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Differences between onset times of bursty bulk flows (BBFs) of two Cluster satellites in the magnetotail

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This paper, using the dataset of BBFs (bursty bulk flows) observed by two Cluster satellites C1 and C4, studies the difference between onset times of BBFs observed by C1 and C4. It is found that the onset time differences of most of BBFs observed by C1 and C4 are smaller than 60 s. The average onset time difference of BBFs of C1 and C4 is 68.5 s. The probabilities of onset time difference of BBFs of C1 and C4 larger than 30, 60, 90 and 120 s are respectively 55%, 35%, 27% and 23%. The largest onset time difference of BBFs of C1 and C4 decreases with the increase of earthward component of maximum velocities of BBFs. The onset time difference of BBFs of C1 and C4 results from the velocity inhomogeneity inside the flow channel of BBF, which may be produced in propagation path and/or in source region of BBFs. Such a wide range of onset time difference of BBFs suggests that the velocity inhomogeneity inside the flow channel of BBF is various. These results are very important to the current study of substorm research based on THEMIS data because they indicate that it is impossible to determine the onset time of BBF with a single satellite.

bursty bulk flows (BBFs), onset, time difference, substorm

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1 Introduction

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 [1–4]. BBFs are the enhanced bulk velocity events of order of 20 min in duration, containing many short-lived (< 10 s) high velocity (400 km s^{-1} or more) flow bursts (FBs) [2, 5, 6].

BBFs are highly localized, which makes it difficult to get a better understanding of the characteristics of BBFs using a single satellite. This localization of BBFs is reflected in their spatial scales. Angelopoulos et al. [7] showed that the scale of a single BBF in the *Y*-*Z* plane was less than $3R_E$ by using multi-satellite data. Slavin et al. [4] 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. Nakamura et al. [8] developed a method to estimate the width of high-speed flows by means of multipoint observations from the Cluster spacecraft. They found that the full width of the flow channel was 2–3 R_E in the "dawn-dusk" direction and 1.5–2 R_E in the north-south direction which is comparable to the

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width of localized channels generated by the interchange instability at the leading part of reconnection jets [9]. Moreover, Nakamura et al. [10] found that the earthward fast flows consisted of flow peaks both in the equator and away from the equator. The spatial localizations of plane of BBFs in the cross tail and in the north-south direction often make a single satellite unable to identify accurately the onset and ending times of BBFs, or sometimes completely miss BBFs. Cao et al. [5] found that the single satellite observations could not tell the true number of BBFs and the missing ratio of BBF of single satellite was 22.4%. They also found that the average duration of BBFs was not the previously estimated 10 min, but about 20 min.

BBFs and their braking may be an unique physics process in the plasma sheet that is related with many important phenomena both in the tail and on the ground such as Pi2s, reconnection, current disruption, aurora and ULF waves [10–16]. For example, Pi2s is an important phenomenon associated with substorm [17]. BBFs can excite simultaneously transient response type Pi2 long period Pi2 (90–130 s), and short period cavity mode Pi2 (~50 s) [18].

In this paper, using the data from two satellites of Cluster in 2001 and 2002, we study the differences between the onset time of BBFs of C1 and C4. The paper is organized as follows. The instrumentation and selection criteria of BBF are presented in Section 2. The statistical studies of onset time difference of BBFs are presented in Section 3. The discussions and conclusions are given in Section 4.

2 Instrumentation

The apogee and perigee of Cluster are respectively 19.6 and 4.0 R_E [19]. 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 in the tail is from 2000 to 4000 km. Thus the Cluster mission can provide a very good and unprecedented opportunity to study BBFs.

The plasma data are from the Composition and Distribution Function Analyzer (CODIF) of the Cluster ion spectrometry (CIS) experiment and the magnetic field data used here are from the Flux Gate Magnetometer (FGM) experiment. The CIS instrument of Cluster can provide 3D 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. FGM can provide magnetic field measurement with a sampling rate up to about 67 Hz. However the magnetic field with a time resolution of 4 s is used for our analysis. The detailed description of CIS and FGM of Cluster can be found in refs. [20, 21]. GSM coordinates are used throughout this paper.

