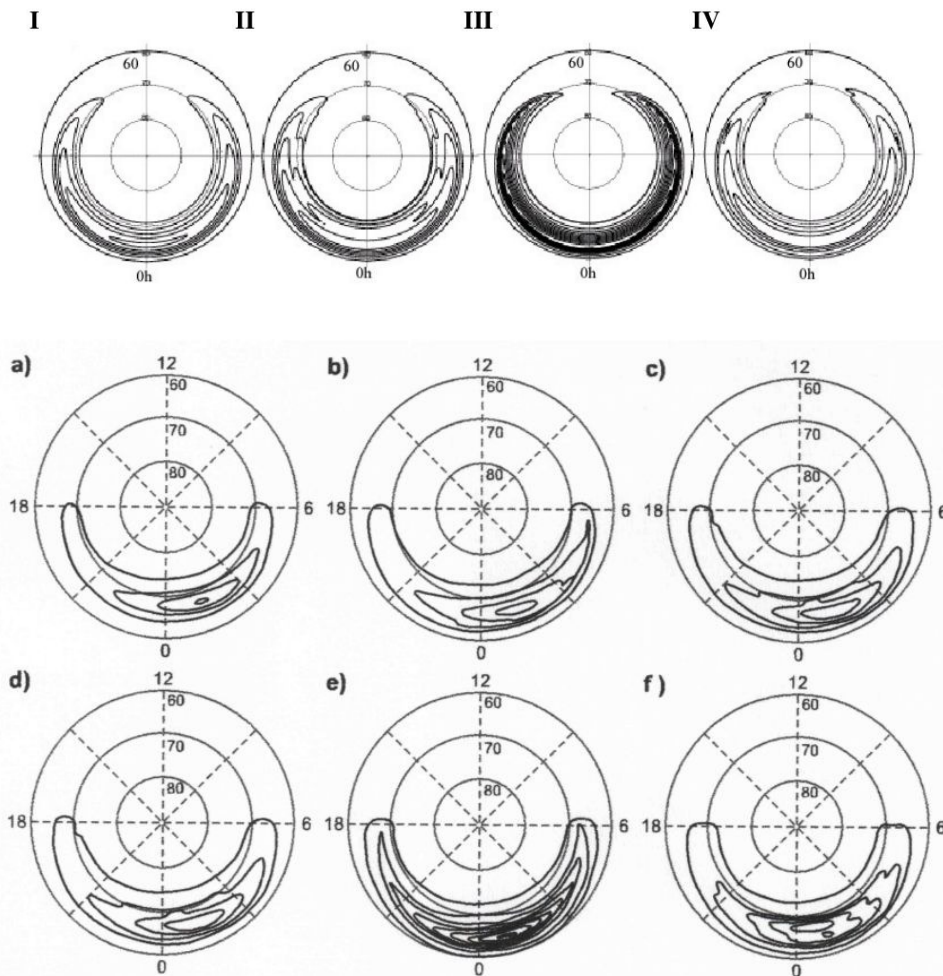

Fig. 3. Equidensity contours of the precipitating electron flux for unsteady boundary conditions: (I) t = 0 s, (II) t = 1000 s, (III) t = 2800 s, and (IV) t = 4500 s. More detailed pictures are for dusk side; results of modeling: contour lines of the intensity of the precipitating electron flux density for the nonstationary boundary conditions- a) t1 = 0 s, b) t2 = 500 s, c) t3 = 1000 s, d) t4 = 1800 s, e) t5 = 2800 s, f) t6 = 4500 s.

Hence the ionization rate is ~ $j_\epsilon/H\delta\epsilon$ ($\delta\epsilon$ in ergs), where j_ϵ is the energy flux density of precipitating electrons (ergs/cm), and the electron density in steady-state conditions:

$$n_e \sim (j_\epsilon/H\delta\epsilon\alpha)^{1/2} \qquad (2.1)$$

here $\delta\epsilon$ is expressed in erg cm^{-2}; recombination coefficient (α), in cm^3 s^{-1}; and H (the dynamo layer thick-ness), in cm.

