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EARTHWARD ELECTRIC FIELD IN THE GEOMAGNETIC CURRENT SHEET

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Abstract. Measurements with the space craft IKB-1300 have shown that the generator of field-aligned currents is located in the geomagnetic tail. The field-aligned currents are generated by the earthward electric field in the magnetotail current sheet (CS). Two-fluid MHD analysis of plasma behavior in CS explains the electric field generation by the Hall effect. The recent space measurements demonstrate that the most current in CS is transferred by electrons. As a result the **j**×**B**/c accelerates electrons and the charges polarization generates the earthward electric field. Connection of the pair of field-aligned currents (FAC) occurs in the ionosphere, and the westward electrojet is located between FAC pair. The current in CS is generated in the interface between plasma of the solar wind and the tail magnetic field. The attempt to explain current generation in CS by the drift of particles in electric and magnetic fields of the tail, which origin isn't connected with the solar wind can't be justified. Using the drift approximation some authors claimed that the current in the current sheet is carried by ions. This conclusion is erroneous. At drift approach the magnetic configuration represents the closed system which is independent of the solar wind, and the stationary electric field exists due to the temperature gradient across a tail. The temperature gradient appears as a result of energy dissipation in CS. The existence of such temperature gradient contradicts the assumption about collisionless conditions.

Introduction

The geomagnetic tail is responsible for the most important energetic phenomena observed in the Earth magnetosphere, such as plasma injection from CS and aurora production. The creation of the radiation belt due to fast particles injection from the magnetic tail has been demonstrated in the laboratory simulation [Dubinin and Podgorny, 1974]. The geomagnetic tail is formed due to interaction of the solar wind with the field of the Earth. The plasma flow (solar wind) extending lines of the magnetic field. An electric generator that produced the current in CS is situated in interface between solar wind and the Earth magnetic field. The role of the CS electric field in the magnetosphere dynamics is still under discussion. The technical problems do not permit to get reliable results of electric field vector measurements in geomagnetic CS. The aim of this paper is to consider up to date situation. The current generated in each of the tail lobes is closed in CS separating opposite directed magnetic lines. Two independent closed electrical circuits are formed as shown in Fig. 1a. These currents can be overlapped in CS, and the current distribution with one maximum is observed in the central plane as shown in Figure 1b. Conditions of overlapping currents I_1 and I_2 are difficult to formulate. Results obtained by Isralevich at al. [2008] show that two current maxima are observed at strong current, i. e. at big magnetic fluxes in the tail.

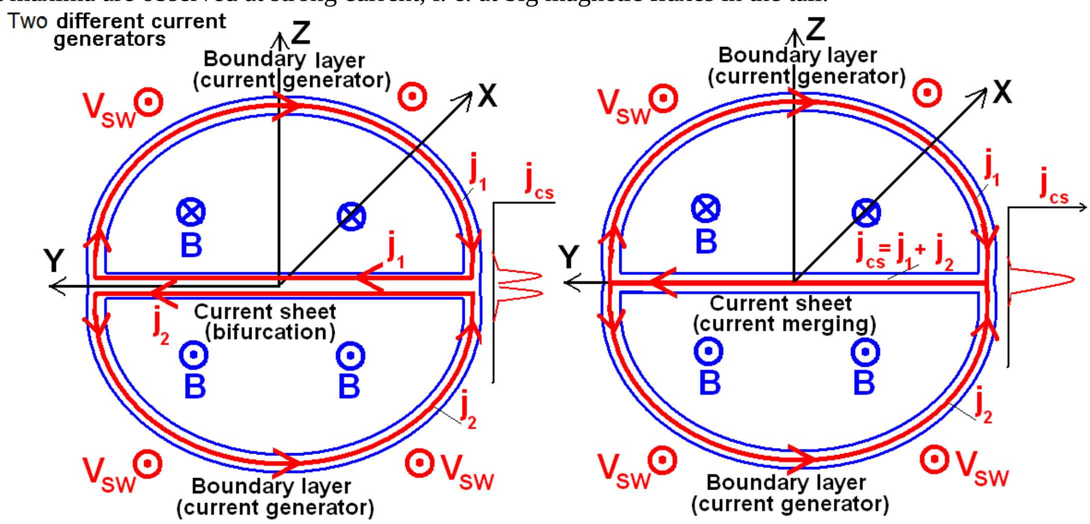

Fig. 1. Two different models of the electric circuit system in the geomagnetic tail.

