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DEPENDENCE OF EDDY DIFFUSION COEFFICIENT ON PLASMA PARAMETER β IN EARTH'S MAGNETOTAIL

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Abstract. The work analyzes dependences of eddy diffusion coefficients in the X, Y, and Z directions of the GSM coordinate system on the plasma parameter β, taking into account the distance from Earth, the direction of the interplanetary magnetic field, and conditions of geomagnetic activity in the magnetotail according to MMS mission data. These parameters are determined by root-mean-square velocities of ions and their autocorrelation time. Eddy diffusion coefficients characterize the magnitude of turbulent transport in the magnetotail and are the parameters of the model of turbulent plasma sheet. We have analyzed more than 20000 12-min intervals during which the MMS satellites were located within a region with plasma density more than 0.1 cm^{-3} and average ion energy more than 0.5 keV. It is shown that as the plasma parameter increases, the eddy diffusion coefficients increase as well. This increase stops at β~1. Analysis of the relative contribution of changes in root-mean-square velocity and autocorrelation time to the eddy diffusion coefficient has revealed that there is no significant dependence on autocorrelation time.

Keywords: magnetospheric turbulence, turbulent transport, coefficients of eddy diffusion.

INTRODUCTION

Turbulent fluctuations are observed in almost all plasma systems, especially at low levels of dissipation; they are specific to laboratory plasma devices [Budaev et al., 2015]. Among cosmophysical plasma systems, solar wind turbulence has been studied for a relatively long time [Bruno, Carbone, 2013; Alexandrova et al., 2013; Podesta, Borovsky, 2010; Tu, Marsch, 1995; Riazantseva et al., 2017; Borovsky, 2020]. Later, publications appeared on magnetosheath turbulence [Yordanova et al., 2008; Rakhmanova et al., 2018, 2020, 2024], which was easier to examine than solar wind turbulence due to a significant increase in the level of near-Earth shock wave fluctuations. This area of research became especially active after the launch of the Magnetospheric Multiscale Mission (MMS) [Sahraoui et al., 2020]. Nonetheless, the effect of solar wind turbulence on magnetosheath turbulence and the effect of the latter on characteristics of the magnetosphere have scarcely been studied so far.

Earth's magnetosphere at altitudes higher than 1000 km can be considered as a collisionless plasma system in which free paths relative to Coulomb collisions exceed the distance from Earth to the Sun, and Reynolds numbers exceed 10^{10} [Borovsky, Funsten, 2003]. In such a system, various plasma instabilities can develop and turbulent flows are formed. These processes have to be studied for space weather predictions. The main feature of Earth's magnetosphere plasma sheet turbulence is turbulent transport. It leads to mixing and equalization of density, pressure, and temperature gradients (see reviews [Ovchinnikov, Antonova, 2017; Antonova, Stepanova, 2021]).

Significant turbulent fluctuations were observed in early space experiments. Their role in the dynamics of the magnetosphere was highlighted in [Antonova, 1985; Montgomery, 1987; Angelopoulos et al., 1993, 1999]. At the same time, the key topic of the research was large-scale phenomena such as dipolization of magnetic field lines. The works [Borovsky et al., 1997, 1998; Borovsky, Funsten, 2003], based on data from the ISEE-2 satellite, have initiated a systematic study of Earth's magnetotail turbulence. Initial versions of the turbulent magnetotail model were developed almost simultaneously [Antonova, Ovchinnikov, 1996a, b, 1999]. They made it possible to estimate the turbulent diffusion coefficient (~10^5 km^2/s), which would have corresponded to simultaneous observations of plasma sheet thickness and the velocity of plasma drift to the equatorial plane of the magnetotail caused by the large-scale dawn-dusk electric field. It was believed that the dawn-dusk field, generated due to closure of large-scale field-aligned Iijima-Potemra currents in the ionosphere [Iijima, Potemra, 1976], is projected onto the geomagnetic tail and causes plasma to be swept out of the tail lobes to the plasma sheet center. Borovsky et al. [1998], when discussing plasma transport from the solar wind into the magnetosphere, introduced a coefficient of eddy diffusion across the plasma sheet, i.e. in the Z direction of the geocentric solar-magnetospheric GSM coordinate system (the Earth centered rectangular coordinate system in which the X-axis is directed to the Sun, the geomagnetic dipole axis is located in the XZ plane). Fluctuations were not measured by ISEE-2 in the Z direction and the fluctuations were assumed to be quasi-isotropic, i.e. their values in the X, Y, Z directions were close. It was also supposed that diffusion is a Markov process, i.e. during the autocorrelation time τ_{auto}, each shift is independent of the previous one. For Z shifts, $\Delta z = v_z \tau_{auto}$, where v_z is the hydrodynamic plasma velocity along Z. The diffusion coefficient in this case

