Reconnection with magnetic flux pileup at the interface of converging jets at the magnetopause


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Key points

- Magnetic flux pileup observed upstream of reconnecting current sheet at the interface of converging reconnection jets.
- Magnetic flux pileup accompanied by increase in magnetic shear and decrease in $\Delta \beta$, leading to conditions favorable for reconnection.
- Magnetic flux pileup leads to enhanced available magnetic energy per particle and strong electron heating.
Abstract

We report Magnetospheric Multiscale (MMS) observations of reconnection in a thin current sheet at the interface of interlinked flux tubes carried by converging reconnection jets at Earth’s magnetopause. The ion skin depth-scale width of the interface current sheet and the non-frozen-in ions indicate that MMS crossed the reconnection layer near the X-line, through the ion diffusion region. Significant pileup of the reconnecting component of the magnetic field in this and three other events on approach to the interface current sheet was accompanied by an increase in magnetic shear and decrease in $\Delta \beta$, leading to conditions favorable for reconnection at the interface current sheet. The pileup also led to enhanced available magnetic energy per particle and strong electron heating. The observations shed light on the evolution and energy release in 3D systems with multiple reconnection sites.

Plain Language Summary

The Earth’s and the solar wind magnetic fields interconnect through a process called magnetic reconnection. The newly reconnected magnetic field lines are strongly bent and accelerate particles, similar to a rubber band in a slingshot. In this paper we have used observations from NASA’s Magnetospheric MultiScale spacecraft to investigate what happens when two of these slingshot-like magnetic field lines move toward each other and get tangled up. We found that the two bent magnetic field lines tend to orient themselves perpendicular to each other as they become interlinked and stretched, similar to what rubber bands would do. This re-orientation allows the interlinked magnetic fields to reconnect again, releasing part of the built up magnetic energy as strong electron heating. The results are important because they show how
interlinked magnetic fields, which occur in many solar and astrophysics contexts, reconnect and produce enhanced electron heating, something that was not understood before.

Index Terms

7835 Magnetic Reconnection (2723)
2740 Magnetosphere Configuration
2724 Magnetopause and boundary layers
7859 Transport processes
2784 Solar wind/magnetosphere interactions
1. Introduction

Magnetic reconnection is a universal plasma process that converts magnetic energy into particle energy. The reconnection process has been observed in-situ by spacecraft at the magnetopause, in the magnetotail, in the magnetosheath, and in the solar wind [e.g., Paschmann et al., 2013]. Together, these observations in vastly different regimes show that reconnection occurs for a wide range of plasma conditions. Furthermore, the observations show that the structures and dynamics of reconnection depend strongly on plasma regimes and boundary conditions; such as the strength of the guide field and the degree of asymmetry of the two inflow regions. Thus, for applications of knowledge gained from in-situ observations to various regimes beyond the near-Earth space, it is important to understand how reconnection operates under different conditions.

Recently, the Magnetospheric Multi-Scale (MMS) mission discovered a new region where reconnection takes place, namely at the interface between converging reconnection jets at the dayside magnetopause [Øieroset et al., 2016; Kacem et al., 2018]. Such compressed, thin interface current sheets had been observed at the interface of converging jets prior to MMS [Hasegawa et al., 2010; Øieroset et al., 2011, 2014], but only the high-resolution MMS plasma instrumentation resolves the thin current sheets well enough to show that they were reconnecting. The large-scale structures of converging jet events resemble magnetic islands/flux ropes because of the reversal of the normal magnetic field component and the enhancement of the field magnitude near the center of the events. However, density depletion and open magnetic field topology typically seen in such events are inconsistent with closed field magnetic island configurations depicted in Figure 1j [Øieroset et al., 2011; 2016]. Furthermore, different electron pitch-angle distributions of the converging jets indicate that such structures are not standard flux
ropes, but rather two interlinked flux tubes where the two converging plasmas are not
magnetically connected [Kacem et al., 2018].

