ISSN 0016-7932, Geomagnetism and Aeronomy, 2024, Vol. 64, No. 2, pp. 172–179. © Pleiades Publishing, Ltd., 2024.

Spatial Distribution of the Eddy Diffusion Coefficient in the Plasma Sheet of Earth's Magnetotail and Its Dependence on the Interplanetary Magnetic Field and Geomagnetic Activity Based on MMS Satellite Data

D. Yu. Naiko[a, b, *], **I. L. Ovchinnikov**[a, **], **and E. E. Antonova**[a, c, ***]

[a] *Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, Russia*

[b] *Department of Physics, Moscow State University, Moscow, Russia*

[c] *Space Research Institute, Russian Academy of Sciences, Moscow, Russia*

**e-mail: daniilnaiko@mail.ru*

***e-mail: ilya@psn.ru*

****e-mail: elizaveta.antonova@gmail.com*

Received July 19, 2023; revised October 19, 2023; accepted November 23, 2023

Abstract—The article presents the results of a statistical analysis of the distribution of the eddy diffusion coefficient depending on the coordinates in the plasma sheet of Earth's magnetosphere based on data from the Magnetospheric Multiscale Mission satellite system (MMS) for the period from 2017 to 2022. The localization of satellites inside the plasma sheet was recorded from the concentration and temperature of plasma ions according to the data of the same instruments and the value of plasma parameter β. Significant anisotropy of the eddy diffusion coefficient was revealed. The dependence of the eddy diffusion coefficient on the interplanetary magnetic field is analyzed, showing that with the southern orientation of the interplanetary magnetic field, the eddy diffusion coefficients are 1.5–2 times greater than with the northern orientation. It is also shown that under disturbed geomagnetic conditions (*SML* < –200 nT), the eddy diffusion coefficients are several times greater than under quiet geomagnetic conditions (*SML* > –50 nT).

DOI: 10.1134/S0016793223600996

1. INTRODUCTION

One of the characteristic features of turbulence development in plasma systems is turbulent transport, which leads to mixing and equalization of the gradients of the hydrodynamic parameters. Earth's magnetosphere is a giant plasma laboratory for studying turbulent transport processes in a collisionless plasma at Reynolds numbers exceeding 10^{10} for Coulomb collisions (Borovsky and Funsten, 2003). In Earth's magnetotail, various instabilities develop and a turbulent flow regime is established.

A high level of turbulent fluctuations is observed in Earth's magnetotail, which was noted in early publications (Antonova, 1985; Montgomery, 1987; Angelopoulos et al., 1993, 1999). However, the main focus was on studying particle beams, dipolization of magnetic field lines, and other large-scale phenomena. Consistent study of turbulence in Earth's magnetotail began with the studies (Borovsky et al., 1997, 1998; Borovsky and Funsten, 2003) based on ISEE-2 satellite data, which focused on magnetic field fluctuations and the plasma velocity. It was shown that the correlation time for velocity fluctuations is ~2 min; for the magnetic field, ~8 min; the correlation length (mixing path length) is ~10000 km. According to magnetic observations, it was established that turbulence in the plasma sheet has intermittency; i.e., zones with strong fluctuations are spatiotemporally adjacent to quiet zones (Angelopoulos et al., 1999; Vörös et al., 2003; Weygand et al., 2005). The results of (Weygand et al., 2005) showed that the correlation length varies from 4000 to 10000 km. The relationship between the spectra of magnetic field fluctuations and jet streams bursty bulk flows (BBF) has been studied. It has been established (Angelopoulos et al., 1999; Vörös et al., 2003; Weygand et al., 2005) that in the plasma sheet, turbulence has intermittency, that is, zones with strong fluctuations are adjacent to quiet zones in space and time. Studies of electric field fluctuations in the magnetotail were fraught with certain difficulties and, in fact, began with the launch of a four-satellite Multiscale Magnetosphere Mission (MMS) (Burch et al., 2016; Torbert et al., 2016; Pollock et al., 2016), when it was possible to obtain reliable measurements of three electric field components (see the work by Ovchinnikov et al. (2024) and references therein).

The role of turbulent transport in the dynamics of magnetospheric flows is governed by the eddy diffusion coefficient. The first estimates of this coefficient across the plasma sheet of Earth's magnetosphere were carried out by Borovsky et al. (1998) based on ISEE-2 satellite data. Measurements on this satellite made it possible to determine plasma velocity fluctuations only in the plane of the plasma sheet (in the direction X, Y of the solar–magnetospheric (SM) coordinate system). Therefore, it was assumed that the level of fluctuations across the sheet coincides with the level of fluctuations along the sheet. The eddy diffusion coefficient was calculated as 2.6×10^5 km^2/s. This estimate coincided in order of magnitude with the predictions of the model of a magnetostatically equilibrium turbulent plasma sheet compressed in the Z-direction by the dawn-dusk field (Antonova and Ovchinnikov, 1996; Antonova and Ovchinnikov, 1998). The results of measurements on the Interball/Tail probe satellite (Ermolaev et al., 2000), which determined velocity fluctuations in the direction (Y, Z), confirmed the estimate by Borovsky et al. (1998). During measurements on this satellite, the values of the eddy diffusion coefficient across the sheet were determined during magnetically quiet times and substorms (Ovchinnikov et al., 2000, 2002a, 2002b). Subsequently, the eddy diffusion coefficients were determined from Geotail, Cluster, and THEMIS satellite data (Troshichev et al., 2002; Stepanova et al., 2005, 2009, 2011; Nagata et al., 2008; Wang et al., 2010; Pinto et al., 2011). The studies (Ovchinnikov and Antonova, 2017; Antonova and Stepanova, 2021) review the results obtained. The intermittent nature of plasma sheet turbulence led to eddy diffusion coefficients that differed by more than an order of magnitude (Stepanova et al., 2005, 2009, 2011; Eyelade et al., 2021), which required continued research depending on the solar wind parameters and geomagnetic activity.

