Electric Field Generation in the Magnetotail discovered by Intercosmos Bulgaria-1300

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Abstract. Measurements of the space craft IKB-1300 have shown that the generator of field-aligned currents of the Earth magnetosphere is located in the geomagnetic tail, where the earthward electric field is created. Two-fluid MHD analysis of the plasma behavior in the current sheet (CS) explains that this electric field generation is occurred by the Hall effect. Connection of the pair of opposite directed field-aligned currents occurs in the ionosphere, and the westward electrojet is located between this pair of field-aligned currents. It is pointed out here that the idea to explain the current generation in CS by the drift of particles in electric and magnetic fields of the tail, in which the origin is independent from the solar wind, cannot be justified. For such an approach, the magnetic field configuration represents the closed current system which does not depend on the solar wind, and the stable electric field exists due to the temperature gradient across the tail. Such temperature gradient existance contradicts to the assumption of the collisionless conditions. The generator of the current of the tail CS is localized at the interface between the solar wind plasma flow and the tail magnetic field. The generated current is closed in the tail CS.

Keywords: geomagnetic tail, current sheet, field-aligned currents, substorm, Hall effect

Introduction

The geomagnetic tail is formed at interaction between the solar wind and the magnetic field of the Earth. The force of plasma flow (solar wind) extending lines of the magnetic field is applied to the interface, where the electric generator is located. The current generated in the tail lobe boundaries is closed in the current sheet (CS) separating the magnetic field lines of an opposite direction. Two independent closed circuits are formed as shown in fig. 1. These currents can be overlapped, creating of current distribution with a single maximum in the central plane (fig. 1a) or produce the double maximum (fig. 1b). Conditions of overlapping currents, I_1 and I_2, are difficult to formulate. Results by Isralevich et al. (2008) show that two maximum currents are observed at the very high magnetic fluxes in the tail.

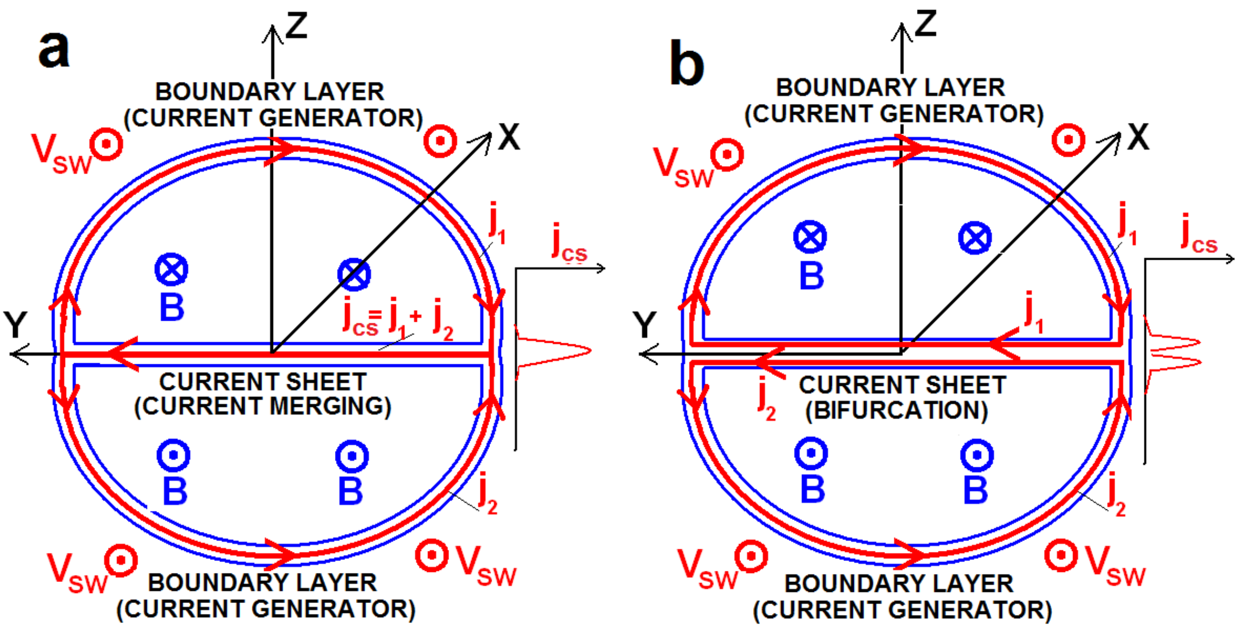

Figure 1. Two different models of the electric circuit system in the geomagnetic tail. The CS is a dissipative element of the electric circuit.