The manner in which two tangled flux tubes interact and reconnect is important for
understanding the evolution and energy release in 3D systems with multiple reconnection sites.

In this paper we present a new event in which MMS crossed the ion diffusion region in a
reconnecting current sheet at the interface of interlinked flux tubes carried by two converging
reconnection jets. We also revisit three similar events previously published. We find that
magnetic field pileup on approach to the interface current sheet has important consequences for
both the occurrence of reconnection and the amount of electron heating in these current sheets.

2. MMS instrumentation and orbits

The event was encountered on 2016-12-10 at 04:52 – 04:55 UT, at 12.1 MLT, when the
average inter-spacecraft separation was 6.5 km. We use data from the magnetometer at 128
samples/s [Russell et al., 2014], the fast plasma experiment [Pollock et al., 2016] at 30 ms
resolution for electrons and 150 ms for ions, and the electric field instrument at 8192 samples/s
[Torbert et al., 2014].

3. Large-scale context

Figures 1a-i shows MMS1 observations, in GSE coordinates, of a thin current sheet at the
interface of converging jets at the subsolar magnetopause. A flux rope-like structure was
observed between 04:52 UT and 04:55 UT, with bipolar $B_x$ (Fig.1b) and a large enhancement in
the magnetic field magnitude up to 90 nT (Fig.1a). However, as will be explained below, the
characteristics of the structure indicate that MMS did not encounter a typical flux rope. The
event was observed during an interval of $B_Y$ dominated IMF, with an IMF clock angle near $-90^\circ$ (Section S1, Fig.1k).

Within the structure, there were fast ion flows, mainly in $V_{iz}$, with speeds up to 200 km/s (Fig.1d). $V_{iz}$ reversed from positive to negative near the center of the structure, at 04:53:32 UT. Coincident with the flow reversal, there were sharp changes in the magnetic field components (Fig.1b), indicating the presence of a thin current sheet at the flow reversal. High-speed flow reversals could indicate converging flows from two X-lines, or diverging flows from one X-line [e.g., Hasegawa et al., 2010; Øieroset et al., 2011]. The enhanced magnetic field magnitude at the jet reversal is consistent with the former, but not the latter where one would expect a magnetic field strength minimum. Furthermore, four-spacecraft timing analysis (Section S2) [Schwartz, 1998] indicates that the normal speed of the thin current sheet at 04:53:32 UT was $V_N = -62$ km/s along the current sheet normal $\mathbf{N} = \text{GSE}(0.628, 0.768, 0.125)$, i.e. $V_N = \text{GSE}(-38.9, -47.6, -7.8)$ km/s. The southward (-z$_\text{GSE}$) motion of the current sheet is well illustrated by the order in which the various MMS spacecraft crossed the current sheet along the z direction (Section S2). If the thin current sheet was caused (compressed) by converging jets, it would be reasonable to assume that the converging jet structure moved in the same frame of reference as the thin current sheet. Thus the southward current sheet motion would confirm that the positive-to-negative $V_{iz}$ reversal represents converging rather than diverging jets. Across the thin current sheet there were also significant tangential velocity shears.

The electron pitch-angle distributions (Fig.2m-o) were different on the two sides of the thin current sheet. To the left of the current sheet the 96 eV electrons were predominantly anti-field-aligned, while the 830 eV electron fluxes were higher along the magnetic field. To the right of the current sheet both the 96 eV and the 830 eV electron fluxes were much more intense and
were observed both at 0° and 180° pitch angles. These differences indicate that the two
converging plasmas were not magnetically connected when they approached each other (see also
Kacem et al. [2018] and Øieroset et al. [2011]), i.e., inconsistent with the scenario in Figure 1j.
The unconnected converging field lines could eventually tangle up as illustrated in Figures 1k
and 1l. Similar scenarios have previously been proposed by Nishida [1989], Hesse et al. [1990],
Lee et al. [1993], Otto [1995], Louarn et al. [2004], Cardoso et al. [2013], Perez et al. [2018],
and Kacem et al. [2018]. The interlinked field line scenario and its association with the observed
enhancement/pileup of magnetic field outside the thin current sheet will be discussed in more
detail in section 5.

