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Estimation of the eddy-diffusion coefficients in the plasma sheet using THEMIS satellite data

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ABSTRACT

We have studied the turbulent processes in the central plasma sheet using the tailward alignments of THEMIS satellites. Fluctuations of the plasma bulk velocity and corresponding eddy-diffusion coefficients were calculated using the simultaneous data obtained by THEMIS satellites situated inside the central plasma sheet between approximately 5 and 30 Earth's radii. The instantaneous profiles of eddy-diffusion coefficients show an increase with distance from the Earth in the tailward direction. This result agrees with previous statistical studies, and it is relevant for the understanding of the dynamics of the turbulent plasma sheet.

1. Introduction

There is mounting evidence that plasmas can demonstrate very complex behavior that includes multi-scale dynamics, emergence and self-organization, phase transitions, turbulence, spatio temporal chaos, etc. (Lu, 1995; Carreras et al., 1996; Uritsky and Pudovkin, 1998; Uritsky et al., 2001, 2006a, 2006b; Rosa et al., 1998; Chang, 1999; Biskamp, 2000; Klimas et al., 2000, 2005, 2010; Valdivia et al., 2003, 2005, 2006; Voros et al., 2004; Zimbardo et al., 2010)

The magnetosphere is formed as a result of the interaction between the solar wind supersonic and super-alfvenic turbulent flow and the geomagnetic field. It is well known that turbulence in ordinary fluids significantly changes the basic properties of the flow patterns around an object; therefore, the turbulent interaction of the Earth's magnetic field and the solar wind should also play an important role in the dynamics of the Earth's magnetosphere. For example, Borovsky and Funsten (2003b) and Borovsky (2005) studied the relevance of the turbulence in the solar-wind/magnetosphere coupling, and found that the geomagnetic activity is greater when the solar wind turbulence is "louder". However, there is a significant difference between the turbulent wake of a fluid behind an ordinary obstacle and the geomagnetic tail. For instance, the cross section radius of the ordinary wake is close to the obstacle size, while the magnetotail is separated into the plasma sheet and the tail lobes.

Along this line (Antonova and Ovchinnikov, 1996, 1999, 2001; Antonova, 2002) proposed that a reasonably stable turbulent plasma sheet can be formed when the regular plasma transport across the plasma sheet, regulated by the dawn–dusk electric field, is compensated by the eddy-diffusion turbulent transport. They consider that the particle flux is equal to

$$\mathbf{S} = n\langle \mathbf{V} \rangle - D\nabla n,$$

where n is the average of the turbulent plasma particle density, $\langle \mathbf{V} \rangle$ is the average bulk velocity, and D is the eddy-diffusion coefficient. When the turbulent fluctuations act to expand the plasma sheet, the large-scale electrostatic dawn–dusk electric field acts to compress it, in a manner that is similar to a laboratory plasma pinch which is compressed by the induction electric field. When the expansion and compression compensate each other, a stationary structure can be formed. This assumption predicts an eddy-diffusion coefficient in the Z direction of the order of 10^5 km^2/s, to reproduce the observed plasma sheet thickness. This value agrees with the estimated eddy-diffusion coefficients obtained from measurements at ISEE-2, Interball/Tail, GEOTAIL and THEMIS satellites (Borovsky et al., 1997, 1998; Borovsky and Funsten, 2003a; Ovchinnikov et al., 2000; Troshichev et al., 2002;

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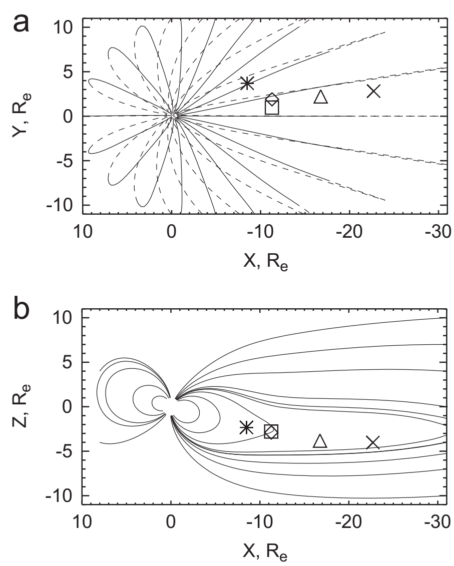

Fig. 1. Positions of the five THEMIS satellites in GSM coordinates during February 22, 2008, at 8:00 UT, which corresponds to a promising satellite alignment in the tailward direction. From left to right: *XY* plane (a) and *XZ* plane (b). The symbols represent each satellite: A (asterisk), B (cross), C (triangle), D (square), and E (diamond).