The implementation of the MMS project made it possible to determine the characteristics of fluctuations in the plasma sheet parameters with a high reliability and higher time resolution than before. Individual BBF events have been studied in detail in higher resolution mode (see, e.g., (Ergun et al., 2018)). Statistical studies of eddy diffusion coefficients using MMS data have not previously been carried out. In this article, a statistical study of velocity fluctuations has been carried out and the eddy diffusion coefficients are calculated for the project period 2017–2022.

2. MATERIALS AND METHODS

To calculate the eddy diffusion coefficient, we used data from measurements of the hydrodynamic velocity of plasma ions from FPI/DIS instruments of the MMS mission (Pollock et al., 2016) with a time resolution of $1/4.5$ s^{-1}. Active fluctuation of the plasma hydrodynamic velocity components in the plasma sheet of the magnetotail was revealed when plotting three-dimensional hodographs of the hydrodynamic velocity. Figure 1 shows an example of the resulting hodograph for the interval 0900–0912 of May 25, 2017.

To highlight the time periods when the spacecraft was within the plasma sheet, we used the criterion proposed by Stepanova et al. (2011): the coordinates of the device in the GSM system satisfy the conditions $X < -6R_E$, $|Y| < |X|$, $|Z| < 8R_E$ (where R_E is the Earth's radius), the concentration of plasma ions $n_i > 0.1$ cm^{-3}, the ion temperature $T_i > 0.5$ keV, and the plasma parameter $\beta > 1$, where β is the ratio of the plasma pressure to the magnetic field pressure. Later, it was shown (Antonova et al., 2013, 2014) that measurements at geocentric distances of up to $\sim 10-13R_E$ correspond to the region of the plasma ring surrounding Earth, onto which most of the auroral oval is projected (Antonova et al., 2014, 2015). Below, we verify the validity of this result.

All parameters were averaged over 6-min time intervals. For 2017–2022, 29000 6-min intervals were identified when at least one MMS mission device was in the plasma sheet and transmitting data. Each of the 6-min intervals was analyzed together with the previous one.

To calculate the eddy diffusion coefficients, the intervals were combined in pairs; i.e., 12-min intervals were used, each containing 160 measured hydrodynamic velocity values.

The eddy diffusion coefficients were estimated from the velocity data in accordance with the methodology (Borovsky et al., 1997, 1998). For the hydrodynamic velocity components of plasma ions V_α, autocorrelation functions were constructed:

$$A_{\alpha\beta}(\tau) = \frac{\sum (V_\alpha(i) - \langle V_\alpha \rangle)(V_\beta(i+\tau) - \langle V_\beta \rangle)}{\sqrt{\sum (V_\alpha(i) - \langle V_\alpha \rangle)^2}\sqrt{\sum (V_\beta(i+\tau) - \langle V_\beta \rangle)^2}}, \quad (1)$$

where $V^2_{rms,\alpha\beta} = \langle (V_\alpha(i) - \langle V_\alpha \rangle)(V_\beta(i) - \langle V_\beta \rangle) \rangle$ is the rms velocity and angle brackets denote averaging over all measurements of the selected interval. Indices α, $\beta \in \{X, Y, Z\}$. Figure 2 shows examples of the resulting autocorrelation functions. To calculate the autocorrelation time $\tau_{\alpha\beta}$, the autocorrelation function was approximated by an exponential function using the least squares method $A_{\alpha\beta}(\tau) = \exp(-\tau/\tau_{\alpha\beta})$. Use of the correlation time procedure following the approach of (Borovsky et al., 1997, 1998) may contain significant errors (see Fig. 2), associated with the intermittency of turbulence. This was taken into account when analyzing the results.