Inside the thin current sheet, marked by the sharp changes in the magnetic field at ~04:53:32
UT, MMS1 observed enhancements in the ion and electron velocities (Fig.1d,e), large current
densities up to 1.4 μA m⁻² (Fig.1f), ~140 mV/m peak electric field (Fig.1i), and enhanced
electron and ion temperatures (Fig.1g,h). In the next section we show that the converging
reconnection jets created a compressed interface current sheet which itself underwent
reconnection.

4. Detailed MMS1 observations of the interface current sheet

4.1. LMN coordinate system of interface current sheet

Figure 2 shows a close-up of the interface current sheet in boundary normal (LMN)
coordinates, which were determined using a hybrid variance analysis method. The current sheet
normal (N) direction was obtained using timing analysis on the interface current sheet crossings
by the four spacecraft (Section S2). The M direction is from $L' \times N$, where $L'$ is the direction of
maximum variance of the magnetic field [Sonnerup and Cahill, 1967]. Finally, $L = N \times M$. The N
direction from the multi-spacecraft timing analysis, GSE(0.628, 0.768, 0.125), differs from the
direction of the minimum variance of the magnetic field [Sonnerup and Cahill, 1967],
GSE(0.705, 0.699, 0.118), by only 6°.

4.2. Plasma and field profiles in the interface current sheet

The boundary conditions of the interface current sheet were weakly asymmetric, with a
factor of two difference in the inflow plasma densities (Fig.2c). The magnetic shear across the
current sheet was 37°, i.e. the guide field was 3 times the reconnecting magnetic field. The
hybrid inflow ion Alfvén speed based on the two inflow densities and magnetic field \( B_L \) [Cassak
and Shay, 2007] was 274 km/s.

The separatrices, marked by the solid vertical black lines in Figure 2 at 04:53:31.975 UT and
04:53:33:205 UT, were identified based on the electron distributions (Section S5). The crossing
duration of the region bounded by the separatrices was ~1.23 s. Using the current sheet
propagation speed of ~62 km/s along \( N \), the width of the region was ~80 km, or 0.8 ion inertial
lengths (\( d_i \)) where \( d_i = 103 \) km based on the hybrid density in the two inflow regions of 5 cm\(^{-3}\)
[Cassak and Shay, 2007]. The thin \( d_i \)-scale current sheet suggests that MMS crossed the
reconnection layer near the X-line. Indeed, the comparison of the ion and electron perpendicular
velocities with the \( E \times B / B^2 \) velocity (Section S4) reveals that the ions were not frozen-in, while
\( V_{e\perp} \) and \( E \times B / B^2 \) showed good overall agreements, except on fine scales. These findings indicate
that the spacecraft encountered the ion diffusion region, but probably not the electron diffusion
region.

Even though the ions were not frozen-in, there were enhanced ion outflows, \( V_{iL} \), inside the
current sheet, with peak speed of 130 km/s relative to the external flows (Fig.2d). This outflow
speed is substantially lower than the hybrid Alfvén speed of 274 km/s. Interestingly, the
enhanced ion flows extended well outside the separatrices, which may be a characteristic of ion dynamics close to the X-line. Together with the negative to positive $B_M$ variation (relative to the guide field; Fig.2b), which is indicative of the Hall magnetic field pattern [Sonnerup, 1979], the $V_{il} > 0$ jet indicates that MMS crossed the reconnection layer on the left side of the X-line in the reconnection configuration shown in Figure 2p.

