Onset of substorm expansion phase: theory predictions and results of experimental observations

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Abstract: The problem of substorm expansion phase onset continues to be one of the most actual problems of the physics of magnetospheric substorm. It is deeply connected to the problems of the plasma transport in the magnetosphere, stability of magnetospheric magnetic and plasma configurations. The most popular mechanisms of substorm expansion phase onset are based on the analysis of the stability of magnetospheric currents and distribution of plasma pressure. The results of observations of substorm expansion phase onset are summarized and compared with predictions of different theories. It is shown that the existence of high level of plasma sheet turbulence produces the limitation on the action of possible mechanisms of substorm expansion phase onset. Configurations of magnetospheric current systems developed during substorm growth and expansion phases are discussed.

Key words: substorm expansion phase onset, magnetospheric plasma pressure, magnetospheric turbulence.

1. Introduction

It is possible to identify three periods of the study of substorm expansion phase onset. Akasofu [1] showed that the most equatorial arc brightening takes place during the substorm expansion phase onset. Posteriori the substorm auroral disturbance moved to the pole. The inner plasma sheet boundary was observed in [42] not so far from the geostationary orbit. Injections of energetic particles near the inner edge of the plasma sheet are known as one of the fundamental signatures of magnetospheric substorms from the beginning of 70-th [27]. The existence of dispersionless injections demonstrated the action of acceleration processes near the geostationary orbit. Therefore the substorm expansion phase onset as the result of the development of the inner magnetospheric instability became the dominant point of view at this first period.

Second period is related to the analysis of geomagnetic tail dynamics. It was shown that the change of the topology of magnetic field lines (reconnection processes) and plasmoid formation occur nearly simultaneously with the substorm expansion phase onset. The concept of tail current instability as a source of substorm expansion phase onset [17] became the dominant one for more than two decades. Great number of brilliant theoretical investigations have been done to describe the tail reconnection process. Nevertheless the tail current instability hypothesis have met a number of difficulties even at the first stages of its development. It was clear that the stability of tail current depends on the value of B_z component of magnetic field, where B_z is given in GSM coordinate system. Theoretical studies showed that the decrease of B_z leads to the instability development. However it also was known that B_z decreases with the increase of geocentric distance. Therefore it was very difficult to explain why the first auroral arc brightening occur near the equatorial plasma sheet boundary. As a consequence, it was proposed [36] that the auroral initical brightening is caused by the braking of earthward high-speed flow (bursty bulk flow — BBF) having as a source the tail reconnection processes. Nevertheless, it also was clear from the beginning of the BBF studies, that they take place even under very quite geomagnetic conditions (see [33]) and that they occur much more frequently than substorms. This means that the probability to observe BBF in the plasma sheet 1–5 min before the substorm expansion phase onset is very high. One-to-one correspondence between flow bursts in the plasma sheet and equatorward-moving auroral structures (auroral streamers) was found later [35]. Another difficulty was connected to the high level of turbulence observed at the auroral field lines and in the plasma sheet [3] as all reconnection models suggest the existence of laminar plasma flows outside the reconnection regions.

Third period began with AMPTE/CCE registration of substorm expansion phase onset at the geocentric distances less than 9 R_E [39] and continues till now. These investigations lead to the appearance of tail current disruption hypothesis (see the review [24]) and disrupted current closing in the ionosphere.

In this paper we try to summarize the latest findings concerning the role of plasma sheet turbulence for substorm dynamics, analyze the substorm expansion phase onset and select a number of effects which can be quite important for the solution of substorm problem. We try to show that the analysis of plasma pressure redistribution can help to clarify some modern findings connected to the physics of substorm. We also try to select the key problems which may be interesting to solve during the realization of future auroral satellite missions.

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2. Magnetospheric turbulence and localization of substorm expansion phase onset

Numerous observations showed (see [9]) the existence of high level of plasma sheet turbulence. These results are quite natural, taking into account that the magnetic field of the Earth represents an obstacle for the solar wind flow. Plasma sheet appears due to solar wind flow around magnetic field of the Earth at very large values of Reynolds number ($> 10^{10}$) forming a turbulent wake. It is necessary to mention also that solar wind can also be considered as turbulent medium [40]. Power low spectra obtained for fluctuations of solar wind parameters, indexes for magnetospheric activity [41] and scale-free statistical distributions of nighttime auroral emission regions [20] demonstrate this feature of magnetospheric dynamics quite clearly.

