Plasma Acceleration in the Magnetotail as an Origin of the Electric Field Generation during a Substorm

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Field-aligned currents and westward electrojet enhancement are produced by electric field generation in the magnetotail during a substorm. The space measurements during the substorm and laboratory experiments support the model of earthward electric field production in the magnetotail current sheet. The results of numerical MHD simulation are presented. The quasistationary current sheet is created at plasma jet injection in the perpendicular magnetic field. The current sheet becomes unstable after plasma injection is ceased, and the local plasma velocity along the sheet drops to zero. The instability development produces fast current density enhancement and plasma acceleration by \( j \times B / c \) force. In such conditions the Earthward \( j \times B / nec \) electric field should appear.

1. Introduction

At substorm onset, the magnetic field in the near Earth magnetotail suddenly relaxes from stressed tail-like configuration—dipolarization. One of the main features of the substorm is plasma earthward flow in the magnetotail current sheet. In the sheet, satellite observations have shown Earth-streaming ion beams, followed by the flux of plasma toward the Earth called an injection.

The observations of magnetic field relaxation have been cited as an evidence for the existence of a substorm current wedge (Lopez, 1990). It is supposed that a portion of the cross tail current is disrupted and delivered via Birkeland currents in the morning sector through the ionosphere via the enhanced westward electrojet. The electrojet current is supposed to return in the tail by upward enhanced Birkeland currents in the evening sector. The tail current decreasing contradicts, however, to the well known fact of plasma acceleration toward the Earth, because the force \( j \times B \) must decrease when the wedge is created. Such mechanism of wedge creation can not explain why the electrojet current is determined by the Hall conductivity, and how the North-South electric field appears in the night side of the polar oval.

The wedge development cannot be considered as a primary link of the substorm events, because the tail current decreasing can not cause plasma injection into the inner magnetosphere as a result of plasma acceleration by the \( j \times B \) force. The plasma pushing to the Earth can be result only of \( j \) increasing due to current sheet thinning, and wedge development apparently occurs only after plasma acceleration. In a such scenario in the phase of plasma acceleration the North-South electric field should be created for initiating the Hall current in the night side of the polar oval.

The space measurements (Podgorny et al., 1988) during a substorm have shown that, in the polar ionosphere region near midnight, the North-South electric field appears as a result of projection along the magnetic field from the tail. The electric field in the tail is directed earthward. This electric field produces Hall current in the ionosphere (westward electrojet), and pair of field-aligned current layers appear in the each hemisphere. Each pair of field-aligned currents is closed in the ionosphere by the Pedersen conductivity. The measurements on the
satellite show two main field-aligned current layers directed oppositely to each other. The layers of field-aligned currents intersect the night ionosphere along a polar oval. Positions of field-aligned currents and direction of electrojet are shown in Fig. 1. The downward current is situated at the higher latitude. The thickness of the field-aligned current layer is of $\sim 100$ km, the current density is of $2 \div 4 \mu A/m^2$ (Podgorny et al., 1988). The northward electric field is located between two oppositely directed field-aligned current layers and is perpendicular to them. Direction of the Pedersen current, which connects field-aligned current layers, is the same as electric field direction in the ionosphere. These measurements show, that energy dissipation occurs ($\langle E, j \rangle > 0$) in the ionosphere. The westward jet is observed by ground based magnetometers between field-aligned current layers at current increasing.

The field-aligned currents supply the energy from a distant part of the magnetosphere. The field-aligned currents projection along magnetic field lines shows, that a current generator is located in the magnetosphere tail at distances of 10–20 $R_E$ (Podgorny et al., 1988). The fast electrons producing discrete aurora are accelerated in potential drops along the magnetic field lines in upward field-aligned current layer. The equi-potential violation of a magnetic field line can be expected in such conditions. The idea of the potential drop appearance is in a good agreement with many experimental and theoretical works (see review, Podgorny, 1982), which have demonstrated appearance of double electrical layers and/or regions of anomalous resistivity, when the electron current velocity in field-aligned currents reaches some critical value, usually $(T_e/m_i)^{1/2}$. Here $T_e$ is the electron temperature, $m_i$ is the ion mass. At a substorm the critical velocity for field-aligned currents can be reached at altitude of $R_E$.

