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Turbulent Transport of the Earth Magnitisphere: Review of the Results of Observations and Modeling

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Abstract—The results of observations of turbulent transport in the Earth's magnetosphere tail are summarized. The results of recent works on the projection of the auroral oval onto the equatorial plane, according to which the main part of the oval is not projected onto the plasma sheet, are taken into account. Analysis of the eddy diffusion coefficient dependences on the geocentric distance and on the phase of a magnetosphere substorm, both across the sheet and in the azimuthal direction, is carried out. The role of eddy diffusion in the creation of quasi-equilibrium plasma structures and in the plasma transport from the magnetospheric flanks into the plasma sheet is considered. The transport along the sheet is discussed. The problems of turbulent transport that can be solved by analysis the data of multisatellite projects are indicated.

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1. INTRODUCTION

The flow by liquid or gas around an obstacle at large Reynolds numbers leads to the formation of a turbulent wake behind the streamlined obstacle (Monin and Yaglom, 1965; Landau and Lifshitz, 1986). Coulomb collisions are almost absent in plasma of the high-latitude Earth's magnetosphere; thus, the Reynolds number calculated with respect to the Coulomb collisions (Borovsky and Funsten, 2003) exceeds 10^{10}. The development of numerous instabilities and turbulent modes of flow are characteristic of plasma with such Reynolds numbers. The high turbulence rate in the plasma sheet of the Earth's magnetosphere was discussed in the literature (Antonova, 1985; Montgomery, 1987; Angelopoulos et al., 1993, 1999; Borovsky et al., 1997, 1998; Borovsky and Funsten, 2003, etc.). The data from numerous observations showed that the dynamics of the plasma sheet is much more complicated than that of a simple turbulent wake behind a streamlined obstacle. A great number of works are devoted to investigations of the beams in the plasma sheet, dipolization of magnetic fied lines, and other peculiarities of the large-scale dynamics of plasma. It was shown (Angelopoulos et al., 1999; Vörös et al., 2003; and Weygand et al., 2005) that the turbulence of the plasma sheet possesses a property of intermittency, i.e., the regions with a high fluctuation level are neighboring to relatively quiet regions in space and time. The existence of this intermittency extremely complicates the study of plasma sheet turbulence. Nowadays, the spectra of turbulent fluctuations of magnetic field in the magnetosphere tail are relatively well studied (Zelenyi et al., 1998; Vörös et al., 2003, 2004, 2006, 2007; Volwerk et al., 2004; and Weygand et al., 2005), and their close relation to the jet streams of BBF (bursty bulk flows) is shown. The averaged characteristics of the plasma sheet vary relatively slowly at the plasma sheet scale. The turbulent transport is related mainly to the large-scale flows which are still poorly understood.

A serious obstacle for studying the plasma sheet turbulence was the idea that the auroral oval region is the projection of the plasma sheet onto the ionospheric altitudes. It was well-known that the level of turbulent fluctuations at the auroral latitudes under quiet magnetosphere conditions is relatively low. The shape of auroral arcs can remain almost unchanged during a few hours (Chamberlain, 1961). Quick irregular movements of the auroral forms were observed only during magnetosphere storms and substorms. Such observations were hardly compatible with the ideas about the turbulent plasma sheet. The problem was solved when a plasma ring was distinguished around the Earth (Antonova et al., 2013, 2014) at heliocentric distances till the magnetopause during the daytime hours and at a distance of 10–13 R_E (where R_E is the Erath's radius) during the nighttime period. It was shown by the morphological projection method without the use of any magnetic field model (Antonova et al., 2014; Antonova et al., 2015) that the main part of the auroral oval is projected not onto the plasma sheet but onto the plasma ring around the Earth. According to these results, the nighttime region from 7 R_E to at least 10 R_E is a part of the plasma ring in which there are transverse currents that are the high-latitudinal continuation of the ring's current, i.e., this region is not a part of the turbulent wake behind the streamlined obstacle. Therefore, the turbulence level in this region can considerably differ from that in the plasma sheet.

