Electron-Only Tail Current Sheets and Their Temporal Evolution

M. Hubbert1, Y. Qi1, C. T. Russell1, J. L. Burch2, B. L. Giles3, and T. E. Moore3

1Earth Planetary and Space Sciences, University of California Los Angeles, Los Angeles, CA, USA, 2Southwest Research Institute, San Antonio, TX, USA, 3Goddard Space Flight Center, NASA, Greenbelt, MD, USA

Abstract The Earth’s magnetotail contains a current sheet separating the anti-Sunward field of the southern lobe from the sunward-pointing northern lobe. Herein, we report tail current sheets that are supported only by electron currents. We examine one electron-only current sheet in detail and briefly discuss 10 others. Three current sheets are interpreted in terms of the time-evolution of reconnection onset. These current sheets show evidence of parallel electron heating, perpendicular ion heating, and current sheet expansion. These features are consistent with electron and ion behavior during traditional “electron-ion” reconnection. Ground-based and in-situ data show that electron-ion reconnection occurs shortly after each “pre-ion reconnection” electron-only reconnection event. This suggests that electron-only reconnection can act as a precursor to electron-ion reconnection. We note that five events occur shortly after a period of electron-ion reconnection, which suggests that electron-only reconnection is more than merely a precursor to ion reconnection.

Plain Language Summary Magnetic reconnection is a key process in conversion of magnetic energy to kinetic and thermal energy in space and laboratory plasmas. The Magnetosphere Multiscale (MMS) mission is designed to study the physics of magnetic reconnection with unparalleled time and spatial resolution. In this letter, we present several MMS observations of electron-supported current sheets that do not show signatures of typical magnetic reconnection, dubbed “Electron-Only” reconnection. We use three events to show that “electron-only” reconnection can lead to “electron-ion” magnetic reconnection. We use six events to suggest that “electron-only” reconnection occurs in more regimes than merely during the onset of “electron-ion” reconnection.

1. Introduction

Magnetic reconnection is a fundamental plasma process that converts magnetic energy into kinetic and thermal energy in laboratory and space plasmas (Dungey, 1961; Yamada et al., 2010). Inside the ion diffusion region (IDR), the curvature of the magnetic field approaches the gyroradius of ions, causing ion trajectories to deviate from simple gyromotion. Closer to the reconnection point, in the electron diffusion region (EDR), electrons in tighter gyro-orbits transition to more chaotic orbits (Fu et al., 2006). These two components of the reconnection region allow ions and electrons to be demagnetized, energized, and ejected in jets directed outward (Pritchett, 2001; Oka et al., 2016), but because of their different masses, these regions are often well separated (Sonnerup et al., 1979). This process can establish a dynamic equilibrium in the magnetosphere. While the maintenance of the currents is a shared responsibility between electrons and protons, a plasma can have charge neutrality and current supplied primarily by electrons. This paper identifies 11 occasions when this occurred in the Earth’s magnetotail.

Recently, using the Magnetosphere Multiscale (MMS) Mission, several observers have reported a phenomenon dubbed “electron-only” reconnection in various magnetic environments (Phan et al., 2018; R. Wang et al., 2018; Stawarz et al., 2019). These observations meet every observational criterion for an EDR except the ion response one might expect in traditional magnetic reconnection (Phan et al., 2018). Two mechanisms have been proposed for this process: low frequency, high amplitude waves (specifically below the lower hybrid frequency; Vega et al., 2020; R. Wang et al., 2018), and the current sheet having a small length (in the L direction) to width (in the N direction) ratio (Mallett, 2020, Pyakurel et al., 2019). However, due to few observations and the disparate nature and rarity of “electron-only” reconnection, a consensus on their origin or nature has not yet been established.
We have surveyed MMS data in the near-Earth magnetotail during Phases 2B and 3B and report on a set of electron-only reconnection observations in the tail current sheet. We examine one case in detail, order three events sequentially by how we believe the process evolves in time and briefly discuss the remaining events. We also analyze ground and satellite data surrounding these events to confirm that electron-only reconnection can occur both before and after traditional ion reconnection. This investigation of electron-only reconnection helps to establish its nature and better understand its role in the dynamics of space plasma.