The strong temperature gradient across the sheet ($T_{e\ max}$ ~ 1 keV) and the earthward plasma ejection show the fast magnetic energy dissipation. An important feature of CS is the existence of a normal magnetic field component. The CS is not a neutral one. The force of the magnetic tension can be compensated by the pressure gradient along the sheet and mainly by inertia of ions. If the current in CS is transferred by electrons, the force of a magnetic tension accelerates electronic gas. The electric charge separation takes place. Ion acceleration to the Earth occurs by the electric field of the formed space charge. Plasma in quasi stationary state is flowing in CS in a vicinity of the X-type singular line, where the magnetic field lines are reconnected. Magnetic energy released by the reconnection is used for the plasma heating in CS and acceleration to the Earth. The compensation of the reconnected magnetic flux apparently occurs, when the southward magnetic field component in the solar wind appears. The magnetic energy sharply decreases during a substorm because of the reconnection rate increasing.

The earthward electric field in the geomagnetic tail

The Soviet-Bulgarian spacecraft IKB-1300 was launched in August 7, 1981 with a polar circular orbit at the altitude of 900 km (Podgorny et al., 1988; Dubinin et al., 1987). Three-axis stabilization is supplied for the unique possibility of measurements of three components of the electric and magnetic fields, and the plasma velocity. The tip - tip distance of 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 electron temperature, the fluxes of fast electrons, the electron spectrum, and the 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 the XY-plane.

Electric and magnetic field measurements during the crossing of the pair of field-aligned currents at the night side region are as shown in Figure 2, when the chain of IZMIRAN magnetic stations has demonstrated an enhancement of the westward electrojet. This successful coincidence of circumstances occurred on December 21, 1981. The measured electric field E_z normal to the Earth has been very small, and the 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 field $\Delta\mathbf{B}$ is situated in the plane perpendicular to the Earth magnetic field (X-Y plane). The $\Delta\mathbf{B}$ is located between the upward (at lower latitude) and downward (at higher latitude) FAC layers. The angle between the normal to the FAC layer and the X-axis is arc-tan ($\Delta Bx/\Delta By$) ~ 50^0. The electric field between the opposite directed FAC is revealed. This electric field is directed perpendicular to opposite directed FAC layers. The total potential drop exceeds ~10 kV. The direction of the electric field corresponds to the closing upward and downward currents in the ionosphere.

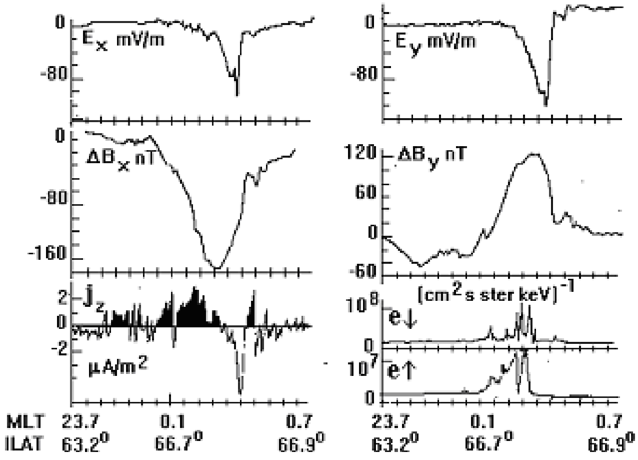

Figure 2. Electric and magnetic fields, current density, and electron flux at crossing field-aligned currents by the spacecraft.

However, electric field distribution between the upward and the downward FAC layers shows asymmetry in the north-south direction. The maximum electric field is shifted to the downward current. Such distribution is a consequence of local increasing of the Pedersen conductivity of the ionosphere in the region of the upward current due to the electron precipitation. Electrons are accelerated in the upward FAC to the Earth somewhere above the spacecraft height (900 km). The electron flux produces aurora and neutral particle ionization in the ionosphere. The Pedersen integrated height conductivity is increasing (Harel et al., 1981) in the precipitation region with electron energy flux to $\Delta\sum_P = 4.7\times10^{12}$ W cm s^{-1}. Here electron energy flux W in erg cm^{-2} s^{-1}. The increasing ionospherice conductivity in the region of the upward FAC produces redistribution of the potential drop. So, the maximum electric field is shifting 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 the scatterings by the ionospheric plasma.

