Unsolved Problems of Magnetospheric Physics

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Turbulent transport and evolution of kappa distribution in the plasma sheet

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Main unsolved questions:

- What do we know about the thermalization of colisionless space plasmas?
- What do we know about the turbulent transport?

Kappa distribution in Space Plasmas

First introduced by Montgomery in 1965

$$f(E) = \frac{n}{\pi^{3/2} E_c^{3/2} \kappa^{3/2}} \frac{\Gamma(\kappa+1)}{\Gamma(\kappa-1/2)} \left[1 + \frac{E}{\kappa E_c}\right]^{-\kappa-1} \quad (1)$$

where n is the particle density, E is the particle energy, E_c is the particle characteristic energy, Γ is the Euler gamma function, and κ is the spectral index characterizing the electron (ion) distribution.

For $\kappa \to \infty$ (1), tends to the Maxwellian distribution:

$$f(E) = \frac{n}{\pi^{3/2} E_c^{3/2}} \exp\left[-\frac{E}{E_c}\right] \quad (2)$$

It is widely used for systems out of thermal equilibrium

In space and astrophysical plasmas:

Collier, 1993; Tsallis et al., 1998; Tsallis, 1988; Treumann, 1999a, 1999b; Milovanov and Zelenyi, 2000; Leubner, 2004; Borges et al., 2002; Livadiotis and McComas, 2009, etc

Kappa distributions in the magnetosphere of the Earth

Fitting the particle fluxes in the magnetosphere of the Earth [Christon et al., 1991; Pisarenko et al., 2002; Wang et al., 2011; Lui, 2013, etc].

The field-aligned acceleration of auroral particles [Olsson and Janhunen, 1998; Dors and Kletzing, 1999; Ermakova and Antonova, 2007; Antonova et al., 2012],

The transverse acceleration of ions during substorm injections [Birn et al., 1997; Zaharia et al., 2000]

The theory of formation of the inverted-V structures [Antonova et al. 2003; Ermakova et al., 2006]

The values of plasma pressure from the DMSP satellites [Wing and Newell, 1998; Wing et al., 2013]

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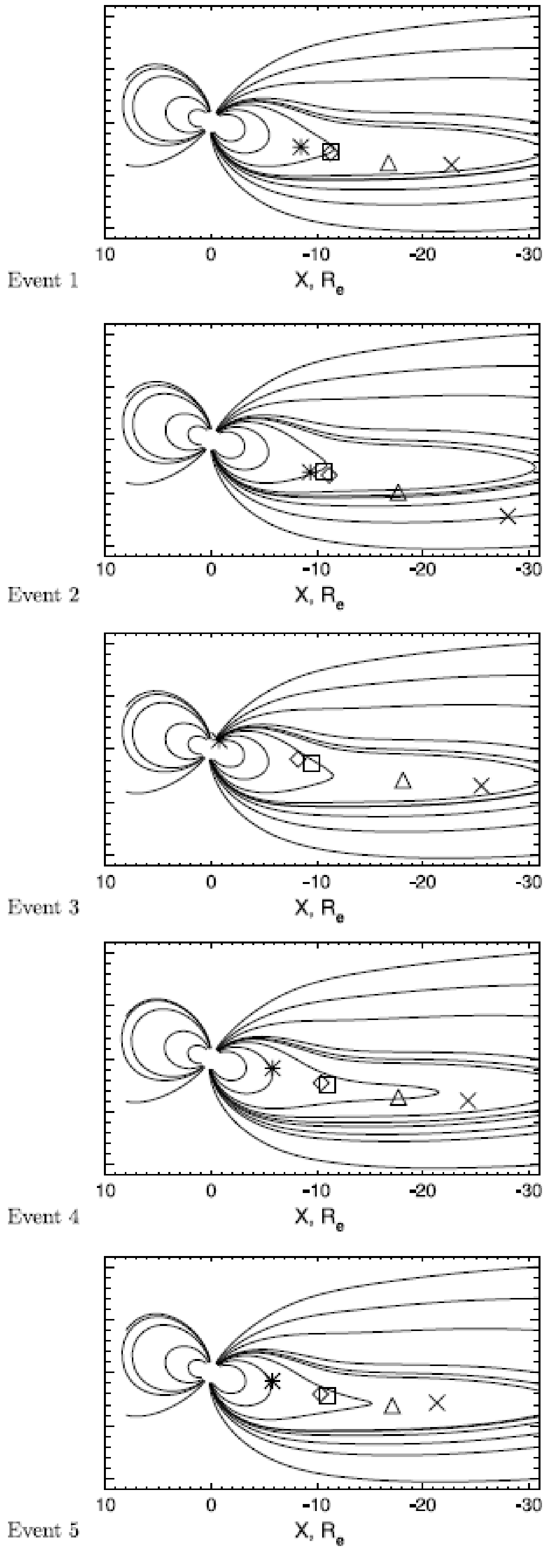
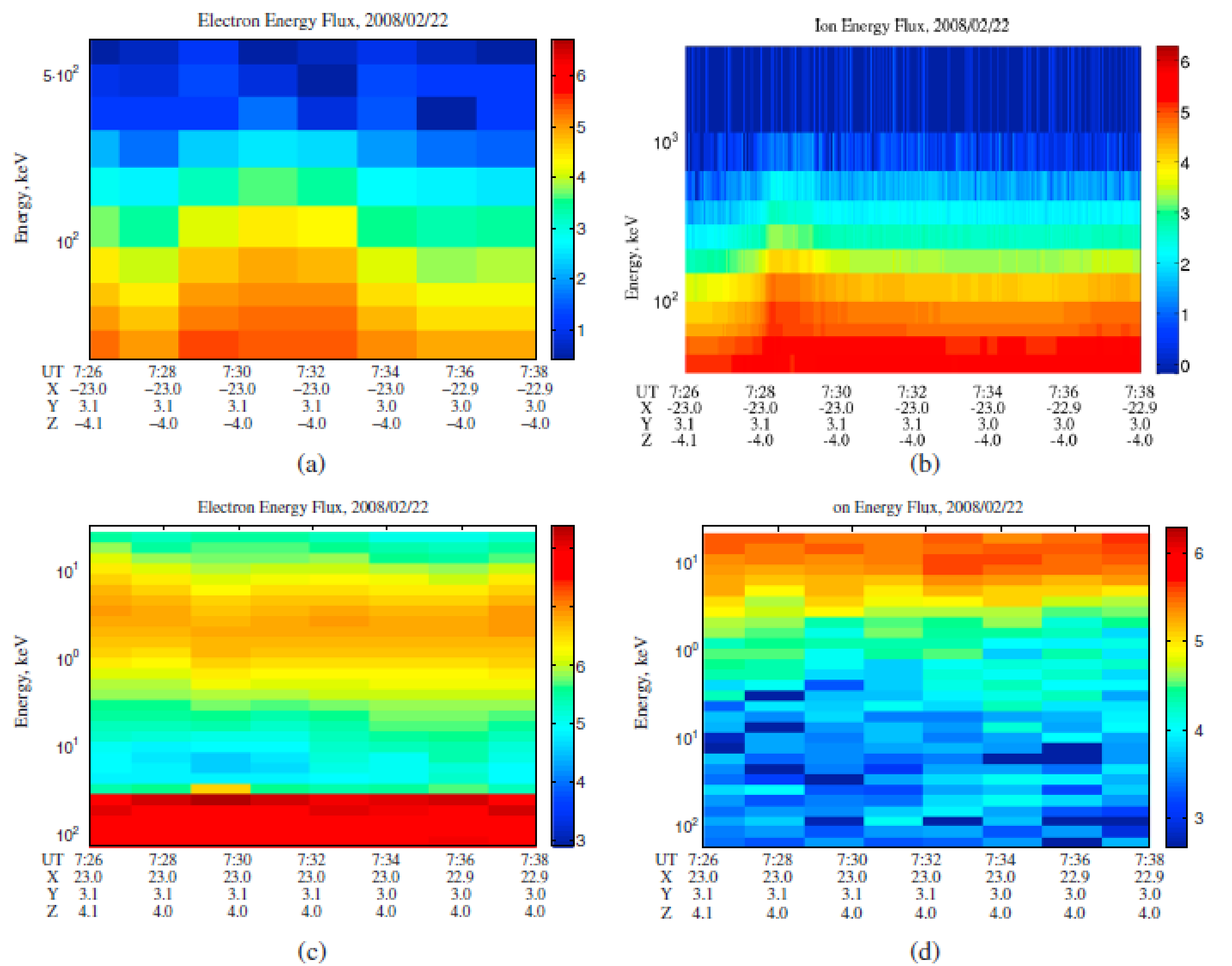
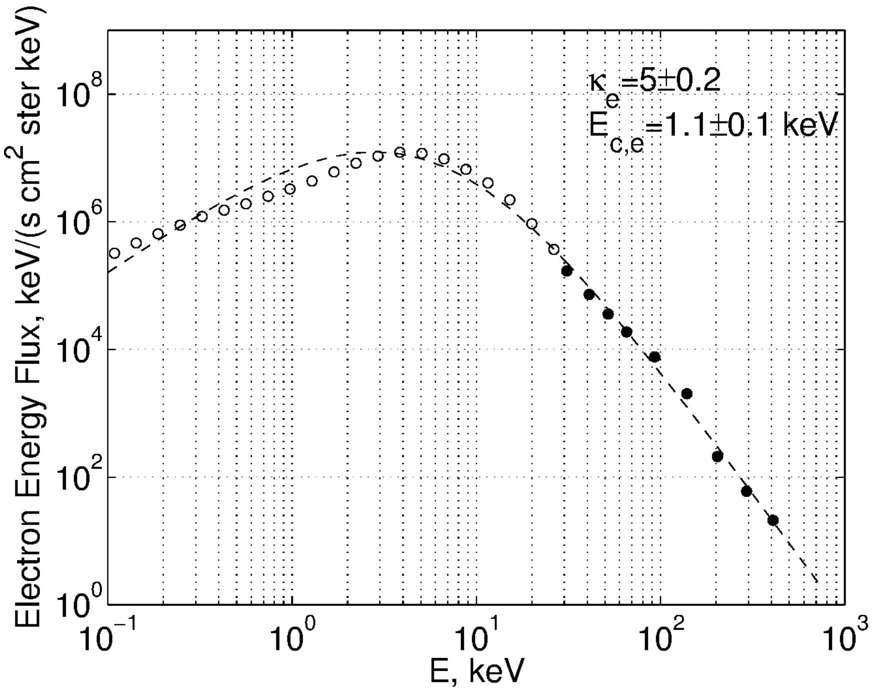
Do exist any radial dependence of kappa parameters on the distance toward the tail in the plasma sheet?

