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Variation of the plasma turbulence in the central plasma sheet during substorm phases observed by the interball/tail satellite

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Abstract

Fluctuations of the plasma bulk velocity across the plasma sheet are studied using single-point measurements from the Corall instrument on board the Interball/Tail satellite. Several hour-long intervals of continuous data corresponding to quiet geomagnetic conditions and different phases of isolated substorms are analyzed. The plasma sheet flow appears to be strongly turbulent, i.e. dominated by fluctuations that are unpredictable. Corresponding eddy diffusion coefficients were obtained as a function of the autocorrelation time and rms velocity of the fluctuations. It was found that the amplitude of the turbulence and the values of eddy-diffusion coefficients increase significantly during substorm growth and expansion phases and they decrease to their initial level during the recovery phase. We also studied a relationship between the eddy-diffusion coefficients and the absolute value of the geomagnetic field, also measured by the Interball/Tail satellite. It was found that this relationship varies depending on the phase of substorm, indicating possible change in the turbulence regimen with substorm phase.

Keywords: Geomagnetc substorm phase; Turbulence; Diffusion coefficient; Plasma sheet

1. Introduction

Large fluctuations in the flow velocity and in the magnetic field with timescales of a few minutes are constantly observed in the Earth's plasma sheet (see for example Angelopoulos et al. (1993); Ovchinnikov et al. (2000) for flow velocities and Coroniti et al. (1978), Troshichev et al. (1999) for magnetic field). This means that on these timescales the plasma sheet flow is turbulent and the plasma sheet magnetic field is strongly distorted (see Borovsky and Funsten (2003) for a most complete review about the turbulence in the plasma sheet). This fact cannot be ignored when we study any magnetospheric process including geomagnetic substorms. As it is well known, turbulence in ordinary fluids has great consequences, changing the basic

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properties of flow and large-scale flow patterns, even under time averaging (Minotti and Dasso, 2001). It introduces eddy diffusion (mixing) and eddy viscosity, and it increases momentum coupling and drag forces by orders of magnitude.

Despite the fact that the first works about plasma sheet turbulence appeared in the 1970s and 1980s (see for example Montgomery, 1987; Antonova, 1985, 1987), the understanding of the turbulence in the Earth's plasma sheet is still at a very initial stage. We know very little about its dynamics, driving, and dissipation. It is likely that the large-amplitude MHD frequency fluctuations within the plasma sheet are due to eddy type flows (Borovsky and Funsten, 2003). The mechanisms that drive the turbulence of the plasma sheet are also not known: stirring by bursty bulk flows (BBFs) seems likely but not a unique source for the turbulence (Angelopoulos et al., 1994). We do not know yet the dissipation mechanisms: coupling to the ionosphere, cyclotron resonance damping, Landau damping, local reconnection, and plasma wave resistivity and viscosity might play roles (Borovsky and Funsten, 2003).

A previous statistical study of the flow velocities measured in the Earth's plasma sheet at the distance of about $20R_E$ by ISEE-2 (Borovsky et al., 1997) showed that the flow fluctuations are much larger than the mean flows. The autocorrelation time τ_{corr} for the bulk flow velocities V is $\tau_{corr} = 140$ s. The integral scalelength (mixing length) $l_{eddy} = V_{rms}\tau_{corr}$, where V_{rms} is the root mean squared velocity, was calculated to be $1.6R_E$, which simultaneously is the size of a characteristic eddy and the characteristic size of a magnetic-field distortion in the plasma sheet. This prediction was based on a picture in which the characteristic spatial scales in the turbulence are related to the characteristic timescales in the turbulence via the fluctuating flow velocities. The agreement between the fluctuation scale sizes measured during special sweeping intervals, which occur after an interplanetary shock compresses the magnetotail, leading to a global earthward flow in the plasma sheet (Borovsky and Funsten, 2003), and the predicted fluctuation scale sizes provides a confirmation of the numerical value of this important parameter and provides support for the picture of the plasma sheet turbulence being composed of flow eddies.

