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Multi-case Study of Current Sheet Flapping Motions Induced by Non-adiabatic Ions*

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Abstract In this paper, the y-component of magnetic field line curvature in the plasma sheet was analyzed, and two kinds of shear structures of the flapping current sheet were found, *i.e.* symmetric and antisymmetric. The alternating bending orientations of the guiding field are exactly corresponding to alternating north-south asymmetries of the bouncing ion population in the sheet center. Those alternating asymmetric plasma sources consequently induce the current sheet flapping motion as a driver. In addition, a substantial particle population with downward motion was observed in the center of a bifurcated current sheet. This population is identified as the quasi-adiabatic particles, and provides a net current opposite to the conventional cross-tail current.

Key words Flapping current sheet, Quasi-adiabatic particles, Magnetotail

Classified index P 353

0 Introduction

The magnetotail current sheet, which separates the northern lobe of the magnetotail from the southern lobe, is one of key objects of magnetospheric physics. As early as in 1967, the magnetotail current sheet was observed to move in the north-south direction[1], which has been referred to as flapping motions[2,3]. Previous studies based on single-spacecraft measurements show that the geometry of the flapping current sheet is more complex than a planar surface, and that the sheet may be wavy[2,4].

The multi-point Cluster spacecraft have provided the chance to distinguish the spatial and time resolutions of the current sheet flapping. In the past two decades, intense investigations using Cluster data were performed to analyze the magnetic and current structures of the flapping current sheet. The flapping motion of the current sheet is interpreted as large amplitude waves with periods from about 30 s to several minutes and amplitudes from several nT to dozens of nT[5−8]. The flapping wave propagates from the central sector of the magnetotail toward the flanks[9], and the propagation velocities of waves are in the range of several tens $\mathrm{km\cdot s^{-1}}$ for the locally quiet sheets, and up to $200\,\mathrm{km\cdot s^{-1}}$ during fast flows. Ref. [8] performed a statistical analysis of the electric current and magnetic field geometries of flapping magnetotail current sheets during the period from July to October 2001. Their results show that J_z is often larger than J_y and the current is almost vertical, and the flapping current sheet strongly deviates from the nominal plane geometry. The flapping waves can extend over $10\,R_\mathrm{e}$ in the Sun-Earth direction by comparing the data from the Cluster and Double Star missions[5]. In addition, the joint observations of THEMIS and Cluster show that the flapping amplitude of the current sheet is from $1\,R_\mathrm{e}$ to $3\,R_\mathrm{e}$[10], and the flapping waves are steep tail-aligned structures with a longitudinal scale of $> 10\,R_\mathrm{e}$.

The triggering mechanism of current sheet flapping remains mysterious. Early researchers suggest

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that flapping motions of the tail plasma sheet can be induced by the interplanetary magnetic field variations[11]. The solar wind dynamic pressure pulse and substorm are also considered to be the sources of flapping waves[12,13]. Some current sheet flapping events were often observed in association with magnetospheric activities. Ref. [11] found that current sheet flapping motions occur during the early phases of substorms. Ref. [3] showed that current sheet flapping events are observed around substorm onsets while Ref. [14], utilizing the Geotail data, showed that the majority of fast crossings of the current sheet occurred during the period of low magnetic activities. Thus, the relationship between the substorm and the current sheet flapping is still unclear. The flapping wavy motions can also be generated by the Kelvin-Helmholtz instability in the presence of dawn-dusk flows with a speed of several tens of $\mathrm{km\cdot s^{-1}}$ are present[4]. Furthermore, when hot magnetospheric plasma is confined in a curvilinear magnetic field, the ballooning mode instability is also able to excite the flapping motion[15]. But this condition can't be often satisfied. The flapping wavelength can usually achieve $4\sim8\,R_{\mathrm{e}}$, while the curvature radius of magnetic field lines within the current sheet is only $0.7\sim1.8\,R_{\mathrm{e}}$. In addition, there are often some transient events in the tail plasma sheet, such as bursty bulk flow[16−18]. Some current sheet flapping events were observed to be associated with these fast flows[14,19]. Their flapping velocities are smaller (several tens of kilometers per second) in the slow-flow regions. Kink-like MHD waves have been considered as the generation mechanism of the flapping motion[20]. Their phase speeds are usually more than hundreds $\mathrm{km\cdot s^{-1}}$ and are not consistent with the flapping wave propagating speeds of tens $\mathrm{km\cdot s^{-1}}$ [9]. Taking account of kinetic effects, some models investigated drift K-H instabilities spreading with ion drift speeds[21,22]. Although these waves have comparable propagation speeds, their propagation directions are unidirectional and also don't match the observations. The Ref. [23] analyzed an asymmetric current sheet model and suggested that hemispheric asymmetric plasma sources can induce the flapping motions. Recently, the Ref. [24], using Cluster data, demonstrated that the flapping motions of the current sheet are closely related to periodic hemispheric-asymmetric populations of bouncing particles. Their results imply that the specific nonadiabatic ion behaviors inside the central plasma sheet may excite the current sheet flapping motions. The latest MMS data analysis shows the period of current sheet flapping was modulated by the reconnection electric field and perpendicular plasma flow, indicating that the flapping motion may be triggered by the periodical unsteady magnetic reconnection[25].