The eddy diffusion coefficients were calculated in accordance with the relation

$$D_{\alpha\beta} = V^2_{rms,\alpha\beta}\tau_{\alpha\beta}/2. \quad (2)$$

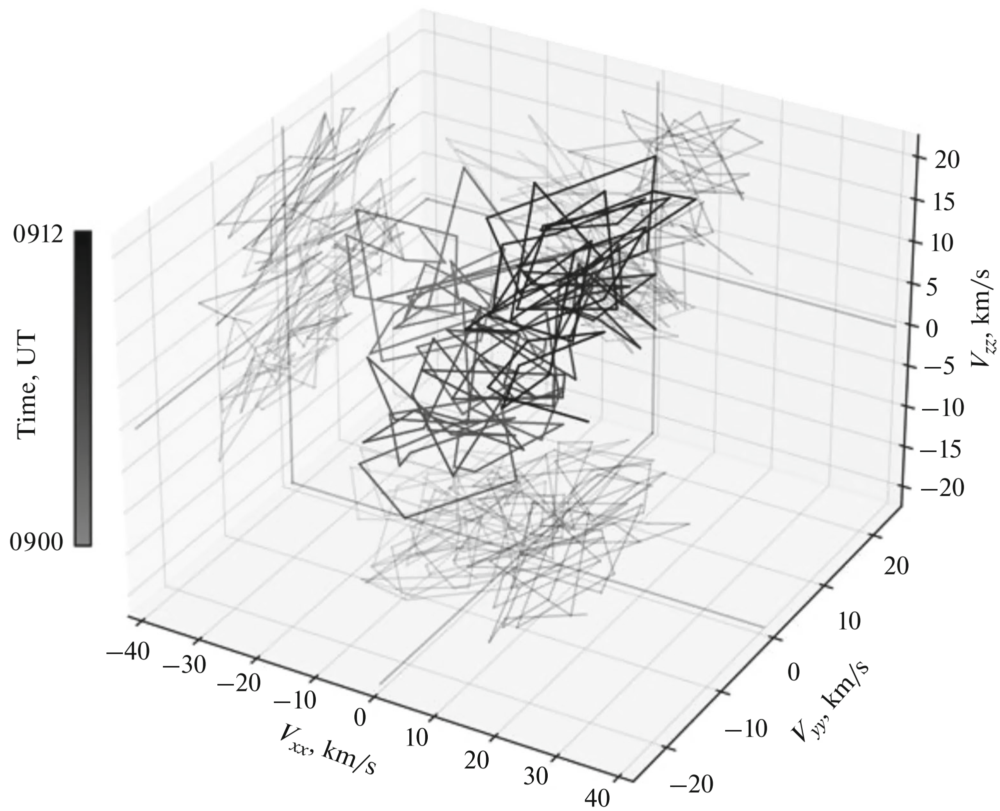

Fig. 1. Example of a hodograph of plasma velocities in planes *xy*, *xz*, *yz* for interval 0900–0912 UT on May 25, 2017, according to MMS1 data.

For each 12-min interval, autocorrelation functions (1) were constructed and the autocorrelation times were calculated. In accordance with formula (2), the eddy diffusion components were obtained. For further analysis, only diagonal components D_{xx}, D_{yy}, D_{zz} were used.

The dependence of the eddy diffusion coefficients on the direction of the interplanetary magnetic field was analyzed using measurements of the interplanetary magnetic field in the solar wind at Lagrange point *L1* based on data from the OMNI database. Each 12-min interval was added to the sample, provided that throughout the entire interval, the *Bz*-component of the interplanetary magnetic field (IMF) did not change sign. The eddy diffusion coefficient values for analyzing their dependence on geomagnetic activity where chosen with account for the values of the SuperMAG geomagnetic index *SML*, calculated similarly to the *AL* index, but for a larger number of stations. For each 12-min interval, the following conditions were verified: $SML > -50$ nT for all observed intervals preceding the one under consideration (and including the one under consideration) for 1 h to select intervals with quiet geomagnetic activity; $SML < -200$ nT for selecting intervals with high geomagnetic activity.

3. RESULTS OF STATISTICAL ANALYSIS

Using the obtained data array for two IMF directions, the distributions of the diagonal components of the eddy diffusion coefficients were constructed as a function of the GSM *X*- and *Y* coordinates in the plasma sheet of the magnetosphere; the averaged radial profiles of the diffusion coefficients were determined (Figs. 3, 4), and the average values of the diagonal components of the eddy diffusion coefficient were calculated. The average values for the northern orientation of the IMF were: 6.7×10^4 km^2/s, 3.1×10^4 km^2/s, 1.1×10^4 km^2/s for D_{xx}, D_{yy} and D_{zz}, respectively; for the southern orientation of the IMF, 16.4×10^4 km^2/s, 5.9×10^4 km^2/s, 1.9×10^4 km^2/s for D_{xx}, D_{yy} and D_{zz}, respectively. During averaging, the region of the plasma ring surrounding the Earth was not selected.

For the selected data sets, the distributions of the diagonal components of the eddy diffusion coefficients were constructed as a function of the GSM *X*- and *Y* coordinates in the plasma sheet of Earth's magnetosphere in a quiet geomagnetic environment for $SML > -50$ nT and during substorms at $SML < -200$ nT. The averaged radial profiles of the eddy diffusion coefficients were constructed for quiet times and substorms (Figs. 5, 6). The average components of the eddy diffusion coefficients in a quiet geomagnetic