2. Earthward Electric Field Generation in the Magnetotail

The currents circuit generated by the tail electric field is shown in Fig. 1. This current system contradicts to conclusions that aurora arcs are located on field lines connected with a X-type tail neutral line. Akasofu (1987) have pointed out that there is no reason to consider a neutral line as magic one which could be responsible for all main substorm phenomena.
The simple analysis of the general Ohm law:

\[
\frac{\partial \vec{J}}{\partial t} = \frac{n e^2}{m_e} \left( \vec{E} + \frac{1}{c} \vec{V} \times \vec{B} \right) - \frac{e}{m_e c} \vec{J} \times \vec{B} + \frac{e}{m_e} \nabla p_e - \frac{\vec{J}}{\tau}
\]  

(1)

shows that the electric field along a current sheet can be generated in homogeneous current sheets with a normal magnetic field component, because of the second term.

For the quasistationary current sheet, if the current is transferred by electrons, the earthward electric field is \(\vec{j} \times \vec{B}/n e c\) (Podgorny et al., 1988). This electric field generates the system of field aligned currents which is closed in the ionosphere. The current inside the generator (magnetotail current sheet) is closed, because of charge separation by \(\vec{j} \times \vec{B}/c\) force which is applied to electrons. This current along the current sheet is directed opposite to electric field, as in every current generator. It is very important to emphasize that a normal magnetic component is always presented in every current sheet. No one have observed a “pure” neutral sheet, and no one demonstrates in theory how a neutral sheet can be created.

The ion angular distributions in the Earth magnetotail current sheet have been measured by Baumjohann et al. (1990). This work demonstrates absence of any West-East asymmetry of the ion velocity at \(V \sim (3 \div 5) \times 10^7\) cm/s. This value corresponds to the current drift velocity in the sheet. This result proves suggestion that the current in the current sheet has been carried by electrons. This is very typical for current sheets in the laboratory and space plasma.

The existence of the normal magnetic field component explains also plasma electrodynamical acceleration, and its injection into the magnetosphere at a substorm. The tail current sheet can not be considered as a static equilibrium system. The plasma flow plays an important role in current sheet dynamics. During the evolution a current sheet becomes unstable (Podgorny, 1989a), the sheet thickness drops, the current density increases, and the strong electric field should appear.

The strong earthward plasma flow has been observed during development of the geomagnetic activity (Baumjohann et al., 1990). This fact demonstrates that \(\vec{j} \times \vec{B}/c\) is much larger than \(\nabla p\) (the pressure gradient) along the sheet.

The creation of the earthward electric field in the magnetotail has been demonstrated in a laboratory simulation experiment (Minami et al., 1993). For a correct reproduction of the space phenomena in the laboratory the principle of limited simulation has been used (Podgorny, 1978). The experiments are carried out in an artificial magnetosphere, which has been created at supersonic and super-Alfvenic plasma flux (artificial solar wind) interaction with the dipole magnetic field. This result proves the theory of the earthward electric field creation and ions acceleration in this field.

The strong electric field increasing should occur at current density increasing in the tail current sheet during a substorm. According to the measurements (Fairfield et al., 1981) a main feature of the plasmadynamics in the tail during a substorm development is sharp decreasing of the current thickness up to \(0.1R_E\), while the total current is almost constant.

The sharp current sheet thickness decreasing can be explained by plasma losses, because of plasma pushing out of a current sheet by the \(\vec{j} \times \vec{B}/c\) force. The plasma losses can not be compensated any more by plasma inflow into the current sheet from the current sheet boundaries (Podgorny, 1989b). The current sheet thickness produces \(j\) increasing, because the tail magnetic field \(B\) is almost constant. The \(\vec{j} \times \vec{B}/c\) force increases, e.g. the process looks like a flare.

3. The Numerical Simulation of Current Sheet Evolution and Earthward Plasma Flow

For the complete simulation of electric field and field aligned current generation it is necessary to use two fluids 3D code. Now several technical problems restrict our possibility to employ such
The main phenomena (increasing the $j \times \vec{B}/c$ force at transitions the current sheet from stable state into unstable one) can be solved in 2D one fluid approximation.

For the numerical simulation of current sheet evolution it is very important to use the initial conditions properly. We use the current sheet, which is produced at a plasma flow interaction with the transverse magnetic field. Such a natural current sheet is used instead of an analytical form. The typical example of later approach consists in using the Harris type sheet (Harris, 1962) with the normal magnetic field component. This analytical form is very convenient, but no one has demonstrated the possibility of such configuration creation in the space or laboratory.