In the sharp field reversal of the magnetotail current sheet, distinct classes of particle orbits can be organized using the κ parameter introduced by Ref. [26, 27]. The κ parameter is defined as $\kappa = (R_{\mathrm{c}}/\rho_i)^{1/2}$, where R_{c} is the minimum curvature radius of the magnetic lines and $\rho_i = (2kT_{\mathrm{i}}/m_{\mathrm{i}})^{1/2}/\omega_i$ is the maximum ion gyroradius. At large (above 3) κ values, the particle's motion is adiabatic, and the guiding center approximation is valid. For κ is between 1 and 3, particles behave in a chaotic manner and their motion cannot be characterized by an invariant[27]. For $\kappa < 1$, those particles possibly meander inside the current sheet[28] and exhibit either transient, trapped, or quasi-trapped behaviors[29].

Furthermore, in the presence of a guiding field, the shear patterns of the magnetotail current sheet in association with the non-adiabatic particle kinetic can be strongly changed. Previous investigations on the non-adiabatic particles in the case of a constant B_y have been executed by both analytic methods and test particle simulations[31]. These results revealed that asymmetrical particle scattering can take place in the vicinity of the neutral line. Particularly, the Ref. [32] suggested an impulsive centrifugal force model to describe the nonadiabatic particle behaviors in the current sheet. In the presence of a guiding field, the effect of a nonzero B_y is considered to impart a rotation of the impulse centrifugal force when particles cross the neutral line[30]. It can be enhanced or attenuated when the rotation occurs along (against) the particle gyromotion[30]. Hence, particles launching from the north part of the current sheet will behave differently from that launching from the south part when they cross the central line. Meanwhile,

the studies of magnetic configurations with a non-constant B_y and the associated nonadiabatic particle behaviors reveal the formation of two general self-organized shear structures, symmetric and antisymmetric respectively[33].

In addition, due to their distinct motion behaviors, different classes of particles within the plasma sheet are supposed to have different capabilities of carrying cross-tail current. Thus, the particle population variations of different classes can change the current structure of the current sheet. For the adiabatic trapped ions, theoretically they do not carry any net current because their orbits are closed. Owing to strongly curved serpentine-like motions near the neutral plane, the quasi-adiabatic particles can support local currents that are directed oppositely to the general cross-tail current[34]. Thus, the existence of prominent populations of quasi-adiabatic particles will result in a current sheet with a bifurcated profile[34]. The magnetic field of a bifurcated current sheet has a plateau profile between the peaks of the enhanced magnetic field gradient[9]. Bifurcated current sheets are often observed during substorms[5,35]. In addition, bifurcated current sheets can exist around the X line, with a flat current sheet in the Ref. [5].

In this paper, the symmetric and antisymmetric shear structures associated with the flapping current sheet are revealed. The alternating bending orientations of the guiding field are exactly corresponding to alternating North-South asymmetries of the bouncing ion population in the sheet center. In addition, the existence of a substantial population with downward motion in the center of a bifurcated current sheet is presented, which is identified as the quasi-adiabatic particles.

1 Observations

1.1 Flapping Current Sheet with Antisymmetric Shear Structures: 3 August 2004 Event and 3 August 2001 Event

Cluster satellites observed long-standing flapping motions on 3 August 2004 when they traveled in the central current sheet. Those flapping motions were measured without notable fast flows (for the details, see Ref. [24] Figure 1a, d). Figure 1 shows the measurements of the first five current sheet crossings during the period of 06:30—07:05 UT, within which each encounter of the neutral line is marked by the vertical dotted line. As revealed by previous investigations[8], although the current sheet inclined significantly in association with the flapping motions, the magnetic fields in the central current sheet are nearly unchanged and mainly in the z-direction.

Figure 2 shows the energy and polar angle spectrograms of energetic ions, which were measured by the CIS/HIA experiment[36]. The polar angle is the angle between the particle movement direction and z_{GSM} axis, in which $\pm 90°$ represents the direction parallel and antiparallel to the z_{GSM} axis, respectively. Firstly, during each crossing of the current sheet center, there are periodic variations of the ion flux concentrated at $\pm 90°$ polar angle respectively. In the magnetotail configuration, this observation means that the bouncing ion populations are North-South asymmetrical. For example, at the first crossing of the current sheet center, the flux of the northward moving ions is about 8×10^4 count/spin, while that of the southward moving ions is about 10^5 count/spin. Secondly, these North-South asymmetries of the ion fluxes are alternating between the adjacent crossings of the sheet center. As the J_z is positive, the current moves southwards, and J_z is negative the current move northwards (see Figure 1c and 2d). When the current sheet moved southwards, the flux of the northward moving ions is smaller than that of the southward motion. While the current sheet moved northwards, the asymmetries become opposite, that is, the flux of the northward moving ions is larger than that of the southward motion. Thirdly, as shown in Figure 2(c), there are polarization variations of γ_{cy} (the y-component of the magnetic field line curvature) measured at the current sheet center. The non-zero γ_{cy} is a manifestation of the bending of the magnetic field line to the y-direction developed in the current sheet center in association with its flapping motion. The sign change of γ_{cy} means an orientation change of