Stepanova and Antonova, JGR,doi:10.1002/2014JA020684.

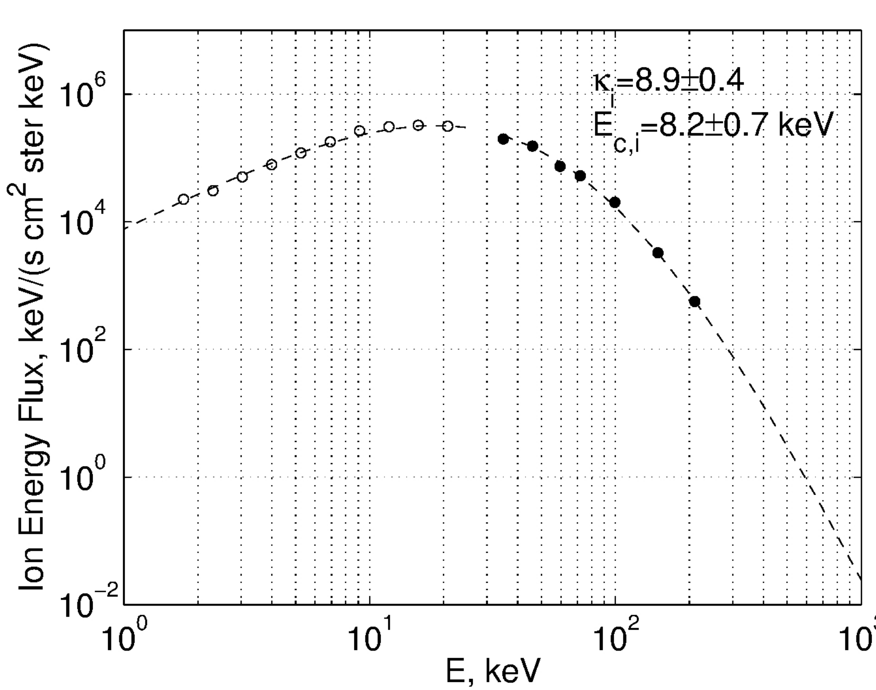




Number fluxes for five satellites located in the plasma sheet were fitted by kappa distribution functions:



(a)

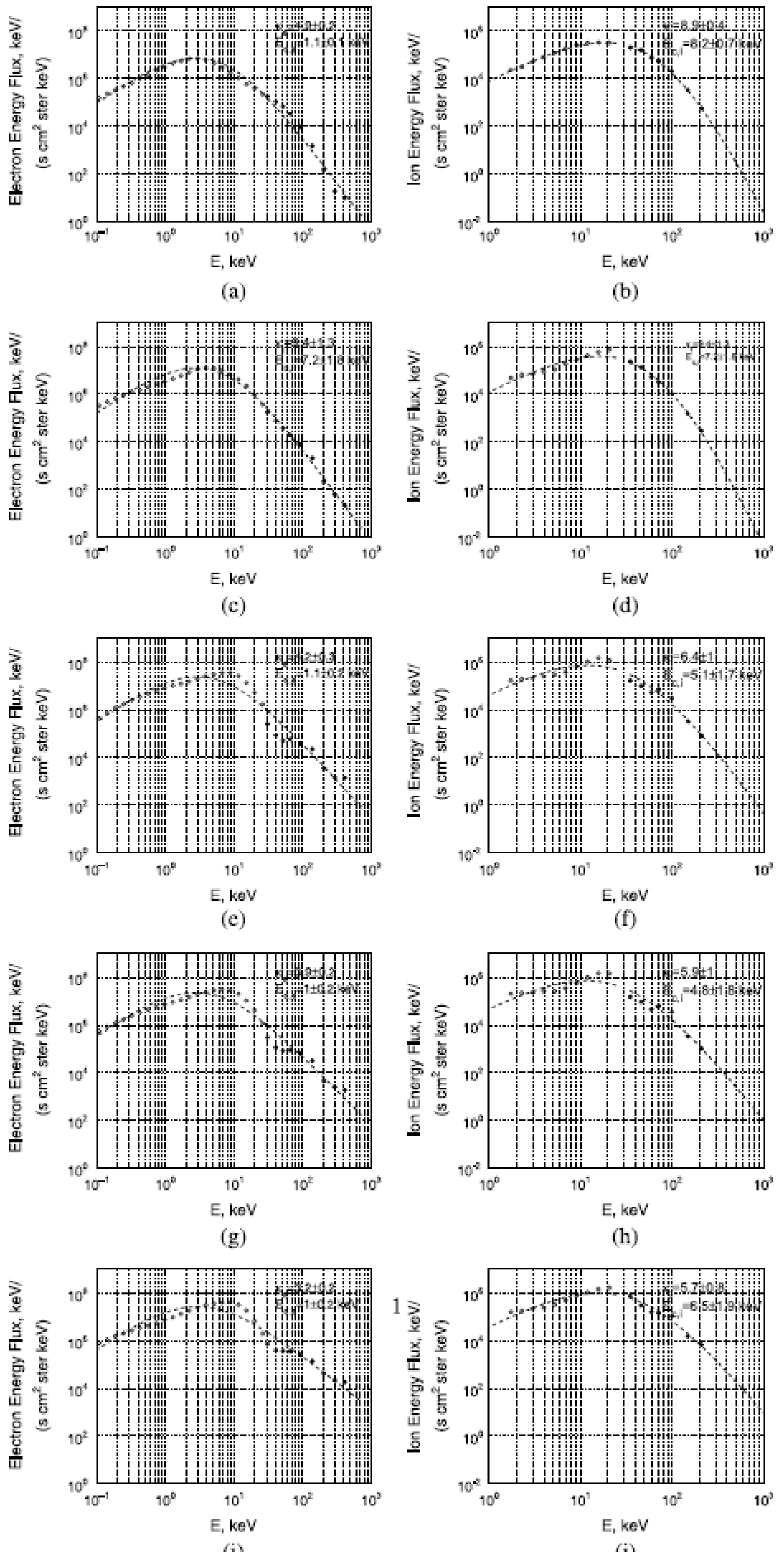


(b)

