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Evidence of guide field magnetic reconnection in flapping current sheets

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Key Points:

- Evidence of guide field reconnection embedded in a twist flapping current sheet is presented for the first time.
- Breaking of the earthward flow is found during two instances of unusual reconnection occurring in a magnetotail flapping current sheet.
- We suggest that unusual reconnection jets can enlarge the magnetotail current sheet flapping amplitude.

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Abstract: Based on current sheet flapping motion on 27 August 2018 in the dusk flank magnetotail, as recorded by instruments aboard Magnetospheric Multiscale (MMS) spacecraft, we present the first study of guide field reconnection observed in the flux rope embedded in kink-like flapping current sheets near the dusk-side flank of the magnetotail. Unlike more common magnetotail reconnections, which are symmetric, these asymmetric small-scale (λ_i ~ 650 km) reconnections were found in the highly twisted current sheet when the direction normal to the sheet changes from the *Z* direction into the *Y* direction. The unique feature of this unusual reconnection is that the reconnection jets are along the *Z* direction — different from outflow in the *X* direction, which is the more usual situation. This vertical reconnection jet is parallel or antiparallel to the up-and-down motion of the tail's current sheet. The normalized reconnection rate *R* is estimated to be ~ 0.1. Our results indicate that such asymmetric reconnections can significantly enlarge current sheet flapping, with large oscillation amplitudes. This letter presents direct evidence of guide field reconnection in a highly twisted current sheet, characterized by enlarged current sheet flapping as a consequence of the reconnection outflow.

Keywords: magnetic reconnection; magnetotail; current sheet

1. Introduction

Current sheet flapping has been reported as a dynamic phenomenon in the Earth's magnetotail (e.g., Lui et al., 1978; Zhang TL et al., 2002, 2005; Sergeev et al., 2003, 2004, 2006; Wei XH et al., 2015; Rong ZJ et al., 2018; Gao JW et al., 2018; Wang GQ et al., 2019; Wei YY et al., 2019).This flapping is characterized by a polarity change of the *x* component of the magnet field, with the minimum value of the total magnitude of the magnetic field near the B_X direction change point (e.g., Zhang TL et al., 2002; Sergeev et al., 2003, 2006). Previous studies suggested that there are two kinds of current sheet flapping, a kink-like flapping and a steady flapping, within the magnetotail plasma sheet (e.g., Rong ZJ et al., 2018; Gao JW et al., 2018; Wei YY et al., 2019). Gao JW et al. (2018) reported that the kink-like flapping mostly occurred near both flanks of the magnetotail, and that the up-down steady flapping was observed in the midnight current sheet. They proposed that the up-down steady flapping around midnight induced the kink-like flapping as the waves propagated toward both flank regions. Different mechanisms have been proposed to explain the generation of these current sheet flapping motions (e.g., Lui et al., 1978; Sergeev et al., 2006, 2008; Erkaev et al.,2008, 2009; Wang GQ et al., 2019; Wei YY et al., 2019). Change in the direction of the solar wind has been proposed as one of the external mechanisms of current sheet flapping (e.g., Sergeev et al., 2008; Wang GQ et al., 2019). Magnetotail reconnection has been suggesteed as one of the internal mechanisms of the flapping (e.g., Wu MY et al., 2016; Wei YY et al., 2019). Wei YY et al. (2019) reported that the current sheet flapping observed by MMS, located near the dusk flank, was induced by periodic unsteady magnetic reconnection in the magnetotail.

Magnetic reconnection is an important process that releases energy during reconfiguration of a magnetic field structure (e.g., Deng XH and Matsumoto, 2001; Nagai et al., 2001; Øieroset et al., 2001; Nakamura et al., 2008; Dai L, 2009; Zhang TL et al., 2012; Dai L et al., 2017, 2021, 2023, 2024; Lu QM et al., 2022; Dai L and Wang