The values of the eddy diffusion coefficients in different regions of the plasma sheet were obtained on the basis of the data of ISEE, Interball/Tail probe, Geotail, Cluster, and THEMIS in (Borovsky et al., 1998; Ovchinnikov et al., 2000, 2002; Ovchinnikov et al., 2002; Troshichev et al., 2002; Stepanova et al., 2005, 2009, 2011; Nagata et al., 2008; Pinto et al., 2011; Stepanova and Antonova, 2011; Wang et al., 2010) at various geocentric distances and under various geomagnetic conditions. The first quantitative results of the study of field and plasma turbulence in the Earth's magnetosphere tail were obtained (Borovsky et al., 1997) on the basis of the data of ISEE-2. It was shown that the correlation time for the velocity fluctuations is ~2 min, and the correlation time for the magnetic field fluctuations is ~8 min; the correlation length (the mixing length) is ~10000 km. According to the results of (Weygand et al., 2005) obtained from the data of Cluster, the correlation length varies from 4000 to 10000 km.

Analysis of the obtained results and their comparison with the results of modeling makes it possible to estimate the role of the turbulent transport in the dynamics of the geomagnetic tail. In is necessary to select the results of measurements directly in the plasma sheet. In this work, we analyze the results of determination of the coefficient of eddy diffusion in the plasma sheet of the Earth's magnetosphere, establish the problems that arise from considering the turbulent transport, and designate the means of their solution.

2. TURBULENT TRANSPORT ACROSS THE PLASMA SHEET (IN *Z*-DIRECTION)

One of the main problems that arises in studying the Earth's magnetosphere is the existence of the plasma sheet in its tail. The plasma sheet occupies only a part of the magnetosphere tail. Such a configuration is not typical of the turbulent wake behind an obstacle, which occupies all the space behind it. The current in the plasma sheet has a direction from dawn to dusk, and its distribution across the plasma sheet (along *Z*-coordinate) has a complicated character due to the turbulent fluctuations but on average corresponds to the magnetostatic equilibrium condition (Baumjohann et al., 1990; Kistler et al., 1992; Petrukovich et al., 1999):

$$p + \frac{B^2}{2\mu_0} \approx \text{const}, \tag{1}$$

where p is the plasma pressure, B is magnetic field, and μ_0 is the magnetic permeability of vacuum.

It was also well known (Frank et al., 1986; Feldstein et al., 1995) that, at a prolonged northern orientation of the interplanetary magnetic field (IMF), the filling of the tail's lobes by the plasma of the plasma sheet occurs simultaneously with the filling of the polar cap by aurora precipitations. The destruction of the plasma sheet occurs correspondingly.

The existence of the plasma sheet and its destruction upon a northern orientation of the IMF was explained in terms of the model suggested by Antonova and Ovchinnikov (1996, 1998) and Antonova and Ovchinnikov (1997, 1999a, b, 2000, 2001, 2002). Regular transport in the *Z*-direction due to the dawn-dusk field $n\mathbf{V}$, where n is the plasma density and $\mathbf{V}$ is the averaged velocity, and the quasi-diffusion transport $D\nabla n$, where D is the coefficient of eddy diffusion directed against the density gradient were considered. In this case, the term "quasidiffusion" is used, since the turbulent vortex scale can be comparable to the plasma sheet thickness. Quick plasma sheet mixing leads to temperature equalization across the plasma sheet. The integral flux has a form

$$\mathbf{J} = n\mathbf{V} - D\nabla n. \tag{2}$$

If the turbulent transport in the plasma sheet is not developed, then a regular movement leads to raking of the plasma. This creates classical conditions for magnetic reconnection. If the turbulence is developing and if there is not a regular averaged movement of plasma along *Z*-axis, then the plasma sheet's thickness must gradually increase with time. If there is a regular velocity directed along *Z*-axis towards the plasma sheet center, then the regular flux may compensate the diffusion flux. As a result, a turbulent layer with a finite thickness is formed. The layer's thickness is defined by the fluctuation level (by the coefficient D_{zz}) and by the regular velocity V_z along *Z*-axis:

$$L \sim D_{zz}/V_z. \tag{3}$$

It follows from relation (3) that, if the level of turbulent fluctuations increases, the plasma sheet must expand; if the level of turbulent fluctuations decreases, the plasma sheet must shrink. The increase in regular flux velocity along the Z axis due to the increase in the dawn-dusk field leads to shrinkage of the plasma sheet, while a decrease in the regular velocity leads to filling of the plasma sheet of the tail lobes by plasma. Figure 1 shows the scheme of the processes. The upper part of Fig. 1 shows the plasma sheet expansion in the absence of the regular velocity. The lower part of Fig. 1 shows the plasma sheet formation upon the compensation for the turbulent transport across the plasma sheet and quasi-diffusion transport. Unlike the scheme of the processes presented by Antonova (2002), the results of studies into the anisotropy of turbulent vortexes are

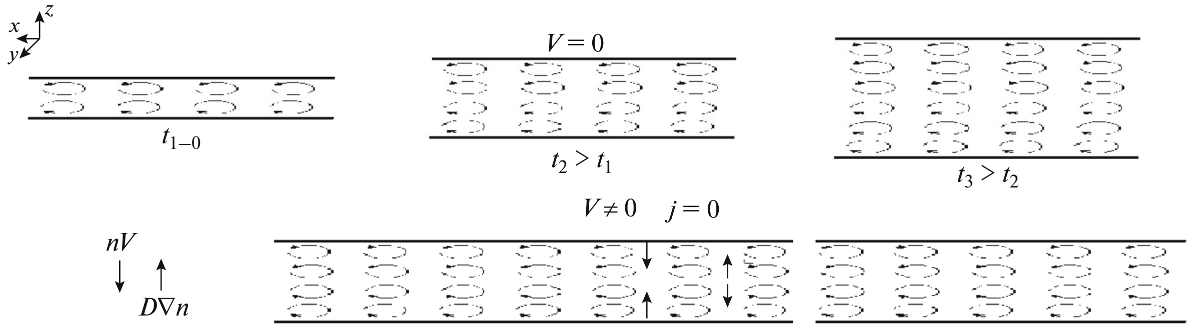

Fig. 1. Scheme illustrating the plasma sheet formation at the vortex diffusion emergence.

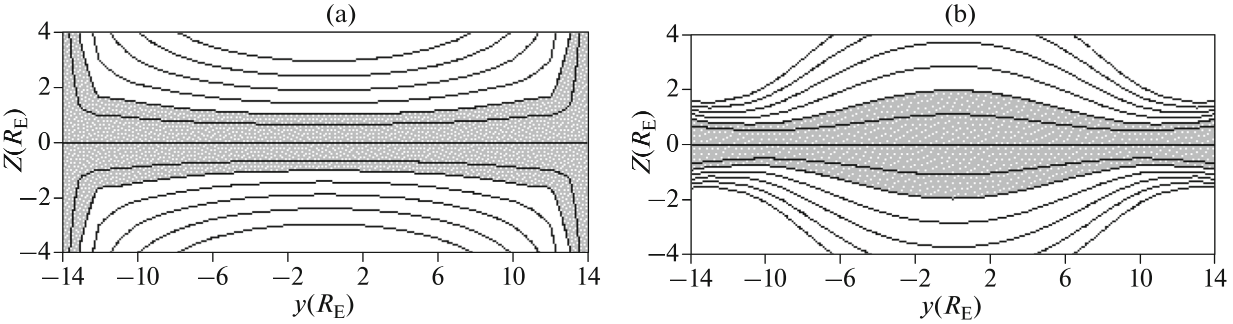

Fig. 2. Results of modeling of the pressure distribution in the plasma sheet in the plane $x = -30R_E$ (a) at $B_z^{IMF} < -4$ nT, (b) at $B_z^{IMF} > +4$ nT with the use of the Tsyganenko-87W model. The ratio between the pressures of neighboring isolines is $e^{1/2}$.

considered (the vortexes scale in the plane of the plasma sheet may considerably exceed its scale in the direction perpendicular to the plasma sheet).