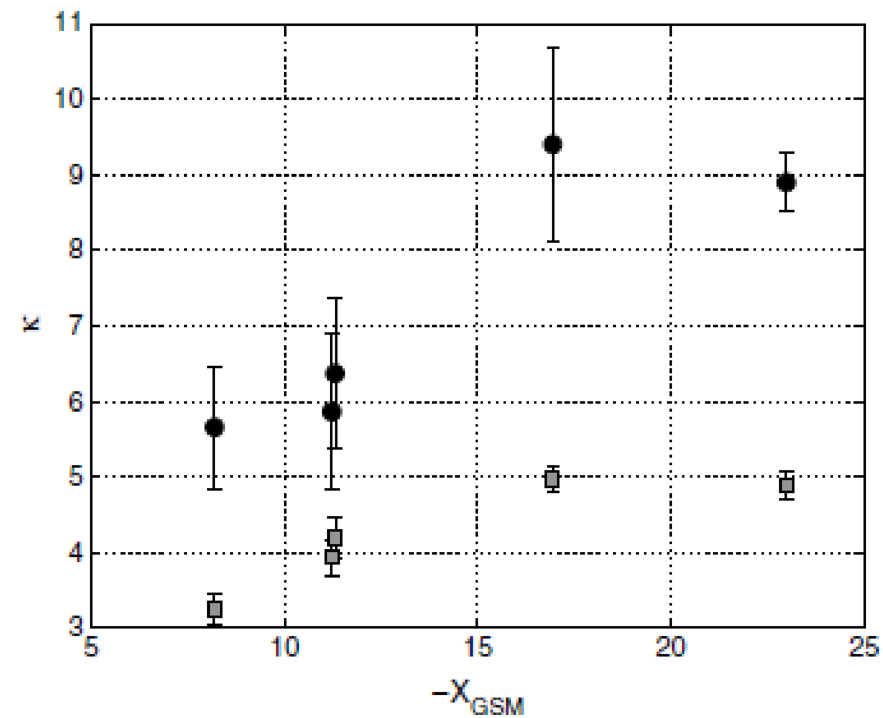
$$F_{e,i}(E) = \frac{1}{\pi}\frac{n_{e,i}}{\sqrt{2\pi m_{e,i}}}\frac{E^2}{E_{c_{e,i}}^{3/2}}\frac{\Gamma(\kappa_{e,i})}{\Gamma(\kappa_{e,i}-1/2)\sqrt{\kappa_{e,i}}}\left[1+\frac{E}{\kappa E_{c_{e,i}}}\right]^{-\kappa_{e,i}-1} \quad (3)$$

where $n_{e,i}$ is the electron (ion) density, $m_{e,i}$ is the electron (ion) mass, E is the particle energy, $E_{c_{e,i}}$ is the electron (ion) energy of the peak differential number flux, and $\kappa_{e,i}$ is the spectral index characterizing the electron (ion) distribution.

Combined ESA and SST measurements. Some low energy ESA and high energy SST channels were discarded. Final range: 1.75 and 210 keV (ions), 0.362 and 203.5 keV (electrons).

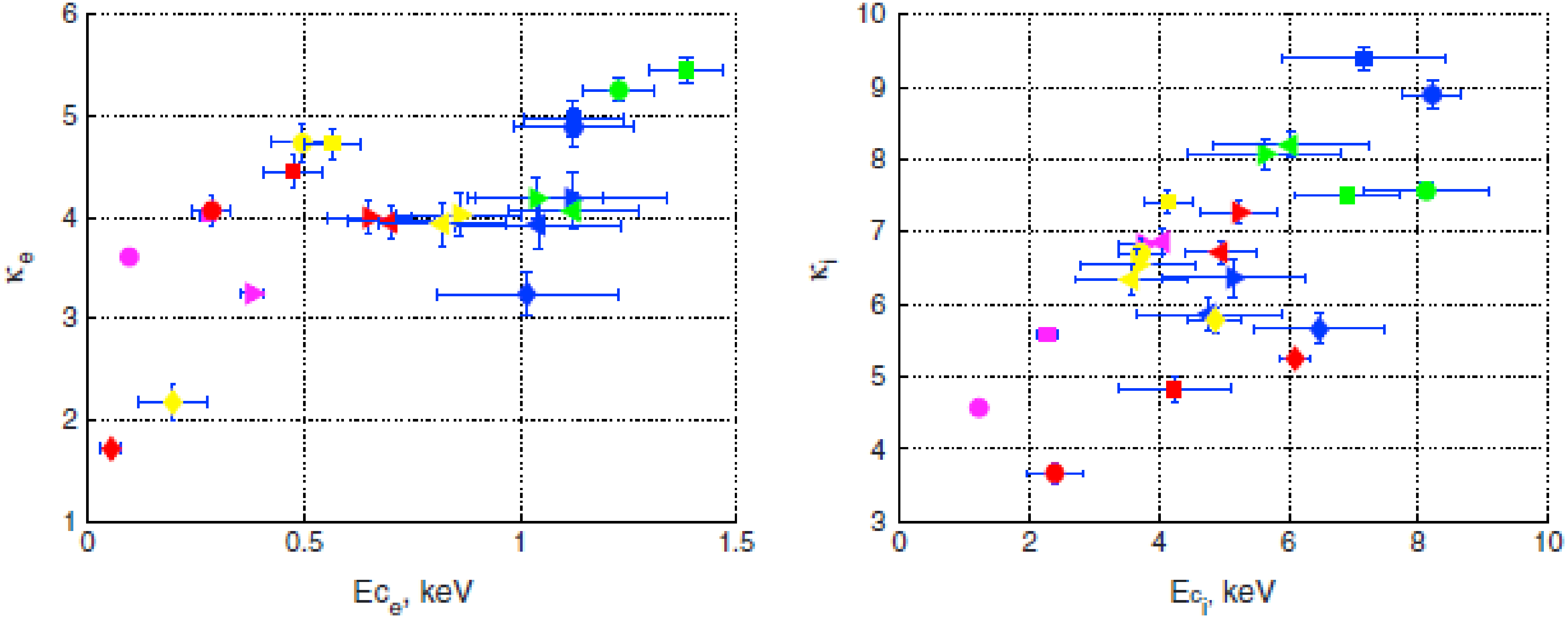


Averaged electron and ion energy flux spectra, measured on 22 February 2008 between 7:26 and 7:38 UT and fitted by kappa distribution: (a, b) THB, XGSM = −22.9RE, (c, d) THC, XGSM = −16.9RE, (e, f) THD, XGSM = −11.3RE, (g, h) THE, XGSM = −11.2RE, and (i, j) THA, XGSM = −8.3RE.



Evolution of κ index with the distance from the Earth on 22 February 2008 between 7:26 and 7:38 UT for ions (black circles) and electrons (grey squares).

