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THE MECHANISM OF ENERGY RELEASE AND FIELD-ALIGNED CURRENT GENERATION DURING SUBSTORMS AND SOLAR FLARES

A.I. Podgorny[1] and I.M. Podgorny[2] ([1]*Lebedev Physical Institute, Moscow, Russia,* [2]*Institute for Astronomy RAN, Moscow, Russia, podgorny@inasan.rssi.ru)*

Abstract. The explosive energy release at a current sheet (CS) reconstruction is considered as a mechanism of substorms and solar flares. The models of field-aligned current (FAC) generation in the Earth magnetosphere and in solar corona are proposed. Upward and downward FAC are closed in ionosphere (chromosphere) by the Pedersen current. The west electrojet (Hall current) is located between two opposite directed sheets of FAC. Many observational data show that energy storage for a solar flare occurs in the coronal CS above an active region. The numerical 3D MHD simulation demonstrates at possibility of energy storage in the CS in the vicinity of a neutral magnetic line. The similar current systems are responsible for energy transfer to the ionosphere during substorms and in the chromosphere at solar flares. The MHD calculations have been carried out for the compressible resistive plasma using PERESVET code.

Introduction

The energy accumulated in the Earth magnetotail can be released due to the reconnection producing a substorm. Numerous observations show that energy accumulation for a solar flare also occurs in the CS, which appears above the active region in the solar corona. The numerical MHD simulations demonstrate CS creation in the corona in the vicinity of a singular magnetic line at focusing disturbances arriving from the photosphere (*Podgorny and Podgorny*, 1992, 2001). These investigations permit to develop the solar flare electrodynamical model. According to the model FAC are generated in the CS. They are closed by Pedersen current in the chromosphere. The FAC are responsible for the energy transport to the photosphere. The electrons accelerated into FAC produce radiation in the visible region and X-rays. This effect is similar to the aurora production during a substorm. The aim of this work is to consider the pattern of currents created in the Earth magnetotail and establish similarity between substorms and to solar flares.

The spacecraft IKB-1300 with a polar circular orbit at the altitude of 900 km provides the unique possibility to produce investigations in the polar oval. A three-axis stabilization is supplied. X - axis is directed along the spacecraft velocity; Z - axis is directed upward the normal one to the Earth surface. In the auroral regions the Z- axis almost coincides with the magnetic field line.

Observations in space show that the energy accumulated in the Earth magnetotail can be released due to a fast reconnection producing a substorm. One of the main manifestations of a substorm is the field-aligned current (FAC) and westward electrojet enhancement. Narrow (~100 km) upward and downward FAC sheets are situated along the polar oval /1/. Here we present the results of investigations that demonstrate the mechanism of FAC and the electrojet generation and similarity between substorms and solar flares.

The field-aligned currents in the auroral oval

The spacecraft measurements when crossing the polar oval at the night sector had been published by *Podgorny et al.* (1988), *Dubinin et al.* (1988), *Podgorny et al.* (1997). During this crossing of December 21, 1981 the chain of IZMIRAN magnetic stations demonstrated an enhancement of the westward jet. The results of IKB-1300 measurements at this crossing during 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 is not disturbed. The electric and magnetic field disturbances in the XY plain are presented here. The main FAC sheets in the night sector are revealed. The magnetic field increasing $\Delta\mathbf{B}$ is located between the upward (at the lower latitude) and downward (at the higher latitude) FAC sheets. The angle between the normal to the CS and X-axis is arc $tg(\Delta B_X/\Delta B_Y) \sim 50°$. The electric field between FAC appears. It is directed perpendicular to the CS. The direction of the electric field corresponds to the closing of upward and downward currents in the ionosphere. The value of height integrated conductivity of ionosphere, which supplies the upward and downward FAC connection, is $\Sigma = (c/4\pi)\ (\Delta B/E) \sim 10^{12}$ cm s^{-1}. This value is a typical Pedersen conductivity in the night sector.

The connection of FAC in the ionosphere shows, that field-aligned currents are generated in the geomagnetic tail due to earthward electric field appearance. The total potential drop exceeds $\Delta V{\sim}10$ kV. This potential drop is projected along the field line from the distance of the order of 20 R_E It is seen from the Ohm low $\mathbf{j} = \sigma[\mathbf{E} + \mathbf{V}\mathrm{x}\mathbf{B}/c - \mathbf{j}\mathrm{x}\mathbf{B}/nec + \nabla p_e/ne]$, that the earthward electric field can be only the Hall electric field $\mathbf{j}\mathrm{x}\mathbf{B}/nec$. It is important to emphasize that a normal magnetic field component is always presented in all CSs in the laboratory and space. The estimations and direct measurements in the tail show that plasma flow is accelerated by jxB/c force, and term ∇p_e

can be neglected.