The direction of the electric field between upward and downward current layers shows that field-aligned currents are generated in the CS of the geomagnetic tail. Such generation demands the appearance of the earthward electric field 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's law, $\mathbf{j} = \sigma[\mathbf{E} + \mathbf{V}\times\mathbf{B}/c - \mathbf{j}\times\mathbf{B}/nec + \nabla p_e/ne]$, shows that the earthward electric field can be only the Hall electric field $\mathbf{j}\times\mathbf{B}$/nec. The term ∇p_e can be neglected in the long CS. For the tail length L~20R_E and the temperature drop ~1 kV, the electric field appeared due to the temperature gradient does not exceed ~ 10^{-6} V/cm. It is important to emphasize that normal magnetic field components always presented in all CSs in the laboratory simulated magnetosphere and in space. The plasma is definitely accelerated by the **j**x**B**/c force.

The tail current density increases during a substorm due to decreasing of CS thickness up to ~ 0.1R_E. As a result, the **j**x**B**/c force increases and produces the accelerated plasma injection into the Earth's magnetosphere. The Hall electric field **j**x**B**/nec also increases. For the 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 = 0.1R*E* the potential drop at distance L = 10R_E can be estimated as $B_tB_n/(2\pi\delta ne)L$ ~50 kV.

For Hall effect appearance, it is necessary that a considerable part of the current in CS should be transferred by electrons. The principal role of electrons in the current is seen in valuable measurements of ion fluxes in the tail CS of the Earth magnetosphere (Baumjohann et al., 1990). The data is acquired from the AMTE/IRM satellite. It has been shown that the ion velocity component, V_{iy}, directed along the current in CS is always very weak, and the earthward ion flux has been detected. This data contradicts the conclusions made by Zelenyi et al. (2002), and Sitnov et al. (2000) about the current production in the tail CS by ions. The conclusions about the current transferring by ions have been made from the consideration of ion trajectories in the Harris type CS magnetic field. The inaccuracy of such a conclusion has been established by the analysis of direct measurements of electron fluxes in the geomagnetic CS and the comparison with *rot***B** measurements. In the works of Runov et al. (2006) and Izrailevich et al. (2008), it has been shown that the basic contribution of the current in CS is due to the electrons.

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

Another independent evidence of the importance of the Hall effect in the geomagnetic tail has been obtained in (Israelevich et al., 2001). It shows the existence of the anti-earthward current order of 1 MA in the geomagnetic CS.

Westward electrojet

The electric field between the 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 during a substorm when the IKB-1300 spacecraft was moved above the chain of IZMIRAN magnetic stations. The westward electrojet is measured by the magnetic stations with the current ~2 10^4 A (Dubinin et al., 1987). The jet is located above the measured ΔB maximum, e.g. between the upward and the downward FAC layers (Figure 3b). Here the Hall current $J_H = (c/4\pi)(\Sigma_H/\Sigma_p)\,\Delta B$ has to exist., 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 et al. (1984) this 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 closed auroral electrojet has been offered McPherron et al. (1973) (Figure 3c). During a substorm the part of the current of CS is connected with the electrojet via FAC, and the dipolization of the Earth's magnetic field occurs.

