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# Magnetostatic equilibrium and turbulent transport in Earth's magnetosphere: A review of experimental observation data and theoretical approaches

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**Abstract.** Multiple data of experimental observations including ISEE 2, AMPTE/CCE, INTERBALL, and GEOTAIL demonstrated the existence of great velocity fluctuations in the plasma sheet of the magnetosphere of the Earth. These data are compared with experimental observational data on the fluctuations of the electric and magnetic field. The analyzed data demonstrate the existence of high levels of plasma sheet turbulence. The velocity fluctuation amplitudes and their correlation times were used to obtain the values of the diffusion coefficients. Comparison of the values obtained with the values predicted by the theory of the plasma sheet with medium-scale developed turbulence demonstrated rather good agreement. The origin of the observed turbulence, its role in the magnetospheric dynamics, and the creation of the magnetostatic, equilibrium configurations are analyzed. It is shown that the existence of high plasma sheet turbulence can help to explain many well known magnetospheric phenomena and requires the development of new theoretical approaches for describing inner magnetospheric plasma transport and dynamics.

## 1. Introduction

The first problem that is solved in analyzing of any plasma configuration is the problem of magnetostatic equilibrium. Plasma begin to move with great velocity if the condition of magnetostatic equilibrium is not fulfilled. Change of the external conditions or the development of internal instability can lead to the destruction of magnetostatic equilibrium. It is well known that the development of plasma instabilities is the main obstacle for solving the problem of thermonuclear fusion. Plasma motions lead to plasma cooling due to interaction with the walls of the chamber. Space plasma configurations, as a rule, have no walls. The velocity of plasma motion in many space plasma objects is much smaller than Alfvén and sound velocity. So the condition of magnetostatic equilibrium (forces connected with the existence of plasma gradients are compensated by the Amper force) is fulfilled in such objects. In spite of more then 40 years of near-Earth space plasma investigations, the problem of the creation and support of magnetostatic equilibrium in the Earth's magnetosphere continue to attract attention and have remained unsolved until now. The situation is especially surprising now that proof of the existence of the rather high level of magnetospheric plasma sheet turbulence has been obtained. The existence of such turbulence is quite natural as the solar wind plasma flow around the Earth has high fluid and magnetic Reynolds numbers. In such a case the turbulent wake must be formed. It is necessary to understand why, in contrast to laboratory plasma, such turbulence does not destroy the plasma sheet, which is constantly observed when the interplanetary magnetic field (IMF) has southward orientation. Also the explosion-like processes of local plasma heating and plasmoid formation during magnetospheric substorm do not lead to plasma sheet destruction. The plasma sheet restores its slab configuration after substorm comparatively quickly. The real changes of the configuration of the plasma sheet (plasma sheet bifurcation) take place when IMF $B_z > 0$ and substorm activity is very weak. Such changes are accompanied with tail-lobe filling and theta-aurora formation. So support of magnetostatic equilibrium in the plasma sheet depends on IMF orientation.

In this paper, we try to summarize the results of exper-



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imental observations of plasma sheet turbulence, some results of theoretical investigations of the properties of this turbulence, and its role in magnetospheric plasma dynamics. Many aspects of the problem discussed correspond to the point of view of the author and do not coincide with the content of existing textbooks on magnetospheric physics. But the formulated problems require the real attention of the specialists, and we hope that the material presented can be useful in attracting such attention.

The paper is organized as follows. The data of experimental observations are analyzed in Section 2. Section 3 is dedicated to the nature of observed turbulence, its spectra and the self-organized criticality (SOC) approach to analyzing the properties of magnetospheric turbulence. Section 4 summarizes arguments in support of the action of the inner magnetospheric source of dawn-dusk electric field and large-scale magnetospheric convection. We discuss the main aspects of the plasma sheet theory with medium-scale developed turbulence and compare its predictions with results of experimental observations in Sections 5 and 6. Section 7 contains conclusions and discussions.

## 2. Plasma Sheet Turbulence

Observations of multiple manifestations of plasma sheet turbulence began with the first systematic investigations of the polar aurora. The "sky image" of near-Earth space plasma demonstrated the presence of multiple structures moving with different, and sometimes very large, velocities (see *Chamberlain* [1961]). The first stages of the investigations were mainly concentrated on periods of great increases in turbulence intensity — magnetospheric substorms. But even at this first stage it was known that the magnetosphere has its own "internal life" and that electromagnetic fluctuations are constantly observed at auroral latitudes in wide frequency ranges. Observations of the magnetic field in the geomagnetic tail beginning with the work of *Ness* [1965], have shown that the magnetic field can be rather regular and that magnetospheric substorms are accompanied by changes in the topology of magnetic field lines (reconnection phenomena). Such phenomena (see the review of *Pudovkin and Semenov* [1985]) and continue to become the main object of interest. Plasma motion in the plasma sheet was, as a rule, considered to be the laminar motion. The observed reconnection phenomena were analyzed as the result of the development of some kind of instability (spontaneous reconnection), but forced-reconnection models were also developed. At the same time it was recognized that plasma-sheet flow may occasionally be in a state of turbulence (see *Swift* [1977, 1981]; *Trakhtengerts and Feldstein* [1987]).

The widely used picture of the existence of the laminar plasma sheet could be changed when multiple measurements of the electric field on the auroral field lines and in the plasma sheet became possible. Such measurements (see *Maynard et al.* [1982]; *Mozer et al.* [1980]; *Weimer et al.* [1985]) and later results of Viking, Freja, Fast satellites have shown that electric fields at auroral field lines are much stronger than the large-scale, dawn-dusk electric field and also highly turbulent. The results of auroral plasma measurements also clearly demonstrated the possibility of the existence of nonequipotential magnetic field lines. First results of auroral and plasma sheet electric field observations were summarized by *Antonova* [1985]. It was shown that in the conditions of the existence of field-aligned electric fields, observed fluctuations of the electric field lead to nonconservation of particles in the magnetic flux tube and intense plasma sheet mixing. The results obtained closed the "convection crisis problem" formulated by *Ericson and Wolf* [1980]. This problem appeared in theoretical works that postulated that particles in the magnetic flux tube are conserved in the process of flux tube convection from the far-tail to the near-tail regions. The existence of fluctuating electric fields, amplitudes of which are much larger than the amplitude of the dawn-dusk electric field, means that the picture of plasma flow is much more complex than has been discussed. The nonequipotentiality of magnetic field lines leads to the magnetic flux tube splitting on segments moving in different directions with different velocities. One main consequence of the existence of plasma sheet turbulence is intense plasma mixing (see *Antonova* [1985]). As a result of such mixing, the temperatures of the plasma sheet ions and electrons must weakly depend on latitude and longitude. The absence of the dependence of ion and electron temperatures from latitude and longitude was demonstrated by *Antonova et al.* [1998, 1999] on the basis of Intercosmos-Bulgaria 1300 satellite results. The comprehensive temperature distributions obtained by *Wing and Newell* [1998] on the basis of DMSP results support the absence of central plasma sheet ion temperature coordinate dependence. At the same time, methods of electric field measurements in the rarefied hot plasma sheet plasma were not very reliable (large values of Debye length). So, plasma transport due to the existence of medium- and small-scale electric field was not introduced in discussion of magnetospheric convection.

All models of magnetospheric convection relate its existence to the interaction of the magnetized solar wind with the Earth's magnetosphere. Multiple investigations (see, for example, the review of *Marsch and Tu* [1997]) have demonstrated the permanent presence of solar wind turbulence. Such turbulence can obviously create magnetospheric turbulence. The clear manifestation of the existence of low-frequency magnetospheric turbulence was obtained through spectral analysis of geomagnetic indexes (see *Takalo et al.* [1993]; *Tsurutani et al.* [1990; *Uritsky and Pudovkin* [1998]). *Uritsky and Pudovkin* [1998] have shown that the $B_z$ component of the IMF, velocity of solar wind plasma, and the coupling function of Akasofu are insufficient factors to explain the behaviors of the $AE$ index of geomagnetic activity. The noncoincidence of forms of Fourier-spectra of solar wind parameters and $AE$-fluctuation spectra means that inner magnetospheric sources of turbulent fluctuations of auroral electrojets exist and is in rather good agreement with the results of plasma sheet electric field measurements.