The BBF selection criterion of Cao et al. [5] is as follows: (1) BBFs are segments of continuous ion flow magnitude V_i above 100 km s^{-1} in the plasma sheet, during which V_i exceeds 400 km s^{-1} at least for one sample period in the IPS (β>0.5); (2) samples of V_i > 400 km s^{-1} that are less than 10 min apart are considered to belong to the same BBF, even if the velocity drops below 100 km s^{-1} between these samples; (3) BBF is defined to begin when its velocity exceed 100 km s^{-1} and ends when the velocity drops below 100 km s^{-1}. The only difference of the criteria of BBFs in the present paper with that of Cao et al. [5] is that the threshold velocity of BBFs is reduced from 400 km s^{-1} to 200 km s^{-1}. The main reason to make such a change is that the speeds of BBFs decrease when BBFs approach the Earth from the source regions and the large threshold velocity will make the number of observable BBFs decrease when the satellite approaches the Earth. Since the average convection speed in the Earth's plasma sheet is about 30 km s^{-1}, the choice of threshold velocity of 200 km s^{-1} can basically exclude the background convection flows and chaotic flows. Nevertheless, some results of BBFs with a threshold velocity value of 400 km s^{-1} are given in Section 3. Here we do not discuss the influence of v_y of BBFs because we focus only on onset of BBFs.

The onset time difference of BBFs of C1 and C4 is defined as the absolute value of the difference between the onset time of BBF observed by C1 and the onset time of BBF observed by C4.

3 Observations

In 2001 and 2002, the Cluster satellites were located in the tail at a geocentric distance between 16.0 and 19.4 R_E. The separation distance of Cluster satellites in the tail (close to the apogee of Cluster) was from 2000 km to 4000 km. C1 and C4 often observed a BBF at different times. In this section, we first present a case study and then make a statistical analysis based on the dataset of 173 BBFs observed by C1 and C4. Besides 173 BBFs, C1 and C4 observed many other BBFs in 2001 and 2002. Since these BBFs observed by C1 and C4 are not obviously correlated, we exclude them from the present study.

In this paper we use three criteria to determine if BBFs at two satellites belong to the same BBF which is similar to those in refs. [5, 22, 23]. (1) BBFs at two satellites overlap in time. (2) The difference between the times of peak velocities of two BBFs is less than 10 min. (3) The difference between the peak velocities of two BBFs at two satellites is less than 20%.

Figure 1 shows the data of plasma and magnetic field observed by C1 and C4 during the interval 10:08–10:12 UT on July 28, 2002. At 10:06:30 UT, C1 is at −95454, −72388, 242 km and C4 is at −98452, −75041, 975 km. The plasma beta, ion density, magnetic field and ion temperature in Figure 1 show that the Clusters C1 and C4 were in the cen-

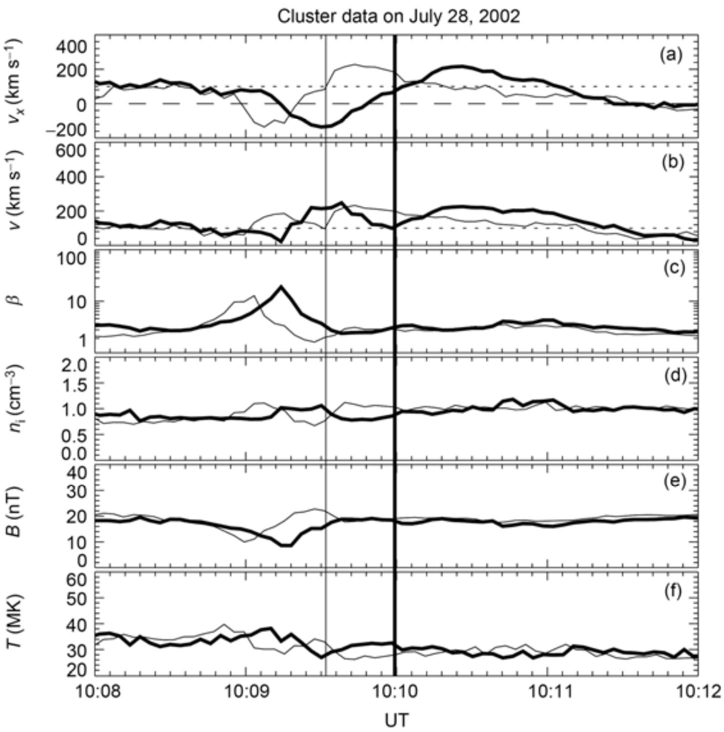

Figure 1 The x component of ion flow velocity v_x (a), ion flow velocity v (b), plasma β (c), ion density n_i (d), magnetic field B (e) and plasma temperature T (f) observed by C1 (thin solid line) and C4 (thick solid line) during the interval 10:08–10:12 UT on July 28, 2002.

tral plasma sheet between 10:08 UT and 10:12 UT. The plasma beta was always larger than 1, suggesting that the two satellites were in the inner plasma sheet (close to the neutral sheet) [7]. The maximum plasma beta, which marks the position of neutral sheet, can even exceed 20. The temperature and density peak in the position of the maximum plasma beta.

