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The mechanism of energy release and field-aligned current generation during substorms and solar flares

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Abstract: In this paper, the mechanisms of field-aligned current (FAC) and westward electrojet generation are considered on the base of space measurements and laboratory simulation. Upward and downward FAC are generated in the Earth magnetotail current sheet (CS) due to the tail earthward electric field. They are connected in the ionosphere by the Pedersen current. The FAC enhancement takes place during magnetic reconnection and explosive energy release at a substorm. Electron acceleration in upward FAC produces fast electron precipitation and aurora appearance. The westward electrojet (Hall current) is located between two opposite directed sheets of FAC. The current in the jet is determined by the Hall conductivity in the ionosphere. The similar current systems in the solar corona are responsible for energy transfer to the chromosphere during a solar flare. The solar flare model is built on the base of observations and 3D MHD numerical simulation for compressible resistive plasma.

key words: substorm, flare, current sheet, field-aligned currents

1. Introduction

Observations in space show that the energy accumulated in the earth's magnetotail can be released due to fast reconnection producing a substorm. One of main manifestation of a substorm is field-aligned current (FAC) and westward electrojet enhancement. The most intrigue phenomenon is the FAC distribution discovered by Iijima and Potemra. The narrow (~50 km) upward and downward FAC sheets are situated along the polar oval (Iijima and Potemra, 1976). Upward and downward sheets of FAC are separated by distance order of 100 km. These FAC are responsible for energy transport to the ionosphere. Electrons accelerated into FAC precipitate in the ionosphere. They produce radiation in visible region (discrete aurora) and X-rays. The most significant manifestation of a substorm is the westward electrojet enhancement. The electrojet enhancement is usually explained by a wedge circuit, which connects a part of the cross tail current via FAC in morning and evening sector. But the wedge circuit does not explain why the electrojet current directed perpendicular to the magnetic field is so narrow (the diameter is order of 50 km), and why the electrojet is located at the altitude where the Hall conductivity reaches a maximum value.

The principal question arises:

(1) Where is a generator of this upward and downward FAC situated?

(2) Is the generator located in some distant region of magnetosphere, or FAC generation occurs due to ionospheric convection?

Available information about FAC generation is obtained from the Soviet-Bulgarian spacecraft IKB-1300. The IKB-1300 spacecraft with a polar circular orbit at the altitude of 900 km provides the unique possibility to produce investigations in the polar oval. Three-axis stabilization is supplied. 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 set of 12 instruments permits to measure vectors of electric and magnetic fields, fluxes of precipitating particles, the ionospheric plasma density, velocity and temperature simultaneously (Serafimov *et al.*, 1983). The information about westward jet parameters is supplied from the IZMIRAN chain of stations (Dubinin *et al.*, 1988). Results of laboratory simulation permit us to understand the mechanism of earthward electric field generation in the magnetospheric tail (Minami *et al.*, 1993). Here we present results of investigations that demonstrate the mechanism of FAC and electrojet generation.

Many observations show that energy for a solar flare is also accumulated in the CS, which appears in the solar corona above an active region. The numerical MHD simulations demonstrate CS creation in the corona in vicinity of a singular magnetic line at focusing disturbances arriving from the photosphere (Podgorny and Podgorny, 1992, 2001a, b). These investigations permit to develop the solar flare electrodynamical model. One aim of this work is to consider the pattern of currents created in the Earth magnitotail and to establish similarity between substorms and solar flares.