Turbulent electric fields should produce fluctuations of plasma bulk velocity. The existence of turbulent plasma flow in the plasma sheet was proved when it became possible to calculate plasma bulk velocities. The results of plasma sheet bulk velocity measurements (see *Angelopou-*

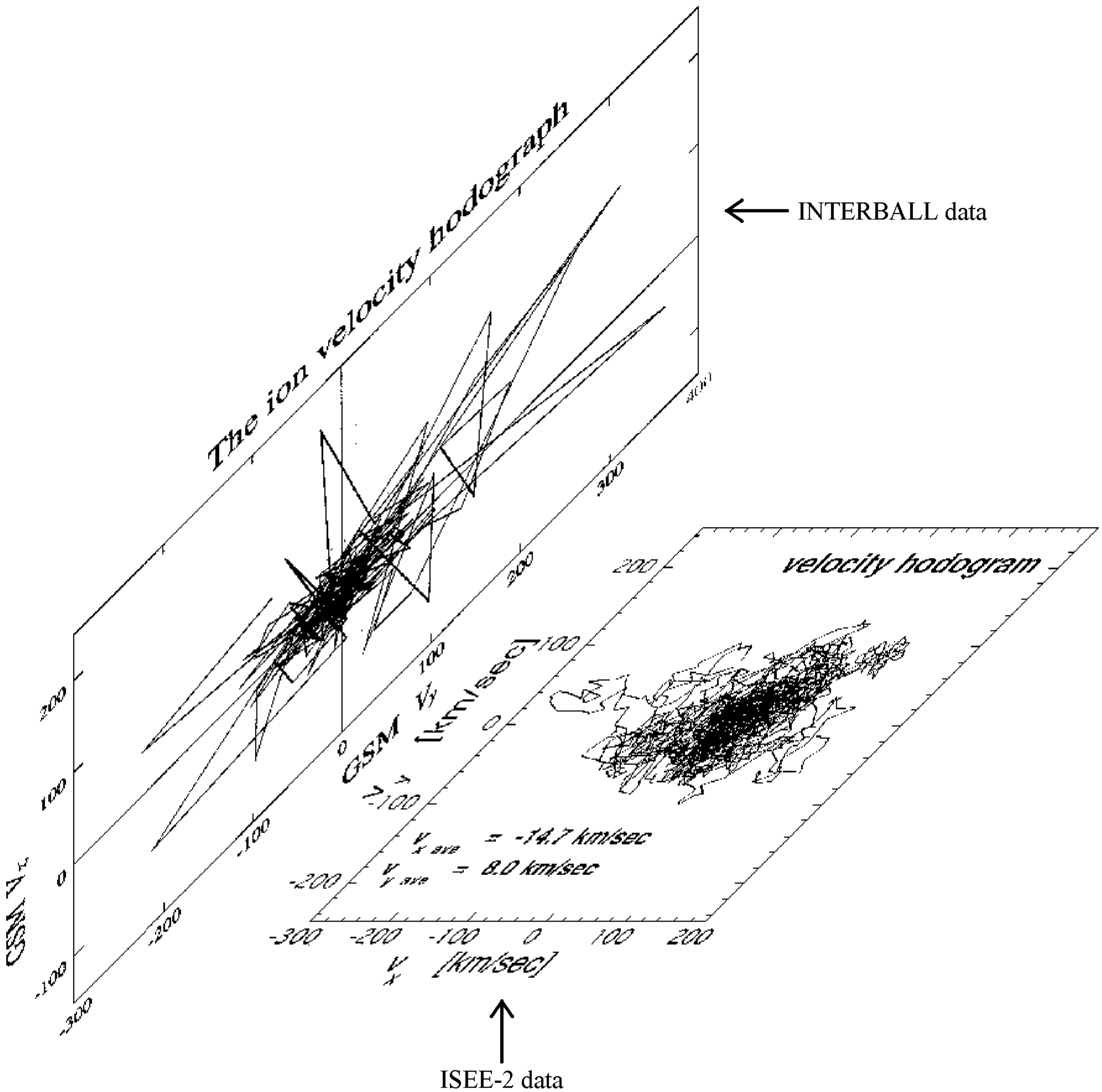


**Figure 1.** A comparison of the velocity hodogram published by *Borovsky et al.* [1997] with the velocity hodogram published by *Yermolaev et al.* [2000].

*los et al.* [1992, 1993, 1996, 1999]; *Borovsky et al.* [1997, 1998]; *Troshichev et al.* [2000]; *Yermolaev et al.* [2000]) have shown that the amplitudes of bulk velocity fluctuations are much larger than the averaged velocities. *Borovsky et al.* [1997, 1998] obtained the velocity fluctuations in the $(X, Y)$ plane. INTERBALL/Tail Probe and GEOTAIL observations make it possible to obtain the velocity fluctuations in the $(Y, Z)$ plain. Figure 1 compares the typical velocity hodogram published by *Borovsky et al.* [1997] with the velocity hodogram published by *Yermolaev et al.* [2000]. It is possible to see that in spite of different temporal resolution, velocity hodograms obtained during different time periods are very similar. The main difference between velocity fluctuations in $(X, Y)$ and $(Y, Z)$ plains is connected with fast flows, termed bursty bulk-flow (BBF) events. These are ~10 min long flow intervals directed mainly to the Earth at geocentric distances smaller than 20 $R_E$. Their peaks are 10 times larger than the average ~20–30 km s$^{-1}$ convection speed. They are composed of flow bursts lasting ~1 min and are observed at substorm growth, expansion and recovery phases. Many BBF occur without classical substorm signatures during pseudo-breakups and auroral brightening. BBF typically

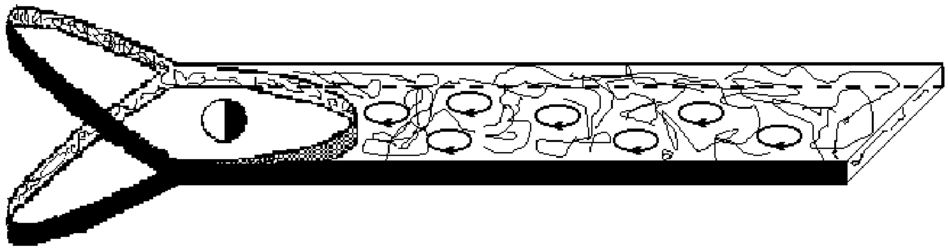

**Figure 2.** High-$\beta$ turbulent plasma localization in the magnetosphere.

cover 10–20% of all measurements (see *Baumjohann* [2000]). In accordance with *Angelopoulos et al.* [1999]; *Borovsky et al.* [1997], the presence of BBF produces asymmetry in the probability density function of the $X$ component of the inner plasma sheet flows. In accordance with *Angelopoulos et al.* [1992, 1993, 1996, 1999], when BBFs are removed from the plasma sheet observational database, flow state has an average convection that is small and a flow variance that is many times larger than its average. The results of *Troshichev et al.* [2000] and *Yermolaev et al.* [2000] demonstrate very large values of velocity fluctuations across the plasma sheet. In accordance with *Angelopoulos et al.* [1993] and *Hori et al.* [2000], averaged velocity in the $(X, Y)$ plane in the central plasma sheet is directed to the Earth. It is natural to associate this result with the existence of the large-scale dawn-dusk electric field and large-scale magnetospheric convection. This field also leads to the clearly observed plasma drift in the tail lobes toward the center of the plasma sheet, but it is very difficult to select average drift inside the plasma sheet. *Angelopoulos et al.* [1999] argued that in the plasma sheet at midnight local time, the average remnant potential convection is to within experimental uncertainty consistent with zero. The BBF occurrence rate peaks close to midnight, and the variance of the remnant flow during high $AE$ is stronger at midnight than at nearby sectors. This result supports the conclusion of *Kennel* [1995] that the magnetotail is in a state of bimodal convection, whereby the potential flow is stagnant unless it is driven by localized flow bursts. Analysis of the properties of velocity fluctuations also make it possible to conclude (see *Angelopoulos et al.* [1999]) that the magnetotail is a system that exhibits sporadic variability and has properties of intermittent turbulence.

