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FEATURES OF HIGH LATITUDE MAGNETOSPHERIC TOPOLOGY AND MAGNETOSPHERIC SUBSTORM

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Abstract. Features of magnetospheric substorm development and the structure of high latitude magnetospheric plasma domains are analyzed taking into account the latest results of ground-based and THEMIS mission observations. Averaged radial distribution of plasma pressure near noon is obtained. Daytime compression of magnetic field lines and the existence of magnetic field minima far from the equatorial plane are taken into account. Dayside integral transverse currents at the geocentric distances 7-10 R_E are calculated under an assumption of the validity of the condition of magnetostatic equilibrium and compared with nighttime transverse currents. Arguments supporting the hypothesis on the existence of high latitude continuation of the ordinary ring current (the existence of cut-ring current - CRC) till geocentric distances ~10 Re are summarized. The role of CRC, partial ring current and tail current in geomagnetic substorms is discussed. It is shown that classical isolated substorm is localized in CRC region.

1. Introduction

Localization of an isolated substorm expansion phase onset is one of the main endeavors of the THEMIS satellite mission. Akasofu [1964] showed that the substorm expansion phase onset starts with the nearest to the equator auroral arc brightening or the formation of a new arc in this region. All present substorm models can be grouped into two types: the convection-braking type and the current-disruption instability type. According to the first type of models, for example, the NENL model, substorm onset occurs 20–30RE down-tail as a consequence of the reconnection process. The current disruption (CD) model suggested by A.T.Y. Lui (see the review [Lui et al., 2004]) predicts the substorm current wedge to develop as a result of an instability in the cross-tail current, with the onset location being at about 6–10R_E.

First results of the analysis of substorm expansion phase onset by THEMIS team [Angelopoulos et al., 2008] were quite controversial. First analysis of the event 26 February 2008, near 04:50 UT was classified as a proof of reconnection triggering substorm onset. In accordance with [Angelopoulos et al., 2008] reconnection was observed at 20 R_E, at least 1.5 minutes before auroral intensification, at least 2 minutes before substorm expansion, and about 3 minutes before near-Earth current disruption. The discussion of this result on Joint Cluster-THEMIS Conference in September, 2008 (see http://www.spaceplasma.unh.edu/wiki/index.php/Final_Joint_Cluster-THEMIS_Presentations) showed the necessity to reanalyze the statement presented by [Angelopoulos et al., 2008]. In accordance with the report of Angelopoulos on this conference, the analyzed event does not correspond to any of the suggested models (see Fig. 1).

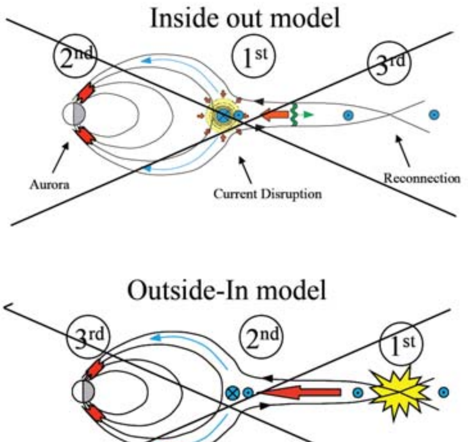

Fig. 1. Scheme illustrating tie interpretation of the THEMIS event 26 February 2008 (http://www.spaceplasma.unh.edu/wiki/index.php/Final_Joint_Cluster-THEMIS_Presentations)

The studied event was considered as not classical time sequence. It was stressed that auroral brightening was observed before near Earth dipolarization and this holds true on several events considered.

The interpretation of the event 26 February 2008 was criticized by A.T.Y. Lui (The report "A Possible Alternative Interpretation of the feb. 26, 2008 substorm presented in the Science paper") who showed that activity around 04:50 UT may be an intensification of a substorm onset that started earlier at 04:03 UT, at least not an isolated substorm case. Results of the analysis of the THEMIS event 29 January 2008, 0700–0900 UT by THEMIS team [Lui et al., 2008] supported the outside in model.