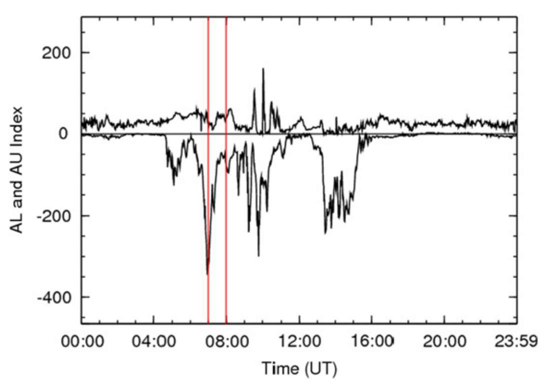

Fig. 2. The AL and AU indexes during February 22, 2008.

Stepanova et al., 2005, 2009, 2011). Recently, this theory has been verified in detail by Stepanova and Antonova (2011), using Cluster satellite data and SuperDarn data. It was shown that all properties of the turbulent plasma sheet are consistent with the prediction of Antonova and Ovchinnikov (1996, 1999, 2001), Antonova (2002), including the sheet thickness and the expected magnetic configuration.

Eddy-diffusion transport in the plasma sheet is affected by both the location inside the plasma sheet and the geomagnetic activity. For example, Neagu et al. (2002, 2005) compared studies made with ISEE-2 and AMPTE/IRM satellite measurements and showed that both velocity and geomagnetic field fluctuations increase with the auroral electrojet (AE) index. It was also found that the level of these fluctuations correlates with solar activity. Ovchinnikov et al. (2000) and Stepanova et al. (2005, 2009, 2011) analyzed the relationship between the eddy-diffusion coefficient in the plasma sheet and the phase of isolated geomagnetic substorms using Interball/Tail and THEMIS satellite data. It was shown that the values of the eddy-diffusion coefficient increase significantly during the growth and expansion phases, being more pronounced in the later. The turbulent transport in the plasma sheet is also affected by the orientation of the interplanetary magnetic field (IMF) (Nagata et al., 2008; Wang et al., 2010).

Nevertheless, the interplay between the turbulent processes in the plasma sheet and geomagnetic substorms is not clear. Hence, it is necessary to concentrate a significant effort in understanding all of the processes involved in the different time and space scales. This work is a first step in attempting to reproduce a simultaneous turbulent eddy transport profile using multiple satellites of the THEMIS mission while they were aligned in the tailward direction close to the tail plasma sheet.

2. Instrumentation and data analysis

For this study we used THEMIS data that was acquired when the five satellites were aligned in the Earth plasma sheet. According to the satellite orbits, we analyzed the data between 5 and 30 Earth Radii. We use the moments of the ion distribution functions obtained from the on-board moments calculations of

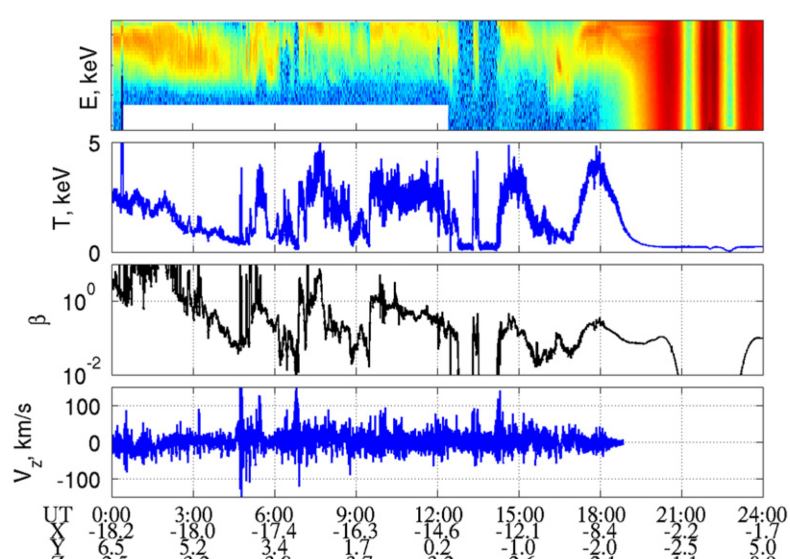

Fig. 3. From top to bottom: the proton energy distribution, equivalent plasma β, magnetic field strength, *Z* component of the plasma bulk velocity, using THEMIS B probe for February 22, 2008.