Unlike the ion jet, the large electron flows (Fig.2e), high current densities (Fig.2g), large electric fields (Fig.2j), and positive magnetic-to-particle energy conversion in the electron frame of reference, $j\cdot E' = j\cdot(E + V_e \times B)$ (Fig.2l), were mostly confined to the region between the separatrices. The largest electron bulk velocity and current density were observed in the out-of-plane (M) direction, reaching 1600 km/s and 1.4 $\mu$A m$^{-2}$, respectively (Fig.2e,g). $V_{el}$ (Fig.2e,f) was bipolar in the current sheet, with $V_{el}< 0$ (directed toward the X-line and opposing $V_{il}$) near the left separatrix and lasting until ~04:53:32.600 UT, followed by $V_{el}> 0$ (directed away from the X-line). Near the center of the current sheet the enhanced $j\cdot(E + V_e \times B)$ in the current layer was dominated by $j\cdot E_{\parallel}$ (Fig.2l), which is a characteristic of strong guide field reconnection [Genestreti et al., 2017; Wilder et al., 2017; Phan et al., 2018].

The bipolar $E_N$ (Fig.2j) is consistent with the Hall electric field in symmetric reconnection [Shay et al., 1998]. The good agreement between $V_{el}$ and $(E \times B)_L/B^2$ (Fig.2f) indicates that the electron outflows were driven predominantly by the dominant $E_N$ and $B_M$, thus perpendicular to the magnetic field.

Finally, enhancements in the ion temperature and the electron parallel temperature were observed in the reconnection layer (Fig.2h,i).

5. Magnetic field pileup
We now discuss how the occurrence of reconnection and the strong electron heating in the interface current sheet could be associated with magnetic field pileup in its inflow regions. Figures 3a-f display two minutes of observations surrounding the interface current sheet for the event presented above. $B_L$ and $B_M$ increased in magnitude toward the thin current sheet on both sides of the current sheet (Fig.3a,b). The accompanying decrease in density (Fig.3d) indicates that the magnetic pileup process was not adiabatic and that the pileup region may be similar to the plasma depletion layer upstream of the Earth’s magnetopause during northward IMF, where plasma is squeezed out along piled-up magnetic field [e.g., Paschmann et al., 1978; Crooker et al., 1979].

Three previously published events where a thin current sheet appeared at the interface of converging jets are shown in Figures 3g-x, two observed by MMS [Øieroset et al., 2016; Kacem et al., 2018] and one by THEMIS-D [Øieroset et al., 2011]. All four events displayed substantial $B_L$ pileup in the inflow region and enhanced $B_M$. We now explore the causes and effects of the magnetic field pileup.

5.1. Magnetic tension and pressure balance in the converging jet structure

In all four events, the magnetic field pileup led to enhanced magnetic pressure (Figures 3f,l,r,x – red curve, labeled $P_B$) which was only partially compensated for by a decrease in the thermal pressure (blue curve, labeled $P_{th}$). The total pressure (Figures 3f,l,r,x , black curves, labeled $P_{tot}$) here is the sum of magnetic pressure, plasma thermal pressure, and plasma dynamic pressure. Since one would expect the events to roughly be in pressure balance, the non-constant total pressure with a peak near the center of the structure implies that not all significant pressure terms have been included. We now investigate what that missing force term could be.
Strong driving from the converging plasma jets exceeding the reconnection rate at the interface current sheet could in principle lead to the observed magnetic field pileup. However, the dynamic pressure contribution, based on the total plasma speed ($P_V$, green) or $V_N$ alone ($P_{VN}$, pink), was much too small to compensate for the enhanced magnetic pressure, indicating that driving did not play a significant role.

It has previously been shown that an apparent violation of pressure balance across flux transfer events could be due the neglect of the magnetic tension term [e.g., Paschmann et al., 1982]. We now consider whether magnetic tension can balance the enhanced pressure in these events as well. Magnetic tension could be significant when magnetic fields from two unconnected X-lines become interlinked (Fig.1k,l).

The total pressure enhancement from the edge of the structure to its center was $\sim 1.5$ nPa in the 2016-12-10 event (Fig.3f). The enhancement occurred over $\sim 30$ s, which corresponds to $\sim 1800$ km using the estimated propagation speed of the structure of 62 km/s. Thus the total pressure gradient was $\sim 0.8 \times 10^{-15}$ Pa/m.