Integral conductivity for the Pedersen current is:

$$\Sigma_p = (e^2 n_e/M_i)\int \nu_{in}/(\omega_{iB}^2 + \nu_{in}^2)dz , \qquad (2.2)$$

where e is the electron charge, M_i is the ion mass, ω_{iB} is the ion gyrofrequency, and ν_{in} is the ion-neutral collision frequency. The integral (dz) is taken over the entire thick-ness of the current-carrying layer, i.e., from 100 to 120 km. Observational data and theoretical estimates show that the scale of the electric field along the latitude is several times larger than the scale of precipitation and, hence, than the scale of the conductivity region.

Since the ionization latitudinal distribution is much more nonuniform in space than the electric field, we will consider that:

$$\partial J_\theta/\partial\theta \approx E_\theta \partial\Sigma/\partial\theta. \qquad (2.3)$$

$$\partial J/\partial\theta = (\partial\Sigma_p/\partial\theta)E_\theta + (\partial E_\theta/\partial\theta)\Sigma_p \sim E_\theta \, \partial\Sigma_p/\partial\theta$$

Hence it follows that the electric field configuration is unimportant for the problem of generation of field-aligned currents in the ionosphere, at least for the divergence of those Pedersen currents, which flow along the latitude and produce "curtain" structures. Of importance are the parameters of precipitation, the intensity of which is closely associated with the spatial distribution of the number density of particles in the magnetosphere and, hence, with the pressure relief. For that reason, there must be a correspondence between the picture of field-aligned currents calculated from the gas pressure distribution in the magnetosphere and the picture of field-aligned currents calculated from the distribution of ionization (i.e. precipitation!).

It is this reasoning that dictated the formulation of the problem. At the first stage of research, the result of which is presented in this paper, we present the pictures of field-aligned current distribution inferred in terms of a very simple model.

Calculations were performed by the formula:

$$j_{\uparrow\uparrow} \approx j_r = [\partial J_\lambda/\partial\lambda + \cos\theta_a J_\theta + \sin\theta_a \partial J/\partial\theta]/r_o \sin\theta_a \qquad (2.4)$$

Since in high latitudes the direction of geomagnetic field lines is close to a radial direction, we identified the field-aligned currents in the ionosphere with radial ones. The error arising in this case in the value of the field-aligned current for the auroral zone is less than 20%. Surface densities of Pedersen currents along the latitude, J_λ, and along the meridian, J_θ, were calculated by standard formulas:

$$J_\lambda = \Sigma_p E_\lambda \quad \text{and} \quad J_\theta = \Sigma_p E_\theta \qquad (2.5)$$

Results of calculations of field-aligned currents "generated" in the ionosphere are shown in Fig. 4.

It should be noted that only the sign of the field-aligned current whose amplitude exceeded some given value, was plotted. For comparison, for the same instants of time Fig. 5 presents the signs of field-aligned currents generated in the magnetosphere.

Calculations were performed by the formula (Vasyliunas, 1970; Ponomarev, 1985):

$$j_{\|} = cB^I \int_0^l \{[\nabla p_g \times \nabla p_B] \cdot B/p_B B^3 \}dl \qquad (2.6)$$