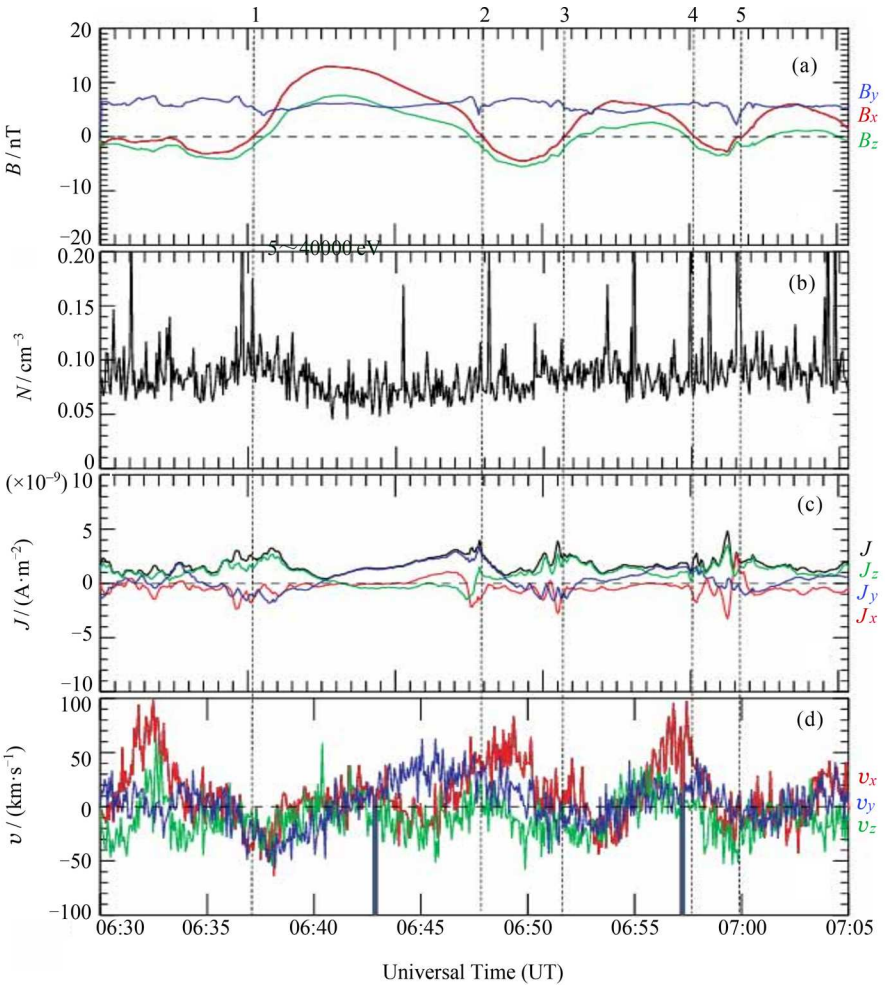

Fig. 1 Detections of the flapping motion by the Cluster/C3 spacecraft on 3 August 2004

the field line curvature y-component, where the field line shape has an antisymmetric configuration (or in other words, an antisymmetric shear structure, see the schematic Figure 3a or Figure 4b in the Ref. [24]). Although all the polarization variations of γ_{cy} seem to have similar profiles, the polarization variations are alternating. For example at the first crossing of the current sheet center, γ_{cy} changes from negative to positive, where its negative (positive) value corresponds to negative (positive) B_x respectively. However at the next crossing, although γ_{cy} also changes from the negative to the positive, its negative (positive) value corresponds to positive (negative) B_x respectively. Thus, the bending in the y-direction of the magnetic field lines measured at the first crossing is actually opposite to the bending direction of the next crossing and so on for subsequent crossings. Alternating orientations of the adjacent crossings are presented as the solid line and the dashed line respectively in Figure 3(a). This picture of the antisymmetric orientation changes of the magnetic field line curvature in the y-direction can also be equivalently interpreted as an effective guiding field existing near the current sheet center due to its alternating inclinations[24].

The particle motion in the magnetotail configuration is usually classified by its adiabaticity parameter. In this event, the adiabaticity parameter $\kappa = (R_c/\rho_i)^{1/2}$ about 1.1, where $R_c \approx 2000$ km, is the curvature radius and $\rho_i \approx 1600$ km, is the ion gyroradius. As mentioned above, the nonadiabatic particle behavior can be affected by the guiding fields, which result in the asymmetrical particle scattering in the vicinity of the neutral line. Especially, it is convenient to consider it as the existence of an impulse centrifugal force due to the field line curvature y-component. Therefore, a series of alternating hemispheric asy-