To check whether the magnetic tension force of the overall structure could balance the pressure gradient, we approximate the tension term $\frac{1}{\mu_0} (\mathbf{B} \cdot \nabla) \mathbf{B}$ by $\frac{1}{\mu_0} \frac{B^2}{r_C}$, where $r_C$ is the radius of curvature for the magnetic field and $B$ is the magnetic field at the edge of the structure (before pileup). Equating $0.8 \times 10^{-15}$ Pa/m to $\frac{1}{\mu_0} \frac{B^2}{r_C}$, and using a pre-pileup magnetic field value of $\sim 50$ nT, $r_C = \sim 2500$ km is obtained. This is comparable to the estimated 1800 km size of the pressure enhancement from the edge of the structure to its center, indicating that the excess pressure can be balanced by magnetic tension associated with interlinked fields.
It should be noted that the local current density (in a structure with $|B| \sim 50$ nT) needed to counter a $10^{-15}$ Pa/m pressure gradient (assuming force balance) is only $0.02\, \mu$A/m$^2$, which is not detectable.

5.2. Magnetic field pileup and the $\Delta\beta$-magnetic shear condition for reconnection

Magnetic field pileup in the inflow region is not commonly observed in reconnection in space. We now examine a possible reason for the occurrence of magnetic field pileup associated with reconnection in the interface current sheet. The analysis below suggests that magnetic flux pileup is required to overcome the suppression of reconnection by diamagnetic drift stabilization [Swisdak et al., 2003; 2010].

For a given magnetic shear $\theta$ across a current sheet, reconnection is allowed (suppressed) if $\Delta\beta$, the difference in plasma $\beta$ in the two inflow regions, satisfies (does not satisfy) the following relation:

$$\Delta\beta < \left( \frac{L}{\lambda_i} \right) \tan \left( \frac{\theta}{2} \right)$$  \hspace{1cm} (1)

where $L/\lambda_i$ is the width of the current sheet in units of ion skin depth $\lambda_i$ [Swisdak et al., 2010].

The relation is shown in Figure 4a for $L/\lambda_i = 1$ (solid curve), which best described solar wind [Phan et al., 2010] and magnetopause reconnection events [Phan et al., 2013a].

Figure 4a also shows the observed $\Delta\beta$ and magnetic shear before (circles) and after (squares) pileup for the four events in Figure 3. The before/after times are marked in Figure 3 with pairs of blue/green vertical lines. In all four events the conditions changed from reconnection being suppressed (i.e. below the curve in Figure 4a) before pileup, to reconnection being allowed (above the curve) after pileup. Interestingly, the magnetic field pileup on approach to the center of the structures is associated with both an increase in magnetic shear and a decrease in $\Delta\beta$.

These results suggest that magnetic field pileup was necessary for the interface current sheet to
reconnect. The increasing magnetic shear, which did not exceed 90° in any of the events, suggests that as field lines tangle up, they tend to rotate to become more perpendicular to each other, as illustrated in Figure 11.

5.3. Magnetic field pile up and electron heating

A striking feature of the reconnecting interface current sheet is the large parallel electron temperature relative to the surrounding plasma (Fig.3e,k,q). There was no perpendicular electron heating, consistent with previous observations and simulations of strong guide field reconnection [e.g., Phan et al., 2013b; Shay et al., 2014].

In an earlier statistical study of electron heating in reconnection exhausts at the magnetopause [Phan et al., 2013b], it was found that the degree of electron heating, $\Delta T_e$, is proportional to the available magnetic energy per particle, $m_i V_{AL}^2$ (see also Shay et al. [2014]; Haggerty et al., [2015]):

$$\Delta T_e = 0.017 m_i V_{AL,\text{hybrid}}^2 \quad (2)$$

where $m_i$ is the ion mass and $V_{AL,\text{hybrid}}$ is the hybrid inflow Alfvén speed [Cassak and Shay, 2007] based on the asymmetric inflow magnetic field $B_L$ and densities. This empirical relation is plotted in Figure 4b (black line).