2. The field-aligned currents in the auroral oval

The IKB-1300 measurements during the spacecraft crossing the polar oval at the night sector have been published by Podgorny *et al.* (1988), Dubinin *et al.* (1988), Podgorny *et al.* (1997). During the crossing on December 21, 1981, the chain of IZMIRAN magnetic stations demonstrates an enhancement of westward jet. The results of IKB-1300 measurements at this crossing during the beginning of a substorm are shown in Fig. 1. The electric field E_z is very small, and the magnetic field normal to the Earth surface B_z is not disturbed. The electric (E_x and E_y) and magnetic (ΔB_x and ΔB_y) field disturbances in the XY plain are presented here. Positive X and Y axis corresponds to northward and westward directions, respectively. The main FAC sheets in the night sector are revealed. The westward ΔB_y profile indicates two sheets FAC flowing away from the ionosphere at low latitudes and flowing into the ionosphere at high latitudes. The spacecraft crosses the sheet at the angle α. The angle between the normal to the FAC and X-axis is $\alpha \approx \mathrm{arctg}\ (\Delta B_x/\Delta B_y)$ ~$50°$. The current density has been inferred by $(c/4\pi)\partial(\Delta B_\perp)/\partial r$, where $\Delta B_\perp = (\Delta B_x{}^2 + \Delta B_y{}^2)^{1/2}$ and r is directed perpendicular to $\Delta B_\perp$. The current density maximum in FAC is about $5\,\mu\mathrm{A/m^2}$. The thickness of upward FAC is order of 100 km. The downward FAC is narrower.

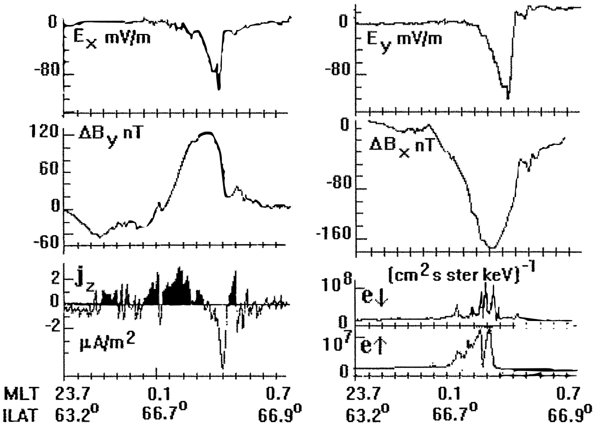

Fig. 1. Magnetic and electric fields, FAC, and flux of electrons measurements at spacecraft crossing the night side polar oval during a substorm.

The electric field between FAC reaches the value about 150 mV/m. The electric field is directed perpendicular to the FAC sheets. Vector product of electric and magnetic disturbances $\mathbf{E}\times(\Delta\mathbf{B}_\perp)$ causes Poynting vector directed toward the ionosphere. The directions of the electric field and FAC correspond to the closed upward and downward currents in the ionosphere. The value of height integrated conductivity of the ionosphere, which supplies upward and downward FAC connection, is $\Sigma_p=(c/4\pi)(\Delta B/E)$ ~1 mho. This value is a typical one for the Pedersen conductivity in the night sector. The upward and downward flux of electrons with energy $W>1$ keV is measured. The flux of precipitated electrons order of 10^8 $(\mathrm{cm^2 s\ ster\ keV})^{-1}$ is detected in upward FAC. Apparently, these electrons are accelerated in a region of equipotential violation of a magnetic field line above the spacecraft. The electron flux with the energy $W>1$ keV directed upward is less by the order of magnitude. Apparently, it consists with electrons reflected from the ionosphere.

The connection of FAC in the ionosphere shows that the FAC is generated in the magnetotail due to the earthward electric field appearance (Fig. 2a). The electric field in MHD approximation is expressed by $\mathbf{E}=-\mathbf{V}\times\mathbf{B}/c+\mathbf{j}\times\mathbf{B}/\mathrm{nec}+\nabla p_e/ne$. The ∇p_e term is negligible. During a substorm $\mathbf{V}$ is directed to Sun, and the electric field directed to Sun can be only the Hall electric field $\mathbf{j}\times\mathbf{B}/\mathrm{nec}$. The potential drop of this field is projected along the field line from the distance order of 20 R_E. It is important to emphasize that the normal magnetic field component B_n is always presented in all CS in the laboratory and space. Direct measurements in the tail demonstrate a plasma flow which is accelerated toward the Earth by $\mathbf{j}\times\mathbf{B}/c$ force (jB_n/c).

