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Key Points:

- Large-amplitude and fast-damped plasma sheet flapping associated with reconnection is analyzed
- Reconnection changes the downstream plasma sheet, thereby facilitating the generation of ballooning instability
- Reconnection should be a possible mechanism of the plasma sheet flapping by inducing ballooning instability

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Observation of the Large-Amplitude and Fast-Damped Plasma Sheet Flapping Triggered by Reconnection-Induced Ballooning Instability

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Abstract In this study, we reported the large-amplitude and fast-damped flapping of the plasma sheet, which co-occurred with magnetic reconnection. Data from the Double Star TC-1 and Cluster satellites were used to analyze the features of the plasma sheet flapping 1.4 R_E earthward of an ongoing magnetic reconnection event. The flapping was rapidly damped, and its amplitude decreased from the magnetohydrodynamics scale to the subion scale in 5 min. The variation in the flapping period (from 224 to 20 s) indicated that the source of the flapping had highly dynamic temporal characteristics. The plasma sheet flapping propagated duskward through a kink-like wave with a velocity of 100 km/s, which was in agreement with the group velocity of the ballooning perturbation. A correlation analysis between the magnetic reconnection and plasma sheet flapping indicated that the magnetic reconnection likely facilitated the occurrence of ballooning instability by altering the state of plasma in the downstream plasma sheet. In this regard, the reconnection-induced ballooning instability could be a potential mechanism to generate the flapping motion of the plasma sheet.

1. Introduction

When fast solar wind interacts with the magnetosphere, the magnetic field in the nightside of the magnetosphere is deformed to form the plasma sheet. The plasma sheet is characterized by the reversed magnetic field lines, and a large amount of magnetic energy is stored in the plasma sheet and surrounding lobes (Zhou et al., 2009; Zong et al., 1997). Most of the explosive processes in the nightside of the magnetosphere, such as magnetic reconnection (Dai et al., 2011; Deng & Matsumoto, 2001), substorms (McPherron et al., 1973; Tang & Wang, 2018), and bursty bulk flows (BBFs) (Angelopoulos et al., 1992; Cao et al., 2006; Lui et al., 1983; Ma et al., 2009), originate in the plasma sheet. Plasma sheets often exhibit a flapping motion in the “vertical” direction (perpendicular to the neutral sheet) (Rong et al., 2010; Speiser & Ness, 1967; Zhang et al., 2005), which can propagate along both the azimuthal and radial direction (Rong et al., 2018; Sergeev et al., 2003; Sun et al., 2014; Zhang et al., 2002). In this manner, plasma sheet flapping can modify the global magnetic configuration in the magnetosphere and transport energy in the magnetotail.

The mechanism of plasma sheet flapping has not been clarified yet, although several mechanisms have been considered to explain the source of flapping. Theoretical analyses and observations have indicated that a magnetohydrodynamics (MHD) process, such as a pressure pulse associated with a substorm, can trigger the flapping of the current sheet (Daughton, 1999; Fruit et al., 2002). Sergeev et al. (2006) highlighted that a strong correlation exists between the occurrence of BBFs and flapping, which indicates that BBFs are a potential mechanism for the generation of flapping (Volwerk et al., 2004). Through an analytical investigation, Golovchanskaya and Maltsev (2005) argued that plasma sheet flapping waves could be eigen oscillations of the hot magnetospheric plasma confined in a curvilinear magnetic field, that is, corresponding to MHD ballooning-type waves. Erkaev et al. (2009) examined the flapping phenomenon by considering the

Figure 1. TC-1 observations between 06:20 and 06:50 UT on 8 November 2004 in GSM coordinates. (a–c) Three components of the magnetic field, and the total magnetic intensity (thick line in panel (b)), (d) X component of the ion velocity, (e) ion density, (f) ion temperature, and (g) plasma β_i . The observations of the plasmoid are shaded in gray. The vertical dashed line represents the B_z turning point.