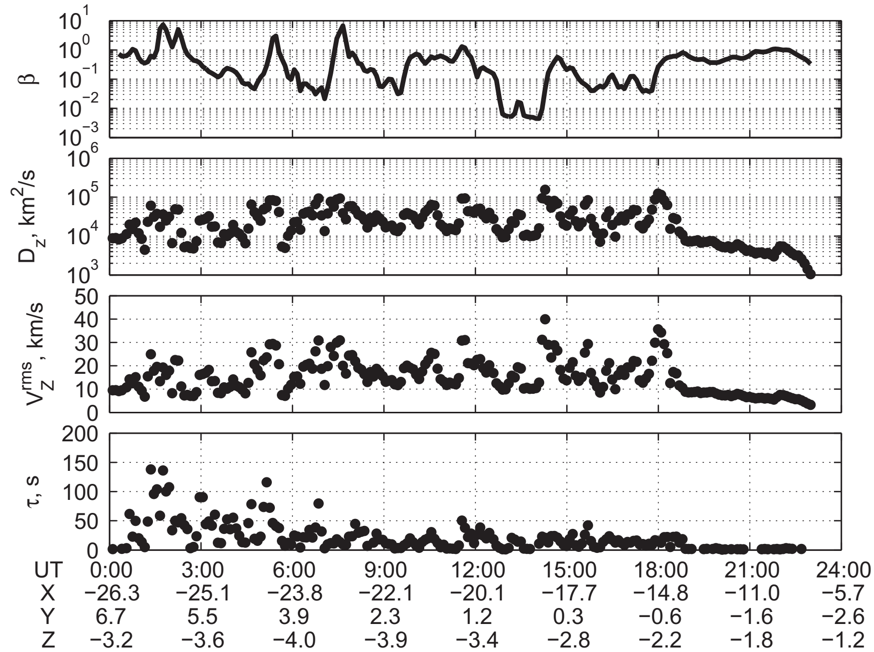

Fig. 4. From top to bottom: average β, D_{zz}, $V_{rms,zz}$, τ_{zz}, during each 12 min interval of February 22, 2008, using THEMIS B probe. Adjacent intervals overlap for half of their interval (6 min), and we use the middle of the interval to mark the time.

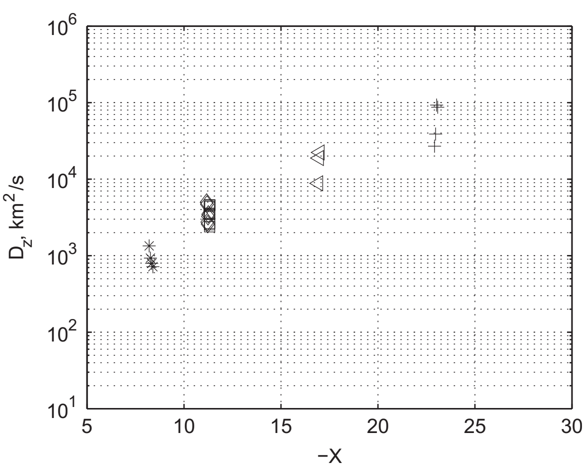

Fig. 5. Multiple estimates of D_{zz} in km^2/s as a function of x, when our criterion is satisfied, for the 5 satellites during the 1-h interval between 7:00 and 8:00 UT of Fig. 4. The symbols represent each satellite: A (asterisk), B (cross), C (triangle), D (square), and E (diamond).