In the 2016-12-10 event the average total electron heating in the current sheet was $\Delta T_e = 1/3(\Delta T_{e\parallel} + 2\Delta T_{e\perp}) \sim 8$ eV. The green vertical lines in Figure 3a-f mark the edges of the current sheet, which for this event were located outside the separatrices, a characteristic of the diffusion region [Phan et al., 2016]. In the 2015-10-31 event, $\Delta T_e$ was 6 eV, and in the 2015-11-07 event, it was 43 eV. In the 2010-10-06 THEMIS event electron heating in the current sheet was not resolved. Using the conditions immediately upstream of the interface current sheet, the hybrid
inflow Alfvén speed for the three MMS events was 274 km/s for the 2016-12-10 event, 200 km/s for the 2015-10-31 event, and 515 km/s for the 2015-11-07 event. Using these values the observed electron heating versus the available magnetic energy for the three MMS events (Fig.4b) are in reasonable agreement with the empirical relation (2) for magnetopause reconnection exhaust heating.

Finally, we note that the inflow region has been significantly affected by the magnetic field pileup in these events. In the 2016-12-10 event $|B_L|$ (Figure 3a) increased by at least a factor of 5 (from $\sim$5nT to 30 nT and 25 nT) from the pre-pileup region (blue vertical lines) to the region immediately upstream of the interface current sheet (green vertical lines). At the same time the density decreased. As a result the hybrid inflow Alfvén speed increased by a factor of $\sim$7, from $\sim$40 km/s to $\sim$274 km/s, and the available magnetic energy, $m_i V_{AL}^2$, increased by a factor of 49. In the two other MMS events (Fig.3g-r) the available magnetic energy increased by a factor of 100 and 49, respectively. Thus the electron heating in these reconnection events, predicted to be proportional to the available magnetic energy in the inflow regions immediately adjacent to the current sheet, was substantially (50-100 times) higher than it would have been without flux pileup. On the other hand, the degree of electron heating in these three events, as well as their dependence on the available magnetic energy, are similar to magnetopause reconnection events without pileup, suggesting that the electron heating physics associated with flux pileup reconnection is not that different from non-pileup reconnection.

6. Summary
We have presented a new MMS event of reconnection in a thin current sheet at the interface of converging reconnection jets and re-examined three previously reported events. We summarize the main findings here:

(1) The ion skin depth-scale width of the interface current sheet and the non-frozen-in ions indicate that MMS crossed the reconnecting interface current sheet near the X-line, in the ion diffusion region.

(2) The electron pitch-angle distributions indicate that the two converging plasmas were not magnetically linked. The large-scale structure of these converging jet events is therefore not consistent with regular flux ropes. They are more consistent with interlinked flux tubes emanating from two X-lines (Figure 1k,l).

(3) Magnetic field pileup was observed on both sides of the interface current sheet and was associated with enhanced magnetic pressure that was not balanced by the thermal or dynamic pressure. We revisited three previously published converging jet events and found similar flux pileup in those events. The enhanced magnetic pressure in these events could be balanced by the magnetic tension, i.e. the magnetic field pileup arises from the effect of interlinking of the magnetic flux tubes, which may not reconnect at first.

(4) The pileup of magnetic flux is associated with an increase in the magnetic shear and a decrease in $\Delta\beta$. This evolution changed the inflow conditions from reconnection being suppressed before pileup to reconnection being allowed after pileup, leading to favorable conditions for reconnection in the interface current sheet.

(5) The magnetic field pileup in the inflow region also significantly enhances the available magnetic energy per particle, and leads to strong electron heating in the interface current sheet.
These findings reveal interesting reconnection onset physics associated with tangled-up flux tubes, a phenomenon that should be common in multiple X-line reconnection scenarios with strong guide fields. At the magnetopause these structures could play a role in flux transfer event formation when the IMF has a significant east-west component, as seen in some global MHD simulations [e.g., Cardoso et al., 2013; Perez et al., 2018].