magnetic double-gradient instability induced by two gradients of the tangential and normal components of the magnetic field along the normal and tangential directions with respect to the current sheet. In terms of the kinetics, the occurrence of ion drift-kink instability can generate kink waves propagating from dawn to dusk (Karimabadi et al., 2003; Lapenta & Brackbill, 1997). Malova et al. (2007) suggested that the presence of an asymmetric plasma across the plasma sheet can cause flapping. Recently, Wei et al. (2015) indicated that current sheet flapping motions are intrinsically excited by nonadiabatic ions. In the presence of a guide field, the motion of nonadiabatic ions induces the hemispherical asymmetries of the bouncing ion population. Such hemispherical asymmetries disturb the pressure balance in the central current sheet and force the current sheet to move upward/downward. Wu et al. (2016) suggested that nonpropagation steady current sheet flapping likely occurred due to the instability caused by the ion temperature anisotropy in the diffusion region of the reconnection. Gao et al. (2018) indicated that the up-down motion of a current sheet around midnight could induce a kink-like flapping motion that propagated toward both flanks. The back-and-forth crossings of a plasma sheet have been observed to be induced by the sudden impulse (SI) of solar wind (Keika et al., 2008). Moreover, SI-excited ULF waves in a plasma sheet have been observed to demonstrate flapping-like disturbances (Shi et al., 2013; Tian et al., 2012; Zong et al., 2017). These results indicate that the flapping phenomenon can be explained by considering the presence of solar wind-induced waves in the plasma sheet. Nevertheless, although the existing findings help explain certain

Figure 2. Schematics of the conjunctural observations of the plasma sheet from TC-1 and Cluster. (a) shows that the reconnection triggers the ballooning instability, which leads to the occurrence of plasma sheet flapping; (b) shows the view of the plasma sheet flapping toward the Earth, with the north plasma sheet on the top; the red dashed curve represents the neutral sheet, and the blue arrows indicate the normal direction at each crossing.

local features of plasma sheet flapping, an inconsistency remains between the global features of plasma sheet flapping and the mechanisms proposed in the existing studies.

In this work, we examined the large-amplitude yet fast-damped flapping of the plasma sheet observed by Cluster (Escoubet et al., 2001). The plasma sheet flapping was occurring tailward of a magnetic reconnection event observed by Double Star TC-1 (Liu et al., 2005). The flapping involved a duskward propagating kink-like wave, induced by the ballooning instability. It was considered that the reconnection facilitated the occurrence of ballooning instability by altering the plasma state in the plasma sheet. The analysis of the reconnection event and plasma sheet flapping observed by TC-1 and Cluster is described in section 2. The relationship between the reconnection and plasma sheet flapping and a likely mechanism for the flapping induction are discussed in section 3. The concluding remarks are presented in section 4.

2. Observation and Analyses

Figure 1 shows the measurements of the magnetic field (Carr et al., 2005) and ions (Rème et al., 2005) obtained from TC-1 between 06:20 and 06:50 UT on 8 November 2004. TC-1 was located on the dusk side of the magnetotail region at $[-7.7, 10.4, -3.0]$ R_E in GSM coordinates. The X components of the magnetic fields B_X and B_Y in Figures 1a and 1b are always negative and positive, respectively, indicating that TC-1 was in the southern hemisphere. As TC-1 was located on the dusk side, the intensity of B_Y was comparable to that of B_X . The total magnetic intensity was approximately 80 nT (Figure 1b), and the ion density and temperature were approximately 0.2 cm^{-3} (Figure 1e) and 2 keV (Figure 1f), respectively. The calculated plasma β_i was approximately 0.02 (Figure 1g). These aspects indicate that TC-1 recorded the measurements in the plasma sheet boundary layer. Between 06:26:30 and 06:37:30 UT, B_Z exhibited an apparent bipolar variation with a negative peak of -17 nT followed by a positive peak of 19 nT, and $B_Z = 0$ at 06:30:20 UT. This bipolar B_Z in the plasma sheet indicated the occurrence of reconnection (Borg et al., 2005; Lu et al., 2010; Wang et al., 2010, 2016) or the presence of a plasmoid (Liu et al., 2013; Slavin et al., 2003; Zong et al., 1997, 2004). In particular, when B_Z changes from a negative to positive value, the ion flow is reversed from the tailward to the earthward direction (Figure 1d). In other words, the ions were convecting toward the point at

