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# Cluster observations of large-scale southward movement and dawnward-duskward flapping of Earth's magnetotail current sheet

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In August 2001, Cluster satellites observed that the mid-tail current sheet (CS) moved southward continuously for almost seven hours. Meanwhile, Cluster crossed back and forth the CS repeatedly. This means that the large-scale southward movement of the CS was accompanied by a small-scale CS flapping during this period. Using the minimum-variation-analysis (MVA) method and the multi-spacecraft data, we calculated the normal vector, current density and the magnetic curvature of the CS, the results showed that the CS alternated between flattened CS and tilted CS for several times. Strong dawn-dusk oscillations were found for the tilted CS, which caused the repeated crossings of the center of CS by the satellites. This feature is obviously different from the previous observations of the vertical flapping of the CS induced by the kink instability. Two types of flapping were observed: One of them is accompanied with bursty bulk flows (BBFs) and the other is not. This suggests that in this event there was no direct relationship between the CS flapping and BBFs.

**flattened current sheet, tilted current sheet, flapping motion, BBFs**

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## 1 Introduction

The magnetotail current sheet (CS) is a relatively narrow region within the magnetotail plasma sheet where the current density is strong and the *X* component of the magnetic field reverses its sign. In the magnetotail CS, the magnetic field intensity reaches a minimum; the plasma is usually dense and hot. The dynamics of the Earth's magnetosphere are greatly influenced by the process (e.g. magnetic reconnection) in the magnetotail CS. The magnetotail CS also plays a crucial role in the magnetic substorm and storm.

Since the first discovery of the magnetotail CS in 1965 [1], considerable efforts have been devoted to understanding the basic structure of the CS, and much attention has been paid to the study of associations between the variation of the CS position and the solar wind parameters [2–4]. The results show that variation of the magnetic field and the physical processes in the CS are associated with interplanetary shocks, magnetic substorm, high speed flows, etc. [5–8]. In the simplest 1-D approximation the CS described by the Harris solution [9], according to the Harris solution, the current density has the maximum value at $z = 0$, where the magnetic field is equal to zero. However, observations show that the geometry and structure of the CS usually differ from the Harris-type structure. Lui et al. [10] found that there is a "hump" in the neutral sheet, and the CS profile in the $(Y–Z)_{GSM}$ plane may be wavy. McComas et al. [5]

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showed that the CS may move upward and downward, and manifest a wave profile in the $(X–Z)_{GSM}$ as well as the $(Y–Z)_{GSM}$ plane. Sergeev et al. [11] pointed out that the CS may be bifurcated. Russell et al. [12], Cowely et al. [13] and Sibeck et al. [14] suggested that the magnetotail can be twisted under a strong *Y* component of the IMF. It should be noted that in those previous studies one could not calculate the gradient of the magnetic field and the normal vector as well as velocity of the CS, since it is difficult to separate between temporal and spatial variations with a single spacecraft. In order to overcome this difficulty, the European Space Agency launched the four-satellite Cluster on August 2000. The Cluster satellites are in a highly elliptical polar orbit, with an apogee of 19.6 $R_E$ and a perigee of 4.0 $R_E$. They have an orbital period of 57 h. The spacecraft form a regular tetrahedron at apogee, and the scale of the tetrahedron varies every 6 months, thus the spacecraft are at different separations for each tail season (~1 August–31 October). The Cluster can measure the three-dimensional structure of the magnetic field thus one can calculate the current density precisely using the data of magnetic field when the inter-satellite distances are small and study the large-scale variation of the magnetic field when the inter-satellite distances are large.

Cluster observations of the magnetotail CS suggest that there are generally three types of CS: normal CS [15], flattened CS [16] and tilted CS [17]. Both the normal and flattened CS have their normal vectors basically along the southward-northward direction. The difference between these two types of CS is that for the normal CS, the *y*-component of the magnetic field $B_y$ is much smaller than the $B_z$-component, while $B_y$ is much larger than $B_z$ in the flattened CS. For the tilted CS, the normal vector is tilted towards the *Y-Z* plane. Many observations suggest that the tilted CS is caused by the flapping of the CS, which can make the local CS deviate from or even perpendicular to the solar-magnetospheric equatorial plane [18–21].

In the past two decades, the studies of the CS have been mainly focused on the tilted CS and its flapping properties. Zhang et al. [18] analyzed a wavy twisted neutral sheet with Cluster observations. Runov et al. [22] and Sergeev et al. [19, 20] reported flapping motions of the CS, and showed that, most likely, the rapid flapping oscillations were generated by a localized source in a central sector of the magnetotail, and then the flapping disturbances propagated dawnward in the morning and duskward in the evening sector with several 10 km/s. Events studies performed during the Cluster-Double Star TC-1 conjunction with a radial separation of 6 $R_E$ showed that the flapping waves could be generated simultaneously in the whole near-Earth magnetotail neutral sheet, and propagating flankward with respect to the spacecraft [23]. A statistical survey of Geotail data showed that the flapping motions of the CS might be related to the plasma bursty bulk flows (BBFs) [24]. Association of CS flapping with fast plasma flows in the plasma sheet and Pi2 pulsation was also shown by Gabrielse et al. [25] based on THEMIS observations. Sergeev et al. [20, 24] and Runov et al. [26] also pointed out the close relationship between CS flapping and the *Z* component of the ion flow velocity. During the repeated crossings of the CS by the spacecraft, the ion velocity $V_z$ showed obviously periodic oscillations.

In this paper we analyze the features of CS crossings observed by the Cluster spacecraft on 7 and 8 August 2001. Cluster was located in the CS and crossed the CS back and forth repeatedly. The Cluster observations showed that the CS moved southward continuously for almost seven hours and alternated between flattened CS and tilted CS for several times. Strong dawn-dusk oscillations were found for the tilted CS, which caused the repeated crossings of CS by spacecraft.

## 2 Observation

We use plasma data obtained by Hot Ion Analyzer (HIA) of Cluster ion spectrometry (CIS) experiment [27]. The CIS of Cluster can provide three-dimensional velocity distribution of ions with a time resolution of spin period 4 s. The magnetic field data are from the Flux Gate Magnetometer (FGM) experiment [28]. The 1-spin (4 s) and 0.2 s resolution magnetic field data are used at different places when necessary in this paper. Geomagnetic solar magnetospheric (GSM) coordinates are used throughout the paper.

During the interval 23:00 UT on 7–06:10 UT on 8 August 2001, Cluster was located in the magnetotail current sheet. Figure 1 shows the trajectory of Cluster 3 during the interval 00:00–06:00 UT and the tetrahedron configuration of Cluster satellites at 00:00 UT. The SC3 moved from [−17.27, −8.46, +2.31] $R_E$ at 00:00 UT to [−17.36, −7.34, +0.02] $R_E$ at 06:00 UT. As seen in Figure 1, the spacecraft moved mainly in the *Y* and *Z* directions (1.12 $R_E$ in the dawn-dusk direction, and almost 2.3 $R_E$ from north to south). SC3 crossed the current sheet from north to south firstly, as it was located most southward among the four satellites, and was separated from the other three satellites by about 1000 km.