The localization of substorm onset at the geocentric distances less than 9 R_E is now supported by many observations (see reviews [2, 12, 24, 25, 28, 32]). Realization of THEMIS program will probably finally identify this exact position. However the reason of such localization is not clear till now. Antonova [9] argues that the localization of substorm expansion phase onset near the equatorial boundary of auroral oval can be explained taking into account the existence of plasma sheet turbulence. It is a common point of view that the substorm expansion phase onset is the result of the development of some kind of instability. However, only a region stable before an onset can become unstable. Comparatively stable plasma distribution exists in the inner magnetospheric region. Therefore the transition region from dipole to tailward stretched field lines (not very far from the geostationary orbit) is selected as the most probable one.

The existence of plasma sheet turbulence requires the reanalysis of the process of plasma transport. The diffusion-like terms appear in transport equations in the simplest one-fluid analysis (see [3, 5]). The continuity equation has the form

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial \mathbf{r}} \left(\rho \mathbf{V} - D \frac{\partial \rho}{\partial \mathbf{r}} \right) = 0 \tag{1}$$

where ρ is plasma density, $\mathbf{V}$ is the regular velocity, D is the effective quisidiffusion coefficient. Correlation time of plasma sheet velocity fluctuations is ~ 2 min and the correlation time of magnetic field fluctuations is ~ 10 min [10]. Therefore it is possible to consider that Amperes force in the momentum equation is nearly constant and consider the velocity fluctuations only. Then taking into account results of [19] the momentum equation has the form

$$\frac{\partial \rho V_i}{\partial t} + \frac{\partial}{\partial r_j} \left[\left(\rho V_j - D \frac{\partial \rho}{\partial r_j} \right) V_i \right] = -\frac{\partial p}{\partial r_i} - \frac{\partial \pi_{ij}}{\partial r_i} + [\mathbf{jB}]_i \tag{2}$$

where p is the plasma pressure, π_{ij} is the viscous tensor, $\mathbf{j}$ and $\mathbf{B}$ are the current density and magnetic field respectively. The observed nonequipotentiality of magnetic field lines and turbulent character of plasma flow leads to the nonconservation of the number of particles in a magnetic flux tube. The solution of the problem of plasma transport in such a case becomes very complicated. The complexity of the problem is increased due to nonisotropic character of plasma sheet turbulence (existence of particle beams). Developed models of plasma transport by dawn-dusk electric field inside the magnetosphere can be used when the value of regular flux becomes much larger than the value of turbulent flux.

3. Mechanisms of substorm onset

Many mechanisms have been developed for the explanation of main features of isolated substorm onset (see reviews [12, 24]). It is possible to select four main classes of these instabilities:

1) instabilities of transverse tail current;
2) instabilities of plasma pressure gradients;
3) instabilities of shear velocity distributions;
4) instabilities of field-aligned currents.

Instabilities which are not related to kinetic effects have definite preferences, because electromagnetic fluctuations are constantly observed at the auroral field lines.

Every suggested theory must explain such well known experimentalresults as auroral brightening, transverse current disruption, magnetic field dipolarization, dispersionless particle injections, fast plasma flows, generation of Pi2 and Pi1B geomagnetic micropulsations. Some new results have been obtained during the lust years, which must be included in substorm onset picture. First of all it is shown that only nearly equatorial arc has a brightening without any auroral activity to the north [16, 26]. Arcs poleward of the arc that breaks up appear to be unaffected by substorm onset until expansion-phase auroral activity moves poleward to the location of such arcs. The azimuthal extent of the initial brightening was determined in [14]. It is found that the projection of the initial dispersionlesss injection into the ionosphere are similar to the brightening arc. It is found also [22] that Pi2 bursts can often lag behind the brightening of the onset arc. Enhanced plasma flows were observed using SuperDarn data in a spatially confined region near the auroral oval for a period of ~ 5 minutes prior to the brightening [11]. Comprehensive ground (optical, riometer and magnetometer) data and FAST satellite field and particle high resolution observations [15] demonstrate the substorm onset at the geocentric distances ~ 8 R_E. The arc flux tube stays in the region of considerable plasma pressure gradient where the pressure values are close to 12 nPa. The arc was located just $0.4°$ poleward of the proton isotropic (b2i) boundary (which roughly gives the value of ~ 40 nT for the equatorial magnetic field) and close to the peak of the diffuse electron precipitation. The results [15] are in a rather good agreements with AMPTE/CCE measurements [23] in which the value of plasma pressure in the region of susbstorm expansion phase onset was ~ 1 nPa. Onset arc in the work [15] is localized in the upward field-aligned current region. Three cases of onset arc observations are analyzed in [37]. The brightening arcs are also located in the upward field-aligned current region.