Many data show, that during a substorm development the CS thickness is sharply decreased up to ~0.1 R_E The current density increases. As a result, the force $\mathbf{j}\times\mathbf{B}/c$ accelerates plasma along the tail to the Earth, and plasma injection in the magnetosphere occurs. One can estimate the potential drop which is produced by Hall electric field along the tail. In the tail CS the magnetic field $B_t=20$ nT, the normal magnetic field component B_n ~2 nT, the plasma density n ~0.2 cm^{-3}, and the CS thickness at a substorm

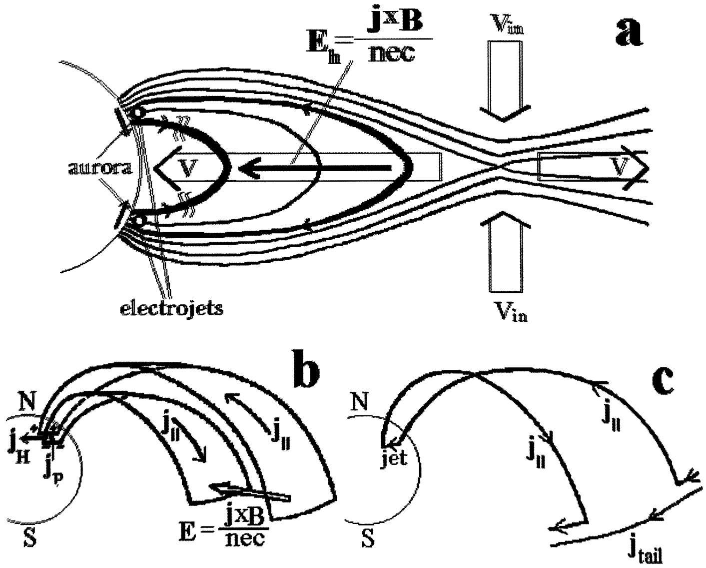

Fig. 2. a) Magnetic field lines and currents (thick lines and arrows) in the night magnetosphere, arrows toward the Earth show the plasma velocity accelerated by $j \times B/c$ *force and the Hall electric field; b) FAC circuit generated by Hall electric field in the tail current sheet; c) electrojet connection circuit.*

$\delta = 0.1\,R_E$. The potential drop at distance $L = 10\,R_E$ can be estimated as $EL = B_t B_n / (2\pi\delta ne) L$ ~50 kV. The mechanism of the Hall electric field generation in the magnetotail has been also demonstrated in the laboratory experiment with an artificial magnetosphere (Minami *et al.*, 1993). The obtained results confirm these estimations.

The data presented in Fig. 1 shows that there is no symmetry in North-South electric field distribution between FAC. The electric field maximum is shifted to the downward current. Such distribution is a consequence of increasing the Pedersen conductivity in a region of upward current due to the ionization produced by the precipitating electrons. Electrons are accelerated in upward current to the Earth somewhere above the spacecraft (above 900 km). The potential drop in the ionosphere becomes non uniform because the electric field distribution here is inverse to Σ_p.

3. Westward electrojet

The electric field between FAC sheets is perpendicular to the magnetic field. Besides the Pedersen current, it must induce westward Hall current in the night ionosphere along the polar oval at the altitude of 100–120 km, where Hall conductivity possesses its maximum value. This Hall current is situated along the polar oval and directed westward, *e.g.* this current is responsible for the electojet generation. The IZMIRAN chain of magnetic stations (Dubinin *et al.*, 1988) has demonstrated the electrojet appearance. The spacecraft trajectory has been situated above this chain crossing the polar oval. The westward electrojet is revealed itself with the current of

~2×10^4A. The jet is located at the maximum of magnetic disturbance ΔB measured by IKB-1300, *e.g.* between upward and downward currents. From the formulas for Pedersen $J_p=\Sigma_p E$ and Hall $J_H=\Sigma_H E$ currents follows $J_H=(c/4\pi)\ (\Sigma_H/\Sigma_p)\ \Delta B$. If one assume the jet diameter is d~50 km, it is possible to estimate the ratio of Σ_H/Σ_p~1.

Bostrom (1964) was the first who proposed combination of two circuit system to understand the jet physics. But, he did not know about electric field generation in the tail. He has supposed that FAC generation is caused by Lorenz electric field due to azimuthal plasma flow in the distant equatorial magnetosphere. He has assumed that the closing of the electrojet occurs by the evening upward and morning downward FAC, which connect the jet and the cross tail currents. But, now we know that the jet current and the cross tail current have the same direction. Bostrom's assumption does not explain the dipolization of the Earth magnetic field during a substorm. So, FAC connects the jet and a part of the current, which is generated on the tail boundary by the solar wind. The jet enhancement is a result of this current branching into the jet and tail CS. As a result the cross tail current decreases, and hence Earth field dipolization occurs. This current circuit is shown in Fig. 2c.