Figure 3. Cluster observations between 06:36 and 06:44 UT on 8 November 2004 in GSM coordinates. (a, b) X and Y components of the magnetic field observed from four spacecraft, (c) three components and total intensity of the magnetic field from C1, (d) three components of the ion velocity from C1, and (e) ion temperature. The vertical dashed lines with the numbers on the top represent the crossings of the plasma sheet.

which $B_Z = 0$, which is not in agreement with the state of a single reconnection point, in which the ions flow away from the X lines. Based on the existing observations and simulations, this bipolar B_Z associated with the convecting ion flows was interpreted as an active plasmoid (Eastwood et al., 2005; Fu et al., 2006). The convecting ion flow inside the plasmoid occurred due to the reconnection jets from the X lines ahead and behind the plasmoid, as shown in Figure 2a. In addition to the convecting ion flow toward the center of the bipolar B_Z , ion flow reversals were also observed at both the leading and trailing edges of the bipolar B_Z . These observations indicated that reconnection occurred at the two X lines around the plasmoid, as shown in Figure 2a. TC-1 did not observe the apparent enhancement of the magnetic field associated with the bipolar B_Z , which is often observed inside flux rope-type plasmoids (Slavin et al., 2003). This phenomenon likely occurred because TC-1 was located in the southern plasma sheet boundary layer, and thus, it traversed only the edges of the plasmoid, wherein the features of the magnetic fields are considerably similar to those in the ambient plasma sheet. In this case, even though the TC-1 could not perform a direct observation inside the diffusion region to conclusively prove the occurrence of magnetic reconnection, the existence of the active plasmoid provided indirect evidence of magnetic reconnection. After passing through the plasmoid at 06:37:30 UT, TC-1 entered the downstream of the reconnection region and observed a persistent $-B_Z$ and tailward reconnection fast flow with a maximum velocity of -278 km/s.

Furthermore, Cluster was located at $[-8.3, 11.7, -0.3]$ R_E in GSM coordinates. With respect to TC-1, the position of Cluster was $0.7 R_E$ tailward, $1.3 R_E$ duskward, and $2.7 R_E$ northward. The relative positions of TC-1 and Cluster are shown in Figure 2a, which indicates that Cluster was present tailward downstream of the location in which TC-1 observed the reconnection. Figures 3a and 3b show the observations of the magnetic fields (Balogh et al., 2001) between 06:36 and 06:44 UT from four Cluster spacecraft (C1, C2, C3, and C4). Before 06:37 UT, Cluster was present in the northern plasma sheet, as indicated by the stable $+B_X$ and $-B_Y$, and after 06:43 UT, it was present in the southern plasma sheet, as indicated by the $-B_X$ and $+B_Y$ values. Between 06:37 and 06:43 UT, the directions of B_X and B_Y changed, corresponding to the nine back-and-forth crossings of the plasma sheet marked by vertical dashed lines (Figure 3c). As shown in Figures 3a and 3b, all the four Cluster spacecraft observed the first three crossings. The first crossing, from the northern into the southern plasma sheet, was observed at 06:37 UT. Subsequently, Cluster traversed into the northern plasma sheet at 06:39:56 UT (second crossing) and returned to the south plasma sheet at

Figure 4. Tetrahedron formation of the Cluster spacecraft and their relative position at 06:41 UT in GSM coordinates.