$$D_{zz} = \frac{\left\langle (\Delta z)^2 \right\rangle}{2\tau_{auto}} = \frac{v_{z\,rms}^2 \, v_{auto}}{2}, \qquad (1)$$

where $v_{z\ rms}$ is the root-mean-square velocity; $v_{z\ rms}$ and τ_{auto} are Lagrangian variables, i.e. they must be obtained from measurements of an instrument moving at the convection velocity. Nonetheless, when the regular velocity is low compared to fluctuations, Eulerian velocity measurements can be used when the plasma velocity is measured relative to a stationary device. Diagonal components of the eddy diffusion tensor are similarly written in X, Y directions. It was taken into account that high plasma velocities are observed only in the X direction, with $v_{y\ rms}$ measured by ISEE-2. The eddy diffusion coefficient D_{zz}=2.6·10^5 km^2/s was obtained. The eddy diffusion coefficients predicted by the model [Antonova, Ovchinnikov, 1996a, b, 1999;] in the Z direction of the GSM coordinate system coincided in order of magnitude with that from ISEE-2 [Borovsky et al., 1998], which might have indicated that the model was valid. In this case, sizes of the vortices proved to be comparable with the plasma sheet thickness.

The eddy diffusion coefficients according to Interball/Tail Probe satellite data might have been derived from direct measurements of v_z and confirmed the model estimates [Yermolaev et al., 2000; Ovchinnikov et al., 2000, 2002a, b]. Calculations of velocity fluctuations by the GEOTAIL satellite [Troshichev et al., 2002; Nagata et al., 2008] also yielded large eddy diffusion coefficients. The corresponding analysis was later carried out with CLUSTER and THEMIS satellites [Stepanova et al., 2005, 2009, 2011; Stepanova, Antonova, 2011; Nagata et al., 2008; Wang et al., 2010; Pinto et al., 2011] (for reviews of works in this area of research, see [Ovchinnikov, Antonova, 2017; Antonova, Stepanova, 2021]).

Borovsky et al. [1997] have shown that fluctuations in plasma sheet velocities have correlation times of ~2 min; magnetic field fluctuations, ~8 min. The correlation length ranges from 4000 to 10000 km as inferred from the results obtained by Weygand et al. [2005]. It was also shown that in the plasma sheet zones of strong fluctuations are recorded along with zones of weak disturbances in space and time. This suggests that plasma sheet turbulence occurs intermittently [Angelopoulos et al., 1999; Vörös et al., 2003, 2004, 2006, 2007; Volwerk et al., 2004; Weygand et al., 2005]. In [Stepanova et al., 2005, 2009, 2011; Eyelade et al., 2021] it has been shown that due to intermittency of turbulence in the plasma sheet the turbulent diffusion coefficient takes values that differ by more than an order of magnitude. This requires further analysis. Moreover, no detailed studies of dependences of RMS velocity fluctuations, their autocorrelation times and eddy diffusion coefficients on characteristics of the solar wind, geomagnetic activity, and localization in the plasma sheet have been conducted, which is important for determining the nature of turbulence.

Note that despite the large number of analyzed observations the problems of plasma sheet turbulence have not yet been resolved or are poorly understood. This was, first, due to the lack of reliable measurements of three electric field components.

The active study of electric field fluctuations in the magnetotail began with the launch of the NASA MMS multi-satellite mission consisting of four identical satellites shaped as a tetrahedron and spaced by tens of kilometers apart [Burch et al., 2016; Torbert et al., 2016; Pollock et al., 2016], after receiving accurate measurements of all electric field components. The main objectives of the project were to examine processes on electronic scales. Therefore, most works on MMS dealt with single short intervals for measurements with extremely high resolution up to 8000 s^{-1}, which did not allow for statistical studies. Such studies with time resolution of 32 s^{-1} in electric field, 16 s^{-1} in magnetic field, and 4.5 s in particle fluxes have recently been carried out in [Ovchinnikov et al., 2024; Naiko et al., 2024]. A number of important conclusions have been drawn about characteristics of electric and magnetic field spectra; data on eddy diffusion coefficients has been confirmed and expanded. Nevertheless, these studies were preliminary and a number of relevant questions remained unanswered. These questions include contributions of RMS values of ion velocity fluctuations and their autocorrelation periods, as well as dependences of eddy diffusion coefficients on the plasma parameter $\beta=2\mu_0 p/B^2$, where p is the plasma pressure; B is the magnetic field; μ_0 is the permeability of free space.

This work is a sequel to the works [Ovchinnikov et al., 2024; Naiko et al., 2024], which have examined turbulence in Earth's magnetotail from MMS data, have obtained statistically averaged eddy diffusion coefficients, and have determined their dependences on averaged velocity fluctuations and autocorrelation times. The second section of our paper briefly describes the research method, the third section analyzes the results obtained, and the fourth is devoted to discussion and conclusions.