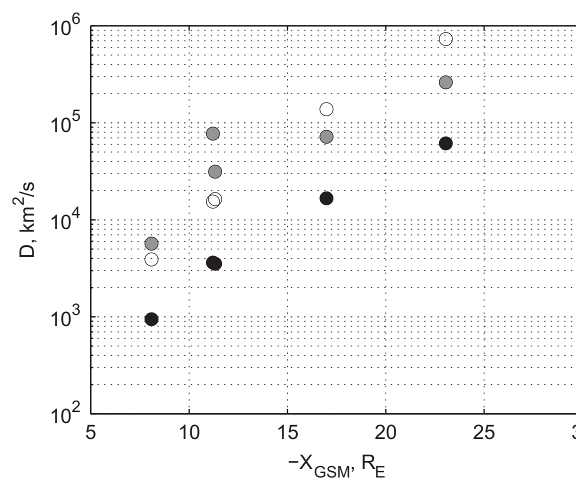

Fig. 6. The time averaged diagonal elements of the eddy-diffusion tensor as a function of x, for all satellites, with D_{xx} (white circle), D_{yy} (gray circle), and D_{zz} (black circle). The values are obtained from the time interval considered in Fig. 5.

the Electrostatic Analyzer (ESA) (McFadden et al., 2008), which works in the range from 25 eV to 25 KeV. Magnetic field measurements were provided by the Flux Gate Magnetometer (FGM) (Auster et al., 2008).

For THEMIS, we can construct the three components of the bulk velocity $V_\alpha(i)$ in the GSM coordinate system with a time resolution of 3 s according to the probe spin time. If we take two such components, for example, α and β, we can calculate the autocorrelation function,

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

where the mean velocity for N data points is defined as

$$\langle V_\alpha\rangle=\frac{1}{N}\sum_{i=1}^{N}V_\alpha(i). \tag{2}$$

The data were separated into 12 min intervals that contain $N=240$ bulk velocity data points. Adjacent intervals overlap for half of their interval (6 min), and we use the middle of the interval to mark the time. The autocorrelation time ($\tau_{\alpha\beta}$) was determined as the best fit to the natural logarithm of the autocorrelation function

$$A_{\alpha\beta}(\tau)=\exp(-\tau/\tau_{\alpha\beta}) \tag{3}$$

by the linear expression $y=1-ax$. We have used three methods to estimate the autocorrelation time. In the first method, we find the value τ_0 at which the auto-correlation function goes through zero. Then we do a number of fits to the value of $\tau_{\alpha\beta}$ using a decreasing number of points between $3\le\tau\le\tau_0$, and select the value of $\tau_{\alpha\beta}$ with the smallest average error. In the second method, we find the value τ_{min} where the auto-correlation function has its first minimum, and fit the value of $\tau_{\alpha\beta}$ using all the points between $0\le\tau\le\tau_{min}$. In the third method, we find the value τ_e where the

