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Determination of the Turbulent Diffusion Coefficient in the Plasma Sheet Using the Project INTERBALL Data

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Abstract—The results of an analysis of velocity fluctuations in the plasma sheet of the Earth's magnetotail measured onboard INTERBALL *Tail Probe* satellite are presented. The hodographs of the velocity in directions (Y, Z) and correlation functions are presented for a number of passages when the satellite was in the plasma sheet for a long time. The turbulent diffusion coefficients are calculated. A comparison of the obtained diffusion coefficients with those predicted theoretically in [1] is carried out. It is shown that the results of observations confirm theoretical predictions.

1. INTRODUCTION

The results of observations of the electric field fluctuations on the auroral field lines and in the tail of the Earth's magnetosphere [2–4] formed a basis for the assumption put forward in [5] regarding the existence of the turbulent mixing in the plasma sheet of the Earth's magnetotail. Observations of the velocity fluctuations in the plasma sheet [6, 7] reinforced the assumption of a persisting turbulization of the plasma sheet. The results of observations formed a basis for the elaboration of a theory of the quasi-equilibrium plasma sheet with a developed medium scale turbulence (see [1, 8]), which gives a possibility of explanation of the quasi-equilibrium existence of a plasma structure in conditions when turbulent fluctuations lead to its destruction. One result of the theoretical analysis was the prediction of the values of turbulent diffusion coefficients. The predictions of the theory were confirmed after the publication in 1998 of the averaged diffusion coefficient obtained by Borovsky *et al.* [9] on the basis of data of the *ISEE-2* satellite. The diffusion coefficient in [9] was calculated by the measurements of the plasma hydrodynamic velocity and its correlation time, and comprised 2.6×10^5 km^2/s. The method of observations onboard the *ISEE-2* satellite (only the velocities in directions X and Y were measured) gave the possibility of calculation of the diffusion coefficient only along the sheet, and the published value in Z direction can be considered only as an assumption. The data of observations with the CORALL instrument onboard the INTERBALL *Tail Probe* satellite allowed one to reconstruct with high accuracy the velocities of plasma motion in the directions Y and Z, which gave a possibility to estimate the value of the coefficient of diffusion across the plasma sheet. In this work, the velocity fluctuations in the plasma sheet are investigated for a number of cases when the satellite was for a long time in the plasma sheet near the neutral sheet, the coefficients of diffusion across the sheet are calculated, and a comparison is carried out of the theoretical predictions [1, 8] with experimental data.

2. MEASUREMENT TECHNIQUE AND ESTIMATIONS OF THE DIFFUSION COEFFICIENT

The *Tail Probe* of the INTERBALL project was launched on August 3, 1995 to the orbit with the following parameters: altitude of apogee $H_a \approx 200000$ km, altitude of perigee $H_p \approx 900$ km, inclination $\approx 63°$, and period $T \approx 92$ h. Such an orbit allowed the measurements of both the geomagnetic tail and outer boundaries of the magnetosphere to be made. The satellite rotated around its axis with a period of about 120 s, the axis of rotation being directed to the Sun.

The results of measurements by the ion energy-angular spectrometer CORALL [10, 11] were used in order to determine the diffusion coefficient. The plasma spectrometer CORALL measured ion characteristics in the energy range from 30 eV to 24.2 keV per unit of charge. A fan-shaped field of view of the instrument had dimensions $5° \times 110°$ and was divided into five angular sectors. A combination of a large field of view and rotation of the satellite allowed one to measure the three-dimensional distribution function of ions every 120 s.

The values of the moments of the ion distribution function measured by the instrument CORALL were used in order to calculate the diffusion coefficient. These moments were calculated by searching a shifted Maxwellian distribution, which would fit best the measured distribution function.

