Joint observations by Cluster satellites of bursty bulk flows in the magnetotail

J. B. Cao,[1] Y. D Ma,[1,2] G. Parks,[3] H. Reme,[4] I. Dandouras,[4] R. Nakamura,[5] T. L. Zhang,[5] Q. Zong,[6] E. Lucek,[7] C. M. Carr,[7] Z. X. Liu,[1] and G. C. Zhou[1]

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[1] Using the observations of three satellites of Cluster (C1, C3, and C4) during the periods July to October 2001 and July to October 2002, we study 209 active time bursty bulk flows (BBFs), the difference between single satellite observations and multisatellite observations, and the difference among three selection criteria (two about BBFs and one about rapid convection event). Single satellite observations show that the average duration of BBFs selected by the criterion of Angelopoulos et al. is 604 s, while multisatellite observations show that the average duration of BBFs is 1105 s. Single satellite sometimes misses the BBFs. The missing ratio of single satellite is 22.4% for the criterion of Angelopoulos et al. and 44.9 % for the criterion of Raj et al. Therefore the single satellite observations cannot tell the true number of BBFs. The multisatellite observations are more important for the criterion of Raj et al. The single satellite observations also show that 22% of substorms are not accompanied by BBFs, while multisatellite observations show that only 4.5% of substorms are not accompanied by BBFs. Thus it seems possible that all substorms are accompanied by BBFs. The occurrence frequency of RCEs in the central plasma sheet obtained by multisatellites is 12.2%. The occurrence frequency of BBFs in the central plasma sheet is 9.5% for single satellite observations and 19.4% for multisatellite observations. So BBFs may contribute more to the transport of magnetic flux, mass, and energy than what was estimated by previous studies based on single satellite observations.

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1. Introduction

[2] The bursty bulk flows (BBFs) in the inner plasma sheet of the magnetosphere are important phenomena that are closely related to magnetospheric activities and transport of energy and magnetic flux. Using data from AMPTE/IRM in the magnetotail, *Baumjohann et al.* [1988, 1989, 1990] studied high-speed flows and magnetic field in the inner plasma sheet. Their results showed that the occurrence rate of high-speed flows in the inner central plasma sheet (ICPS) may approach or even exceed those in the outer central plasma sheet (OCPS) and the plasma sheet boundary layer (PSBL). *Angelopoulos et al.* [1992] studied high-speed flows in the ICPS and called them bursty bulk flows. They found that BBFs are related to the *AE* index, phases of substorms, and solar wind conditions. *Angelopoulos et al.* [1994], using data of AMPTE/IRM and ISEE2, analyzed statistical characteristics of BBFs in the ICPS. Among the results they found is that BBFs mainly occur during magnetospheric active periods and the average duration of BBFs is about 10 min.

[3] The importance of BBFs to magnetospheric physics is their contribution to the transport of mass, energy, and magnetic flux. *Angelopoulos et al.* [1996] estimated the earthward transport of mass, energy, and magnetic flux of typical BBFs during a substorm by using a typical BBF with a duration of 10 min and a cross-section area of $3 \times 3\ R_E^2$. They found that BBFs are responsible for 60–100% of measured earthward transport of mass, energy, and magnetic flux past the satellite in the region of maximum occurrence rate, even though they last only 10–15% of the observation time there. Thus BBFs represent the primary transport mechanism in those regions. However, a single BBF can account for the transport rate of a medium substorm only when the cross-section area in the Y-Z plane reaches 100 R_E^2. Even in this case, the total BBF energy transport is about 10 percent of the transport of substorm. Thus *Angelopoulos et al.* [1996] concluded that BBF is not the main transport mechanism during a substorm. Alternatively,

[1]Key Laboratory of Space Weather, CSSAR/CAS, Beijing, China.
[2]Also at Graduate School of the Chinese Academy of Sciences, Beijing, China.
[3]Space Sciences Laboratory, University of Washington, Seattle, Washington, USA.
[4]Centre d'Etude Spatiale des Rayonnements, Toulouse, France.
[5]Space Research Institute, Austrian Academy of Sciences, Graz, Austria.
[6]Center for Space Physics, Boston University, Boston, Massachusetts, USA.
[7]Blackett Laboratory, Imperial College London, London, UK.

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many BBFs might last longer than their median observed duration of 10 min; however, they are not observed due to the localization of BBFs and the fact that there are only a limited number of satellites in the BBF occurrence region. *Sergeev et al.* [2000] also thought that the BBF transport rate cannot account for the total transport rate of magnetotail. *Paterson et al.* [1998, 1999] questioned the results of *Angelopoulos et al.* [1992, 1994] using different statistical approach and came to the conclusion that bursty bulk flows do not contribute significantly to transport in the near-Earth plasma sheet, at least during quiet times. Thus the contributions of BBFs to the energy transport in substorms and their role in substorm are still under debate [*Lui et al.*, 2000].

[4] *Angelopoulos et al.* [1997] showed that the scale of a single BBF in the Y-Z plane is less than 3 R_E by using multisatellite data. *Slavin et al.* [1997] suggested that the scale of BBFs during substorm expansion phase must have large-scale lengths and/or be distant relative to the 5–10 R_E spacing of the three spacecraft (GOES, Wind, and Geotail) observing the southward field pulse and BBFs. However, they also pointed out that during the substorm recovery phase, Wind observed some BBF events, which are not observed by other satellites. Thus the characteristics of BBFs may be different in different regions and different substorm phases.

[5] Using the Geotail data, *Baumjohann et al.* [1999] studied the relation between fast ion bulk flows and substorms. They found that around substorm onsets, fast flows emerge from a region around -20 R_E and stream unhindered both earthward and tailward. After onset, the occurrence rate of earthward flows is typically decreasing in the regions of depolarization between 16 and 21 R_E. *Angelopoulos et al.* [1996] thought that the relation of BBFs with substorm phase was not apparent from a visual inspection of the database. However, a clear association of BBFs with geomagnetic activity emerged from both the AMPTE/IRM and ISEE data sets. Very few BBFs occur when AE is less than 100 nT.

[6] *Angelopoulos et al.* [1997] thought that the duration of BBF might be longer than 10 min, but due to highly localization of BBF, it is very hard to observe it. *De La Beaujardiere et al.* [1994], using the burst flows in the ionosphere, found that the burst flows in the ionosphere relevant to BBF often last tens of minutes. *Sergeev et al.* [2001] found that the auroral streamers relevant to high-speed flows may last 10–20 min. However, owing to the difficulty to distinguish between high-speed flows in the PSBL and BBF in the CPS from ground observations and the difficulty to map the ionospheric regions to the magnetotail, it is difficult to identify the duration of BBFs observationally.