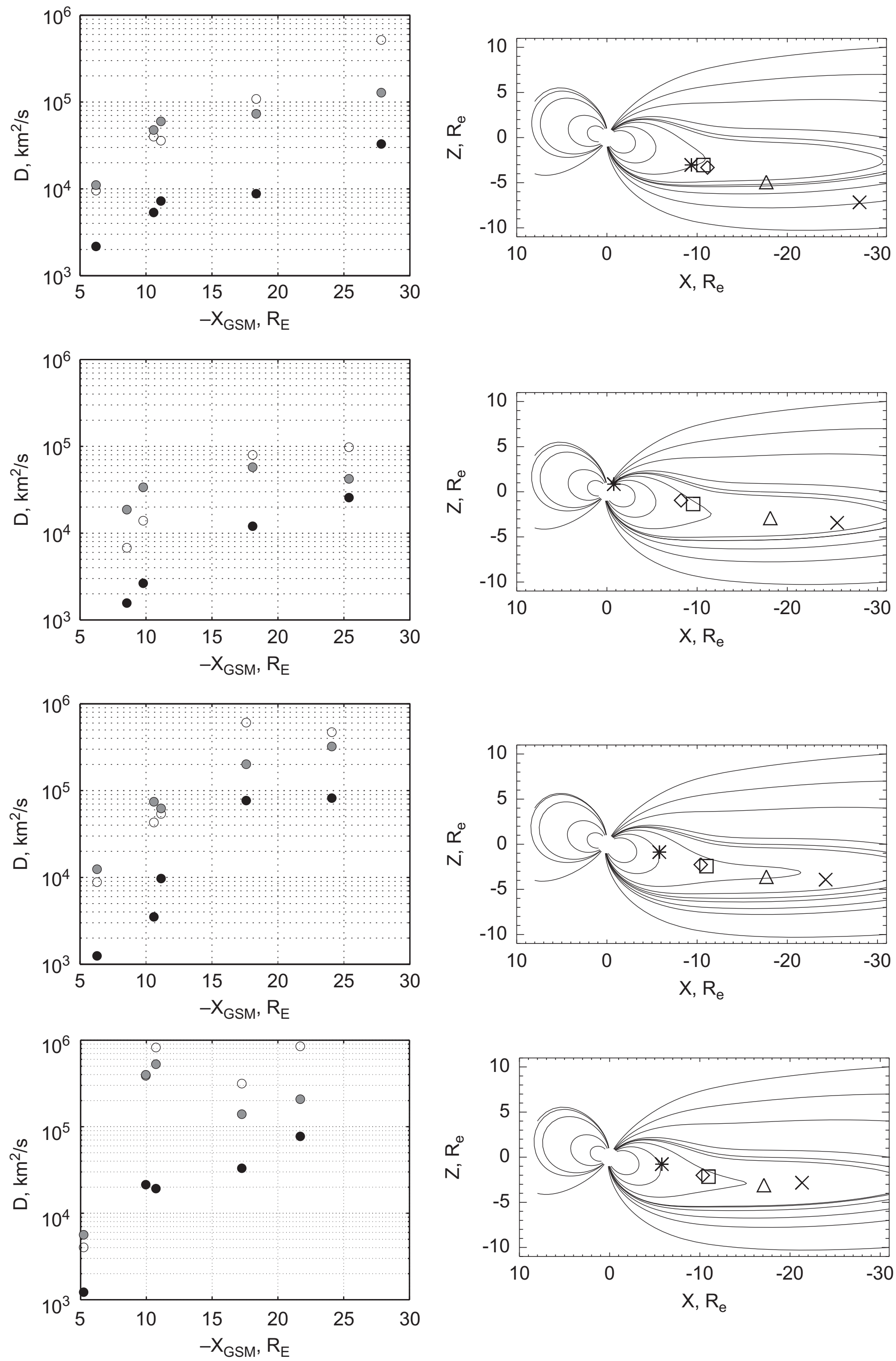

Fig. 7. The combined eddy-diffusion coefficients for all satellites, with D_{xx} (white circle), D_{yy} (gray circle), and D_{zz} (black circle). We consider 4 times intervals during the month of February 2008. Form top to bottom: 04:00 to 07:00 UT on February 14; 01:00 to 04:00 UT on February 22; 05:00 to 06:00 UT on February 22; 03:00 to 06:00 UT on February 26. We also show the satellite positions at the same time as a reference.

auto-correlation function goes below e^{-1}, and fit $\tau_{\alpha\beta}$ using all the points between $0 \le \tau \le \tau_e$. With these three values of $\tau_{\alpha\beta}$, we can estimate an average value of $\tau_{\alpha\beta}$.

Similarly, the mean square (rms) speed during the chosen time interval is determined from

$$V^2_{rms,\alpha\beta} = \frac{1}{N}\sum (V_\alpha(i) - \langle V_\alpha \rangle)(V_\beta(i) - \langle V_\beta \rangle), \tag{4}$$

and the eddy diffusion coefficient finally is obtained from

$$D_{\alpha\beta} = \frac{V^2_{rms,\alpha\beta}\tau_{\alpha\beta}}{2}. \tag{5}$$

Note that following this procedure we can estimate all the six independent components of the eddy-diffusion coefficient tensor in the GSM basis, but for the purpose of the present manuscript we will analyze only the diagonal terms D_{xx}, D_{yy} and D_{zz}. We are aware that without D_{xz} and D_{yz} the ability to calculate diffusion fluxes in the *x*- or *y*-directions is severely restricted, because the largest gradients are in the *z*-direction.

While the second and third methods of calculating τ give similar values, the first method gives in general results that are quite different from the other two. Hence, we chose the maximum of the values provided by the second and third methods, which gives consistent curves as a function of the distance into the magnetotail.