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C, 2023). The properties of magnetic reconnection change significantly as the *out-of-plane* or *guide* field varies. Many studies — in-situ measurements, simulations, and theories — have concluded that there are significant differences between general reconnection and *guide field reconnection* (e.g., Fu XR et al., 2006; Eastwood et al., 2010, 2013; Huang C et al., 2010, 2014; Lu QM et al., 2010; Wang RS et al., 2012). The observational studies found that the quadrupole Hall field structure is affected when a guide field is present (Huba, 2005; Zhang YC et al., 2023). Guide field reconnection may be related to asymmetric quadrupole Hall magnetic fields, which are different from the ones usually associated with symmetric reconnection cases. In the magnetotail current sheet, earthward and tailward high ion bulk flows are considered to be generated by magnetic reconnection (i.e., Nagai et al., 2001; Øieroset et al., 2001; Nakamura et al., 2008). Wu MY et al. (2016) reported that current sheet flapping was occurring in the tailward flow flux rope induced by magnetotail reconnection. Simulations (Huang C et al., 2017; Lu QM et al., 2023) and observation (Wang SM et al., 2020) both have demonstrated that small scale reconnections could occur inside flux ropes. Statistical study (Sergeev et al., 2006) found similarity between bursty bulk flows (BBFs) (Angelopoulos et al., 1992) and flapping occurrences, both of which had a peak in the magnetotail center. Till now, however, magnetic reconnection occurring in a highly tilted current sheet vertical to the magnetic equator plane, during current sheet flapping, has rarely been reported or studied.

The tilting and warping magnetotail neutral sheet which shows departure from its usual planar geometry, accompanied by flapping motion, may involve other small-scale processes. In this letter we report an observation of guide field reconnection within a flux rope during a current sheet flapping event.

2. Observations

We used magnetic field data from the MMS fluxgate magnetometer (FGM) (Russell et al., 2016), electric field data from its electric field double probe (EDP) (Ergun et al., 2016; Lindqvist et al., 2016), and plasma data from the MMS fast plasma instrument (FPI) (Pollock et al., 2016) to investigate the current sheet flapping.

2.1 An MMS1 Observation Overview of a Kink-like Current Sheet Flapping

Figure 1 presents an overview of MMS1 observations during the flapping event observed between 09:28 and 09:34 UT on 27 August 2018. The position of the spacecraft was (−21.0, 13.9, 0.8) R_E in geocentric solar magnetospheric (GSM) coordinates at approximately 21:48 magnetic local time (MLT). Figure 1a shows that B_X is the dominant component, with bipolar signatures, indicating that the spacecraft was crossing the magnetotail current sheet near the dusk flank region. The up-and-down feature of the *x* component of the magnetic field presents evidence of the wavy structure of the current sheet. Six vertical dashed lines mark each time the spacecraft was crossing the magnetotail's current sheet; the current sheet's flapping period was approximately 30 s. These vertical lines also mark the times when magnetic field strength reached a minimum, corresponding to the definition of "current sheet".

We applied the single-point technique developed by Rong ZJ et al. (2015) to diagnose the flapping type of this event. In this technique, a parameter *k* defined as $k = \text{sign}(n_M \times n_N) \times \text{sign}(\Delta B)$ has been constructed. Three eigenvalues and their corresponding eigenvectors were obtained by the Minimum Variance Analysis (MVA) of magnetic field (***B***) vector data (MVAB) for each crossing. Normal directions determined by the MVA analysis are displayed in Table 1. The normal direction is seen to have varied significantly in the *Y-Z* plane during these crossings, confirming that the current sheet surface was undergoing a fluctuation. The fact that the value of *k* is the same (−1) for all crossings implies that the case can be categorized as a wavy-like flapping motion, also termed "kink-like" (Rong ZJ et al., 2021). The reversal in B_Y may be produced by the gradient in the *z* component of the cross-tail current (Lui et al., 1978); it can be interpreted as a signature of a hump or valley in the neutral sheet surface, also consistent with the propagation of flapping waves towards the flanks.