[7] The radial evolution of BBFs strongly influences the BBF observations made by satellites on different locations. *Schodel et al.* [2001], on the basis of several years of Geotail data, performed a comprehensive statistical analysis of rapid convective transport in the near-tail and midtail central plasma sheet. They chose a new approach by using flux transport and not ion bulk velocity as the threshold parameter for the identification of rapid flows and found that the occurrence rate of earthward rapid flux transport events was constant at radial distances >15 R_E and that it started to drop only earthward of 15 R_E. However, on the basis of the data of AMPTE/IRM and ISEE2, *Angelopoulos et al.* [1994] found that the occurrence rate of earthward BBFs ($Vx > 0$) in the inner plasma sheet increased with the distance from Earth up to $x = -19$ R_E. The discrepancy in the two results may arise from the different selection criteria of flows used in the two papers. It is generally accepted that the speeds of BBFs decrease when BBFs approach the Earth from the source regions.

[8] The bulk flows and field-aligned beams are similar in terms of their velocity moments and may occur at the same magnetic latitudes but are easily distinguishable based on their ion distributions. However, it is often not feasible to examine each and every particle distribution in statistical studies of high-speed flows in the plasma sheet involving a large amount of data. Recently, *Chen et al.* [2000] questioned the true nature of high-speed bulk flows. They argued that bursty bulk flows observed in the CPS do not represent bulk motion of a single ion population, contrary to the conclusion reached by a large number of previous studies [e.g., *Baumjohann et al.*, 1989; *Nakamura et al.*, 1991; *Angelopoulos et al.*, 1992; *Nagai et al.*, 1998]. In order to better distinguish between field-aligned beams and bulk flows, several new selection criteria are proposed by *Nagai and Machida* [1998] and *Raj et al.* [2002]. *Raj et al.* [2002] impose two strict conditions to the selection criterion: perpendicular flow speed >250 km/s and plasma βxy (based on the x and y components of the magnetic field) >2. The new selection criterion can eliminate 95% of beam events while retaining 60% of bulk flow events.

[9] BBFs are often classified into two categories: substorm and nonsubstorm events. As suggested by *Amm and Kauristie* [2002], BBFs which occur during substorm expansive phases can differ greatly in their phenomenology from nonsubstorm events [*Yeoman and Lühr*, 1997; *Yeoman et al.*, 1998; *Wild and Yeoman*, 2000; *Grocott et al.*, 2004]. Moreover even for nonsubstorm events, there is a difference between the BBFs within so-called "quiet" intervals, where, for example, there is no evidence of the substorm cycle, and BBFs within the intervals of substorm growth phases [*Amm and Kauristie*, 2002; *Grocott et al.*, 2004].

[10] In this paper we use the data from three satellites of Cluster (C1, C3, and C4) to study 209 active time BBFs and the difference between the joint observations of multisatellite and observations of single satellites. Although the ion velocity distribution function can better distinguish field-aligned beams and bulk flows, we still use the moment-based selection criterion. This is because the statistical studies of high-speed flows involve a large amount of data and examining each and every particle distribution is not feasible. Since previous studies of BBFs selecting those using criterion of *Angelopoulos et al.* [1994] already provided many important results concerning BBFs, we still use the BBF selection criterion of *Angelopoulos et al.* [1994] in order to compare the results of multisatellites with the previous results of single satellite, instead of using some new selection criteria proposed by *Nagai and Machida* [1998] and *Raj et al.* [2002]. However, a comparison between the selection criterion of *Angelopoulos et al.* [1994], the selection criterion of *Raj et al.* [2002], and the selection criterion of rapid convection events of *Schodel et al.* [2001] are made for both multisatellite observations and single satellite observations.

[11] The paper is organized as follows: The instrumentation and selection criteria of BBF are presented in section 2 and section 3. The case studies of BBFs are presented in section 4. The statistical studies of active time BBFs are presented in section 5. The conclusions are presented in section 6.

2. Instrumentation

[12] The apogee and perigee of Cluster are 19.6 and 4.0 R_E, respectively. The inclination of Cluster orbit is 90°. The spin period is 4 s. From July to October of 2001 and 2002, Cluster moved through magnetotail regions. The distance among satellites is from 200 to 4000 km. To our knowledge, this distance is smaller than the distance between previous multisatellites that observed BBFs. Thus the Cluster mission can provide a very good and unprecedented opportunity to study BBFs.

[13] The plasma data is from Composition and Distribution Function Analyzer (CODIF) of the Cluster ion spectrometry (CIS) experiment and the magnetic field data used here is from the Flux Gate Magnetometer (FGM) experiment. The CIS of cluster can provide three-dimensional (3-D) velocity distribution of ions with a time resolution of spin period 4 s. The moment parameters (such as density, velocity, and temperature) are calculated based on velocity distributions. The FGM can provide magnetic field measurement with a sampling rate up to about 67.249 Hz. However, the magnetic filed with a time resolution of 4 s is used for our analysis. The detailed description of FGM and CIS of Cluster can be found in the work of *Reme et al.* [2001] and *Balogh et al.* [2001].

[14] Since the data of six instruments (FGM and CODIF of three satellites) are used in our studies, the data gap and/or slightly poor quality of data of one instrument can make it impossible to perform multipoint analysis. Thus among the observed 618 substorm BBF events, only 209 BBFs are used in the multipoint analysis.

3. Selection Criteria of BBFs

[15] The BBF selection criterion of *Angelopoulos et al.* [1994] is as follows: (1) BBFs are segments of continuous ion flow magnitude V_i above 100 km/s in the plasma sheet, during which V_i exceeds 400 km/s at least for one sample period in the IPS ($\beta > 0.5$); (2) samples of $V_i > 400$ km/s that are less than 10 min apart are considered to belong to the same BBF, even if the velocity drops below 100 km/s between these samples; (3) the BBF is defined to begin when its velocity exceed 100. km/s and ends when the velocity drops below 100. km/s.

[16] Like *Angelopoulos et al.* [1994], we limited our database to outside the hinge point region, $X_{AGSM} < -10$ R_E. In order to avoid crossings of the magnetopause, we also confined our analysis to the region $|Y_{AGSM}| < 15$ R_E. In addition, we eliminated other possible magnetopause boundary crossings by searching for times during which the ion temperature T_P dropped below 500 eV, the proton density N_P increased beyond 1 cm^{-3} and the flow was persistently (>5 min) tailward (>200 km/s) at distances of ($|Y_{AGSM}| >$ 10 R_E). Mantle crossings were also removed from the region $(Y^2_{AGSM} + Z^2_{AGSM})^{1/2} > 10$ R_E and $Z_{AGSM} > 6$ R_E.