It is not difficult to understand the results of multiple papers demonstrating supports of outside in model. Multiple results of experimental observations of BBF (bursty bulk flows) and plasma sheet velocity and magnetic field fluctuations show the existence of high level of plasma sheet turbulence (see the review of Antonova [2002] and the latest results of Stepanova et al. [2009]). The existence of such turbulence is quite natural as geomagnetic tail is formed as a turbulent wake under an obstacle (geomagnetic dipole) in conditions of very high Reynolds number ($>10^{10}$). The probability to observe directed to the Earth particle beam ~2 min before the isolated substorm onset in such conditions is very high (see Rostoker [2002], Antonova [2006]). Therefore the registration of tail reconnection and directed to the Earth ion beam before an isolated substorm onset can be considered as a proof of outside in model when it would be possible, for example, to trace such beam from the region of reconnection till the "root" of the most equatorial auroral arc. It is difficult to imagine that such beam will not disturb auroral structures to the pole from the most equatorial auroral arc. Therefore, the validation of outside in and inside out models requires the analysis of ground based observations of auroral arcs during isolated substorm expansion phase onsets with maximal possible resolution. It is also very interesting to clarify the possibility of auroral brightening before current disruption.

In this paper we discuss the results of ground based observations of isolated substorm expansion phase onset and show that the physics of such onset is not connected to the tail current dynamics. From our point of view isolated substorm expansion phase onset starts in the outer region of the ring current.

2. Features of substorm expansion phase onset in accordance with ground based observations

The television (TV) observations at Lovosero observatory (64.1°N, 115.5° E, MLT=UT+3 h), belonging to the Polar Geophysical Institute, provide the possibility to analyze the auroral breakup fine structure with a time resolution of 25 frames per second and with a high spatial resolution (~100m in the zenith). Preliminary results of such analysis summarized by Kornilov et al. [2008a, b] demonstrated different pictures of the auroral breakups. It was possible sometimes to select some subvisual precursors of breakup moving from the north (see Kornilova et al. [2004]). However, such motions were comparatively slow (Kornilov et al., [2008a]).

Antonova et al. [2009] presented the results of the analysis of the event 28 January 2003. The main feature of this event is the possibility to observe an isolated substorm with first brightening arc just near zenith of the Lovosero observatory. The isolated substorm was developed near 20:00 UT with maximal auroral electrojet index AE~400 nT. The value of AE was smaller than 100 nT during ~7 h before the substorm onset, whereas the D_{st} index module was ~5 nT. In accordance with OMNI database solar wind dynamic pressure constituted ~4 nPa, solar wind velocity was nearly 435 km/s, IMF B_z had southward orientation and was −2 to −1 nT, B_y was near to ~~(~~−3.5 nT~~)~~. Analysis of the variations of solar wind parameters shows that it is difficult to find the appropriate trigger of expansion phase onset in the solar wind parameters. IMF B_z and B_y do not change direction, velocity and dynamic pressure are practically stable.

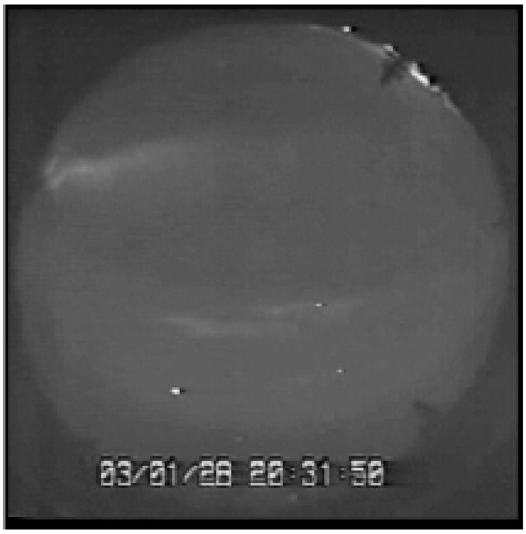

Fig. 2. Auroral imager 15 sec before the start of brightening for the event 28 January 2003

Auroral data were provided by SIT vidicon TV camera with all-sky lens. Computer framegraber videocard and special software allowed digitization of TV frames (up to 720×512 pixels) and the arbitrary chosen frame fragments. The method used to process TV data is based on the sliding averaging of successive frames in combination with the effective spatial–temporal filtering of these data (Kornilov et al., [2003]). The special methods for the television images processing were used to detect fine subvisual structures and to trace the details of motion of fine auroral structures. Fig. 2 shows the TV frame 15 sec before the start of brightening.