2.1. February 22, 2008

During February 22, 2008, the satellites were approximately aligned in the tailward direction. Fig. 1 shows the position of the five satellites at 8:00 UT in the *XY* and *XZ* planes, which again confirms that the time between 7:00 and 8:00 UT is a promising interval for our comparative multi-satellite analysis, as all five THEMIS satellites were approximately aligned in the tailward direction close to the plasma sheet. Fig. 2 indicates moderate geomagnetic activity, as represented by the AL and AU indexes.

Fig. 3 shows the variation of the proton energy distribution, equivalent plasma β, magnetic field strength, and *Z* component of the plasma bulk velocity, for THEMIS B probe during February 22, 2008. Fig. 4 shows the corresponding $V_{rms,zz}$, τ_{zz}, $D_{zz} \pm \sigma_{D_{zz}}$, and average value of β, during each 12 min interval of February 22, 2008, using the same THEMIS B probe. The relative error $\sigma_{D_{zz}}/D_{zz}$ is less than 15% during this day, and it is small enough on the logarithmic scale that it is not noticeable in the figure.

Figs. 1 and 3 suggest that we may select intervals in which the satellite is close to the plasma sheet using plasma β as a proxy. For the purpose of this work, we selected an interval if the average plasma β during a 12 min interval is $\beta \geq 1$ simultaneously for all five THEMIS satellites. This proxy seems to be consistent with what we would expect in the variation of the proton energy distribution, as seen in Fig. 3. Other values of β can be used as the selection criterion but the main results do not seem to change considerably. Of course, there are other criteria for selecting intervals when the satellite is close to the plasma sheet, but for the present work we will use $\beta \geq 1$ for choosing our intervals. In Figs. 3 and 4 we see three clear intervals in which we satisfy our criteria. Of particular interest is the case between 7:00 and 8:00 UT that we will analyze in detail now.

For the time between 7:00 and 8:00 UT Fig. 5 shows the estimates of D_{zz} at each of the five THEMIS satellites when our criterion is satisfied. The value of D_{zz} is plotted at the position of each satellite during this 1-h interval, and it is possible to see that the eddy-diffusion coefficient D_{zz} in the plasma sheet gradually increases in the tailward direction. Given the large range of values of the eddy-diffusion coefficient D_{zz}, we show in Fig. 6 the average of D_{zz} as a function of *x*, for the time between 7:00 and 8:00 UT. It is important to note that during this 1-h interval the variations in *z* are relatively small. But the problem with using *z* as a criterion for the closeness to the plasma sheet is that the tail may be flapping. On the other hand, if we take our proxy of $\beta \geq 1$ as the criterion for the closeness to the plasma sheet we can observed in Fig. 4 that there is no ordering between β and D_{zz}. At the same time, Fig. 6 seems to suggest an ordering with *x*.

We have done the same analysis for D_{xx} and D_{yy}. The results are shown in Fig. 6, where we have displayed the averaged values of the diagonal elements of *D* and average β for all five satellites during this hour-long interval. By looking at the position of each satellite during this 1-h interval, it is possible to see that the eddy-diffusion coefficients in the plasma sheet gradually increase in the tailward direction, and in general we have $D_{xx}, D_{yy} > D_{zz}$. It is interesting to note that for $-x < 15\ R_E$ we have the ordering $D_{yy} < D_{xx}$, while for $-x > 15\ R_E$ we have $D_{yy} > D_{xx}$, suggesting a change in the type of dynamics.

We have also analyzed other time intervals where all five THEMIS satellites were approximately aligned in the tailward direction, close to the plasma sheet, satisfying our criteria. Fig. 7 shows the three diagonal components of the eddy-diffusion tensor as a function of *x*, which again displays the same trend with increasing distance into the tail as we discussed above.

3. Conclusions

We have computed the three diagonal eddy-diffusion coefficients using all THEMIS satellites simultaneously. It was found that the plasma sheet is strongly turbulent and that the values of the eddy-diffusion coefficients vary significantly. Simultaneous measurements of the plasma parameters at different distances in the plasma sheet show that the diagonal components of the eddy-diffusion tensor increase in the tailward direction. This change in the value of the eddy-diffusion coefficients may be related to the transition from a nearly dipolar to a purely tail configuration of the magnetic field.

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