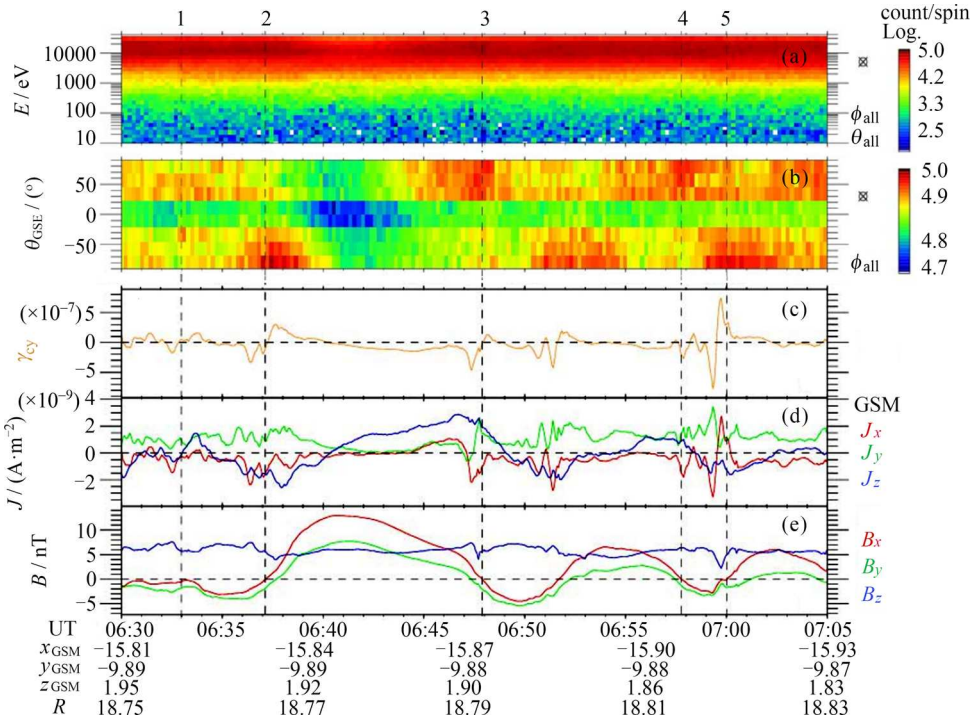

Fig. 2 Ion observations of alternating hemispherical asymmetries of the bouncing ion population on 3 August 2004

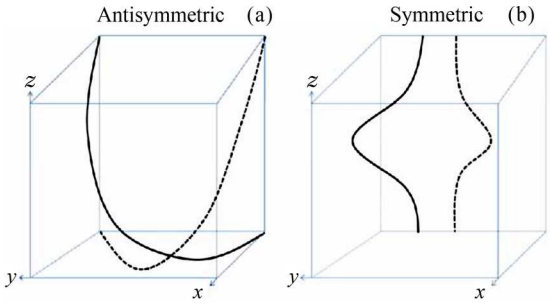

Fig. 3 Schematic of field line shapes of the flapping current sheet. Alternating bendings in the y-direction of the adjacent crossings are presented as the solid line and the dashed line respectively

mmetric ion populations can develop due to the occurrence of the alternating orientations of the field line bending in the y-direction. Theoretically, asymmetric plasma sources will violate the pressure balance condition of the current sheet in the North-South direction and consequently drive the sheet to reach a new equilibrium position[23]. Furthermore, this process is self-consistent to preserve a complete flapping period. In the first half of a flapping period, asymmetric plasma sources developed due to a specific orientation of the field line bending and drove a vertical motion of the current sheet. Meanwhile, they reform the shear configuration of the current sheet, *i.e.*, the field line bending in the y-direction, to the opposite orientation. In the second half of the flapping period, opposite asymmetric plasma sources were caused by guiding fields with an opposite bending orientation, and in their turn propel the current sheet to move vertically in the opposite direction. Thus, the alternating asymmetric plasma sources maintain the continuous oscillations of the current sheet. (See the schematic Figure 1b in Ref. [24]).

A similar event of the current sheet flapping with antisymmetric shear structures is shown in Figure 4. Two crossings of the neutral line during the period of 09:00—09:25 UT on 3 August. 2001 were recorded. There is no high speed flows during this current sheet flapping event (not shown in Figure 4). The flux of the northward moving ions (1.3×10^5 count/spin) is larger than that of the southward moving ions (1.0×10^5 count/spin) at the first travel through the neutral line, while the flux of the northward moving ions (1.0×10^5 count/spin) is smaller than that of the southward moving ions (1.4×10^5 count/spin) at the second travel through. Corresponding to the alternating asymmetric ion fluxes, the alternating orienta-

