

## Electron-Scale Quadrants of the Hall Magnetic Field Observed by the Magnetospheric Multiscale spacecraft during Asymmetric Reconnection

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An *in situ* measurement at the magnetopause shows that the quadrupole pattern of the Hall magnetic field, which is commonly observed in a symmetric reconnection, is still evident in an asymmetric component reconnection, but the two quadrants adjacent to the magnetosphere are strongly compressed into the electron scale and the widths of the remaining two quadrants are still ion scale. The bipolar Hall electric field pattern generally created in a symmetric reconnection is replaced by a unipolar electric field within the electron-scale quadrants. Furthermore, it is concluded that the spacecraft directly passed through the inner electron diffusion region based on the violation of the electron frozen-in condition, the energy dissipation, and the slippage between the electron flow and the magnetic field. Within the inner electron diffusion region, magnetic energy was released and accumulated simultaneously, and it was accumulated in the perpendicular directions while dissipated in the parallel direction. The localized thinning of the current sheet accounts for the energy accumulation in a reconnection.

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Magnetic reconnection, as an effective mechanism for converting magnetic energy into plasma kinetic and thermal energy, has been believed to be responsible for a large number of explosive phenomena in space, astrophysics, and laboratory plasmas [1,2]. Because of the Hall effect, ions are unmagnetized and electrons are magnetized in the ion diffusion region [3,4], and the relative motion between ions and electrons results in a quadrupole pattern of the out-of-plane magnetic field and a bipolar pattern of the Hall electric field pointing to the center at both sides of the reconnecting current sheet [5–14]. The unique signature of the Hall quadrupolar structure has now been regarded as one critical criterion to identify the ion diffusion region [9,10,15–18]. The quadrupolar structure is symmetric in an antiparallel reconnection (i.e., the shear angle  $\alpha = 180^\circ$ ) and can be distorted by a guide field ( $\alpha < 180^\circ$ ) [19,20]. It is well known that the width of each quadrant is of the ion scale [3–6,15]. If the asymmetric distribution of the reconnecting field and plasma was considered, the quadrupole pattern was replaced by a bipolar pattern, as predicted in simulations [21,22]. However, a recent measurement shows that the quadrupole pattern might still exist in an asymmetric reconnection [23].

In this Letter, we present an asymmetric magnetic reconnection event encountered at the magnetopause by

the Magnetospheric Multiscale (MMS) spacecraft, which was designed to explore electron physics in a reconnection [24]. Since the MMS crossed the ion diffusion region both north and south of the  $X$  line, all four Hall quadrants can be measured very well. Such a situation should be frequently found from the MMS measurement, based on the preliminary analysis.

The data from several instruments are used. The mission and its instruments are described in several papers [24–28]. During 06:04:40–06:06:00 UT, on 22 October 2015, the MMS was located at [9.6, 3.5,  $-2.0$ ]  $R_E$  in Geomagnetic Solar Magnetospheric coordinates. At this time, the spacecraft traversed the magnetopause outbound, with a short excursion back to the magnetosphere in 06:05:16–06:05:21 UT. Figure 1 represents an overview of the crossing in the local boundary normal LMN coordinates (see Supplemental Material [29]).

In the beginning, the spacecraft was located in the magnetosphere, characterized by the stable and northward  $B_L$  [ $\sim 58$  nT, Fig. 1(a)], low density [ $< 2$  cm $^{-3}$ , Fig. 1(h)], and high-energy electrons [ $> 2$  keV, Fig. 1(i)]. After 06:05:03 UT, the MMS entered into the magnetosheath, with higher density (10 cm $^{-3}$ ) and low-energy electrons ( $< 1$  keV). From 06:05:05 to 06:05:32 UT, high-speed ion flows ( $v_{iL}$ ) up to 150 km/s were detected, comparable