The dynamics of the plasma sheet during a magnetosphere substorm corresponds to the scheme described above. The constructed model made it possible to describe the thinning of the plasma sheet during the growth phase of the substorm and the expansion of the plasma sheet after the beginning of the expansive phase (Antonova and Ovchinnikov, 1998; Antonova and Ovchinnikov, 1999a). The filling of the tail lobes by plasma of the plasma sheet at a northern orientation of IMF (Antonova and Ovchinnikov, 1999a, 2001), when the fall of the dawn-dusk field is observed, was also explained. The model allows one to reconstruct the plasma pressure distribution across the plasma sheet at a given distribution of the regular flow velocity to the center of the plasma sheet and a given value of the vortex diffusion coefficient. Figure 2 shows the results of modeling of the pressure distribution of the geomagnetic tail at a distance of $30R_E$ (a) at $B_z^{IMF} < -4$ nT (b) at $B_z^{IMF} > +4$ nT with the used Tsyganenko-87W model. The ratio between pressures of neighboring isolines is $e^{1/2}$.

The developed theory of the plasma sheet with a mesoscale turbulence made it possible to estimate the value of the turbulent diffusion coefficient $D_{zz} \sim LV$, which would correspond to the observed plasma sheet thickness. At a plasma sheet half-thickness of $1–3R_E$ and a velocity of 10–50 km/s, the value of the vortex diffusion coefficient must be a few units per 10^5 km^2/s.

An algorithm of calculation of the vortex diffusion coefficient was suggested (Borovsky et al., 1998) on the assumption of the smallness of the regular velocity as compared with its fluctuations

$$D = \left(v_z^{rms}\right)^2 \tau_{\text{auto}}/2, \tag{4}$$

where v_z^{rms} is the root-mean-square velocity in the Z-axis direction, τ_{auto} is the autocorrelation time of the velocity. It was assumed that diffusion is a Markovian process, i.e., each plasma displacement does not depend on its previous displacements. The quantity τ_{auto} is a measure of the persistence of a fluctuating quantity and is calculated by analysis of the autocorrelation function