[17] The definition of the duration of BBF observed by a single satellite is the same as that of *Angelopoulos et al.* [1994]. The duration of BBFs observed by three Cluster satellites is defined as follows [*Ma et al.*, 2005]: (1) The earliest beginning time of BBF observed by any one of three satellites is the beginning time of BBF; (2) The latest ending time of BBF observed by any one of three satellites is the ending time of BBF; (3) The time between the beginning time and ending time of BBF is the duration of BBF observed by three satellites.

[18] About the selection criterion of *Raj et al.* [2002], two conditions that perpendicular flow speed >250 km/s and plasma β_{xy} (based on the x and y components of the magnetic field) >2 replaced the two conditions in the work of *Angelopoulos et al.* [1994] that ion speed >400 km/s and plasma $\beta > 0.5$, respectively.

[19] *Schodel et al.* [2001] proposed a method to identify rapid convection event. Their selection criterion of flux rope event is as follows: (1) $\beta > 0.5$; (2) $v_\perp > v_{II}$; and (3) the maximum electric field $E_H = ((V_x B_z)^2 + (V_y B_z)^2)^{1/2} > 2$ mV/m; (4) the rapid convection event is defined to begin when E_H exceed 0.5 mV/m and ends when E_H drops below 0.5 mV/m. This selection criterion emphasizes the importance of magnetic flux convection.

[20] Since BBFs correlate with *AE* increases in a statistical sense [*Angelopoulos et al.*, 1994; *Angelopoulos et al.*, 1996], many previous papers studying the relation between BBF and substorms used *AE* index [*Angelopoulos et al.*, 1992, 1994; *Baumjohann et al.*, 1990; *Angelopoulos et al.*, 1996; *Lakhina*, 1996]. Since we wish to compare our results with those of previous studies, we adopt *AE* index to categorize BBFs in spite of its shortcomings in identifying substorms. In this paper, active time BBFs mean BBFs with $AE > 200$ nT.

[21] Through this paper, we name BBF selected by the criterion of *Angelopoulos et al.* [1994] as BBF/Ang, BBF selected by the criterion of *Raj et al.* [2002] as BBF/Raj, and the rapid convection event defined in the way of *Schodel et al.* [2001] as RCE.

4. Case Studies of BBFs

[22] We first make a case study to show why the duration of BBF observed by single satellite is smaller than that observed by multisatellites by using the selection criterion of *Angelopoulos et al.* [1994].

[23] Figure 1 shows the plasma beta, plasma bulk velocity *V*, perpendicular velocity V_{perp}, and magnetic fields *B*x, *B*y, and *B*z of the BBF/Ang within the interval 2135–2155 UT on 7 September 2001. The observations of C1, C3, and C4 are indicated by black, green, and blue. The magnetic observations and plasma beta show that three satellites C1, C3, and C4 entered the central plasma sheet ($\beta > 0.5$) at about 2141, 2135, and 2141 UT. The BBF/Ang observed by C1 on 7 September lasts from 2144:38 UT to 2153:49 UT, the BBF/Ang observed by C3 on 7 September lasts from 2135:58 UT to 2151:00 UT, and the BBF/Ang observed by C4 lasts from 2141:18 UT to 2153:44 UT. The similarity of velocity characteristics of BBF/Ang observed by C1, C3, and C4 in Figure 1 indicates that the BBF/Ang observed by three satellites belongs to the same BBF/Ang. This conclusion is also justified by the BBF

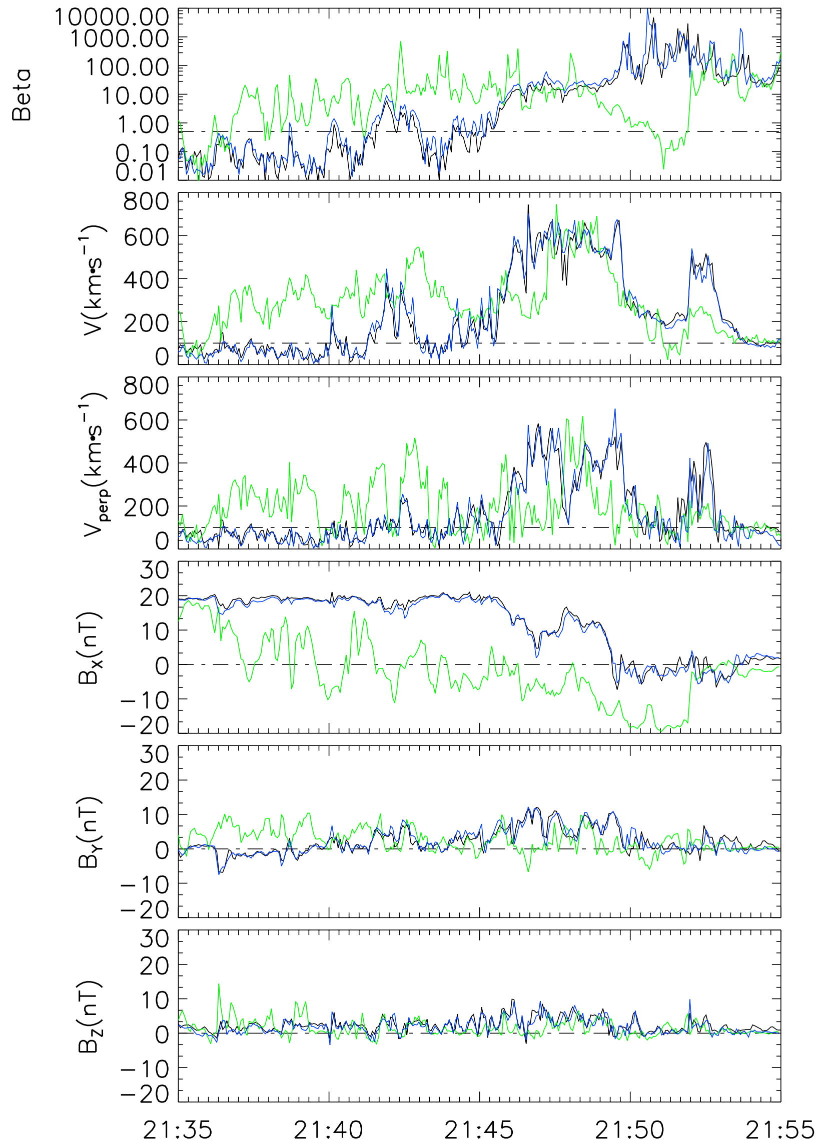

Figure 1. The plasma Beta, bulk velocity V, perpendicular velocity V_{perp}, and magnetic fields Bx, By, and Bz of the BBF/Ang within the interval 2135–2155 UT on 7 September 2001. C1: black, C3: green, and C4: blue.

dimension estimations. *Nakamura et al.* [2004] developed a method to estimate the width of high-speed flows. They first use multipoint observations from the Cluster spacecraft to calculate the spatial gradient. Then they calculate the full width of the flow channel by taking the average or median of the spatial gradients and by assuming that the flow channel has a linear gradient. The calculation by means of the method of *Nakamura et al* [2004] shows that the dimension of this BBF/Ang in the Y direction is 0.9 R_E. During the whole BBF event, the largest distance between the Cluster satellites is about 0.15 R_E, which is not only smaller than the above-calculated BBF dimension but also smaller than the size of patchy reconnection obtained in a 3-D two-fluid simulation of reconnection [*Shay et al.*, 2003], the wavelength of magnetic bubbles formed due to interchange instability in a 3-D hybrid simulation [*Nakamura et al.*, 2002], and the width of the current sheet [e.g., *Runov et al.*, 2005]. Thus the BBFs/Ang observed by Cluster satellites belongs to the same class of events.