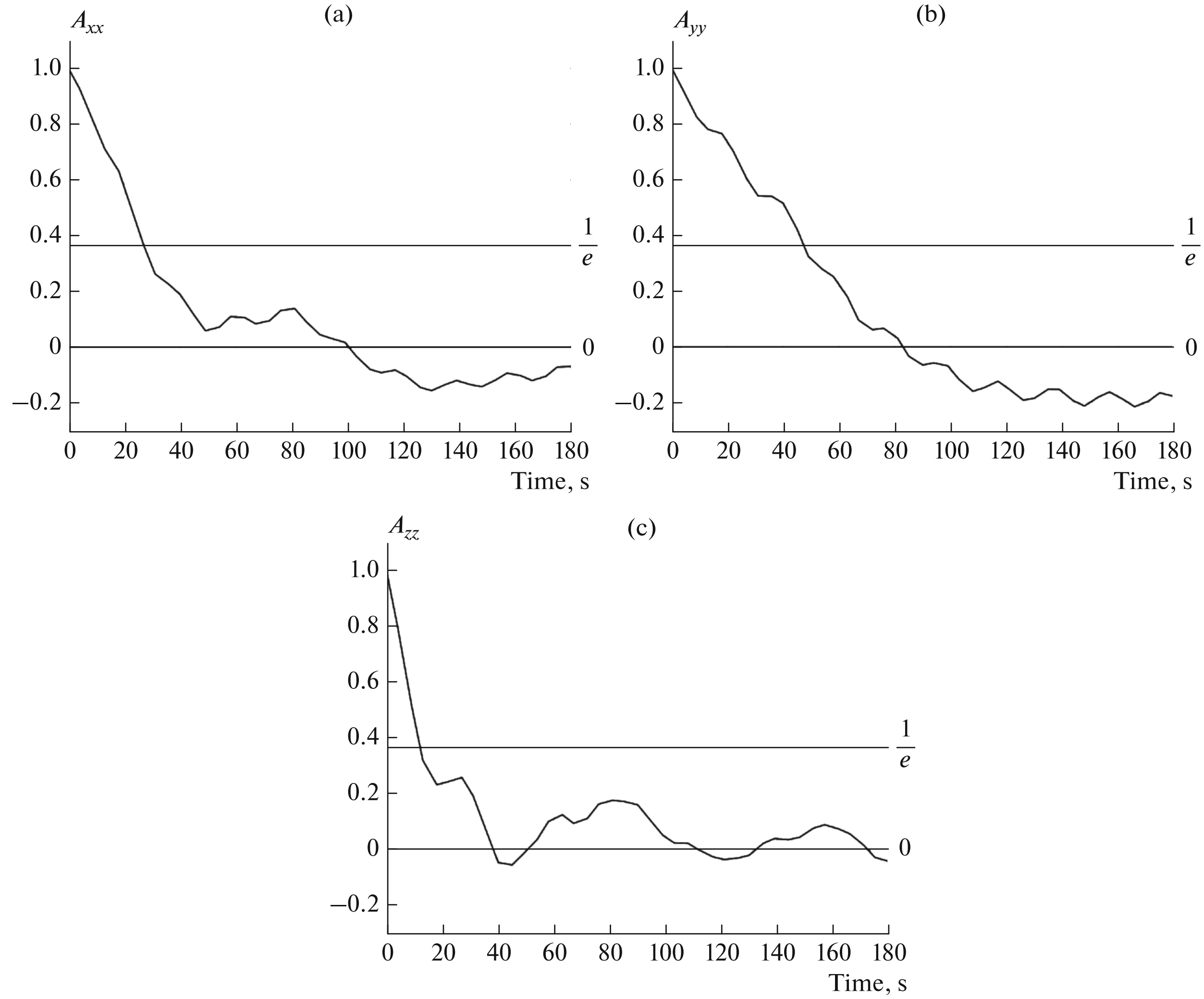

Fig. 2. Examples of autocorrelation functions of plasma velocity components for interval 020–032 UT May 28, 2017 according to MMS1 data: (a) A_{xx}, (b) A_{yy}, (c) A_{zz}.

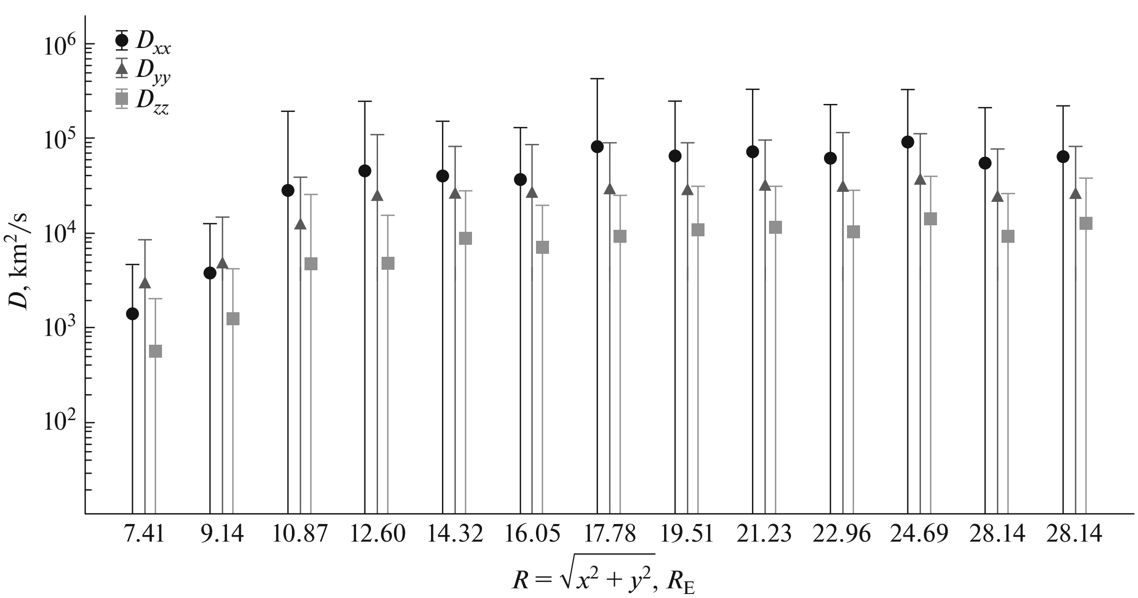

Fig. 3. Averaged radial profiles of eddy diffusion coefficients for northern direction of interplanetary magnetic field.