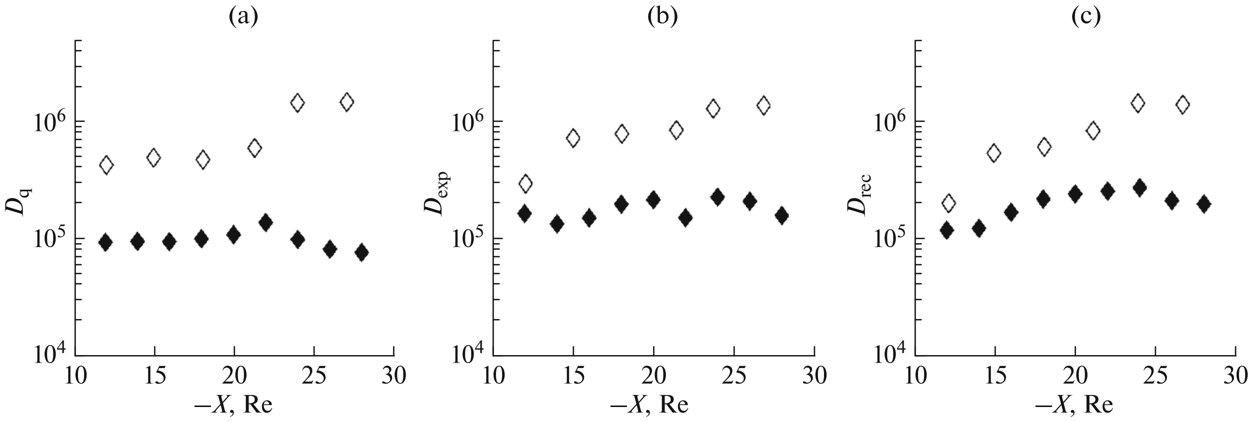

Fig. 3. Comparison of the dependences of D_{zz} on the radial distance and on the phase of a magnetosphere substorm from (Stepanova et al., 2009) (white rhombs) and (Stepanova et al., 2011) (black rhombs).

$$A(\tau) = \frac{\sum\left(v_z^{rms}(t) - \left\langle v_z^{rms}(t)\right\rangle\right)\left(v_z^{rms}(t+\tau) - \left\langle v_z^{rms}(t+\tau)\right\rangle\right)}{\sum\left(v_z^{rms}(t) - \left\langle v_z^{rms}(t)\right\rangle\right)^2}. \quad (5)$$

It was considered that the autocorrelation time is a time after which the value of autocorrelation function was reduced to e^{-1}. The results (Borovsky et al., 1997, 1998) show that the averaged over the distance of ~20 R_E velocity component $v_y^{rms} \approx 60$ km/s and $\tau_{auto} \approx 140$ s. In the ISEE-2 experiment, the z-component of velocity was not determined; however, on the assumption of the isotropic turbulence, the vortex diffusion coefficient will be 2.6×10^5 km^2/s. The obtained value of the vortex diffusion coefficient proved to coincide by order of magnitude with that predicted in the paper (Antonova and Ovchinnikov, 1996). However, the value of D_{zz} obtained by (Borovsky et al., 1998) was only estimated. Real values of D_{zz} were obtained in the Interball/Tail probe, Geotail, Cluster, and THEMIS experiments. In the Interball/Tail probe experiment, the velocity in the direction of Y and Z axes were determined, while the velocity in the ISEE experiment could be obtained in the direction of X and Y axes. All of the tree components of the velocity were determined in the Geotail, Cluster, and THEMIS experiments. The values of D_{zz} were obtained with the use of data from the Interball/Tail probe experiment (Ovchinnikov et al., 2000, 2002; Ovchinnikov et al., 2002; Antonova et al., 2002). It was demonstrated that there is a considerable increase in D_{zz} during a substorm, accompined by heating of the central part of the plasma sheet. The values of the vortex diffusion coefficient were determined at the Geotail satellite at geocentric distances from 130 to 200 R_E (Troshichev et al., 2002). The obtained values lie within a range of 3×10^4–1.2×10^5 km^2 s^{-1}, which allows us to conclude that the vortex diffusion coefficient diminishes at large geocentric distances in comparison with geocentric distances from 10 to 30 R_E.

The values of vortex diffusion coefficient D_{zz} were obtained for a magnetically quite period and for a period of substorm on the basis of a large statistical material (Stepanova et al., 2005, 2009, 2011). It was shown (Stepanova et al., 2009, 2011) that the averaged vortex diffusion coefficient drastically decreases at geocentric distances of <~10 R_E. However, this region is related to the high-latitude part of the ring current. Thus, we used in our analysis only averaged values obtained at geocentric distances of >10 R_E. Figure 3 shows the summarized results of analysis for the dependence of D_{zz} on the phase of a magnetosphere substorm. The white rhombs refer to the averaged results obtained on the basis of the measurements made at the Interball/Tail probe satellite (Stepanova et al., 2009); the black rhombs refer to the data of the THEMIS experiment (Stepanova et al., 2011). The values of D_{zz} obtained in the Interball/Tail probe experiment exceed those obtained on the basis of the data of the THEMIS experiment, which apparently is related to the intensity of the analyzed substorms. The AL index selection criterions for the substorm periods were indentical in both cases; however, the operating period of the THEMIS experiment is characterized by an extremely low geomagnetic activity. Figure 3 demonstrates an apparent increase in the vortex diffusion coefficient during the geomagnetic substorm.