2. Instrumentation

This paper uses measurements from the MMS mission, a constellation of four identical spacecraft, flying in a tetrahedron formation (Burch et al., 2016). Magnetic field data were obtained at a time resolution of 128 Hz from the Flux Gate Magnetometer (FGM; Russell et al., 2016), and plasma data were obtained at time resolutions of 150 ms (ions) and 30 ms (electrons) from the Fast Plasma Instrument (FPI) (Pollock et al., 2016). Electric field data at a time resolution of 8,192 Hz were provided by the Electric Field Double Probe (EDP; Ergun et al., 2016; Lindqvist et al., 2016). The average spacecraft separation in our 11 events is approximately 25 km. All data in this paper are taken from the MMS2 spacecraft because observations are identical across the four spacecraft and are presented in Geocentric Solar Magnetospheric (GSM) coordinates unless stated otherwise.

3. Observation of Electron-Only Reconnection

On June 17, 2017, from 20:24:00 to 20:24:30, MMS was located at (X: –19.3, Y: –10.3, Z: 5.5) Re (GSM) and crossed the near-Earth plasma sheet from the southern lobe to the northern lobe. The local coordinate system is: L: (0.948,0.315,−0.049), M: (−0.149,−0.304,0.934), N: (0.180,−0.926,−0.330) with respect to GSM coordinates. We determine the normal direction (N) using the four-spacecraft timing method (Russell et al., 1983). The L-direction is the field in the northern lobe averaged with the negative of the field in the southern lobe. The M-component is N × L. FGM Magnetic field (B) and EDP electric field (E) components (Figures 1a and 1d) are averaged to FPI νE cadence. FPI nE is averaged to FPI nE cadence (Figure 1e). Energy conversion (Figure 1h) is calculated using \[ J \cdot E' = E + \nuE \times B \] , where \( J \) is the current density calculated using the FGM curlometer method (\( J = (\nabla \times B) / \mu_0 \)) and \( E' \) uses the four-spacecraft averages of EDP electric field, FPI νE, and FGM magnetic field. We calculate the expected ExB drift velocity (\( \nu_{ExB} \)) using \( \nabla \times B / B^2 \). Electric field data are averaged to magnetic field cadence to perform the calculation, then the resulting vector is averaged to FPI νE cadence. We then compare \( \nu_{ExB} \) to the perpendicular electron velocity (\( \nu_{\perp} \)), which is calculated as \( -\left( (\nuE \times B) \times B \right) / B^2 \). Each time series in Figure 1 is smoothed using a 3-point running average.

This interval displays several criteria for identifying electron-only reconnection. At \( \sim 20:24:07.1 \), when \( B_L \) approaches 0, MMS2 observes an absolute minimum in \( B_{\mu\nu} \) (Figure 1a), a super-Alfvenic \( v_A \) jet (Figure 1c) and no super-Alfvenic \( v_{EL} \) (Figure 1b). The ion Alfven speed (\( v_{AI} \)) is calculated as \( B_0 / \mu_0 m_e n_e \), where \( B_0 \) and \( n_e \) are the magnetic field strength and proton density, respectively, in the lobe region surrounding the current sheet crossing. This system’s geometry generates strong \( B_L \) and \( E_N \) (Figures 1a and 1d). \( n_e \), and \( n_e \) (Figure 1e) are equal within FPI uncertainty, indicating that the electrons are primarily carrying the current (Huang et al., 2018). Far from the current sheet, the parallel electron temperature (\( T_{e\parallel} \)) exceeds the perpendicular electron temperature (\( T_{e\perp} \)) (Figure 1g), but as MMS2 approaches the current sheet center, both directions are energized, and \( T_e \) becomes more isotropic. This is consistent with previously observed EDR crossings during “electron-ion” reconnection in the near-Earth magnetotail (Chen et al., 2019; Li et al., 2019; Zhou et al., 2019). However, the perpendicular ion temperature (\( T_{i\perp} \)) only slightly exceeds the parallel ion temperature (\( T_{i\parallel} \)) (Figure 1f) and does not vary during current sheet crossing. During a typical magnetotail EDR crossing, \( T_{i\parallel} \) significantly exceeds \( T_{i\perp} \) (Zhou et al., 2019). \( J \cdot E' \) (Figure 1h) is significant and positive near the \( B_L \) reversal point and significant and negative far from the current sheet center. Positive and negative \( J \cdot E' \) is consistent with electrons gaining energy from annihilating fields and transferring energy back to fields, respectively (Torbert et al., 2018). This negative-positive-negative \( J \cdot E' \) structure is consistent with an N-direction trajectory through the electron demagnetization region of a reconnecting current sheet (Pucci et al., 2018). Figures 1i–1k compare each component of \( \nu_{\perp} \) and \( \nu_{ExB} \).
Deviation of $v_{E⊥}$ from $v_{E×B}$ close to the current sheet center (20:24:06.7–20:24:07.3) shows that electrons became demagnetized in this region (Torbert et al., 2018). Lastly, MMS2 observed a crescent distribution in the $v_{E⊥1−v_{E⊥2}}$ plane (Figure 1l) and strong wave activity near the lower hybrid frequency in both magnetic (Figure 1m) and electric field (Figure 1n) power spectra. These features suggest that MMS crossed a current sheet supported by electrons inside which electrons were demagnetized and energized due to annihilating magnetic field, but ions were mostly unaffected, justifying the terminology “electron-only reconnection” for this event.