As mentioned earlier, observations of the turbulent plasma sheet containing rarefied plasma of thermonuclear (1–10 keV) energies are quite natural in view of attempts to create laminar high-temperature plasma in laboratory conditions. In such plasma, many instabilities lead to very quick plasma turbulization. This is also very natural since the high Reynolds number of the plasma flow around the obstacle leads to the appearance of a turbulent wake even in the conditions of stable solar wind parameters. The transition region from the turbulent solar wind to the turbulent plasma sheet — the low latitude boundary layer (LLBL) — in accordance with *Sandahl* [1999] is also quite turbulent. It is necessary to note that the region of minimal magnetic field at the daytime magnetic field lines is situated far from the equatorial plane because of magnetospheric compression. Thus, taking into account that the plasma sheet continues in the daytime magnetosphere until noon, and summarizing the data of experimental observations, it can be seen that the regions of high plasma parameter $\beta = 2\mu_0 p/B^2 \gg 1$, where $\mu_0$ is magnetic permiability of vacuum, $p$ is the plasma pressure, $B$ is the magnetic field, schematically shown in Figure 2, are highly turbulent. Plasma flow is ordinary in the regions where $\beta \ll 1$ (tail lobes, mapped on the polar cap, and deep ($L < 5$) inner-magnetosphere regions) and it is of nonregular character where $\beta > 1$. The distribution of the most turbulent magnetospheric domains makes it possible to suggest that the main sources of inner magnetospheric turbulence are concentrated in high $\beta$ magnetospheric regions and on the boundaries of such regions. Only large-scale fields partially penetrate the low $\beta$ regions. But this suggestion requires real experimental verification.

## 3. Turbulence Nature, Spectra, and Self-Organized Criticality

The nature of observed turbulence is not yet clear. According to *Antonova et al.* [2000]; *Borovsky et al.* [1997]; and *Yermolaev et al.* [2000], plasma sheet velocity fluctuation correlation times (~2 min) are much larger than the correlation times of magnetic field fluctuations (~10 min). The results of *Troshichev et al.* [2000] clearly demonstrate the inconsistency of magnetic field and plasma velocity variations even in the distant plasma sheet. Therefore, plasma sheet turbulence is not MHD turbulence. The difference between the correlation times of velocity and magnetic field fluctuations suggests that electrostatic modes (which can more easily develop in a collisionless plasma) dominate in many cases. Particle beams formed in the process of plasmoid motion and particle acceleration in electric field fluctuations can constitute ballistic modes of the observed turbulence. The level of turbulence can evidently depend on the level of geomagnetic activity. It grows after the substorm expansion phase onset and decreases 1–2 h later (see *Antonova et al.* [2000]).

*Antonova and Tverskoy* [1998] analyzed the role of plasma pressure gradients in generating the magnetospheric electric fields and discussed the possibility of the existence of nonlinear transport of energy between large- and medium-scale electrostatic harmonics. It was shown that the two-vortex electric field is the zero harmonic of the solution of the problem of magnetosphere-ionosphere interaction and four-vortex electric field — the first harmonic. The generation of smaller scale harmonics in the case of the equipotential field line was analyzed by *Ivanov and Pochotelov* [1987] and in the case of the existence of the field-aligned potential drops by *Antonova* [1993]. The magnetospheric vortexes are coupled with the dissipative ionosphere (magnetosphere-ionosphere interactions). Another source of dissipation is the heating of magnetospheric particles. *Horton et al.* [1993] analyzed the generation of large-scale vortexes due to the development of drift instabilities and velocity shear. Powerful sources of inner magnetospheric turbulence are waves from the solar wind and magnetosheath.

Rather high levels of the observed turbulence show that it is strong. The balance of the generation of turbulence and its dissipation determines the form of spectra of the turbulence. Linear analysis can give the characteristic scales of the most unstable harmonics. Obtaining the turbulence spectra requires use of the theory of a strong turbulence, which is not well developed, or corresponding computer modelling. The difficulties of creating the necessary models are partially connected with the existence of the dynamic chaos of plasma sheet particle motion. For example, postulated in many models, magnetized motion of plasma sheet electrons is not supported by the data of experimental observations (see *Antonova et al.* [1999]), and it is quite possible that the existence of small-scale fluctuations of the electric field produces the stochastization of electron motion when the scale of fluctuations is of the order of the electron Larmor radius.

Information on the spectra of magnetospheric turbulence is quite limited. *Gurnett and Frank* [1977] presented measured spectra in a wide frequency range with broad maximum near ion gyrofrequency (1–10 Hz). Many papers contain information on spectra of geomagnetic micropulsations. *Weimer et al.* [1985] and *Basu et al.* [1988], using DE 1 and DE 2 satellite data, showed that the expansion of electric field measurements at low altitudes in the Fourier series give the Kolmogorov-type spectrum of transverse electric field fluctuations

$$E_k^2 \sim (k/k_{\min})^{-5/3} \tag{1}$$

where $k$ is a module of the wave vector and $k_{\min}$ is a constant. Measurements by the DE 1 satellite at an altitude of 12,000 yielded

$$E_k^2 \sim (k/k_{\min})^{-5/3}(1 + k^2/k_0^2) \tag{2}$$

where $k_0$ is a constant.

Long-period fluctuations of the geomagnetic $AE$ index have the power spectrum $f^{-b}$ (where $f$ is a Fourier frequency) with exponent $b = 1$ at $f < 0.05$ mHz and $b > 2$ at higher frequencies, and they are characterized by a fractal structure stable for long intervals of moderate solar activity (see *Uritsky and Pudovkin* [1998]). *Hoshino et al.* [1994] have shown that fluctuations of the magnetic field observed in the distant plasma sheet are characterized by a "kink" Fourier power law spectrum that could be approximated by two power law functions with two different spectral indices. It was found that the power spectrum of the $B_z$ of the magnetic field could be well fitted by

$$P(f) \propto f^{-\alpha} \tag{3}$$

where $\alpha = \alpha_1$ and $0.49 \le \alpha_1 \le 1.48$ if $f < 0.04$ Hz, $\alpha = \alpha_2$ and $1.78 \le \alpha_2 \le 2.43$ if $f > 0.04$ Hz. *Borovsky et al.* [1997] obtained the occurrence distributions of plasma sheet bulk flows $P(v_x)$ and $P(v_y)$ in $X$ and $Y$ directions based on 53,408 measurements of flow in the plasma sheet between 15 and 22 $R_E$ behind the Earth on the ISEE 2 satellite. They selected an isotropic distribution of flows at low flow velocities (eddy turbulence) and an anisotropic distribution of fast flows (BBFs). In accordance with *Borovsky et al.* [1997],

$$P(v_x) = 0.32 \exp(-|v_x - 8|/41) \tag{4}$$

$$P(v_y) = 0.32 \exp(-|v_y - 5|/54) \tag{5}$$

where $v_x$ and $v_y$ are measured in km s$^{-1}$. The distribution of fast BBF flows can be fit by

$$P(v_x) = 0.030 \exp(-|v_x|/149) \qquad \text{for } v_x > 0 \tag{6}$$

$$P(v_x) = 0.011 \exp(-|v_x|/159) \qquad \text{for } v_x < 0 \tag{7}$$

The study of *Borovsky et al.* [1997] reveals power-law spectral shapes of the time history of flows and fields, which would be consistent with turbulent spectra in $k$ space if a random-sweeping model of the vortices is assumed.