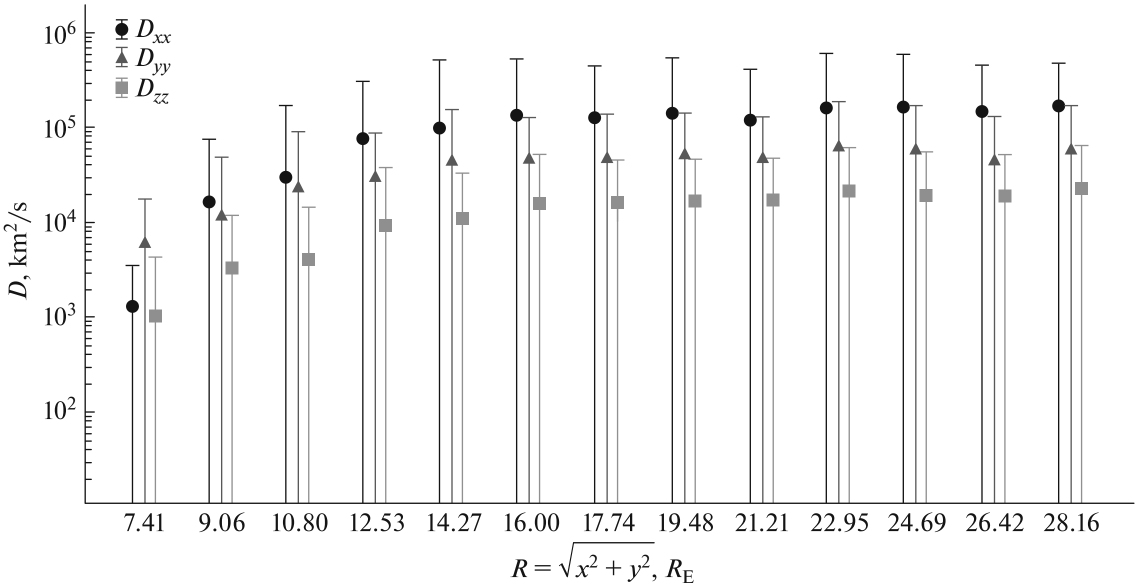

Fig. 4. Averaged radial profiles of eddy diffusion coefficients for southern direction of interplanetary magnetic field.

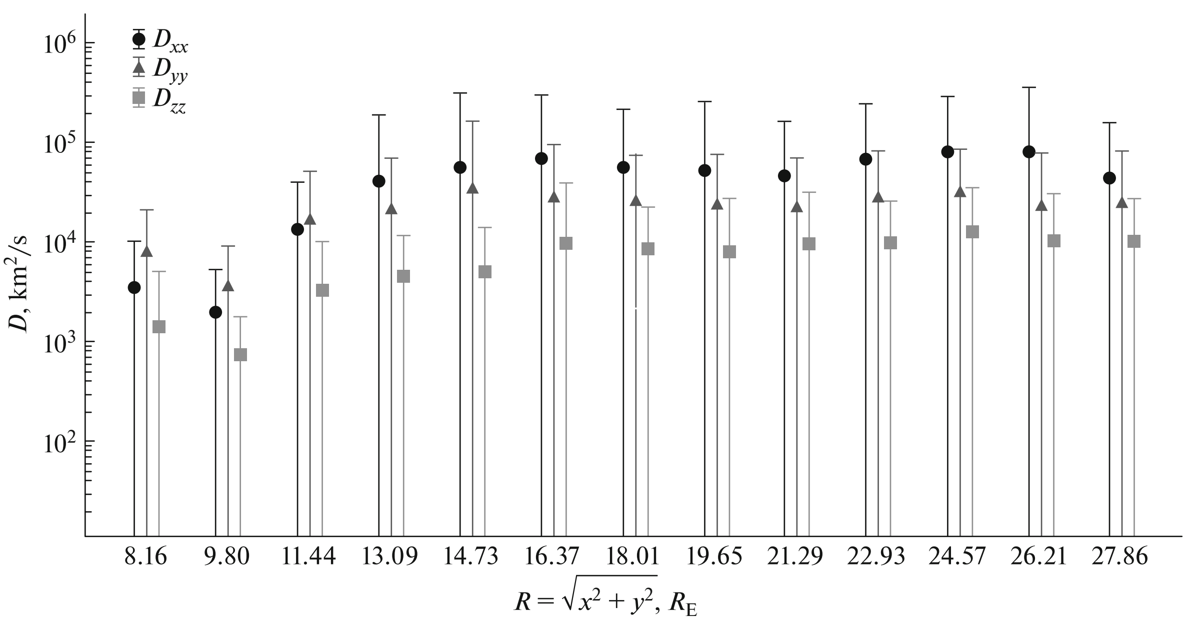

Fig. 5. Averaged radial profiles of eddy diffusion coefficients in quiet geomagnetic conditions ($SML > -50$ nT).

environment were: 5.9×10^4 km^2/s, 2.7×10^4 km^2/s, 0.9×10^4 km^2/s for D_{xx}, D_{yy} and D_{zz} respectively; during substorms, the values were 19.5×10^4 km^2/s, 7.6×10^4 km^2/s, 2.5×10^4 km^2/s for D_{xx}, D_{yy} and D_{zz}, respectively.

4. DISCUSSION

The statistical analysis confirmed the permanent existence of high-level plasma velocity fluctuations in Earth's magnetotail, calculated in the MMS project using the standard method for determining the hydrodynamic parameters of the plasma. It should be noted that the method used for determining the autocorrelation time is not the only possible one (Borovsky et al., 1997) and can lead to underestimation of the calculated eddy diffusion coefficients.