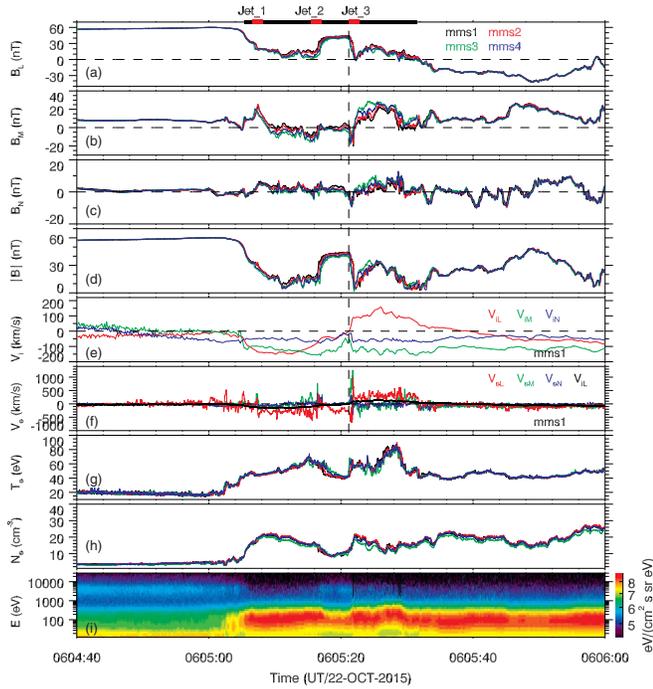


FIG. 1. (a)–(d)  $B_L$ ,  $B_M$ ,  $B_N$ , and  $|B|$  at the four satellites, (e) ion flows  $v_{iL}$ ,  $v_{iM}$ , and  $v_{iN}$ , and (f) electron flows  $v_{eL}$ ,  $v_{eM}$ ,  $v_{eN}$ , and  $v_{eI}$  at mms1. The electron (g) temperature, (h) density, and (i) energy spectrum at mms1.

to the magnetosheath Alfvén speed  $v_A = 146$  km/s ( $N \approx 20$  cm $^{-3}$  and  $B_L \approx 30$  nT). The ion flow was initially southward and then reversed to northward at  $\sim 06:05:21.3$  UT (the vertical dashed line), accompanied with the  $B_N$  reversal from Sunward to anti-Sunward [Fig. 1(c)]. Comparing  $v_{eL}$  and  $v_{iL}$  [Fig. 1(f)],  $v_{eL}$  was much higher than  $v_{iL}$  during 06:05:06–06:05:32 UT (the black bar at the top). The decoupling of the ion and electron flows represents a feature of the ion diffusion region, consistent with the violation of the ion frozen-in condition (not shown). So, we conclude that the MMS passed through the ion diffusion region of an asymmetric reconnection. The ambient field ( $B_M$ ) was  $\sim 10$  nT before 06:05:06 UT [Fig. 1(b)] and disturbed around the reconnection site. The ratio of the guide field to the reconnecting field was only  $\sim 0.2$ ; therefore, the guide field was weak. Based on the observations, the MMS trajectory is shown in Fig. 2(a).

In the southward ion flows,  $B_M$  was substantially enhanced for  $\sim 1.0$  s from 10 nT at  $\sim 06:05:06.5$  UT to 25 nT at  $\sim 06:05:07.5$  UT and then became negative for  $\sim 12$  s during 06:05:08–06:05:20 UT [Fig. 1(b)]. In the northward flows,  $B_M$  was mainly positive except a short negative spike ( $\sim 0.8$  s) at  $\sim 06:05:21.5$  UT. Given the trajectory, it seems that a strongly distorted quadrupolar structure was observed. The durations of the lower-right and upper-right quadrants were approximate 0.8 s, much shorter than their counterquadrants in the magnetosheath ( $\sim 9$  s). At 06:05:32 UT when the MMS left the ion diffusion

region north of the X line into the magnetosheath, a southward electron flow was measured [Fig. 1(f)], corresponding to the inflowing Hall electrons.

Just after the  $v_{iL}$  reversal point, an intense electron jet pulse [Fig. 1(f)] was detected at  $B_L \sim 30$  nT, marked as Jet\_3, while the MMS was moving towards the magnetosheath. The jet pulse was located immediately north of the X line and was enlarged in the first column in Fig. 3. The electron jets were simultaneously observed in the  $L$  and  $M$  directions [Figs. 3(a) and 3(b)]. Their speed was as high as 1300 km/s, substantially larger than the Alfvén speed  $v_A$  (146 km/s) yet less than the electron Alfvén speed in the magnetosheath ( $v_{e,A} = 6200$  km/s). The electron shear flow was evident in the  $L$  direction, and  $v_{eL}$  evolved from south to north [Fig. 3(a)].  $v_{eM}$  peaked near the center of the shear flow at each satellite [Fig. 3(b)]. Furthermore, the jet pulse was directly related to the negative spike of  $B_M$  [Figs. 1(b) and 3(e)], i.e., the upper-right quadrant [Fig. 2(a)].  $v_{eN}$  was much weaker than the other two components [Fig. 3(c)] and also changed sign from Sunward ( $v_{eN} > 0$ ) to anti-Sunward ( $v_{eN} < 0$ ). Since Jet\_3 was measured in close proximity to the X line, the  $v_{eN}$  reversal indicates that the spacecraft encountered the stagnation point, as proposed in simulations [30].