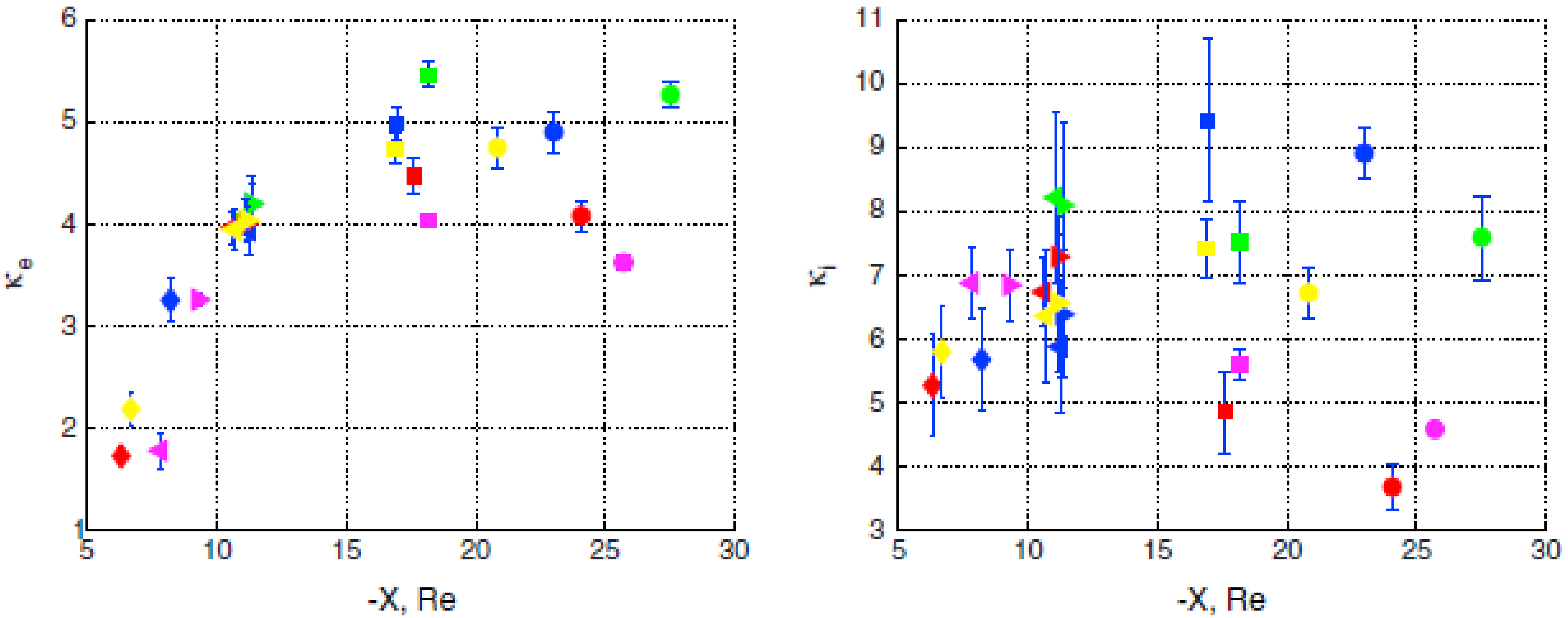
Relation between the kappa indexes and the core energy



Colors indicate the event numbers (1 = blue, 2 = green, 3 = magenta, 4 = red, and 5 = yellow). Symbols indicate the satellite used (THB = circle, THC = square, THD = right-pointing triangle, THE = left-pointing triangle, and THA = diamond).

A relation between the values of κ and the core energy, in general, follows the statistical results obtained by Christon et al. [1989]

Variation of the kappa indexes with the distance toward the tail



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Hypothesis about particle acceleration, loss and transport

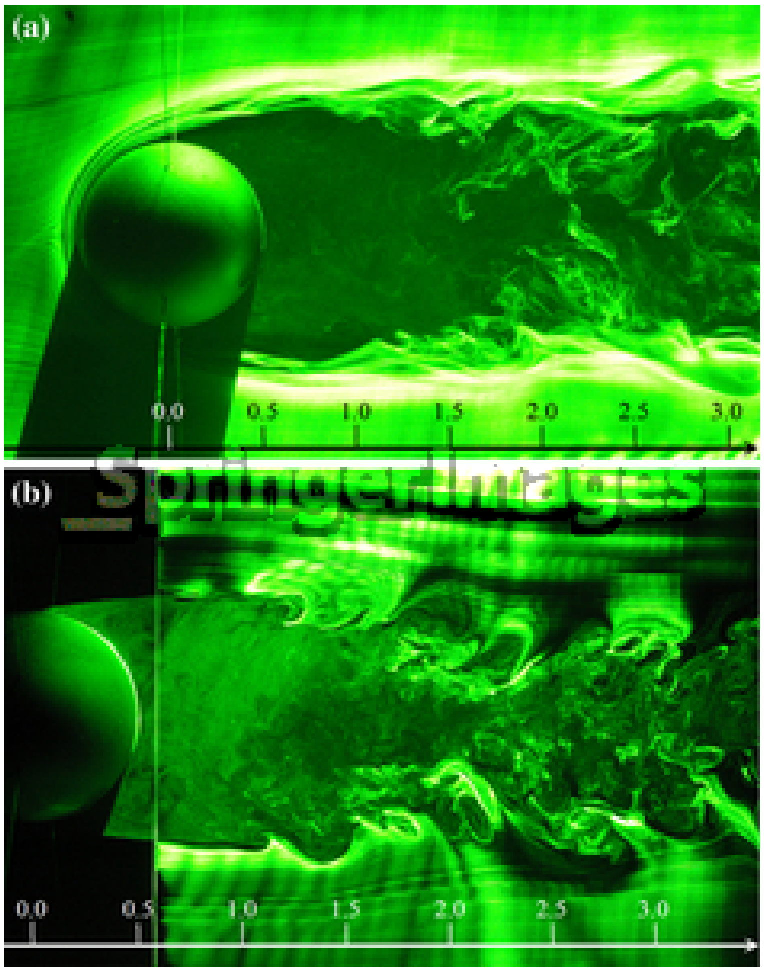
The source of the particle acceleration is located near the Earth.
Agrees with works of Denton and Cayton [2011], Borovsky and Denton [2011], Reeves et al. [2013].

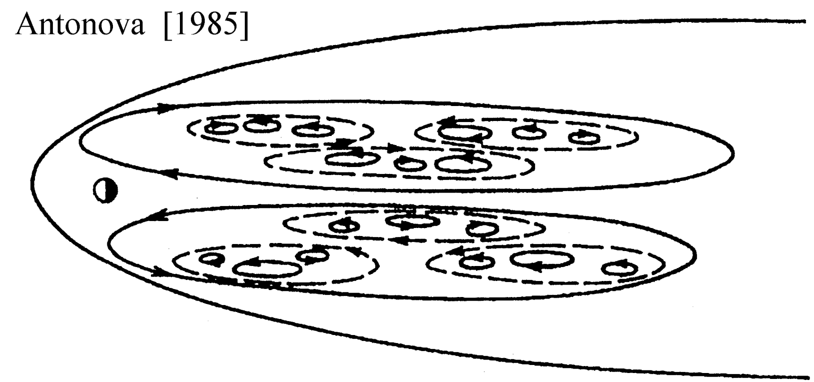
The relaxation of the distribution function to a Maxwellian is due to diffusion in velocity space [Collier, 1999]

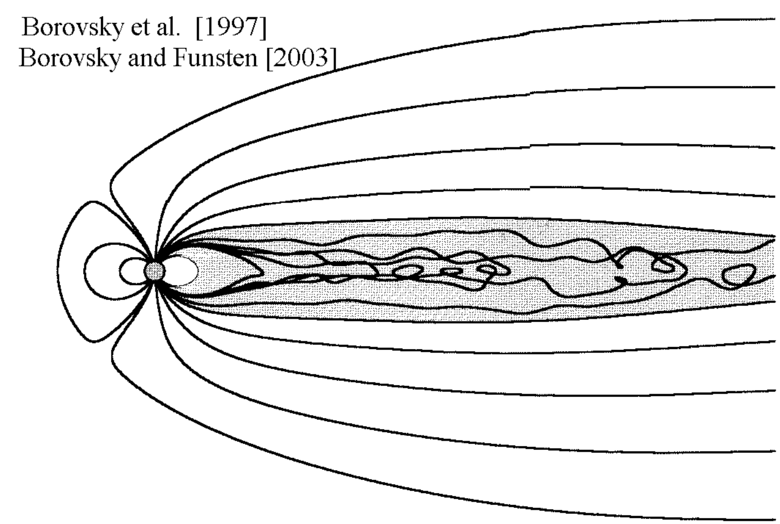
Net transport toward the tail?

Transports having mainly earthward direction: regular transport due to the dawn-dusk electric field, BBFs, dipolarization fronts.

Turbulent transport in the plasma sheet







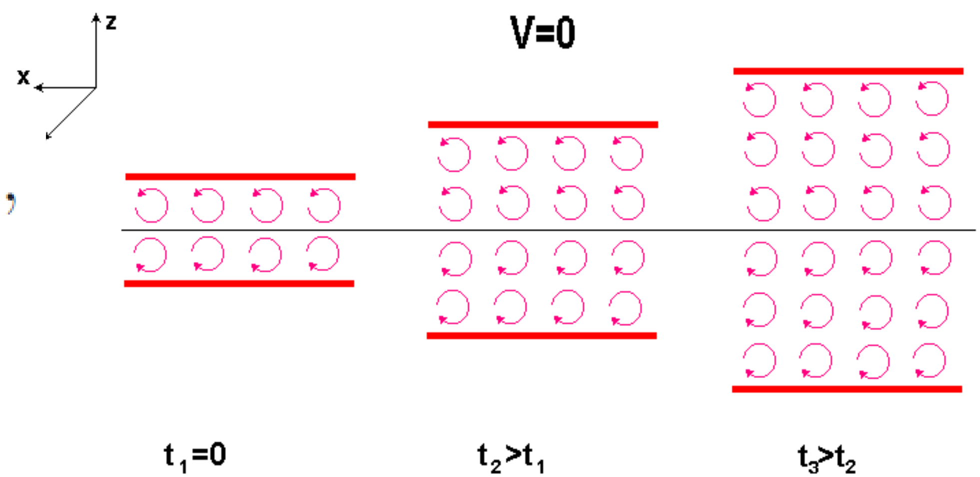
Even for laminar solar wind, we would expect the formation of a turbulent wake behind an obstacle, considering the very high values of Reynolds number (> 10^{10}, Borovsky and Funsten, 2003).