Prior to the onset, the aurora was relatively stationary with an extended east west arc located relatively near to the zenith of the observatory. Comparatively week diffuse-like luminosity and comparatively bright arc were observed to the north of the prebreakup arc. The appearance of localized brightening takes place at 20:32:05 UT (see Fig. 3).

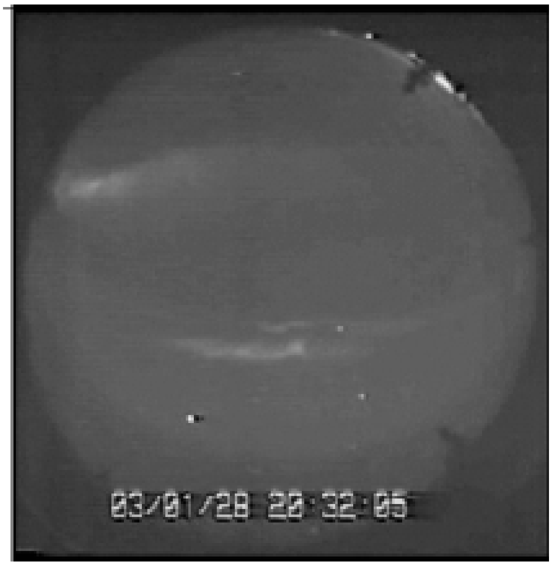

Fig. 3. Auroral imager at the moment of the start of brightening for the event 28 January 2003

The first localized brightening was formed as a “hot spot” with approximately the same scale in the east-west and north-south directions. Brightness of this spot continuously increased till 20:32:21UT for 15 s interval. Auroral arc with waved structure was observed only after 20:32:21 UT (see Fig. 4), which is consistent with the previous results by Mende et al. [2007] and Liang et al. [2008]. The process was followed later by the breakup arc flash and by the appearance of new bright rayed formations, which propagated poleward.

Fig. 5 shows standard and filtered keograms of the analyzed event. Filtered keogram was obtained using gradient filtering method based on the fast Fourier transform technique (see Kornilov and Kornilov [2003]). Such method gives the possibility to reveal fine details in time-spatial structure of diffuse and discrete auroras. The gradient filtered keogram makes it possible to enter into details of auroral arc dynamics. One can see from the filtered keogram (on the second plate of Fig. 5) that it is difficult to identify any distortion poleward of the brightening arc, which can be treated as the arc activation.

The analysis of magnetic observations shows that small magnetic oscillations in the Pi1–Pi2 frequency range constantly occurred near the noise level, but amplitude of these oscillations increased essentially only ~1 min after the beginning of brightening. The later finding supports the conclusions of Liou et al. [1999], Mende et al. [2007], Angelopoulos et al. [2008] about the existence of definite time delay between the beginning of brightening and the appearance of the magnetic field disturbance.

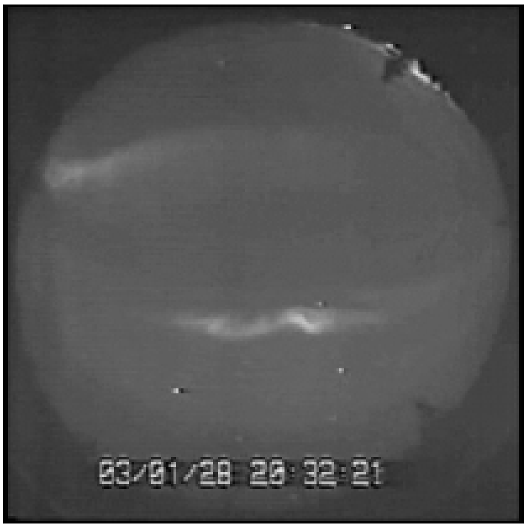

Fig. 4. Auroral imager at the moment of waved structure formation for the event 28 January 2003

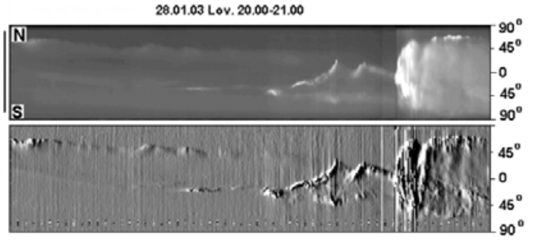

Fig. 5. Standard and filtered keograms of the event 28 January 2003

It is necessary to mention that the existence of time delay ~1 min between the first auroral arc brightening and the start of the distortion of the geomagnetic field provides the real constrains to existing theories concerning the substorm expansion phase onset and bright auroral arc formation. Theories of current disruption and ballooning instability formation suggest development of the electromagnetic disturbances. Therefore, it is difficult to explain the existence of the observed time delay between the brightening and start of magnetic disturbance. The explanation of observed phenomena is contained in the paper Stepanova et al. [2002] (see also Antonova et al. [2008]).