As shown in Figure 1, soon after crossing the neutral sheet, a BBF was observed by C1 and C4. The onset time of BBF observed by C1 is 10: 09:32 UT, earlier than that of BBF observed by C4 (10:09:59 UT). Thus the difference between onset times of BBF observed by C1 and C4 is 27 s.

Figure 2 shows the histograms of the number of BBFs as a function of the difference between onset times of BBFs on C1 and C4. The onset time differences of most of BBFs observed by C1 and C4 are smaller than 60 s. The largest onset time difference even exceeds 240 s. The average onset time difference is 68.5 s. The ratio of number of BBFs with onset time difference larger than 60 s to total number of BBFs is 35%. As pointed out in Section 1, the onset time differences between BBFs of C1 and C4 result from the localization of BBFs in the plane perpendicular to the BBF velocity vector, i.e., velocity inhomogeneity inside the flow channel of BBFs. Such a wide range of onset time differences of BBFs indicates that the velocity gradient inside the flow channel of BBFs is not uniform.

In order to clearly see the probability to observe certain onset time difference, we establish the probability function of onset time difference between BBFs of C1 and C4 based on the data shown in Figure 2. Figure 3 shows the probability distribution of onset time difference (OTD) larger than time (t). It can be seen that the probabilities of onset time difference of BBFs larger than 30, 60, 90 and 120 s are respectively 55%, 35%, 27% and 23%. The expected value of the onset time difference is 69.3 s, almost the same as the average onset time difference.

Figure 4 shows the scatter plot of BBFs as a function of

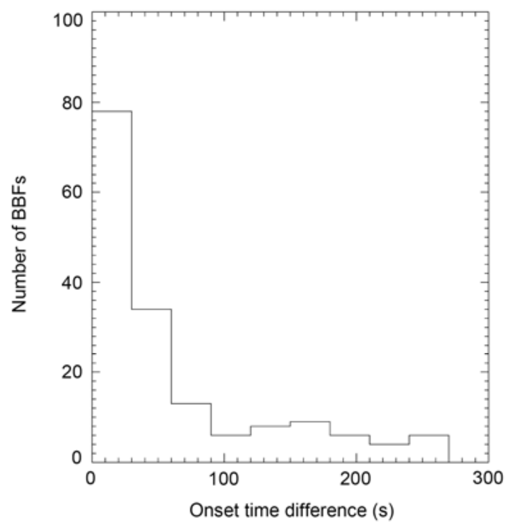

Figure 2 Histograms of the number of BBFs as a function of the difference between onset times of BBFs of C1 and C4.

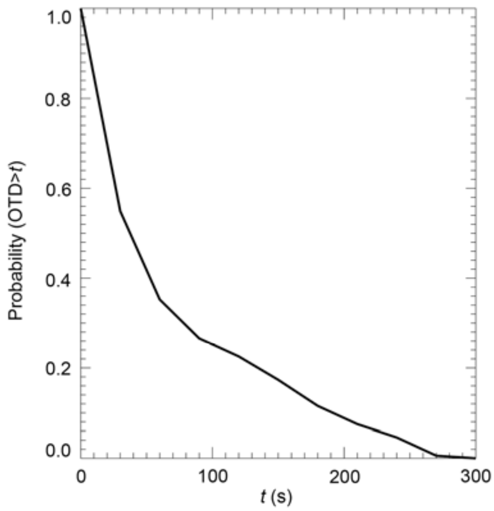

Figure 3 Probability function of the difference between onset times of BBFs of C1 and C4 larger than certain time (t).