On the whole, as expected, the values of the eddy diffusion coefficients depend both on the direction of the IMF and on geomagnetic activity due to the

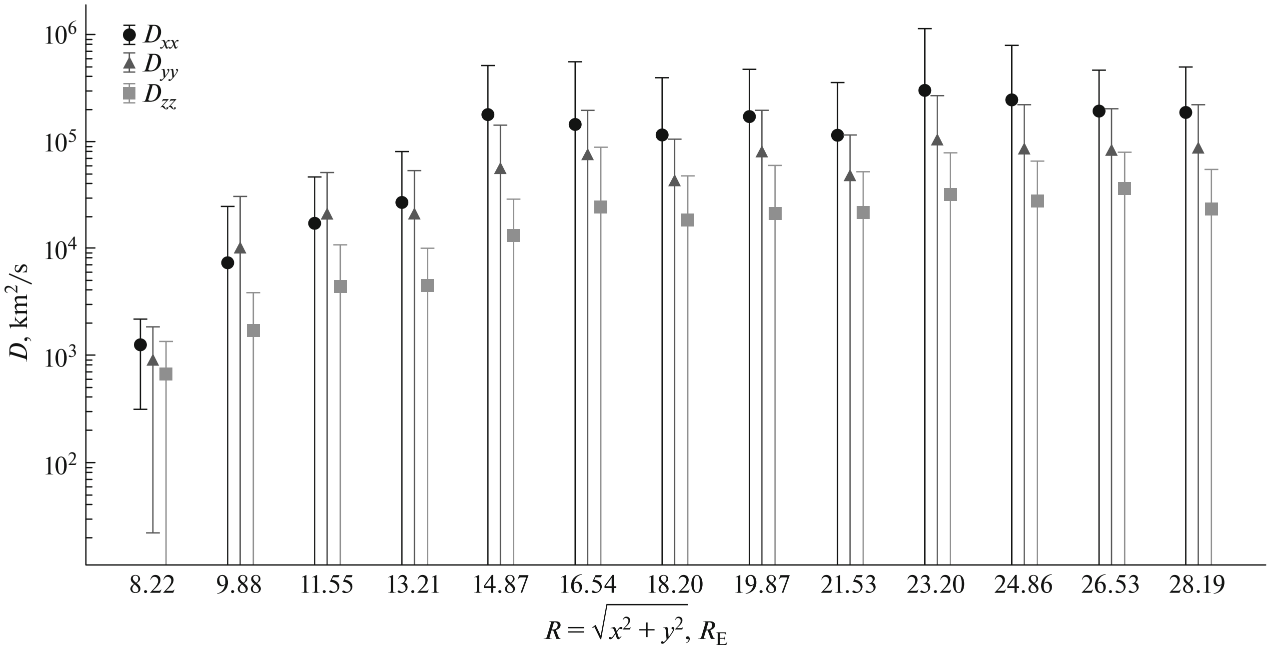

Fig. 6. Averaged radial profiles of eddy diffusion coefficients in disturbed geomagnetic conditions (*SML* < –200 nT).

known statistical dependence of geomagnetic activity on the IMF components.

The results of the statistical analysis of MMS data, in general, confirm the previously obtained patterns and allow us to identify new features. Figures 3 and 4 show that for the southern orientation of the IMF, the average eddy diffusion coefficients are 1.5–2 times greater than for the northern orientation. On average, the eddy diffusion coefficient in the *X*-direction exceeds the value of the eddy diffusion coefficient in the *Y*-direction. The values of the eddy diffusion coefficient are minimal cross the plasma sheet. Overall, the average $D_{xx} > D_{yy} > D_{zz}$. It should be noted that this pattern may not be observed in individual events.

The dependences $D_{xx} > D_{yy} > D_{zz}$ persist for periods of magnetospheric substorms (Fig. 6). During magnetospheric substorms, the eddy diffusion coefficients are several times higher than in quiet times.

The radial profiles of the eddy diffusion components (Figs. 3–6) are characterized by increased values of the coefficients with increasing geocentric distance up to ~$14R_E$, after which plateau is reached. This pattern confirms the conclusions of studies about projection of the auroral oval onto the outer part of the ring current, and not onto the plasma sheet itself, where the turbulence level is constantly high. As is known, at latitudes of the auroral oval in magnetically quiet conditions, nearly stationary vortices can be observed, leading to the formation of inverted-V auroral structures (Antonova and Ovchinnikov, 1998) and stable auroral arcs. In general, the pattern is close to the results of (Stepanova et al., 2009, 2011; Pinto et al., 2011), but was obtained with larger statistics.

5. CONCLUSIONS

The analysis performed using data from the MMS mission confirmed the presence of large fluctuations in plasma velocities in the plasma sheet.

A database was created that made it possible to obtain the first results on the dependence of the eddy diffusion coefficients in the (*X*, *Y*, *Z*) directions on the direction of the IMF and level of geomagnetic activity.

Fluctuations in plasma velocity were analyzed in 12-min intervals in the nighttime sector at $X < -6R_E$, $|Y| < |X|$, $|Z| < 8R_E$ in the region where the plasma parameter exceeds unity, which includes the part of the plasma ring surrounding the Earth and the plasma sheet itself. The values of the diagonal components of the eddy diffusion tensor and their averaged values were obtained.

The dependences of the eddy diffusion tensor components on the IMF direction were studied. It was shown that for a southern orientation of the IMF, the eddy diffusion coefficients are 1.5–2 times greater than for the northern orientation.

The averaged dependences on the level of geomagnetic activity were determined in quiet conditions for *SML* > –50 nT and in perturbed conditions for *SML* < –250 nT. It has been established that during magnetic substorms, the eddy diffusion coefficients are several times higher than the values during quiet geomagnetic activity.

ACKNOWLEDGMENTS

The authors are grateful to the MMS project team for the opportunity to use the data, as well as to the creators of the OMNI database (https://omniweb.gsfc.nasa.gov/) and the SuperMAG project (https://supermag.jhuapl.edu/info/).