[24] We used the BBFs/Ang observed by C1 as an example of BBF observed by single satellite and compare them with BBFs/Ang jointly observed by three satellites C1, C3, and C4. The observations of C1 show that the duration of BBF/Ang is 551 s. However, the joint observations of three satellites show that the BBF/Ang should begin at 2135:58 UT (observed by C3) and not at 2144:38UT (observed by C1). According to the definition of the duration of BBFs of multisatellites in section 3, the BBF/Ang therefore should begin at 2135:58 UT (observed by C3) and end at 2153:49 UT (observed by C1), and its duration is therefore 1071 s.

[25] If we use the selection criterion of *Raj et al.* [2002], the BBF/Raj observed by C1 lasts from 2145:47 UT to 2152:49 UT, the BBF/Raj observed by C3 lasts from 2135:58 UT to 2151:00 UT, and the BBF/Raj observed by C4 lasts from 2142:22 UT to 2152:40 UT. The duration of BBF/Raj observed by C1 is 422 s while the duration BBFs/Raj given by multisatellites (C1, C3, and C4) is

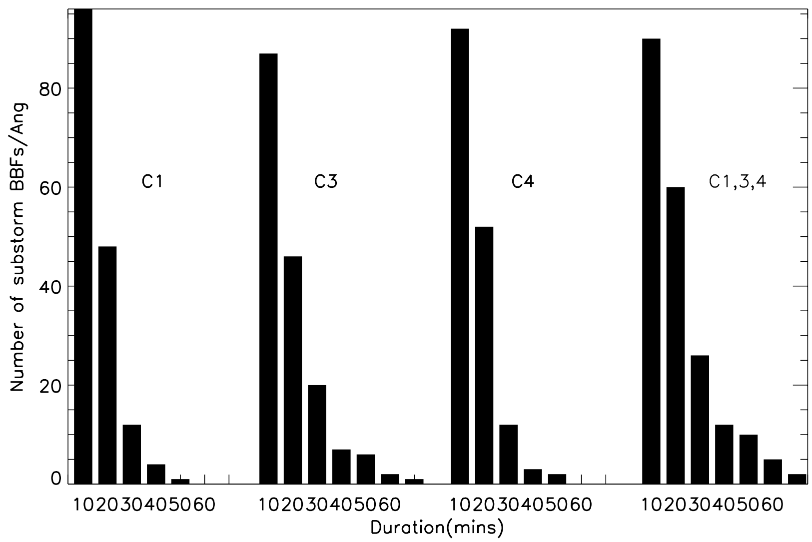

Figure 2. Histograms of duration distributions of BBFs/Ang of single satellites C1, C3, and C4, and multisatellites C1, 3, 4.

1011 s. Thus the analyses based on both selection criteria indicate that the duration of BBF given by multiple satellites is much larger than that given by a single satellite.

5. Statistical Analysis of BBFs

5.1. Active Time BBFs/Ang

[26] We identified 618 substorm-associated BBFs/Ang during the period July to October 2001 and July to October 2002. Among these 618 BBFs/Ang, there are 209 BBFs/Ang during which CIS and FGM of all three satellites (C1, C3, and C4) provided high-quality data without gaps that enabled us to make a multipoint analysis. Thus we mainly focus on these 209 active time BBFs.

[27] Figure 2 shows the histograms of duration distributions of BBFs/Ang of each single satellite. It can be seen that the number of BBFs/Ang with durations larger than 10 min obtained from multiple satellites is larger than that of any single satellite. Among the 209 active time BBFs/Ang, the single satellite (C1) only detected 162 BBFs. The average duration of 162 BBFs/Ang observed by C1 is 604 s, which is almost identical with the duration of BBF of previous studies (10 min). The average duration of 209 BBFs/Ang of three satellites (C1, C3, and C4) is 1105 s. If considering that three satellites only occupy a limited region in the IPS, the average duration of BBF/Ang may be larger than 1105 s. Thus the duration of active time BBFs/Ang is possibly of the same magnitude order with the duration of substorms.

[28] This result means that the duration of BBF observed by single satellite does not reflect the total life span of BBFs since a satellite can only observe at one point in space. The BBFs may move away from a satellite and persists at some other locations in the tail for a duration much longer than the 10 min which is estimated from single satellite. This conclusion is in agreement with ground observations of auroral streamers that are associated with BBFs [*Sergeev et al.*, 2001] and of the burst flows in the ionosphere relevant to BBF [*De La Beaujardiere et al.*, 1994]. The extended duration of active time BBFs will enhance the transport of mass and energy of BBF in substorm and indicates BBFs play an important role in the magnetospheric activities.

[29] The main reason that the observations of multisatellites can increase the duration of BBFs is that multisatellites can stay in the central plasma sheet longer than a single satellite and thus they can have more time in the central plasma sheet to observe BBFs. A single satellite may miss BBF event and/or observe only one part of BBF due to the localization and limited spatial scale of BBF, even when it is in the central plasma sheet. However, for multisatellites, if one satellite goes out of the BBF region and/or the thin current sheet, other satellites may still stay in the BBF region and continue observing BBFs. Thus the duration of BBFs observed by multisatellites is larger than that observed by single satellite.

[30] The separation distance of three satellites may also have influence to the results. The separation distance of Cluster satellites in the tail (close to the apogee of Cluster) is about 2000 km from July to October 2001, while it is about 4000 km from July to October 2002. Among the 209 BBFs/Ang (137 in 2001 and 72 in 2002) observed by three satellites, C1 observed 162 BBFs/Ang (134 in 2001 and 28 in 2002). This indicates that in the case of small separation distance (for example, 2000 km in 2001), the number of BBFs observed by single satellite is almost equal to the number of BBFs observed by three satellites. However, in the case of large separation distance (for example, 4000 km in 2002), the single satellite can only observe 39% (28/72) of BBFs observed by three satellites. The selection criteria of *Raj et al.* [2002] and *Schodel et al.* [2001] give the similar results.