DATA AND ANALYSIS METHOD

We have calculated eddy diffusion coefficient components by analyzing measurement data on the hydrodynamic plasma ion velocity, using MMS FPI/DIS instruments [Pollock et al., 2016]. Time resolution of these instruments is 1/4.5 s^{-1}. For 4.5 s, particle spectra were measured and hydrodynamic parameters were calculated. Selection of analyzed data is described in detail in [Ovchinnikov et al., 2024; Naiko et al., 2024].

Determination of eddy diffusion components required identification of periods with average velocities $|V_x|<100$ km/s, which made it possible to filter out intervals with possible BBF-type (bursty bulk flows) events. This restriction allowed us to obtain reliable values of the diffusion coefficients according to the restrictions justified in [Borovsky et al., 1998]. At the same time, it should be remembered that the omitted BBF periods can make a significant contribution to turbulent transport during magnetically active periods.

When selecting data suitable for the planned analysis for each of the satellites, we isolated 6-min intervals from the entire MMS data array when the satellite was inside the plasma sheet or inside the transition region from the plasma sheet to magnetotail lobes. The overall database [Ovchinnikov et al., 2024; Naiko et al., 2024] contained measurements when coordinates of the satellites in the GSM system satisfied the conditions $x<-6R_E$, $|y|<|x|$, $|z|<8R_E$, where R_E is the Earth radius. The data was analyzed from May 5, 2017 to September 1, 2023.

In this study, regions at geocentric distances of 15 $R_E<R<30$ R_E are identified in which the ion temperature $T_i>0.5$ keV. We believe that if the plasma ion concentration $n_i>0.05$ cm^{-3}, the satellites are located in the plasma sheet, including its central and boundary regions. If $n_i>0.1$ cm^{-3}, measurements are carried out in the central region of the plasma sheet. To separate the central plasma sheet, we also compute the plasma parameter for each time interval. At $0.1<\beta<1$, measurements are carried out in the boundary region; at $\beta>1$, near the center of the plasma sheet. In general, the selected criteria correspond to the criteria adopted in [Stepanova et al., 2011], which makes it possible to further compare the obtained eddy diffusion coefficients.

For each of the 6-min intervals, we average the parameters, then unite the intervals up to 12 min in pairs, i.e. in the statistical study each of the initial 6-min intervals is examined together with the previous one. Each 12-min interval contains 160 measurements of the hydrodynamic plasma velocity. The MMS project was generally focused on making measurements near the equatorial plane. In total, we have therefore examined 14206 12-min intervals in the central region of the plasma sheet and 6407 intervals in the boundary region, which allowed us to collect the necessary statistics. For each selected interval in the directions along the sheet, along Y, and across the sheet, the RMS velocity $v_{rms}=\langle v_i\rangle$ is determined and the autocorrelation time τ is computed by constructing and analyzing the autocorrelation function

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

where $\alpha, \beta \in \{X, Y, Z\}$. The autocorrelation function is approximated by the exponential function $A_{\alpha\beta}(\tau)=\exp(-\tau/\tau_{\alpha\beta})$, and the autocorrelation time $\tau_{\alpha\beta}$ is calculated by the least square method. The diagonal eddy diffusion coefficient tensor components D_{xx}, D_{yy}, and D_{zz} are calculated in accordance with (1), i.e.

$$D_{xx,yy,zz} = \frac{v^2_{x,y,z\,\mathrm{rms}}\,\tau_{xx,yy,zz\,\mathrm{auto}}}{2}. \quad (3)$$

The dependence of the eddy diffusion coefficients on the direction of the interplanetary magnetic field (IMF) is analyzed as in [Naiko et al., 2024], by measuring the IMF component B_z in the solar wind from the OMNI database. Each 12-min interval is added to the sample provided that throughout the entire interval minimum observed $B_z>0$ for northward IMF and maximum $B_z<0$ for southward IMF are recorded an hour before the interval of interest. The eddy diffusion coefficients for the analysis of their dependence on geomagnetic activity are selected taking into account the geomagnetic index SuperMag *SML*. It is similar to the *AL* index, but is calculated from data from 110 stations instead of 12 and is available in numerical form until the end of 2023; it is fully described in [Newell, Gjerloev, 2011]. For each 12-min interval, the following conditions were checked: *SML*>–50 nT for all observed intervals preceding that under study (and including it) for an hour in order to select intervals of quiet geomagnetic conditions; *SML*<–200 nT for selecting intervals of high geomagnetic activity an hour before the interval under study. It is shown further that despite the limited applicability of the selected criteria it is possible to distinguish the main features of the characteristics considered from the plasma parameter.