In Ref. [31], Jet\_3 was interpreted as a filamentary current associated with a reconnection, as many other currents in the exhaust far away from the X line. In order to establish the relation of the jet to the electron diffusion region, we further analyzed the similar jet pulses south of the X line at  $\sim 06:05:17$  UT and  $\sim 06:05:07$  UT [Fig. 1(f)], shown in the second (Jet\_2) and third (Jet\_1) columns in Fig. 3, respectively. Jet\_1 and Jet\_2 were both detected at  $B_L \sim 25$  nT. Jet\_1 was detected while the MMS was approaching the magnetosheath [Fig. 3(t)], and Jet\_2

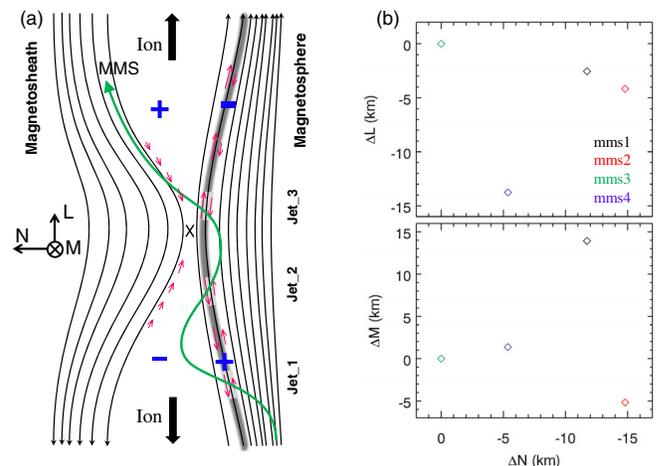


FIG. 2. (a) A schematic illustration for the reconnection. The shadow region denotes the electron current layer, and the pink arrows mean the electron flows. The blue signs of “+” and “−” mean the positive and negative  $B_M$ . (b) Relative position of the four satellites at 06:05:21 UT.

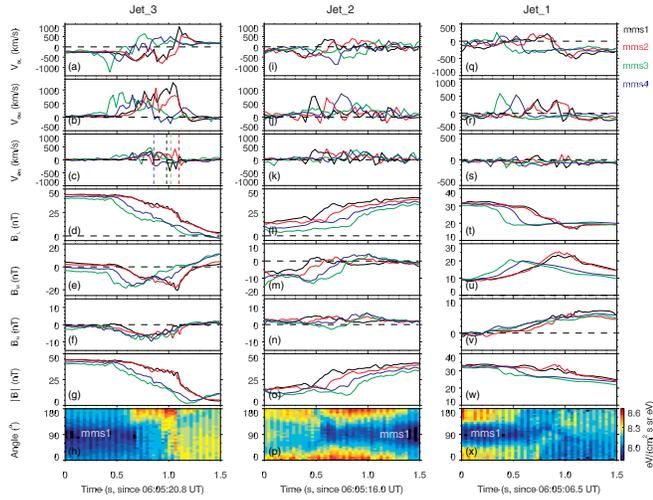


FIG. 3. (a)–(c)  $v_{eL}$ ,  $v_{eM}$ , and  $v_{eN}$  at all four satellites, (d)–(g)  $B_L$ ,  $B_M$ ,  $B_N$ , and  $|\mathbf{B}|$ , and (h) electron pitch angle distribution during 200–2000 eV at mms1. Panels (i)–(p) and (q)–(x) show the data in Jet\_2 and Jet\_1, respectively.

was measured as the MMS was moving deeply into the magnetosphere [Fig. 3(l)].  $v_{eL}$  changed its direction from north to south [Fig. 3(q)] in Jet\_1 while reversed from south to north [Fig. 3(i)] in Jet\_2. In Jet\_1 and Jet\_2, the speed of the southward jet was considerably stronger than the northward jet, and  $v_{eM}$ , pointing to the dawn side, got its maximum value within the shear flow [Figs. 3(j) and 3(r)]. In Jet\_1,  $B_M$  was significantly enhanced from  $\sim 10$  to 25 nT [ $\delta B_M \sim 15$  nT, Fig. 3(u)]. In Jet\_2,  $B_M$  was positive also within the shear flow and  $\delta B_M$  was close to 15 nT yet without a clear peak [Fig. 3(m)]. The positive enhancements of  $B_M$  in Jet\_1 and Jet\_2 corresponded to the lower-right quadrant of the quadrupole pattern.