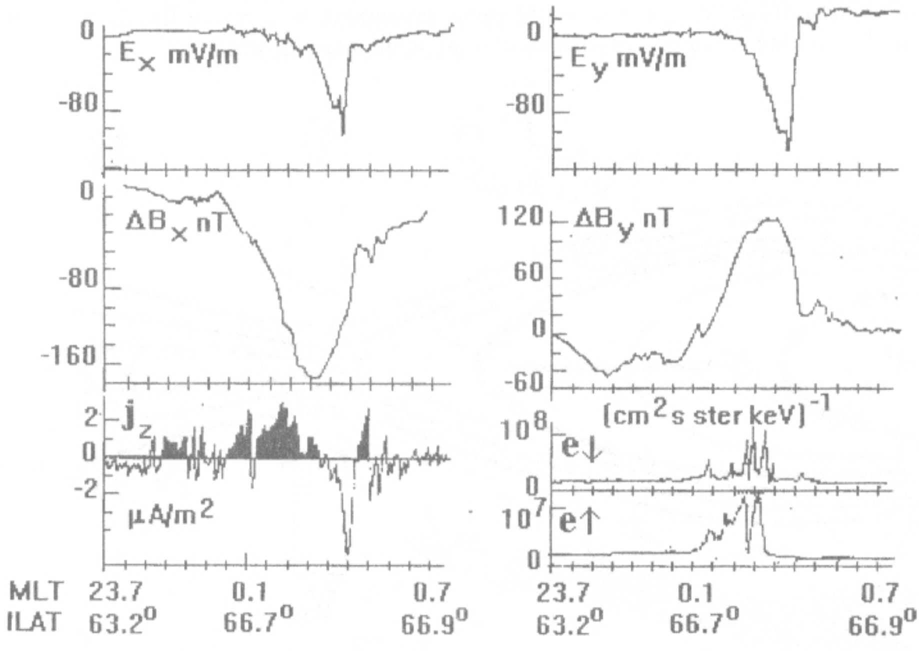

Fig.1. Magnetic and electric fields, FAC, and flux of electrons in the polar oval during a substorm.

Numerous data show that during a substorm development the CS thickness is sharply decreased up to ~ $0.1R_E$. The current density increases. As a result the force **jxB**/c accelerates plasma along the tail to the Earth, and plasma injection in the magnetosphere occurs. The Hall electric field also increases. For the tail magnetic field B_t =20 nT, the normal magnetic field component $B_n \sim 2$ nT in the tail CS, the plasma density n ~ 0.2 cm^{-3}, and the CS thickness at the substorm $\delta = 0.1\ R_E$ the potential drop at the distance $L = 10R_E$ can be estimated as $B_tB_n/(2\pi\delta ne)L$ ~50 kV. The Hall electric field generation in the magnetotail has been simulated in the laboratory experiment with an artificial magnetosphere (*Minami et al.* 1993). The obtained results confirm these estimations.

The data presented in fig. 1 show, that there is no symmetry in the North-South electric field distribution between CS. The electric field maximum is shifted to the downward current. Such distribution is a consequence of increase of the Pedersen conductivity in the region of the upward current. Electrons are accelerated in the upward current to the Earth somewhere above the spacecraft (above 900 km). The electron flux produces ionization in the ionosphere, and Pedersen current is increasing. Apparently, an equipotential violation of a magnetic field line appears above the spacecraft.

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 ionosphere along the polar oval. The electrojet appearance have been measured by the IZMIRAN chain of magnetic stations (*Dubinin et al.* 1988). When crossing the polar oval the spacecraft trajectory has passed above the chain. The westward electorate was revealed with the current ~2 10^4 A. The jet was located at magnetic disturbance ΔB maximum, 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 assumes that the jet diameter is d~50 km, it is possible to estimate the ratio of $\Sigma_H/\Sigma_p \sim 1$. Apparently, so high ratio is determined by the electron precipitation.

Discussion

In fig. 2a magnetic field lines and currents (thick lines and arrows) are shown corresponding to the large-scale current system in the night sector by IKB-1300. The electric field in the tail generator is directed earthward. The current in the generator is directed opposite to the electric field. The generator produces the pair of FAC that propagates along the magnetic lines with the Alfvenic velocity. After reaching the ionosphere FAC are closed by the Pedersen current. The high plasma conductivity along the magnetic field resuets in a drop of the generated potential in the ionosphere between the sheets of FAC. This electric field produces the Hall current in the ionosphere (westward electrojet) along the polar oval in the night sector of both hemispheres. The FAC connection can be presented in 3D space as a combination of two circuits. One of them - the FAC connection by the Pedersen current is presented in fig. 2b. The electric field between upward and downward currents produces the Hall current called electrojet at the altitude of about 120 km. The connection of electrojet current is shown in fig. 2c. It is closed by enhanced upward current in the evening sector and downward current in the morning sector.