The radial dependence of the vortex diffusion coefficients was obtained for simultaneous measurements at five satellites of the THEMIS project under quiet magnetosphere conditions at one straight line along the geomagnetic tail up to 25 R_E (Pinto et al., 2011). It

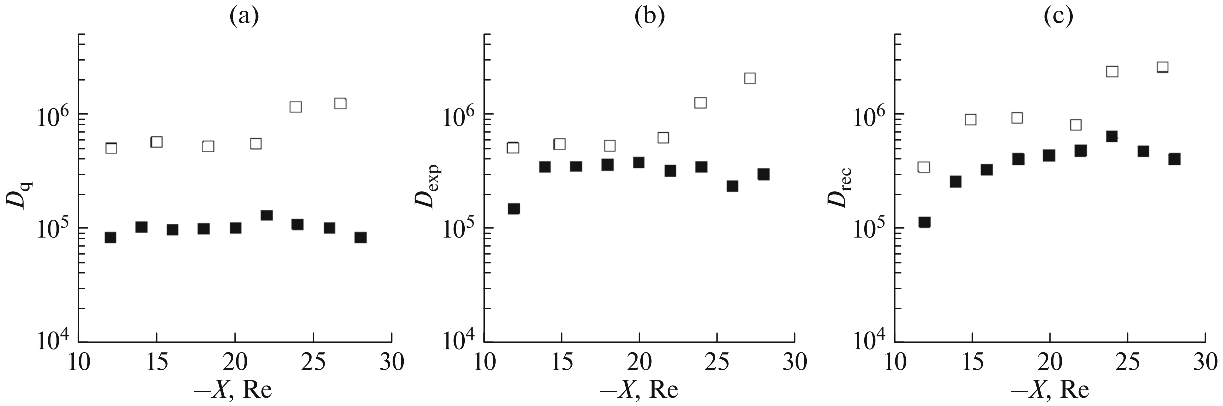

Fig. 4. Comparison of the dependences of D_{yy} on the radial distance and on the phase of a magnetosphere substorm from (Stepanova et al., 2009) (white squares) and (Stepanova et al., 2011) (black squares).

was demonstrated that the coefficient D_{zz} increases as the distance grows. The predictions of the theory presented in (Antonova and Ovchinnikov, 1996, 1998; Antonova and Ovchinnikov, 1997, 1999a, b, 2000, 2001, 2002) were verified for the crossing of the plasma sheet by the satellites of the Cluster project on September 12, 2004, under exclusively quiet geomagnetic conditions (Stepanova and Antonova, 2011). The value of the dawn-dusk field that defines the regular plasma velocity in the Z-axis direction was calculated with the use of data from the SuperDarn radars; the vortex diffusion coefficient and the plasma sheet thickness were calculated from data of the Cluster project. It was shown that the observation results agree with the theory predictions. Thus, on the whole, the ideas that the plasma sheet formation in the Earth's magnetosphere tail occurs due to the concurrence between the processes of plasma raking towards the center of the plasma sheet, on the one hand, and the broadening of the plasma sheet due to the vortex diffusion, on the other hand, were experimentally verified. However, it is necessary to carry out a more detailed verification and clarification of the properties and nature of turbulent vortices.