The typical FAC density in the night sector at a substorm is 2–5 μA/m^2, and the FAC thickness is about 100 km. The length of the electrojet along the polar oval is order of ~3000 km. So, the Hall generator in the tail supplies the FAC current must produce order of 1 MA. If the model proposed by Podgorny *et al.* (1988) is correct, the current in anti Sun direction order of 1 MA should exist along the Earth tail. Recently, the development of large array of data obtained by Geotail measurements has permitted to show existence of the current in anti Sun direction order of 1 MA (Israilevich *et al*., 2001).

The magnetotail Hall generator supplies the main current systems in the polar ionosphere except the downward FAC in the evening sector. It is so called the Region 2 of downward FAC. It situated at the lower latitude of about 65°. This FAC layer flows along the field lines projected to the equator plane at a distance of ~7 R_E. This FAC may arise due to compensation of the space charge of ions by the ionospheric electron's motion along the magnetic field. The ions are captured in the Earth magnetic field after plasma injection from the tail. They drift to the West and produce a ring current in the magnetosphere.

4. Similarity between substorms and solar flares

There is a similarity between explosive events in the Earth magnetosphere and in the solar corona. A fast energy release in the Sun during a solar flare often occurs in the corona, where only the magnetic field can be a source of the released energy. On the basis of observations and numerical simulations, the electrodynamical model of the solar flare (Fig. 3) has been developed (Podgorny and Podgorny, 1992, 2001a, b). It is based on the CS creation above a solar active region. According to this model FAC (thick lines) are generated in the CS. They are closed by Pedersen current in the chromosphere. The accelerated electrons in the FAC produce chromosphere luminosity – flare ribbons. This effect is similar to the aurora production during a substorm. There are many resembling phenomena in substorms and solar flares: energy accumulation in

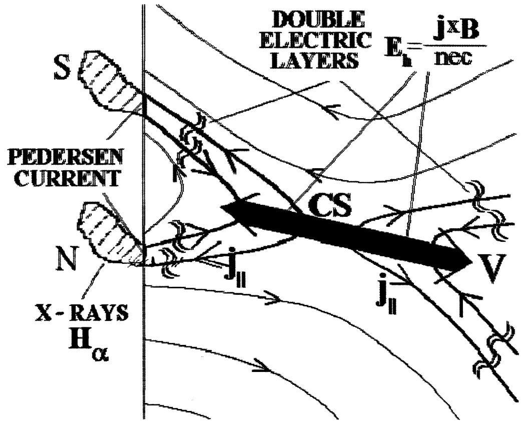

Fig. 3. The solar flare electrodynamical model. Thin lines show magnetic field lines, thick lines show currents. The big arrow shows plasma acceleration along the current sheet in both directions.

the CS, luminosity of lower atmosphere due to electron precipitation, plasma ejection from the CS, etc. This plasma ejection produces coronal mass ejections and shock waves in the interplanetary space, which initiate strong disturbances of the magnetosphere.

The luminosity of the atmosphere (flare ribbon and aurora) is a typical feature of the both explosive phenomena (flare and substorm). The luminosity displacement takes a part in the both phenomena, because of tail new magnetic lines are involved into reconnection. This effect is responsible for both the aurora motion to the poles during a substorm and motion of flare luminosity ribbons apart.

5. Conclusion

The energy of solar flares and substorms is accumulated in the magnetic field of CS. Both explosive phenomena are developed by simmilar scenario. The normal component of the magnetic field inside CS plays an important role. The magnetic stretching accelerates plasma along the CS. The normal magnetic field component is responsible for the earthward electric field appearance and the FAC generation. The FAC plays a decesive role in energy transfere from CS to the lower atmsphere. Apparently, the simmilar conditions for energy accumulation in CS and their fast release are responsible for some explosive phenomena in other planets and stars.

Acknowlegments

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