We have chosen the following passages of the *Tail Probe* through the plasma sheet: November 28, 1995, 09:40–16:00; December 9, 1995, 14:00–19:30; December 17, 1995, 08:40–13:00; December 28,

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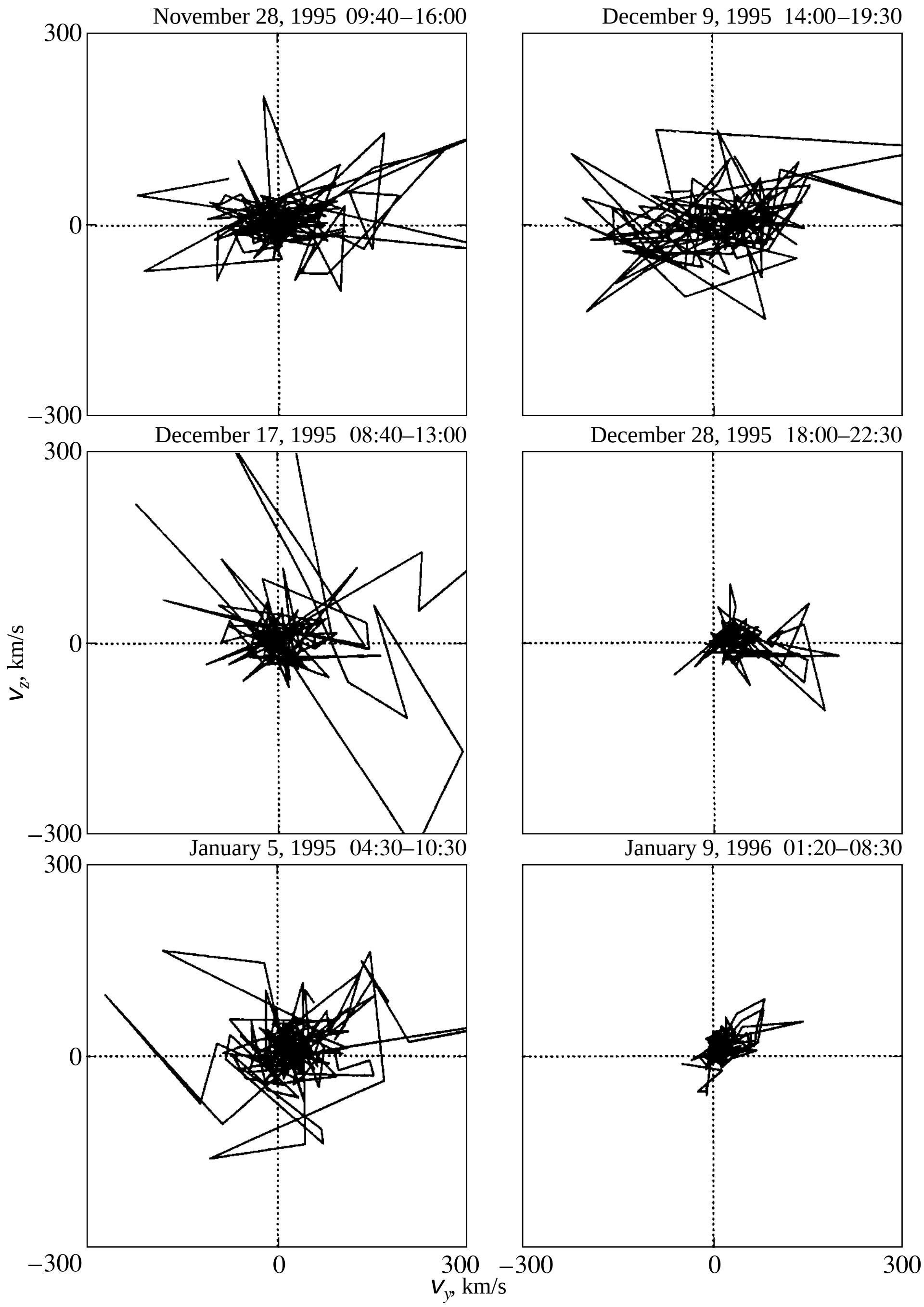

Fig. 1. Hodographs of plasma velocities in the plasma sheet according to the data of the CORALL instrument (INTERBALL project).

1995, 18:00–22:30; January 5, 1996, 04:30–10:30; and January 9, 1996, 01:20–08:30.