3. TURBULENT TRANSPORT IN THE PLASMA SHEET PLANE

The changes in the plasma parameters across the plasma sheet can be relatively quickly obtained when the satellite crosses the plasma sheet. The variations of the parameters in the plasma sheet's plane can be obtained so far only statistically. Estimation of the role of diffusion fluxes in the plasma sheet plane requires knowledge of the vortex diffusion coefficients and the density gradients. The plasma sheet scale in the Y-axis direction is ~40 R_E. The plasma density at the magnetosphere flanks is much greater than that in the plasma sheet center. Therefore, the value of the vortex diffusion in the Y-axis direction D_{yy} is crucial for solving the problem of plasma sheet filling by the magnetosheath plasma from the magnetosphere flanks (Antonova, 2006; Wang et al., 2010). It was shown (Stepanova et al., 2005) that D_{yy} can be twice as much as D_{zz}. However, those are only averaged values over the whole observation interval presented in this work. The values of D_{yy} are presented in the range of 10^5 to 10^6 km^2 s^{-1}; they were obtained on the basis of data from the Geotail satellite (Wang et al., 2010). It was shown that the cold plasma transport to the center of the plasma sheet is associated with the vortex diffusion processes.

The spatial distribution D_{yy} obtained on the basis of the data of the Interball/Tail probe and THEMIS experiments was presented by Stepanova et al. (2009, 2011). Figure 4 shows the averaged values of D_{yy} with respect to the phase of magnetosphere substorm and the radial distance. The white squares indicate the data obtained in the Interball/Tail probe experiment, and the black squares indicate the data of the THEMIS experiment. As in the case of D_{zz}, the values of D_{yy} obtained in the Interball/Tail probe experiment exceed those obtained from the THEMIS data. It follows from Fig. 4 that D_{yy} increases during a substorm. One can notice also the D_{yy} increases as the geocentric distance grows at geocentric distances of $<30\,R_E$.

Analysis of the transport in the X-axis direction is complicated because of the observation of BBF plasma jet streams (Baumjohann et al., 1989, 1990) in which the peak velocities are by an order of magnitude greater than the usually observed velocity fluctuations. According to the results of Borovsky et al. (1997), the BBFs are directed towards to Earth two times more often than from the Earth at a geocentric distance of $<20\,R_E$. It was obtained (Stepanova et al., 2011) that the values of vortex diffusion in the X-axis direction exceed by almost an order of magnitude the vortex diffusion coefficients in the Y-axis and Z-axis directions. However, the BBFs were not selected from the complete database, unlike those in the earlier study (Borovsky et al., 1997).

The transport in the plasma sheet was analyzed depending on the values of parameters of the solar wind and interplanetary magnetic field on the basis of the measurements carried out at the Geotail satellite (Nagata et al., 2008). The spatial distribution of the vortex diffusion coefficient was obtained at a geocentric distance up to 30 R_E with a maximum in the center of the plasma sheet but only at a northern orientation of the interplanetary magnetic field. The obtained values of the vortex diffusion coefficient lie within a range of (1–6) × 10^5 km^2 s^{-1}. The results of the analysis allowed the authors to conclude that the vortex diffusion makes a considerable contribution to the radial transport only at the northern orientation of the interplanetary magnetic field. It implies that, apparently, the transport in the X-axis direction is related mainly to the phenomena like the BBF. It also should be noted that the gradients of plasma parameters in the X-axis direction are relatively small, which also complicates the clarification of the role played by the vortex diffusion in the particle transport in the X-axis direction.

So far, the relation between the BBF and vortex structures is not clear. The results of MHD modeling with great Reynolds numbers (El-Alaoui et al., 2010, 2012) demonstrated the formation of the vortex flows elongated in the antisolar direction in the plasma sheet in a broad scale range. The spectra of a developing turbulence in the (X, Y) plane are obtained, and it is shown that they have a shape of a power law with a turning point at a frequency of 30 mHz. Vortex flows were revealed during magnetosphere substorms (Keika et al., 2009; Keiling et al., 2009). From the data of simultaneous observations made by a chain of five satellites of the THEMIS project along the midnight meridian, the flows directed both to the Erath and from the Earth were registered (Stepanova and Antonova, 2015), which confirmed the conclusions made earlier (Denton and Cayton, 2011; Borovsky and Denton, 2011) about the acceleration of particles inside the magnetosphere with their subsequent transportation to the tail.