FUNDING

The study was supported by the Russian Science Foundation, grant no. 23-22-00076 (https://rscf.ru/project/23-22-00076/).

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

REFERENCES

Angelopoulos, V., Kennel, C.F., Coroniti, F.V., Pellat, R., Spence, H.E., Kivelson, M.G., Walker, R.J., Baumjohann, W., Feldman, W.C., and Gosling, J.T., Characteristics of ion flow in the quiet state of the inner plasma sheet, *Geophys. Res. Lett.*, 1993, vol. 20, no. 16, pp. 1711–1714.
https://doi.org/10.1029/93GL00847

Angelopoulos, V., Mukai, T., and Kokubun, S., Evidence for intermittency in Earth's plasma sheet and implications for self-organized criticality, *Phys. Plasmas*, 1999, vol. 6, no. 11, pp. 4161–4168.
https://doi.org/10.1063/1.873681

Antonova, E.E., On nonadiabatic diffusion and adjustment of concentration and temperature in the plasma sheet of the Earth's magnetosphere, *Geomagn. Aeron.*, 1985, vol. 25, no. 4, pp. 623–627.

Antonova, E.E. and Ovchinnikov, I.L., Equilibrium of a turbulent current sheet and the current sheet of geomagnetic tail, *Geomagn. Aeron. (Engl. Transl.)*, 1996, vol. 36, no. 5, pp. 597–601.

Antonova, E.E. and Ovchinnikov, I.L., Magnetostatically equilibrated plasma sheet with developed medium-scale turbulence: structure and implications for substorm dynamics, *J. Geophys. Res.*, 1999, vol. 104, pp. 17289–17297.
https://doi.org/10.1029/1999JA900141

Antonova, E.E. and Stepanova, M.V., The impact of turbulence on physics of the geomagnetic tail, *Front. Astron. Space Sci.*, 2021, vol. 8, p. 622570.
https://doi.org/10.3389/fspas.2021.622570

Antonova, E.E., Kirpichev, I.P., Vovchenko, V.V., Stepanova, M.V., Riazantseva, M.O., Pulinets, M.S., Ovchinnikov, I.L., and Znatkova, S.S., Characteristics of plasma ring, surrounding the Earth at geocentric distances ~7–10 R_E, and magnetospheric current systems, *J. Atmos. Sol.-Terr. Phys.*, 2013, vol. 99, pp. 85–91.
https://doi.org/10.1016/j.jastp.2012.08.013

Antonova, E.E., Vorobjev, V.G., Kirpichev, I.P., and Yagodkina, O.I., Comparison of the plasma pressure distributions over the equatorial plane and at low altitudes under magnetically quiet conditions, *Geomagn. Aeron. (Engl. Transl.)*, 2014a, vol. 54, no. 3, pp. 278–281.
https://doi.org/10.1134/S0016793214030025

Antonova, E.E., Kirpichev, I.P., and Stepanova, M.V., Plasma pressure distribution in the surrounding the Earth's plasma ring and its role in the magnetospheric dynamics, *J. Atmos. Sol.-Terr. Phys.*, 2014b, vol. 115, pp. 32–40.
https://doi.org/10.1016/j.jstp.2013.12.005

Antonova, E.E., Vorobjev, V.G., Kirpichev, I.P., Yagodkina, O.I., and Stepanova, M.V., Problems with mapping the auroral oval and magnetospheric substorms, *Earth Planets Space*, 2015, vol. 67, no. 1, p. 166.
https://doi.org/10.1186/s40623-015-0336-6

Borovsky, J.E. and Funsten, H.E., MHD turbulence in the Earth's plasma sheet: Dynamics, dissipation and driving, *J. Geophys. Res.*, 2003, vol. 107, no. A7.
https://doi.org/10.1029/2002JA009625

Borovsky, J.E., Elphic, R.C., Funsten, H.O., and Thomsen, M.F., The Earth's plasma sheet as a laboratory for turbulence in high-β MHD, *J. Plasma Phys.*, 1997, vol. 57, no. 1, pp. 1–34.
https://doi.org/10.1017/S0022377896005259

Borovsky, J.E., Thomsen, M.F., and Elphic, R.C., The driving of the plasma sheet by the solar wind, *J. Geophys. Res.*, 1998, vol. 103, no. A8, pp. 17617–17639.
https://doi.org/10.1029/97JA02986

Burch, J.L., Moore, T.E., Torbert, R.B., and Giles, B.L., Magnetospheric multiscale overview and science objectives, *Space Sci. Rev.*, 2016, vol. 199, pp. 5–21.
https://doi.org/10.1007/s11214-015-0164-9

Ergun, R.E., Goodrich, K.A., Wilder, F.D., et al., Magnetic reconnection, turbulence, and particle acceleration: Observations in the Earth's magnetotail, *Geophys. Res. Lett.*, 2018, vol. 45, pp. 3338–3347.
https://doi.org/10.1002/2018GL076993

Eyelade, A.V., Espinoza, C.M., Stepanova, M., Antonova, E.E., Ovchinnikov, I.L., and Kirpichev, I.P., Influence of MHD turbulence on ion kappa distributions in the Earth's plasma sheet as a function of plasma β parameter, *Front. Astron. Space Sci.*, 2021, vol. 8, p. 647121.
https://doi.org/10.3389/fspas.2021.647121

Montgomery, D., Remarks on the MHD problem of generic magnetospheres and magnetotails, in *Magnetotail Physics*, Lui, A.T.Y., Ed., Baltimore, Md.: John Hopkins Univ. Press, 1987.