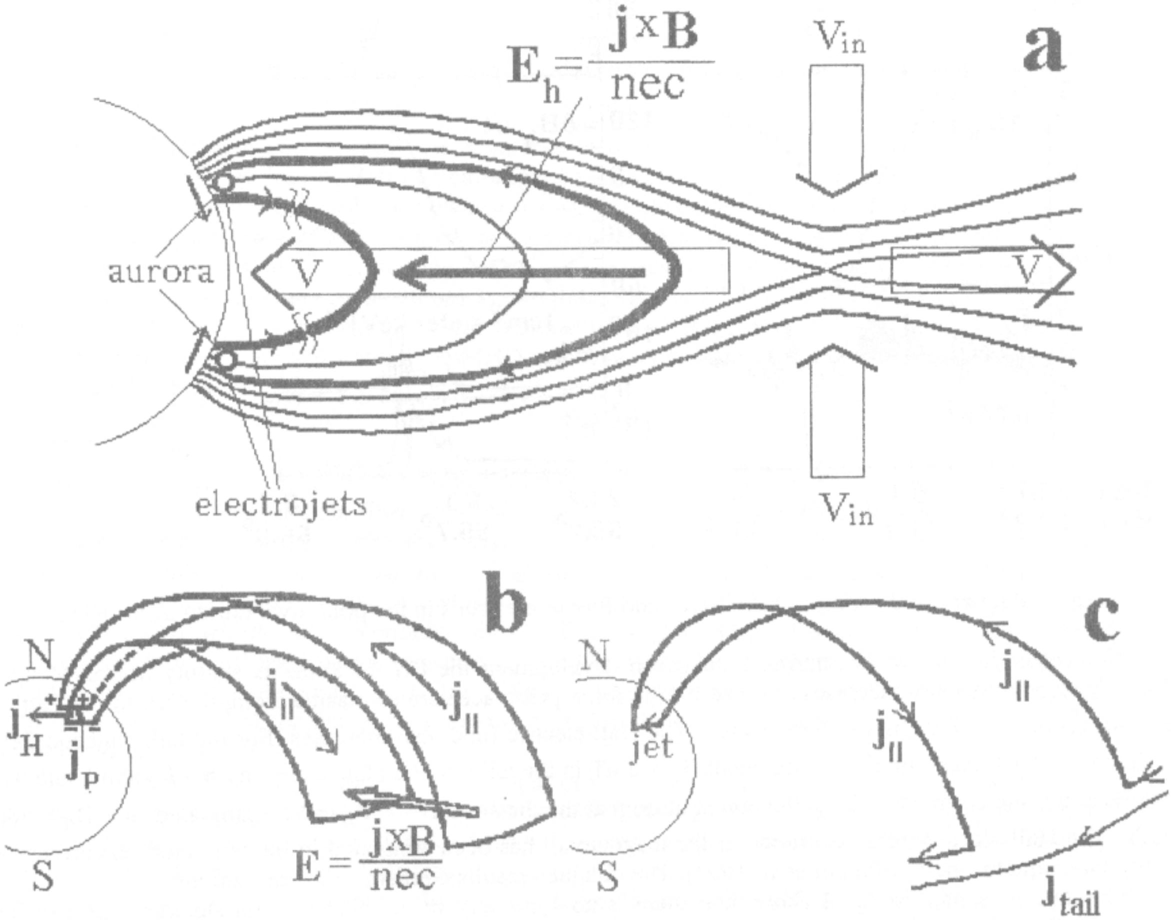

Fig. 2. a) Magnetic field lines and currents (thick lines and arrows) in the night magnetosphere; b) FAC circuit; c) electrojet connection circuit.

Bostrom .(1964) was the first who proposed a combination of two circuits for understanding the jet physics. But, he did not know about electric field generation in the tail. He has supposed that FAC generation causes by Lorenz electric field due to the azimuthal plasma flow in the distant equatorial magnetosphere. He has assumed that jet closing occurs by the evening upward and morning downward currents, 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. Such assumption contradicts to the fact that during a substorm the dipolization of the Earth magnetic field takes place. So, FAC connects the jet and a part of the current that is generated at the tail boundary by the solar wind. During the jet enhancement this current is branched into the jet and tail CS. This current circuit is shown in fig. 2c.