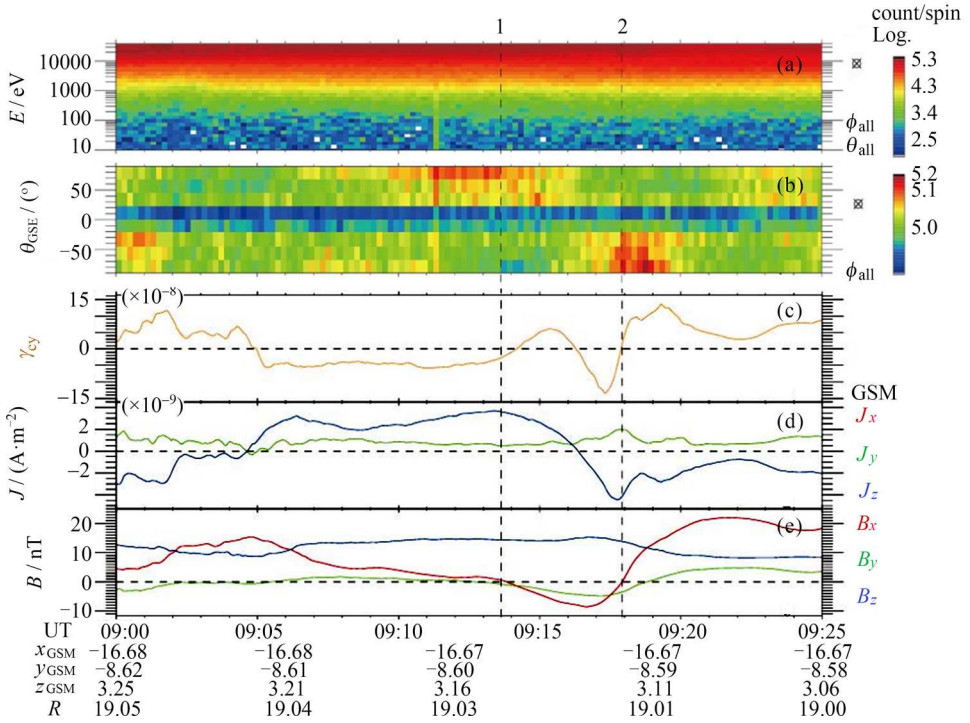

Fig. 4 Ion observations of alternating hemispherical asymmetries of the bouncing ion population on 3 August 2001

tions of the field line bending in the y-direction were measured as shown in Figure 4(c). In the first crossing of the current sheet center, the field line bending is to the negative y-direction in the north hemisphere and positive y-direction in the south hemisphere. While in the second crossing, the bending is to the positive y-direction in the north-hemisphere and negative y-direction in the south-hemisphere. In this event, the adiabaticity parameter $\kappa = (R_c/\rho_i)^{1/2} \approx 1.05$, where $R_c \approx 1000\,\text{km}$, and $\rho_i \approx 900\,\text{km}$. As expected, κ is within 1∼3 regime, so that the bouncing particles behave in a chaotic manner in the vicinity of the neutral line and experience asymmetric scattering. All the observational features can be interpreted as the same as the above event.

1.2 Bifurcated Flapping Current Sheet with Symmetric Shear Structures: 26 September 2001 Event

On 26 September 2001, during the period of 22:20−22:35 UT, Cluster observed a bifurcated flapping current sheet event when they were located at $(-18, 7, 0)\,R_e$ (in GSM coordinates), which had been previously reported by the Ref. [6]. Figure 5 displays an overview of this event, in which no remarkable bulk burst flows were encountered. As shown in Figure 5(a), during each crossing of the sheet center, B_x displays a plateau profile, which is more easily identified during the last four crossings. Correspondingly, the maximum cross-tail current J_y deviates from the exact center of the current sheet as shown in the third panel, that is, the total J_y does indeed decrease in the exact current sheet center and sometimes displays a double-peak profile.

In association with the flapping motion of this bifurcated current sheet, alternating hemispheric asymmetries of the bouncing ion population can as well be observed as shown in Figure 6(b). Corresponding to the hemispheric asymmetric of ion populations, non-zero values of γ_{cy} were observed during each crossing of the central current sheet. Nevertheless, the measurements of the non-zero γ_{cy} are different from that of the events with antisymmetric shear structures. All these non-zero γ_{cy} don't change their signs at the crossing of the neutral plane, the non-zero γ_{cy} without a sign change represents a symmetric bending shape of the field lines in the y-direction (see the schematic Figure 3b, or Figure 4a in Ref. [23]).