We note that, for this event, MMS’s trajectory was directed primarily in the $N$ direction (G. Q. Wang et al., 2019), which may complicate observation of ion response. However, MMS observes the same features described above during more traditional trajectories in Events #1 & 3 in Table 1 (See supporting materials, Figures SM1 and SM2). This suggests that the lack of ion response is not an artifact of MMS’s trajectory. In addition, past simulation work (Lu et al., 2020) reconstructed this interval using 3D-PIC simulation to support the claim that MMS’s observations are consistent with electron-only reconnection. Specifically, they simulated MMS’s $N$-direction trajectory through the reconnection region during the “electron-only” phase of reconnection, when it was occurring on electron scales. With this model, they successfully reproduced the electron outflow ($v_{E⊥}$) and temperature components ($T_{E⊥,L}$), Hall fields ($E_{L}$) and currents, ion outflow ($v_{E⊥}$), and temperature components ($T_{E⊥,L}$), and $J×E$ profile observed in Figure 1.
| Event Number | Time Interval | CS normal | CS thickness | Normal Vel. | MMS location | ΔTe/ \( mvi_A^2 \) |
|--------------|--------------|-----------|--------------|-------------|--------------|-----------------|
| #            |              | X         | Y           | Z           | [d_e]        | [km/sec]        | X [RE] | Y [RE] | Z [RE] | \( \Delta T_e \) |
| 1            | 7-20-17/09:59-10 | 0.36 | 0.88 | −0.29 | 9.3 | 16.8 | 77 | −21.6 | 7.9 | 1.3 | 0.21 | 0.0011 |
| 2            | 6-17-17/20:24-25 | 0.18 | −0.93 | −0.33 | 10 | 27.2 | 69 | −19.3 | −11.1 | 3.5 | 0.32 | 0.0015 |
| 3            | 6-19-17/09:43-44 | 0.08 | 0.24 | −0.97 | 14.6 | 38.3 | 73 | −20.5 | −2.0 | 3.1 | 0.41 | 0.0026 |
| 4            | 6-13-17/21:09-10 | 0.08 | 0.35 | 0.94 | 86 | 95.6 | 172 | −20.9 | −5.6 | 1.9 | 0.4 | 0.0032 |
| 5            | 7-06-17/05:38-39 | 0.08 | −0.57 | −0.82 | 29 | 56.4 | 31 | −20.7 | 3.3 | 2.7 | 0.23 | 0.0007 |
| 6            | 7-24-17/13:04-05 | 0.22 | −0.79 | 0.57 | 21 | 39.1 | 294 | −18.4 | 1.9 | 5.0 | 0.31 | 0.0043 |
| 7            | 7-26-17/17:39-40 | 0.65 | 0.75 | 0.03 | 72 | 113.2 | 284 | −23.5 | 6.4 | 4.6 | 0.93 | 0.002 |
| 8            | 8-07-17/11:04-05 | 0.07 | 0.47 | 0.88 | 39 | 53.9 | 82 | −19.1 | 6.9 | 2.8 | 0.39 | 0.0014 |
| 9            | 7-23-18/15:04-05 | 0.41 | −0.34 | 0.84 | 8.4 | 4.3 | 10 | −17.4 | 6.1 | 4.4 | 0.35 | 0.0033 |
| 10           | 7-26-18/13:05-06 | −0.58 | 0.73 | −0.36 | 60 | 86.5 | 120 | −18.7 | 7.0 | 4.2 | 0.56 | 0.00049 |
| 11           | 8-01-18/12:58-59 | 0.35 | 0.87 | 0.35 | 40 | 104.3 | 38 | −22.2 | 7.9 | 4.8 | 0.17 | 0.00056 |

Abbreviations: EDR, electron diffusion region; GSM, Geocentric Solar Magnetospheric; MMS, Magnetosphere Multiscale.