For the numerical simulation of plasma flow influence on current sheet stability the 2D mode of PERESVET program has been used (Podgorny and Podgorny, 1995). The implicit finite difference scheme solves MHD equations sequentially along each coordinate. The MHD equations (see Podgorny and Podgorny, 1992) are solved for the compressible plasma. The terms of plasma heating, heat conductivity and radiation are taken into account. For a current sheet creation the super-Alfvenic plasma jet is injected in the transverse magnetic field with the low density plasma ($\beta \ll 1$). The jet dynamic pressure $\rho V^2$ is larger than $B^2/8\pi$. The dimensionless parameters (the magnetic Reynolds number, $Re_m$, the ratio of plasma pressure to magnetic one, $\beta$, the Alfvenic Mach number, $M_A$) are chosen according to the principal of limited simulation (Podgorny, 1978): $Re_m = 10$, $\beta = 10^{-2}$, $M_A = 4$. Such set of dimensionless parameters are suitable for numerical simulation of magnetospheric phenomena (see for example Matsumoto and Omura, 1993). The jet is injected perpendicular to the magnetic field. The size of the numerical region $L$ is chosen as a length unit.

Calculations are carried out in the region ($0 \leq X \leq 1, 0 \leq Z \leq 1$). As an initial condition the magnetic field of a two-dimensional dipole is used. The dipole is located out of simulation box at $X = -0.4$, $Z = 0.5$. It is directed along the Z-axis. The magnetic field value in the point $X = 0$, $Z = 0.5$ is taken as the magnetic field unit $B_0$. The initial plasma density are uniform, its value $\rho_0$ is taken as the density unit. The velocity unit is taken as the Alfven velocity, corresponded to $B_0$ and $\rho_0$, $V_A = B_0/\sqrt{4\pi \rho}$. At boundaries $X = 0$ (except the jet injection region $Z = 0.4 \leq Z \leq 0.6$) free exit conditions are set: $\partial \vec{V}/\partial X = 0$, $\partial \rho/\partial X = 0$, $\partial B_Z/\partial X = 0$. $B_z$ is determined from $\text{div} \vec{B} = 0$. The free exit conditions are set also on $Z = 0$ and $Z = 1$ boundaries. The jet is injected along the X-axis from the $X = 0$ boundary in the $Z = 0.4 \leq Z \leq 0.6$ interval.

No MHD instability is observed at current sheet formation and in the stationary state during plasma jet injection. Apparently, the fast plasma stream transports all occasional disturbances from the region and does not permit to develop any MHD instability. The jet injection has been started at $t = 0$, and the stationary state is established at $t > 0.8$. The Alfvenic time $L/V_A$ is taken as a time unit. The lines of the magnetic field and velocity vectors are shown in left upper panel of Fig. 2. At $t = 0.9$ the steady state current sheet is shown. This current sheet has been used as an initial condition for its evolution investigation.

After $t = 0.9$ plasma injection has been ceased: everywhere on the $X = 0$ boundary conditions $\partial \vec{V}/\partial X = 0$ and $\partial \rho/\partial X = 0$ have been set. The $j \times \vec{B}/c$ force begins to push the plasma back from the sheet. The sharp decrease of the current sheet thickness takes place, and in the region of $V \sim 0$, where plasma flux reverses its direction, an MHD instability is developed. The typical for tearing mode ring is observed at $t = 1.5$ (Fig. 2, right lower panel). Plasma inflow in the sheet from its both borders demonstrates that instability sharply increases energy dissipation. The very important feature of this stage is reverse of the plasma velocity direction along the sheet. Plasma flows backward (left lower panel), and the plasma density begins to decrease at $X = 0$ boundary (right lower panel). This figure shows that the current sheet thickness drops by order of magnitude. It means that the current density $\sim B/a$ increases, and the strong $j \times \vec{B}/ne\epsilon$ electric field along the sheet must be produced. Here $a$ is the current sheet thickness.
The next step in understanding of the substorm development should include the two fluids 3D MHD-analysis of electric field and field-aligned currents generation. We hope that two fluids 3D simulation permits to get field-aligned current distribution and to compare it with results of space measurements.

4. Conclusion

The results of numerical MHD simulation show that during the current sheet evolution it can be transferred in an unstable state. The current sheet thickness drops, and the current density increases. During current sheet evolution and its behavior after an MHD instability development the normal magnetic field component plays a decisive role. The rather strong earthward electric

Fig. 2. Magnetic field lines and velocity vectors in the current sheet - 1. The velocity scale, V is presented in the Alfvénic velocity. Magnetic field lines - 2, velocity vectors - 3, and plasma density distribution - 4 at instability development in the current sheet. The data are presented in the plane \(0 \leq X \leq 1, \ 0 \leq Z \leq 1\).
field \( \vec{E} = \vec{j} \times \vec{B} / n_e c \) should appear. These data confirm the idea that field aligned currents are generated in the magnetotail. A couple of opposite directed field aligned currents should be produced in northern and southern hemispheres.

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