Similarly, as shown as the solid and dashed lines

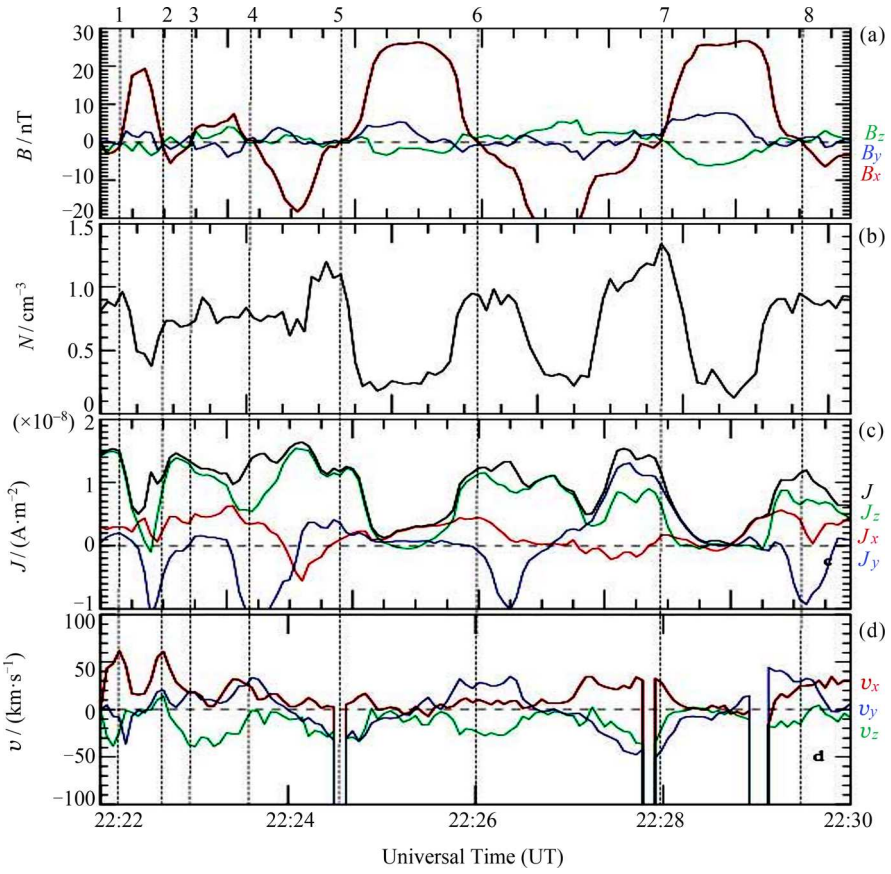

Fig. 5 Detections of the bifurcated flapping current sheet on 26 September 2001

respectively in Figure 1(b), the orientations of the bending shapes are alternating between the adjacent crossings of the sheet center, that is, γ_{cy} is positive when the current sheet moved northwards, while is negative when the current sheet moved southwards. Here, the adiabaticity parameter $\kappa = (R_c/\rho_i)^{1/2} \approx 0.9$, where $R_c \approx 500\,\text{km}$, and $\rho_i \approx 540\,\text{km}$. Thus, asymmetric ion populations are supposed to develop due to the alternating orientations of the bending shapes in the y-component.

Figure 6(c) shows the azimuthal angle spectrograms of energetic ions. The azimuthal angle ($-180°\sim+180°$) is the angle between the particle movement direction and x-axis, in which 0° represents the $+x$-direction, and $\pm 90°$ represents the direction parallel and antiparallel to y-axis respectively. During each crossing of the sheet center except the first two, the angular distribution of a substantial population is concentrated at $-90°$, which means that this population move to the $-y$-direction, namely to the dawn direction. It is worth noting here that this particular observation is rare and cannot be found in the above events (not shown in this paper). In this event, the adiabaticity parameter $\kappa \approx 0.9 < 1$, thus it is reasonable to believe that a part of the nonadiabatic ions belongs to the so-called quasi-adiabatic particles. Those particles meander in the current sheet center, and have a drift motion in the $-y$-direction owing to their strongly curved serpentine-like motions near the neutral plane. Thus, this population carries a net current opposite to the cross-tail current in the sheet center. Consequently, the total cross-tail current carried by the whole population will decrease in the sheet center and display a bifurcated profile, that is, the current density maximum is not at the sheet center as the usual Harris-type sheet. Here, the fact that there exists a substantial population with downward motion in a bifurcated current sheet gives a firm observational evidence for its theoretical generation mechanism.

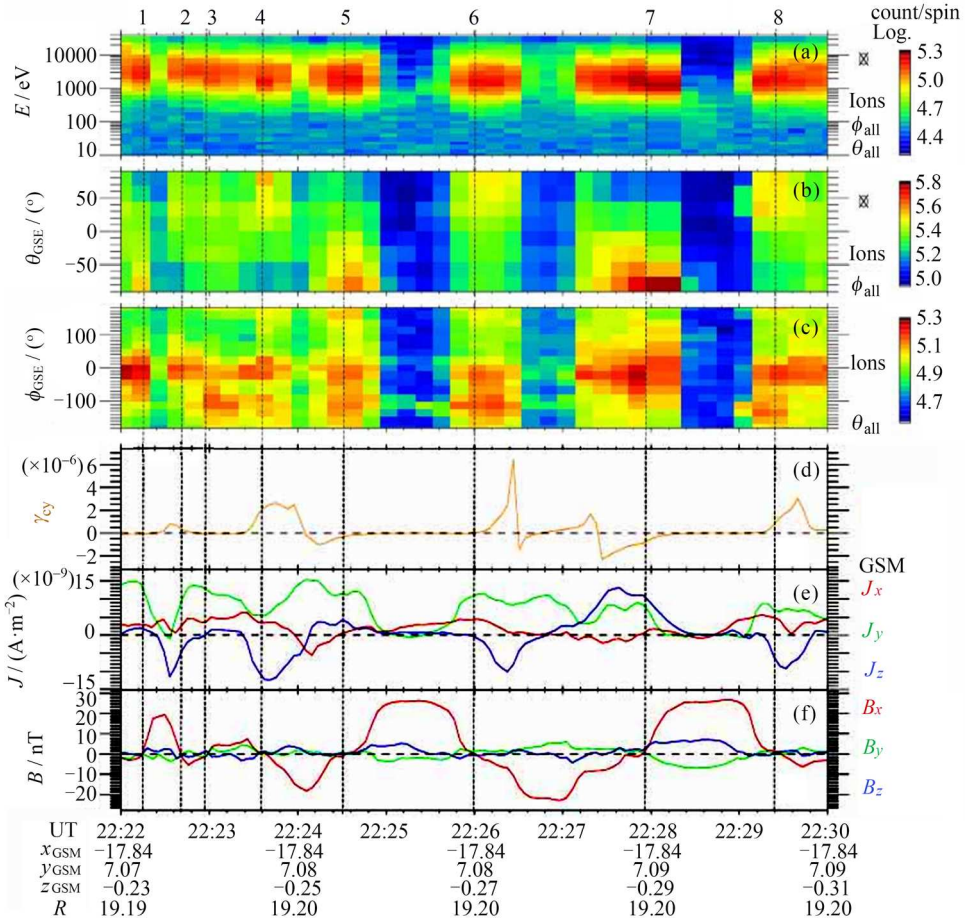

Fig. 6 Ion observations of alternating hemispherical asymmetries of the bouncing ion population and the downward moving population on 26 September 2001. (a)∼(c) The omnidirectional energy, polar angle and azimuthal angle spectrogram of hot ions, respectively. The values of 0° azimuthal angle represent the $+x$-direction, and ±90° represent the direction parallel and antiparallel to y-axis respectively