06:40:48 UT (third crossing). After the third crossing, C2, C3, and C4 remained in the southern plasma sheet, while C1 still traversed the plasma sheet in a back-and-forth manner, detecting another five crossings. As Cluster was in the descending phase of its orbit during the observation, the back-and-forth crossings likely occurred due to the up-down flapping motion of the plasma sheet. Figure 4 shows the Cluster tetrahedron configuration at 06:41 UT. It can be noted that C1 was the most northward spacecraft. Four spacecraft entered the southern plasma sheet after the third crossing. Only C1 performed five additional crossings, which indicate that the flapping of the plasma sheet did not reach the three other spacecraft, which were located approximately 1,000 km southward of C1. In other words, the amplitude of the flapping decreased with time. The peak values of the total intensity of the magnetic fields measured by C1 (B_T in Figure 3c) between the first and seventh crossings gradually decreased. In the plasma sheet, the intensity of the magnetic fields decreased toward the central plasma sheet. The decreasing peak values indicate that C1 approached the central plasma sheet between the first and seventh crossings, and this aspect also explains the decrease in the flapping amplitude. The calculation of the flapping amplitude is described in a subsequent section.

Several parameters can be used to quantify the plasma sheet flapping. The propagation direction indicates the direction of propagation of the plasma sheet flapping; the normal direction indicates the tilt of the flapping plasma sheet relative to the X - Y plane; and the speed in the normal direction indicates how fast the plasma sheet moves in the normal direction. Cluster multipoint measurements can be used to determine these parameters (Paschmann & Daly, 1998; Shi et al., 2019). A timing analysis was performed by considering the point at which $B_X = 0$ (Russell et al., 1983) to calculate the normal direction and corresponding speed

Table 1
The Parameters for Plasma Sheet Crossings on 8 November 2004

Crossing	Time	Normal direction	Normal speed (km/s)	k	Amplitude (km)	Period (s)
1	06:37:00	0.373, 0.866, 0.332	109	+1	15,120	
2	06:40:00	0.544, 0.838, -0.039	86	+1	3,064	228
3	06:40:38	0.366, 0.372, 0.853	77	+1	1,231	
4	06:41:09	0.399, 0.491, -0.775	N/A ^a	+1	117	48
5	06:41:26	0.413, 0.001, 0.911	N/A	+1	602	
6	06:41:42	-0.044, 0.443, -0.896	N/A	+1	161	24
7	06:41:50	-0.265, -0.550, +0.792	N/A	+1	1,590	
8	06:42:20	0.674, 0.492, -0.551	N/A	+1	121	45
9	06:42:35	0.759, 0.079, 0.646	N/A	+1	202	

^aN/A indicates that the normal velocity is not available.

for the first, second, and third crossings. Only C1 detected the fourth to ninth crossings, and thus, the corresponding normal directions were determined by performing a minimum variation analysis (MVA) (Sönnnerup & Scheible, 1998) based on the magnetic measurements from a single spacecraft; however, the corresponding speed in the normal direction was not determined. Based on the results of the normal direction, the k parameter method developed by Rong et al. (2015) was used to determine the propagation direction for all the crossings. The results are presented in Table 1.