It can be seen in Figure 1e that the *x* component of ion bulk velocity stays positive during the entire current sheet flapping event, which indicates that the event may have taken place in the earthward flow of magnetic reconnection in the distant magnetotail. The V_X component decreases significantly in the highlighted regions, which we suggest is a manifestation of the breaking of the earthward flow. We note a signature of bipolar B_Z in the highlighted time interval, as the magnitude of the magnetic field reaches its maximum value, providing evidence that the spacecraft was crossing a flux rope (Russell and Elphic, 1979; Elphic et al., 1986). In these two highlighted regions, Figure 1f shows that the V_Z is reversed with the braking of earthward flow (the minimum value of earthward flow approaching to several tens of km/s, as presented in Figure 1e) and intense electric field fluctuations (Figure 1c), especially, the strong parallel electric field (Figure 1d). The number density of ions in the two highlighted regions is about 0.10 cm^{-3} and 0.12 cm^{-3}, respectively. The ion inertial length in the first interval is 697.2 km (0.11 R_E); in the second, it is 651.51 km (0.10 R_E). The B_X component is positive in the two highlighted regions, indicating that the spacecraft is located in the northern hemisphere above the flapping current sheet. The bipolar B_Z, the reversed V_Z, and the strong electric field all suggest that small-scale reconnection was taking place in these two highlighted regions, in which, as shown in Figure 1f and Figure 1a, the larger V_Z component (containing the reconnection jets) is accompanied by stronger B_X fluctuations. These observations suggest that the reconnection jets can enlarge the amplitude of magnetotail current sheet flapping.

2.2 Observations of Guide-field Reconnection in the Flux Ropes Embedded in Flapping Current Sheets

Figure 2 shows the magnetic field, ion velocity, and electric field in local *LMN* coordinates, as obtained by MVAB to investigate the guide field reconnection. The strong guide field, B_G, is ~−14 nT, *represented by the horizontal dashed purple line* in Figure 2a. According to the kink-like flapping current sheet, highly twisted, this reconnection took place nearly on the *YZ*-plane given by the normal vector ***N*** = (0.00, −0.98, 0.20) GSM. Figure 2a shows that, in the time interval between the two vertical dashed lines, B_L reversed from 4 nT to −5 nT; the Hall magnetic field in the out-of-