CS is a dissipative element of the electric circuit. The strong temperature gradient across the sheet ($T_{e\ max}$ ~ 1 keV) and earthward plasma ejection demonstrate fast magnetic energy dissipation. An important feature of CS is the existence of a normal magnetic field component. CS isn't a neutral one. The force of a magnetic tension can be compensated by the pressure gradient along the sheet and mainly by inertia of ions. As electrons in CS are magnetized, the force of a magnetic tension accelerates electronic gas. The electric charge separation takes place. Ion acceleration to the Earth occurs in the electric field of a formed space charge.

In quasi stationary state plasma is flowing in CS. In the vicinity of the X-type singular line magnetic field lines are reconnected. Magnetic energy released at magnetic reconnection is used for plasma heating in CS, and the plasma is accelerated toward the Earth. Compensation of the reconnected magnetic flux occurs, apparently, with southward magnetic field component in the solar wind. The balance of magnetic energy is sharply broken during a substorm because of reconnection rate increasing.

The Earthward electric field in the geomagnetic tail

The Soviet-Bulgarian spacecraft IKB-1300 was launched in 1981, August 7 on a polar circular orbit with the altitude of 900 km (Podgorny at al., 1988, Dubinin at al., 1987). Three-axis stabilization supplied unique possibility of comfortable measurements of three components of the electric and magnetic fields, and the plasma velocity. The tip – tip distance of the electric field sensors was 7.5 m. X - axis is directed along the spacecraft velocity; Z - axis is directed upward normal to the Earth surface. In the auroral regions the Z- axis almost coincides with a magnetic field line. The fluxes of fast electrons, the electron spectrum, and atmosphere luminosity in several spectral lines are also measured. The measured value of the electric field component perpendicular to the Earth magnetic field is controlled by plasma drift velocity measurements in XY-plane.

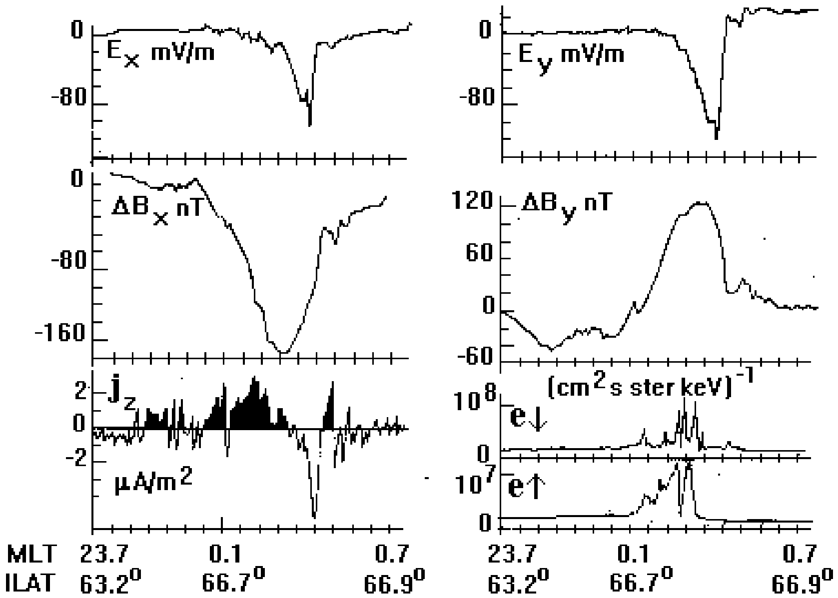

Fig. 2. Measured electric and magnetic fields, current density, and electron flux at crossing field-aligned currents by the spacecraft.