1.3 Flapping Current Sheet with Mixed Shear Structures: 26 October 2002 Event

Bulk burst flows are common phenomena in the magnetotail. Figure 7 shows the overview of a flapping current sheet with high speed flows observed by C3 on 26 October 2002. There are 8 crossings of the current sheet center during the period of 09:18—09:28 UT. The periods of current sheet flapping are less than 2 minutes. Apparent earthward fast flows were observed during this current sheet flapping event as shown in Figure 7(d). The maximum high speed flow v_x is larger than 400 km·s^{-1}, which encountered at the seventh crossing. The burst feature of this flow can be found from the observations that the flows encountered at the second and seventh crossings are remarkable, while the ones encountered at the fourth and fifth crossings are ignorable.

In this flapping current sheet with high speed flows, the alternating hemispheric asymmetries of the bouncing ion population can also be recognized as shown in Figure 8(b). However, the asymmetries recorded at the upward motions of the current sheet seem to be more pronounced than the ones recorded at the downward motions, except the last one. Meantime, the upward amplitudes of the current sheet flapping seem to also be more pronounced than the downward amplitudes, except for the last two flapping motions. Two populations concentrated at 0° polar angle were encountered between the second and third crossings and at the seventh crossing, which is the earthward fast flows. Corresponding to the hemispheric asymmetric of ion populations, non-zero values of c

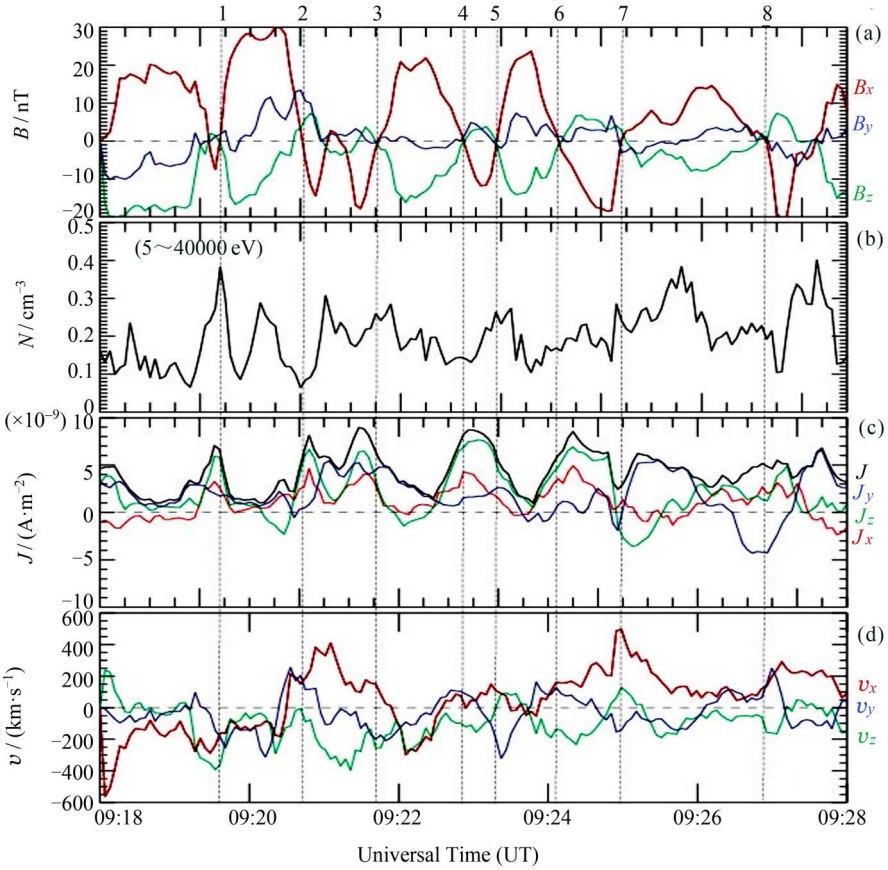

Fig. 7 Detections of the flapping motion with bulk flows on 26 October 2002

were observed in the vicinity of the neutral line. Besides the non-zero $\gamma_{cy}w$ with a sign change, the non-zero $\gamma_{cy}w$ without a sign change was recorded at the second, fourth and sixth crossings of the sheet center. Thus, the shear structures in this event are mixed, *i.e.* both symmetric and antisymmetric bendings have existed. It is in contrast to the events presented above, where all the non-zero $\gamma_{cy}w$ have similar profiles. In this event, the adiabaticity parameter $\kappa = (R_c/\rho_i)^{1/2} \approx 1.8$, where $R_c \approx 1000\,\mathrm{km}$, and $\rho_i \approx 315\,\mathrm{km}$. Although the magnetic structures with fast flows are more complex than that of the case without fast flows, the intrinsic excitation mechanism of flapping motion induced by nonadiabatic ions have still prevailed.