RESULTS

The results of the analysis of the dependences of the values under study on the plasma parameter β are presented below. The diagonal eddy diffusion coefficient D components are plotted as function of β. Figure 1 illustrates the dependences $D(\beta)$ for different IMF directions: southward (*a* — $B_z<0$) and northward (*b* — $B_z>0$). Figure 2 plots $D(\beta)$ as function of geomagnetic activity: under disturbed (*a* — *SML*<–200 nT) and quiet (*b* — *SML*>–50 nT) conditions (the intervals –200 nT< *SML*<–50 nT were omitted). The numbers at the top of the panels denote the number of analyzed intervals when selected according to β. Red circles indicate the parameter of interest in *x*; green triangles, in *y*; and blue squares, in *z*.

Analysis of Figures 1, 2 shows that there is a fairly clear dependence of the diagonal components $D(\beta)$: at $\beta<1$, its increase is accompanied by an increase in D, and at $\beta\geq1$ $D=const$. At the same time, at IMF $B_z<0$ and $\beta<1$ $D_{xx}>D_{yy}>D_{zz}$, and at IMF $B_z>0$ and $\beta<1$ $D_{xx}\sim D_{yy}>D_{zz}$. In the region of large β, i.e. close to the equatorial plane of the plasma sheet, it is almost always $D_{zz}<D_{xx}$, D_{yy}. Diffusion in *x* generally dominates over diffusion in *y*, but sometimes there are

regions with high diffusion in y, which may correspond to the events of diffusive penetration of magnetosheath plasma into the plasma sheet from sides of the magnetosphere [Antonova, 2006]. Similar conclusions can be drawn when analyzing the dependences of D on geomagnetic activity level according to the *SML* index, which is due to the close dependence of geomagnetic activity level on the direction of the north-south magnetic field component in the solar wind. Some small discrepancies seem to be related to the statistics of selected events.

Clarifying the observed patterns requires a separate analysis of the RMS hydrodynamic plasma velocity $v_{\rm rms}$ and the autocorrelation time τ.

Figure 3 illustrates averaged dependences of $v_{\rm rms}$ in three directions at IMF B_z<0 (*a*), IMF B_z>0 (*b*); and Figure 4, at *SML*<–200 nT (*a*), *SML*>–50 nT (*b*).

When examining the dependence $v_{\rm rms}(\beta)$ on IMF B_z orientation, we can observe that the $v_{\rm rms}$ components approximately doubled at southward IMF compared to northward IMF. The dependence also changes under different geomagnetic conditions: higher $v_{\rm rms}$ components are recorded under disturbed geomagnetic conditions.

Figure 5 exhibits averaged dependences $\tau_{\rm auto}(\beta)$ in three directions at IMF B_z<0 (Figure 5, *a*), IMF B_z>0 (Figure 5, *b*); and Figure 6, those at *SML*<–200 nT (*a*), *SML*>–50 nT (*b*).

Analysis of Figures 5, 6 shows that there are no significant differences in the dependence on IMF direction, geomagnetic activity level, and plasma parameter. It follows that variations in the turbulent diffusion coefficient D depend largely on the level of fluctuations in hydrodynamic plasma velocities $v_{\rm rms}$.

DISCUSSION AND CONCLUSIONS

The analysis has allowed us to identify the dependence of diagonal components of the eddy diffusion tensor on the plasma parameter and to trace the existence of such dependence for $v_{\rm rms}$ and τ at geocentric distances from 15 $R_{\rm E}$ to 30 $R_{\rm E}$. This range of geocentric distances does not include the plasma ring surrounding Earth, whose outer boundary is within 13$R_{\rm E}$ at night (see [Eyelade et al., 2024a, b] and references therein). At the geocentric distances considered, near the equator there is the main part of the tail current, which is closed by currents at the magnetopause. The plasma parameter dependences we have found are useful for the planned recasting of the theory of plasma sheet formation under conditions of magnetostatic equilibrium across the sheet since the theory, developed in the late 90s [Antonova, Ovchinnikov, 1996a, b, 1999], ignored the dependence of eddy diffusion coefficients on β. The theory allowed us to describe the thinning of the plasma sheet during the substorm growth phase and its thickening during the recovery phase, explained the decay of the plasma sheet, filling of the tail lobes, and the occurrence of theta aurora at northward IMF. However, when developing a 3D version of the model, a number of difficulties arose related to projection of the large-scale dawn-dusk electric field from the ionosphere into the magnetotail, whose overcoming in view of new information can clarify the model's predictions.

The study is also of interest for describing the formation of a turbulent wake behind a streamlined obstacle in a collisionless plasma. It is well known that the development of hydrodynamic instabilities depends on plasma parameter. For example, at low β, a flute-like or interchange instability is considered; and at β comparable to 1, balloon modes develop, which were widely discussed when analyzing magnetospheric substorms during the past decade. Development of universal drift modes also depends heavily on β. An increase in D with increasing β and its independence of β at β>1 distinguish the region with large β near the center of the plasma sheet for special conditions during the formation of tail turbulence spectra.

