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CROSS-TAIL FAST FLOWS AND THEIR RELATION TO BBFs IN THE PLASMA SHEET

N.P. Dmitrieva (*Institute of Physics, University of St-Petersburg, St-Petersburg, Russia*)

Introduction

An interest in studying fast plasma flows in the magnetospheric plasma sheet (Bursty Bulk Flows - BBFs) has been growing during the last decade. This is because BBFs have a close relation to the magnetic field reconnection processes in the magnetotail (which apparently are the reason of the BBFs occurrence) [Baumjohann and Pashmann, 1990; Baumjohann, 2002; Angelopoulos et al., 1994] and also due to their key role in the magnetotail transfer processes. Indeed, as known, BBFs provide 50-80% of plasma and magnetic flux transport [Schödel et al., 2001; Angelopoulos et al., 1994, 1996].

The BBF's basic properties are revealed and described as follows: the plasma density and pressure are reduced and the temperature is enhanced inside them compared to the environment; the magnetic field exhibits typical variations (negative $|B_x|$ excursion and bipolar B_z variation) [Angelopoulos et al., 1994; Slavin, et al., 2003; Ohtani et al., 2004]. As to the velocity direction, it is shown that on average the total plasma velocity practically coincides with V_x component [Angelopoulos et al., 1992, 1994]. It means that BBFs are collimated along the magnetotail axis at least at distances >15 R_E. On the other hand the results of [Baumjohann, and Pashman, 1990] indicate a considerable V_y component in the fast flows at distances <20 R_E. Indeed, the velocity vector deviation relative to the tail axis is about 30 degree in ~ 50% of cases. It means that the cross-tail velocity component is equal to about a half of the total velocity value.

The cross-tail velocity component comparable with $|V_x|$ ones was observed also in a few cases studies [Sergeev and Lennartsson, 1988, Borodkova et al., 2002].

Are such events rather rare exceptions? Where in the plasma sheet are they preferably observed? Up to now there are no statistical studies to answer these questions.

On the other hand, the cross-tail velocity component comparable with V_x is found in the average plasma flow pattern at distances 10<X<30 R_E [Hori et al., 2000; Kaufmann et al., 2001]. Furthermore, flows with dawn-to-dusk V_y component prevail in the pattern. Is this cross-tail component attributed mainly to the slow background plasma flow? Do BBFs have $|V_y|$ component large enough to add a significant contribution to the average pattern? To solve the problem it is necessary to investigate the probability occurrence of the large V_y observation.

The study of the occurrence of the large cross-tail plasma velocity is one of the goals of the present paper. We also investigate the relation of these events with BBFs.

Data

Our study is based on Geotail satellite data for the period from May 1995 to May 1999. Magnetic field components and plasma parameters (12-second resolution) are used. Only periods when Geotail coordinates were within X<-15 R_E, -15<Y<20 R_E, and plasma parameter β was >0.5 are considered.

Statistics of large $|V_y|$ occurrence

In this section each 12-second interval with $|V_y|>V_{thr}$ (where V_{thr} is a threshold value) is considered as a separate event. Three threshold values are used: V_{thr} =200, 400, 600 km/s. Also, all events with $|V_x|>V_{thr}$ under the same conditions are selected to compare the $|V_y|>V_{thr}$ and $|V_x|>V_{thr}$ occurrences. The occurrence is defined as the ratio of the number of events observed in the certain space area to the number of all 12-second intervals in the same area.

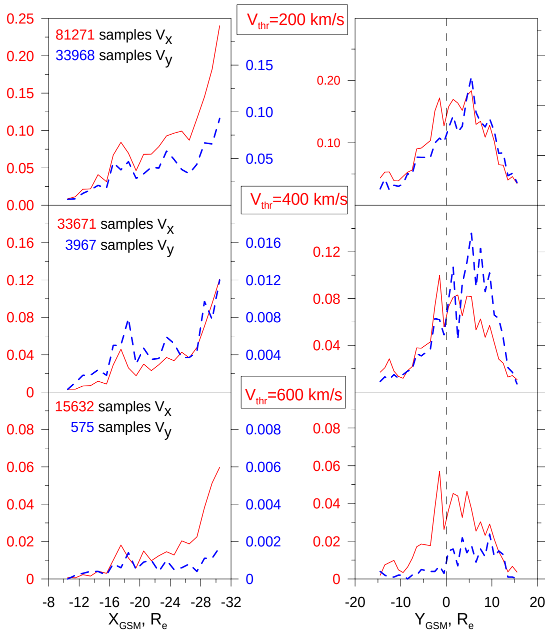

Fig. 1. Occurrences of $|V_y|>V_{thr}$ (dashed) and $|V_x|>V_{thr}$ (solid) against X_{GSM} (the left column) and Y_{GSM} (the right column).