[31] This result is reasonable, since if the separation distance is too large, three satellites may move through the central plasma sheet at different times. Many BBFs observed by one or two satellites are often not observed by the rest satellites. Thus the number of BBFs observed by single satellite is less than the number of BBFs observed

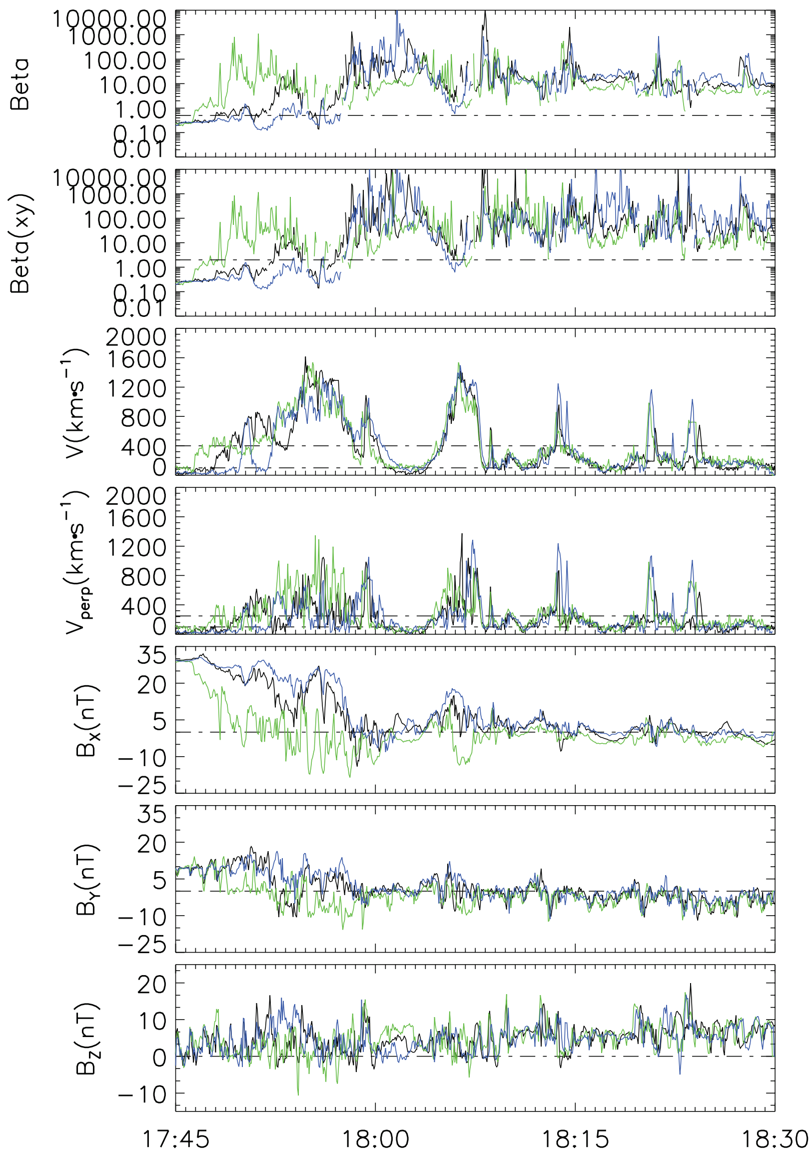

Figure 3. The plasma beta, beta (xy), plasma bulk velocity V, perpendicular velocity V_{perp}, and magnetic fields Bx, By, and Bz within the interval 1745:00–1830:00 UT on 30 July 2002. C1: black, C3: green, and C4: blue.

by three satellites. If the separation distance is small, three satellites can be considered approximately as one point in space and almost always observe the same BBFs together, although the beginning times and ending times of BBFs observed by different satellites may be different.

[32] It is interesting to compare BBFs and RCEs which are defined in the way of *Schodel et al.* [2001]. During the same period of 209 active time BBFs/Ang, three satellites detected 306 RCEs, while the single satellite (C1) only detected 215 RCEs. The average duration of 215 RCEs observed by C1 is 338s, which is in agreement with the duration of RCEs of *Schodel et al.* [2001] (about 350s). The average duration of 306 RCEs of three satellites (C1, C3, and C4) is 445 s. Thus the duration of RCEs obtained by multi satellite observations is much larger than that obtained by single satellite.

[33] In addition, the above results also indicate that the duration of RCEs is much smaller than the duration of BBFs, although the number of RCEs is larger than the number of BBFs.

5.2. Comparison Among Two BBF Selection Criteria of *Angelopoulos et al.* [1994] and *Raj et al.* [2002] and the RCE Selection Criterion of *Schodel et al.* [2001]

[34] When we use magnetic field and plasma data to identify BBFs, many high-speed flows can satisfy the two selection criteria of BBFs. However, there are also some exceptions.

[35] Figure 3 shows the high-speed flows during the interval 1745:00–1830:00 on 30 July 2002, in which two selection criteria of BBFs can be satisfied.

[36] The first BBF/Ang lasts from 1747:59 to 1808:47 and its durations is 1248 s. The first BBF/Raj lasts from 1749:11 to 1810:47 and its duration is 1296 s. Thus the results given by two selection criteria are very similar.

[37] The first high-speed flow also satisfies the selection criteria of RCE of *Schodel et al.* [2001]. The RCE lasts from