The turbulence Reynolds number for the plasma sheet $R_{turb} = V_{rms}l_{eddy}/\nu$ was estimated to be $R_{turb} = 10^{11}$ using Coulomb collisions as a source for the kinematic viscosity ν (Borovsky et al., 1997). The magnetic Reynolds number $R_M = 10^{13}$ of the turbulent flows is very high, too. Although the Reynolds numbers are lowered substantially if the electrical coupling of flows to the ionosphere is accounted for, this introduces time delays to the effective viscosity and results in a high-Reynolds-number behavior of the plasma sheet even when coupled to the dissipative ionosphere (Borovsky and Bonell, 2001; Borovsky and Funsten, 2003).

The eddy-diffusion coefficient was reconstructed by Borovsky et al. (1997, 1998) from plasma sheet flow statistics by assuming the eddy transport to be a Markov process. For the majority of studies using the high-altitude satellite data, including this work, the solar-magnetospheric (GSM) coordinate system is used. GSM coordinates are the Cartesian geocentric coordinates, where X-axis is directed to the Sun, Z-axis lies in the one plane with OX-axis and geomagnetic dipole, and Y-axis supplements the X- and Z-axes to the right-hand system. Borovsky et al. (1997, 1998) found that in the X-direction the diffusion coefficient $D_{xx} = 2.6 \times 10^5\,\mathrm{km}^2/\mathrm{s}$. Using the same methodology, Ovchinnikov et al. (2000) have obtained the diffusion coefficient in the Z direction: $D_{zz} = (1-5) \times 10^5\,\mathrm{km}^2/\mathrm{s}$.

Introducing the obtained value of eddy-diffusion coefficient in a diffusion equation, Borovsky et al. (1998) concluded that eddy diffusion could transport material across the z-thickness of the plasma sheet in about 1 h, which is a timescale that roughly agrees with timescales for the density of the plasma sheet to change after sudden changes in the solar wind density. Antonova and Ovchinnikov (1999) obtained similar results. If this estimate is correct, then eddy diffusion (random flow) dominates convection (mean flow) in the plasma sheet for the transport of material (both of which are probably dominated by BBF transport (see Angelopoulos et al. (1994) and references therein)).

In addition to transport the eddy diffusion should also produce mixing in the plasma sheet. For the plasma sheet turbulence (Borovsky et al., 1997), it is observed on the timescale of a few hours that $\Delta n/n \approx 0.15$ and $\Delta T/T \approx 0.15$, while $\Delta V/V \approx 1$. Here n and T are plasma number density and temperature, respectively. There are larger variations in the plasma sheet properties over longer periods, but much of the slower variation is due to variation in the properties of the solar wind (Borovsky et al., 1998). Hence the plasma sheet in general appears to be well mixed, and this mixing may be a consequence of the flow turbulence present therein.

Antonova and Ovchinnikov (1999) developed a model of the turbulent plasma sheet based on the assumption that the compression of the plasma by the dawn–dusk electric field is compensated by a eddy-diffusion flux, creating a quasi-stable configuration. This made it possible to predict the size and the shape of the plasma sheet for different values of the interplanetary magnetic field (IMF). In particular, it was found that under strong northward IMF a bulge develops in the center of the plasma sheet. When the northward orientation persists for a long time, this leads to the bifurcation of the plasma sheet and the formation of the theta aurora (Antonova and Ovchinnikov, 1999; Antonova, 2002).

However, the model developed is sensitive to the relationship between the eddy-diffusion coefficient and the geomagnetic field, which until now has not been studied.

For understanding the dynamics of the magnetosphere, it is important to determine whether a relationship exists between the plasma turbulence and geomagnetic substorms. Ovchinnikov et al. (2000) studied this relationship by analysing the variation of the eddy-diffusion coefficients obtained with INTERBALL/TAIL probe data during the development of isolated substorms. It was found that the eddy-diffusion coefficient increases during growth and expansion phases. However, the small number of cases (only three) prevented definitive conclusions.