*Angelopoulos et al.* [1999], using 2.8 years of GEOTAIL satellite data, studied the probability distribution functions of flows in the plasma sheet and show that they can be readily approximated with two log-normal distributions, as expected from intermittent turbulence. They argue that the presence of fast flow log-normal component in the distribution is evidence of intermittency, that is, long periods of slow flow interrupted by short-lived periods of fast convection. *Angelopoulos et al.* [1999] suggested that turbulent flows resemble the turbulent field adjacent to a jet and that strongly driven turbulence spreading away from the BBFs alter the fundamental process of material transport and momentum in the collisionless plasma sheet plasma by introducing an effective diffusion process.

In the physical system exhibiting self-similarities over a broad range of temporal and spatial scales, spatial scales may be described by fractal geometry, and time scales lead to $1/f$-like power spectra. *Bak et al.* [1987, 1988] suggested that there may be an intimate connection between scale invariance in space and time as it happens at critical transitions. Because there is no externally controlled critical parameter in many natural systems, they call this basic property self-organized criticality (SOC). SOC describes systems that naturally reside far from an equilibrium state. It describe the interaction between fractal processes (fluctuations with the spectrum like $f^{-b}$) and spatial fractal structures. The ensemble average of the system is its most common state rather than steady state. Such systems, envisioned as dissipative and subject to continuous variable external driving, exhibit intermittent output that is governed by power-law spectra. The running sandpile has been used as a paradigm and simple dynamic model that exhibits these general SOC properties. An SOC model describes the dynamics of the transport without relying on the underlying local fluctuation mechanisms. Noise-driven SOC systems can maintain average profiles that are linearly stable (submarginal) and yet are able to sustain active transport dynamics. The dynamics of SOC can be computationally investigated with a cellular automata model of "running sandpile" dynamics. In such models, localized fluctuation is modeled by grid site (cell), local turbulence mechanism by automata rules, critical gradient for local instability by critical sandpile slope, local eddy-induced transport by number of grains moved if the slope is unstable, total energy/particle content by total number of grains, heating noise/background fluctuations by random rain of grains, energy particle flux by sand flux, mean temperature/density profile by average slope of sandpile, and transport event by avalanche (see *Newman et al.* [1996]).

From the moment of its suggestion, SOC models have been widely used to explain the forms of magnetospheric turbulence spectra as power-law spectra are a natural consequence of a system driven in a state of SOC. The effect of SOC was proposed by *Uritsky and Pudovkin* [1998] as an internal mechanism to generate $f^{-b}$ fluctuations of geomagnetic intensity. It was shown that power spectrum of sandpile model fluctuations controlled by real solar wind parameters reproduce spectral features of the $AE$ fluctuations. The origin of $f^{-b}$ fluctuations in nonequilibrium systems with many degrees of freedom was connected with the superposition of numerous instabilities with the large relaxation time range. *Zelenyi et al.* [1998] have shown that the form of magnetic field fluctuation spectra in the far tail region can be explained if the turbulence has a fine fractal structure. *Angelopoulos et al.* [1999] have shown that many features of tail velocity fluctuation spectra can be explained using the SOC approach. The latest substorm models of *Sitnov et al.* [2000] and *Klimas et al.* [2000] are based on SOC hypothesis.

At the same time, in spite of the great popularity of SOC models, they cannot comprehensively explain all observed spectra. SOC hypothesis also does not solve the problem of the existence of confined, comparatively stable plasma structures (such as, for example, the plasma sheet of Earth's magnetosphere) filled with turbulent plasma. It is necessary to also mention that the values of plasma velocity fluctuation across the plasma sheet are, as a rule, smaller than the sound, and Alfvén velocities and plasma pressure distribution are near isotropic. This may suggest that the condition of magnetostatic equilibrium is fulfilled across the plasma sheet on scales larger than the characteristic dimension of plasma eddy. Later, we show that such suggestion can help solve the problem of turbulent plasma sheet formation.

## 4. Magnetospheric Asymmetry as the Source of Field-Aligned Currents and Magnetospheric Convection

One of the main features of magnetospheric convection is the existence of two large-scale electrostatic vortexes and the dawn-dusk electric field. Determination of the nature of this field is one of the main problems of the physics of the magnetosphere. Beginning with the works of *Axford and Hines* [1961] and *Dungey* [1961] it has been ordinarily suggested that dawn-dusk electric field is produced by MHD dynamo in the magnetospheric boundary layers or penetrates from the solar wind. Dungey mechanism of reconnection deposits the reverse of the magnetospheric convection from antisunward to sunward on the boundary of open and closed field lines. The results of the analysis presented by *Elphinstone et al.* [1991]; *Feldstein and Galperin* [1985]; and *Galperin and Feldstein* [1991] clearly demonstrated that the polar cap boundary does not coincide with the polar auroral oval boundary. The region of precipitation from the plasma sheet boundary layer is deposited between these boundaries. In accordance with multiple models of the action of MHD generator in the magnetospheric boundary layers, Region 1 currents must be mapped on the boundary layers. Boundary layers are mapped on the near cusp regions in accordance with all existing magnetic field models. The picture of Region 1 current density with maxima near 1400–1500 and 0700–1000 MLT of *Iijima and Potemra* [1976] was considered as the proof of this mapping. But it is necessary to mention that the published [*Iijima and Potemra*, 1976] distribution of Region 1 current density was missed with the distribution of integral currents. Current sheet widths in the picture of the field-aligned current distribution of *Iijima and Potemra* [1976] are much larger near 0600 and 1800 MLT than near 1400–1500 and 0700–1000 MLT. Thus, the integral current maxims are localized near 0600 and 1800 MLT, which is supported by radar observation data [*Foster et al.*, 1989]. It is impossible to map 0600 and 1800 MLT regions on the boundary layers using any of the existing magnetic field models.

Region 1 current mapping on the inner magnetospheric region requires searching for the inner magnetospheric mechanism that supports such currents. Such a mechanism was suggested by *Antonova and Ganushkina* [1996] (see also [*Antonova and Ganushkina*, 1997]) and was named the magnetospheric topology mechanism. As this mechanism is not as popular as widely discussed boundary layer mechanisms, we discuss its action and try to show that this mechanism can be considered as the real candidate for dawn-dusk electric field generation.