Therefore, the analysis of ground based observation of isolated substorm 28 January 2003 supports the inside out scenario and the existence of ~1 min time delay between the first auroral arc brightening and the start of magnetic disturbance. Such feature is of crucial importance for the selection of the instability responsible for substorm expansion phase onset. Substorm development is traditionally accounting to the tail current dynamics. However, it is possible to show that substorm expansion phase onset is localized in the region of high latitude continuation of the ring, as it will be shown in the next section.

4. Daytime transverse current in the conditions of magnetostatic equilibrium

One of the problems, which became possible to clarify using data of THEMIS mission, is the structure of magnetospheric plasma domains near noon. Fig. 6 illustrates the results of THEMIS satellite crossings of the magnetopause 18 July 2007 near noon. Fig. 6a shows orbit positions, Fig. 6b the electron and ion spectrograms of TEMIS-D satellite (ESA device). It is possible to see analyzing Fig. 6 that the magnetopause at subsolar point is rather sharp and the mixture of magnetosheath and plasma sheet like plasma (low latitude boundary layer) is observed just at the inner boundary of the magnetopause. It is also possible to see plasma sheet like plasma at the equator to LLBL.

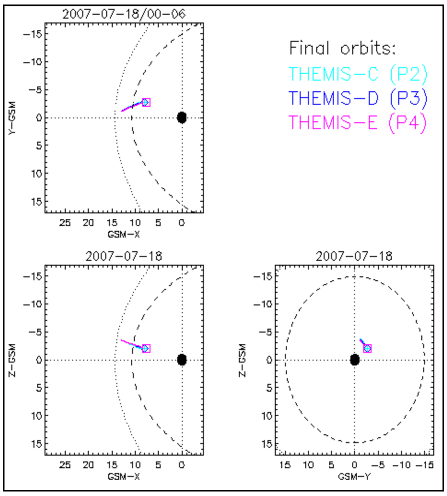

Fig. 6a. Positions of the orbits of THEMIS satellites for the event 18 July 2007

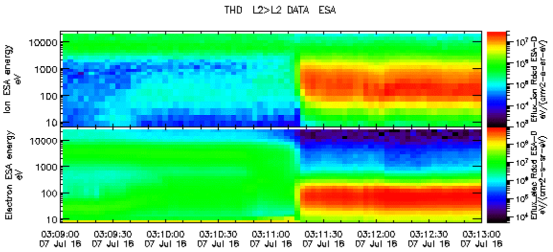

Fig. 6b. Ion and electron spectrograms of THEMIS-D satellite for the event 18 July 2007

It is necessary to mention that the existence of plasma sheet like plasma domain surrounding the Earth became clear after the publication of the paper of Newell and Meng [1992], in which they showed that plasma sheet particle precipitations come from a region situated at the equator from the low latitude boundary layer (LLBL). Starkov et al. [2002] improved this picture and showed that the daytime precipitation region identified by Newell and Meng [1992] as a "void" is the region of plasma sheet like precipitations. Yagodkina and Vorobjev [2004] supported this result. They showed the closed loop structure of plasma sheet precipitations under all geomagnetic conditions.

Daytime compression of magnetic field lines is the well known feature of magnetospheric topology. Therefore, the magnetic field minima are shifted from the equatorial plane near noon. The majority of existing models of the magnetospheric magnetic field reproduces such topology of the daytime field lines. Daytime structure of magnetic field determines the drift trajectories of energetic particles. Region from the geostationary orbit till ~10R$_E$ was named the region of quastrapping at the first stages of magnetospheric study. It is well known that energetic particle trajectories cross the magnetopause if particle pitch angle is equal to 90°. Drift shell splitting effect is observed for particles with smaller pitch angles [Shabansky and Antonova, 1968]. Drift trajectories of such particles are closed inside the magnetosphere. The appearance of drift echo is one of the constantly observed features of magnetospheric substorm. Hori et al. [2003] using results of Geotail observations showed the existence of the effect of drift echo until geocentric distances ~12-13R_E near midnight. This means the existence of quasiring region having special properties at geocentric distances >7R_E. The dayside boundary of this region is the inner boundary of the low latitude boundary layer. Nightside boundary is located at the geocentric distances ~10-12R$_E$, where drift trajectories of energetic particles with pitch angles <90° begin to cross the magnetopause.