In this work we extend these studies of eddy-diffusion for quiet geomagnetic time intervals and for isolated geomagnetic substorms. We also study the influence that geomagnetic substorms have on the relationship between the eddy-diffusion coefficients and the absolute value of the geomagnetic fields.

2. Instruments and data analysis

For this study we used INTERBALL/TAIL probe data, obtained in October, November, December, and January 1997–1998. During these months, the satellite orbit was crossing the plasma sheet between 7 and 20 Earth's radii in the antisolar direction. Ion measurements were made by a hemispherical electrostatic ion energy spectrometer (CORALL) in the range from 30 to 24,200 eV/q (Yermolaev et al., 1997). We also used 2 min averaged geomagnetic field data, obtained by a digital fluxgate magnetometer MIF-M/PRAM (Klimov et al., 1997).

To obtain the eddy-diffusion coefficient we first calculated the autocorrelation function of the bulk flow velocities in the Y- and Z-directions as

$$A_{V_{Y,Z}}(\tau) = \frac{\sum_{i=1}^{N}(V_{Y,Z}(i) - \langle V_{Y,Z}\rangle)(V_{Y,Z}(i+k) - \langle V_{Y,Z}\rangle)}{\sum_{i=1}^{N}(V_{Y,Z}(i) - \langle V_{Y,Z}\rangle)^2}, \quad (1)$$

where $V_{Y,Z}$ is the bulk velocity for Y or Z-directions in the GSM coordinate system, calculated from ion distribution functions obtained once each satellite rotation period, $\tau = \Delta\tau k$ is the time delay in seconds, $\Delta\tau$ is the satellite rotation period (120 s), $\langle V\rangle = \sum_{i=1}^{N} V_{Y,Z}(i)/N$ is the mean bulk velocity.

The autocorrelation time ($\tau_{\text{auto}\,Y,Z}$) was determined by fitting the autocorrelation function $A_{V_{Y,Z}}(\tau)$

$$A_{V_{Y,Z}}(\tau) = \exp(-\tau/\tau_{\text{auto}\,Y,Z}). \quad (2)$$

Fig. 1shows an example of the autocorrelation function fitted by Eq. (2). The root mean squared (rms) velocity