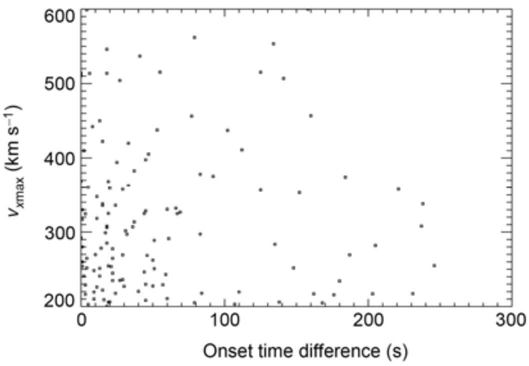

Figure 4 The scatter plot of BBFs as a function of the difference between onset times and earthward component of maximum velocity of BBFs of C1 and C4.

onset time difference and earthward component of maximum velocity of BBFs. It is interesting to find that the largest onset time difference decreases with the increase of earthward component of maximum velocity of BBFs. The largest onset time difference of BBFs is 132 s at $v_{x\max} = 560$ km s^{-1} and 238 s at $v_{x\max} = 340$ km s^{-1}. The correlation coefficient between the largest time difference and the earthward component of maximum velocities of relevant BBFs is negative and equals –0.88. Therefore, for BBFs observed by a single satellite, the accuracy of onset time of BBFs increases with increase of earthward component of maximum velocities of BBFs.

Figure 4 also shows that even the threshold velocity of BBFs is chosen to be 400 km s^{-1}, the onset time differences of BBFs of C1 and C4 still have similar probability distributions. The difference is that the largest onset time difference between BBFs of C1 and C4 become small.

4 Discussions and conclusions

This paper, using the observations of ion flows and magnetic field of two satellites of Cluster, studied the onset time difference between BBFs of C1 and C4. It is found that the onset time differences of most of BBFs observed by C1 and C4 are smaller than 60 s. The largest onset time difference of BBFs even exceeds 240 s. The average onset time difference of BBFs is 68.5 s. Such a wide range of onset time differences of BBFs indicates that the velocity gradient inside the flow channel of BBFs is not uniform.

The probabilities of onset time differences of BBFs of C1 and C4 larger than 30, 60, 90 and 120 s are respectively 55%, 35%, 27% and 23%. The expected value of the onset time differences of BBFs is 69.3 s, almost the same as the average onset time difference. The largest onset time difference decreases with the increase of earthward component of maximum velocities of BBFs.

The differences between onset times of BBFs observed by two satellites result from the localization of BBFs, i.e., velocity inhomogeneity inside the flow channel of BBFs. Nakamura et al. [9] used the velocity gradient of BBFs observed by two satellites to estimate the scale of BBF. Naturally, these velocity gradients of BBFs inside the flow channels are certainly accompanied with the difference between onset times of BBFs of C1 and C4. There are two possible mechanisms that can cause the velocity inhomogeneity inside the flow channel of BBF.

The first is the velocity inhomogeneity inside the flow channel of BBF produced in the source regions, i.e. reconnection regions. The reconnection process is not uniform in the dawn-dusk direction and the north-south direction of the central plasma sheet. The scale of reconnection region is proportional to the square root of the ion inertial length d_i (= c/ω_{pi}, where c is light speed, ω_{pi} is ion plasma frequency) and is about several times the ion inertial length in the magnetotail [24–26]. Since the ion inertial length (d_i) in the reconnection layer in the magnetotail near ~18–19 R_E is around 500 km, the length of reconnection layer in the magnetotail is about 1–2 R_E, which is of the same order of magnitude of the scale of BBFs (2–3 R_E in the "dawn-dusk" direction and 1.5–2 R_E in the north-south direction.) estimated by Nakamura et al. [8].

The second is the velocity inhomogeneity inside the flow channel of BBF produced in propagation process. Generally BBFs are rarely measured at their point of origin. In nearly all cases they have to propagate some distance before they encounter the instrument that takes their measure. This is because BBFs that arrive at different satellites move in somewhat different propagation paths where the background magnetic field and plasma parameters are different. Slavin et al. [27] thought that the propagation process added noise and dispersion into the studies of when a given process or phenomenon occurs relative to substorm expansion onset. In addition, Nakamura et al. [28] found that the interaction between BBFs and the pre-existing plasma sheet ahead of it could excite interchange instability in front of the reconnection jets. This kind of large scale MHD instability can also produce the velocity inhomogeneity of BBFs in the cross tail plane. The mechanism of propagation produced velocity inhomogeneity exists for every BBF. The small onset time difference of BBFs between C1 and C4 may be caused by this kind of mechanism. The mechanism of source produced velocity inhomogeneity may cause large onset time difference since the velocity inhomogeneity produced in source region can be augmented in the propagation process.