How to stabilize the turbulent plasma sheet?

$$\mathbf{\Gamma} = \langle n\mathbf{V} \rangle = n_0\mathbf{V}_0 - D\nabla n = 0,$$

A balance between the regular and turbulent transports (Antonova and Ovchinnikov, 1996, 1997, 1999)

The total pressure balance across the geotail (Michalov et al. [1968], Stiles [1978], Spence et al. [1989], Tsyganenko [1990], Baumjohann et al. [1990], Kistler et al. [1993], Petrukovich [1999], Tsyganenko and Mukai [2003])



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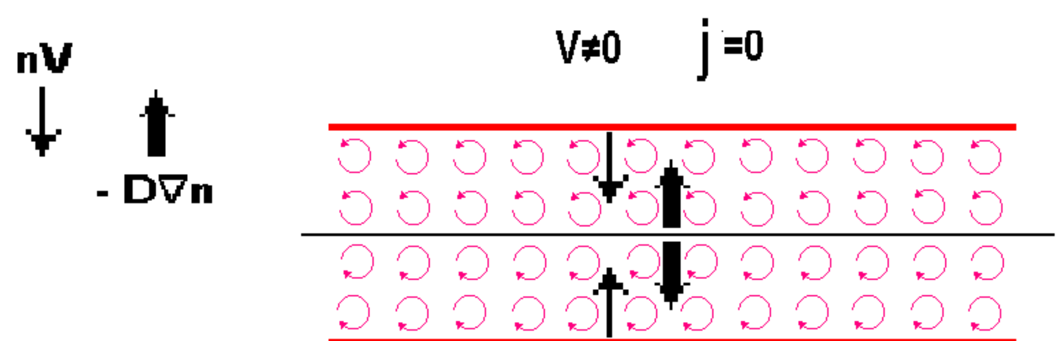


б

Antonova and Stepanova JASTP (2011), doi:10.1016/j.jastp.2011.02.009

The regular plasma transport, which is transverse to the plasma sheet and related to the dawn-dusk electric field, is compensated by the eddy diffusion turbulent transport.

$$\mathbf{\Gamma} = \langle n\mathbf{V} \rangle = n_0\mathbf{V}_0 - D\nabla n = 0, \tag{1}$$

where $\mathbf{\Gamma} = \langle n\mathbf{V} \rangle$ is the total number flux, $n_0\mathbf{V}_0$ is the number flux due to regular transport, and $D\nabla n$ is the number flux due to the turbulent transport. Here n and $\mathbf{V}$ are the plasma number density and velocity, n_0 and $\mathbf{V}_0$ are their average values, and D is the coefficient of eddy diffusion transverse to the plasma sheet.

Assuming existence of a total pressure balance across the plasma sheet, and constant ion temperature across the sheet:

$$\frac{l}{p}\frac{dp}{dz} = f(b) \tag{2}$$

where $b = B/B_L$, B_L is the magnetic field in the tail lobes, $f(b) = lV_z(b)/D(b)$, $l = (D/V_z)|_{B=B_L}$ is the characteristic scale, and D is the coefficient of eddy diffusion.

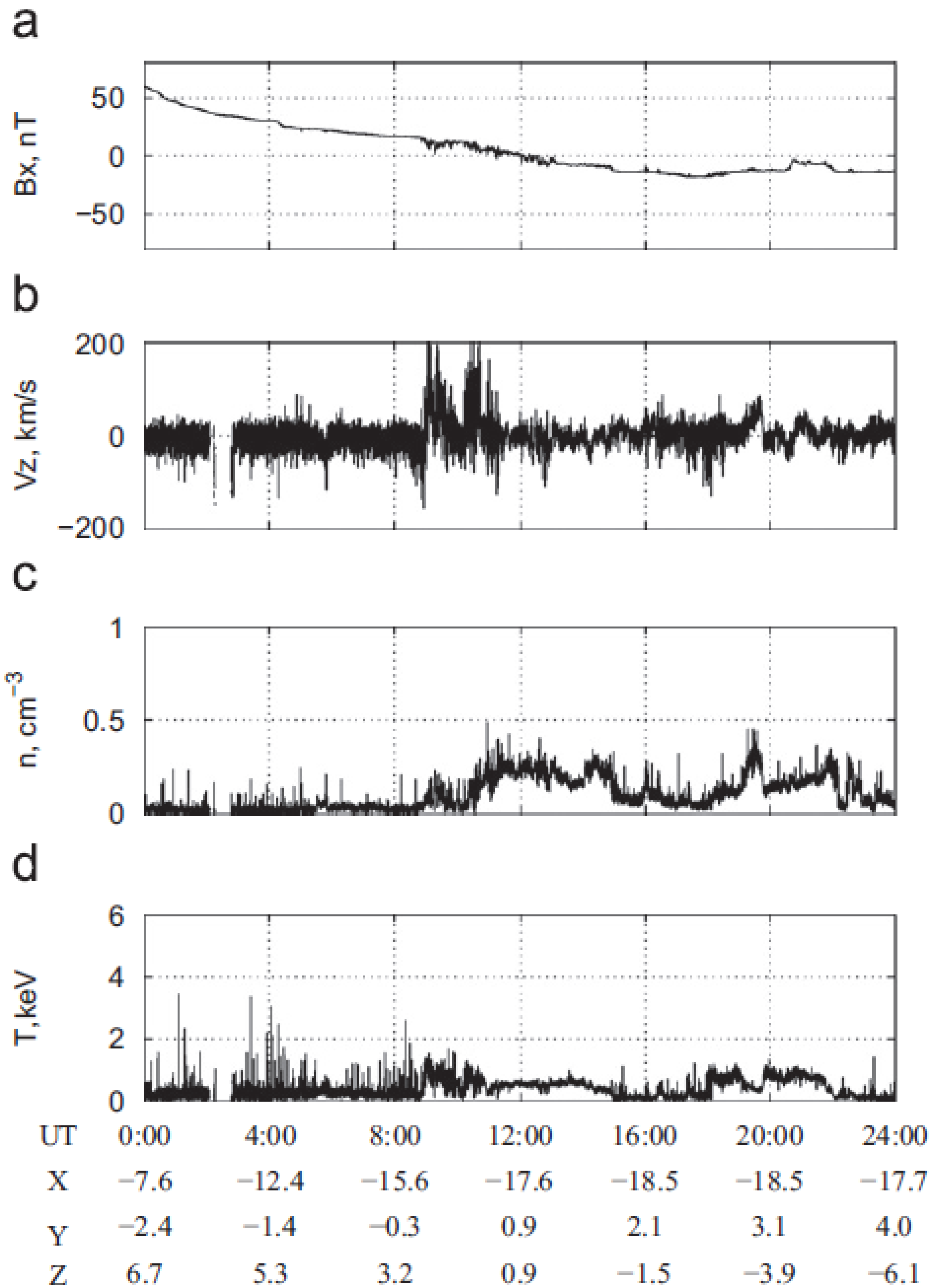
For $D \sim B^{-2}$ and $f(b) \sim b$. Taking into consideration that the total pressure across the tail is constant, i.e. $p = p_0\left(1 - b^2\right)$, we integrate (2) to obtain a Harris-type solution for the geomagnetic field,