The data on the interplanetary magnetic field, plasma density, the velocity and pressure in the solar wind at the chosen time intervals were obtained from the *WIND* spacecraft.

During intervals of December 9, 1995, December 28, 1995, and January 9, 1996 the solar wind was quiet, its velocity was 350–400 km/s, pressure ≈2 nPa; the *z*-component of the interplanetary magnetic field (IMF) varied from –3 to +3 nT. On January 5, 1996, and December 17, 1995, the velocity and pressure in the solar wind were somewhat larger: ≈430 km/s and 2–4 nPa respectively; the *z*-component of IMF varied from 0 to –5 nT. On the contrary, on November 28, 1995, the solar wind was strongly disturbed. The velocity varied from 400 to >600 km/s, pressure from 2 to >10 nPa, *z*-component of IMF from –10 to 10 nT.

Figure 1 presents the hodographs of the velocities for the chosen intervals. In four cases the fluctuations of

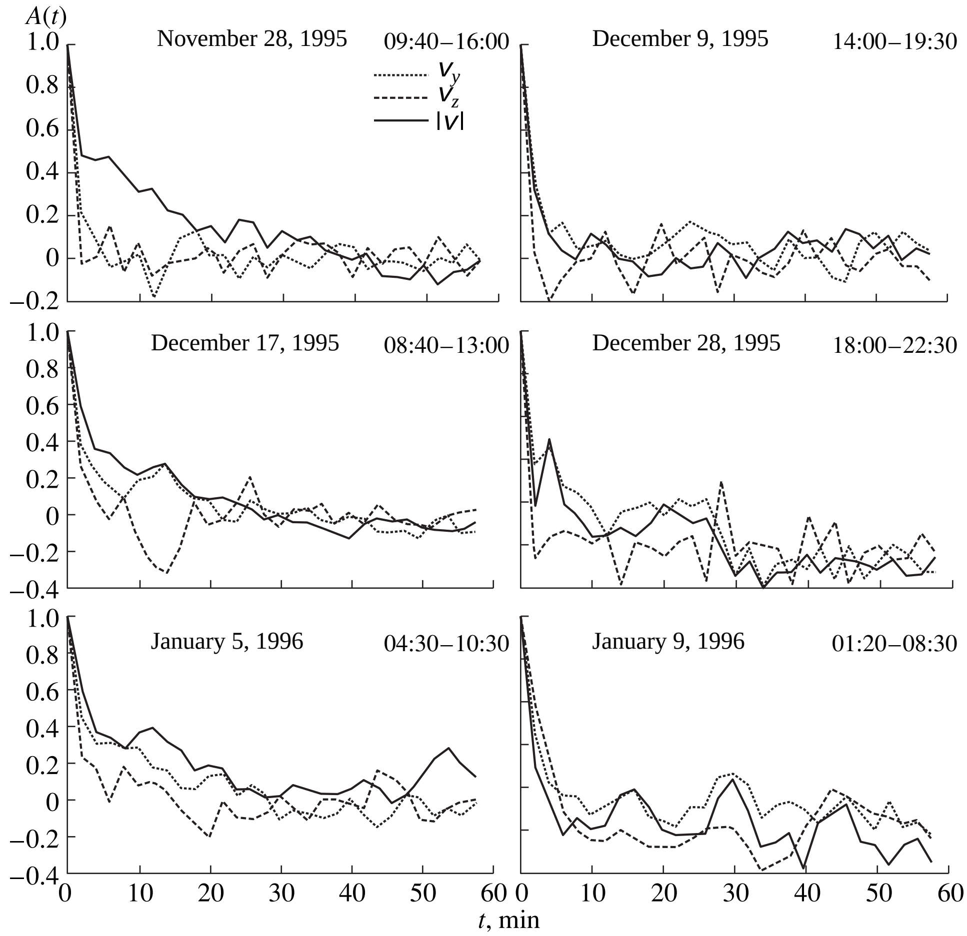

Fig. 2. Autocorrelation functions of *y*-, and *z*-components, and of the velocity magnitude in the plasma sheet.

velocities turned out to be much larger than the mean velocity, in two cases they are comparable. No clear-cut relation with the conditions in the solar wind is observed. However, this does not exclude the existence of such a relation due to the small statistics of observations.