The results for three threshold values are presented in Fig. 1 where occurrences of $|V_y|>V_{thr}$ and $|V_x|>V_{thr}$ are plotted against X and Y GSM coordinates. The number of events for each threshold value is indicated. Each point in the plot is the $|V_y|>V_{thr}$ and $|V_x|>V_{thr}$ occurrence in the 1 R_E width strip along X for all values of Y or along Y for all values of X. Data in

Fig.1 show that the $|V_y|>V_{thr}$ distribution is similar to the $|V_x|>V_{thr}$ one for all V_{thr} values, but probability values are different: the $|V_x|$ occurrence is much larger than the $|V_y|$ one (2÷15 times, depending on the threshold value and the observation region). Common occurrence characteristics for $|V_y|$ and $|V_x|$ are: 1) growth of the occurrence towards the tail, and 2) localization near the central sector of the tail (in overwhelming majority of events both $|V_x|>V_{thr}$ and $|V_y|>V_{thr}$ are observed at -10 R_E<Y<10 R_E). The difference of distributions is formed by appreciable shift of the $|V_y|$ maximum to the dusk.

To understand the reasons of the dawn-dusk asymmetry we have repeated the above analysis separately for $V_y>0$ and $V_y<0$. The results are presented in Fig.2, where we can see that dawn-dusk asymmetry is formed practically entirely due to excess of events with $V_y>0$ on the dusk side.

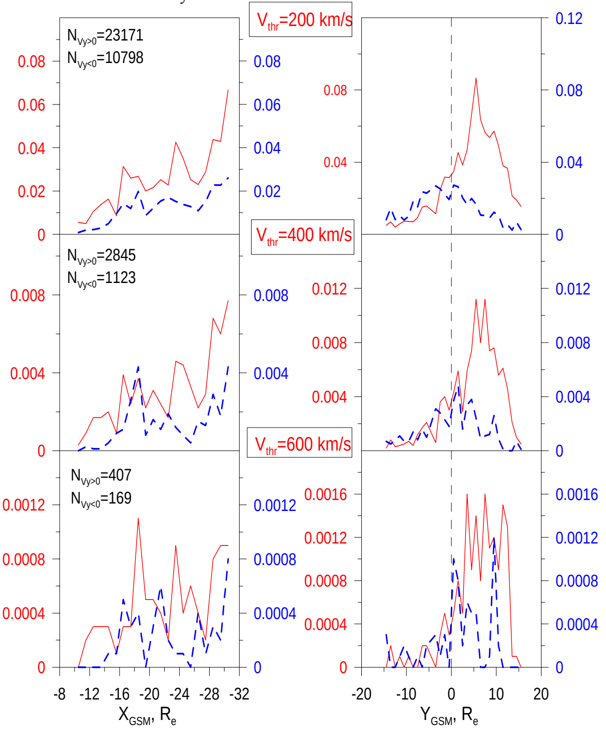

Fig. 2. Occurrences of $|V_y|>V_{thr}$ depending on V_y sign: $V_y<0$ (dashed) and $V_y>0$ (solid) against X_{GSM} (the left column) and Y_{GSM} (the right column).

The distribution of $V_y<0$ and $V_y>0$ on Y_{GSM} changes for symmetric ($V_y<0$ prevails under Y<0 and $V_y>0$ prevails under Y>0) by addition of V_y =-30÷-50 km/s to the velocity in each event (not shown). Following Kaufman et al. [2000] we consider this value as a cross-tail drift (current) velocity of ions. This value depends on the observation point in the tail; however the study of this dependence is beyond the scope of this paper.

Relation of $|V_y|>V_{thr}$ events with high-speed plasma streams in the tail

The similarity of $|V_y|>V_{thr}$ and $|V_x|>V_{thr}$ occurrences points to the possibility of relation of large $|V_y|$ events to BBFs. The analysis of separate events shows that short (<1 min) impulses of $|V_y|>V_{thr}$ are often observed during longer (up to 10 min and more) intervals of the velocity enhancement above the average level (that is, above several tens km/s, see the example in Fig.3). In these events the $|V_x|$ enhancement up to greater than 400 km/s value, density and pressure reduction as well as temperature growth simultaneously with $|V_y|$ growth are observed. These variations are well-known as BBFs attributes (see, Introduction).