Figure 2 presents the observations of Cluster CIS and FGM during the interval 23:00 UT on 7–07:00 UT on 8 August 2001 (there are no data from 06:10 to 07:00 UT). We use the colors of black, red, green and blue to represent the data from SC1, SC2, SC3 and SC4, respectively. During this interval, the spacecraft was inside the mid-tail plasma sheet according to the criteria of the plasma sheet in Cao et al. [29]. At 23:44 UT (marked by the dashed line "1" on the plot), $B_x$ recorded by C3 was decreasing to zero, suggesting that the satellite was crossing the current sheet. At the same time, the spacecraft observed a burst bulk flow (BBF) [30], with the Earthward and duskward components of the velocity reaching about 1000 and 400 km/s, respectively. The

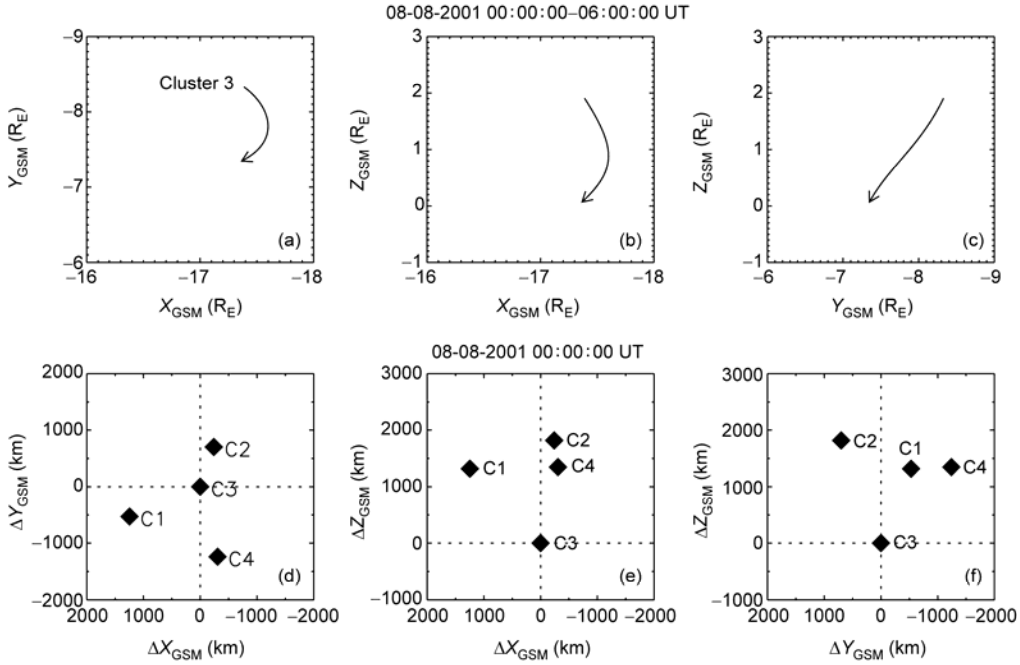


**Figure 1** Trajectories of Cluster 3 and Cluster tetrahedron configurations on 8 August 2001 in GSM coordinates. (a), (b) and (c) show the projections of the trajectories in the *X-Y*, *X-Z* and *Y-Z* planes; (d), (e) and (f) show the relative positions of the four satellites in three planes, respectively.

BBF lasted until 00:44 UT on 8 August (marked by the dashed line "2" on the plot). The three components of magnetic field display strong oscillations. Especially the oscillation of component $B_x$ is clearly periodic, suggesting that the current sheet was flapping periodically with a period of about 170–190 s. Previous observations showed that ULF waves with period at 40–200 s could be excited by BBFs [31–33]. These waves may be either compressional waves, or ULF waves excited both by periodical high speed flows and K-H instability. The result of Figure 2 suggests that periodic oscillations of current sheet accompanied with high speed flows can also generate ULF waves.

From 23:44 UT on 7 August (marked by the dashed line "1"), the Cluster spacecraft observed $B_x$ = 0 for several times (this is especially evident in the observation of SC3). From 02:36 UT on 8 August (marked by the dashed line "3"), $B_x$ oscillated around zero. The behavior of $B_x$ suggests that spacecraft was in the CS region and crossed the center of the CS for many times. Although there were already a lot of studies focused on the CS crossings in the previous reports, it was rarely reported that the spacecraft stayed in the CS for such a long time (almost 7 h) as the present event. The spacecraft moved about 2.3 $R_E$ in the $Z_{GSM}$ direction (Figure 1) and crossed CS back and forth repeatedly ($B_x$ = 0 for several times), suggesting that the CS oscillated and moved southward when the spacecraft passed from north to south. During the whole process, the ion density was about 0.15 $cm^{-3}$ and the ion temperature was about 50 MK. We compare three components of the ion velocity, and find that $V_y$ oscillates more periodically and has a larger amplitude than the oscillation of $V_z$. This result is different from the previous studies of the CS flapping motion which showed that the plasma oscillations is dominant in the *z* direction.

To further study the motion of the CS in detail we give an analysis of the time derivative of the *Z* coordinate of the spacecraft location d*z*/d*t*. Here we only give the result from SC3 since results from the other satellites are similar. Figure 3(a) shows the $B_x$ component observed by SC3; (b) shows the time derivative d*z*/d*t*, which represents the velocity of spacecraft in the *Z* direction. The symbol "×" is used to denote the location where the satellite crossed the CS from north to south, and the symbol "o" for the case of south to north crossing. As seen in the figure that the satellite moved almost 2.5 $R_E$ from south to north. The velocity (d*z*/d*t*) varied from 1.0 km/s at 23:00 UT on 7 August to 0.5 km/s at 04:00 UT on 8 August, and then increased slowly. If we neglect the small periodic oscillations, the movement of CS is the same as the satellite. Therefore, during this interval, the magnetotail CS moved from north to south continuously. Its velocity was about 1.0 km/s at first, then decreased gradually, and reached 0.50–0.55 km/s at the end.