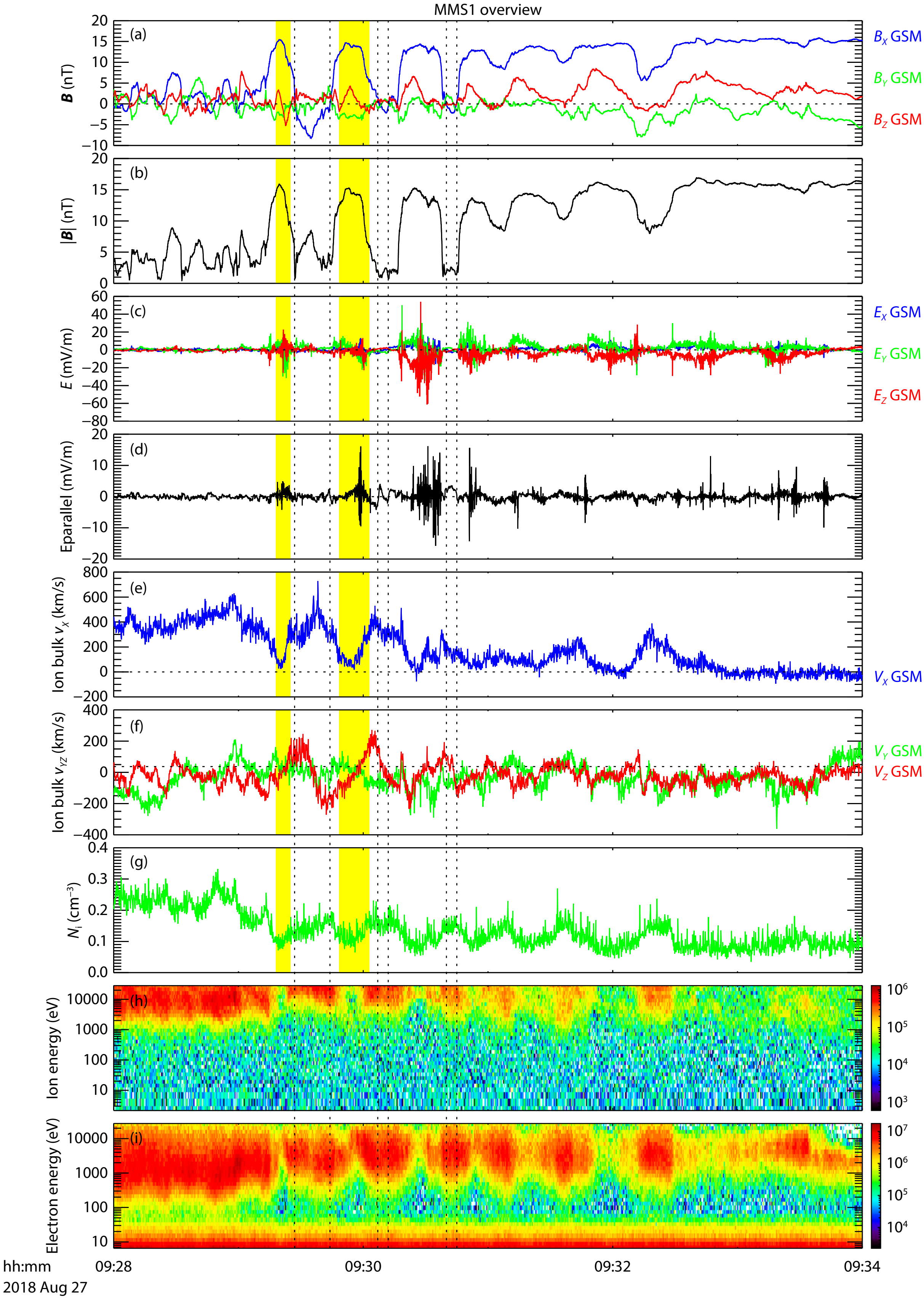

Figure 1. MMS1 observation: (a) the magnetic field, (b) the total magnetic field, (c) the electric field, (d) the parallel electric field, (e) *x* component of ion bulk velocity, (f) *y* and *z* components of ion bulk velocity, (g) the number density of ions, (h) the energy spectrum of ions, (i) the energy spectrum of electrons.

Table 1. Current sheet crossings on 27 August 2018 by MMS1.

No.	Type[a]	Crossing Time[b]	Duration (s)[c]	Normal[d]	Tilt angle (°)[e]	λ_2/λ_3[f]	k
1	+−	09:29:26	8	0.00, 0.98, 0.21	62.9	1.66	−1
2	−+	09:29:44	8	−0.06, −0.13, 0.99	22.7	2.73	−1
3	−+	09:30:07	8	0.27, 0.50, 0.82	16.5	3.90	−1
4	+−	09:30:12	2	−0.47, −0.85, 0.25	88.5	12.44	−1
5	−+	09:30:40	4	0.10, 0.02, 1.00	14.1	3.52	−1
6	+−	09:30:45	4	−0.16, −0.38, 0.91	37.8	8.80	−1

[a] Crossing from positive (or negative) to negative (or positive) magnetic field; [b] The time when spacecraft crossed the current sheet; [c] Selected minimum variance analysis calculation of time interval, centered around the crossing time; [d] MVA normal direction in Geocentric Solar Magnetospheric coordinates; [e] The tilt angle between the normal and the undisturbed normal direction $\boldsymbol{N}$ = (−0.03, 0.26, 0.96) GSM; [f] The ratio of eigenvalues λ_2/λ_3.

plane, B_M subtracted by the guide field, reversed from ~−1 nT to ~3 nT. It is obvious in Figure 2b that V_L has a reversal signature – from −100 km/s to 200 km/s. Figure 2c presents the Hall electric field, E_N, which has a bipolar signature, as follows: when $B_L > 0$, E_N is negative, with magnitude less than 10 mV/m; when $B_L < 0$, E_N is mostly positive, its magnitude reaching 30 mV/m, except for a negative peak exceeding −20 mV/m at t = 21.5 seconds. The reversals observed in B_L and V_L, and the bipolar E_N with different values, all indicate that a reconnection that was asymmetric with the guide field occured in this kink-like flapping current sheet.

Electric current density (Figure 2d) was obtained by curlometer calculations (Robert et al., 1998) using magnetic data from the FGM instrument. Features of the exhaust region current are less obvious compared to the current fluctuations near the crossing regions. Parallel and perpendicular currents (Figure 2e) are enveloped by positive and negative current magnitudes. The estimated dimensionless reconnection rate is defined as $R = V_{\rm in}/V_A$. $\boldsymbol{E} \times \boldsymbol{B}$ drift is used in order to calculate electron velocities outside the ion diffusion region. The plasma inflows on opposite sides of the current sheet were found to be 43.5 km/s and 59.8 km/s. We compute that the Alfvén velocity became 436 km/s just outside the reconnection region at 09:29:25 UT, where the magnetic field strength was 8 nT and the ion density was 0.16 cm^{-3}. The estimated R is 0.1 on the left side and 0.14 on the right side, which corresponds to a fast reconnection rate. Figure 3 shows the first reconnection event, zoomed in on the diffusion region. As shown in Figure 3d, $E \cdot J > 0$ indicates that the electromagnetic field energy was converted into plasma energy. That corresponds to higher energy (>1 keV) flux increases in the electron (Figure 3e) and ion (Figure 3f) energy spectra.