Electron thermal gyroradius (\( \rho_{th} = v_T / \omega_e \)) is calculated using magnetic field strength and electron temperature in the lobe region. Event labeled “EDR” indicates MMS magnetotail observation of an EDR during traditional “electron-ion” reconnection. Dominant current sheet normal component is bolded for each event. Bolded Event #’s (Events #1–5) indicate “pre-ion reconnection” electron-only events. Italicized events (Events #1–3) display the time evolution of reconnection onset in Section 4.
4. Magnetotail Survey of Electron-Only Reconnection Events

Using the features described in Figure 1 consistent with Lu et al. (2020), we have identified 10 additional MMS observations of electron-only reconnection in the near-Earth magnetotail. We used the following criteria: (1). Current Sheet Crossing ($B_t$ reversal), (2). Absolute $B_{tot}$ minimum, (3). Lack of ion exhaust jets ($v_{iz} < v_{Aiz}$, no $B_t$ reversal), (4). Super-Alfvenic electron exhaust jets ($v_{iz} > v_{Aiz}$), (5). Lack of total $T_i$ response, (6). Significant $T_i$ energization, (7). Positive $J-E^*$, and (8). Deviation of $v_{iz}$ from $v_{Phas}$. Times and locations of these events are given in Table 1. Events in this paper were found during MMS Phase 2B (June-August 2017) and 3B (June-August 2018), when MMS was in the low-latitude magnetotail with an apogee of $\sim$25 RE. Using the four-spacecraft timing method (Russell et al., 1983) on the $B_t$ measurement, we calculated the current sheet normal orientation and speed (See Table 1). These values are consistent throughout each crossing. We calculate current sheet thickness by multiplying the temporal width (seconds) of each perpendicular current enhancement with each current sheet normal speed in km/sec. This thickness is converted to electron inertial lengths ($d_e$) using the upstream electron number density ($n_e$) $d_e = c*(4\pi n_e e^2/m_e)^{-1/2}$.

An important question is whether electron-only events occur before, after, or independent of traditional "electron-ion" reconnection. Thus, we surveyed MMS satellite data and ground AE index data for traditional "electron-ion" reconnection signatures prior to and following our electron-only observations. We use the following criteria to identify traditional reconnection in MMS data: (1). $B_t$ reversal (current sheet crossing), (2). $B_{tot}$ minimum, (3). super-Alfvenic $v_{iz}$, and (4). $T_i$ increase (ion energization) within 10 min of the electron-only observation. We use the following criterion to identify traditional reconnection in AE Index data: >100% increase in the AE index within 60 min of the electron-only observation. If MMS and AE index observations conflict, MMS observations takes priority because of MMS’s proximity to each electron-only event. Five events displayed traditional reconnection signatures after electron-only events (Events #1–5, See Table 1). These electron-only events will be called "pre-ion reconnection" events throughout the paper. Five events displayed traditional reconnection signatures prior to electron-only events (Events #6–8,10,11, See Table 1). One event showed no traditional reconnection signature before or after (Event #9, See Table 1), indicating that the X-point did not move across MMS or generate a lasting geomagnetic response.

Two-dimensional (2D) projections of each event’s location, current sheet normal velocity, and current sheet thickness (See Table 1) are plotted in Figure 2. In the $XY$ plane, the current sheet center is rotated to account for solar wind aberration due to Earth’s orbit. 2D projections of current sheet normal velocity are presented as arrows whose midpoints are fixed at the event location (Figures 2a and 2b). An arrow’s length and direction indicate a 2D projection of the current sheet normal speed and orientation, respectively. Meanwhile, current sheet thickness during each event is presented as shaded points (Figures 2c and 2d). The shade of each point indicates its current sheet thickness in $d_e$. These events appear in both the dawn and dusk sectors (Figures 2a and 2c), and are all located in positive GSM $Z$ (Figures 2c and 2d). We attribute this to MMS surveying mostly positive GSM $Z$ during Phases 2B and 3B. These events are typically composed of slow ($\leq$200 km/sec) current sheets split evenly in orientation between GSM $Y$ and $Z$ (See Table 1). No current sheets are moving primarily in the GSM $X$ direction. Events range in thickness from sub-ion scale ($\sim$8 $d_e$) to ion scale ($\sim$86 $d_e$), indicating that these thin current sheets need not be sub-$d_e$ to occur.