The latest findings and early mentioned difficulties of tail reconnection theories lead to the real restrictions of possible scenario of substorm expansive phase onset. It is clear that local instability is developed in the region mapped into the equatorial boundary of discrete auroral precipitations. This instability produces auroral brightening, launches Pi1B and Pi2 micropulsations. The development of processes must create the change in magnetospheric transverse currents. The latest process produces magnetic field dipolarization and corresponding particle injections. The development of instability must also lead to the changes in tail current configuration, appearance of reconnection events and corresponding fast plasma flows. The brightening of the arc before the beginning of Pi2 burst and the existence of fast plasma flow before brightening can mean the

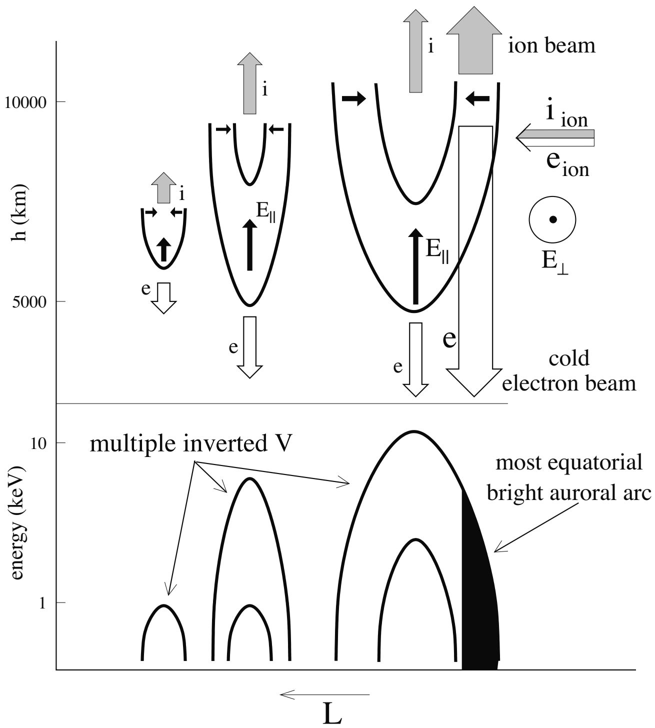

Fig. 1. Sketch illustrating the scheme of onset arc brightening.

development of some kind of electrostatic instability. Electrostatic instabilities generally have greater increments than electromagnetic ones because they do not require the distortion of magnetic field. These findings are in agreement with the predictions of [4, 38].

The analysis of multiple inverted V structures during substorm growth phase demonstrates the existence of latitudinal asymmetry [38]. The most equatorial inverted V is the most powerful one. This means that the upward field-aligned current is distributed inhomogeneously during substorm growth phase across current band and the most intense field-aligned current is concentrated at the equatorial boundary of the band.

Particle acceleration inside an inverted V structure is connected with the existence of field-aligned potential drop. The existence of such field-aligned potential drop means magnetosphere-ionosphere decoupling. Ionospheric damping of magnetospheric disturbances is decreased in such regions. Penetration of cold ionospheric plasma inside the region of field-aligned potential drop creates the powerful directed to the ionosphere anisotropic electron beam and ion beam directed to the magnetosphere at the boundary of inverted V [38]. Energy of electrons in such a beam are smaller than field-aligned potential drop and the electron flux in it can be 1–2 orders of magnitude larger than the flux of accelerated magnetospheric electrons. Therefore the auroral arc brightening or the formation of new very bright arc can be the result of discussed process. The analysis of Fig. 3 of [15] and Fig. 5 of [37] supports the possibility of such process development.

