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Key Points:
• First in situ observation of secondary reconnection diffusion region beside ion-scale flux rope at the magnetopause is reported
• The observation provides further evidence for the creation and evolution of flux ropes in the reconnection exhaust region

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Abstract Using high-resolution data from Magnetospheric Multiscale (MMS) mission, we report an in situ observation of a secondary reconnection electron diffusion region (EDR) beside the leading edge of an ion-scale flux rope at the magnetopause. This reconnection EDR is characterized by strong electron current and electron jet reversal, a normal Hall electric field, unmagnetized electrons with non-gyrotropic distributions, a large parallel electric field, and strong energy dissipation. The ion-scale flux rope beside the EDR consists of a force-free structure with diameter of only ~3 ion inertial lengths. Our observation of secondary reconnection beside the flux rope gives further evidence that flux ropes can be created and evolved in the reconnection exhaust region.

Plain Language Summary Small-scale flux transfer events (FTEs), characterized by a helical flux rope structure, play a significant role in the macroscopic and microscopic physical process during magnetic reconnection at the magnetopause. Although they are widely observed at the magnetopause boundary layer, the mechanisms of generation and evolution remain an open question. In this letter, we report in situ observation of a secondary reconnection region beside the leading edge of a small-scale FTE, and thus, our work could contribute to understanding the relation between flux ropes and magnetic reconnection at the magnetopause.

1. Introduction
Flux transfer events (FTEs) (Russell & Elphic, 1978) are the flux ropes caused by unsteady reconnection at the magnetopause region, allowing the transportation of solar wind into the terrestrial magnetosphere (Paschmann et al., 1982). In addition to the initial “elbow-shaped” model by patchy reconnection (Russell & Elphic, 1978), several models based on MHD simulations and theoretical models have now be proposed, including the bursty, single X-line reconnection model (Scholer, 1988; Southwood et al., 1988); the flow vortex-induced reconnection model (Liu & Hu, 1988; Pu et al., 1990), and the multiple reconnection model (Lee & Fu, 1985; Raeder, 2006). These models are widely used in observations to typical spatial FTEs scales of 1–2 R_E, where R_E represent the earth radii (e.g., Fear et al., 2008; Hasegawa et al., 2010; Øierset et al., 2011; Pu et al., 2013; Zhang et al., 2011).

Due to the high-resolution plasma data and small separation of the four spacecraft Magnetospheric Multiscale (MMS) mission (Burch et al., 2016), the detailed plasma and field structure of ion-scale flux rope FTEs have been investigated for the first time (e.g., Alm et al., 2018; Dong et al., 2017; Eastwood et al., 2016; Hwang et al., 2016; Teh et al., 2017; Zhao et al., 2016). The formation mechanism of these ion-scale flux rope and its relationship with typical size FTEs are still outstanding questions. From particle-in-cell simulation results, ion-scale flux rope can be created by secondary reconnection due to an instability of the reconnection current sheet (Daughton et al., 2009; Drake et al., 2006). Recently, the results from 3-D simulations show that flux ropes can be created by secondary reconnection in the exhaust of the primary reconnection site (Lapenta et al., 2015). Secondary reconnection regions present in the outflow region of a primary X-line have been observed in the magnetotail (Huang et al., 2018; Wang et al., 2014), while no evidence has been found...
at the magnetopause. Dong et al. (2017) found a series of evolving flux ropes in the reconnection exhaust region with size increasing from several ion-scales to the mesoscale. However, secondary reconnections required for their magnetic flux growth were not directly observed.

In this letter, we show a direct observation of a secondary reconnection region beside the edge of a flux rope, which provide further evidence that flux ropes can be created and then evolve through the operation of secondary reconnection in the exhaust region. This reconnection region is characterized by strong electron current and electron jet reversal, electron crescent distributions, a large parallel electric field, and strong energy dissipation. The magnetic field, plasma data, and electric field are from Fluxgate Magnetometer (Russell et al., 2016), Fast Plasma Investigation (Pollock et al., 2016), and Electric field Double Probe (Ergun et al., 2016; Lindqvist et al., 2016) on board MMS, respectively.