The results are also interesting in describing turbulent transport in Earth's magnetotail. The qualitative coincidence of the D(β) dependences at southward IMF and increased geomagnetic activity and the same coincidence at northward IMF and quiet geomagnetic conditions indicates not only the role of the IMF orientation in determining the level of geomagnetic activity, but also a close connection between turbulent transports in the X, Y, and Z directions in the geomagnetic tail. In general, this proves the essential role of turbulent transport in forming the magnetosphere and characteristics of geomagnetic activity, as was assumed in the first publications [Antonova, 1985; Montgomery, 1987].

The statistical study we have carried out generally confirms the previously obtained results and allows us to identify a number of new features of turbulent transport in Earth's magnetotail. To quantitatively verify the equilibrium model of turbulent plasma sheet proposed in [Antonova, Ovchinnikov, 1996a, b, 1999], estimated large-scale electrostatic convection fields arising from the closure of large-scale field-aligned currents in the high-latitude ionosphere should be added to measurements of eddy diffusion coefficients. The latter requires analysis of distribution of convection fields in the polar cap from radar data. Follow-up studies suggest a more detailed analysis of the dependence of eddy diffusion coefficients on substorm phases. At the same time, prominence is to be given to the periods of thinning of the plasma sheet.

We are grateful to the team of the MMS project [https://lasp.colorado.edu/mms/sdc/public/data/] for providing access to the data, as well as to the developers of the OMNI database [https://omniweb.gsfc.nasa.gov/] and the SuperMag project [https://supermag.jhuapl.edu/info/].

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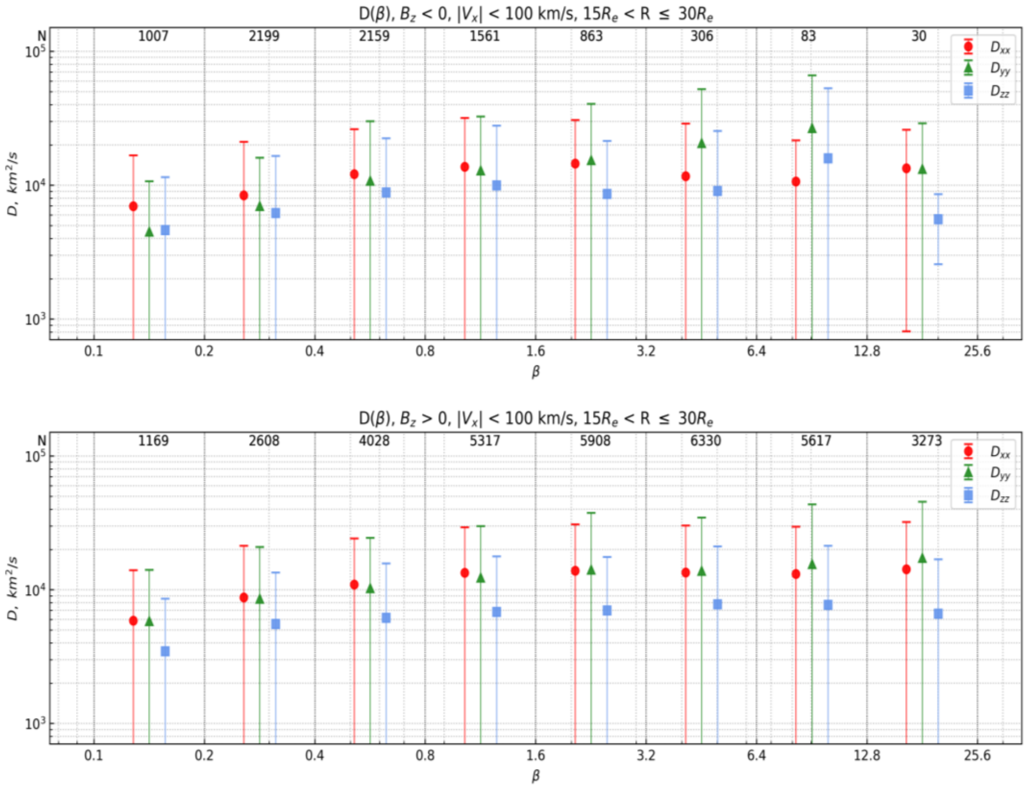

Figure 1. Eddy diffusion coefficient *D* versus plasma parameter β for different directions of IMF: B_z<0 (*a*); B_z>0 (*b*)