The other event with signatures of guide field reconnection is presented in Figure 4. This reconnection also took place nearly on the YZ-plane, with normal vector $\boldsymbol{N}$ = (0.32, 0.93, 0.16) GSM. In Figure 4a, the guide field B_G of ~13 nT is represented by the horizontal dashed purple line. The above and below part of B_M after subtraction of the guide field can be seen as the Hall magnetic field of the reconnection in the flux ropes. The positive part is about 1 nT and the negative part is about −3 nT. However, the reversal of B_L shows asymmetry in this reconnection event, which we suggest is due to the flapping motion of the current sheet, leading to distortion of the flux rope. The reconnection flow speed (Figure 4b) is similar to that observed in the previous, single flux rope, event (Figure 2), with negative V_L = ~−200 km/s changed into positive V_L = ~340 km/s with a continuing earthward flow in the M direction. In Figure 4c, clear bipolar Hall electric fields also appear in the exhaust region, from about 15 mV/m to −20 mV/m. The current densities (Figure 4d) are irregular compared to the single flux rope case. However, bipolar variations still have been observed multiple times in the exhaust region.

The two sets of B_L and V_L reversal and bipolar E_N with different values all indicate that asymmetric reconnection with guide field occurs in this type of kink-like flapping current sheet.

3. Discussion

Our observation shows that a wavy structure of current sheet propagates as travelling waves from midnight to the dusk flank, consistent with kink-type current sheet flapping (Lui et al., 1978). Various previous studies of current sheet flapping have been summarized by Wei YY et al. (2019). The reported semi-periods vary from seconds to no more than ten minutes in those cases, which may be produced by different triggering mechanisms. Many such mechanisms have been proposed (e.g., Lui et al., 1978; Sergeev et al., 2006, 2008; Erkaev et al.,2008, 2009; Wang GQ et al., 2019; Wei YY et al., 2019), including external and internal triggering mechanisms.

We also examined solar wind conditions from 9:00 to 10:00 UT recorded by OMNI. We found some quasiperiodic fluctuations of IMF B_Z with periods of several minutes, obtained from 1 min resolution instrument data, that may be related to the IMF condition change triggering (Sergeev et al., 2008; Runov et al., 2009; Wang GQ et al., 2019).

In this case we found the electric field, density, and plasma flow variations in the first three cycles are synchronized with the flapping motion, showing a 30-second-period feature. As described above, there is a strong correlation between the variations of the z component of ion bulk velocity and the magnetic field x component fluctuation amplitude in the reconnection region highlighted in Figure 1. We suggest that the flapping motion is enlarged by the magnetic reconnection jets. Like the previous study of current sheet flapping embedded in the diffusion region of magnetic reconnection, the flapping motion may be triggered by the periodic unsteady magnetic reconnection (Wei YY et al., 2019). Unlike the previous observation of reconnection that occurred between two colliding jets in a compressed current sheet at the center of a magnetic flux rope, reported by Øieroset et al. (2016), this case