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Figure 1. (a)-(i) MMS1 observations of the large-scale context of the event, in GSE. The interval of enhanced magnetic field and converging jets is marked with the horizontal double-arrow. (a,b) Magnetic field magnitude and components, (c) ion and electron densities, (d) ion velocity, (e) electron velocity, (f) current density calculated using plasma data, \( j = e N_e (V_i - V_e) \), (g) electron temperature, (h) ion temperature, (i) electric field. (j) 2D cartoon illustrating two converging reconnection jets forming closed magnetic loops, a scenario that is inconsistent with the electron pitch angle data (see Figure 2), (k) 3D sketch showing how non-simultaneous reconnection at two locations at the magnetopause (first at ‘1’ and then at ‘2’) can lead to converging plasma jets and interlinked flux tubes, (l) interlinked flux tubes forming a thin interface current sheet.

Figure 2. Detailed MMS1 observations of the interface current sheet in LMN, with \( L = \text{GSE}(-0.731, 0.530, 0.416) \), \( M = \text{GSE}(0.253, -0.352, 0.894) \), and \( N = \text{GSE}(0.628, 0.768, 0.125) \). (a) magnetic field components (\( B_M \) shifted by -45 nT), (b) out-of-plane magnetic field \( B_M \), (c) ion and electron densities, (d) ion velocity, (e) electron velocity, (f) \( V_{il}, V_{el} \), and \( (E \times B/B^2)_l \), (g) current density \( j = e N_e (V_i - V_e) \), (h) electron temperature, (i) ion temperature, (j) electric field, (k) \( E_M \) and \( E_{\parallel} \), (l) \( j \cdot E' = j \cdot (E + V_e \times B) \), (m)-(o) electron pitch angle spectrograms for 96 eV, 484 eV, and 830 eV electrons, (p) conceptual sketch of the 2D projection of the magnetic field in the interlinked 3D structure (Fig.1k,l) in the L-N plane, with a close-up of the interface current sheet and a possible MMS trajectory. Different energy flux intensity and pitch-angle behavior to the left and to the right of the current sheet indicate that the two inflow regions are not magnetically
connected. The vertical solid lines in (a)-(o) mark the separatrices (see Section S5). The vertical
dashed line marks $B_L=0$.

Figure 3. Presence of significant magnetic flux pileup in four reported converging jet events. (a-f) The 2016-12-10 MMS event presented in detail in this paper. (a,b) reconnecting and out-of-plane component of the magnetic field, (c-e) $V_i$, electron density, and electron temperature, (f) total, magnetic, thermal, and dynamic pressure based on total $V$ and $V_N$. (g-l) The 2015-10-31 MMS event [Øieroset et al., 2016]. The panels are the same as in a-f. (m-r) The 2015-11-07 MMS event [Kacem et al., 2018]. The panels are the same as in a-f. (s-x) The 2010-10-06 THEMIS event [Øieroset et al., 2011, 2014]. The panels are the same as in a-f. The blue and green vertical lines indicate times of pre-pileup and post-pileup of the magnetic field.

Figure 4. (a) Magnetic shear vs. difference in $\beta$ on the two sides of the interface current sheet, before pileup (circles) and after pileup (squares) for the four events in Figure 3. The theoretical curve from (1) for $L=1$ is also plotted. (b) Electron heating in a reconnecting current sheet as a function of available magnetic energy per particle immediately upstream. The black line shows the empirical relation from Phan et al. [2013b], and the circles the three MMS events in Figure 3.
Figure 1.
Figure 2.
High density inflow

Low density inflow

MMS

Bguide

Hall

High density inflow

Low density inflow

MMS

Bguide

Hall
Figure 4.
\[ \Delta \beta = \tan\left(\frac{\theta}{2}\right) \]

\[ \Delta T_e = 0.017 m_i V_{A,L,\text{hybrid}}^2 \]