Observed fast plasma flows before the substorm expansion phase onset in the conditions of stable magnetic field can be the result of the development of some kind of electrostatic instability. One of such instabilities is connected to the existence of azimuthal plasma pressure gradients. It can be named modified interchange instability. The main features of such instability development in the region of upward field-aligned current are discussed in [4, 38]. Azimuthal plasma pressure gradients are identified as a source of large-scale Region 1 and Region 2 field-aligned currents of Iijima and Potemra. Therefore the growth of field-aligned currents during substorm growth phase is connected to the increase of azimuthal plasma pressure gradients. The lost of the stability of azimuthal plasma pressure gradient leads to the appearance of localized electric fields. Fig. 1 schematically shows the suggested scenario of auroral arc brightening. Accelerated in the preexisted field-aligned potential drop electrons and ions of ionospheric origin create thin sheet of field-aligned current which leads to launching of Alfvén waves (Pi1B and Pi2 micropulsations) and the destabilization of magnetic configuration.

4. Substorm onset and transverse current configuration

The configuration of magnetospheric currents before the substorm expansion phase onset is not clear till now. Theories of tail magnetic field reconnection and current disruption suggest that the substorm expansion phase onset takes place at the tail current lines. Near Earth tail current in accordance with these theories is increased during substorm growth phase. Decrease of tail current and magnetic field line dipolarization takes place when tail current is decreased. Tail current lines are closed by magnetopause currents. But it is possible to argue that current lines in the region of substorm expansion phase onset do not cross the magnetopause.

The appearance of drift echo is one of the constantly observed features of magnetospheric substorm. The drift echo in accordance with [18] can be observed till geocentric distances 12–13 R_E. Therefore the trajectories of the part of substorm injected particles are closed inside the magnetosphere. However trajectories of particles may not coincide with current lines. The configuration of current lines is clear in the case of magnetostatic equilibrium when plasma pressure is nearly isotropic and plasma bulk velocity is much smaller than Alfvén and sound velocity. Then

$$[\mathbf{jB}] = \nabla p. \quad (3)$$

The relation (3) shows that plasma pressure is constant at current lines. Therefore plasma pressure can be considered as a marker of current lines. According to [23] plasma pressure is nearly isotropic in the region of substorm expansion phase onset and is ~ 1 nPa. This value is typical for regions inside the magnetoshere in accordance with AMPTE/CCE investigations [13]. The value of plasma pressure at current lines closed by the magnetopause currents is limited by the condition of magnetopause stress balance on the tail flanks (see [7]). Traditionally modeled magnetospheric current configuration includes magnetopause current, tail current, ring current and field-aligned currents. Ring current is ordinarily concentrated at geocentric distances $\sim 5\ R_E$. Nevertheless, plasma population similar to the plasma sheet is observed at daytime to the equator from cusp and low latitude boundary layer (see