Lastly, we examine the solar wind and geomagnetic features surrounding “pre-ion reconnection” electron-only reconnection observations to determine if they are typically generated by external solar wind triggering and if they typically produce a significant geomagnetic response. To investigate solar wind features, we propagated WIND satellite data to the Earth’s magnetopause (Lai et al., 2019). We observe southward IMF $B_z$ turning fewer than 2 h prior to three of five events (Events #2,3,5, Figure SM4), suggesting that magnetic flux was being carried to the nightside during these intervals. To investigate ground geomagnetic features, we examined AE index and DST index data from the Kyoto World Data Center for Geomagnetism over the 60 min prior to and following each “pre-ion reconnection” observation. The AE index was perturbed significantly within 60 min after three of our five “pre-ion reconnection” observations (Events #2,3,5, Figure SM4).
We now use three “pre-ion reconnection” electron-only events (Event #1 ($t_1$), Event #2 ($t_2$), and Event #3 ($t_3$) (Yu et al., 2019), italicized in Table 1) and one magnetotail EDR crossing by MMS during traditional “electron-ion” reconnection to describe the time evolution from electron-only reconnection to traditional “electron-ion” reconnection. Specifically, we pose that these three “pre-ion reconnection” events act as snapshots (Events #1, 2, and 3 corresponding to $t_1$, $t_2$, and $t_3$, respectively) displaying a transition from a relatively undisturbed, thin current sheet to a well-developed, traditionally reconnecting current sheet. MMS’s EDR observations were taken from the interval 08-10-2017/12:18-19 (Li et al., 2019; Zhou et al., 2019; see Table 1, row labeled “EDR”). For overview plots of Event #1 and #3 structured identically to Figure 1, see the supporting materials (Figures SM1 and SM2). We argue that these “pre-ion reconnection” events are approximately time stationary because, during Events #2 (2 s) and #3 (6 s), we observe a static current sheet normal speed and symmetric electron velocity profile. We classify these electron-only events as “pre-ion reconnection” events because all three are followed fewer than 10 min later by traditional reconnection. Specifically, MMS observes traditional “electron-ion” reconnection signatures fewer than 10 min following Event #1 ($t_1$) and Event #3 ($t_3$) (See supporting materials, Figure SM3), and the AE Index grows significantly (>100%) fewer than 10 min after Event #2 ($t_2$) (See supporting materials, Figure SM4g). We note that our interpretation of these events (snapshots in the same time-dependent process) is limited, because these observations were made days apart and have no direct causal link. We also note that, in Event #3, there is...
a change in both parallel and perpendicular components of ion temperature, but the total ion temperature does not change significantly.

The electron-only events are thin ($\leq 21\,d_e$), slow ($\leq 100\,\text{km/sec}$) current sheets (Forbes et al., 1981) with varied current sheet normal orientations (two in Y, one in Z). However, to compare the features of these events one-to-one, we convert time to distance from the current sheet center. We calculate the current sheet thickness in $d_e$ by multiplying the perpendicular current’s temporal width by the current sheet normal speed and converting to electron inertial lengths ($d_e = c\sqrt{4\pi ne^2/m_e}^{1/2}T_e$). We first indicated the temporal current sheet center of each event using the time at which $B_{als}$ reached its minimum value. We then converted time separation into $d_e$ the same way we calculated current sheet thickness. The “distance” resolution of each line was then averaged to match the distance resolution of the lowest resolution array. Presenting the data this way allows current sheet properties to be compared one-to-one, regardless of ambient tail conditions or coordinate system.

Event #1 (labeled $t_1$ in Figure 3) displays weak perpendicular electron heating (Figure 3a), displays no ion heating (Figure 3c) and occurs in the thinnest current sheet (Figure 3e). However, as the process develops (Event #2, labeled $t_2$ in Figure 3), $T_{e,1}/T_{i,1}$ and $T_{i,1}/T_{i,2}$ increase far from the current sheet center. $J_e$ width (Figure 3e) and $E_e$ also increase. Eventually (Event #3, labeled $t_3$ in Figure 3), the temperature anisotropy and current sheet thickness of “electron-only” reconnection become consistent with the thickness and anisotropy of well-developed reconnection in the near-Earth magnetotail (Figures 3b, 3d and 3f). Importantly, in the furthest developed example of “electron-only” reconnection (Event #3, $t_3$), $T_{e,1}$ strongly exceeds $T_{i,1}$ close to the current sheet center (Figure 3c). This feature is also seen in well-developed reconnection (Figure 3d). We note that Events #2 and 3 contain a thick ($\sim 20\,d_e$) region close to the current sheet center in which the electrons are isotropic, and Event #3 contains a thin ($<10\,d_e$) region where parallel ion heating surpasses perpendicular ion heating. While the traditional EDR observation also displays these features, they occur in a notably thinner ($<5\,d_e$) region. The process that would reduce the size of this region is a subject for future study.