Table 1 indicates that the normal of the plasma sheet at the crossings pointed nearly to the Y direction (dawnward or duskward) or Z direction (northward or southward), except in Crossings 8 and 9, in which the normal pointed to the X direction. The normal direction for Crossing 1 pointed [0.373, 0.866, 0.332] in GSM coordinates, which indicates that the normal of the plasma sheet pointed mainly duskward. In other words, the plasma sheet was highly tilted relative to the X - Y plane. A similar phenomenon was noted in Crossing 2, with the normal direction at [0.544, 0.838, -0.039]. For Crossings 3 to 7, the normal direction pointed mainly toward $+Z$ or $-Z$; therefore, the crossings for Cluster occurred at the peak location of the plasma flapping. Owing to the decrease in the flapping amplitude, C1 samples only the edge of the flapping in Crossings 3 to 7. Based on the normal direction of the plasma sheet at each crossing, Figure 2b shows the configuration of the plasma sheet flapping and the location of the crossings. The northern plasma sheet marked by $+B_X$ and $-B_Y$ is shown on the top of the figure, and the southern plasma sheet is at the bottom. Viewed from the tail to the Earth, the plasma sheet flapping exhibited a kink-type wave (Sergeev et al., 2004). The normal speed of the plasma sheet in Crossings 1 and 2 was 109 and 86 km/s, respectively. The consistency of the positive values indicates that the series of plasma sheet flapping motions propagated duskward. Figure 4 shows that C2 was located duskward of C3, and they had the largest interseparation of 1,200 km in the Y direction, among those of the four spacecraft. The cross-correlation analysis shows that the magnetic variations at C2 were consistently delayed 12 s relative to the variations at C3 (Sergeev et al., 2003). Consequently, the duskward propagation velocity was $u = 100$ km/s, which is roughly in agreement with the normal speed of the plasma sheet motion in Crossings 1 and 2. The k parameter analysis indicates that k was positive for all the crossings (Table 1), which also indicates that the flapping motion propagated along the duskward direction. In the work of Rong et al. (2015), a consistent negative k corresponded to a duskward propagation. However, these findings are not necessarily conflicting. In this case, Crossings 4 to 9 were represented more clearly by the variation of B_Y rather than that of B_X (Figure 3c). Therefore, we used ΔB_Y instead of ΔB_X in the k parameter analysis (Rong et al., 2015). As the sign of ΔB_Y is opposite to that of ΔB_X for the plasma sheet crossings at the dusk side, the positive k in this work and negative k in Rong et al. (2015) indicate the duskward propagation of the plasma sheet flapping.

We set the observation of B_Y between Crossings 1 and 3 as an entire flapping waveform (as indicated by the shaded portion in Figure 3c) with a period of T and a phase of 2π . The period of this waveform was $T = 228$ s. Considering the propagation velocity of $u = 100$ km/s, the wavelength could be estimated as $\lambda = uT = 3.5 R_E$. The period of the following waveforms (waveforms between Crossings 3 and 5 and between Crossings 5 and 7) gradually decreased, as indicated in Table 1 and Figure 2b. The period of flapping is generally influenced by the temporal feature of the source. Thus, the varied period in this flapping event implies that the flapping was triggered by a highly dynamic source.

The measurement of the ion velocity (Rème et al., 2001) shown in Figure 3d indicates that the downward/upward crossings were negatively correlated with the upward/downward ion flow. To examine this correlation quantitatively, we compared the plots of B_Y and V_Z between Crossings 1 and 3 and observed that the V_Z variation led the B_Y variation by $\pi/2$, as indicated in Figure 3d. This phase shift was also observed in the other crossings. The periodical variation of the positive and negative V_Z enabled the estimation of the amplitude of the plasma sheet flapping. Specifically, the amplitude of the plasma sheet flapping was calculated by integrating V_Z over time (Sergeev et al., 2003), $A = \int_{t_1}^{t_2} V_Z dt$, where t_1 and t_2 , respectively, denote the time of crossing and following $V_Z = 0$ at which the flapping exhibits a peak or valley. The amplitude of the plasma sheet flapping was of the order of 15,120 km or 2.3 R_E at the MHD scale after Crossing 1. The amplitude of the flapping after each following crossing is listed in Table 1. The amplitude exhibits a decreasing trend, which is consistent with the variation of the total magnetic intensity shown in Figure 3c. The ion inertial length ($D_i = c/\omega_{pi}$) for the plasma in the plasma sheet was 415 km. The flapping amplitudes after Crossing 3 ranged from approximately 100 to 600 km, except for the amplitude after Crossing 7. These amplitudes were in the ion or subion scales, which implies that the initial large-amplitude flapping of the plasma sheet degenerated into a current sheet flapping with the amplitude at the ion scale. The decreasing amplitude indicated that the flapping was damped by the ambient plasma. In the period of 300 s between Crossings 1 and 7, the amplitude gradually decreased from the order of R_E to 100 km, which is a reduction of approximately 100 times; therefore, the ambient plasma damping was considered to be extremely high in the plasma sheet. The damped plasma sheet flapping indicated that the source of the flapping could not provide sufficient energy to balance the damping. The source likely released the energy in a pulsed manner instead of a stable manner, which could not sustain flapping with a constant amplitude.