Combining all three jet pulses, a dawnward out-of-plane electron jet ( $v_{eM}$ ) was always observed at  $B_L \sim 25$  nT and bounded by an electron shear flow  $v_{eL}$ . The corresponding currents were shown in Figs. 4(b)–4(d), 4(j)–4(l), and 4(r)–4(t), respectively. For simplicity, only the data at mms1 were shown. Based on the total current  $\mathbf{J} = nq(\mathbf{v}_i - \mathbf{v}_e)$  (thick traces) and electron current  $\mathbf{J} = -nev_e$  (thin traces) in Figs. 4(b), 4(j), and 4(r), the deviation between the total current and electron current is small, indicating that the current was mainly carried by electrons. Apparently, there was an electron current layer on the magnetosphere side of the ion diffusion region. The electron current layer consisted of an out-of-plane current ( $j_M$ ) near its center and the bidirectional current ( $j_L$ ) at its boundaries [Figs. 4(c), 4(k), and 4(s)]. The out-of-plane current mainly contributed to the perpendicular current, and the bidirectional current formed the field-aligned current [Figs. 4(d), 4(l), and 4(t)], which can be found also in the electron pitch angle distribution [Figs. 3(h) and 3(x)] except for in Jet\_2 [Fig. 3(p)]. The out-of-plane current layer was in accordance with

simulations of an asymmetric reconnection [21,22,32], where an out-of-plane current layer was produced by the electric field drift  $(\mathbf{E} \times \mathbf{B})_M$ .

The current layer was mainly lying in the  $L - M$  plane, and its normal velocity was  $-34.4$ ,  $17.5$ , and  $-27.1$  km/s for Jet\_3–Jet\_1, respectively (see Supplemental Material [29]). As for Jet\_3, its thickness was  $\sim 8.6c/\omega_{pe}$  (electron inertial length) at mms3 and mms4 and became  $\sim 5.8c/\omega_{pe}$  at mms1 and mms2. The layer thicknesses in Jet\_2 and Jet\_1 were  $\sim 2.9$  and  $\sim 4.5c/\omega_{pe}$ , respectively. So, the current layer (the corresponding quadrants of Hall field) was electron scale. However, the width of the counter-quadrant was estimated to be 4.3 ion inertial lengths ( $\Delta t \sim 9$  s, 0605:23–0605:32 UT;  $v_N \sim -34.4$  km/s).

Because of the intermittent presence of cold plasma wakes from the MMS [33], the electric fields here were recalibrated to remove baseline offsets of  $\mathbf{E} + \mathbf{V}_e \times \mathbf{B}$  that endured for more than 5 s. This offset removal does not affect a deviation between  $\mathbf{E}$  and  $-\mathbf{V}_e \times \mathbf{B}$  with a duration of less than 2.5 s. Prior to 0605:21.4, an abrupt cold plasma wake, seen in the ion distribution and in strong plasma waves [34], exceeds 2 mV/m in  $E_z$ . In the first 0.6 s of the Jet\_3 interval, the uncertainty in  $E_z$  is  $\sim 5$  mV/m, which primarily affects the  $L$  component. In each jet pulse, the striking signature was the intense positive  $E'_N$  ( $\mathbf{E}' = \mathbf{E} + \mathbf{V}_{xline} \times \mathbf{B}$ ) in the  $X$ -line frame [blue traces in Figs. 4(e), 4(m), and 4(u)], where  $\mathbf{V}_{xline}$  is the velocity of the  $X$ -line frame relative to the MMS.  $E'_N$  directed to the magnetosheath and was as intense as 30 mV/m at Jet\_3, up to 10 mV/m at Jet\_2 and less than 10 mV/m at Jet\_1.  $v_{eM}$  decreased with the distance from the  $X$  line [ $\sim 1300$  km/s at Jet\_3,  $\sim 900$  km/s at Jet\_2, and  $\sim 400$  km/s at Jet\_1 in Figs. 4(a), 4(i), and 4(q), respectively], and so did the current density  $j_M$  [ $2.0 \mu\text{A}/\text{m}^2$  at Jet\_3,  $1.2 \mu\text{A}/\text{m}^2$  at Jet\_2, and  $0.8 \mu\text{A}/\text{m}^2$  at Jet\_1 in Figs. 4(c), 4(k), and 4(s), respectively].  $j_M$  and  $v_{eM}$  show a similar evolution to  $E'_N$ , suggesting that they were formed by the  $(\mathbf{E}' \times \mathbf{B})_M$  drift. The calculated drift velocity  $[\mathbf{E}' \times \mathbf{B}/|\mathbf{B}|^2]$ , thick traces in Figs. 4(f), 4(n), and 4(v) matched pretty well with the measured electron velocity ( $\mathbf{V}_{e\perp}$ , thin traces) except in the  $M$  component at Jet\_3 and Jet\_2. In particular, a larger difference can be found in the  $M$  component at Jet\_3, which indicates that the electrons were slipping from the magnetic field.