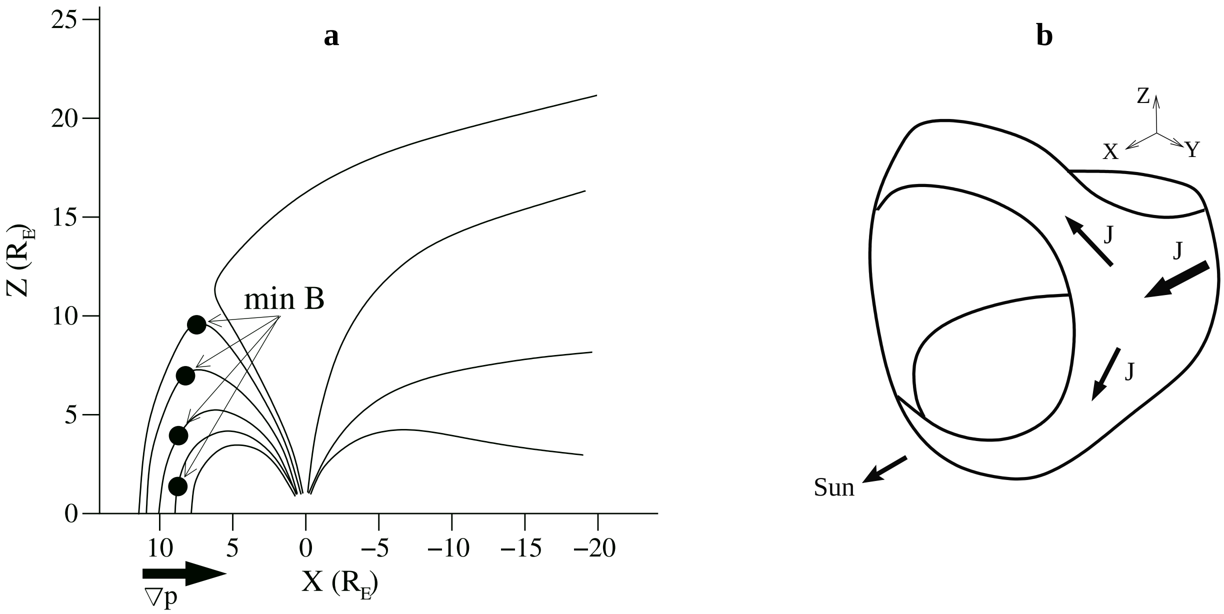

Fig. 2. The positions of magnetic field minima on daytime magnetic field lines (a) and sketch illustrating the configuration of cut ring current (CRC).

[30]). Pictures of plasma pressure distribution in the equatorial plane [13] show the existence of near to ring structures of plasma pressure. Therefore directed to the Earth radial daytime plasma pressure gradients are nearly the same as nighttime plasma pressure gradients. But daytime values of magnetic field near the equator are much larger than near noon. Therefore calculated in [13] values of transverse current are much smaller at noon than at midnight. However, the position of the magnetic field minimum for the daytime fieldlines are situated far from the equatorial plane (see Fig. 2a). This means that daytime transverse currents connected to directed to the Earth plasma pressure gradient are concentrated far from the equatorial plane. It is suggested (see [6]) that ordinary ring current has the high latitude continuation (see Fig. 2b) cut ring current (CRC). Current lines of this system close inside the magnetosphere, and are concentrated in the equatorial plane near midnight and at high latitudes near noon. It is possible to see using plasma pressure as a marker of current line that substorm expansion phase onset is localized at CRC current lines.

CRC is not unique large scale inner magnetosphere current system missed during the magnetic field modeling. The increase of the plasma pressure during magnetospheric substorm near the geostationary orbit is supported by many experimental observations. Two possible cases of such increase are analyzed in Fig. 3. Fig 3a correspond to pressure increase without change in the direction of plasma pressure gradient, Fig. 3b corresponds to the appearance of antiearthward directed plasma pressure gradient. However the eastward transverse current must appear in both cases. Case on Fig. 3a corresponds to the creation of effective eastward current (due to decrease of westward current), Fig. 3b corresponds the appearance of real high latitude eastward current. Eastward current increase the value of the magnetic field to the Earth and increase this value to the tail. It was shown in [8] that the appearance of eastward current can lead to the decrease of B_z component of near tail magnetic field till the formation of neutral line. Therefore the observed tail reconnection during substorm can have the forced character and can be connected to the increase of plasma pressure at the quasidipole magnetic field lines.

Another important aspect of eastward current formation is the possibility of appearance of over-dipolarization after the beginning of substorm expansion phase. It was stressed in [2] that when the eastward current becomes stronger than the cross-tail current the over-dipolarization of magnetic field lines occurs (B_z component of magnetic field at the equator from the region of increased pressure becomes larger than in the case of dipole field). The case of over-dipolarization corresponds to plasma pressure distribution shown on Fig. 3b.

One of the main features of the magnetospheric substorm is the magnetic field line stretching before the substorm expansion phase onset. Such stretching is ordinarily prescribed to the formation of a thin and intensified cross-tail current sheet in the near-Earth plasma sheet region ($\sim$ 6–13 R_E) [34]. But such interpretation encounters with a number of difficulties. Tail current is closed by magnetopause currents. Therefore the increase of tail current can not have the local character. Nevertheless many observations show the local longitudinal character of field line stretching and dipolarization. This means that currents which produce magnetic field stretching and dipolarization have local character and are closed inside the magnetosphere. The configuration of local currents producing the field line stretching is not clear till now. Analysis of Fig. 1 helps to select the process which leads to field line stretching during substorm growth phase and appearance of thin current sheets. Multiple inverted V structures are the sources of upward directed beams of ionospheric ions. Ions in such beams have energy ~ 10 keV after field-aligned acceleration. Ionospheric ion beam leads to the increase of plasma pressure at the top of field line. Such increase can produce local field line stretching. Azimuthal scale of the inverted V region is much smaller than