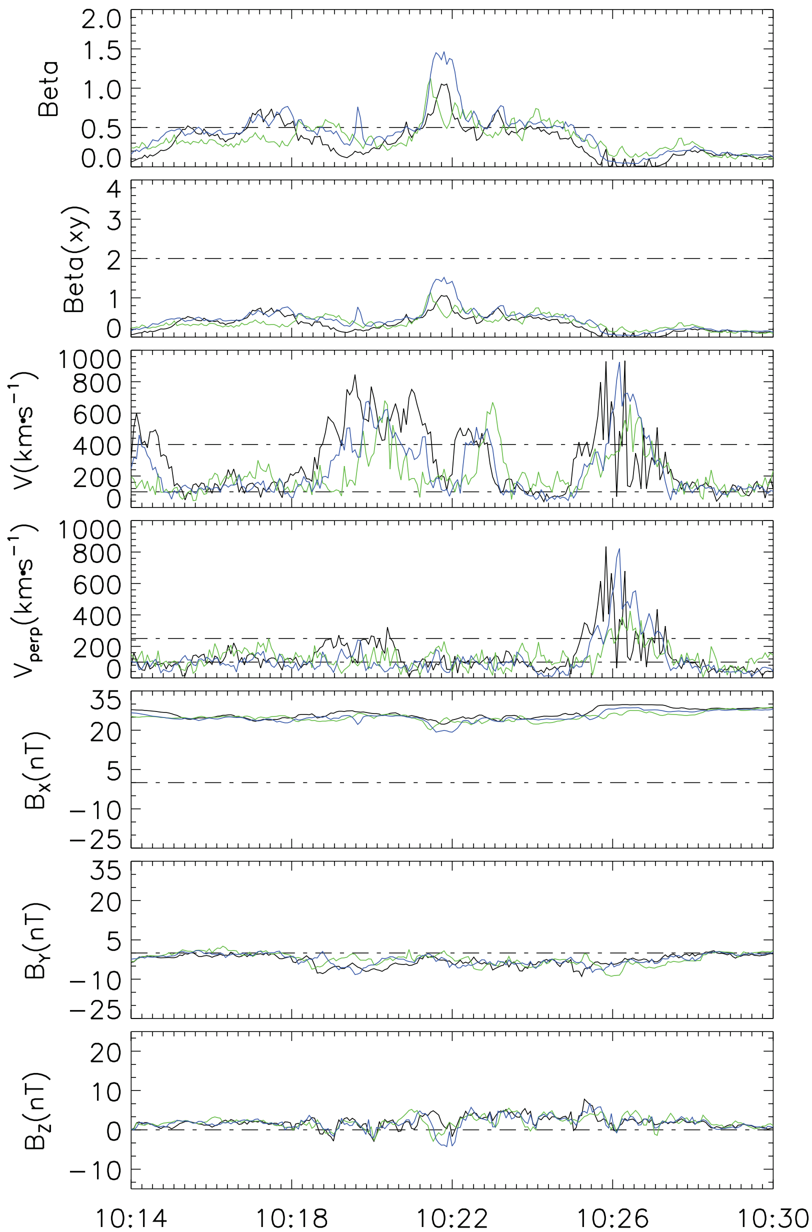

Figure 4. The plasma beta, beta (xy), plasma bulk velocity V, perpendicular velocity V_{perp}, and magnetic fields Bx, By, and Bz within the interval 1014–1030 UT on 12 September 2001. C1: black, C3: green, and C4: blue.

1750:23 to1759:43. The duration of RCE is only 560 s. So the selection criterion of RCE of *Schodel et al.* [2001] is more restrictive than the selection criteria of BBFs at the distance from the Earth of $x{\sim}19\ R_E$.

[38] Figure 4 shows an example on 12 September 2001, in which the high-speed flow is identified as BBF by the selection criterion of *Angelopoulos et al.* [1994] but excluded by the selection criterion of *Raj et al.* [2002] and *Schodel et al.* [2001]. In Figure 4, the maximum plasma beta (>0.5) satisfy the selection criteria of *Angelopoulos et al.* [1994], whereas the maximum Beta_{xy} is smaller than 2 and cannot satisfy the selection criterion of *Raj et al.* [2002]. Therefore this high-speed flow is not BBF if we use the selection criterion of *Raj et al.* [2002]. The condition that $E_H > 2$ mV/m cannot be satisfied as well, and this flow event is not a RCE.

[39] Figure 5 shows a contrary example. In Figure 5, the maximum perpendicular velocity is larger than 250 km/s and satisfies the selection criterion of *Raj et al.* [2002], the electric field E_H is larger than 2 mV/m and satisfies the selection criterion of RCE of *Schodel et al.* [2001], whereas the maximum velocity is smaller than 400 km/s and can not satisfy the selection criterion of *Angelopoulos et al.* [1994]. Thus this event can be seen as a BBF/Raj, or a RCE, and but not a BBF/Ang.

[40] So, it may be not appropriate to say that the selection criterion of *Raj et al.* [2002] can retain a part of *Angelopoulos et al.* [1994], since the two selection criterions give different BBF lists. Using the selection criterion of *Raj et al.* [2002] may miss some BBFs identified by *Angelopoulos et al.* [1994] and meanwhile add some new BBFs.

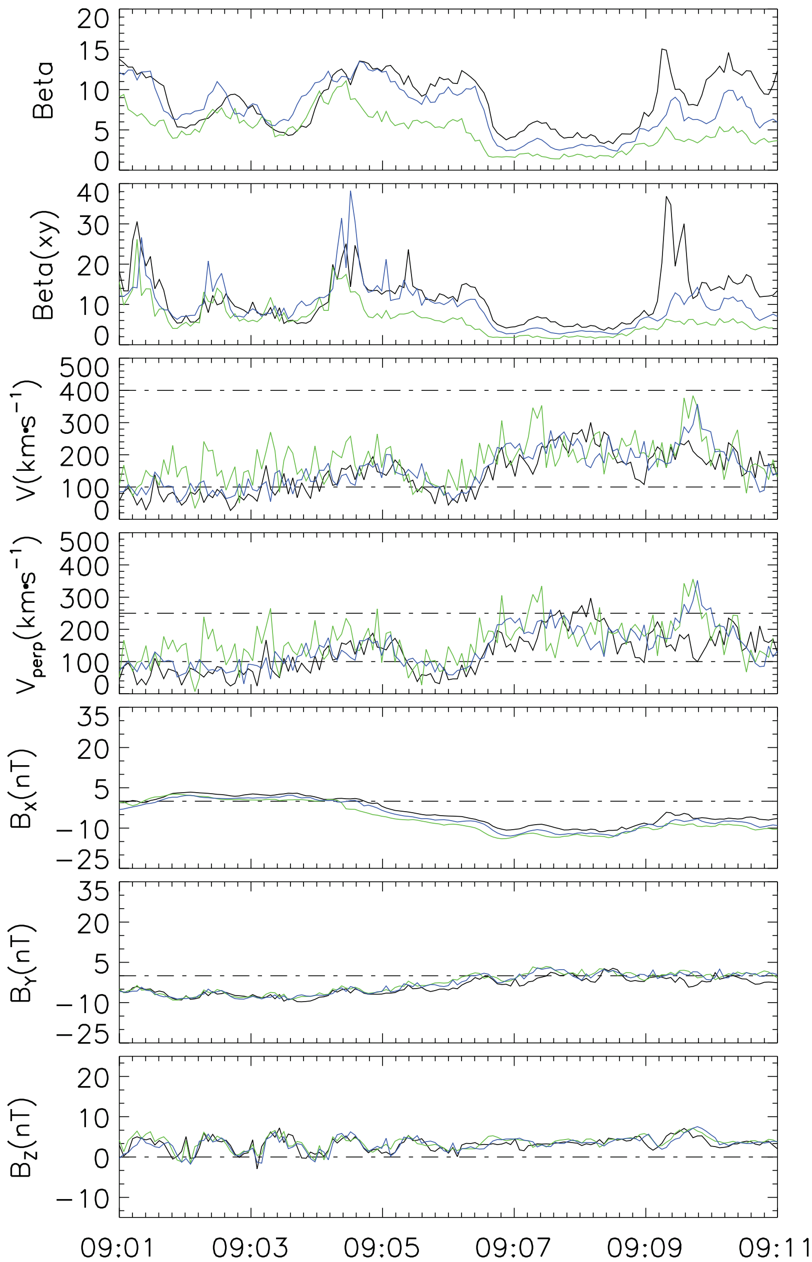

Figure 5. The plasma beta, beta(xy), plasma bulk velocity V, perpendicular velocity V_{perp}, and magnetic fields Bx, By, and Bz within the interval 0901–0911 UT on 13 October 2001. C1: black, C3: green, and C4: blue.