The diffusion coefficient was calculated according to the formula

$$D = \frac{(V_z^{\rm rms})^2 \tau_{\rm auto}}{2}. \quad (1)$$

The correlation time $\tau_{\rm auto}$ was derived by investigating the autocorrelation function

$$A(\tau) = \frac{\sum (V(t) - \langle V \rangle)(V(t+\tau) - \langle V \rangle)}{\sum (V(t) - \langle V \rangle)^2}. \quad (2)$$

Calculated autocorrelation functions are presented in Fig. 2. Two-minute data that are available do not allow us to calculate exactly the correlation time. As a rule, the correlation between two consecutive measurements of velocity is already very small. This result for V_y and $|V|$ completely agree with the data of [12]. The autocorrelation function and the time of correlation for V_z turned out to be close to those obtained in [12], which confirms plausibility of the assumption of an isotropic nature of the turbulence. Thus, we assume in the estimation of the diffusion coefficient that the time of correlation is 2 min. Table contains the mean plasma velocities, their root mean square values in the directions *Y* and *Z*, respectively, and the diffusion coefficient across the sheet. In this case, we restricted ourselves to the consideration of only this coefficient, since the goal of our work was a comparison of theoretical predictions with experimental data. At this stage of investigation, we could not obtain a distribution of the diffusion coefficient along the *Z* direction, across the plasma sheet, and its dependence upon the magnetic field. Deduced values of the diffusion coefficients can be considered only as some averaged estimated values.

3. THEORETICAL PREDICTION OF THE TURBULENT DIFFUSION COEFFICIENT AND COMPARISON WITH EXPERIMENTAL DATA

The assumption of the compensation of the convective and diffusion flows across the equilibrium plasma sheet [1], provided for a possibility of prediction, on the

Table

Date	UT	$\langle v_y \rangle$, km/s	v_y^{rms}, km/s	$\langle v_x \rangle$, km/s	v_x^{rms}, km/s	D_{zz}, km^2/s
November 28, 1995	09:40–16:00	12.0	72.5	6.7	39.2	0.92×10^5
December 9, 1995	14:00–19:30	12.1	89.1	4.0	45.4	1.24×10^5
December 17, 1995	08:40–13:00	16.8	80.9	15.1	79.2	3.76×10^5
December 28, 1995	18:00–22:30	41.3	4.0	57.5	25.4	0.39×10^5
January 5, 1996	04:30–10:30	28.6	73.7	11.7	48.8	1.43×10^5
January 9, 1996	01:20–08:30	15.2	25.5	13.5	23.1	0.32×10^5

basis of the data on the distribution of the magnetic field across the plasma sheet, of the value of the diffusion coefficient that is necessary for the quasi-equilibrium existence of the plasma sheet with a prescribed distribution of the magnetic field in the sheet and a given value of the velocity of regular motion of plasma toward the sheet in the tail lobes. In this case, it was assumed that the regular motion to the center of the sheet is compensated by the quasi-diffusion flow opposite in direction to the density gradient, that a condition of magnetostatic equilibrium across the sheet is valid, and that the plasma temperature is specified and does not depend on coordinates. Then