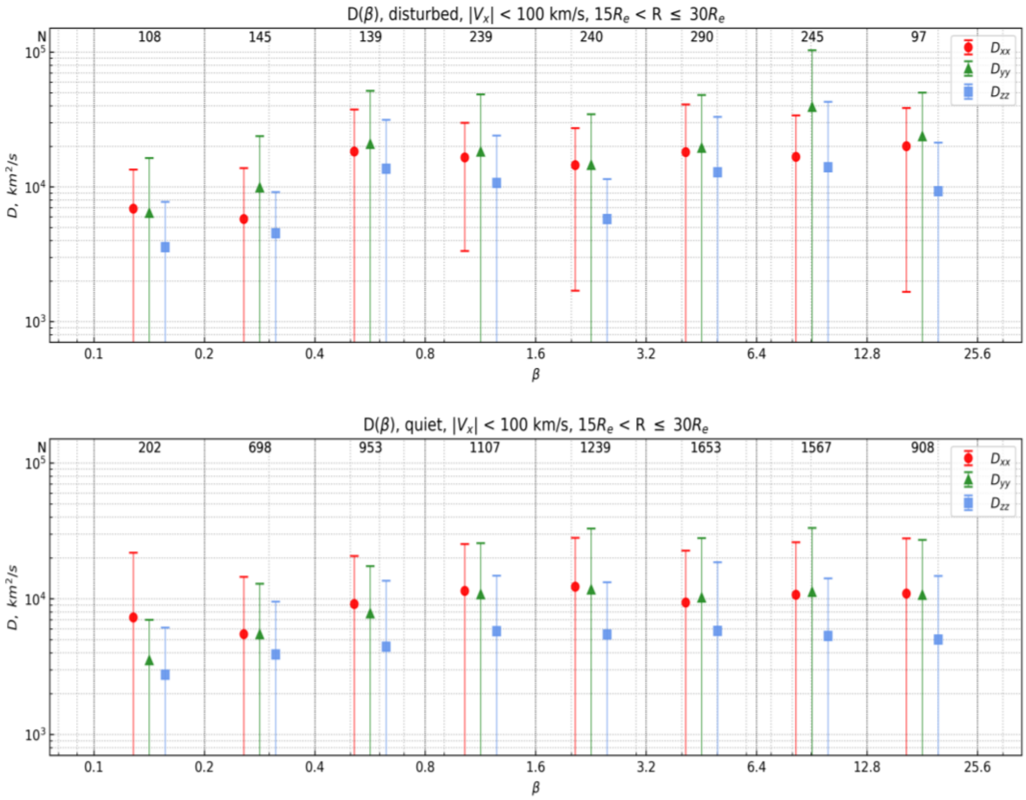

Figure 2. The same as in Figure 1 under different geomagnetic conditions: *SML*<–200 nT (*a*), *SML*>–50 nT (*b*)

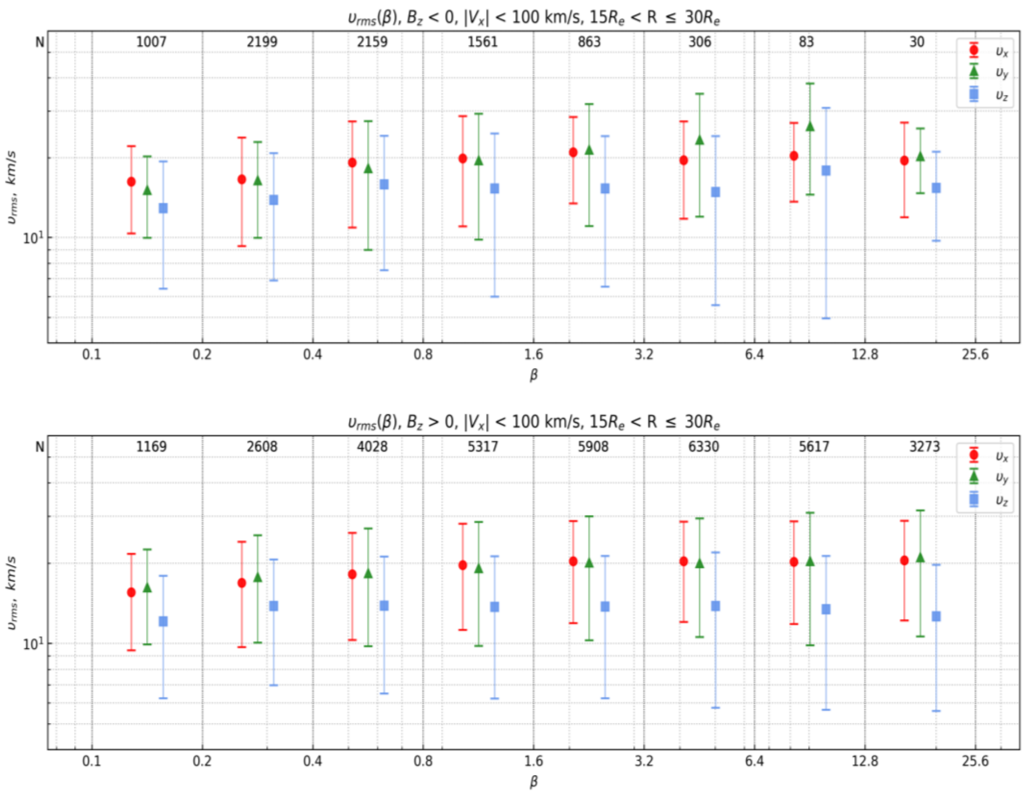

Figure 3. Dependence of RMS velocity $v(\beta)$ at $B_z<0$ (*a*); $B_z>0$ (*b*)