where B^I is the magnetic field strength in the ionosphere, the integral is taken over the entire flux tube from the equator to the ionosphere, and p_B is the magnetic pressure.
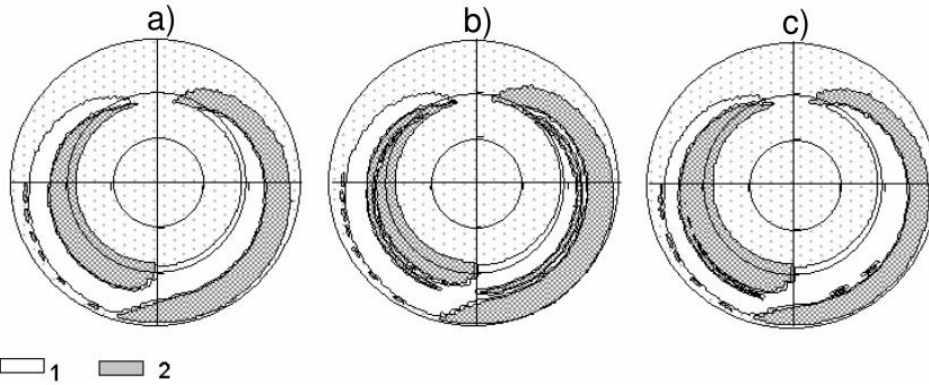

Fig. 4. Field-aligned currents "generated" in the ionosphere: 1 - zone of inflow currents, 2 - zone of outflow currents; a) t=0 s; b) t=1000 s; c) t=2800 s.
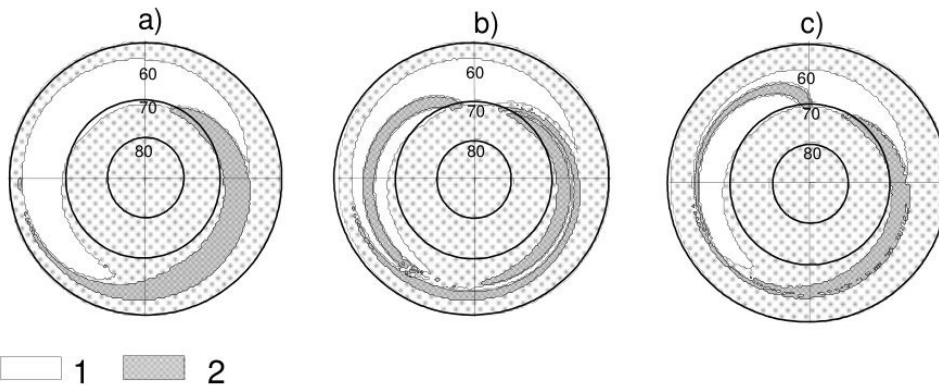

Fig.5. Field-aligned currents generated in the magnetosphere: I - zone of inflow currents, 2 - zone of outflow currents; a) t=0 s; b) t=1000 s; c) t=2800 s.
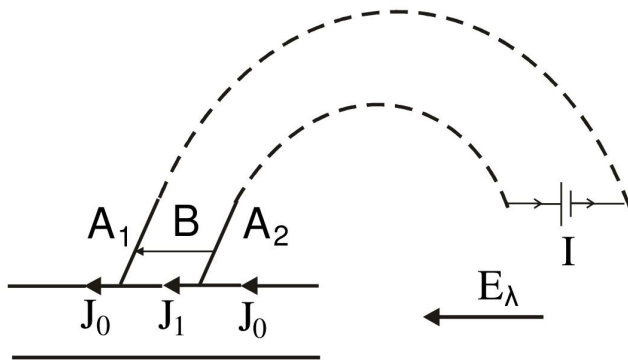
Fig.6. A - ionospheric region with background (low) conductivity.
B - ionospheric region with increased conductivity. The
portion A_1-A_2 has a large-scale (quasi-homogeneous)
meridional electric field E^A_λ that produces the electric
current. If the source of current I in the corresponding
magnetospheric region is absent, then the current j flows in
the entire portion A_1-A_2; however, the electric field in
region B, E^B_λ, is decreased. If, however, the source of
current I is present in the magnetosphere, then E_λ is
everywhere identical, and on portion B the electric current j^B
is enhanced. Hence in the former case $j^B = j_0$ and $E^B_\lambda < E^A_\lambda$,
and in the latter case $E^B_\lambda = E^A_\lambda$, but $j^B = j_0$.