## 3 The configuration of the current sheet

To analyze the configuration of the CS one can use the minimum and maximum variance analysis (MVA) [34] as well as inter-satellites timing analysis (TA) [35] during which the spacecraft crosses the center of the CS. In this

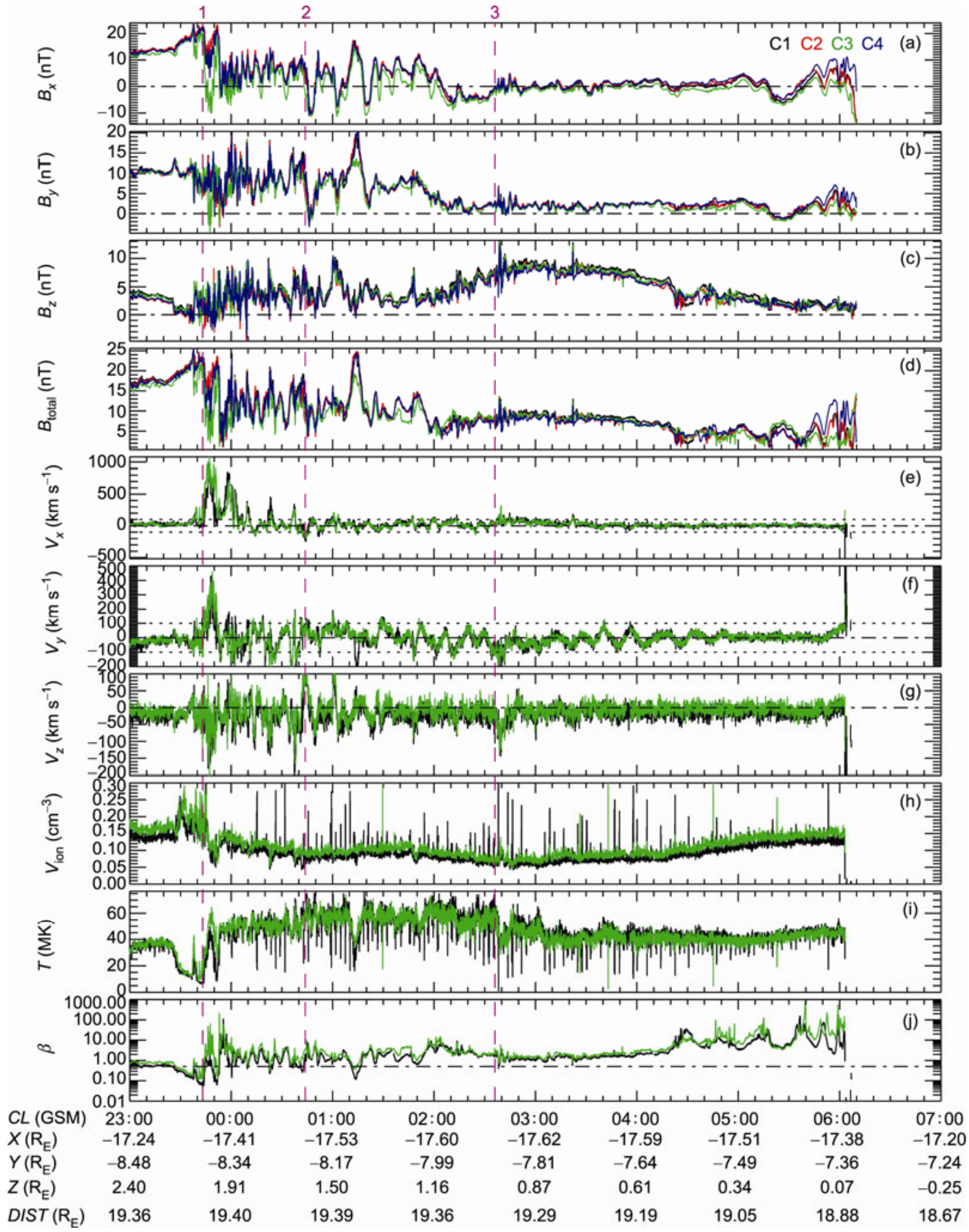


**Figure 2** (a)–(d) The three components of magnetic field $B_x$, $B_y$, $B_z$ and the total magnetic field $\boldsymbol{B}$; (e)–(j) Three components of the ion flow velocity $V_x$, $V_y$, $V_z$ and the ion number density $N_{ion}$, the ion total temperature $T$ and the plasma $\beta$ during the interval 23:00 UT on 7 August 2001 to 07:00 UT on 8 August 2001 observed by Cluster. Coordinates of the barycenter of the four spacecraft are shown at the bottom. For more detail, see the text.

study, we mainly use MVA to calculate the normal vector of the CS.

The main application of MVA is to estimate the normal vector $\boldsymbol{n}$, a direction perpendicular to approximately one-dimensional structures, such as current layers and plane wave fronts, form a set of magnetic field data measured by a single spacecraft during traversal of the structure. To apply MVA magnetic field data, one first needs to construct the magnetic variance matrix, and then find its eigenvalues ($\lambda_1$, $\lambda_2$, $\lambda_3$) and corresponding eigenvectors ($x_1$, $x_2$, $x_3$). The direction of minimum variance, $x_3$, is used as an estimator of $n$, the corresponding eigenvalue, $\lambda_3$, being the variance of the field component along $x_3$. A small value of $\lambda_3$, compared to $\lambda_1$ and $\lambda_2$, generally means a good determination of $\boldsymbol{n}$ [34]. In order to reduce the errors of the application of MVA, we can construct a large data set or average the data over consecutive non-overlapping time intervals to provide filtering of sufficient quality.

In this paper, we use 0.2 s resolution magnetic field data from each of the four Cluster spacecraft to determine the

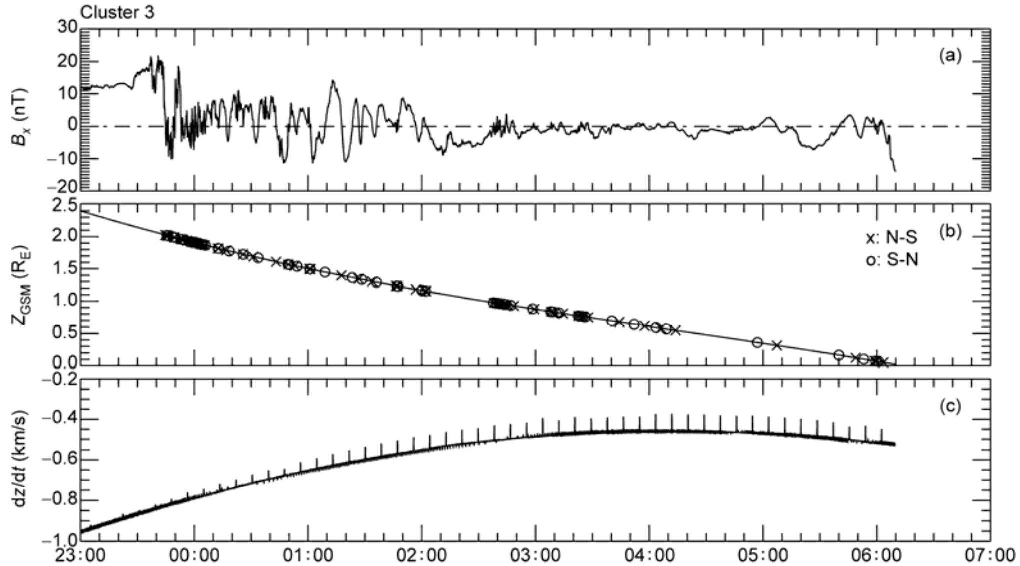


**Figure 3** (a) The $B_x$ component of the magnetic field from C3 spacecraft; (b) $Z_{GSM}$ of SC3, "×" and "o" represents the 'N-S' and 'S-N' crossing points, respectively; (c) the velocity of C3 in the *Z* direction.

normal vector of the current sheet and take the results with intermediate-to-minimal eigenvalue ratio exceeding 3 ($\lambda_2/\lambda_3 > 3$) as the well-resolved MVA normal.