In this section we study average characteristics of $|V_y|>V_{thr}$ intervals. Now the event is defined as an interval satisfying the following criteria: $|V_y|>200$ km/s during the whole interval, $|V_y|_{max}>400$ km/s, and $\beta>0.5$ before the front of the stream. The short-term decrease of β below 0.5 can be observed inside the event due to strong magnetic field and plasma parameters variations. To get a more distinct picture at the front we consider only isolated events for which $|V_y|<200$ km/s during at least 8 minutes before the sharp velocity growth.

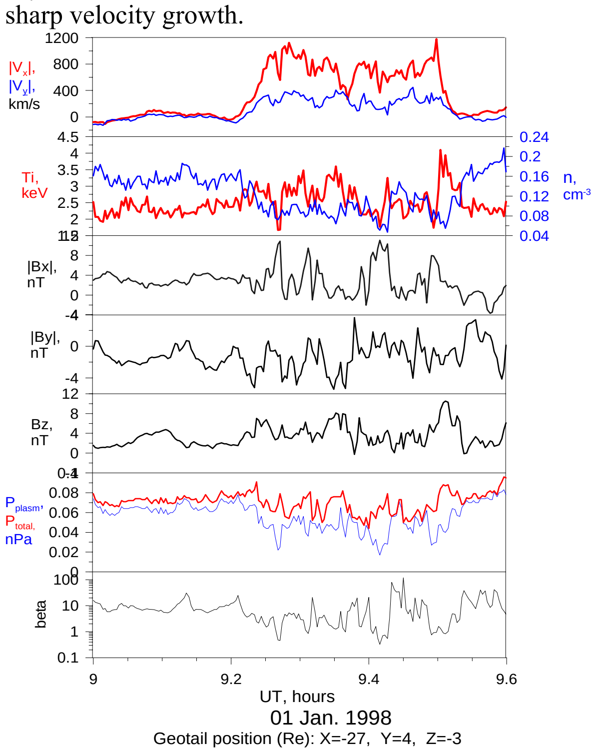

Fig. 3. An exapmle of the long time velocity enhancement with large V_y value and typical variations of magnetic field and plasma parameters.

The analysis of selected events with $|V_y|>400$ km/s (98 intervals) shows all attributes typical for BBFs in 95 % of cases. To get the average portrait of the $|V_y|>V_{thr}$ events we used superposed epoch analysis with reference time (T_0) defined as the start of sharp $|V_y|$ growth above 200 km/s. The results are presented in Fig. 4. Note that the average $|V_y|_{max}$ value does not achieve the value defined as the threshold. The reason is that different events have different front durations, so the maxima do not coincide and the average picture blurs. Fig. 4 confirms the suggestion about the relation of the $|V_y|>V_{thr}$ events with BBFs: the $|V_x|$ value on average exceeds the $|V_y|$ one, and the magnetic field and plasma variations are analogous to those obtained by Angelopoulos et al. [1994], Ohtani et al. [2004] for BBFs.

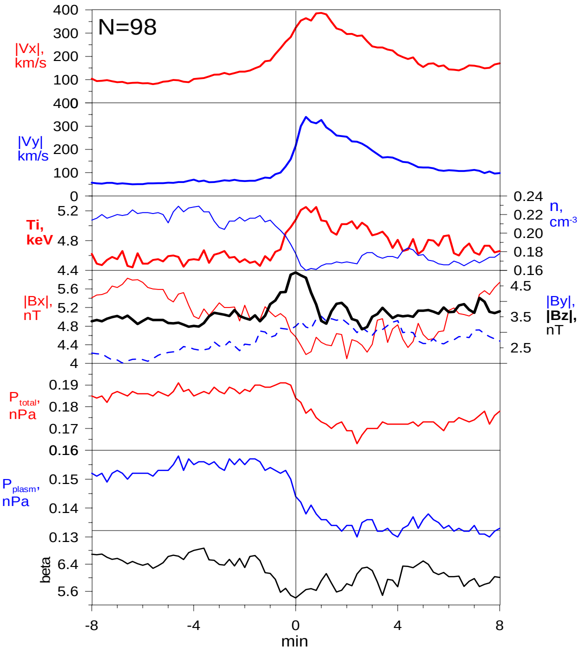

Fig. 4. The result of superposed epoch analysis for isolated events with $|V_y|$>400 km/s; the reference time (T_0) defined as the start of sharp growth $|V_y|$ above 200 km/s.