$$B = B_L \tanh(z/2l). \tag{3}$$

The plasma pressure varies across the sheet as

$$p = p_0 \cosh^{-2}(z/2l). \tag{4}$$

Cluster vertical crossing



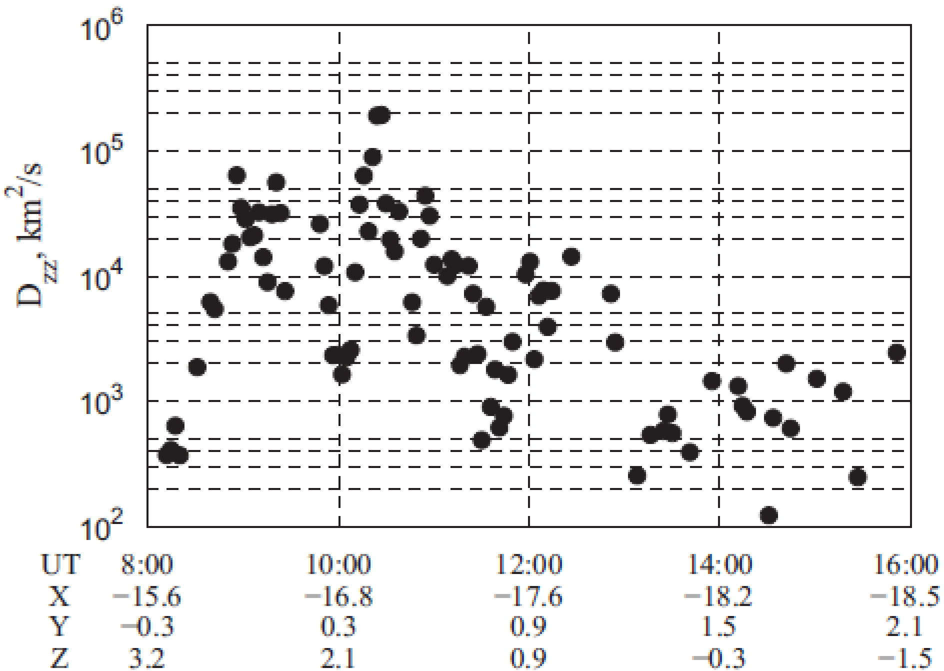


Fig. 2. Variation of eddy-diffusion coefficient *D* in the direction *Z* across the plasma sheet during quiet geomagnetic conditions.

September 12, 2004

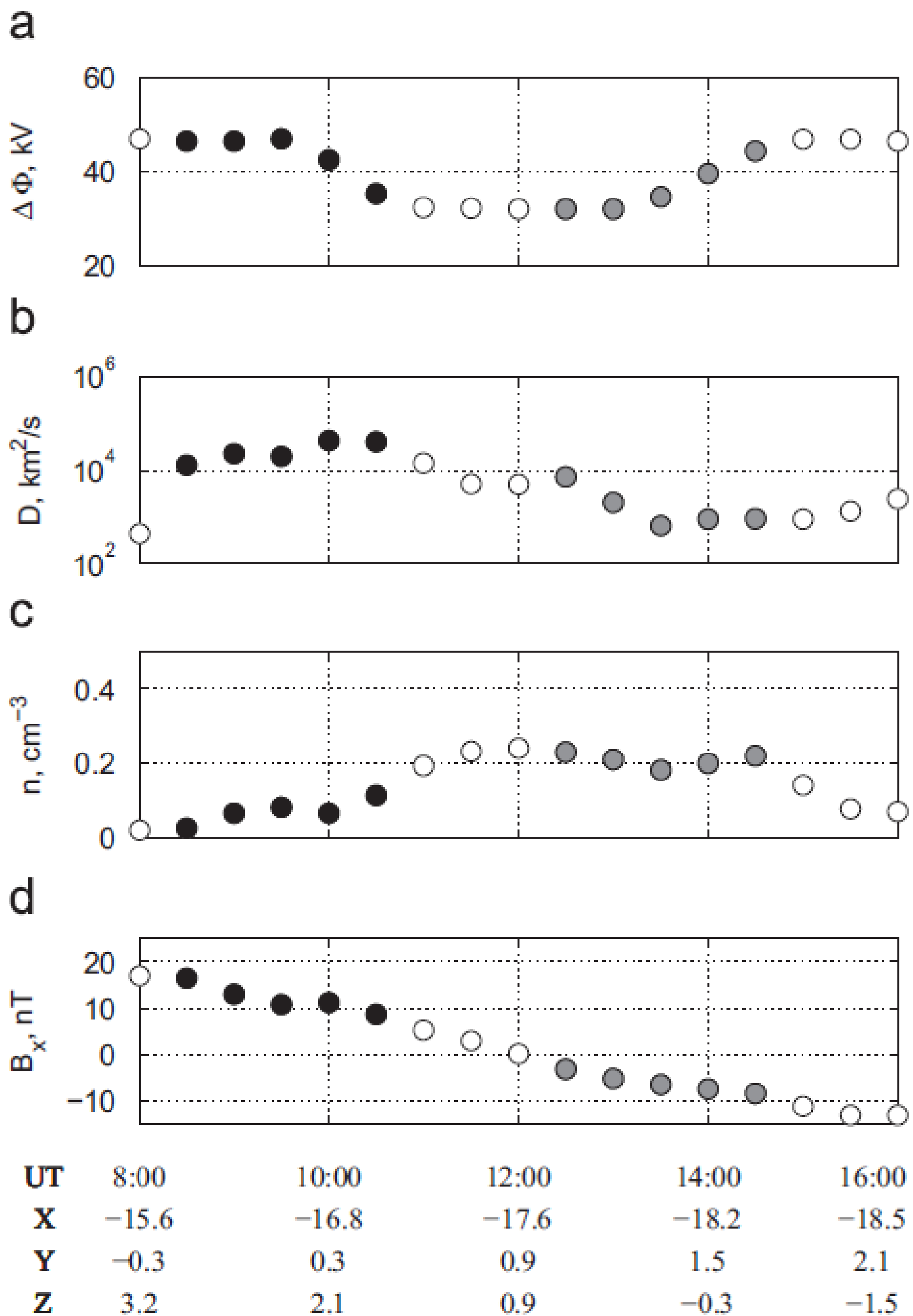


Fig. 3. From top to bottom: averaged values of the polar cap potential difference (a), *Z* component of the eddy diffusion coefficient (b), the ion number density (c), and the *X* component of the geomagnetic field (d), in the GSE coordinate system for September 12, 2004 event.

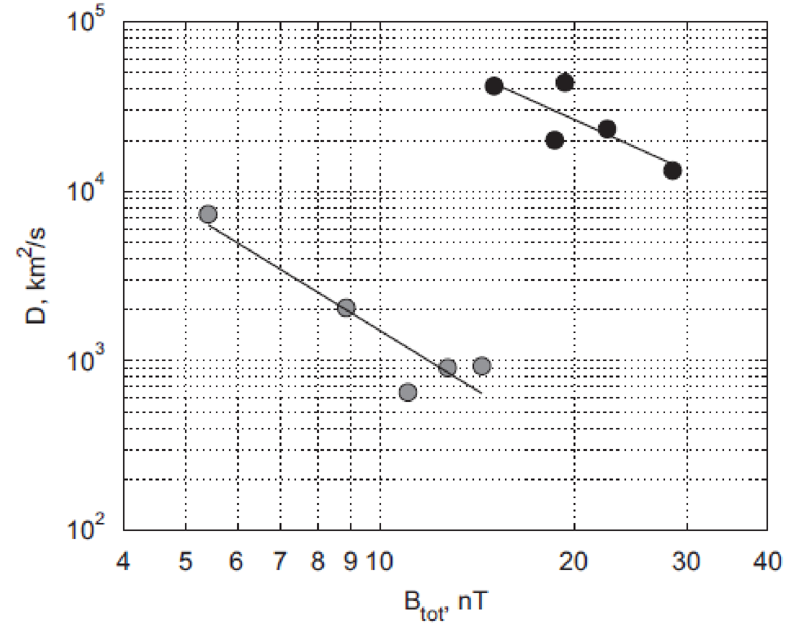


Fig. 4. Variation of the eddy-diffusion coefficient vs. the absolute value of the geomagnetic field, the circle color is the same as for Fig. 3. The lines represent the best fit, $D(B) = (4.5 \pm 0.8) \cdot 10^6 \cdot B^{(-1.7 \pm 0.7)}$ km^2/s for $\Delta\Phi = 46$ kV while in the case of $\Delta\Phi = 32$ kV it is $D(B) = (0.33 \pm 0.03) \cdot 10^6 \cdot B^{(-2.3 \pm 0.5)}$ km^2/s.