Since the event lasted a long duration, we divide it into three periods: T1 (23:30–02:10 UT), T2 (02:10–04:10 UT) and T3 (04:10–06:10 UT). Since the MVA results from the four spacecraft are basically similar, we only show the results from SC3 in Figures 4, 5 and 6, which are corresponding to periods T1, T2, and T3, respectively. In all the three figures, the variation of $B_x$ is shown in panel (a) as reference, the projections of the MVA normal to the *X-Z* and *Y-Z* planes are displayed in panels (b) and (c) separately, and the absolute values of the three components of the normal vectors are shown in panel (d), where the *x*, *y* and *z* components are respectively denoted by "+", "Δ" and "×" symbols. We can see from Figure 4 that $n_z$ is always larger than $n_y$ and $n_x$ in period T1. The averages of the absolute values of three normal components ($n_x$, $n_y$, $n_z$) are (0.216, 0.351, 0.875), and the corresponding standard deviations are (0.166, 0.178, 0.079), suggesting that the current sheet in interval T1 might be the normal CS or flattened CS. Figure 5 and Figure 6 show that in the interval 02:10–05:50 UT the normal CS is mainly along the *Y* direction, while the *x* and *z* components of the normal vector are very small. The three mean normal components are (0.321, 0.858, 0.289), the corresponding standard deviations are (0.189, 0.101, 0.179), which suggests that the CS in this duration was the tilted CS. At 05:50–06:10 UT (see the dashed frame in Figure 6) the *z* component of the normal is dominant. The averages of the absolute values of three normal components are (0.131, 0.352, 0.903) and the corresponding standard deviations are (0.083, 0.185, 0.096), suggesting that the CS turned to normal or flattened CS again. In summary, the current sheet alternated between different types at 02:10 UT and 05:50 UT. For the sake of description in the following, we name the intervals (23:00–02:10 UT), (02:10–05:50 UT) and (05:50–06:10 UT) as $T_A$, $T_B$ and $T_C$, respectively.

In order to ascertain the specific types of the current sheet in intervals $T_A$ and $T_C$, we investigate the *y* and *z* components of the magnetic field. Figure 7 displays the overview of SC3 observations (the observations from the other three satellites are not shown here since they have similar results). The solid and dotted curves represent the y and *z* components of the parameters in panels (a) and (c), and the vertical dashed lines separate the different types of CS. The *y* and *z* components of the magnetic field in Figure 7(a) show clearly that during the interval $T_A$ and $T_C$, $B_y > B_z$, meaning that the current sheet was a flattened CS. The tilted angle of the magnetic field lines ($\alpha = \tan^{-1}(B_y/B_z)$) (see Figure 7(g)) characterized the flat property of the current sheet also shows that the CS was flattened types during $T_A$ and $T_C$ because the tilted angles are very large (~80°).

The *x* and *y* components of the current density are dominant through the event (Figure 7(b), (c)). During the interval 23:44 UT on 7–02:10 UT on 8 August, the averages of the three components of the current density $j_x$, $j_y$ and $j_z$ are −0.823, 2.131 and 0.352 nA/m$^2$, and the corresponding standard deviations are 1.384, 1.833 and 0.906, respectively; during $T_B$, the average values are −0.509, 0.937 and 0.051 nA/m$^2$, and the standard deviations are 0.424, 0.534 and 0.398 separately; during $T_C$, the averages are −1.652, 3,482 and 1.425 nA/m$^2$, the corresponding standard deviations are 0.473, 1.461 and 1.223, respectively. Consequently, the behaviors of $j_x$, $j_y$ and $j_z$ show that the three components of the current density in the flattened CS (in $T_A$ and $T_C$) are larger than current density in the tilted CS (in $T_B$). Statisti-

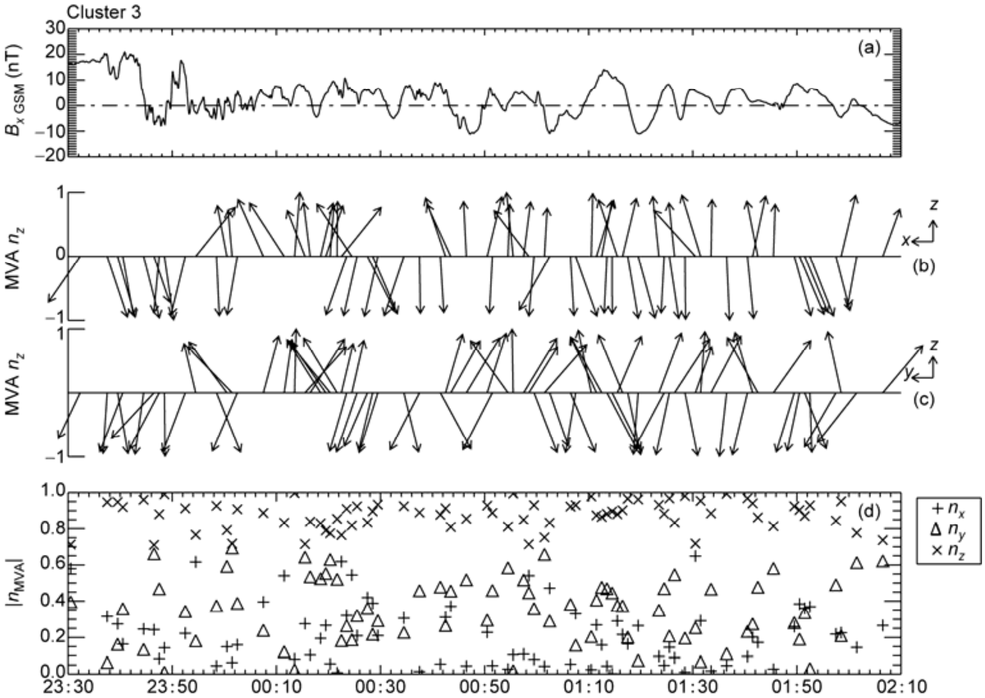


**Figure 4** Overview of the normal directions of the current sheet from 23:30 UT on 7 August to 02:10 UT on 8 August: the *x* component of the magnetic field from Cluster 3 spacecraft (a); $X_{GSM}$–$Z_{GSM}$ and $Y_{GSM}$–$Z_{GSM}$ projections of the normal direction of the current sheet (b) and (c), the absolute values of three components of the normal vector (d) (the *x*, *y*, *z* components are respectively denoted by "+", "Δ" and "×" symbols).