4. DISCUSSION

For a long time, the analysis of plasma transport in the Erath's magnetosphere was mainly limited by the consideration of regular flows under quiet magnetosphere conditions and by the analysis of burst flows (dipolizations) under disturbed magnetosphere conditions. The creation of models that would take into account the turbulent transport requires consideration of nonlinear processes of development of large-scale instabilities of interchange, ballooning, and Kelvin—Helmholtz type and the energy transfer over the turbulence spectrum. At the present time, only the results of MHD modeling with the use of powerful computers make it possible to simulate the formation of multiscale vortex structures in the geomagnetic tail; however, turbulent transport processes are still not considered in the MHD models. It should also be noted experimental study of the vortex diffusion in the tail is still at the initial stage.

The used approach considering the turbulent transport makes it possible to describe such processes as the transport of magnetosheath plasma from the magnetosphere flanks into the plasma sheet and the formation of the plasma sheet itself. However, this approach certainly does not describe all of the observed processes in the collisionless magnetosphere plasma. Thus, for instance, the observed beam structures in the boundary layer of the plasma sheet require the kinetic analysis. “Ballistic” particle transport by beams is realized. It should be noted that the observed high level of turbulence is evidence of the inapplicability of the freezing-in condition to the description of transport processes in the plasma sheet. However, this work does not consider this problem.

The role of diffusion flows is determined by the density gradients. The diffusion flow is proportional to the density gradients; it must therefore fall to zero upon the disappearance of gradients, even at very large fluctuations in velocity. Despite the realization of multisatellite projects, only averaged distributions of MHD parameters were obtained; therefore, the calculations of the turbulent transport in the (X, Y) plane so far have an evaluative character. The involvement of turbulent transport in the Z-axis direction makes it possible to solve the problems of the formation of a plasma sheet separated from the magnetosheath by nearly empty parts of the tail, as well as the problems of plasma sheet thinning during the growth phase of a substorm and its expansion after the beginning of the expansion phase and the filling of the tail lobes during a prolonged northern orientation of the interplanetary magnetic field.

The study of turbulent transport in the plasma sheet of the Earth's magnetosphere requires analysis of the data of multisatellite observations. The selection of vortex flows inside the plasma sheet is of greatest interest. Observations at various distances between the satellites will make it possible to select vortices of various scales. It is necessary to clarify the structure of vortices and the mechanism of their formation. The realization of the MMS (Magnetospheric Multiscale mission) project, the program of which includes studies on the turbulence in the plasma sheet of the geomagnetic tail (Goldstein et al., 2015), must be helpful in solving the formulated problems.

5. CONCLUSIONS

The few results of analyzed theoretical and experimental works allow us to come to the following conclusions:

- The performed separation of the data of measurements of the vortex diffusion coefficient directly in the plasma sheet and in the nighttime part of the plasma ring surrounding the Earth explains the relatively low fluctuation level at the latitudes of the auroral oval under quiet magnetosphere conditions at a constantly high fluctuation level in the plasma sheet.
- The need to consider vortex diffusion for the analysis of transport processes, both along and across the plasma sheet of the Earth's magnetosphere, was demonstrated.
- The initial information about a spatial distribution of vortex diffusion coefficients in the plasma sheet plane and their dependences on the phase of a magnetosphere substorm is obtained. The vortex diffusion coefficients increase as the geocentric distance increases to $30 R_E$. The increase in the coefficients is observed after the beginning of the expansion phase of the substorm. There is an indication that the vortex diffusion coefficients decrease rapidly at large ($>100 R_E$) geocentric distances.
- Solving the problem of transport in the Erath magnetosphere tail requires simultaneous analysis of data from multisatellite observations at various distances between the satellites.

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