6. Discussion

During Events #2 (2 s) and #3 (6 s), we observe a static current sheet normal speed and symmetric electron velocity profile. This implies that “pre-ion reconnection” events grow on a timescale that well exceeds 10 s. We also note that Event #3’s current magnitude is significantly weaker than Event #1 and 2’s current magnitudes. However, the electron drift speed strengthens from Event #1 ($t_1$) to Event #2 ($t_2$) to Event #3 ($t_3$).

As electron-only reconnection develops in time, its perpendicular electron crescent (Figures 11 and SM1, SM2) becomes centered at higher energies. In Event #1 (earliest temporal snapshot), when $v_{\perp,1}$ equals zero, the $v_{\perp,1}$ velocity agyrotropy only extends to very low $v_{\perp,1}$ values. However, as time progresses (i.e., Event #2 then Event #3), the $v_{\perp,1}$ agyrotropy appears at greater and greater $v_{\perp,1}$ values. This increase persists when normalizing the crescent speed by the electron thermal speed ($v_{th} = \sqrt{kT_e/m_e}$). This supports that the evolution of the current sheet, not the inflow electron temperature, is responsible for the electron temperature increase. We also observe increases in both $v_{\perp,1}/v_{th}$ and current sheet thickness normalized to $\rho_{th}$ from Events #1–3 (See Table 1, Columns 8, 13). Past simulation work (Pyakurel et al., 2019) reported that increased reconnection exhaust width increases ion response to reconnection. Thus, as reconnection onset develops in time and the reconnection exhaust width thickens, ions start to participate in the reconnection onset process.

Events #1–3 display perpendicular electron heating (Figures 1g, SM1g, SM2g) close to the current sheet center. This indicates that MMS crosses the inflow region during each interval. Oddly, in Figure 3a, Event #1 ($t_1$) displays mild perpendicular electron temperature anisotropy at the current sheet center. This is the only “pre-ion reconnection” event that displays perpendicular anisotropy. Past simulation work (Shuster et al., 2015) has reported that, during symmetric reconnection, in low guide-field EDRs downstream of the X-line, electrons are perpendicularly energized during partial cyclotron orbits driven by local $B_{\perp}$. This cyclotron acceleration process produces strong perpendicular electron heating and temperature anisotropy ($T_{e,\perp}>T_{e,\parallel}$). Thus, we argue that the observed perpendicular electron anisotropy in Event #1 is plausible during electron-only reconnection.
Lastly, given that three events (Events #2,3,5) show coincident southward IMF $B_z$ turning and AE index response, we argue that “pre-ion reconnection” electron-only reconnection is typically generated by external solar wind triggering and can develop into well-developed reconnection that produces a significant geomagnetic response. However, we note that multiple events (Events #1,4) do not display these signatures. This suggests that “electron-only” reconnection is not always triggered by solar wind driving and does not always result in traditional reconnection that produces a significant geomagnetic response. These findings are consistent with past simulation work (Pyakurel et al., 2019) reporting that electron-only reconnection is a transient process that does not necessarily produce global effects on the surrounding plasma.
7. Conclusions

In this study, MMS observed 11 events of “electron-only” reconnection, characterized by a $B_z$ reversal, $B_{int}$ minimum, super-Alfvénic $v_E$, lack of ion response, electron heating, positive $J \cdot E'$, deviation of $v_E$ from $v_{E\bot}$.

Five events occurred prior to traditional reconnection, five events occurred after traditional reconnection, and one occurred with no traditional reconnection signature before or after the event. The thicknesses of these current sheets vary from sub-ion scale to ion scale. Isolating three “pre-ion reconnection” electron-only events, we find that electron-only reconnection develops in time into traditional “electron-ion” reconnection with an increase in parallel electron heating and perpendicular ion heating. This anisotropy eventually reaches the scale seen in well-developed reconnection regions. Over time, these current sheets also increase in thickness. These events’ durations suggest that this process develops on a timescale that well exceeds 10 s. These events can also occur less than 60 min after southward IMF $B_z$ turning and prior to geomagnetic response. Our findings provide evidence that electron-only reconnection occurs in a transient fashion and can contribute to the onset of traditional magnetic reconnection in Earth’s magnetotail.