There are two possible generation mechanisms of BBFs: patchy impulsive reconnection process and/or an interchange instability of a plasma depleted flux bubble [29–31]. No matter which mechanism BBFs are generated by, the velocities of BBFs are not uniform in the cross tail plane in the source regions due to the limited scale of source region. It is natural that the profile of the velocity gradient of the flow inside the flow channel is augmented in the earthward propagation process. Mashida [32] [2006] found that the different propagation velocities of the BBF front critically modified the form of BBFs. The earthward propagation of BBFs is rather complex. A long-time earthward flow burst might be split into several short time flow bursts in the propagation process [33]. During the propagation process, BBFs can excite the ULF waves [34] and produce the depolarization front, which is considered to play some important role in the particle acceleration and substorm process [35, 36].

As a concluding remark we note that the results in the present study can bring a better understanding of the temporal relation between BBFs and other substorm phenomena (Pi2, aurora and reconnection), and may be helpful to the THEMIS mission of NASA. The main scientific objective of THEMIS is to study the relation between three main phenomena of substorm: reconnection, current disruption and aurora. The clarification of temporal relation between these three phenomena will make great contribution to identifying substorm model. Since time intervals between the three phenomena are from 30 s to 120 s, the accurate identification of onset time of BBFs, which are considered to be a key factor in the identification of time of reconnection [27], is very important for the THEMIS mission. The results in the present paper can help to estimate the accuracy of the onset time of BBFs.

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1 Baumjohann W, Paschmann G, Lühr H. Characteristics of the high-speed flows in the plasma sheet. J Geophys Res, 1990, 95: 3801–3809
2 Angelopoulos V, Baumjohann W, Kennel C, et al. Bursty bulk flows in the inner central plasma sheet. J Geophys Res, 1992, 97: 4027–4039
3 Slavin J A, Fairfield D H, Lepping R P, et al. WIND, GEOTAIL and GOES 9 observations of magnetic field dipolarization and bursty bulk flows in the near-tail. Geophys Res Lett, 1997, 24: 971–974
4 Du A M, Nakamura R, Zhang, T L, et al., Fast tailward flows in the plasma sheet boundary layer during a substorm on 9 March 2008:THEMIS observations. J Geophys Res, 2011, 116: A03216, doi:10.1029/2010JA015969
5 Cao J B, Ma Y D, Parks G, et al. Joint observations by Cluster satellites of bursty bulk flows in the magnetotail. J Geophys Res, 2006, 111: A04206, doi: 10.1029/2005JA011322
6 Ma Y D, Cao J B, Nakamura R, et al. Statistical analysis of earthward flow bursts in the inner plasma sheet during substorms. J Geophys Res, 2009, 114: A07215, doi:10.1029/2009JA014275
7 Angelopoulos T, Phan D, Larson E, et al. Magnetotail flow bursts: association to global magnetospheric circulation, relationship to ionospheric activity and direct evidence for localization. Geophys Res Lett, 1997, 24: 2271–2274
8 Nakamura R, Baumjohann W, Mouikis C, et al. Spatial scale of high-speed flows in the plasma sheet observed by Cluster. Geophys Res Lett, 2004, 31: L09804, doi:10.1029/2003GL019558
9 Nakamura R, Baumjohann W, Schodel R, et al. Earthward flow bursts, auroral streamers, and small expansions. J Geophys Res, 2001, 106: 10791–10802
10 Nakamura R, Baumjohann W, Mouikis C, et al. Multi-point observation of the high-speed flows in the plasma sheet. Adv Space Re, 2005, 36: 1444–1447
11 Shiokawa K, Baumjohann W, Haerende G. Breaking of high-speed flows in the near-Earth tail. Geophys Res Lett, 1997, 24: 1179–1182
12 Baumjohann W. Modes of convection in the magnetotail. Physics Plasma, 2002, 9(9): 3665–3667
13 Kepko L, Kivelson M G, Yumoto K. Flow bursts, braking, and Pi2 pulsations. J Geophys Res, 2001, 106: 1903–1915
14 Duan S P, Liu Z X, Cao J B, et al. TC-1 observation of ion high-speed flow reversal in the near-Earth plasma sheet during substorm. Sci China Ser E-Tech Sci, 2008, 51 (10): 1721–1730
15 Lu L, McKenna-Lawlor S, Barabash S, et al. Plasma sheet Stretching accompanied by field aligned energetic ion fluxes observed by the NUADU instrument aboard TC-2. Chin Sci Bull, 2007, 52(12): 1719–1723
16 Cao J B, Yan C X, Dunlop M, et al. Geomagnetic signatures of current wedge produced by fast flows in a plasma sheet. J Geophys Res, 2010, 115: A08205, doi:10.1029/2009JA014891
17 Cao J B, Wang D, Zhao H. Relationship between Pi2s in Beijing and AE indexes. Chin J Geophys, 2004, 47: 1069–1075
18 Cao J B, Duan J, Du A, et al. Characteristics of mid-low latitude Pi2 excited by Bursty Bulk Flows. J Geophys Res, 2008, 113: A07S15, doi:10.1029/2007JA012629
19 Escoubett C P, Fehringer M, Goldstein M. Introduction: The Cluster mission. Ann Geophys, 2001, 19: 1197–1200
20 Reme H, Acoustin C, Bosqued J M, et al. First multispacecraft ion measurements in and near the Earth's magnetosphere with the identical Cluster Ion Spectrometry (CIS) experiment. Ann Geophys, 2001, 19: 1303–1354
21 Balogh A, Carr C, Acuna M, et al. The Cluster magnetic field investigation: Overview of in-flight performance and initial results. Ann Geophys, 2001, 19: 1207–1217
22 Ma Y D, Cao J B, Zhou G C, et al. Multi-point Analysis of the temporal scale of bursty bulk flow events during the quiet time of magnetotail. Chin J Geophys, 2005, 48(2): 277–283
23 Ma Y D, Cao J B, Zhou G C, et al. Multipoint analysis of the rapid convection event. Chin J Geophys 2007, 50(5): 1100–1106
24 Wang X G, Bhttacharjee A, Ma Z W. Scaling of Collisionless Forced Reconnection. Phys Res Lett, 2001, 87(26): 1–4, doi:10.1103/PhysRevLett.87.265003
25 Shay M A, Drake J, Rogers B. The scaling of collisionless, magnetic reconnection for large systems. Geophys Res Lett, 1999, 26: 2163–2166
26 Thompson S M, Kivelson M, Khurana K, et al. Dynamic Harris current sheet thickness from Cluster current density and plasma measurements. J Geophys Res, 2005, 110: A02212, doi: 10.1029/2004JA010714