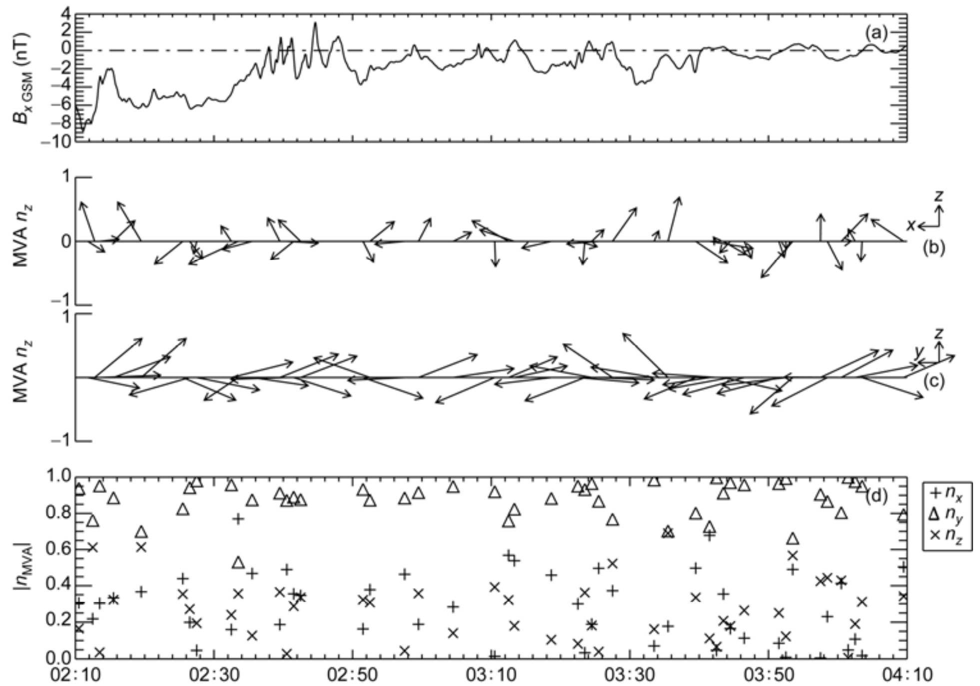


**Figure 5** The same format as in Figure 4, but for the interval 02:10 UT–04:10 UT on 8 August.

cal surveys of the current sheet flapping performed by Sergeev et al. [20] and Runov et al. [21] showed that during the current crossings the $j_z$-component is often larger than $j_y$-component and the alternating behavior of $j_z$ is distinct (i.e., the signs of the $j_z$ during NS crossings and SN crossings are different). They considered that there was a dawnward or duskward propagation of the kink-type wave in the current sheet, i.e., the current sheet exhibited flapping mo-

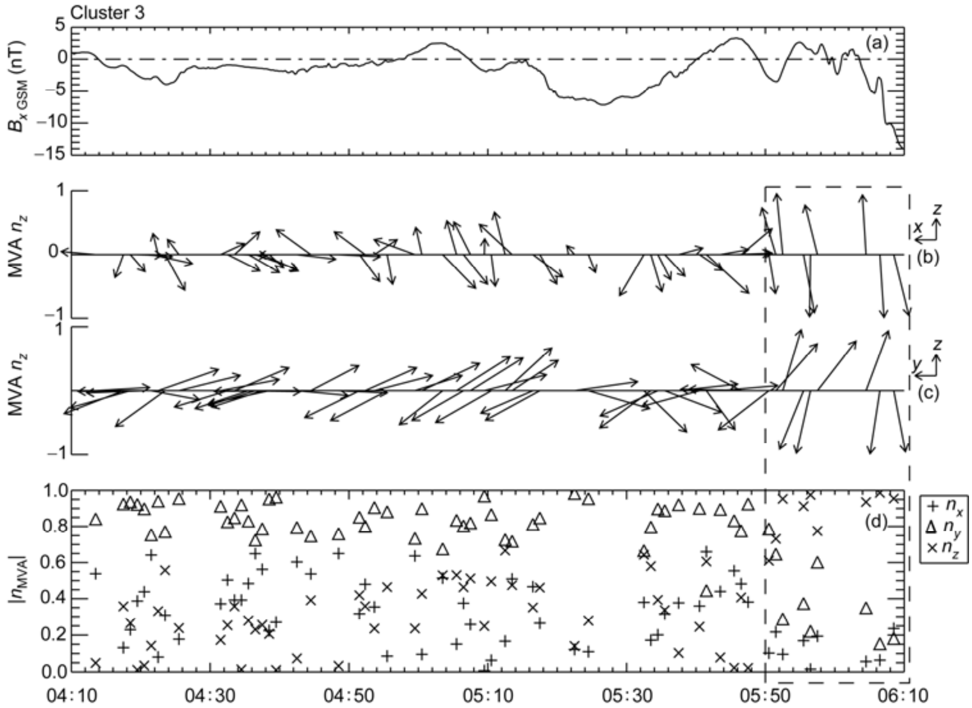


**Figure 6** The same format as in Figure 4, but for the interval 04:10 UT–06:10 UT on 8 August.

tion because of the kink-like instability. However, in our case, $|j_y| > |j_z|$ and there is no bipolar property for $j_z$ during the CS crossings. We note that the magnetic field curvature vector is dominantly aligned along the *x* direction during all the crossings (Figure 7 (d), (e), (f)).

## 4 Flapping motions of the current sheet

Since the first discovery of the magnetotail current sheet [1], a lot of studies showed that the current sheet frequently moved in the north-south direction. This motion has been referred to as flapping [6, 10, 36]. The studies of the CS flapping motions show that the rapid flapping oscillations are generated by a localized source in the mid-night sector of the magnetotail and produce tailward [37] and/or dawn-dusk ward waves with several 10 km/s [10, 18–20, 22]. Event studies performed during the multi-spacecraft conjunction showed that the flapping waves can be generated and propagate simultaneously in the whole near-Earth magnetotail neutral sheet (at least within 8–19 $R_E$ in the radial direction) [23, 38]. Sergeev et al. [20, 24] and Runov et al. [26] suggested that the z-component of the ion velocity shows an alternating behavior during the current sheet crossings: $V_z > 0$ during NS crossings whereas $V_z < 0$ during SN crossings. They pointed out that the bipolar property of the $V_z$ was correlated with a large-scale wave propagating along the dawn-dusk direction.

Figure 8 displays the *x*-component of magnetic field and the three components of ion velocity observed by SC1 and SC3 during the interval 02:00–05:00 UT when the CS was tilted. We notice that among the three components of ion velocity the $V_z$ component shows no obvious oscillation, that $V_x$ oscillation is relatively obvious with the average amplitude of 50 km/s, and that $V_y$ has the strongest oscillation motions with amplitudes of about 50–100 km/s and the average period of 16 min. These mean that the CS flapped mainly in the *Y* direction. This feature obviously differs from the previous observations of the vertical flapping of the CS induced by the kink-like instability (i.e., $V_z$ has the strongest oscillating motions) [20, 24].