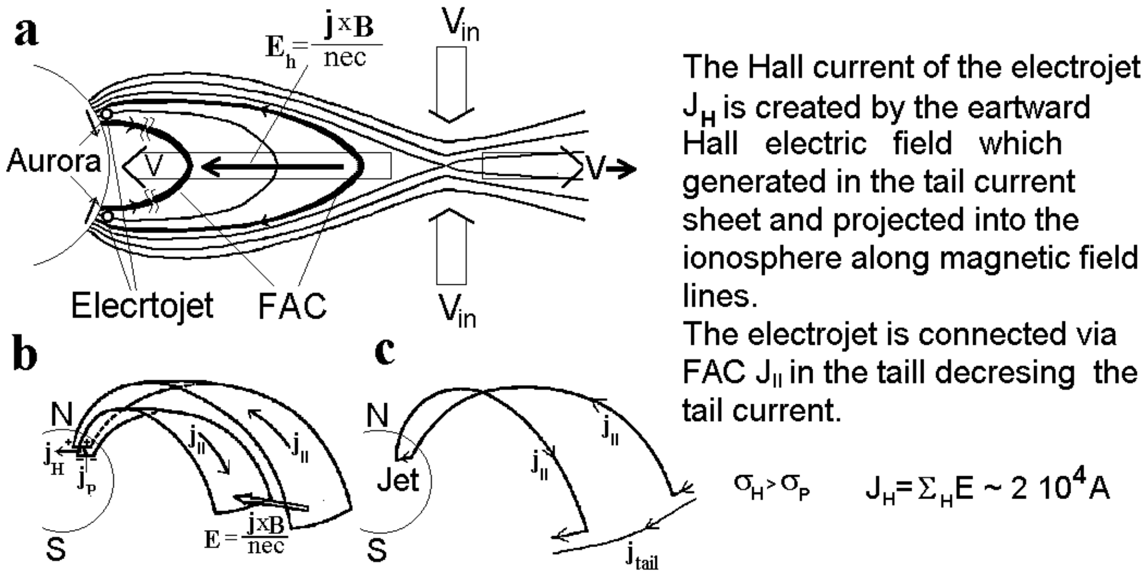

Figure 3. (a) Magnetic field lines and field-aligned currents (thick lines). (b) The layers of field-aligned current and the electrojet. (c) Electrojet connection with the tail current.

The possibility of the earthward electric field estimated, by using the ion drift approximation.

Recently, Zelenyi et al. (2010a) published the paper in which the other mechanism of the earthward electric field generation in the geomagnetic tail is offered. The two-dimensional stationary existing configuration of the CS with anti-parallel magnetic field lines B_x on which a normal component of the magnetic field B_z is imposed has been considered. The two-dimensional stationary existing configuration of the CS with anti-parallel magnetic field lines B_x is considered with the imposed normal magnetic field component B_z. Such artificial configuration exists independently of external conditions (the Earth's magnetic field, the solar wind, etc.). Existence of any external sources of current generation in this magnetic configuration is completely neglected. It is supposed that a stationary CS is created by the current generation inside the sheet, instead of in the boundary layer of the magnetospheric tail, where the current is generated at interaction between the solar wind 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 as a consequence of electric field E_z existance directed across a sheet. The X axis is directed to the Earth, and Z axis is directed upwards, perpendicular to the CS. For a generation of the electric field E_x directed to the Earth, the electric field component E_z is set in (Zelenyi et al., 2010b). As the mechanisms of generation of the electric field E_z across the CS, the gradient of electron pressure across CS is set and pushing out electrons due to the magnetic mirror force is proposed. The electric field E_z, which unequivocally defines a drift of particles in CS, is not connected at all with the mechanism of geomagnetic tail formation at the expense of interaction of the solar wind with the magnetic field of the Earth's dipole. Authors (Zelenyi et al. 2010a) connect the origin of E_z components with potential occurrence $\sim kT_e \sim 1$ kV arising because of "motion of un-magnetized non-adiabatic ions and magnetized electrons in the vicinity of CS central region should be different". In the work (Zelenyi at al., 2010a) for setting the electric field E_z the potential difference across a sheet is estimated from the electron temperature of a hot CS on the basis of two-liquid MHD as $\sim kT_e/2e$. The strong temperature gradient can stationary exist only at strong magnetic energy dissipation. Strong energy magnetic dissipation is inconsistent with the conditions of collisionless. Zelenyi at al., (2010a) correctly affirms that the magnetic field configuration of CS cannot be influenced by the electric field distribution in CS, if the magnetic field is independent of X. However, Zelenyi et al. (2010a) supposed, if the normal magnetic field component depends on X, the electric field distribution should be changed, and the electric field component E_x directed to the Earth will arise. The scheme (Zelenyi et al., 2010a) (Figure 4) gives the relationship $E'_x = E_x + \frac{\partial(\Delta S)}{\partial\varphi}\frac{\partial\varphi}{\partial S}$ from which E_x directed to the Earth has been estimated. Here, S is the coordinate along the magnetic field line, and φ is the potential. E_x is directed to the Earth. The second term describes the electric field directed to the Earth that was calculated under the assumption that the potential drops on ΔS_1 and ΔS_2 are different. In the written formula, the physically un-defensible assumption is made. It is assumed that the electric field component, directed along the magnetic field line, $\partial\varphi/\partial s$, is invariant at any change of the inclination of the magnetic field line. The further calculation with the use of such CS model gives value $E_x \sim 1$ mV/m in this CS configuration. Zelenyi et al. (2010a) conclude that the electric field E_x directed to the Earth obtained by such a way is a hidden one. It cannot influence plasma outside the sheet and create FAC. The assumption that $\partial\varphi/\partial s$, is invariant at any change of the inclination of the magnetic field line is wrong, $d\varphi/ds$ changes with the inclination of the magnetic field line. Namely, $\partial\varphi/\partial s = (\partial\varphi/\partial z)\cos\alpha$, where α is the angle of inclination of the magnetic line to the Z axis. Instead of relationships among φ_1', φ_1, φ_2' and φ_2 written in Figure 4 it should be written: $\varphi_1'=\varphi_1+(\partial\varphi/\partial s)_1\Delta s_1$; $\varphi_2'=\varphi_2+(\partial\varphi/\partial s)_2\Delta s_2$, where $(\partial\varphi/\partial s)_1=(\partial\varphi/\partial z)(\Delta z/\Delta s_1)$, $(\partial\varphi/\partial s)_2=(\partial\varphi/\partial z)(\Delta z/\Delta s_2)$. It means that $\varphi_2'-\varphi_1' = \varphi_2-\varphi_1$, so $E_x'=E_x=\text{const}=0$, the electric field E_x must not appear in such conditions.