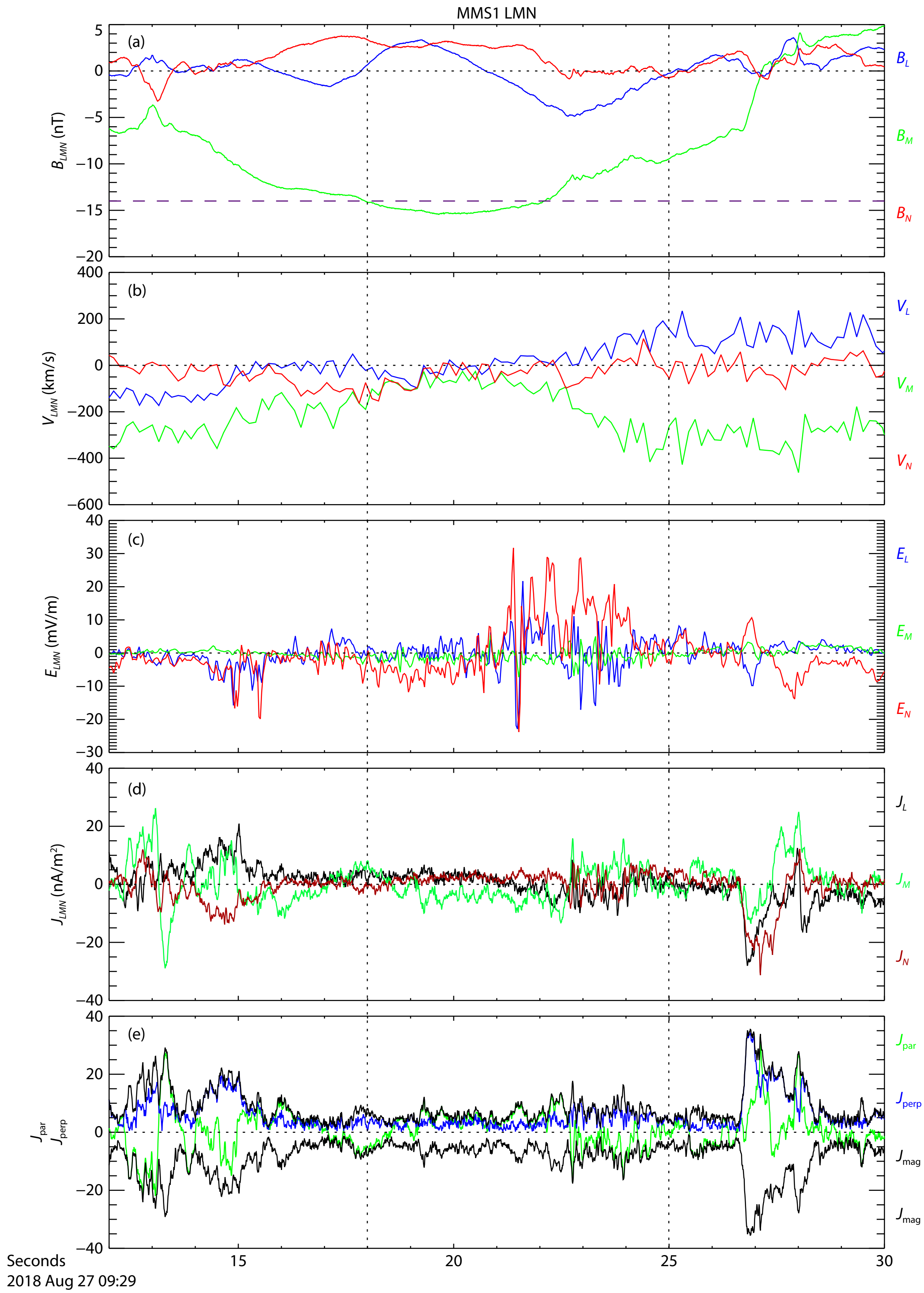

Figure 2. The first reconnection event observed by MMS1 in *LMN* coordinates. From top to bottom, (a) the magnetic field, (b) ion bulk velocity, (c) the electric field, (d) curlometer current density, (e) the parallel and perpendicular current densities. The horizontal dashed purple line in Figure 2a marks the guide field.