It is well known that in conditions of magnetostatic equilibrium, plasma pressure gradients determine the large-scale transverse $\mathbf{j}$ and field-aligned $j_\parallel$ currents. The presence of velocity fluctuations much smaller than Alfvén and sound velocity does not destroy magnetostatic equilibrium. In discussing large-scale currents we deal with plasma pressure averaged on the fluctuations (at scales much larger than the characteristic scale of a turbulent vortex and characteristic times much longer than the length of vortex existence). In the high-latitude magnetosphere, where plasma pressure is near isotropic, such currents are equal (see the review of *Antonova and Tverskoy* [1998] and references therein).

$$\nabla p = [\mathbf{j} \times \mathbf{B}] \tag{8}$$

$$j_\parallel = 0.5\mathbf{n}[\nabla p \times \nabla W] \tag{9}$$

where $p$ is the plasma pressure, $\mathbf{B}$ is the magnetic field, $\mathbf{n} = \mathbf{B}_i/B_i$, $\mathbf{B}_i$ is the magnetic field on the ionospheric altitudes, $W$ is the flux tube volume ($W = \int dl/B$). The volume of the magnetic flux tube is the important magnetic field characteristic widely used in analysis of high-latitude plasma stability. As in accordance with (8), $p$ is the constant for all points on the field line, and it can be used as one of the Euler potentials:

$$\mathbf{B} = [\nabla p \times \nabla \beta] \tag{10}$$

where $\beta$ is the angular coordinate. So,

$$\nabla W = \frac{\partial W}{\partial p}\nabla p + \frac{\partial W}{\partial \beta}\nabla \beta \tag{11}$$

Taking into account the relation (9) we have

$$j_{\|} = 0.5\mathbf{n}[\nabla p \times \nabla \beta]\frac{\partial W}{\partial \beta} = 0.5 B_i \frac{\partial W}{\partial \beta} \tag{12}$$

In accordance with (12), field-aligned current in the magnetostatic equilibrium configuration is equal to zero if $\partial W/\partial \beta = 0$ and is automatically generated if $\partial W/\partial \beta \neq 0$. $\partial W/\partial \beta = 0$ in the azimuthally symmetric configurations. The asymmetry must automatically lead to the generation of field-aligned currents. The Earth's magnetosphere is azimuthally symmetric in the deep inner magnetosphere regions where the Earth's magnetic field is near the dipole field and highly asymmetric at the auroral latitudes. In the far tail regions the dependence of the flux tube volume on the angular coordinate becomes weaker, which leads to the decrease in field-aligned current intensity. Thus, only the transition region from the dipole to highly tailward stretched field lines becomes the source of field-aligned current.

The dependence of the dawn-dusk electric field on the IMF orientation can be explained as the result of the solar wind's large-scale magnetic field influence on the inner magnetosphere's magnetic configuration. This influence will be especially pronounced in the regions where magnetospheric magnetic field **B** is comparable with IMF **B**. Such influence is possible to see by analyzing (8). If the sign of the externally added (in the simplest case penetrated) magnetic field is inverse to the sign of **B** in the equation (8) and the plasma pressure gradient does not change, the external source must lead to transverse current growth. The equation (9) shows that transverse current change leads to the field-aligned current change. The change of Region 1 currents naturally produces the change of the dawn-dusk electric field. It is easy to see that the influence of the additional southward $B_z < 0$ leads to a larger effect than the influence of $B_z > 0$. For example, if $j_0 = |\nabla p| / B_z^0$ and $\delta B_z = 0.9 B_z^0$, then disturbed $j = 10 j_0$ if $\delta B_z < 0$ and disturbed $j \approx 0.5 j_0$ if $\delta B_z > 0$. It is clear that the real process of inner magnetospheric magnetic field change under the influence of IMF is the complex nonlinear problem. The increase of current in one part of the magnetosphere produces magnetic field change in its other parts. The inner magnetospheric magnetic field change affects the pressure balance of the magnetopause and the Chapman-Ferraro currents. It is necessary to mention that this change will be accompanied by transport of the magnetic flux between the daytime and nighttime parts of the magnetosphere. The reconnection of field lines near magnetopause in such a case will be the consequence, but not the cause, of the change in the magnetospheric magnetic field. The energy deposited in the magnetosphere in the linear approximation is proportional to the flux of solar wind electromagnetic energy and strongly depends on the angle between the solar wind magnetic field and the directions of the magnetospheric current flow.

Comparison of the well known boundary layer mechanisms of dawn-dusk electric field generation (MHD generator in the magnetospheric boundary layers is considered as the development of *Axford and Hines* [1961] and *Dungey* [1961] mechanisms) with "magnetospheric topology" mechanism shows that the latter mechanism has some preference. Boundary layer mechanisms require the existence of finite conductivity (Dungey type mechanisms) or finite and comparatively large viscosity (Axford and Hines type mechanisms). Such parameters cannot be directly obtained and it is well known that their introduction in the collisionless plasma present principal difficulties. The "magnetospheric topology" mechanism does not require the introduction of unmeasurable parameters. Thus, it can be verified directly if the distribution of the magnetic field and plasma pressure is known.

The "magnetospheric topology" mechanism action requires the field-aligned current mapping on the magnetospheric regions with high values of plasma pressure. First measurements of field-aligned currents (see *Zmuda and Armstrong* [1974]) have reviled the connection of these currents with the regions of real plasma populations. Field-aligned currents were observed on the auroral oval latitudes. Multiple later observations support the existence of field-aligned currents only in the regions where intense plasma precipitation take place. Region 1 currents of *Iijima and Potemra* [1976] are properly oriented to support the dawn-dusk electric field in the polar cap. The NBZ current system in accordance with *Iijima and Shibaji* [1987], has the reverse direction of the Region 1 current system and supports the dusk-to-dawn distribution of the electric field between sheets of NBZ current. This current system is observed simultaneously with the theta-aurora type of precipitation on the boundaries of the polar cap auroral band. Thus, NBZ currents are also mapped on the regions filled with plasma. The appearance of such regions in the tail lobes is the result of plasma sheet bifurcation when IMF $B_z > 0$.

It is possible to verify the discussed "magnetospheric topology mechanism" action if the distribution of $p$ and $W$ is known. The averaged global distribution of $p$ was obtained by *Wing and Newell* [1998] on the basis of DMSP observations mapped on the equatorial plane and by *DeMichelis et al.* [1999] on the basis of AMPTE/CCE observations. $W =$ const isolines can be obtained using the empirical models of the magnetic field. Such distribution was obtained by *Antonova and Ganushkina* [1995] when they suggested using $W =$ const picture to create the coordinate system in the high-latitude magnetosphere, which can be used to analyze the high-latitude processes. Unfortunately, global pictures obtained of the plasma pressure contain the mixture of substorm and quiet time data. The sharp increase of the particle fluxes near midnight during substorm expansion phase is accompanied by the near-tail current disruption and corresponding change of the $W =$ const picture in this region (see *Antonova and Ganushkina* [2000]). So, it is impossible now to compare the $p$ and $W$ distribution picture. But extracting from the pictures of [*DeMichelis et al.*, 1999; *Wing*