A statistical survey of Geotail data reported by Sergeev et al. [24] showed that the flapping motions of the CS may be related to the plasma bursty bulk flows (BBFs). Using THEMIS data, Gabrielse et al. [25] observed a one-to-one correspondence between the current sheet flapping and high speed flows. The current sheet flapping motions without localized high speed flow were also reported [19, 20]. In order to ascertain the relationship between the current sheet flapping and BBFs, we display the *x*-component of magnetic field in Figure 9(a) and ion velocity in Figure 9(b). The BBFs initiated at 23:44 UT on 7 August (marked by the dashed line “1” on the plot). The *x*-component of ion velocity was about 1000 km/s at the time and the *x*-component of magnetic field started to oscillate, with an amplitude of about 20 nT. When $V_x$ decreased to 800 km/s, the amplitude of $B_x$ oscillation decreased to 12 nT, and maintained this value until 00:44 UT on 8 August when the BBFs vanished (marked by the dashed line “2”). During this one-hour interval, the average period of $B_x$ oscillation was about

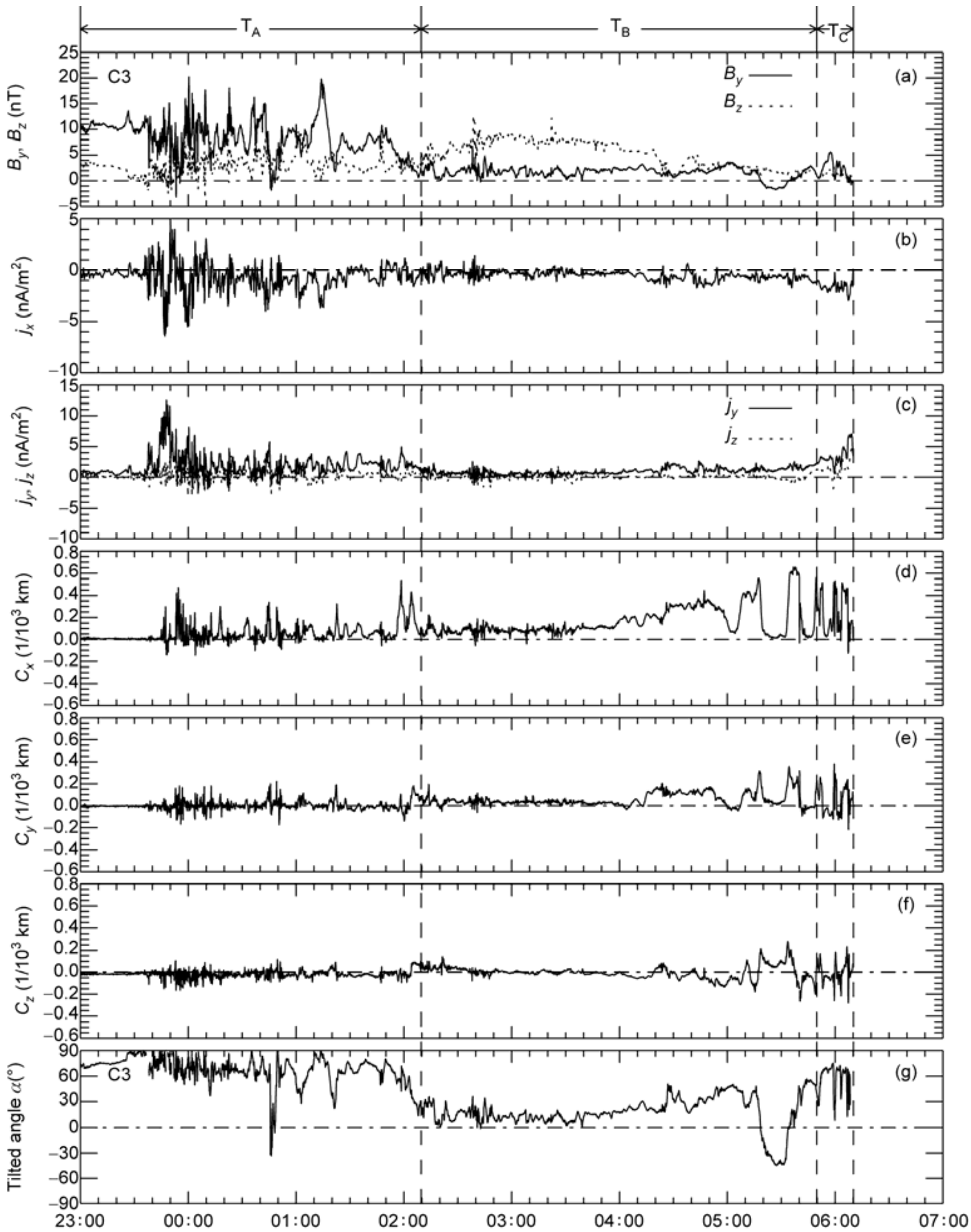


**Figure 7** (a) The $y$ and $z$ components of the magnetic field from C3; (b) and (c) the three components of the current density; (d) (e) (f) the three components of the magnetic curvature vectors Curl $\boldsymbol{B}$ from the multi-point data; (g) the tilted angle ($\alpha=\tan^{-1}(B_y/B_z)$) of the magnetic field line from C3 data. The vertical dashed lines are used to separate the different types of CS.

3 min. $B_x$ kept on oscillating even after the BBFs disappeared. The amplitude sustained about 10–15 nT until 02:10 UT (marked by dashed line "3") when the CS alternated from flattened CS to tilted CS. During 02:10–05:50 UT (between dashed lines "3" and "5", i.e. the $T_B$ duration) the CS was tilted, and the flapping amplitude of $B_x$ was $\leqslant$5 nT during 02:10–05:20 UT (between dashed lines "3" and "4") and increased to 8 nT during 05:20–05:50 UT (between dashed lines "4" and "5"). From 05:50 UT (marked by dashed line "5"), the CS turned from flattened to tilted type, and the flapping amplitude of $B_x$ increased to 10 nT. It can be concluded from the above results that two types of flapping were observed, in which one of them was accompanied with BBFs and the other was not. This suggests that in this event there was no direct relationship between the CS flapping and BBFs; in addition, the flapping amplitude in the flattened CS was larger than that in the tilted CS.

As we mentioned above, the statistical analysis of current sheet flapping using Cluster data performed by Sergeev et al. [20] and Runov et al. [21] showed that the current sheet is often tilted, and the normal vector is mainly in the $Y$ direction, with the component $n_y < 0$ in the dawn sector as well as $n_y > 0$ in the dusk sector. They pointed out that the