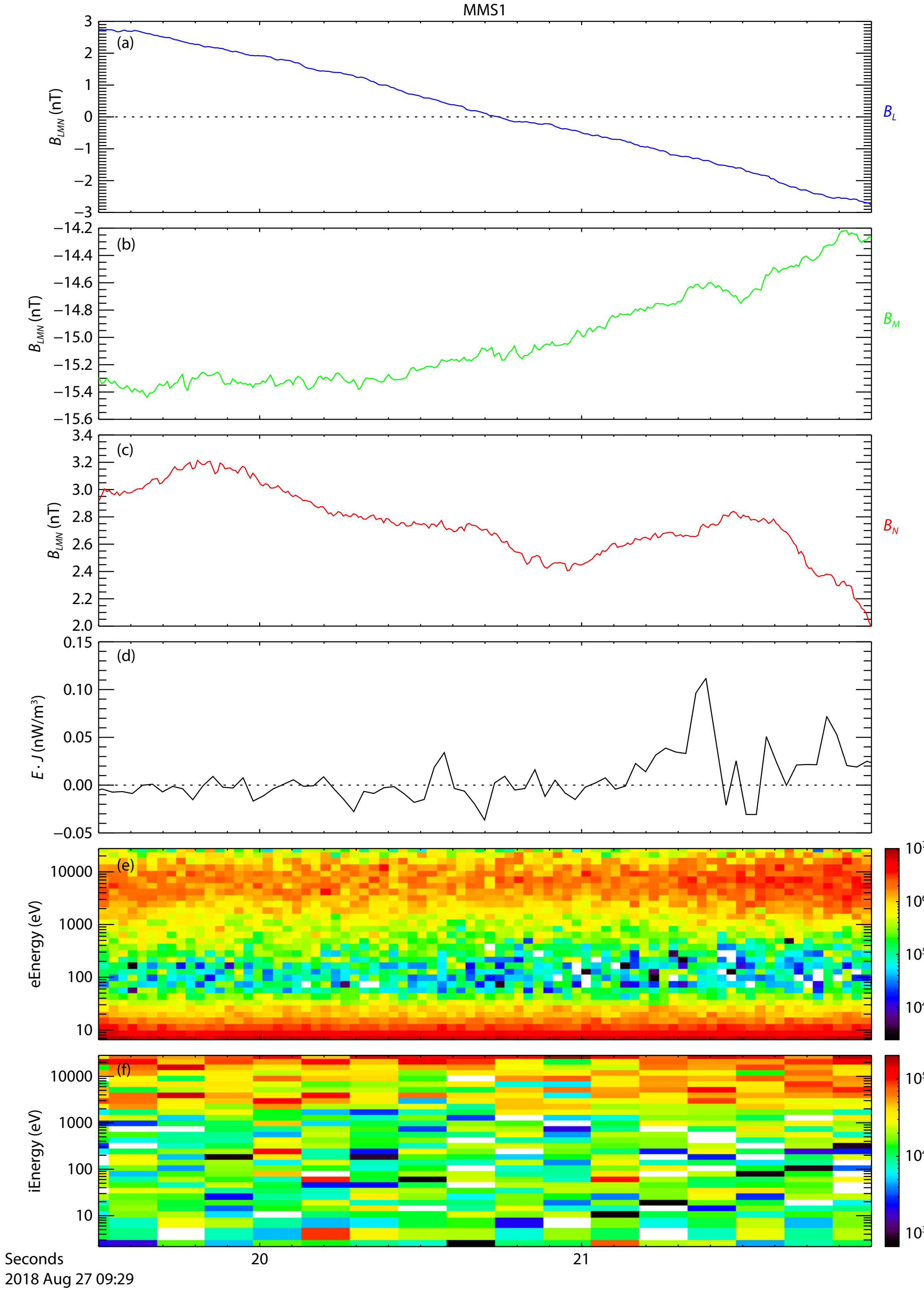

Figure 3. The reconnection parameters of the first event observed by MMS1 in the ion diffusion region. From top to bottom, (a) reconnection magnetic field B_L, (b) B_M, (c) B_N, (d) the value of $E \cdot J$, (e) energy spectrum of electrons, (f) energy spectrum of ions.

happened in the magnetotail current sheet instead of the magnetopause; however, we find similar field signatures. After analyzing two events identified as reconnection independently existing in flux ropes, we suggest that the ions were accelerated in the reconnection region and then contributed to the local onset of the flapping motion.