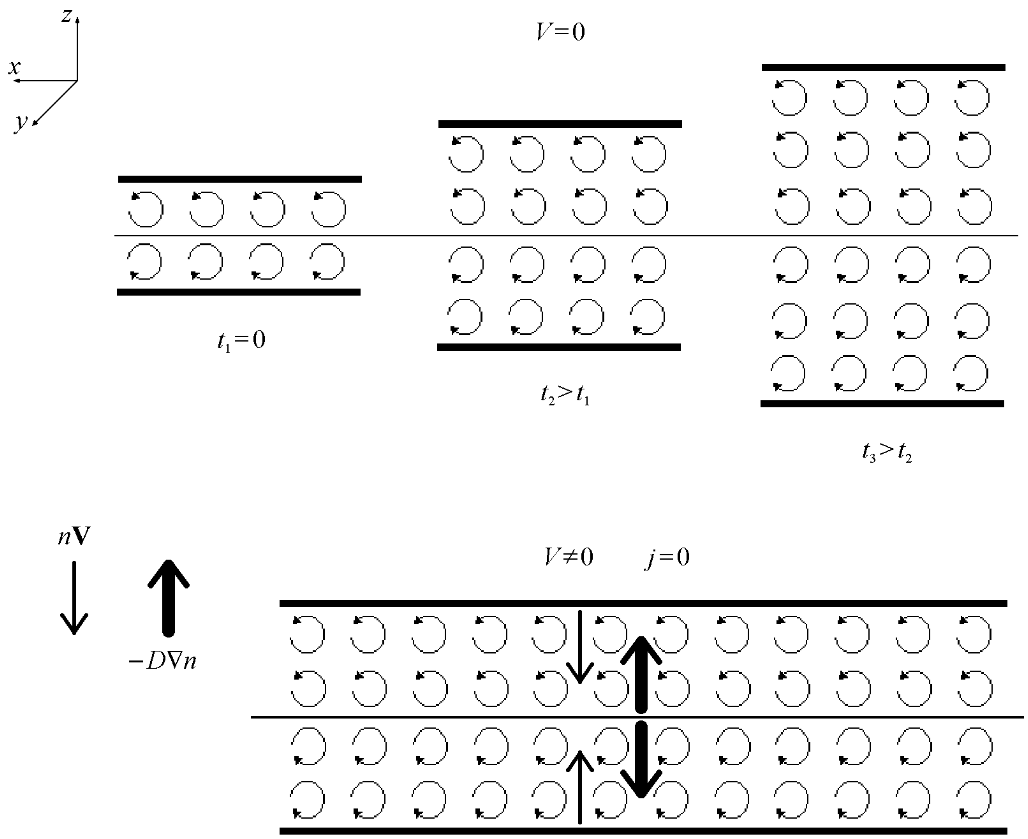


**Figure 3.** Mechanism of formation of a turbulent plasma sheet suggested by *Antonova and Ovchinnikov* [1996].

*and Newell*, 1998] the expansion phase periods allows this possibility. It is necessary to mention that *Kozelova et al.* [1986, 1989] have demonstrated the formation of the substorm pressure hole near midnight that is responsible for generating the Birkeland current wedge.

It is also possible to verify the "magnetospheric topology" mechanism action using only magnetic measurement data. In accordance with (8), plasma pressure $p$ = const on the current line. So the picture of rot**B** distribution can be used instead of $p$ distribution in the region where plasma pressure is near isotropic. The empirical magnetic field models can be used for the analysis. Most of the currently available models are half-empirical (see [*Tsyganenko*, 1990, 2000]). Thus, its use in the suggested analysis can meet with definite difficulties connected with the models' current line geometry. In spite of this difficulty, *Antonova and Ganushkina* [1996a, 1996b, 1997], in analyzing the $W$ = const isoline and current line distribution in Tsyganenko 87 and Tsyganenko 87W models, have supported the possibility of the "magnetospheric topology mechanism" action. It was shown that the curvature of the near-tail current lines is higher than the curvature of flux tube volume isolines. So, the distribution of plasma pressure along $W$ = const isoline must have the minimum near midnight and the gradients of the plasma pressure must be directed from midnight to dawn and dusk in the morning and evening hours respectively.

One problem connected with the possibility of verifying the "magnetospheric topology" mechanism action is the possible difference of the current systems in the real magnetosphere and in the magnetospheric magnetic field models. The magnetic field has minima on the dayside field lines far from the equatorial plane (see Figure 2). So, transverse currents in the daytime magnetosphere are concentrated far from the equatorial plane. *Antonova and Ganushkina* [2000] have suggested that a cut-ring current system can exist in the high-latitude magnetosphere. Current lines of this system are concentrated in the equatorial plane near midnight and at high latitudes near noon. The addition of this current system changes the topology of the current lines in the near-tail region. Correspondingly, it will change the configuration of the flux tube volume isolines. Future investigation will verify the importance of the "magnetospheric topology" mechanism of magnetospheric convection but, it is now possible to mention that only this mechanism can explain the current mapping of inner magnetosphere Region 1.

## 5. The Existence of the Quasi-Stable Plasma Sheet and Possible Causes of the Magnetospheric Reconnection

The existence of high levels of plasma sheet turbulence require using the system of transport equations averaged on the turbulent fluctuations instead of ordinary magnetic hydrodynamics. The problem can be solved half-phenomenologically by introducting the anomalous fluxes of particles and heat. This approach is ordinarily used in theories of anomalous plasma transport in laboratory conditions (see, for example, *Horton* [1984]). The system of transport equations is obtained for the averaging fluctuating hydrodynamic values (concentration, temperature, pressure etc.). Monographs of *Klimontovich* [1990, 1999] contain more careful substantiation of the possibility of such averaging.

Two main problems that arise in view of a high level of plasma sheet turbulence are the existence of a quasi-stationary plasma sheet geometry and the nature of observed reconnection phenomena. The turbulent magnetospheric plasma sheet has the comparatively stable equilibrium configuration. *Antonova and Ovchinnikov* [1996, 1999] suggested an explanation of the observed phenomena. The model of *Antonova and Ovchinnikov* [1996, 1999] was developed under the assumption that the regular plasma transport related to the dawn-dusk electric field is compensated by quasidiffusive transport related to the existence of turbulent transport that is, the integral flux is equal to zero

$$\mathbf{j} = \langle n\mathbf{V}\rangle = n_0\mathbf{V}_0 - D\nabla n = 0 \qquad (13)$$

where $n$ is the concentration, $n_o$ is the averaged concentration, $\mathbf{V}$ is the velocity, $\mathbf{V}_0$ is the averaged velocity, $D$ is the coefficient of quasidiffusion. The theoretical approach developed by *Antonova and Ovchinnikov* [1996, 1999] takes into account two major effects: constant plasma sheet compression by the dawn-dusk electric field and the diffusion of the turbulent plasma in the direction opposite the gradient of plasma concentration. Figure 3 illustrates the main features of the mechanism action. Turbulent fluctuations destroy the plasma sheet. Its thickness is constantly increased. The large-scale electrostatic dawn-dusk electric field tries to compress the sheet just as it takes place in the laboratory pinch compressed by the induction electric field. If the velocity of destruction and compression are equal, the stationary structure is formed. Quick plasma sheet mixing equalizes the temperature across the sheet. So, it is possible to use the approximation of constant temperature $T = \text{const}$, supported by the data of experimental observations. The equilibrium distribution of concentration across the plasma sheet gives the equilibrium distribution of plasma pressure $p = nT$. If the dependence of the regular velocity and the quasidiffusion coefficient from the value of the magnetic field is known, the condition $\mathbf{j} = 0$ determines the dependence of the plasma pressure from the magnetic field. In the case of the one-dimensional problem

$$p^{-1}\frac{dp}{dz} = -L^{-1}f(b) \qquad (14)$$

where $b = B/B_L$, $B_L$ is the magnetic field in the tail lobes, $f(b) = Lv_z(b)/D(b)$, $L = (D/v_z)\,|_{B=B_L}$, $D$ is the coefficient of quasidiffusion or eddy diffusion, $L$ is the plasma sheet half-thickness. The actual dependence of $v_z$ and $D$ in the plasma sheet, where particle motion can be demagnetized, is not known. The dependence $p(b)$ is determined only by their relation. For example, if the correlation time of turbulent fluctuations $\tau = \text{const}$, and the value of the regular velocity and turbulent fluctuations $\propto B^{-1}$ (just as in the case of electrostatic drift), $f(b) \propto b$, and we have a Harris-type solution

$$B = B_L \tanh(z/2L) \qquad (15)$$

Vector potential of the magnetic field $A$ in such a case is

$$A = A \ln\cosh(z/2L) \qquad (16)$$

The relation between the plasma pressure and the magnetic field can be generalized to the two-dimensional case in the tail approximation developed by *Schindler and Birn* [1986] if the plasma sheet half-thickness $L$ is much smaller than the plasma sheet characteristic length. Let $A = A(x,z)$ be the $y$ component of the vector potential. In the two-dimensional case, if the magnetic field dependence on the plasma pressure $p = p(A)$ is known, the Grad–Shafranov equation

$$\Delta A + \mu_0\frac{dp}{dA} = 0 \qquad (17)$$

can be solved, and in the tail approximation field line shape can be determined. If the characteristic scale $d_z$ along the $z$ axis is much smaller than the characteristic scale $d_x$ along the sheet ($d_z/d_x \ll 1$), the solution of (17) has the form

$$z - z_0 = \int\limits_{A_0}^{A} \frac{dA'}{\sqrt{2\mu_0(p_0 - p(A')}} \qquad (18)$$