As an additional mechanism connecting with increase of the earthward electric field E_x Zelenyi at al., 2010a consider plasma drift to the Earth. For this purpose, the existence of E_y field component is also introduced, but in this case magnetic energy dissipation ($E_yJ_y > 0$) is inconsistence with the collisionless plasma. It is proposed 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 the 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 along CS, but also field direction.

The drift approach used in work of Zelenyi et al. (2010a) is useful only for rough estimates of plasma behavior. However, it does not consider several effects of basic plasma physics. It does not consider the force of magnetic tension in the real CS, forces of inertia and a pressure gradient counteract. In the absence of such forces, a magnetic configuration must turn in the potential one. In the Zelenyi model, only electrons are connected with magnetic field lines (magnetized). This means that the force of a magnetic tension is enclosed to the electrons. Forward electron motion induces electric charge polarization. Due to the 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 $E = j\times B/nec$.

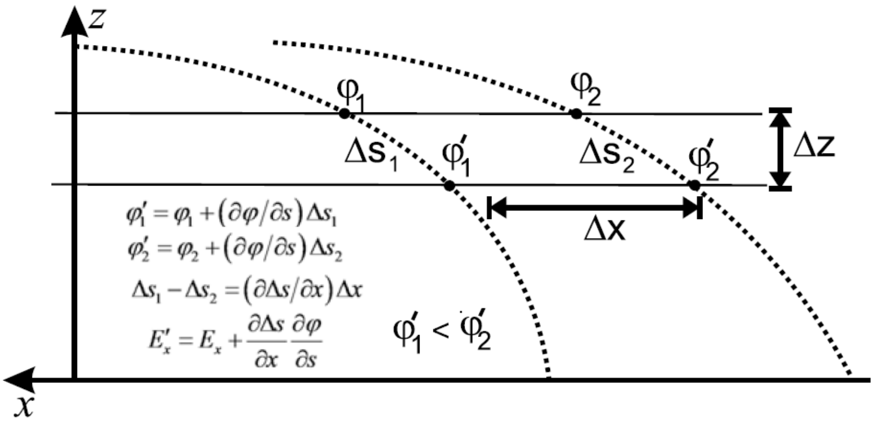

Fig. 4. Magnetic field lines (dotted lines) and potential drops in CS according to Zelenyi et al. (2010a).

Conclusion

Measurements performed on the space craft IKB-1300 show that field-aligned currents generation during the substorm takes place in the current sheet of geomagnetic tail. The field-aligned currents have to be generated by Hall electric field, if the current in the current sheet is carried by electrons. Runov et al. (2006) and Izrailevich et al. (2008) showed that the current in the sheet is carried by electrons. It is contrary to previously made erroneous conclusions by Zelenyi et al. (2002), and Sitnov et al. (2000) based on consideration of the motion of particles in the current sheet in the drift approximation.

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, using the drift approximation the existence of strong temperature gradient across CS is assumed by Zelenyi et al. (2010a). This gradient indicates efficient magnetic energy dissipation. Existence of a temperature gradient contradicts the requirement of the drift approximation applicability.

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

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