The analysis of space distribution of the $|V_y|>V_{thr}$ and $|V_x|>V_{thr}$ samples in the previous section showed that for fixed V_{thr} the probability of large $|V_y|$ values is much smaller than that of large $|V_x|$ (10-fold for V_{thr}=400). Does it mean that only a small part of BBFs has a large V_y-component? Or is it due to the smaller space-time scale of the $|V_y|>V_{thr}$ events compared with BBFs? What is the ratio of the maximum $|V_x|$ and $|V_y|$ in the fast flows in the plasma sheet?

To get the answer we selected all intervals with $|V_x|$>400 km/s (618 isolated events) using criteria described above for the $|V_y|>V_{thr}$ events. The average characteristics of these events were studied by superposed epoch analysis method. The key moment of this method is the choice of the reference time. As shown by Othani et al. [2004] the result of such method will be different depending on which parameter dictates the T_0 choice: excess of the velocity threshold or start of the typical magnetic field variation. Our results support this conclusion. In particular, T_0 chosen for our Fig. 4 (according to criterion $|V_y|$>200 km/s) is obviously delayed relative to the start of the density, pressure, and temperature variations typical for the BBF front. Therefore in this study we have determined the reference time as the moment when the ion thermal pressure had achieved its maximum during a 2-min interval before the velocity increase (Fig. 5). In our opinion, the moment corresponds to the boundary between the heated and condensed plasma grabbed by the BBF front and the depleted magnetic field tube (that is the BBF).

The average picture of the BBF-associated plasma parameters and magnetic field variations presented in our Fig. 5 coincides with similar sketches published by our predecessors in all aspects except one: - the V_y component magnitude.

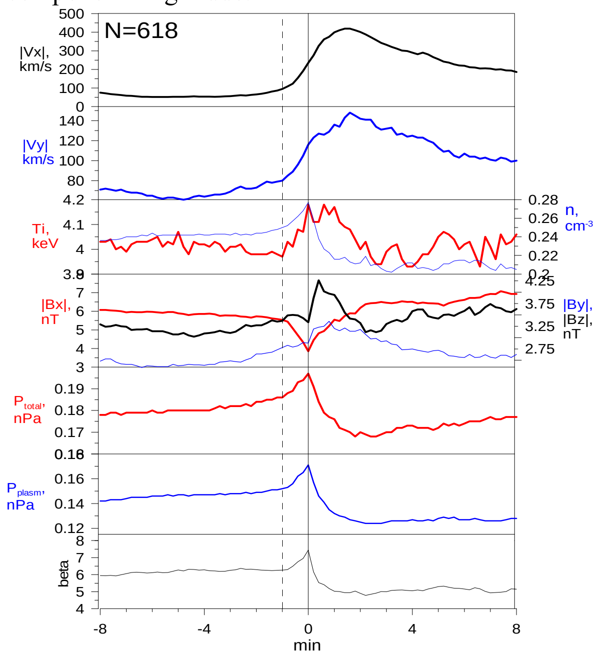

Fig. 5. The result of superposed epoch analysis for isolated events with $|V_x|$>400 km/s; reference time (T_0) defined as the time of the plasma pressure maximum. The dashed vertical line corresponds to the start of parameter variation before the fast flow front.

According to our data, $|V_y|$>400 km/s (300 km/s) is observed for 21% (43%) of all events when $|V_x|$>400 km/s. Moreover, the total part of events, for which $|V_y|$ does not exceed 100 km/s, amounts to less than 5%. The average duration of time interval when $|V_y|$ exceeds 200 km/s is 3 minutes (Fig.4); the corresponding time interval for $|V_x|$ is 6.5 minutes (Fig.5).

To make more precise quantitative relations between $|V_x|$ and $|V_y|$ we have compared maximal magnitudes ($|V_x|_{max}$ and $|V_y|_{max}$) as well as the corresponding extreme time moments for each event with $|V_x|$>400 km/s. The average ratio ($R=|V_x|_{max}/|V_y|_{max}$) is found to be of about 2. The times of the $|V_x|$ and $|V_y|$ maxima coincide with the deviation of about ±2 min at the 0.5 of the histogram maximum.