2 Discussion and Conclusion

In association with the current sheet flapping motion, there are two type bending patterns of the field lines in the y-direction, symmetric and antisymmetric as revealed by the observations. In the two events on 3 August 2004 and 3 August 2001, the unperturbed magnetic fields in the current sheet center are mainly in the z-direction. Correspondingly, their bending patterns are antisymmetric. This picture can be equivalently interpreted as an effective guiding field due to the inclinations of the current sheet itself[24]. While in the events on 26 October 2002 and 26 September 2001, both the z- and y-component of the unperturbed magnetic fields are rather small. Correspondingly, their bending patterns are symmetric or complicated (two patterns coexist). Thus, the case of an unperturbed magnetic field may be associated with a dominant z-component, and it is favorable to develop an asymmetric bending pattern of the field lines in the y-direction during the flapping motion It is consistent with the previous conclusion that a higher probability of the formation of symmetric shear configuration at lower values of the normal magnetic component[6,33].

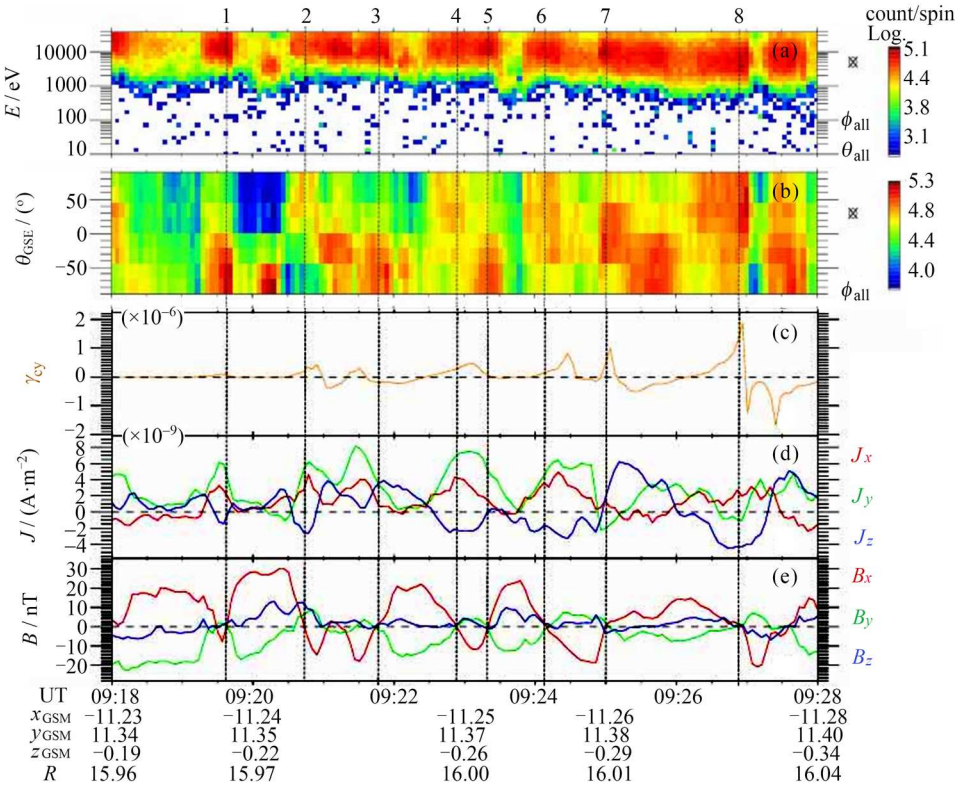

Fig. 8 Ion observations of alternating hemispherical asymmetries of the bouncing ion population on 26 October 2002

Although an understanding of the asymmetric particle scattering of the bouncing ion populations by guiding fields has been pointed out in Ref. [24], the scenario shown here relevant to the detailed shear structures of the current sheet is more general since the two kinds of shear patterns are self-consistently formatted from some initial magnetic perturbation[33]. Also, in the view of an impulse centrifugal force model which is applicable to describe ion behaviors with adiabaticity parameter 1∼3 as in the case of flapping events, it is more convenient to investigate directly the magnetic line curvature rather than an effective guiding field.

In summary, observations of flapping current sheet in the magnetotail are presented to reveal their intrinsic excitation mechanism induced by nonadiabatic ions. The current sheet up-down motions are exactly corresponding to alternating hemispherical asymmetries of the bouncing ion population. These asymmetric ion populations are present in the magnetic field configuration with a local bending y-component and interpreted as a result of the nonadiabatic particle scattering in the vicinity of the neutral line. Hence, the alternating asymmetric ion populations can develop due to the occurrence of the alternating orientations of the field line bending. Those alternating asymmetric plasma sources consequently induce the current sheet flapping motion as a driver. In addition, a substantial population with dawnward motion in the center of a bifurcated current sheet is observed by spacecraft. This population is identified as the quasi-adiabatic particles, which supports a net current opposite to the cross-tail current. The present results suggest that nonadiabatic ions play a substantial role to determine current sheet dynamics, both its bulk mechanical instability and current profiles.

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