[41] Table 1 shows the number and average duration of active time BBFs/Ang and active time BBFs/Raj. The single satellite (C1) detected 134 active time BBFs/Raj. The ratio of active time BBFs/Raj to active time BBFs/Ang is 82% (134/162). This ratio is a little larger but comparable to the "retaining ratio" obtained by *Raj et al.* [2002] (60%). The difference may be due to the fact that WIND and Cluster have different orbits and the fact that the two selection criteria give different BBF lists. The noteworthy point in Table 1 is that in contrast to the single-satellite observations, three-satellite observations (C1, C3 and C4) show that the number of active time BBFs/Raj (243) is larger than that of active time BBFs/Ang (209). Among 243 BBFs/Raj observed by three satellites, 142 BBFs/Raj can satisfy the selection criterion of *Angelopoulos et al.* [1994], while 101 BBFs/Raj cannot.

[42] The above analyses show that a single satellite sees less BBFs than multiple satellites, the BBF/Ang missing ratio of single satellite C1 is 22.4% (=(209−162)/209). If

Table 1. Number and Average Duration of Active Time BBFs in July to October 2001 and July to October 2002

	Number		Average Duration, s	
	C1	C1, 3, 4	C1	C1, 3, 4
Active time BBFs/Ang	162	209	604	1105
Active time BBFs/Raj	134	243	527	771

Table 2. Some Active Time BBFs Not Observed By All Satellites, UT

	C1	C3	C4
2001.07.26	No	Yes (2042–2050)	Yes (2039–2048)
2001.07.29	No	Yes (1307–1312)	No
2001.08.22	Yes (1554–1604)	No	Yes (1556–1607)
2002.07.17	Yes (0008–0011)	Yes (0005–0019)	No
2002.07.20	Yes (2256–2315)	No	No
2002.08.04	No	No	Yes (0502–0513)

we use the selection criterion of *Raj et al.* [2002], the missing ratio will increase to 44.9% (=(243–134)/243). So the multisatellite observations are more important for the criterion of *Raj et al.* [2002] than for the criterion of *Angelopoulos et al.* [1994].

[43] The average durations of active time BBFs/Ang based on single-satellite observations and multisatellite observations are 604 s and 1105 s, respectively, while the average duration of active time BBFs/Raj based on single satellite observations and multisatellite observation are 527 s and 771 s, respectively. Thus both single satellite observations and multisatellite observations show that active time BBFs/Raj has a shorter duration than active time BBF/Ang. The total time of BBFs/Raj (243 × 771 = 187,353) is shorter than that of BBFs/Ang (209 × 1105 = 230,945), suggesting that the selection criterion of *Raj et al.* [2002] is more restrictive than the criterion of *Angelopoulos et al.* [1994].

[44] As presented in section 3, there are two important different conditions in the selection criterion of *Raj et al.* [2002]. The condition of selection criterion of *Raj et al.* [2002] that plasma $\beta_{xy} > 2$ tends to reduce the duration and spatial size of BBFs. Contrary the condition that $v_\perp >$ 250 km/s, tends to enlarge the duration and spatial size of BBFs in most cases. It is evident that the first condition plays a more important role in deciding the duration and size of BBFs.

5.3. Substorm and BBF Correlation

[45] During the periods that three satellites moved in the inner central plasma sheet and that all three satellites provided high-quality data without any gap, 67 substorms were identified by ground observations. The single satellite observations (C1) show that among the 67 substorms, 15 substorms are not accompanied by BBFs/Ang. However, if we use multisatellite observations (C1, C3, and C4), only three substorms are not accompanied by BBFs/Ang. Even for these three substorms not accompanied by BBFs/Ang, there are still some flow bursts. However since their maximum velocities are below 400 km/s, they cannot be called BBFs according to the criterion of *Angelopoulos et al.* [1994]. This kind of situation may arise from the radial evolution of BBFs. When BBFs approach the Earth during substorm time, the maximum velocities of BBFs decrease in the regions of depolarization between 16 and 21 R_E [*Baumjohann et al.*, 1999]. When the maximum velocities drop below the 400 km/s criterion for BBFs, these BBFs will not be identified as BBFs and can only be seen as slow flows. The speed decrease is an important reason that causes the occurrence rate of BBFs to decrease with the decrease of distance from Earth inside $x = -19$ R_E. *Angelopoulos et al.* [1994] also pointed out that the lack of BBFs at these regions may suggest that the transport is taking place in a qualitatively different manner, i.e., by slow nonbursty flows.

[46] Since the observation points of Cluster are inside the apogee of orbit (19.6 R_E) and the speeds of flow bursts decrease when BBFs approach the Earth. Thus for some small weak BBFs in the tail, when they approach the Earth, they may exist in the form of slow nonbursty flows. The slow nonbursty flows are also observed by *Shiokawa et al.* [1997], *Tu et al.* [2000], and *Kepko et al.* [2001].

[47] Table 2 shows some examples of BBF events during which not all three satellites observed BBFs/Ang. For example, on 26 July 2001, only C3 observes BBFs/Ang and the other two satellites (C1 and C4) do not. If one uses single satellite (C1) observations, one reaches a wrong conclusion that there are no BBFs during substorm. On 22 August 2001, C1 and C4 observed BBFs/Ang; however, C3 did not. So the number of BBFs/Ang observed by single satellite cannot represent the true number of BBFs in the CPS.

[48] Since previous studies of BBFs/Ang are mostly based on single satellite observations, their conclusion that not all substorms are accompanied by BBFs/Ang may be not very correct due to the limitation of single satellite observations. According to our results, it seems possible that almost all substorms are accompanied by BBFs.

[49] *Kepko et al.* [2001] studied six near-Earth dipolarization events during which rapid flows were observed by Geotail at distances between 8 and 15 R_E in the magnetotail. They found that each rapid flow event was associated with local dipolarization, auroral arc brightening, and Pi2 pulsations. However, on the basis of six flow events, it is difficult to get a statistical conclusion about the correlation between BBFs and substorms.