where $p_0 = p_0(x)$ is the plasma pressure at the tail axis, $z_0 = z_0(x)$, and $p[A_0(x)] = p_0$. The profile $p_0(x)$ is specified on the basis of the tail lobe observations. The term diffusion is changed to quasidiffusion as the condition of the smallness of the turbulent vortex in comparison with the width of the plasma sheet (its scale can constitute 0.1–0.2$L_z$) and is not fully fulfilled. The local thickness of the plasma sheet in the developed theoretical approach is determined by the local value of the dawn-dusk electric field and the local value of the quasidiffusion coefficient. The increase of the large-scale field produces plasma sheet thinning, the increase of the coefficient of the quasidiffusion — plasma sheet thickening. If the large-scale electric field becomes equal to zero or changes sign, the equilibrium solution cannot be obtained and plasma sheet configuration cannot be formed. If the distribution of the electrostatic potential on the ionospheric altitudes and the value of the quasidiffusion coefficient is known, the model of *Antonova and Ovchinnikov* [1996, 1999] makes it possible to obtain the distribution of plasma in the plasma sheet at given geocentric distances. The $Y$ dependence of the plasma sheet thickness for $X = -15\ R_E$ obtained by *Antonova and Ovchinnikov* [1999] is shown in Figure 4. The Volland–Stern model for distribution of the electric field at ionospheric altitudes and Tsyganenko 87W model for such distribution

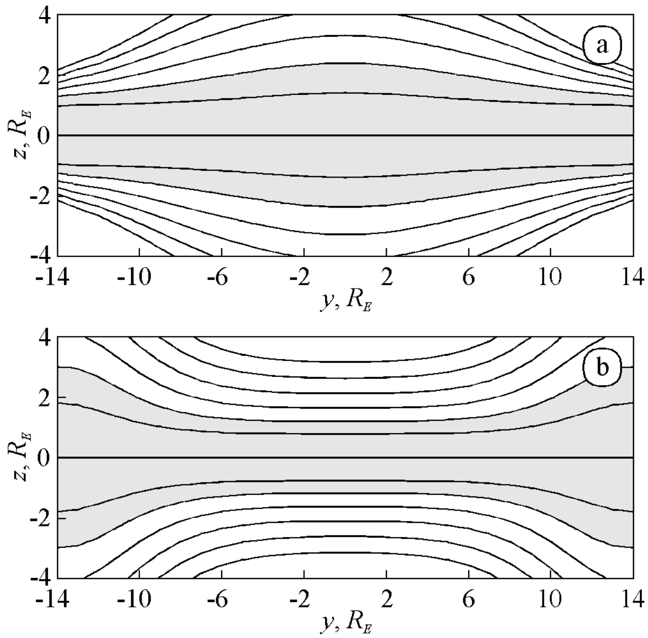


**Figure 4.** Plasma sheet structure during northward and southward IMF direction [*Antonova and Ovchinnikov*, 1999].

mapping were used to obtain plasma pressure profiles at different IMF $B_z$ values. In agreement with Figure 4, the form of the plasma sheet when IMF $B_z < 0$ is concave. If $B_z > 0$ it is possible to see the bulge in the center of the structure. The appearance of such a bulge makes it possible to formulate the hypothesis on the nature of plasma sheet bifurcation and a theta-aurora formation at IMF $B_z > 0$. If the small plasma bulge is formed in the first stage of the process, ion and electron drift motion results in the appearance of the polarization charges on the borders of the plasma bulge. The charges produce a dusk-to-dawn polarization electric field. Hence, the dawn-to-dusk electric field in the bulge region decreases and can even change its sign. Such a decrease thickens the local plasma sheet, and the bulge increases in size. If the electric field changes its sign, the plasma sheet structure acquires the form of the Maltese cross. This structure, mapped to the ionosphere resembles a tongue that originates near midnight and crosses the polar cap. The electric field in the tongue has the dusk-to-dawn direction, which corresponds to sunward convection in the polar cap. Thus, in accordance with *Antonova and Ovchinnikov* [1999], the plasma sheet can be stable if IMF $B_z < 0$. If IMF $B_z > 0$, the plasma sheet becomes unstable, magnetospheric lobes are filled by plasma from the plasma sheet, and a theta-aurora is formed. The instability of the magnetospheric configuration at IMF $B_z > 0$ exists for a long time period (~10 hours) and results in the disappearance of the high latitude magnetospheric gradients and the auroral oval. So, when IMF $B_z > 0$, the stable magnetosphere will have no plasma sheet and tail lobes. In such conditions, the auroral oval should transform into a circle filled with precipitation. Such a case was observed on 11 January 1997, and was analyzed by *Koshkinen et al.* [2000].

*Sergeev and Lennartson* [1988] and *Sergeev et al.* [1994] observed periods of steady magnetospheric convection at IMF $B_z < 0$ and demonstrated the possibility of the existence of the quasistationary magnetospheric configurations for long periods. It is natural to suggest that such periods can exist when the external source of turbulence is weak and the change of the external conditions does not interrupt the process of inner magnetosphere turbulent spectra formation. The existence of periods of stationary magnetospheric convection at IMF $B_z < 0$ can be considered as proof of the external nature of the tail reconnection source in the near-tail region, where turbulence is mainly electrostatic. It is natural to suggest that when the external source excites an MHD wave with $B_z < 0$, the amplitude of which is higher than the minimal meaning of $B_z < 0$ in the plasma sheet, the loss of magnetostatic equilibrium and a change in the magnetic topology should take place. In such a case, we have a forced reconnection. Another possibility, is the excitation of some kind of large-scale electromagnetic mode in the region where the level of turbulent plasma sheet fluctuations is decreased. The first scenario may be more probable as it is well known (see *Akasofu* [1964]) that the substorm expansion phase begins with the brightening of the most equatorward auroral arc. Thus, the existence of plasma sheet turbulence can explain the substorm expansion phase onset deep inside the magnetosphere in the regions where plasma is comparatively stable before onset. An effective eastward ring current discussed by *Antonova and Ganushkina* [2000] can be considered as another possible external source that can produce a change in tail topology. Any plasma pressure increase in the inner magnetosphere produces the effective eastward ring current near the equatorial edge of this increase (due to decreased westward current). It produces the positive magnetic field distortion near the Earth and negative magnetic field distortion in the near-tail regions.

Reconnection at the magnetopause (see [*Antonova*, 2000; *Tsyganenko and Sibeck*, 1994]) can be explained as a result of inner magnetosphere current change. *Tsyganenko and Sibeck* [1994] analyzed the near-noon magnetic field distortion by the Region 1 currents, and *Antonova* [2000] discussed the role of the effective eastward ring current. The eastward ring current produces a negative magnetic field distortion not only in the tail region, but also near the daytime magnetopause. Thus, its development leads to magnetopause motion toward the Earth. Such motion is accompanied by the motion of cusps toward the equator and by changes in the magnetopause configuration and thus, field line reconnection at the magnetopause.