The electron shear flow was another distinct feather in the layer. In the north of the  $X$  line (Jet\_3), the electrons were moving southward, i.e., towards the  $X$  line (inflowing electrons) and on the magnetospheric side and northward, i.e., away from the  $X$  line (outflowing electrons), on the other side. In the south of the  $X$  line (Jet\_1 and Jet\_2), on the contrary, electrons were flowing northward on the magnetospheric side and southward on the other side. This shear flow was consistent with the observed  $B_M$ , which was negative north of the  $X$  line and positive south of the  $X$  line. The comparable inflowing and outflowing speeds at Jet\_3 indicate that Jet\_3 should be very close to the  $X$  line.

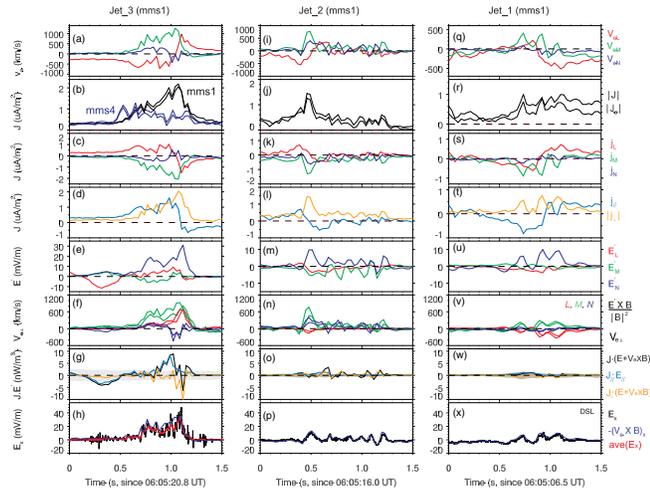


FIG. 4. (a)  $v_{eL}$ ,  $v_{eM}$ , and  $v_{eN}$  at mms1, (b) the total (thick curve) and electron current (thin curve) density, (c)  $j_L$ ,  $j_M$ , and  $j_N$ , (d)  $j_{\parallel}$  (blue curve) and  $|j_{\perp}|$  (yellow curve), (e) the electric field ( $E'_N$ , blue curve;  $E'_M$ , red curve;  $E'_L$ , green curve) in the  $X$ -line frame  $\mathbf{E}' = \mathbf{E} + \mathbf{V}_{xline} \times \mathbf{B}$ , (f) the drift velocity ( $\mathbf{E}' \times \mathbf{B}/|\mathbf{B}|^2$ ) and  $\mathbf{V}_{\perp} = [\mathbf{B} \times (\mathbf{E} \times \mathbf{B})/|\mathbf{B}|^2]$ , (g)  $\mathbf{J} \cdot (\mathbf{E} + \mathbf{V}_e \times \mathbf{B})$  (black curve),  $\mathbf{J}_{\parallel} \cdot \mathbf{E}_{\parallel}$  (pale blue curve),  $\mathbf{J}_{\perp} \cdot (\mathbf{E} + \mathbf{V}_e \times \mathbf{B})_{\perp}$  (yellow curve), the shadow means the errors of  $\mathbf{J} \cdot (\mathbf{E} + \mathbf{V}_e \times \mathbf{B})$ , and (h)  $E_x$  (black curve) and  $-(v_e \times B)_x$  (blue curve). Panels (i)–(p) and (q)–(x) show the data in Jet\_2 and Jet\_1, respectively.