Coming back to our Fig.1 one can see that for one and the same point the occurrence of $|V_y|$>200 km/s coincides quantitatively with the occurrence of $|V_y|$>400 km/s.

Discussion and conclusion

The results of the statistical analysis presented above provide quite convincing evidences that the great majority of the magnetospheric plasma sheet fast flows have V_y-component comparable with the corresponding V_x-component.

This fact allows us to achieve agreement between the average plasma flow patterns having a considerable V-component toward the flanks [Hori et al., 2000, Kaufmann et al., 2001] and BBFs providing the lion's share of plasma and magnetic flux transport along the axis of the magnetospheric tail [Angelopoulos et al., 1994, 1996].

Indeed, the above obtained spatial distributions of the great V_y-component occurrence seem to be qualitatively coincident with the average plasma flow patterns: cross-tail component of the plasma velocity grows tailward and is observed much more often in the evening side. Our estimate of the asymmetric part of the cross-tail velocity component is in a satisfactory quantitative agreement with the corresponding value obtained by Kaufmann et al. [2001].

A question arises: what is the physical nature of this large V_y of BBFs? The $|V_y/V_x|=0.47$ ratio obtained in the present study gives the average angle of velocity vector deviation from tail axis equal to 25 degrees. This value is in agreement with result of [Baumjohann and Pashman, 1990] obtained for distances less than 20 R_E. On the other hand, the BBF having the V_y velocity greater than 200 km/s shall be shifted toward flanks by more than 10 R_E during the pass time from -30 till -10 R_E. However, this is in contradiction with the fact that the maximum of the BBF occurrence is observed at the central sector of the magnetotail. Thus, the large V_y component unlikely relates to the BBF movement as a whole. Besides, no correlation of V_y and V_x variation was observed.

According to our results the spatial size of the considered typical (average) V_y velocity disturbance along the X-axis is of about one half of the whole X-size of the BBF. That's why the BBF-associated V_y-component can not be a manifestation of the local small-scale plasma sheet irregularities. Therefore, the above comparisons lead us to the natural conclusion that the considered V_y-component variation has a large-scale or meso-scale spatial size. We consider the scale as a typical size of the plasma movements inside and/or outside of the BBF near its boundary.

Let us remind that one point satellite data, in principle, can not provide unambiguous information about 2D plasma velocity patterns. There are no multi-satellite data available on the topic (at least as far as we know). However, it seems to be useful to compare our results with the BBF-associated MHD modeling. One of such models describes the BBFs as an earthward moving electric dipole [Birn et al., 2004]. As known, the latter is formed by the polarization electric charges induced by the large-scale cross-tail magnetospheric electric field at the BBF flanks. The polarization electric field has a component along the tail axis in the regions near to the leading (earthward moving) BBF front where two plasma vortices should exist [Sergeev, et al., 1996, Birn, et al., 2004]. The sign of the V_y-component of the convection here should be the same as the sign of the Y-component of the outer normal vector (N_y-component) transverse to the front. We have used the data of Nakamura et al. [2001], who calculated normal vector components for 14 events using the Geotail data. We analyzed the data for all the events in order to test the validity of the model prediction. For the purpose we considered the sign of the transverse to the geomagnetic field V_y-component of the convection near the BBF's front. The steep falls of the thermal plasma pressure are used by us as the criteria of the BBF front crossings for these events. The results of the comparison of our analysis with the data published by [Nakamura, et al., 2001] are the following: for the absolute majority of the considered events (for 13 events from the listed 14 ones) signs of the V_y and N_y components are the same. We consider the only event with the opposite sign as an exception because for this event the N_y/N_x ratio is about 0.2, whereas the ratios are 0.5-1.5 for other events. Therefore, in our opinion, the results of the comparison allow us to conclude that both the experimental findings by Nakamura et al., [2001] and those presented in the present paper) are in a qualitatively reasonable agreement with the model by Birn et al. [2004].

Let us also note that for the majority of the studied events the sign of the V_y-component reversed after the moment of the BBF's going by. We consider this feature as an additional argument of the validity of our assumption on the large-scale nature of the $|V_y|$ variation.

Thus, as shown in the present study the V_y-component equal to about a half of V_x-value is observed for the majority of fast plasma flows at the distances of 10-30 R_E in the plasma sheet. This phenomenon, probably, relates with two plasma vortices near the BBF leading front.

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