5.4. Occurrence Frequency of BBFs

[50] *Angelopoulos et al.* [1999] found that the occurrence frequency of BBFs is less than 15% in the central plasma sheet of $-16 < x < -20$ R_E. *Paterson et al.* [1998] also estimated the occurrence frequency of high-speed flows in the whole plasma sheet (including its boundary layer) and found it is less than 0.2%. For the purpose of comparing observations of multi satellites with previous observations of single satellite, we still use the selection criterion of *Angelopoulos et al.* [1994].

[51] For the 209 BBFs/Ang studied in this paper, the total durations of BBFs/Ang observed by single satellite C1 is 27.2 hours and the total time of C1 in the central plasma sheet is 286.9 hours. Thus the occurrence frequency of BBFs in the central plasma sheet obtained by single satellite is about 9.5%. This result is in agreement with that of *Angelopoulos et al.* [1999]. The total duration of 209 BBFs/Ang is 64.17 hours. The total time of three satellites in the central plasma sheet is about 329.94 hours. The occurrence frequency of BBFs/Ang obtained by multisatellites is therefore about 19.4%, much larger than the occurrence frequency of BBFs obtained by single satellite C1. So BBFs in the central plasma sheet may contribute more to the transport of magnetic flux, mass, and energy than what was estimated from previous observations of single satellite.

[52] We also calculate the occurrence frequency of RCEs. It is found that although the number of RCEs (306) is larger

than the number of BBFs/Ang (209), the total time of RCEs is smaller than that of BBFs/Ang (since the duration of RCE is smaller). The occurrence frequencies of RCEs are 7.89% (given by single satellite C1) and 12.2% (given by multi-satellites). These two values are smaller than those of BBFs/Ang. So the selection criterion of RCE of *Schodel et al.* [2001] is more restrictive than the selection criterion of *Angelopoulos et al.* [1994], which is also in agreement with the conclusion of *Schodel et al.* [2001].

6. Discussion and Conclusions

[53] This paper, using the observations of three satellites of Cluster, studied the duration of BBFs and the difference between multisatellite observations and single satellite observations, the difference between the selection criteria of *Angelopoulos et al.* [1994] and *Raj et al.* [2002], and the selection criterion of *Schodel et al.* [2001]. The conclusions can be summarized as follows:

[54] 1. The duration of active time BBFs/Ang given by single satellite observations (604 s) is similar to that of previous studies (600 s). The duration of active time BBFs given by multisatellites is 1105 s. This conclusion is in agreement with ground observations of auroral streamers that are associated with BBFs [*Sergeev et al.*, 2001] and of burst flows in the ionosphere relevant to BBF [*De La Beaujardiere et al.*, 1994]. Thus it is possible that the BBFs may contribute more to the transport of energy, mass, and magnetic flux in substorms. Although the BBFs with long durations cannot increase their transport rate in substorms, they can increase the total amount of the transport of energy, mass, and magnetic flux in substorms. Previous studies show that if the cross section area in the Y-Z plane can reach 100 R_E^2, the BBFs will be responsible for 10 percent of the transport of substorm. According to our results, BBFs are able to offer 20 percent of the transport under the same condition.

[55] 2. The average duration of active time BBFs/Raj based on single-satellite observations and multisatellite observation are 527 s and 771 s, respectively. Thus both single and multisatellite observations show that active time BBFs/Raj has a shorter duration than that of active time BBF/Ang. The total time of BBFs/Raj (243 × 771 = 187,353) is shorter than that of BBFs/Ang (209 × 1105 = 230,945). This means that the selection criterion of *Raj et al.* [2002] is more restrictive than the criterion of *Angelopoulos et al.* [1994]. In addition, the two selection criteria give different BBF lists. Some high-speed flows that are regarded as BBFs by the criterion of *Angelopoulos et al.* [1994] are not regarded as BBFs by the criterion of *Raj et al.* [2002] and vice versa. Among 243 BBFs/Raj observed by three satellites, 142 BBFs/Raj can satisfy the selection criterion of *Angelopoulos et al.* [1994], while the rest 101 BBFs/Raj cannot.

[56] 3. Multiple satellites can see more BBFs than single satellite for both the selection criteria of *Angelopoulos et al.* [1994] and of *Raj et al.* [2002]. The single satellite sometimes can miss the BBF events even when it is in the inner central plasma sheet. The BBF missing ratio of single satellite is 22.4% for selection criterion of *Angelopoulos et al.* [1994] and 44.9% for the selection criterion of *Raj et al.* [2002]. Thus single satellite observations cannot give the true number of BBFs even if it is in the central plasma sheet. In addition, the multisatellite observations are more important for the selection criterion of *Raj et al.* [2002] than for the selection criterion of *Angelopoulos et al.* [1994].

[57] 4. The observations of a single satellite (C1) show that about 22% (15/67) of substorms are not accompanied by BBFs. However, the joint observations of multisatellites show that only 4.5% (=3/67) of substorms are not accompanied by BBFs. Thus it seems possible that all substorms are accompanied by BBFs.

[58] 5. For the 209 BBFs/Ang studied in this paper, the occurrence frequency of BBFs in the central plasma sheet obtained by single satellite is about 9.5%. This result is in agreement with that of *Angelopoulos et al.* [1999]. The occurrence frequency of BBFs/Ang obtained by multisatellites is about 19.4%. So it is possible that BBFs in the central plasma sheet contribute more to the transport of magnetic flux, mass, and energy than what estimated from previous observations of single satellite.

[59] 6. The duration of rapid convection event is 338 s (calculated from the data of single satellite C1) and 445 s (calculated from the data of multisatellites). The occurrence frequency of rapid convection events is smaller than that of BBFs/Ang. So the selection criterion of rapid convection event of *Schodel et al.* [2001] is more restrictive than the selection criterion of *Angelopoulos et al.* [1994], which is also in agreement with the conclusion of *Schodel et al.* [2001].

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J. B. Cao, Z. X. Liu, Y. D. Ma, and G. C. Zhou, Key Laboratory of Space Weather, CSSAR/CAS, 100080 Beijing, China. (jbcao@center.cssar.ac.cn)

C. M. Carr and E. Lucek, Blackett Laboratory, Imperial College London, Prince Consort, London, SW7 2BZ, UK. (c.m.carr@imperial.ac.uk; e.lucek@imperial.ac.uk)

I. Dandouras and H. Reme, Centre d'Etude Spatiale des Rayonnements, F-31028 Toulouse, France.

R. Nakamura and T. L. Zhang, Space Research Center, Austrian Academy of Sciences, 8042 Graz, Austria.

G. Parks, Space Sciences Laboratory, University of Washington, Box 351650, Seattle, WA 98195-1650, USA.

Q. Zong, Center for Space Physics, Boston University, One Sherborn Street, Boston, MA 02215, USA. (zong@bu.edu)