27 Slavin J A, Fairfield D H, Lepping R P, et al. Simultaneous observations of earthward flow bursts and plasmoid ejection during magnetospheric substorms. J Geophys Res, 2002, 107: A7, doi: 10.1029/2000JA003501
28 Nakamura M S, Matsumoto H, Fujimoto M. Interchange instability at the leading part of reconnection jets. Geophys Res Lett, 2002, 29(8): 1247–1250, doi:10.1029/2001GL013780
29 Chen C X, Wolf R. Interpretation of high-speed flows in the plasma sheet. J Geophys Res, 1993, 98: 21409–21419
30 Sergeev V A, Semenov V, Sydneva M. Impulsive reconnection in the magnetotail during substorm expansion. Planet Space Sci, 1987, 35(9): 1199–1212
31 Sergeev V A, Angelopoulos V, Gosling J, et al. Detection of localized, plasma-depleted flux tubes or bubbles in the midtail plasma sheet. J Geophys Res, 1996, 101: 10817–10826
32 Mashida S. A theoretical model of bursty bulk flows. J Geophys Res, 2006, 111: A06210, doi: 10.1029/2005JA011375
33 Ma Y D, Cao J B, Reme H, et al. Multi-spacecraft observations of earthward flow bursts. Sci China Tech Sci, 2012, 55(5): 1305–1311
34 Wang Z Q, Cao J B, ULF waves associated with the periodical high speed flows in magnetotail plasma sheet. Chin J Geophys, 2010, 53(2): 231–236
35 Duan S P, Liu Z X, Liang J, et al. Multiple magnetic dipolarizations observed by THEMIS during a substorm. Ann Geophys, 2011, 29: 331–339
36 Fu H S, Khotyaintsev Y V, André M, et al. Fermi and betatron acceleration of suprathermal electrons behind dipolarization fronts. Geophys Res Lett, 2011, 38: L16104, doi:10.1029/2011GL048528