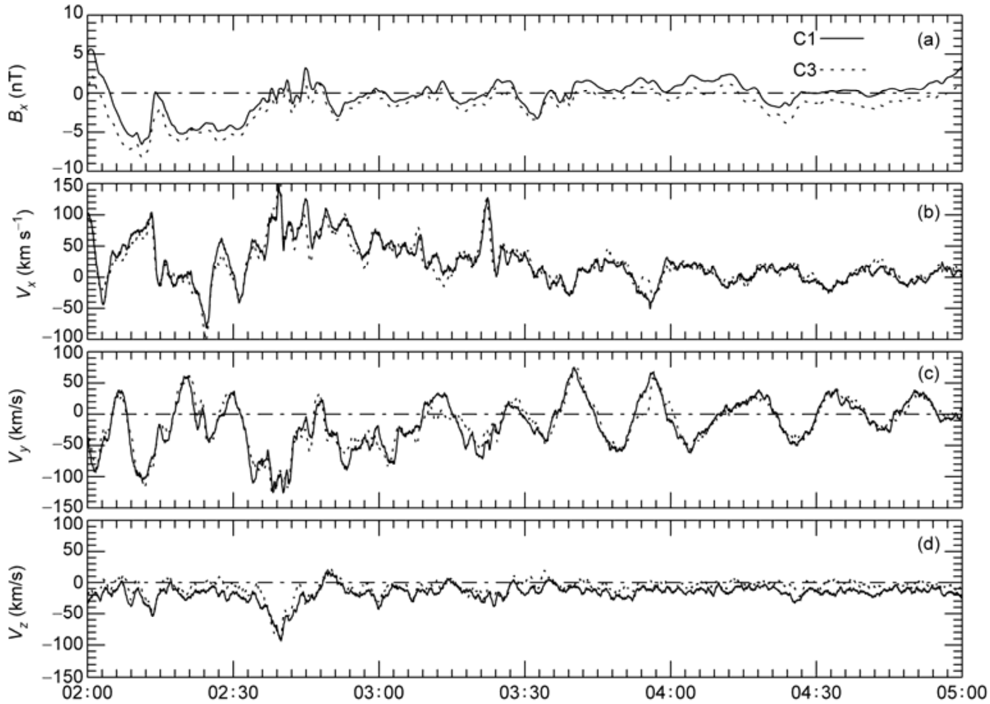


**Figure 8** The $x$ component of the magnetic field (a) and three components of the plasma flow speed from C1 and C3 (b), (c), (d).

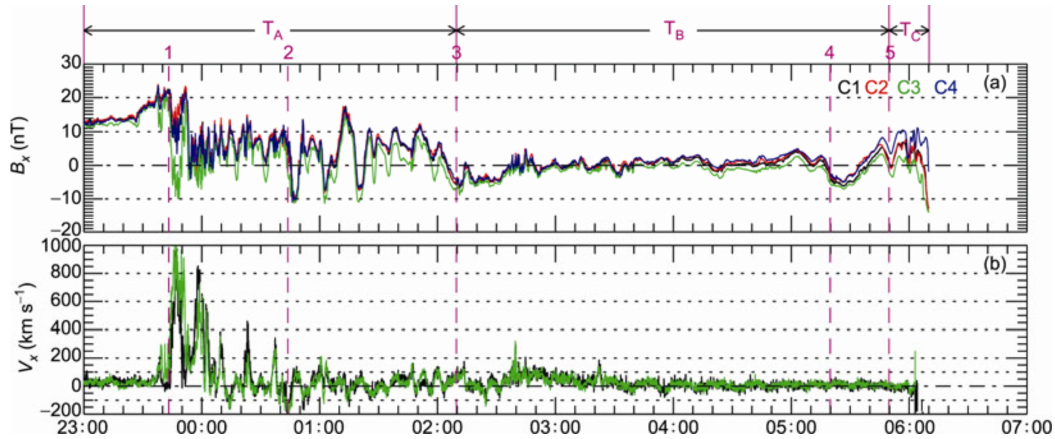


**Figure 9** The relationship between current sheet flapping and the plasma bursty bulk flows: the $x$ component of magnetic field from Cluster four spacecraft (a), the $x$ component of plasma flow velocity from C1 and C3 (b).

flapping of the current sheet is mainly induced by the kink-like instability. The kink mode is a class of MHD instabilities which usually develop in a thin plasma column carrying a strong axial current. If a kink begins to develop in such a column the magnetic forces on the inside of the kink become larger than those on the outside, which leads to growth of the perturbation. The column then becomes unstable and can be displaced into the walls of the discharge chamber, causing a disruption.

Sergeev et al. [20] depicted the generation and propagation processes of the kink mode in the magnetotail: there is an internal origin, i.e., the kink instability is generated by a localized source in a central sector of the magnetotail, and then propagates toward the flanks along the dawn-dusk direction. The tilted current sheet flapping excited by the kink mode displays some features, e.g. the relation between the two main components of the current density is $|j_z| > |j_y|$; the $z$-component of the ion velocity has the strongest oscillation motions; $j_z$ and $V_z$ are bipolar when the spacecraft crosses the current sheet back and forth. The kink mode in the magnetotail CS implies that the sheet is tilted as a whole rather than being locally expanded and contracted. If the CS is extremely twisted and warped, one can observe $|j_z| > |j_y|$. However, in our case, we observed $|j_y| > |j_z|$. There may be two reasons for this discrepancy: One is that the current sheet did not tilt as a whole, i.e., there was no kink mode in the current sheet; and the other is that the kink mode might exist in the current sheet, but it could not produce enough twist of the CS, so the $y$-component of current density was still predominant. In any case, we can confirm that if there is a kink mode in the current sheet, $j_z$ and $V_z$ should be bipolar during repeated crossings of the CS by the spacecraft. The above analyses show that the variations of $j_z$ and $V_z$ are not consistent with the features of the kink mode of the current sheet, thus we conclude that the current flapping in our event might not be induced by kink instability.

## 5 Conclusions and discussions

In 2001, Cluster spacecraft observed a rare event in the mid-tail current sheet. The current sheet moved southward continuously for almost seven hours during the interval 23:10 UT on 7–06:10 UT on 8 August. Meanwhile, Cluster crossed the CS back and forth repeatedly. This means that the large-scale southward movement of the CS was accompanied by a small-scale CS flapping during this period. Using the minimum and maximum variation analysis (MVA) method and the multi-spacecraft data, we calculated the normal vector, current density and the magnetic curvature of the CS. The results showed the followings. 1) During 23:10 UT on 7–02:10 UT on 8 August, the $z$-component of the normal vector was dominant; 2) during 02:10–05:50 UT on 8 August, the normal vector was tilted in the $y$ direction; and 3) during 05:50–06:10 UT, the normal vector turned to be along the $z$ direction again. In order to ascertain the exact type of the CS when the normal was mainly in the $z$ direction, we compared the $y$ and $z$ components of the magnetic field and found $B_y > B_z$ in both intervals, which suggested that the CS was flattened CS. We examined the tilted angles of the magnetic field lines, and found that there were large tilted angles in the flattened CS (~80°) whereas the tilted angles in the tilted CS were small (~30°). The characteristics of the variation of tilted angles of the magnetic field lines also indicate that the current sheet alternated between flattened CS and tilted CS. The $j_y$ component of the current density was predominant through the current sheet, and $j_y$ in the flattened CS was larger than that in the tilted CS. In the tilted CS, $|j_y| > |j_z|$, which was different from $|j_z| > |j_y|$, the previous observations of the vertical flapping of the CS induced by the kink instability. There was also no bipolar property for $j_z$ in this event.

The $y$-component of the ion velocity had the strongest oscillation with amplitude of about 100 km/s and a period of 16 min. The component $V_x$ exhibited much weaker oscillation than $V_y$ and there was no obvious oscillation in $V_z$. The results were different from the previous observations which showed $V_z$ oscillated the most strongly in the tilted CS flapping induced by the kink instability. The results suggested that the tilted CS oscillation in our case might not be excited by the kink instability.