Latest model of Tsyganenko – TS07 [Tsyganenko and Sitnov, 2007; Sitnov et al., 2008] presents the model of the field of equatorial currents using large sets of spacecraft data. They analyzed currents localized near the equatorial plane and showed that fully developed ring current extends quite far down the tail (through X_{GSM} ~-10 R$_E$). They argue that it is a combination of the partial ring current closed through Region 2 field-aligned currents of Iijima and Potemra and the enhanced tail current closed via the magnetopause on both dusk and dawn sides. All transverse currents in TS07 model are localized at the equatorial plane. However, positions of magnetic field minima at the magnetic field lines show the possibility of existence of comparatively large transverse currents near noon far from the equatorial plane. Nighttime currents can be closed by such currents forming a surrounding the Earth current ring. Such current ring was named by Antonova and Ganushkina [2000] cut ring current (CRC) as the daytime part of this ring splits into two branches (see also Antonova [2003, 2004] for details). Fig. 7 [Antonova et al., 2009] illustrates the configuration of CRC

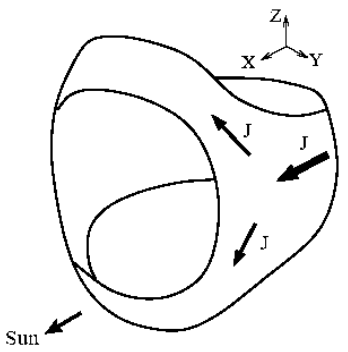

Fig. 7. Sketch illustrating the configuration of currents in CRC

Localization of magnetic field minima far from the equatorial plane shows that the determination of the current distribution at the daytime field lines requires simultaneous data of multisatellite observations far from the equatorial plane. Such data are not available now. However, values of current densities and integral transverse current can be estimated in the suggestion of the validity of the condition of magnetostatic equilibrium when distribution of plasma pressure is near to isotropic.

Plasma pressure is nearly isotropic at large geocentric distances (see [DeMichelis et al., 1999]). In such a case, transverse current $\mathbf{j}_\perp$ is equal

$$\mathbf{j}_\perp = \mathbf{B} \times \nabla p / B^2 , \qquad (1)$$

where ∇p is the plasma pressure gradient, B is the magnetic field value. Surrounding the Earth plasma sheet like plasma distribution contains transverse westward current if plasma pressure gradient has the earthward direction. Plasma pressure has constant value along field line in accordance with the condition of magnetostatic equilibrium. Therefore, it is possible to evaluate current density at any point of field line if plasma pressure distribution at the equatorial plane is known using one of magnetic field models. Such approach is not self consistent. However, it gives the possibility to obtain estimations of current densities far from the equatorial plane.

Lui and Hamilton [1992]; DeMichelis et al. [1999] obtained the distribution of plasma pressure at the equatorial plane using data of AMPTE/CCE observations. The global picture of magnetospheric plasma pressure distribution at L<9 demonstrates the presence of nearly azimuthally symmetric plasma distribution at L~7-9 [DeMichelis et al., 1999]. Such distribution supports the existence of plasma domain surrounding the Earth. The plasma pressure gradient in this domain has an earthward direction, which implies the existence of a westward transverse current. DeMichelis et al. [1999] reproduced current density in the equatorial plane using values of plasma pressure gradients derived from AMPTE/CCE satellite and the Tsyganenko-87 [Tsyganenko, 1987] magnetic field model. The nighttime part of the obtained by DeMichelis et al. [1999] picture corresponds to comparatively large current densities ~3-5 nA/m^2 and was attributed to the partial ring current. Daytime current densities were smaller ~1 nA/ m^2. The obtained values of current density can be used for the estimation of integral transverse current near noon only at the geocentric distances smaller than 7R$_E$ where field lines are not compressed.