Electric and magnetic fields measurements at crossing the pair of field-aligned currents at night side as shown in Fgure 2 , when the chain of IZMIRAN magnetic stations demonstrates an enhancement of the westward jet. This successful coincidence of circumstances has occurred on December 21, 1981. The measured electric field E_z normal to the Earth has been very small, and B_z magnetic field component has not been disturbed. The main upward and downward field-aligned current (FAC) layers in the night sector are recorded. The increasing magnetic filed $\Delta\mathbf{B}$ is situated in the plane perpendicular to the Earth magnetic field (XY plane). $\Delta\mathbf{B}$ is located between upward (at lower latitude) and downward (at higher latitude) FAC layers. The angle between the normal to the FAC layer and X-axis is arctan($\Delta B_X/\Delta B_Y$) ~ 50°. The electric field between opposed directed FAC is revealed. This electric field is directed perpendicular to the FAC layers. The total potential drop exceeds ~10 kV.

But there is no symmetry in North-South electric field distribution between upward and downward FAC layers. The electric field maximum is shifted to the downward current. Such distribution is a consequence of increasing the Pedersen conductivity in the region of upward current due to electron precipitation. Electrons are accelerated in upward FAC to the Earth somewhere above the spacecraft (900 km). The electron flux produces aurora neutral particle ionization in the ionosphere. The Pedersen height integrated conductivity is increasing in the precipitation region according to $\Delta\sum_P = 4.7\times10^{12}$[W(erg cm^{-2} s^{-1})] cm s^{-1} [Harel at al., 1981]. Increasing ionospheric conductivity in the region of upward FAC produces redistribution of the potential drop. So, the electric field maximum is shifted to the downward current. In the region of the upward current, the weak upward electron flux is also observed.

Apparently, these electrons appear due to scatterings with ionospheric plasma.

The direction of the electric field between the upward and downward current layers shows that field-aligned currents are generating in CS of the geomagnetic tail. Such generation demands the earthward electric field appearance in the tail CS. The potential drop ~10 kV is projected in the tail along the field line up to the distance order of 20 R_E The Ohm law $\mathbf{j} = \sigma[\mathbf{E} + \mathbf{V}\mathrm{x}\mathbf{B}/c - \mathbf{j}\mathrm{x}\mathbf{B}/nec + \tilde{N}p_e/ne]$ shows that the earthward electric field can be only the Hall electric field $\mathbf{j}\mathrm{x}\mathbf{B}/nec$. The term $\tilde{N}p_e$ can be neglect in a long CS. For the tail length L~20RE and the temperature drop ~1 kV, the electric field does not exceed ~ 10^{-6} V/cm. It is important to emphasize that normal magnetic field component is always appeared in all CSs in the laboratory simulated magnetosphere and in space. The electron gas is accelerated by the $\mathbf{j}\mathrm{x}\mathbf{B}/c$ force.

The tail current density increases during a substorm due to the decreasing of CS thickness up to ~ $0.1R_E$. As a result the $\mathbf{j}\mathrm{x}\mathbf{B}/c$ force increases and produces accelerated plasma injection into the Earth's magnetosphere. The Hall electric field $\mathbf{j}\mathrm{x}\mathbf{B}/nec$ also increases. For tail magnetic field B_t =20 nT, the normal magnetic field component B_n ~ 2 nT in the tail CS, the plasma density n ~ 0.2 cm^{-3}, and the CS thickness at a substorm δ = 0.1 R_E the potential drop at distance L = $10R_E$ can be estimated as $B_t B_n L/(2\pi\delta ne)$ ~50 kV.

The independent proof of the Hall effect existence in CS manifestation is made in the laboratory experiment (Minami et al., 1993). The magnetosphere with a magnetic tail has been created at supersonic and superalfvenic plasma flow interaction with the dipole magnetic field. It has been shown that the Hall electric field generation occurs in a tail CS. The electric field is directed to the Earth's dipole. The stream of the ions which have been accelerated by the Hall field enters the strong dipole magnetic field creating of positive space charge accumulation. In this place the opposite directed electric field is registered.

Another independent evidence of the Hall effect in the geomagnetic tail has been shown by Israelevich et al., [2001], which is indicated existence in the geomagnetic CS the antiearthward current order of 1 MA.