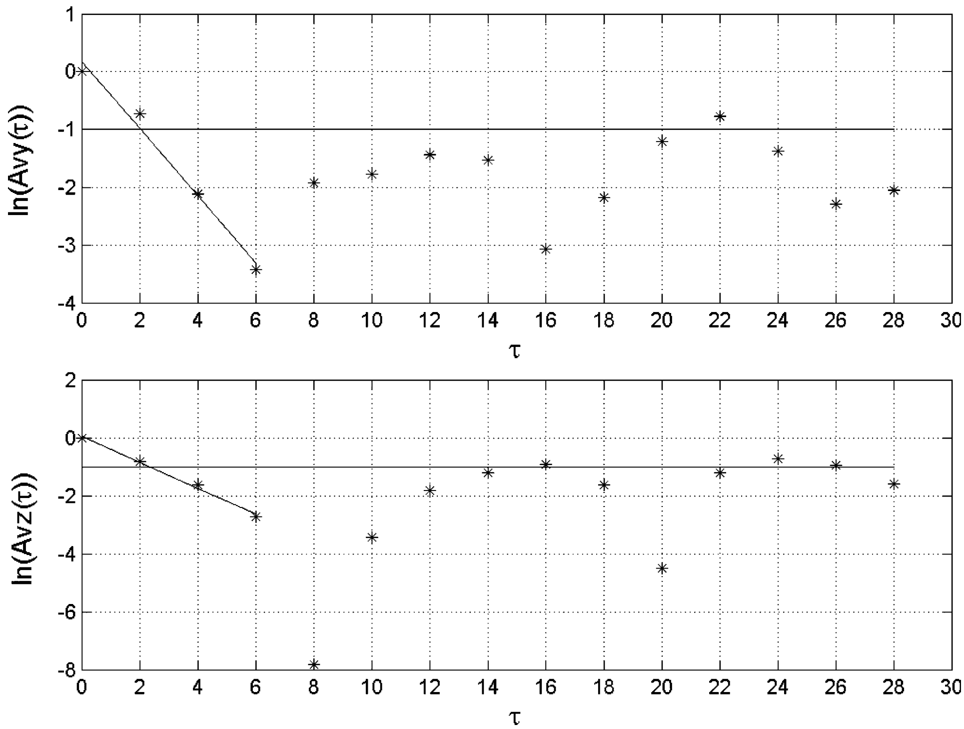

Fig. 1. An example of the autocorrelation function fit by $A_V(\tau) = \exp(-\tau/\tau_{\text{auto}})$. Horizontal line remarks the decay in e times.

was determined as

$$V_{\mathrm{rms}\,Y,Z} = \sqrt{\frac{\sum_{i=1}^{N} (V_{Y,Z}(i) - \langle V_{Y,Z} \rangle)^2}{N}}. \tag{3}$$

The eddy-diffusion coefficient was obtained as

$$D_{YY,ZZ} = \frac{V^2_{\mathrm{rms}\,Y,Z}\tau_{\mathrm{auto}\,Y,Z}}{2}. \tag{4}$$

Autocorrelation times, rms velocities, and the resulting eddy-diffusion coefficients were determined using 15 bulk velocity points, i.e. every 30 min. From the analysis of auroral electrojet (AL and AE) indices, we found 30 time intervals for growth phase, 24 for expansion phase, 64 for recovery phase, and 598 for quiet geomagnetic conditions ($AE < 100$ nT), when the satellite was situated inside the plasma sheet. It is necessary to mention that we were not always able to follow all phases of an isolated substorm. Sometimes we were able to analyse only the beginning or the end of them. Fig. 2 summarizes the mean eddy-diffusion coefficients for all mentioned situations. The satellite position with respect to the neutral sheet and the distance from the Earth, as well as the intensity of substorm, varied significantly from substorm to substorm. This produced strong spread of individual points. Still, the average picture is convincing. The eddy-diffusion coefficient increases almost one order of magnitude during the expansion phase.

Antonova and Ovchinnikov (1999) examined a model for the turbulent plasma sheet for three different cases: the diffusion coefficient is inversely proportional to squared magnetic field, to the magnetic field, and does not depend on the geomagnetic field. At that time, was no experimental evidence about this relationship and its possible change during substorm. Fig. 3 shows the dependence of the eddy-diffusion coefficient on the absolute value of geomagnetic field for quiet time intervals, and for the phases of isolated substorms. As can be seen, there is a "cloud" of points corresponding to each 30-min time interval eddy-diffusion coefficient versus the absolute value of geomagnetic field, averaged during the same time interval. Taking into consideration, that the points were not distributed homogeneously with the magnetic field, we divided the data set into non-equal intervals, marked in the Fig. 4 by vertical dashed lines. Inside each interval both the eddy-diffusion coefficient and the geomagnetic field were averaged, and after that the mean values were fitted

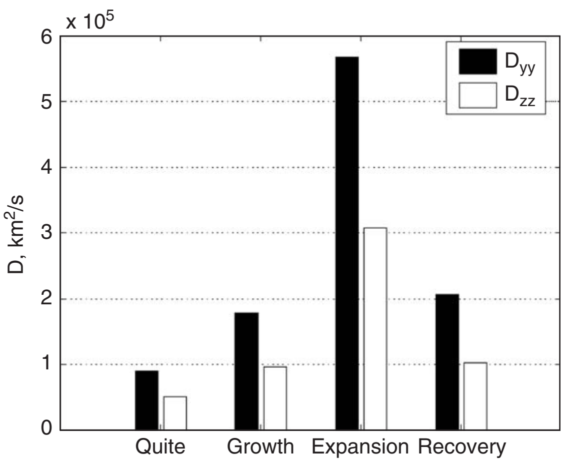

Fig. 2. Mean values of diffusion coefficients for growth, expansion, and recovery phases of isolated substorms, and quiet time intervals.