$$D = \frac{n v_z}{\partial n / \partial z}, \quad (3)$$

$$n = \frac{1}{8\pi T}(B_L^2 - B^2), \quad (4)$$

$$v_z = v_z^0 \frac{b_k + 1}{b_k + b}, \quad (5)$$

where n is the plasma density, v_z is the velocity of the plasma regular motion toward the sheet in the tail lobes, B_L is the magnetic field in the tail lobes, B is the magnetic field inside the sheet, T is ion temperature (it was assumed that ions made dominant contribution to the plasma pressure), $b = B_L/B$, and $b_k \ll 1$ is a correction factor, which takes into account the deviation of the plasma motion regular velocity from the drift velocity in the center of the sheet. It was assumed that $v_z^0 = 50$ km/s (which corresponds to the dawn–dusk electric field of 1 kV/1 R_E and to the magnetic field in the tail lobes $B_L = 30$ nT), and $b_k = 0.1$. The magnetic field distribution across the plasma sheet was taken from [13]. In [13], the magnetic field distribution across the plasma sheet was obtained on the basis of measurements onboard the *AMPTE/IRM* satellite by the method of superposed epochs for the preliminary and explosive phases of a substorm. In accordance with data of [13], the current before the substorm is located in a narrow region near the neutral line (the current sheet constitutes about ~0.2 of the thickness of the plasma sheet). Within 45–67.5 min after the beginning of the explosive phase, the current is almost uniformly distributed along the sheet, and the magnetic field almost linearly increases when one moves off the sheet center. Solid lines in Fig. 3 represent the predicted values of the diffusion coefficient at the preliminary and explosive phases of the substorm. Horizontal straight lines represent the values which are put in table, except for the case of December 17, 1995. In the latter case, the diffusion coefficient turned out to be essentially larger than in other cases. This seems to be associated with the

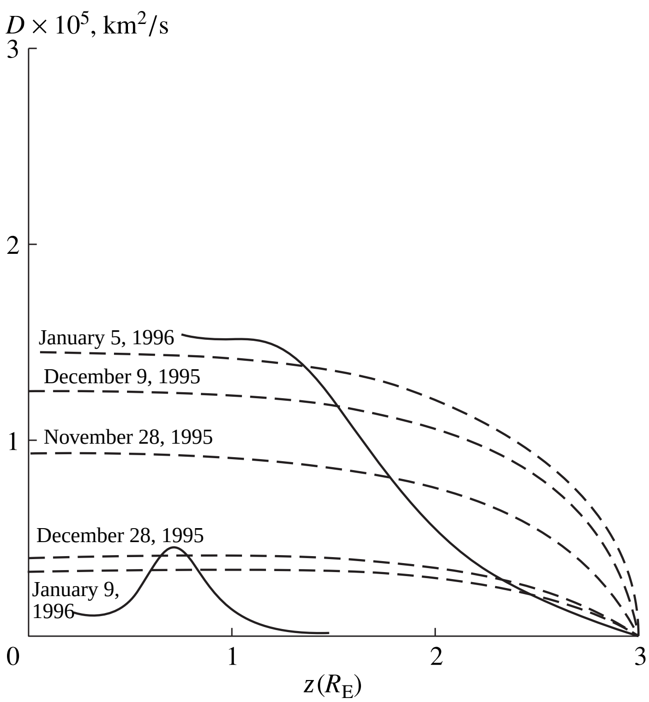

Fig. 3. The comparison of the values of the turbulent diffusion coefficients D calculated on the basis of measurements onboard the INTERBALL *Tail probe* with their predicted values.

Solid lines represent the results of model calculations based on the data [13]: the lower one corresponds to 22.5–0 min before the beginning of the explosive phase, and the upper one corresponds to 45–67.5 min after the beginning of the explosive phase. Dotted lines are the turbulent diffusion coefficients calculated according to the data of the INTERBALL *Tail Probe* satellite (except for December 17, 1995). The dependence of D on z is chosen according to [9].

existence of intense regular plasma flows. The analysis of the obtained experimental values and of those predicted theoretically shows that they agree well.