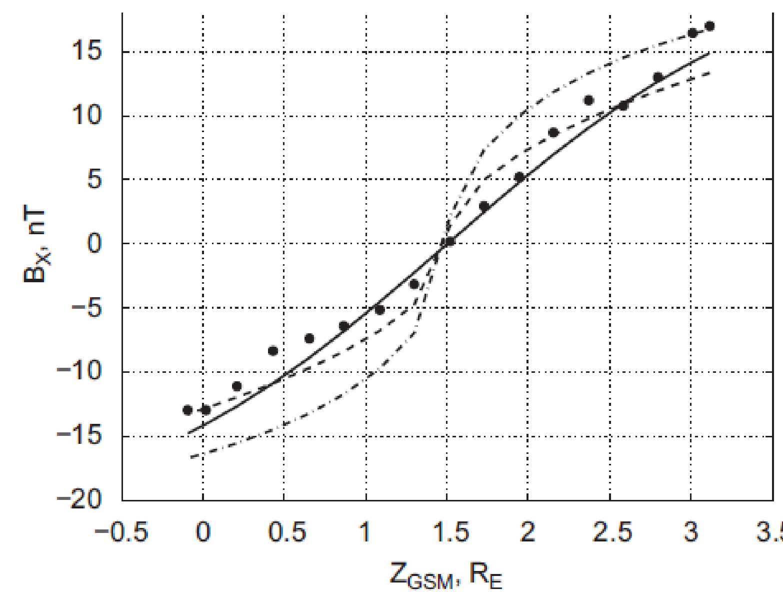
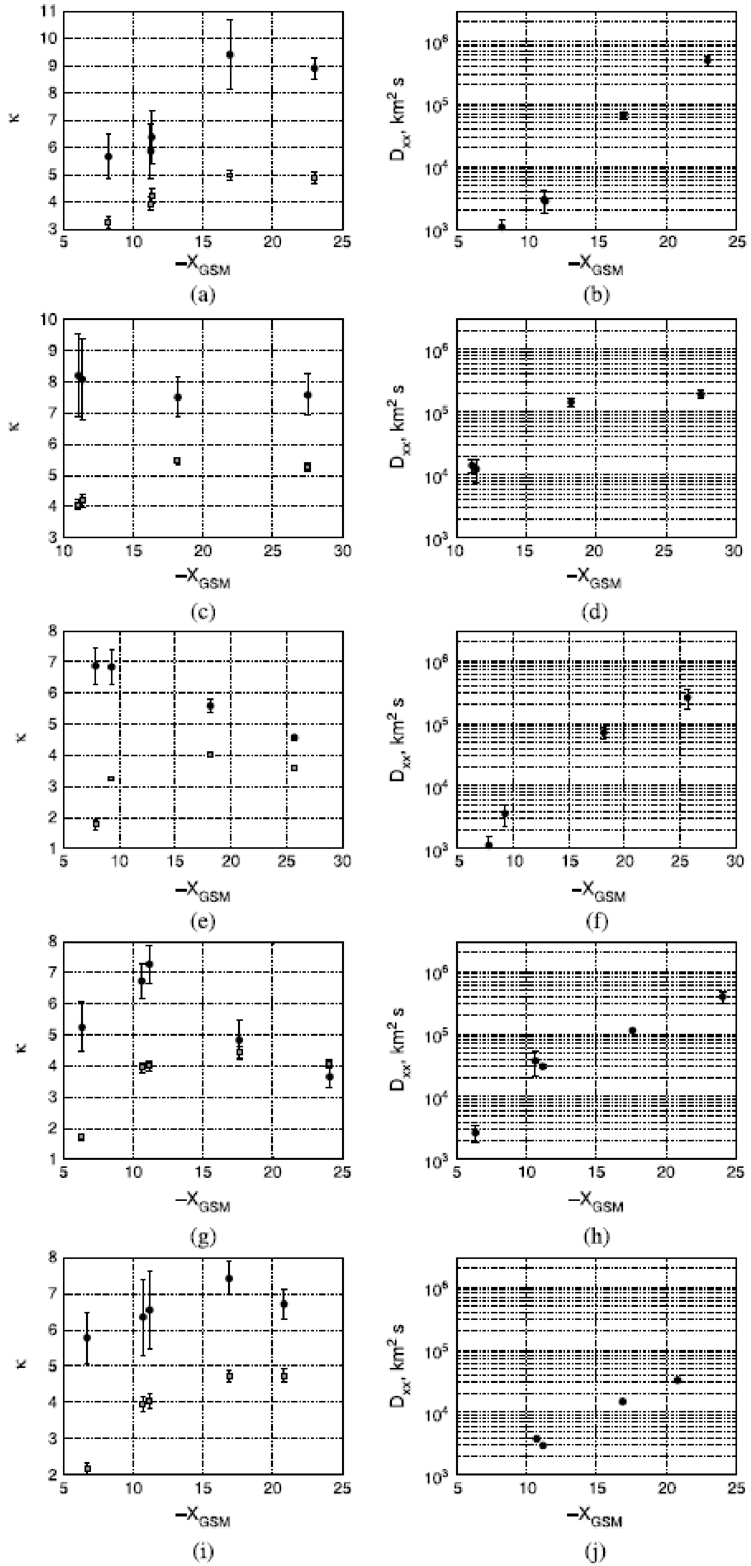


Fig. 5. The *X*-component of the magnetic field B_X vs. *Z* (dots) fitted by the expression (4) (solid line), fitted by (7) (dashed line, green online). The curve given by (7) with a realistic value of $2l = 2R_E$ (dashed–dotted line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

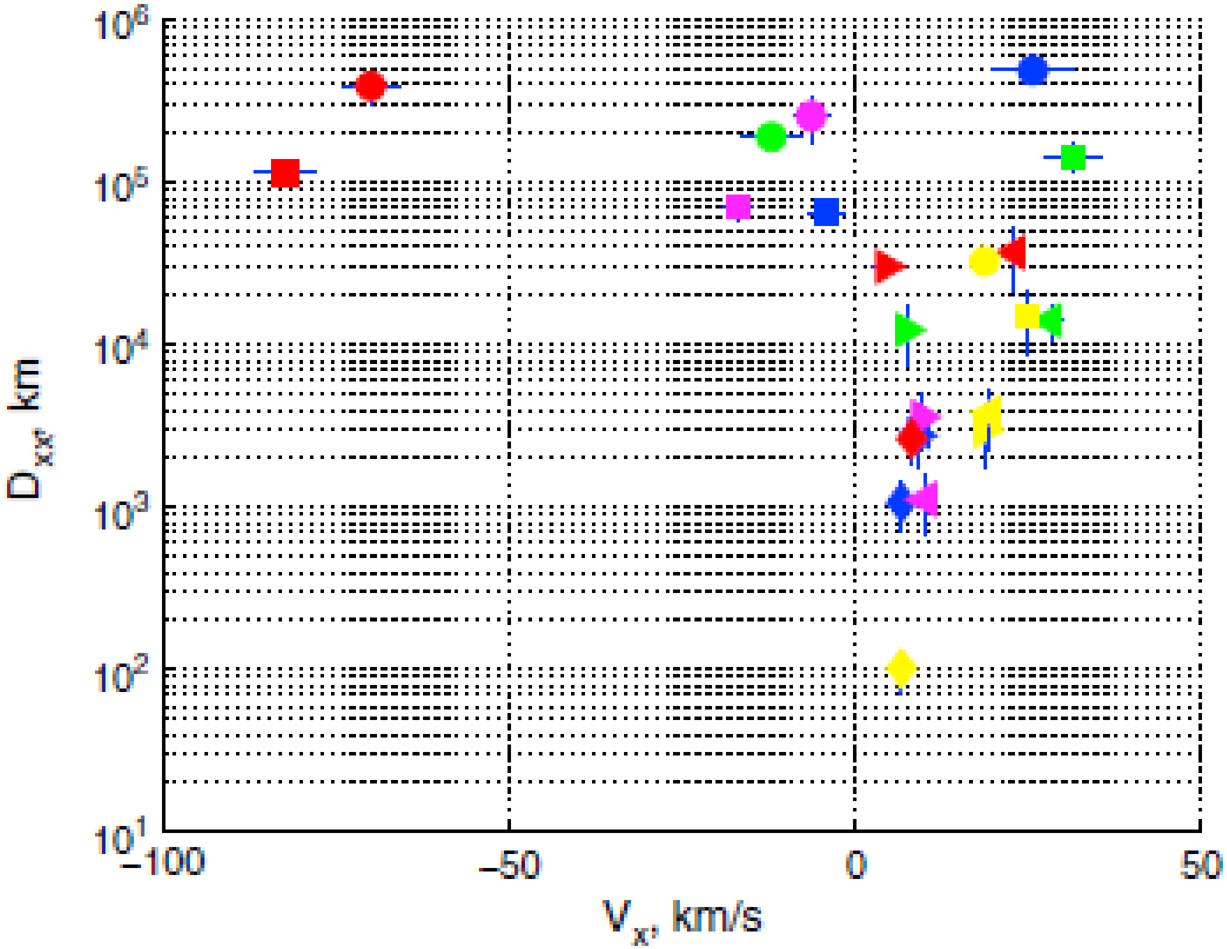


Is it possible to have a tailward turbulent transport?

$$t_{diff} \approx \frac{\Delta L^2}{< D_{xx} >}$$

The characteristic times of eddy diffusion are about 3-12 hours.