Data Availability Statement

All MMS data used in this work are available at the MMS Data Center (https://lasp.colorado.edu/mms/sdc/public/).

Acknowledgments

The authors appreciate helpful discussions and suggestions from S. Lu, A. Runov, A. Artemyev, R. Strangeway, and J. Middleton. This research was supported by the NASA Magnetospheric Multiscale Mission, in association with NASA contract NNG04EB99C. The work at UCLA was supported through a subcontract 06-001 with the University of New Hampshire.

References

Burch, J. L., Moore, T. E., Torbert, R. B., & Giles, B. L. (2016). Magnetospheric multiscale overview and science objectives. Space Science Reviews, 199, 5–21. https://doi.org/10.1007/s11214-015-0164-9

Chen, L.-J., Wang, S., Hesse, M., Ergun, R. E., Moore, T., Giles, B., et al. (2019). Electron diffusion regions in magnetotail reconnection under varying guide fields. Geophysical Research Letters, 46, 6230–6238. https://doi.org/10.1029/2019GL082393

Dungey, J. W. (1961). Interplanetary magnetic field and the auroral zones. Reviews of Geophysics, 35, 1–21. https://doi.org/10.1029/RG035i003p000061

Ergun, R. E., Holmes, J. C., Goodrich, K. A., Wilder, F. D., Stawarz, J. E., Eriksson, S., et al. (2016). Magnetospheric multiscale observations across the electron diffusion region in the magnetotail reconnection. Geophysical Research Letters, 43, 5626–5634. https://doi.org/10.1002/2016GL068992

Forbes, T. G., Hones, E. W., Bame, S. J., Ashbridge, J. R., Paschmann, G., Schopke, N., & Russell, C. T. (1981). Evidence for the tailward retreat of a magnetic neutral line in the magnetotail during substorm recovery. Geophysical Research Letters, 8, 261–264. https://doi.org/10.1029/GL008i003p00261

Fu, X. R., Lu, Q. M., & Wang, S. (2006). The process of electron acceleration during collisionless magnetic reconnection. Physics of Plasmas, 13, 012309. https://doi.org/10.1063/1.2164808

Huang, S. Y., Jiang, K., Yuan, Z. G., Sahraoui, F., He, L. H., Zhou, M., et al. (2018). Observations of the electron jet generated by secondary reconnection in the terrestrial magnetotail. The Astrophysical Journal, 862, 144. https://doi.org/10.3847/1538-4357/aac4dc

Lai, H. R., Russell, C. T., Jia, Y. D., & Connors, M. (2019). Magnetized dust clouds penetrating the terrestrial bow shock detected by multiple spacecraft. Geophysical Research Letters, 46, 14262–14268. https://doi.org/10.1029/2019GL085318

Li, X., Wang, R., Lu, Q., Hwang, K.-J., Zong, Q., Russell, C. T., & Wang, S. (2019). Observation of nongyrotropic electron distribution across the electron diffusion region in the magnetotail reconnection. Geophysical Research Letters, 46, 14263–14273. https://doi.org/10.1029/2019GL085014

Lindqvist, P.-Å., Olsson, G., Torbert, R. B., King, B., Granoff, M., Rau, D., et al. (2016). The spin-plane double probe electric field instrument for MMS. Space Science Reviews, 19–4, 137–165. https://doi.org/10.1007/s11214-014-0116-9

Lu, S., Wang, R., Lu, Q., Angelopoulos, V., Nakamura, R., Artemyev, A. V., et al. (2020). Magnetotail reconnection onset caused by electron kinematics with a strong external driver. Nature Communications, 11, 5049. https://doi.org/10.1038/s41467-020-18787-w

Mallet, A. (2020). The onset of electron-only reconnection. Journal of Plasma Physics, 86, 1069. https://doi.org/10.1017/S0022377819000941

Oka, M., Phan, T.-D., Giermatos, M., & Angelopoulos, V. (2016). In situ evidence of electron energization in the electron diffusion region of magnetotail reconnection. Journal of Geophysical Research: Space Physics, 121, 1955–1968. https://doi.org/10.1002/2015JA022040

Phan, T. D., Eastwood, J. P., Shay, M. A., Drake, J. F., Sonnerup, B. U. Ö., Fujimoto, M., et al. (2018). Electron magnetic reconnection without ion coupling in Earth’s turbulent magnetosheath. Nature, 557, 202–206. https://doi.org/10.1038/s41586-018-0091-5