3. Discussion

On 8 November 2004, TC-1 observed the formation of a plasmoid after a near-Earth tail reconnection event, and Cluster (located 0.7 R_E tailward, 1.3 R_E duskward, and 2.7 R_E northward) observed the flapping motion of the plasma sheet. The separation between TC-1 and Cluster (3.1 R_E) was comparable to the maximum wavelength (3.5 R_E) and amplitude of the plasma sheet flapping (2.3 R_E). Therefore, the flapping was inevitably affected by the reconnection.

The occurrence of BBFs, which are associated with magnetic reconnection, has been suggested as a trigger of the large-amplitude oscillation of plasma sheets (Volwerk et al., 2004; Vörös, 2011). In our observations (Figure 3d), the fast flow was tailward with a peak value of -288 km/s after Crossing 3; however, the flow before Crossing 3 was slow, and its direction switched between earthward and tailward. The initial large-amplitude flapping was ahead of Crossing 3. Thus, these observations did not indicate that the observed flapping was induced by the BBFs from the reconnection. Wu et al. (2016) reported on the flapping motion of a current sheet detected in the tailward flow of a magnetic reconnection event. In the authors' work, the flapping was confined in the current sheet of the ion diffusion region tailward of the X line. The flapping exhibited a vertical oscillation without propagating along the azimuthal direction, and the flapping event was attributed to the instability associated with the ion temperature anisotropy. Although the plasma sheet flapping in this case was also observed tailward of the reconnection, its features were different from those of the current sheet flapping considered by Wu et al. (2016). Consequently, the generation mechanism of the flapping was likely also different.

Reconnection is an explosive process characterized by two key consequences, that is, the energy conversion from a magnetic field to plasma, and a change in the magnetic topology. These two aspects considerably modify the features of the downstream plasma sheet. During the process of reconnection, the plasma acceleration due to the energy conversion expels the plasma from the inflow region into the outflow region, thereby increasing the plasma density in the downstream plasma sheet (Borg et al., 2005; Shay et al., 2016). Owing to the change in the magnetic topology, the reconnected field lines bend with an increased curvature. These alternations facilitate the triggering of a kind of plasma instability known as ballooning instability (Roux et al., 1991). The ballooning instability is triggered under the combination of the plasma pressure gradient and curved magnetic field lines (Ohtani & Tamao, 1993). According to an analytical investigation based on the one-fluid MHD approximation, the ballooning instability criterion can be expressed as (Ohtani & Tamao, 1993) $(V_A^2 + V_{SL}^2)k_{\parallel}^2 - 2V_{SL}^2\kappa_c(\kappa_p - \kappa_c - \kappa_b) < 0$, where V_A is the Alfvén velocity;

$V_{SL}^2 = V_A^2 V_S^2 / (V_A^2 + V_S^2)$, in which V_S is the acoustic speed; $k_{\parallel}$ represents the wave vectors in the direction of the magnetic field; and $\kappa_p = [(\mathbf{n} \cdot \nabla)P]/P$, $\kappa_b = [(\mathbf{n} \cdot \nabla)B]/B$ and $\kappa_c = (\mathbf{b} \cdot \nabla)\mathbf{b}$ denote the typical spatial scale of the plasma pressure gradient, magnetic field gradient, and field line curvature, respectively. $\mathbf{n}$ is directed to the center of the field line curvature, and $\mathbf{b}$ denotes the direction of the magnetic field. As κ_c is always positive, the criterion equation yields a necessary but not a sufficient condition for the occurrence of ballooning instability, that is, $\kappa_p - \kappa_c - \kappa_b > 0$. By considering the force balance $(\beta/2)\kappa_p + \kappa_b - \kappa_c = 0$, the necessary condition can be expressed as $\frac{(2+\beta)}{4}\kappa_p > \kappa_c > 0$. For the high β plasma in plasma sheet, an approximate necessary condition for the ballooning instability is $\kappa_p > \kappa_c > 0$. To determine both κ_p and κ_c , the multipoint measurements of plasma in the source region of the instability are required. However, as shown in the observations of TC-1, TC-1 passed through the edge of the reconnection region, and therefore, it could not measure the critical source region. Consequently, the in situ information of the plasma pressure gradient and magnetic curvature was not available to verify if the ballooning instability criterion was satisfied precisely at the place of its origin.