In Figs. 4(h), 4(p), and 4(x), the DSL (Despun, Sun-pointing L-momentum vector) coordinates where the electric field was measured was used. In Jet\_1 and Jet\_2,  $E_x$  and  $-(v_e \times B)_x$  matched perfectly [Figs. 4(p) and 4(x)], and  $\mathbf{J} \cdot (\mathbf{E} + \mathbf{V}_e \times \mathbf{B})$  was very small [Figs. 4(o) and 4(w)]. Hence, the electrons were frozen-in and the energy dissipation was negligible. In Jet\_3,  $E_x$  or its average value [the electrostatic fluctuations removed, red trace in Fig. 4(h)] show a clear deviation from  $-(v_e \times B)_x$ , up to 20 mV/m. It means that the electron frozen-in condition was violated. Namely, the MMS entered into the inner electron diffusion region [35,36]. Inside Jet\_3,  $\mathbf{J}_{\parallel} \cdot \mathbf{E}_{\parallel}$  was always positive [blue trace in Fig. 4(g)] and  $\mathbf{J}_{\perp} \cdot (\mathbf{E} + \mathbf{V}_e \times \mathbf{B})_{\perp}$  was basically positive except for a 40 ms interval near the  $|J_{\perp}|$  peak at 06:05:21.9 UT [Fig. 4(d)]. Such a short interval corresponded to a region of  $1.0c/\omega_{pe}$ , where  $\mathbf{J}_{\perp} \cdot (\mathbf{E} + \mathbf{V}_e \times \mathbf{B})_{\perp}$  and  $\mathbf{J} \cdot (\mathbf{E} + \mathbf{V}_e \times \mathbf{B})$  were both negative.

Some simulations predicted that the Hall field in an asymmetric reconnection displayed a dipolar pattern [21,22,32]. However, evident Hall quadrupolar structure was confirmed in this asymmetric reconnection. The distorted quadrupole pattern in a symmetric reconnection was attributed to the guide field effect [19,20]. The guide field deflected the outflow electron jets and caused a distorted pattern. The previous observations showed that their widths were ion scale near the  $X$  line; even the ratio of the guide field to the asymptotic field was up to 0.3 [20]. In the present event, the ratio was only  $\sim 0.2$ , yet the two quadrants adjacent to the

magnetosphere were compressed into the electron scale. So, the guide field cannot be the unique reason. It seems that an asymmetric distribution of the field and plasma is the main reason for the enhanced compression.

In Jet\_3, the current layer thickness became thinner while mms2 and mms1 crossed it. It means that the layer might be thinning. A thinning current layer would cause an increase of the local field and current intensity. The current intensity at mms1 was substantially stronger than that at mms4 [Fig. 4(b)], and a clear field enhancement was indeed observed at mms1 and mms2, in comparison with the smooth decrease at mms3 and mms4 [Fig. 3(g)]. The negative  $\mathbf{J}_{\perp} \cdot \mathbf{E}'_{\perp}$  and  $\mathbf{J} \cdot (\mathbf{E} + \mathbf{V}_e \times \mathbf{B})$  in Jet\_3 could be attributed to the thinning process, since magnetic energy will be accumulated in a thinning current layer. In addition, the two minimums of the southern jet  $v_{eL}$  [at  $\sim 0605:21.5$  and  $0605:21.7$  UT in Fig. 3(a)] at mms1 and mms2 can be referred to the thinning also. A possible scenario is that, as mms1 and mms2 encountered the first  $v_{eL}$  peak at 0605:21.5 UT, the layer started to thin and then made the two satellites retreat out of the layer. Approximately 100 ms later (at 0605:21.6 UT), they got into the layer again and then crossed it. The current sheet thinning has been regarded as one necessary condition for reconnection onset [37]. Our observations indicate that the thinning can take place in an ongoing reconnection, instead of only before the onset. The energy dissipation and accumulation can occur simultaneously near the inner electron diffusion region.

All the MMS data used in this work are available at the MMS science data center [38].

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