Pollock, C., Moore, T., Jacques, A., Burch, J., Giese, U., Saito, Y., et al. (2016). Fast plasma investigation for magnetospheric multiscale. Space Science Reviews, 199, 331–406. https://doi.org/10.1007/s11214-016-0245-4

Pritchett, P. L. (2001). Collisionless magnetic reconnection in a three-dimensional open system. Journal of Geophysical Research, 106, 25961–25977. https://doi.org/10.1029/2001JA000016

Pucci, F., Usami, S., Ji, H., Guo, X., Horiiuchi, R., Okamur, S., et al. (2018). Energy transfer and electron energization in collisionless magnetic reconnection for different guide-field intensities. Physics of Plasmas, 25, 122111. https://doi.org/10.1063/1.5050992

Pyakurel, P. S., Shay, M. A., Phan, T. D., Matthaeus, W. H., Drake, J. F., Tenhage, I. M., et al. (2019). Transition from ion-coupled to electron-only reconnection: Basic physics and implications for plasma turbulence. Physics of Plasmas, 26, 082307. https://doi.org/10.1063/1.5094034

Russell, C. T., Anderson, B. J., Baumjohann, W., Bronnund, K. R., Dearborn, D., Fischer, D., et al. (2016). The magnetospheric multiscale magnetometers, Space Science Reviews, Dordrecht, 199, 189–236. http://dx.doi.org/10.1007/s11214-014-0057-3

Russell, C. T., Mellott, M. M., Smith, E. J., & King, J. H. (1983). Multiple spacecraft observations of interplanetary shocks: Four spacecraft determination of shock normals. Journal of Geophysical Research, 88, 4739–4748. https://doi.org/10.1029JA088IA00p04739
Shuster, J. R., Chen, L.-J., Hesse, M., Argall, M. R., Daughton, W., Torbert, R. B., & Bessho, N. (2015). Spatiotemporal evolution of electron characteristics in the electron diffusion region of magnetic reconnection: Implications for acceleration and heating. *Geophysical Research Letters*, 42, 2586–2593. https://doi.org/10.1002/2015GL063601

Sonnerup, B. U. Ø. (1979). Magnetic field reconnection. *Solar System Plasma Physics*, 45–108.

Stawarz, J. E., Eastwood, J. P., Phan, T. D., Gingell, I. L., Shay, M. A., Burch, J. L., et al. (2019). Properties of the turbulence associated with electron-only magnetic reconnection in earth’s magnetosheath. *The Astrophysical Journal*, 877, L37. https://doi.org/10.3847/2041-8213/ab21c8

Torbert, R. B., Burch, J. L., Phan, T. D., Hesse, M., Argall, M. R., Shuster, J., et al. (2018). Electron-scale dynamics of the diffusion region during symmetric magnetic reconnection in space. *Science*, 362, 1391–1395. https://doi.org/10.1126/science.aat2998

Vega, C., Roytershteyn, V., Delzanno, G. L., & Boldyrev, S. (2020). Electron-only reconnection in kinetic-Alfvén turbulence. *The Astrophysical Journal*, 893, L10. https://doi.org/10.3847/2041-8213/ab7eba

Wang, G. Q., Zhang, T. L., Wu, M. Y., Schmid, D., Cao, J. B., & Volwerk, M. (2019). Solar wind directional change triggering flapping motions of the current sheet: MMS observations. *Geophysical Research Letters*, 46, 64–70. https://doi.org/10.1029/2019GL080023

Wang, R., Lu, Q., Nakamura, R., Baumjohann, W., Huang, C., Russell, C. T., et al. (2018). An electron-scale current sheet without bursty reconnection signatures observed in the near-earth tail. *Geophysical Research Letters*, 45, 4542–4549. https://doi.org/10.1002/2017GL076330

Yamada, M., Kulsrud, R., & Ji, H. (2010). Magnetic reconnection. *Reviews of Modern Physics*, 82, 603–664. https://doi.org/10.1103/RevModPhys.82.603

Yu, X., Wang, R., Lu, Q., Russell, C. T., & Wang, S. (2019). Nonideal electric field observed in the separatrix region of a magnetotail reconnection event. *Geophysical Research Letters*, 46, 10744–10753. https://doi.org/10.1029/2019GL08538

Zhou, M., Deng, X. H., Zhong, Z. H., Pang, Y., Tang, R. X., El-Alaoui, M., et al. (2019). Observations of an electron diffusion region in symmetric reconnection with weak guide field. *The Astrophysical Journal*, 870, 34. https://doi.org/10.3847/1538-4357/aaf16f