Electron or ion current in CS?

For Hall effect appearance, it is necessary that the $\mathbf{j}\mathrm{x}\mathbf{B}/c$ force has to be applied to the electron gas, i.e. the considerable part of the current should be transferred by electrons. The principal role of electrons in the tail current is seen in valuable measurements of ion fluxes in the tail CS of the Earth magnetosphere ([Baumjohann at al., 1990]). The data are acquired from the AMTE/IRM satellite. It has been shown that the ion velocity component V_{iy} directed along current in CS is always is very weak, and the earthward ion flux has been detected. These data contradict with the conclusions made by Zelenyi at al. (2002), and Sitnov at al. (2000) about current production in CS by ions.

The conclusions about the current transferring by ions have been made from consideration of ion trajectories in the CS magnetic field. The magnetic tension force in the current layer is completely ignored. The conclusion is declared: "The current in CS mainly supported by the ion currents". Such self-contained ideal CS is constructed without the force applied to magnetosphere from the solar wind. The mistake of such conclusion has been established at the analysis of direct measurements of electron fluxes in geomagnetic CS and comparison these measurements with curl measurements. In works of Runov at al. (2006) and Izrailevich at al., (2008) it has been shown that the basic contribution of the current of CS is due to electrons.

Westward electrojet

The electric field between layers of opposite directed FAC is perpendicular to the magnetic field. Besides the Pedersen current, it must induce Westward Hall current in the ionosphere along the polar oval. The strong FAC appears when the IKB-1300 space craft has been flown above the chain of IZMIRAN magnetic stations. The westward electrojet is revealed itself with the current ~2 10^4 A (Dubinin at al., 1987). The jet is located above the measured ΔB maximum, e. g. between upward and downward FAC layer (Fig. 3b). Here the Hall current $J_H = (c/4\pi)(\Sigma_H/\Sigma_p)\,\Delta B$ has to be exists, where Σ is the height integrated conductivity. Apparently the ratio Σ_H/Σ_p is increased due to the fast electron precipitation. According to Reiff at al. ([1984]) the ratio is $\Delta\Sigma_H/\Delta\Sigma_p \sim W^{5/8}$, where W is the electron energy in keV.

The most probable scheme of the auroral electrojet short circuit has been offered by McPherron et al. (1983) (Figure. 3c). During a substorm, the part of the current of CS is connected with the electrojet via FAC, and dipolization of the Earth magnetic field occurs.

On the possibility of the earthward electric field estimated by the drift approximation

Recently L. M. Zelenyi et al. (2010) are offered the other mechanism of the earthward electric field generation in the geomagnetic tail The two-dimensional stationary existing configuration of the magnetic field with antiparallel lines

B_x, on which it is imposed a normal component of the magnetic field B_z, is considered. Such artificial configuration exists independently from external conditions (the Earth magnetic field, the solar wind, etc.). Existence of any external sources of current generation in this magnetic configuration is completely neglected. It is considered that a stationary CS is driven by the current generator is located inside the sheet, instead of in a boundary layer of the magnetospheric tail, where the current is generated as an interaction between the solar wind plasma and the tail magnetic field. It is supposed that current in such CS is created by the electron drift in the crossed fields B_z and E_x. The earthward electric field E_x in CS appears in a consequence of electric field E_z existing directed across CS. The axis X is directed to the Earth, and axis Z is directed upwards, perpendicular to CS. For a substantiation of the mechanism of generation of the electric field E_x directed to the Earth, the electric field component E_z is set in Zelenyi at al. work (2010b). As the mechanisms of generation of the electric field E_z across the sheet, the gradient of electron pressure across CS and pushing out electrons due to the magnetic mirror force are proposed. These mechanisms produce opposite directed E_z in CS. Authors (Zelenyi at al. 2010b) connect origin of E_z component with potential occurrence ~1 kV arising because of “motion of unmagnetized nonadiabatic ions and magnetized electrons in vicinity of CS central region should be different”. In work (Zelenyi at al., 2010b) for setting the electric field E_z the potential difference across CS is estimated from the electron temperature of a hot CS on the basis of two-liquid MHD as $\sim kT_e/2e$. Inserting of the electric field E_z, it is assumed that CS plasma colisionless and drift of particles unequivocally defines by this electric field. The inserted electric field isn't connected in any way with the mechanism of geomagnetic tail formation at the expense of solar wind interaction with the magnetic field of the Earth dipole.