4. DISCUSSION AND CONCLUSIONS

The results of measurements onboard the INTERBALL *Tail Probe* spacecraft provided a possibility to make a direct comparison of the experimental data with the predictions of the theory of a plasma sheet with developed medium scale turbulence [1, 8]. The obtained diffusion coefficients across the plasma sheet fell into the range $(0.32–3.76) \times 10^5$ km^2/s. They should be considered as coefficients averaged over a sufficiently long time interval (2–4 h) and over the plasma sheet thickness. These measured values of the diffusion coefficient agree well with those predicted theoretically. Investigation of the spatial distribution of the diffusion coefficient requires a higher time resolution. Our subsequent works will be dedicated to the investigation of the dependence of the diffusion coefficient on both the solar wind parameters and geomagnetic activity. The first results of such investigations presented at the Fifth International Conference on Substorms ICS-5 [14] demonstrated a strong dependence of the turbulent diffusion coefficient on the substorm phase. In this case, the level of fluctuations and the diffusion coefficient strongly increased in the beginning of the explosive phase and then gradually decreased to the quiet level. Of a special interest is the investigation of the nature of the observed turbulence and dependence of its level on the solar wind parameters. A considerable difference of the time of correlation of the magnetic field and plasma velocity noted in [12] does not favor the magnetohydrodynamic nature of the observed turbulence. The ion distribution functions frequently differ from Maxwellian ones and contain the beams, which can be considered as ballistic modes of the plasma turbulence. Investigations of the forming of such modes can be of interest not only for the physics of plasma processes in the tail of the Earth's magnetosphere, but also for other plasma systems. Thus, this work can be considered only as one of the first steps in investigating the properties of the plasma sheet turbulence using a number of specific examples.

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REFERENCES

1. Antonova, E.E. and Ovchinnikov, I.L., Equilibrium of a Turbulent Current Layer and the Current Sheet of the Earth's Magnetotail, *Geomagn. Aeron.*, 1996, vol. 36, no. 5, pp. 7–14.
2. Mozer, F.S., Cattell, C.A., Hudson, M.K., Lysak, R.L., Temerin, M., and Torbert, R.B., Satellite Measurements and Theories of Low Altitude Auroral Particle Acceleration, *Space Sci. Rev.*, 1980, vol. 27, no. 2, pp. 153–213.
3. Maynard, N.C., Heppner, J.P., and Aggson, T.L., Turbulent Electric Fields in the Nightside Magnetosphere, *J. Geophys. Res. A*, 1982, vol. 87, no. 3, pp. 1445–1454.
4. Weimer, D.R., Goertz, C.K., Gurnett, D.A., Maynard, N.C., and Burch, J.L., Auroral Zone Electric Fields from *DE-1* and *2* at Magnetic Conjunctions, *J. Geophys. Res. A*, 1985, vol. 90, no. 8, pp. 7479–7494.
5. Antonova, E.E., Nonadiabatic Diffusion and Equalization of Density and Temperature in the Plasma Sheet of the Earth's Magnetosphere, *Geomagn. Aeron.*, 1985, vol. 25, no. 4, pp. 623–627.
6. Angelopoulos, V., Baumjohann, W., Kennel, C.F., *et al.*, Bursty Bulk Flows in the Inner Central Plasma Sheet, *J. Geophys. Res. A*, 1992, vol. 97, no. 4, pp. 4027–4039.
7. Angelopoulos, V., Kennel, C.F., Coroniti, F.V., *et al.*, Characteristics of Ion Flow in the Quiet State of the Inner Plasma Sheet, *Geophys. Res. Lett.*, 1993, vol. 20, no. 16, pp. 1711–1714.
8. 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. A*, 1999, vol. 104, no. 8, pp. 17289–17298.
9. Borovsky, J.E., Thomsen, M.F., and Elphic, R.C., The Driving of the Plasma Sheet by the Solar Wind, *J. Geophys. Res. A*, 1998, vol. 103, no. 8, pp. 17617–17639.
10. Yermolaev, Yu.I., Interball Observations of the Plasma Sheet, *Adv. Space Res.*, 1997, pp. 983–991.
11. Yermolaev, Yu.I., Observations of the Plasma Sheet: INTERBALL Project, *Kosm. Issled.*, 1998, vol. 36, no. 3, pp. 273–281.
12. 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, pp. 1–34.
13. Kistler, L.M., Baumjohann, W., Nagai, T., and Möbius, E., Superposed Epoch Analysis of Pressure and Magnetic Field Configuration Changes in the Plasma Sheet, *J. Geophys. Res. A*, 1993, vol. 98, no. 6, pp. 9249–9258.
14. Antonova, E.E., Ovchinnikov, I.L., and Yermolaev, Yu.I., The Coefficient of the Diffusion in the Plasma Sheet during Substorm: *Interball/Tail* Observations, *Fifth Int. Conf. on Substorms (ICS-5), Abstracts*, St. Petersburg, 2000, p. 79.