There were two types of flapping in our event: one accompanied with BBFs and the other not. This suggested that in this event there was no direct relationship between the CS flapping and BBFs. In addition, the flapping amplitude in the flattened CS was larger than in the tilted CS.

A lot of important physical processes like the magnetic reconnection and plasma acceleration usually take place in the magnetotail current sheet. These processes can influence the dynamics of the Earth's magnetosphere considerably. The magnetosphere frequently appears to be in motion when solar wind changes and IMF changes rapidly. Thus the study of the magnetotail current sheet is also significant to understanding the interaction of the solar wind and the Earth's magnetosphere.

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1 Ness N F. The Earth's magnetic tail. J Geophys Res, 1965, 70: 2989–3005
2 Russell C T, Brody K I. Some remarks on the position and shape of the neutral sheet. J Geophys Res, 1967, 72: 6104–6106
3 Bowling S B, Russell C I. The position and shape of the neutral sheet at 30-Re distance. J Geophys Res, 1976, 81: 270–272
4 Fairfield D H. A statistical determination of the shape and position of the geomagnetic neutral sheet. J Geophys Res, 1980, 85: 775–780
5 McComas D J, Russel C T, Elphic R C, et al. The near-Earth cross-tail current sheet: Detailed ISEE 1 and 2 case studies. J Geophys Res, 1986, 91: 4287–4301
6 Toyichi T, Miyazaki T. Flapping motions of the tail plasma sheet induced by the interplanetary magnetic field variations. Planet Space Sci, 1976, 24: 147–156
7 Bauer T M, Baumjohann W, Treumann R A. Neutral sheet oscillations at substorm onset. J Geophys Res, 1995, 100: 23737–23742
8 Sergeev V A, Angelopulous V, Carlson C, et al. Current sheet measurements within a flapping plasma sheet. J Geophys Res, 1998, 103: 9177–9188
9 Harris E G. On a plasma sheet separating regions of oppositely directed magnetic field. Nuovo Cimento, 1962, 23: 115–121
10 Lui A T Y, Meng C I, Akasofu S I. Wavy nature of the magnetotail neutral sheet. Geophys Res Lett, 1978, 5: 279–282
11 Sergeev V A, Mitchell D G, Russel C T, et al. Structure of the tail plasma/current sheet at ~11 and its changes in the course of a substorm. J Geophys Res, 1993, 98: 17345–17365
12 Russell C T. The configuration of the magnetosphere. In: Critical Problems of Magnetospheric Physics, 1972. 1–16
13 Cowely S W H. Magnetospheric asymmetries associated with the $y$-component of the IMF. Planet Space Sci, 1981, 29: 79–96
14 Sibeck D G, Siscoe G L, Slavin J A, et al. The distance magnetotail's response to a strong interplanetary magnetic field: twisting, flattening, and field line bending. J Geophys Res, 1985, 90: 4011–4019
15 Shen C, Li X, Dunlop M, et al. Analyses on the geometrical structure of magnetic field in the current sheet based on Cluster measurements. J Geophys Res, 2003, 108, doi: 10.1029/2002AJ009612
16 Shen C, Liu Z X, Li X, et al. Flattened current sheet and its evolution in substorms. J Geophys Res, 2008, 113: A07S21, doi: 10.1029/2007JA012812
17 Petrukovich A A, Zhang T L, Baumjohann W, et al. Oscillatory of flux tube slippage in the plasma sheet. Ann Geophys, 2006, 24: 1695–1704
18 Zhang T L, Baumjohann W, Nakamura R. A wavy twisted neutral

sheet observed by Cluster. Geophys Res Lett, 2002, 29: 1899, doi: 10.1029/2002GL015544
19 Sergeev V A, Runov A, Baumjohann W, et al. Current sheet flapping motion and structure observed by Cluster. Geophys Res Lett, 2003, 30: 1327, doi: 10.1029/2002GL016500
20 Sergeev V A, Runov A, Baumjohann W, et al. Orientation and propagation of current sheet oscillations. Geophys Res Lett, 2004, 31: L05807, doi: 10.1029/2003GL019346
21 Runov A, Sergeev V A, Baumjohann W, et al. Electric current and magnetic field geometry in flapping magnetotail current sheets. Ann Geophys, 2005, 23: 1391–1403
22 Runov A, Nakamura R, Baumjohann W, et al. Current sheet structure near magnetic X-line observed by Cluster. Geophys Res Lett, 2003, 30: 1579, doi: 10.1029/2002GL016730
23 Zhang T L, Nakamura R, Volwerk M, et al. Double Star/Cluster observation of neutral sheet oscillations on 5 August 2004. Ann Geophys, 2005, 23: 2909–2914
24 Sergeev V A, Sormakov D A, Apatenkov S V, et al. Survey of large-amplitude flapping motions in the midtail current sheet. Ann Geophys, 2006, 24: 2015–2024
25 Gabrielse C, Angelopoulos V, Runov A, et al. Propagation characteristics of plasma sheet oscillations during a small storm. Geophys Res Lett, 2008, 35: L17S13, doi: 10.1029/2008GL033664
26 Runov A, Nakamura R, Baumjohann W. Multi-point study of the magnetotail current sheet. Adv Space Res, 2006, 38: 85–92
27 Reme H, Aoustin 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
28 Balogh A, Carr C M, Acuna M H, et al. The Cluster magnetic field investigation: overview of in-flight performance and initial results. Ann Geophys, 2001, 19: 1207–1217
29 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
30 Angelopoulos V, Kennel C F, Coroniti F V, et al. Statistical characteristics of bursty bulk flow events. J Geophys Res, 1994, 99: 21257–21280
31 Cao J B, Duan J T, Du A M, et al. Characteristics of mid-low latitude Pi2 excited by bursty bulk flows. J Geophys Res, 2008, 113: A07S15, doi: 10.1029/2007JA012629
32 Volwerk M, Zhang T L, Nakamura R, et al. Plasma flow channels with ULF waves observed by Cluster and Double Star. Ann Geophys, 2005, 23: 2929–2935
33 Wang Z Q, Cao J B. ULF waves associated with the periodical high speed flows in magnetotail plasma sheet. Chin J Geophy (in Chinese), 2010, 53: 231–236
34 Sonnerup B U O, Scheible M. Minimum and Maximum Variance Analysis. In: Analysis Methods for Multi-Spacecraft Data, 1998. 185–220
35 Chanteur G. Spatial interpolation for four spacecraft: Theory. In: Analysis Methods for Multi-spacecraft Data, 1998. 349–369
36 Speiser T W, Ness N F. The neutral sheet in the geomagnetic tail: its motion, equivalent currents, and field-line reconnection through it. J Geophys Res, 1967, 72: 131–141
37 Speiser T W. Magnetospheric current sheets. Radio Sci, 1973, 8: 973–977
38 Runov A, Angelopoulos A, Sergeev V A, et al. Global properties of magnetotail current flapping: THEMIS perspectives. Ann Geophys, 2009, 27: 319–328