Antonova et al. [2009] used the values of plasma pressure measured by Lui and Hamilton [1992] for geocentric distances till 9 R$_E$ and Tsyganenko-01 [Tsyganenko, 2002a,b] magnetic field model to obtain current densities on the daytime field lines. The radial dependence of plasma pressure from 9 till 10 R$_E$ was approximated used exponential dependence. The calculation of the integral current between 7.5 and 9.7Re gives integral current ~2□10^5 A in each hemisphere or the integral transverse current 4□10^5 A in both hemispheres for quite geomagnetic conditions (IMF Bz = -5 nT, By = 0, solar wind dynamic pressure equal to 1.6 nPa and Dst = -5 nT). Simple estimations show that the same current value exists at the same geocentric distances in the region, which is ordinarily considered the near Earth tail.

THEMIS observations gives the possibility to obtain the radial plasma pressure gradient till the magnetopause position and to increase the accuracy of daytime current calculations. Orbits of 5 satellites of THEMIS are located near to the equatorial plane which give the possibility to restore the radial distribution of plasma pressure. Results of THEMIS-B satellite observations for the period 02/06/2007-29/10/2007 (http://www.nasa.gov/mission_pages/themis/) were used to obtain radial plasma pressure distribution near noon at the equatorial plane. Parts of trajectories were selected at the geocentric distances 7 < r < 12 R_E with limitation of the azimuthal angle in ±20°. The distribution of plasma pressure inside the magnetosphere near noon can be greatly influenced by the solar wind conditions. To take into account this dependence special algorithm of obtaining averaged plasma pressure profile is selected. Data of Wind satellite are used for the determination of the solar wind dynamic pressure P_{sw} and Z-component of the interplanetary magnetic field. Shue et al. [1997] model is used for the determination of the magnetopause location for every used THEMIS-B measurement. The averaged solar wind dynamic pressure - P_{sw} = 2.5 nPa and averaged IMF B_Z = -5 nT were selected for the determining the average magnetopause position. The radial distance for the subsolar point in such a case is equal to 9.8 R_E. All coordinates of satellite THEMIS-B are transformed in accordance with the averaged magnetopause position by linear compression or expansion. All obtained values are distributed along X axes with the bin equal 0.5R$_E$. Then values of plasma pressure are averaged in accordance with the number of obtained points. Fig. 8 shows the obtained radial plasma pressure profile (points). Thick line on Fig. 8 shows the approximation of obtained radial plasma pressure distribution by exponential dependence. Tsyganenko-01 model [Tsyganenko, 2002a,b] for IMF B_z=-5 nT, B_y=0, solar wind dynamic pressure equal to 2.5 nPa and Dst=-5 nT is used for estimation of magnetic field distribution along the dayside magnetic field lines.

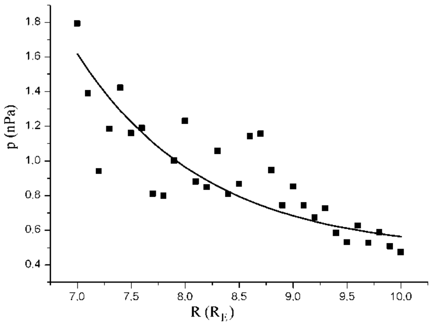

Fig. 8. Dayside radial plasma pressure profile obtained using data of THEMIS-B observations and its approximation used for the calculation of current densities

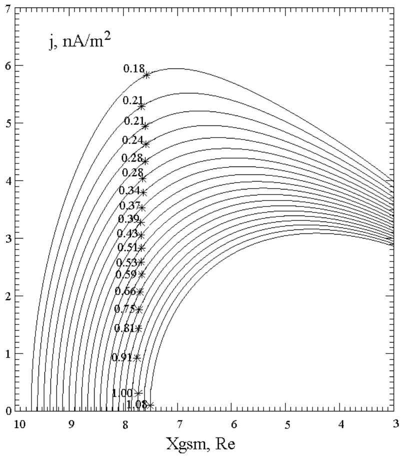

Fig. 9. Positions of minima of the magnetic field at the daytime magnetic field lines and calculated transverse current densities in the regions of magnetic field minima

Shown on Fig. 8 radial plasma pressure distribution is used for the obtaining values of current densities in accordance with the relation (1). Fig. 9 shows the position of minima of the magnetic field at the daytime magnetic field lines and calculated current densities in the regions of magnetic field minima.