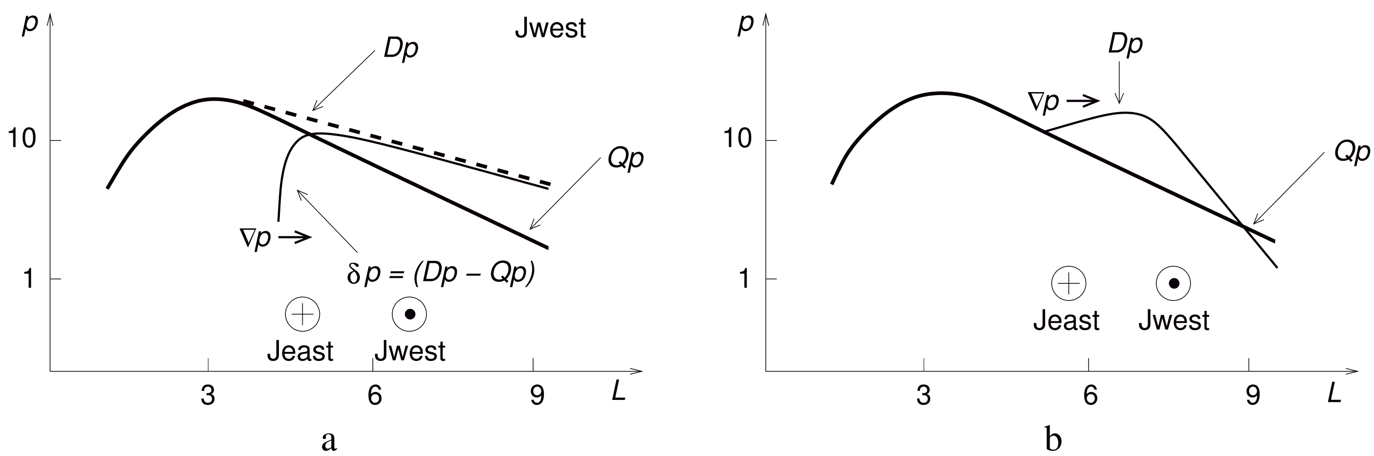

Fig. 3. Two possible cases of pressure increase and transverse current formation during substorm.

azimuthal scale of tail current. Therefore produced field-line stretching is longitudinally limited. Time scale of the process is $\sim$ 30 min. It is necessary to mention also that ionospheric ion beam can be considered as a source of the anisotropy of ion distribution. Such anisotropy is the necessary condition for the creation of super thin transverse current sheets in the kinetic models [21, 43]. Therefore it may be interesting to investigate more carefully the distribution of plasma and its anisotropy in the region of substorm onset.

Ion beam (see Fig. 1) formed in the process of onset arc formation is 1–2 orders of magnitude more powerful than ion beam connected to the inverted V structure. Its development in the process of first auroral arc brightening can help to explain explosive growth phase of roughly 30 sec period just before the beginning of dipolarization (Ohtani effect [31]).

5. Conclusions and discussion

More than forty years of study of substorm dynamics does not lead to the agreement about the cause and location of the substorm onset. Realization of THEMIS program will greatly increase the understanding of the substorm process. But THEMIS mission is designed mainly to solve the problem of onset location. The additional efforts will require for the understanding the mechanisms of substorm dynamics. The conducted analysis shows that the latest auroral substorm findings can be used as important tests of suggested substorm theories. We try to show that the development of the system of multiple inverted V with the most powerful inverted V at the equatorial boundary of the upward field-aligned current band can be considered as a mechanism of change in the magnetospheric plasma distribution and magnetic configuration and that the formation of onset auroral arc is the key process of substorm onset. It contains powerful upward field-aligned current and produces impulse injection of accelerated ionospheric ions into the magnetosphere. At the same time it creates the magnetic field distortion and launches irregular Alfvénic waves (Pi1B and Pi2 micropulsations). The injected ion beam leads to superstretching of magnetic field lines. Such magnetic configuration becomes unstable. The developed instability leads to field line dipolarization and powerful particle acceleration. But all these suggestions need the experimental verification.

Very important aspect of the problem also is the configuration of magnetospheric currents connected with substorm onset. We summarize the arguments showing that these currents are closed inside the magnetosphere and have local character.

Acknowledgments

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