What is happening with regular transport?



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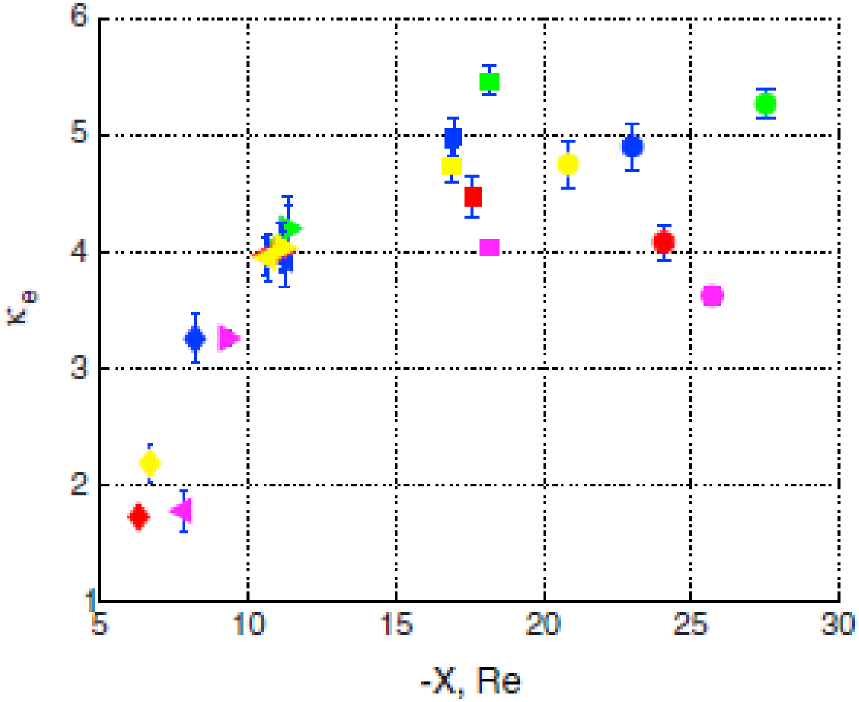

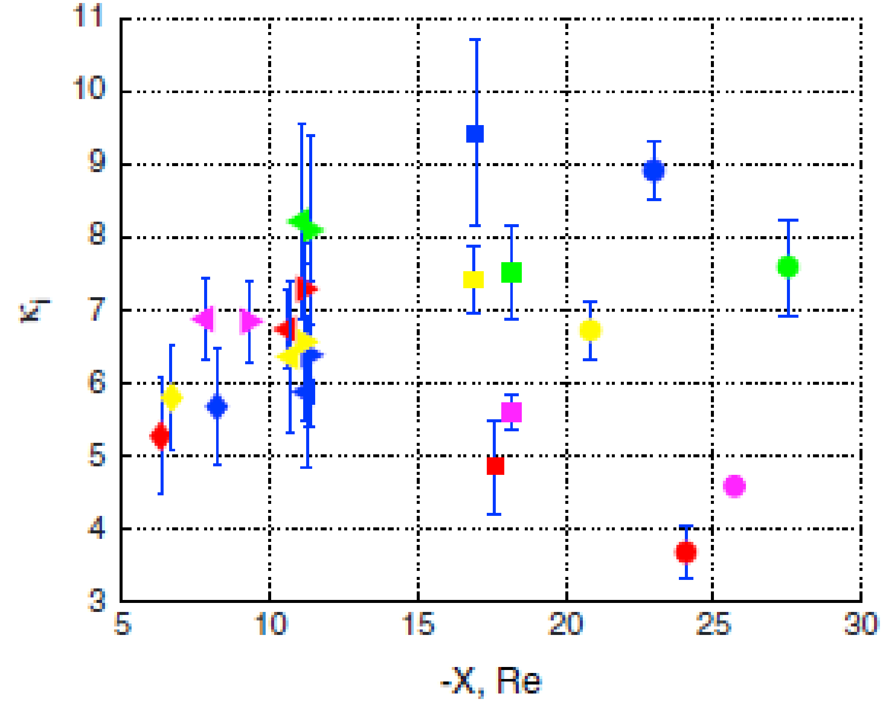

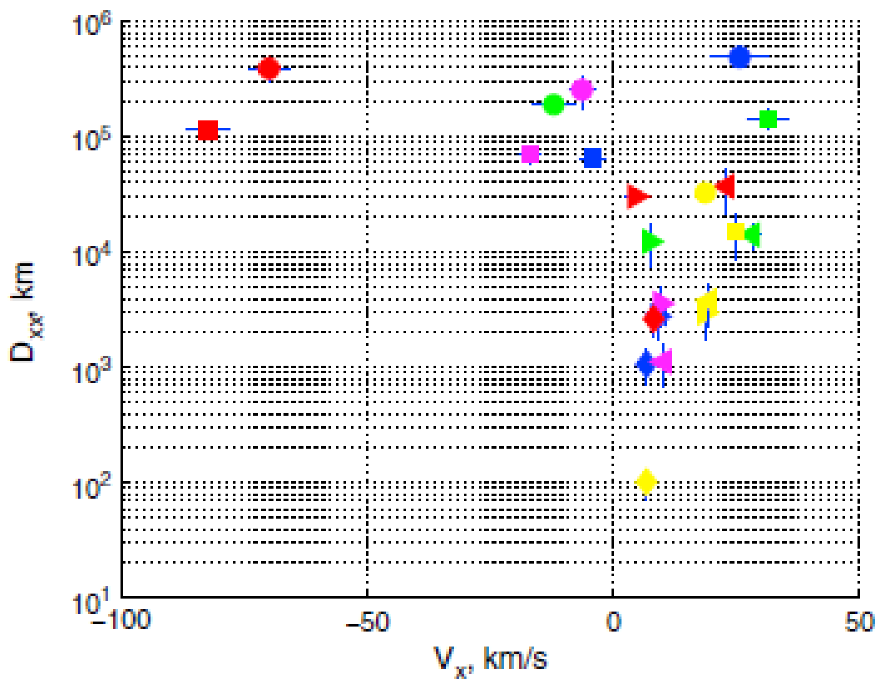

Deviation from the common trend is observed for the events when the regular transport was directed tailward (red and magenta diamond and square)

Conclusions

Under comparatively quiet geomagnetic conditions, the parameters of the κ approximation have a clear radial dependence, increasing in the tailward direction for the majority of events.

The action of stochastic acceleration mechanisms near the Earth leads to particle spectra hardening and to the appearance of suprathermal tails in particle fluxes, hence reducing the value of κ.

The relaxation of the κ distribution to the Maxwellian due to diffusion in velocity space takes place in the plasma sheet at the distances between 12 and 30 RE.

An increase in the values of κ with the distance to the tail requires the net transport to be directed tailward. However, on average, the regular convection due to a dawn-dusk electric field is directed earthward, although even in our study we observed events as with earthward as with tailward average bulk velocity.

Turbulent eddy diffusion is present in all events analyzed The turbulent transport toward the tail takes a few hours, sufficient for the aging of distribution functions, observed in all events.

In the events with the average bulk velocity pointed to the tail, both regular and turbulent mechanisms contributed to the net tailward transport, shortening the time available for relaxation. For these events we observed more steep spectra in the distant plasma sheet.