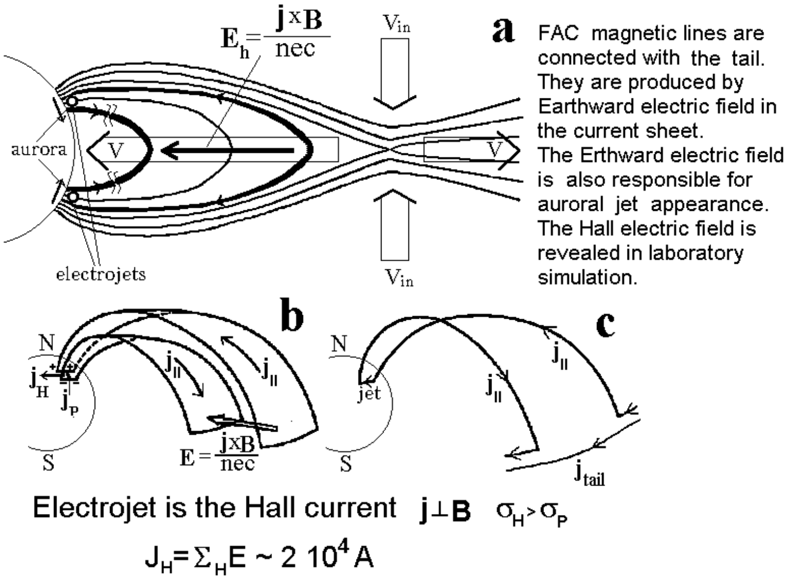

Fig. 3. a) Magnetic lines and field-aligned currents (thick lines). b) Field-aligned currents and the electrojet. c) Electrojet connection with the tail current.

The strong temperature gradient can stationary exist only at strong energy dissipation. However within the limits of used drift approach the energy dissipation is absent completely. Strong magnetic energy dissipation is inconsistent with conditions of collisionless.

It is correctly affirms that the magnetic field configuration of CS cannot influence on the electric field distribution in CS, if the magnetic field configuration is independent from X. However, in (Zelenyi at al., 2010a) it is supposed, if the normal magnetic field component depends on X, the electric field distribution should change, and the electric field component E_x directed to the Earth will arise. The scheme in (Zelenyi at al., 2010a) (fig. 4) gives relationship $E'_x = E_x + \frac{\partial(\Delta S)}{\partial j}\frac{\partial j}{\partial S}$ from which E_x directed to the Earth has been estimated. Here, S is a coordinate along magnetic field line, φ is the potential. E_x directed to the Earth. The second term describes the electric field directed to the Earth that calculated under assumption that the potential drops on ΔS_1 and ΔS_2 are different. At a writing of this formula the physically not defensible assumption is made. It is assumed that the electric field component, directed along the magnetic field line dφ/ds, is invariant at any change of inclination of a magnetic line. This assumption is proved by nothing. For such statement there are no bases. So instead of formulas in fig.4 it must be written $j'_1 = j_1 + (\partial j/\partial s)_1 \Delta s_1$ and $j'_2 = j_2 + (\partial j/\partial s)_2 \Delta s_2$, where $(\partial j/\partial s)_1 \Delta s_1 = (\partial j/\partial s)_2 \Delta s_2$, because projection of field E_z on magnetic line (dφ/ds) decrease in the same times in which the length of line ΔS is increased. It means that $E'_x = E_x$ and nonzero E_x can not appear. The further calculation with use of model of CS gives value E_x ~ 1 mV/m in the CS configuration. The authors of (Zelenyi at al., 2010a) conclude that the electric field E_x directed to the Earth obtained in such a way is a hidden one. It can't to influence on the magnetospheric plasma outside the sheet and to create FAC.