Calculated current densities at any point of field line give the possibility to evaluate the integral transverse current at the geocentric distances from 7.5 R_E till the magnetopause in both hemispheres. It is also necessary to take into account that daytime currents are spread at larger areas than nighttime currents. Integral current constitutes $5.8\cdot10^5$ A in both hemispheres for selected parameters. This value is in agreement with the results obtained by Antonova et al. [2009]. The center of transverse currents situated at the dayside field-lines is deposited at X_{eff}=7.3Re, Z_{eff}=2.7Re. It is possible to see analyzing near Earth tail current distribution in Tsyganenko quite time models that considerable part of tail current can be closed inside the magnetosphere by dayside transverse currents.

4. Conclusions and discussion

Presented analysis shows the necessity to change many traditional approaches to the problem of substorm expansion phase onset.

Using the special methods of image filtering we could not find any signatures of the luminosity disturbance poleward to the arc during ~1 min before the arc brightening. This means that the brightening is a local effect at comparatively small geocentric distances.

The formation of bright "hot spot" ~15 s ahead ~~of~~ the classical brightening of the whole arc is an interesting result of the presented observations. The existence of such "hot spot" can be treated as a definite stage of the first auroral arc brightening. It is necessary to mention that ordinarily the moment of the brightening is selected when comparatively bright structure just as shown at Fig. 5 is observed. However, the process of brightening began ~15 s earlier. Location of the "hot spot" was practically unchanged during the analyzed period. This feature can indicate development of the very local instability during the first stage of arc brightening. Scenario of substorm expansion phase onset developed by Antonova [1993], Stepanova et al. [2002] is supported by the results shown in this work (see also the discussion in Antonova et al. [2008]). However, a lot of efforts are required to clarify all details of this scenario..

Our analysis shows that traditional interpretation of the nighttime magnetospheric region at geocentric distances from 7 till ~10-12R_E as the tail region needs to be corrected. It can be considered as a part of the ring current region. It is possible to show analyzing the distribution of radial plasma pressure gradients and dayside magnetic field configuration that comparatively large transverse current flows in the daytime magnetosphere. The formation of these current is connected to the existence of radial plasma pressure gradients directed to the Earth. The value of integral current coincides with transverse current values at the nighttime magnetosphere at the same geocentric distances. Therefore, the suggestion made by Antonova and Ganushkina [2000], Antonova [2003, 2004] about the existence of high latitude continuation of ordinary ring current having the same nature as ordinary ring current (RC) seems quite probable. Nevertheless, the verification of such suggestion requires also the analysis of global plasma pressure distribution, which will be possible to do in the future.

It is clear that susbstorm injections take place at geocentric distances smaller then 10 R_E (see Yahnin et al. [2002]). From our point of view, this region is not the boundary of plasma sheet and inner magnetosphere, but is the region of cut-ring current (CRC) – high latitude continuation of the ordinary ring current. Therefore, instead of tail current disruption during substorm we deal with high latitude part of ring current disruption. This conclusion is not very important for theories of current disruption. However, it can be very important for the analysis of substorm growth phase, as it will be necessary to explain CRC current growth before the dipolarization. More or less self consistent picture can be obtained if we take into account that Region 2 currents are developed during substorm growth phase and the processes of first auroral arc brightening in accordance with Stepanova et al. [2002] can be connected to the growth of upward field aligned currents.

The inclusion of CRC in the picture of magnetospheric currents can also help to clarify the connection between the partial ring current and symmetric ring current. Traditional picture including TS07 model consider partial ring current as a part of tail current systems. However topologically partial ring current is localized at the CRC radial distances. The distribution of plasma pressure and corresponding currents in CRC may become azimuthally asymmetric. This feature is especially pronounced during magnetic storm when powerful partial ring current is developed. Symmetrization of the plasma pressure distribution supporting partial ring current takes place during storm time recovery phase. This process has the inner magnetospheric nature and is explained by particle drift effects. This can mean that the development of partial ring current and its symmetrization is a part of CRC dynamics.

The existence of current systems not included in Tsyganenko magnetic field models can explain some difficulties of these models as all transverse currents inside the magnetosphere in these models are localized near to the equatorial plane.

The reanalysis of some important features of substorm dynamics does not mean that obtained earlier results are incorrect. It is only a contribution to the elaboration of the unified self-consistent picture of the substrom dynamics, which will include all previous findings.

Acknowledgments

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