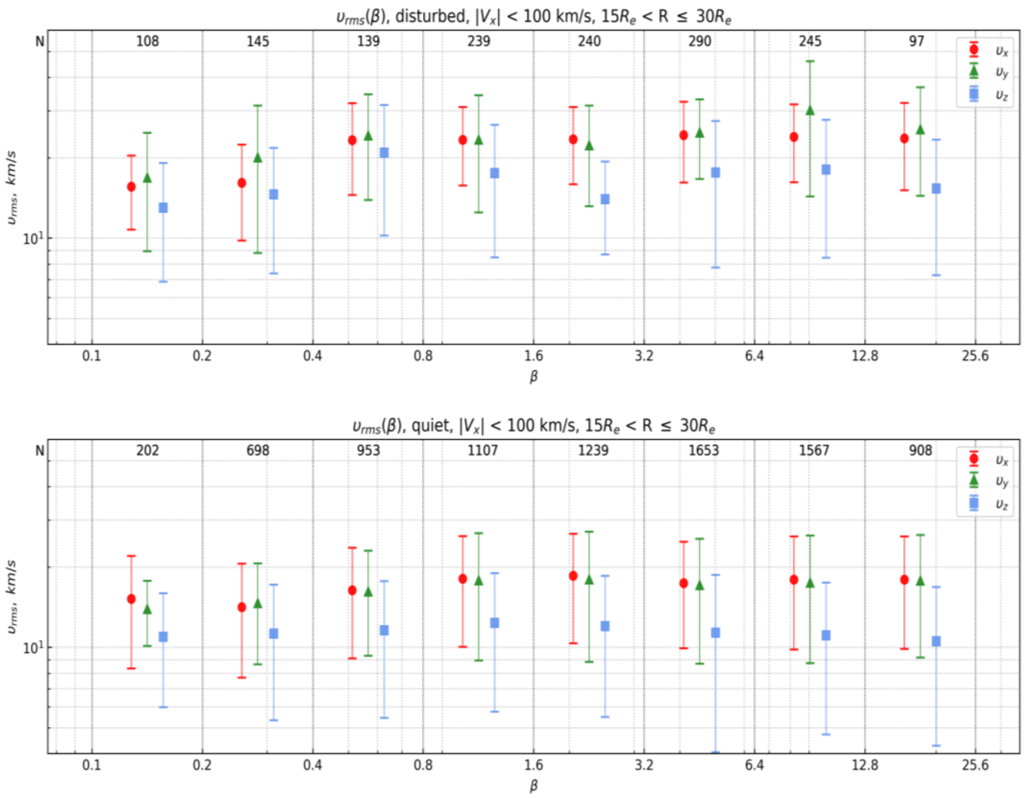

Figure 4. The same as in Figure 3 at *SML*<–200 nT (*a*); *SML*>–50 nT (*b*)