It is clear that the integrand in (2.6) is proportional to the sine
of the angle between the contour lines p_g=const and p_B=const. In a
dipole approximation, lines of equal magnetic pressure are
concentric circles, and isobars follow plasma pressure relief
contour lines.

3. Discussion of results

The problem of compatibility of field-aligned currents
generated in the magnetosphere, and of field-aligned currents,
which are produced as a result of a spatial inhomogeneity of
conductivity (and to a lesser extent, of the electric field), that is, as
if they were "generated" in the ionosphere, is part of the problem
of ionosphere-magnetosphere coupling. It is clear that in actual
fact they are simply parts of one and the same global ionospheric-
magnetospheric current system. The problem of ionosphere-
magnetosphere coupling primarily implies that it is necessary to
solve the question as to how the magnetospheric producer of
current and power "adjusts itself" to the ionospheric consumer.
For a certain special configuration, this problem was solved in
(Sedykh, Ponomarev, 2002; Ponomarev, Sedykh, Urbanovich,
2006; Sedykh, 2011; Sedykh, 2014).

It turned out, firstly, that the ionospheric consumer updates the
convection rate and through it the plasma pressure gradient, which
determines the density of bulk currents which, in turn, determines
the behavior of field-aligned currents through its divergence.
Secondly, it turned out that ionospheric and magnetospheric
currents are not rigidly linked. Some of the current (and power!)
that is not "demanded" by the ionosphere can go into feeding the
MHD compressor pumping plasma into the region of increase
magnetic pressure - in the earthward direction.

For us, the most important issue in this paper is that of
ascertaining the direction of the cause-and-effect relationship.
Current is primary in the magnetosphere, whereas the electric field
is primary in the magnetosphere. Furthermore, the convection
system can undergo some adjustment, and together with it the
electric field in the ionosphere. But such adjustment is possibly
only as corrections of the first approximation to the zero-order
approximation. And hence the zero-order approximation, that is,
the picture of field-aligned currents obtained essentially for an
arbitrary but smooth initial electric field must contain the main
elements of the natural system of field-aligned currents which is
determine by the distribution of electron precipitation closely

associated with the plasma pressure distribution in the
magnetosphere. Let us now consider from this standpoint Figs. 4
and 5.

Fig. 4 shows a classical picture of field-aligned currents that
coincides in its main traits with the well-known Iijima-Potemra
scheme (Iijima, Potemra, 1978). This correspondence indicates
that the factor that determines the main features of the
configuration of field-aligned currents is the existence in the
ionosphere of a well conducting channel produced by zones of
intense precipitation of electrons from the plasma pressure hump
region (see Figs. 1-3).

However, whether or not the enhancement of current in this
channel with enhanced conductivity is possible will depend on
whether the magnetospheric source is able to supply field-aligned
currents this peculiar "discharge gap", as shown in Fig.6.

Fig. 5 shows the picture of field-aligned currents that is
"offered" by the magnetosphere. One can see that "demand" and
"supply" are more or less identical for the arrangements of the
zones. It should be noted that the integral over all inflow and
outflow currents in Fig. 5 is virtually zero.

4. Conclusion

The results presented in this study induce us to hope that the
compatibility of field-aligned currents of magnetospheric and
ionospheric origins is feasible.

Perhaps the mystery of the substorm lies in the plasma
pressure distribution, or more precisely, in the global
redistribution of the plasma pressure on the night side of the
magnetosphere. Direct observations of plasma distribution in the
magnetosphere are faced with large difficulties, because pressure
must be known everywhere in the plasma sheet at high resolution,
which in situ satellites have been unable to provide. Modelling of
distribution of plasma pressure (on ~ 3-12 R_E) is very important,
because the data from multisatellite magnetospheric missions for
these purposes would be a very expensive project. Therefore there
arises a necessity for modelling processes of near-Earth space. A
selection and applying of correct initial system of equations are
also very important.

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