## 6. Plasma Sheet Coefficient of Quasidiffusion

The theory of the plasma sheet with medium scale-developed turbulence of *Antonova and Ovchinnikov* [1996] has predicted the value of the coefficient of diffusion across the sheet $D_{zz}$ (GSM frame of reference is used). The order of magnitude of $D_{zz}$ was determined by the layer half-thickness

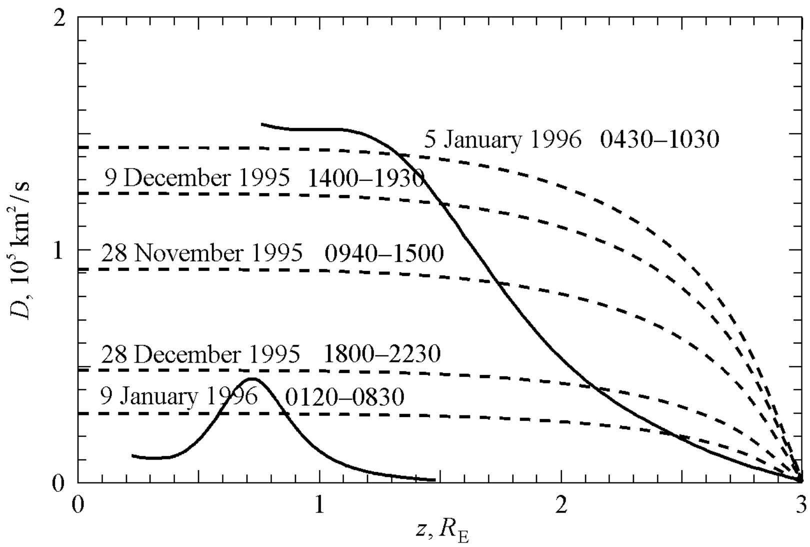


**Figure 5.** Comparison of predicted [*Antonova and Ovchinnikov*, 1996] values of the eddy-diffusion coefficient with the values measured on the basis of INTERBALL observations [*Ovchinnikov et al.*, 2000].

$L_z$ and the velocity of regular convection to the neutral sheet $V_z$, so $D_{zz} \sim V_z L_z$. The distribution of $D_{zz}$ across the sheet was determined by the selected dependence of the regular velocity and quasidiffusion coefficient on the magnetic field. The data of ISEE 2 observations were used by *Borovsky et al.* [1997] to calculate hydrodynamic velocity fluctuations and their correlation times in $X$ and $Y$ directions. A statistical analysis of the flow velocities $V_x$ and $V_y$ in the magnetotail plasma sheet finds two populations: a population of fast flows in the $\pm V_x$ directions (bursty bulk flows) and a population of slower, turbulent flows that are near isotropic in $V_x$ and $V_y$. Flows in the $z$ direction were not measured in that study. For evaluation of $D_{zz}$, *Borovsky et al.* [1998] have suggested that turbulent flows are quasi-isotropic and measured statistical properties of the $V_y$ have been used for $V_z$ flows. $D_{zz}$ was calculated in accordance with the relation

$$D_{zz} = \frac{V_{z\,\mathrm{rms}}^2 \tau_{\mathrm{auto}}}{2} \qquad (19)$$

where $D_{zz}$ is the eddy-diffusion coefficient, $V_{z\,\mathrm{rms}}$ is the fluctuating velocity, $\tau_{\mathrm{auto}}$ is the autocorrelation time of the flow velocity. For calculated $V_{\mathrm{rms}} = 60.8$ km s$^{-1}$ and $\tau_{\mathrm{auto}} = 140$ s, $D_{zz} = 2.6 \times 10^5$ km$^2$ s$^{-1}$. *Borovsky et al.* [1998] have suggested that $D_{zz}$ reduced till zero near the plasma sheet boundary layer.

The INTERBALL/Tail observation data (see [*Ovchinnikov et al.,* 2000]) allow the plasma sheet distribution functions in $Y$ and $Z$ directions to be measured every 2 min, to obtain $D_{zz}$ and compare it with theory predictions. Figure 5 compares calculated $D_{zz}$ (dashed lines) with the theoretical predictions of *Antonova and Ovchinnikov* [1996] (solid lines) and results obtained by *Borovsky et al.* [1998] (dashed line). It is possible to see that the evaluations of $D_{zz}$ based on the theory of medium-scale plasma sheet developed turbulence agree closely with experimentally observed values of the plasma sheet quasidiffusion coefficient.

## 7. Conclusions and Discussion

Experimental observational discussed data clearly demonstrate the existence of comparatively large turbulent fluctuations in the plasma sheet. Turbulent fluctuations of the $AE$ index (and naturally in $AL$, $AU$, $AO$), and the electric and magnetic field are observed at all levels of geomagnetic activity. The amplitudes of fluctuations are increased with the increase in turbulence. The nature of observed turbulence has been unclear until now. It can include large-, middle- and small-scale vortexes (eddies), bursty bulk flows, particle beams etc. The mechanisms of turbulence generation are also unclear. Possible sources of turbulence fluctuations are plasma pressure gradients, velocity shears, nonstable current sheets, and nonequilibrium features of the distribution functions. The observed turbulence can have the intermittent character and fractal structure. In many cases, the SOC approach to describing the observed turbulent fluctuations makes it possible to develop a sandpile cellular automation model that adequately reproduces the observed fluctuation spectra. At the same time, the analysis presented demonstrates the necessity of the development of new approaches for describing the plasma sheet. One unresolved problem continues to be the nature of large-scale, two-vortex magnetospheric convection and the dawn-dusk electric field. The well-known mechanisms for its generation by MHD-dynamo in the magnetospheric boundary layers meet with experimental difficulty mapping the boundary layers. The mechanism discussed for dawn-dusk electric field generation in the inner magnetosphere regions due to magnetospheric topology makes it possible to solve many of the problems of magnetospheric dynamics, including Region 1 current mapping on the inner magnetospheric regions, the change of magnetic field global topology (reconnection of field lines) when the level of global turbulent fluctuation is high and IMF control of inner magnetosphere dynamics when magnetosheath, boundary layer, and plasma sheet electric fields are highly turbulent. But, naturally, as with every new hypothesis, the suggestion of the creation of plasma pressure gradients along flux tube volume isosurfaces due to magnetospheric asymmetry needs careful experimental verification.

Very popular MHD models of the formation of the magnetosphere and reconnection in the plasma sheet are based on the suggestion of the validity of MHD with finite (real or numerical) conductivity. They make it possible to reproduce events connected with the generation of large-scale induction electric field. In most cases, the effects connected with the creation of plasma pressure gradients and finite conductivity go hand in hand. The real difference of the published numerical MHD solutions from the real magnetosphere is very high level of plasma turbulence in the real magnetosphere and the existence of electrostatic electric fields. So it is not clear what configuration will be created if the conductivity is infinite or plasma pressure gradients do not exist. But comparatively quick progress in modeling methods, including analysis of particle motion suggests the possibility of more comprehensive models in the near future.

The existence of intense plasma sheet turbulence possibly suggests a very simple explanation for substorm expansion phase onset (brightening of the most equatorial auroral) deep inside the magnetosphere. It is natural to argue that only the region, which was stable before substorm expansion phase onset, can become unstable. In accordance with the data of experimental observations, this region is situated near the inner plasma sheet boundary.

The existence of intense velocity fluctuations across the plasma sheet in $z$ direction was necessary to bring them in line with well developed slab-type plasma sheet geometry. The first attempt in this direction discussed is based on the hypothesis of the formation of turbulent electrostatic pinch compressed by dawn-dusk, large-scale electrostatic field. The theory of plasma sheet with medium-scale developed turbulence suggests the simple explanation of plasma sheet thinning during substorm growth phase (due to dawn-dusk electric field increase) and plasma sheet thickening during substorm expansion phase (due to increase of the amplitudes of fluctuations). The value of the coefficient of quasidiffusion was theoretically predicted 2 years before the first published value of such coefficient and agrees well with the results of experimental observations.

It is necessary to mention also that the approach discussed has the real possibility of direct verification. It is based on rather simple relations that do not contain unmeasurable parameters such as, for example, finite conductivity or finite viscosity in the collisionless plasma. Simultaneous measurements of the magnetic field and plasma pressure in the multi-satellite projects could provide better verification than was done on the basis of the discussed analysis. The investigation of the turbulent properties of Earth's magnetosphere may be rather interesting not only in relation to physics of the magnetosphere, but also to plasma physics and astrophysics. Only first steps in such investigations were done until now. The near future may bring exiting results in this direction.

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