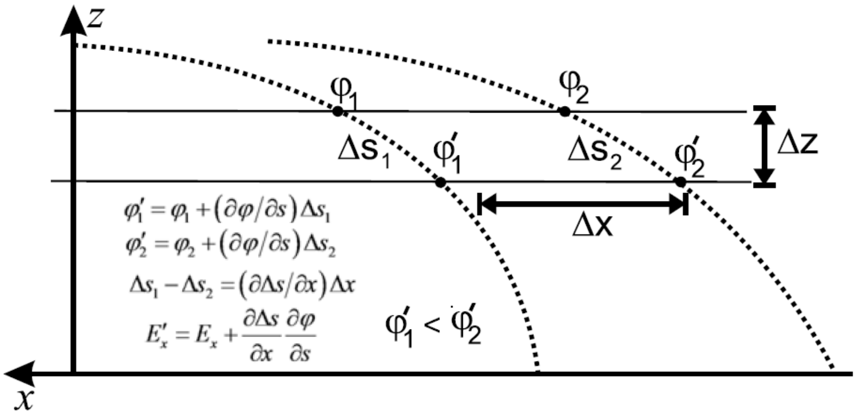

Fig. 4. Magnetic field lines (broken lines) and potential drops in CS according Zelenyi et al.

As the additional mechanism causing increase of the earthward electric field E_x authors (Zelenyi at al., 2010a) consider ion drift to the Earth. For this purpose existence of E_y field component is also introduced, but in this case energy dissipation ($E_y \times J_y > 0$) is inconsistence with plasma collisionless, which is necessary for drift approximation. It is confirmed that the ion drift velocity is bigger than the electron drift velocity: $V_{xi} - V_{xe} = \Delta V_x \sim \rho_i^2 \nabla^2 (E_y/B_z)$. However, ions moving forward create the field of polarization directed not to the Earth, but from the Earth. Therefore the account of the fast ion drift will lead to reduction of the field directed to the Earth, or to change of the electric field direction on the opposite. Thus, within the frame of drift approach it is impossible to estimate not only the electric field value, but also field direction.

Used in the work (Zelenyi at al., 2010a, b) drift approach is extremely useful to rough estimates of plasma behavior. However, it doesn't consider of several effects which in some problems of plasma physics are basic. It doesn't consider the force of a magnetic tension, to which in the real CS forces of ion inertia and the pressure gradient counteract. In absence of such forces a magnetic configuration must to turn in potential one with the light velocity. In the Zelenyi model only electrons are connected with magnetic field lines (magnetized). It is correct, but it means that force of a magnetic tension is applied to electrons. Forward electron gas motion induces electric charge polarization. Because of plasma polarization the electric field directed to the Earth is created. Thus the Hall effect, which is absent in drift approach, is gracefully described in magnetohydrodynmics by the formula $E = j \times B/nec$.

Conclusion

Recent measurements show that most of the current in CS is transferred by electron. So the previous conclusion of Zelenyi et al. (2002) about ion role in CS current can not be considered as a reason against Hall effect appearance in the Earth magnetic tail. Application of the drift approximation assumes the conditions of collisionless, i.e. absence of magnetic energy dissipation including heating due to anomalous resistivity in CS. However, in formulating the problem of the drift approximation, the existence of strong temperature gradient across CS is assumed (Zelenyi at al., 2010a, b). This gradient indicates efficient energy dissipation. Existence of a temperature gradient contradicts to the requirement of the drift approximation applicability. Plasma heating shows magnetic energy dissipation in CS in spite of energy dissipation inconsistent with drift approximation. So, the ideology based on drift approximation that does not take into account the role of solar wind for CS generation is not applicable. The Earthward electric field in drift approximation has been obtained in presence of the electric field normal to the CS, if the electric field projection on the magnetic line is changed at angle inclination of this line, but the length of magnetic line remains constant. These geometric considerations are wrong; the nonzero Earthward electric field never can appear such a way.

The earthward electric field in the geomagmetic tail is a result of plasma polarization due to the $F = j \times B/c$ force applied to electrons. This electric field can be responsible for FAC and westward jet creation.

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