Qualitative and remote quantitative analyses were performed to estimate the possibility of occurrence of reconnection-induced ballooning instability. In the plasma sheet downstream of the reconnection considered in this case, the expelled plasma from the diffusion region can induce a plasma pressure gradient toward the tailward direction. Moreover, the cut of the near-Earth plasma sheet leads to the tailward curvature of the magnetic field lines, in which the moving particles experience an earthward centrifugal force, as shown in Figure 2a. The resulting positive κ_p and κ_c satisfy only the sign-related requirements in the aforementioned approximate condition for the ballooning instability. In the existing studies of the reconnection (Zhang et al., 2013, 2016), the curvature of the magnetic field lines in the plasmoid and outflow region was investigated. In the considered cases, the curvature radius ranged from 0.5 to 2.5 R_E . In addition to the increase in the plasma density (Borg et al., 2005; Shay et al., 2016), the temperature increased away from the X line in the reconnection (Nagai et al., 2015). These aspects indicate that the reconnection event changes the features of the plasma and fields in the plasma sheet to provide a possible condition that could induce ballooning instability with an amplitude of the order of R_E (Golovchanskaya & Maltsev, 2005). The

dispersion relation for small ballooning-type perturbations can be expressed as $\omega^2 = V_A^2 k_{\parallel}^2 + \omega_g^2 \frac{k_y^2}{k_n^2 + k_y^2}$

(Golovchanskaya & Maltsev, 2005), where V_A is the Alfvén velocity, and $k_{\parallel}$, k_n , and k_y denote the wave vectors in the direction of the magnetic field, direction of the magnetic field curvature, and azimuthal direction, respectively. The phase velocity and the group velocity are two parameters to evaluate the speed of wave propagation. The phase velocity is the propagation velocity of the phase of the wave. From it, we can know how fast the parts of a waveform, such as the peak phase of the wave, propagate, while it is difficult to measure it in in situ observations. The group velocity does carry the entitative physical information, for example, the speed of energy transportation. In the study of the propagation of the flapping, the group velocity is adopted to represent the propagation velocity and to be compared with the measurements (Erkaev et al., 2009; Golovchanskaya & Maltsev, 2005). From above dispersion relation, the group velocity of a

ballooning-type wave in the Y direction can be derived as $v_y^{group} = \frac{\partial \omega}{\partial k_y} = \frac{\omega_g^2}{\omega} \frac{k_n k_y}{(k_n^2 + k_y^2)^2}$. Under a high β limit,

such as that in the plasma sheet, by considering $k_n \sim k_y$, the equation of the group velocity can be simplified as $v_y^{group} \approx v_T / (2ak_y)$, where v_T is the average thermal velocity of the ions and a is the half thickness of the current sheet. In Figure 3e, the ion temperature in the plasma sheet is 3.6 keV, which corresponds to a thermal velocity of 600 km/s. By performing a timing analysis for Crossings 1 to 3, the average half thickness can be determined to be $a = 1.5 R_E$. Under a wavelength of $\lambda_y = 3.5 R_E$, $k_y = 2\pi/\lambda_y = 1.795 R_E^{-1}$. Based on these parameters derived from the in situ observations, the group velocity of the ballooning-type wave can be estimated to be $v_y^{group} \approx 111$ km/s. The observed flapping propagation velocity of $u = 100$ km/s is approximately consistent with this value, which indicates that the plasma sheet flapping is triggered by the ballooning instability from a quantitative aspect. The ballooning instability first displaces the plasma sheet back and forth in the vertical direction, and subsequently, the displacement propagates toward the dawnward/duskward direction, as shown in Figure 2a. The duskward propagation with a velocity of

100 km/s and phase shift of $\pi/2$ between the variations of V_Z and B_Y indicates that the disturbance from the ballooning instability propagates with a kink-like wave (Sergeev et al., 2004).