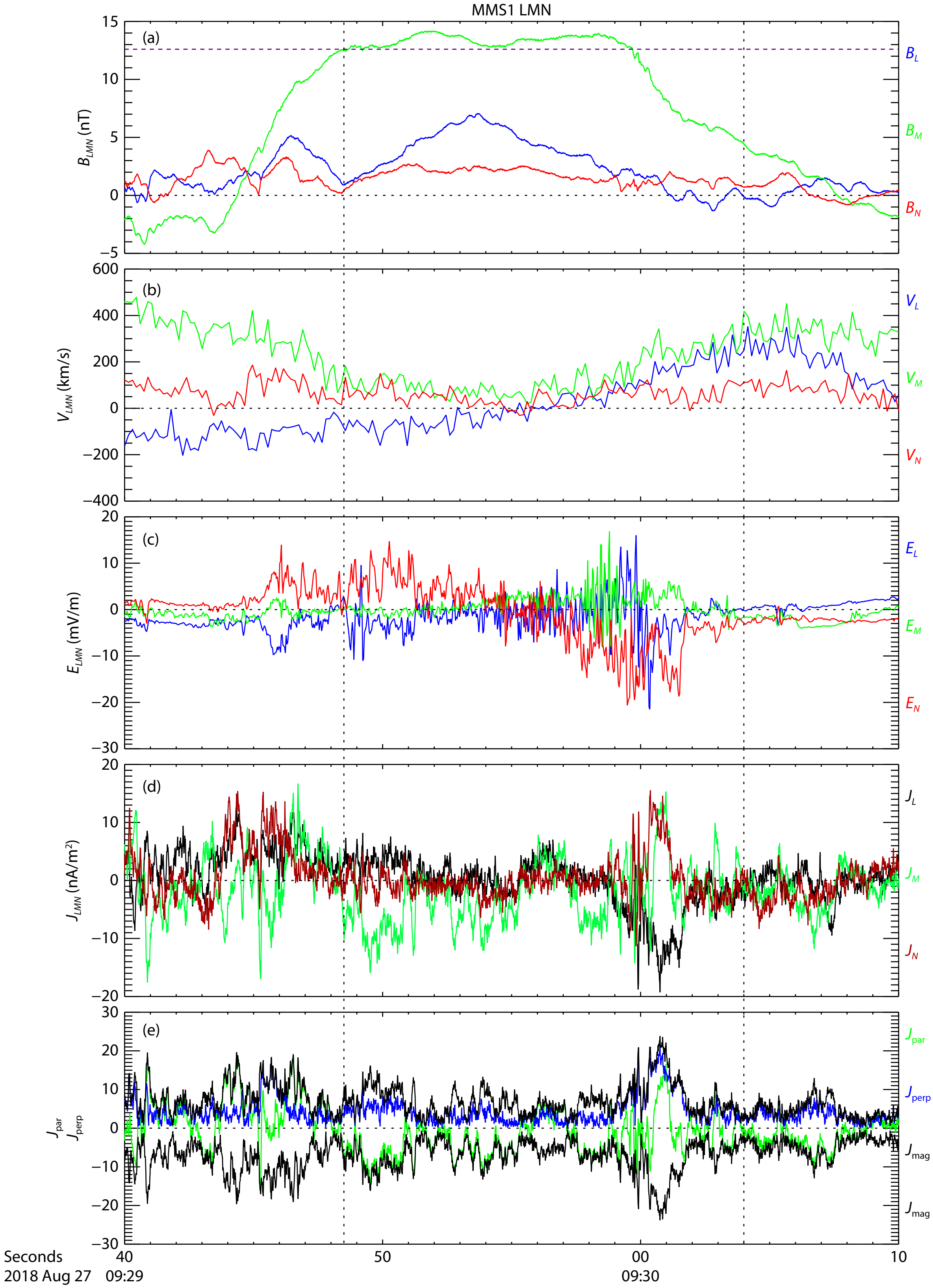

Figure 4. The second reconnection event observed by MMS1 in *LMN* coordinates, with the same layout as in Figure 2.

4. Conclusion

Observations made by instruments aboard MMS spacecraft in the dusk flank of the current sheet near the earthward stream of magnetotail reconnection during current sheet flapping motion are reported, including detection of current sheet oscillation behavior observed in six crossings. After using the single-point technique to analyze data from these six crossings, we conclude that the flapping motion was of the kink-type, travelling outward from the center to the flank region. Electric field fluctuations were observed during the first three flapping events, as well as the strong variations of the ion velocity V_Z, accompanied by breaking of the earthward flow. Between those crossings, the spacecraft encountered bipolar B_Z structures when the magnitude of the magnetic field reached its maximum values. These structures are identified as flux ropes. We examined two instances of guide field reconnection in the flux ropes. Both of them exhibit signatures of Hall electromagnetic field and reconnection plasma flow in the *YZ* plane of the titling and warping magnetotail current sheet. Such unusual reconnection jets appear to be able to enlarge the amplitude of magnetotail current sheet flapping. Those patterns roughly fit the flapping motion frequency, indicate that the flapping motion may be triggered by such periodic reconnection.

Acknowledgments

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