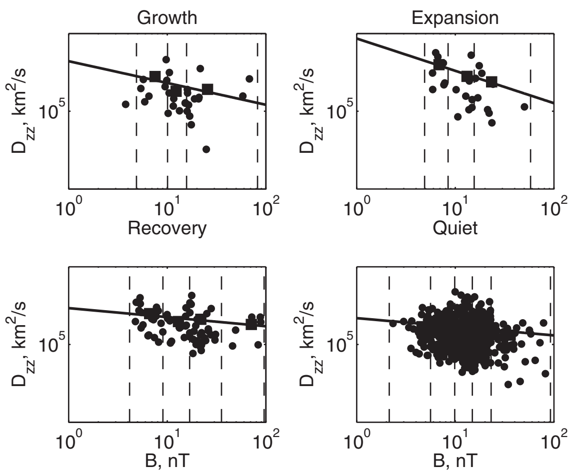

Fig. 3. Relationship between the eddy-diffusion coefficient and the absolute value of geomagnetic field for growth, expansion, and recovery phases of isolated substorms, and quiet time intervals. Best fits by $D = bB^{\alpha}$ are shown as straight lines.

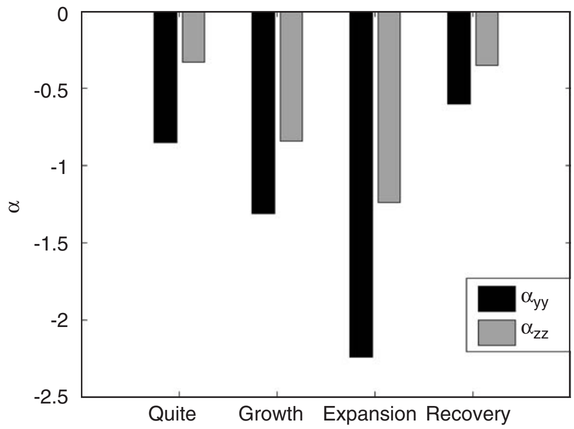

Fig. 4. Variation of the relationship between the eddy-diffusion coefficient and the absolute value of geomagnetic field with the phase of isolated substorm.

according to $D = bB^{\alpha}$. Fig. 4 shows the variation of the α coefficient with the phases of isolated substorms. As can be seen, the relationship between the eddy-diffusion coefficient and the absolute value of the geomagnetic field changes significantly with the substorm phase. The diffusion coefficient decreases much more strongly with geomagnetic field during growth and especially expansion phases. This effect is more notable for the Y-direction. We also studied the variation of the eddy-diffusion coefficient with the variation of the absolute value of the geomagnetic field components and obtained similar results.

3. Conclusions

The plasma sheet is affected by the turbulence within during quiet and disturbed geomagnetic conditions. It was found that the eddy-diffusion coefficient, which characterizes the level of mixing of plasma inside the plasma sheet, increases significantly during the growth and especially the expansion phases. The eddy-diffusion coefficient becomes more dependent on the strength of the geomagnetic field. For quiet time intervals the dependence obtained corresponds more to the case of non-magnetized high-β plasma ($\alpha \approx 0$). During the growth and especially the expansion phases this relationship changes ($\alpha \approx -2$) and has no clear theoretical explanation.

According to the Antonova and Ovchinnikov (1999) model, these changes in the eddy-diffusion coefficient should affect the thickness of the plasma sheet, producing its expansion during the expansion phase.

In our study we used the following satellite data: $-26 < X < -6$, $-20 < Y < -20$, and $-12 < Y < -12 R_E$ in GSM coordinate system. Of course, the quasi-diffusion coefficient must depend on the satellite position respect to the neutral sheet and to the midnight meridian. Preliminary analysis showed that the most turbulent area is situated close to the neutral sheet, with the diffusion coefficient increasing with the distance from the Earth. Now we are doing the careful analysis of these effects.

The changes observed also should affect the eddy-diffusive transport of plasma, the mixing of plasma that tends to homogenize the plasma sheet, and the momentum transfer from the magnetosheath flow into the magnetotail.

We plan to analyse these features in future works.

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