Once the reconnection is triggered in the central plasma sheet, the magnetic fields outward of the central plasma sheet are continuously connected to the lobe region. The plasma sheet is cut off, and the downstream plasma sheet starts to flap under the facilitating curvature and pressure gradient due to the reconnection, as shown in Figure 2. TC-1 in the reconnection region has little chance to detect the flapping, while Cluster in the downstream plasma sheet is at the right position to detect. The downstream plasma sheet retreats tailward, and the lobe plasma flows toward the central plasma sheet. The strong magnetic fields from the lobe can help stabilize the displacement of the plasma sheet triggered by the ballooning instability, thus inducing the observed fast damping of the plasma sheet flapping. Statistical investigations have confirmed that the plasma sheet flapping originates from the tail center and propagates toward the flanks (with few exceptions) (Gao et al., 2018; Sergeev et al., 2003). This flapping phenomenon is induced by the reconnection at the dusk side of the plasma sheet. Therefore, it is possible for a spacecraft dawnward of TC-1 to observe a dawnward propagating flapping on the dusk side of the plasma sheet, as shown in Figure 2a. The dawnward (duskward) propagation of dusk side (dawn side) flapping events has been reported in previous studies (Gao et al., 2018; Sergeev et al., 2003), although they have not been commonly observed.

4. Summary

The close-by observations of TC-1 and Cluster in the magnetotail indicate that the plasma sheet on the dusk side flaps near the tail, downstream of the magnetic reconnection. The separation of TC-1 and Cluster is comparable to the maximum amplitude and wavelength of the flapping. The features of this plasma sheet flapping, which is associated with the reconnection, can be summarized as follows:

1. The flapping of the plasma sheet propagates duskward with a velocity of approximately 100 km/s, which is in quantitative agreement with the propagation of ballooning-type perturbations.
2. During the flapping, the B_Y variation is well correlated with the V_Z variation, with a constant phase shift of $\pi/2$, which indicates that the flapping is systematically organized as a kink-like wave.
3. The amplitude of the flapping decreases rapidly, along with its period and wavelength. The initial plasma sheet flapping with the amplitude of the MHD scale gradually degenerates into the current sheet flapping with an amplitude of the subion scale. These features imply that this flapping is not stable but highly dynamic. Furthermore, the flapping is generated by an external source that releases energy impulsively.

In general, plasma sheet flapping with a large amplitude but fast damping has been rarely observed tailward of a magnetic reconnection event. This event provides a unique opportunity to analyze the relationship between the plasma sheet flapping and magnetic reconnection. The characteristics of the reconnection indicated that it can release energy impulsively and alter the state of the downstream plasma and magnetic configuration. Although TC-1 could not realize the in situ measurement of the plasma pressure and magnetic curvature, these alternations likely physically favored the occurrence of the ballooning instability. The consistency between the deduced group velocity of the ballooning perturbation and the calculated velocity of the flapping propagation based on the Cluster in situ observations indicates that the kink-like flapping is triggered by the occurrence of the ballooning instability. The fast damping may be a characteristic of the plasma sheet flapping associated with the reconnection, since the inflow of strong magnetic fields from the lobe regions after the triggering of reconnection can stabilize the displacement of the plasma sheet.

Until now, the flapping mechanism has not been fully understood. Based on the results of this study, we propose that although magnetic reconnection itself is a process at the microscale, it may contribute to the generation of the plasma sheet flapping at the macroscale, after changing the local plasma features in the downstream plasma sheet.

Data Availability Statement

All data used in this paper are available at Cluster Science Archive (<https://www.cosmos.esa.int/web/csa>; Laakso et al., 2010).

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