Nagata, D., Machida, S., Ohtani, S., Saito, Y., and Mukai, T., Solar wind control of plasma number density in the near-Earth plasma sheet: Three-dimensional structure, *Ann. Geophys.*, 2008, vol. 26, no. 12, pp. 4031–4049.
https://doi.org/10.5194/angeo-26-4031-2008

Ovchinnikov, I.L., Antonova, E.E., and Yermolaev, Yu.I., Determination of the turbulent diffusion coefficient in the plasma sheet using the project INTERBALL data, *Cosmic Res.*, 2000, vol. 38, no. 6, pp. 557–561.

Ovchinnikov, I.L., Antonova, E.E., and Yermolaev, Yu.I., Turbulence in the plasma sheet during substorms: A case study for three events observed by the INTERBALL Tail probe, *Cosmic. Res.*, 2002a, vol. 40, no. 6, pp. 521–528.

Ovchinnikov, I.L., Antonova, E.E., and Yermolaev, Yu.I., Plasma sheet heating during substorm and the values of the plasma sheet diffusion coefficient obtained on the base of Interball/Tail probe observations, *Adv. Space Res.*, 2002b, vol. 30, no. 7, pp. 1821–1824. https://doi.org/10.1016/S0273-1177(02)00456-8

Ovchinnikov, I.L., Antonova, E.E., and Naiko, D.Yu., Fluctuations of the electric and magnetic fields in the plasma sheet of the Earth's magnetotail according to MMS data, *Cosmic Res.*, 2024, vol. 62, no. 1, pp. 10–33. https://doi.org/10.1134/S0010952523700788

Pinto, V., Stepanova, M., Antonova, E.E., and Valdivia, J.A., Estimation of the eddy-diffusion coefficients in the plasma sheet using THEMIS satellite data, *J. Atmos. Sol.-Terr. Phys.*, 2011, vol. 73, no. 7, pp. 1472–1477. https://doi.org/10.1016/j.jastp.2011.05.007

Pollock, C., Moore, T., Jacques, A., et al., Fast plasma investigation for magnetospheric multiscale, *Space Sci. Rev.*, 2016, vol. 199, pp. 331–406. https://doi.org/10.1007/s11214-016-0245-4

Stepanova, M. and Antonova, E.E., Modeling of the turbulent plasma sheet during quiet geomagnetic conditions, *J. Atmos. Sol.-Terr. Phys.*, 2011, vol. 73, no. 8, pp. 1636–1642. https://doi.org/10.1016/j.jastp.2011.02.009

Stepanova, M.V., Vucina-Parga, T., Antonova, E.E., Ovchinnikov, I.L., and Yermolaev, Yu.I., Variation of the plasma turbulence in the central plasma sheet during substorm phases observed by the Interball/tail satellite, *J. Atmos. Sol.-Terr. Phys.*, 2005, vol. 67, no. 11, pp. 1815–1820. https://doi.org/10.1016/j.jastp.2005.01.013

Stepanova, M., Antonova, E.E., Paredes-Davis, D., Ovchinnikov, I.L., and Yermolaev, Y.I., Spatial variation of eddy-diffusion coefficients in the turbulent plasma sheet during substorms, *Ann. Geophys.*, 2009, vol. 27, no. 4, pp. 1407–1411. https://doi.org/10.5194/angeo-27-1407-2009

Stepanova, M., Pinto, V., Valdivia, J.A., and Antonova, E.E., Spatial distribution of the eddy diffusion coefficients in the plasma sheet during quiet time and substorms from THEMIS satellite data, *J. Geophys. Res.*, 2011, vol. 116, no. 1. https://doi.org/10.1029/2010JA015887

Torbert, R.B., Russell, C.T., Magnes, W., et al., The FIELDS instrument suite on MMS: Scientific objectives, measurements, and data products, *Space Sci. Rev.*, 2016, vol. 199, pp. 105–135. https://doi.org/10.1007/s11214-014-0109-8

Troshichev, O.A., Antonova, E.E., and Kamide, Y., Inconsistence of magnetic field and plasma velocity variations in the distant plasma sheet: Violation of the "frozen-in" criterion?, *Adv. Space Res.*, 2002, vol. 30, no. 12, pp. 2683–2687. https://doi.org/10.1016/S0273-1177(02)80382-9

Vörös, W., Baumjohann, W., Nakamura, R., Runov, A., et al., Multi-scale magnetic field intermittence in the plasma sheet, *Ann. Geophys.*, 2003, vol. 21, no. 9, pp. 1955–1964. https://doi.org/10.5194/angeo-21-1955-2003

Wang, C.-P., Lyons, L.R., Nagai, T., Weygand, J.M., and Lui, A.T.Y., Evolution of plasma sheet particle content under different interplanetary magnetic field conditions, *J. Geophys. Res.*, 2010, vol. 115, no. 6. https://doi.org/10.1029/2009JA015028

Weygand, J.M., Kivelson, M.G., Khurana, K.K., Schwarzl, H.K., et al., Plasma sheet turbulence observed by Cluster II, *J. Geophys. Res.*, 2005, vol. 110, no. 2. https://doi.org/10.1029/2004JA010581

Yermolaev, Yu.I., Petrukovich, A.A., Zelenyi, L.M., Antonova, E.E., Ovchinnikov, I.L., and Sergeev, V.A., Investigation of the structure and dynamics of the plasma sheet: The CORALL experiment of the INTERBALL project, *Cosmic Res.*, 2000, vol. 38, no. 1, pp. 13–19.