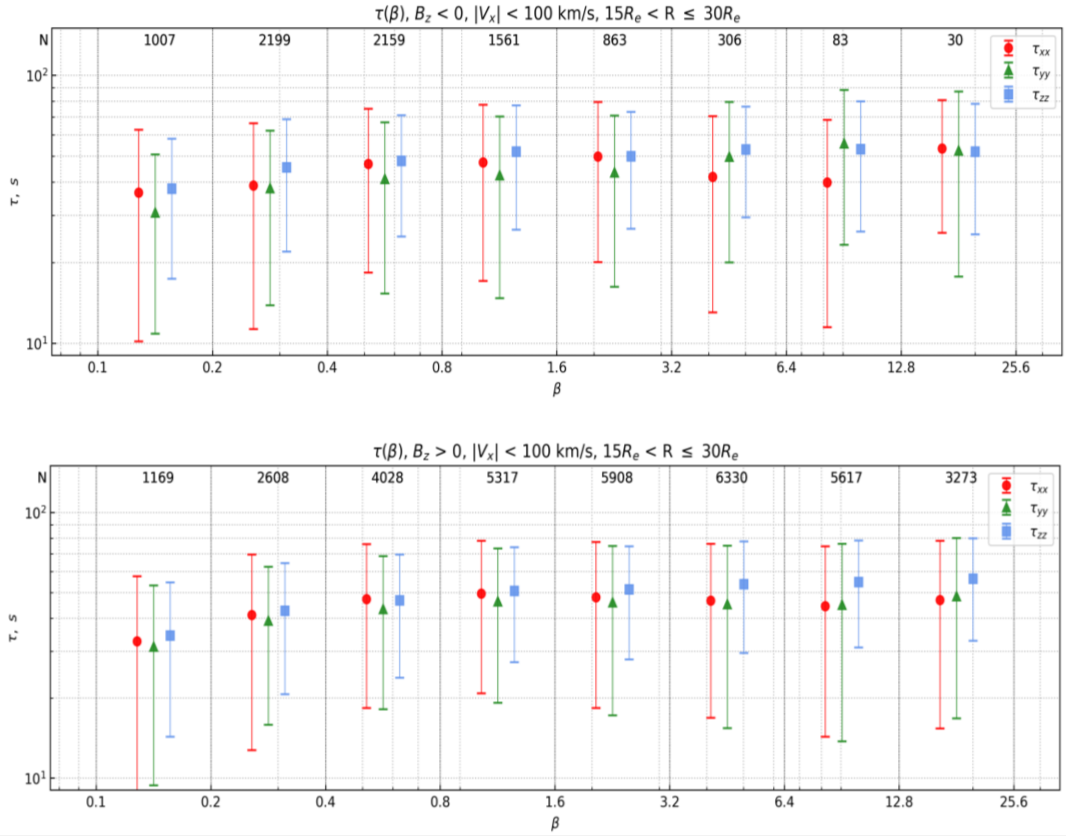

Figure 5. Dependence of autocorrelation time $\tau_{auto}(\beta)$ at B_z<0 (*a*); B_z>0 (*b*)

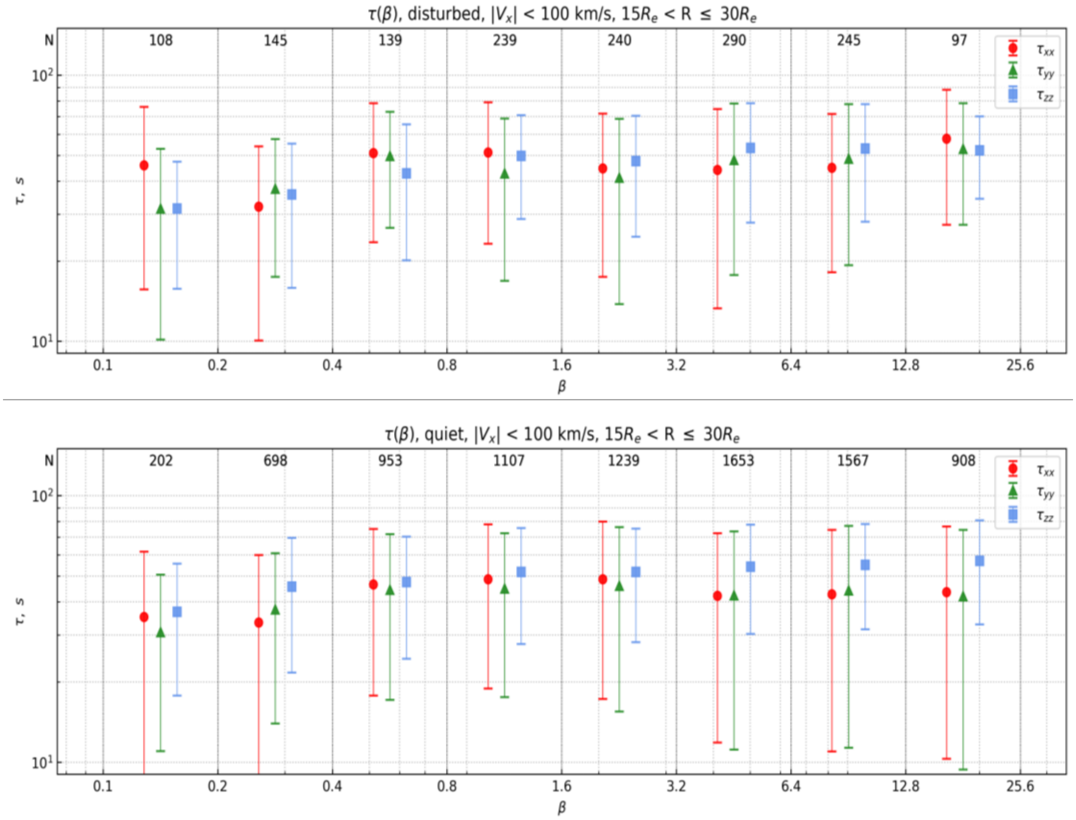

Figure 6. The same as in Figure 5 at *SML*<–200 nT (*a*); *SML*>–50 nT (*b*)

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