The typical FAC density in the night sector during a substorm is 2 -5 $\mu A/m^2$, and the FAC thickness is about 100 km. The length of the electrojet along the polar oval is of the order of ~3000 km. So, the Hall generator in the tail that supplies the FAC current must produce the order of 1 MA. If the model proposed in /2/ is correct, the current in the counter Sun direction of the order of 1 MA should exist along the Earth tail. The large array of data, recently, obtained by Geotail measurements has permitted to show the existence of the current in the counter Sun direction of the order of 1 MA (*Israilevich*, 2000).

The magnetotail Hall generator supplies the main current systems in the polar ionosphere except the downward FAC in the evening sector. It is the downward FAC of the so called Zone 2. It is situated at the lower latitude of about 65^0. This FAC layer flows along the field lines projected to the equator plane at the distance of ~ 7 R_E. This FAC may arise due to compensation of the space charge of ions by ionospheric electrons. 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.

There is a similarity between explosive events in the Earth magnetosphere and in the solar corona. The fast energy release in the Sun during a solar flare occurs high in the corona, where the only magnetic field can be a source of released energy. On the basis of observation and numerical simulation the electrodynamical model of the solar flare (Fig. 3) has been developed (Podgorny and Podgorny, 1992, 2001), that is based on the CS creation above the solar active region. There are many resembling phenomena in substorms and solar flares: the energy accumulation in the CS, the luminosity of lower atmosphere due to the electron precipitation, the plasma ejection from the tail, etc.

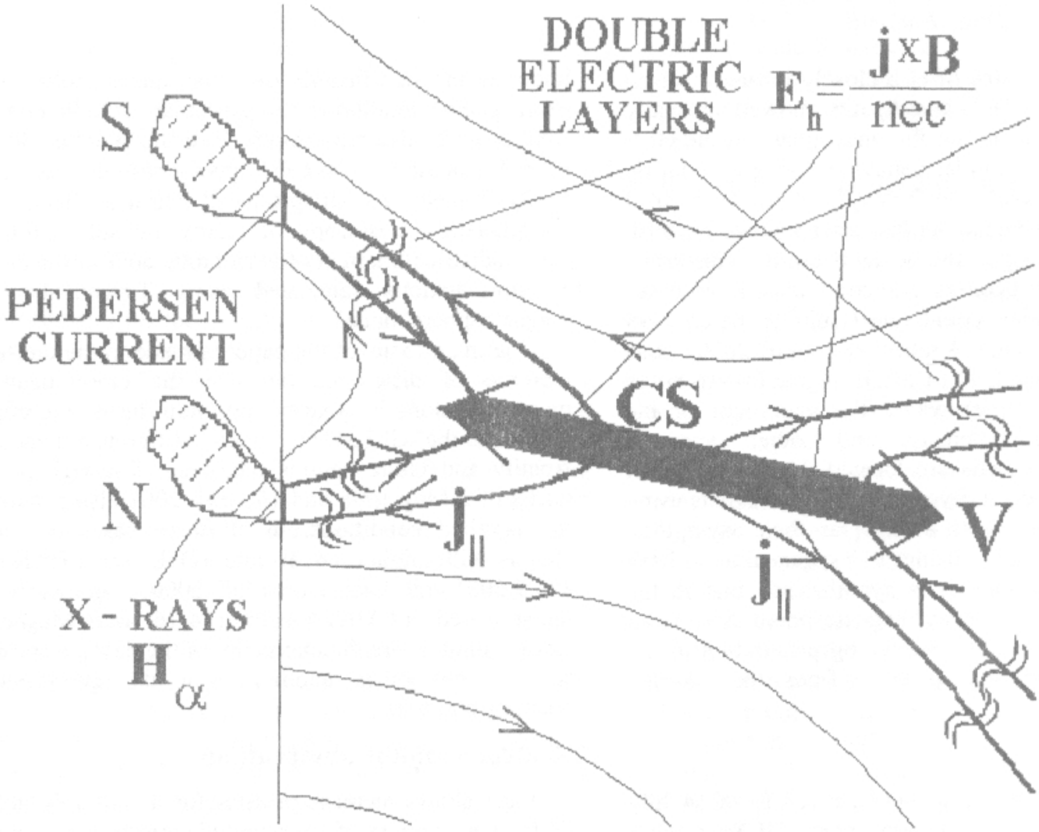

Fig. 3. The solar flare electrodynamical model.

Acknowledgements. The luminosity displacement is taking part in both explosive phenomena, because the tail new magnetic lines are involved into the reconnection. This effect is responsible for both the aurora motion to the poles during a substorm and the motion of flare luminosity ribbons apart. The work is supported by the Russian Foundation for Basic Research pos. 01-02-16168 and 00-01-00091.

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