2. Observation

We present MMS observations on 12 December 2017. During this magnetopause crossing, the MMS spacecraft is located around (9.6, −2.8, −0.2) Re in Geocentric Solar Ecliptic coordinates. We establish a boundary normal coordinate using minimum variance analysis (MVA) on the magnetic field data taken from 17:15:10–17:15:28 UT and find stable maximum, medium, and minimum directions as: \( L = \left(-0.05, -0.33, 0.94\right) \), \( M = \left(-0.18, -0.92, -0.34\right) \), and \( N = \left(0.98, -0.19, -0.02\right) \) in Geocentric Solar Ecliptic coordinates, respectively. Figure 1 shows that the MMS spacecraft are initially in the magnetosphere (MSP), characterized by a stable, northward magnetic field and low plasma density (Figures 1a and 1c). When exiting into the magnetosheath (MSH), the magnetic field was southward, and the plasma density was around 25 cm\(^{-3}\). The shear angle between MSP and MSH is about 152° with a negative \( B_M \sim 10 \) nT, which corresponds to a guide field of ~20%. From 17:15:00 UT, plasma densities begin to increase (Figure 1c) with bistreaming electron distributions in the parallel and antiparallel directions (Figure 1k) and an ion jet in \( L \) and \( M \) directions. This kind of bistreaming electrons usually appears in the inflow region near the reconnection X-line (Egedal et al., 2011). The direction of the ion jet in \( L \) and \( M \) directions is consistent with intrusion of the ion outflow jet into the MSP inflow region and the finite ion Larmor gyroradius effect of overshot MSH ions in the inflow region near the X-line (Shay et al., 2016). The above features at the MSP side are clear different from the typical low latitude boundary layer further downstream of the X-line (e.g., Dong et al., 2019). These features, in conjunction with the negative ion jet \( V_L \) throughout the magnetopause region, indicate that this MMS crossing region is south of, but not far from the X-line. This is consistent with the result of Maximum Magnetic Shear model (Trattner et al., 2007a, 2007b) which is shown in the Figure 3a. We identify the MSP boundary of the reconnection layer (electron edge) around 17:15:16.3 UT (blue vertical dashed line), characterized by the strong electric current density, large positive normal electric field \( E_N \), and decrease of electron parallel temperature (Pritchett, 2008). The MSH boundary of reconnection layer (red vertical dashed line) on the other side is characterized by a decrease of the electron perpendicular temperature and a change in the electron distribution from approximately isotropic to bistreaming (Lavraud et al., 2016). Inside the reconnection boundary layer, two flux ropes, characterized by bipolar normal magnetic field \( B_N \) and enhanced \( B_\| \) and total pressure (Figures 1b and 1d), are observed (around 17:15:20.4 UT and 17:15:21.9 UT), and we will focus on the first one between the two vertical dotted line. We see that strong current densities exist, both around the center (~3,000 nA/m) and beside the leading edge (~5,700 nA/m) of the flux rope structure. Current structure around the center of two flux ropes shows a similar bifurcated feature with the observation in Dong et al. (2017). Such strong current densities in the flux rope are relatively rare and may indicate that it is still highly dynamic (Huang et al., 2019). The strong current beside the leading edge of flux rope is associated with secondary magnetic reconnection region which we will focus on below.

Figure 2 shows the detailed plasma and field characteristics zoomed in around the flux rope in a 2 s interval (magenta mark in Figure 1). Due to the irregular structure within the four spacecraft tetrahedron, with MMS4 further away from the other three, this flux rope signature (bipolar \( B_N \) structure with enhanced core field) is only observed by MMS4, meaning that multiple spacecraft analysis methods are not applicable (i.e., Curlometer and Timing). There is a dominant, parallel current during the flux rope region, indicating the force-free (\( j \times B = 0 \)) nature of the structure (Figure 2c). Thus, the medium variance direction of MVA on magnetic field can best fit the axial orientation of flux rope (Xiao et al., 2004). Here the axis direction based on the MVA method on the center region of the flux rope is \( (-0.36, 0.92, -0.16)_{LMN} \) and is approximately...
consistent with the predicted orientation of the X-line (0.11, 0.99, 0)LMN by \( \mathbf{N} \times (\mathbf{B}_{\text{MSP}} - \mathbf{B}_{\text{MSH}})/|\mathbf{N} \times (\mathbf{B}_{\text{MSP}} - \mathbf{B}_{\text{MSH}})| \) (Sonnerup, 1974). To estimate the velocity of the flux rope, we use the Hoffmann-Teller (HT) analysis (Sonnerup et al., 1987) on electron velocity and magnetic field data during the flux rope time interval (17:15:20.04–17:15:20.71 UT). The calculated HT velocity \( \mathbf{V}_{\text{HT}} = (-259, 110, -25) \pm (29, 35, 24) \text{ km/s} \) in LMN coordinates (fitted with a slope = 1.00 and cc = 0.82). With a component of above \( \mathbf{V}_{\text{HT}} \) onto the crossing section of the flux rope (202 ± 48 km/s) and the duration of 0.66 s, the calculated size of the flux rope is 134 ± 32 km ~ 3\( d_i \) (the magnetosheath density ~25 cm\(^{-3} \) corresponding to ion inertial length \( d_i = 43 \) km). The result confirms that this is a typical ion-scale flux rope.

Let us now focus on the strong current region beside the leading edge of the flux rope (cyan shaded region in Figure 2). Evidence of an electron diffusion region (EDR) encountered in this interval is strongly indicated.
by the following evidence. During this time interval, an intense positive electron jet $V_{el}$ up to 1,626 km/s is observed, within an order of magnitude of the electron Alfvén speed (approximately 4,700 km/s). The magnetic field component $B_{d}$ is negative initially and turns positive for a short time around 17:15:20.026 UT. Corresponding to this reversal, the normal electric field component, $E_{N}$, turns from negative to positive (Figure 2h), which is consistent with a Hall electric field pointing to the center of the reconnection current sheet. The above signatures indicate that MMS4 has crossed the neutral line of the reconnection current sheet. The electron jet, $V_{el}$, decreases from $-971$ to $-108$ km/s (Figure 2c).
can indicate a velocity reversal from negative to positive if we consider a negative background velocity (~−400 km/s) of the entire structure and this change corresponds to crossing from southward of the X-line to northward. Figures 2f–2h show the comparison between direct measurement of electric field and the convection term \(-V \times B\). Indeed, the deviation of \(E\) and \(-V_e \times B\) in the L and M components indicates that the electrons are unmagnetized during this interval. These unmagnetized electrons, with the parallel electric field (Figure 2i) and parallel current (Figure 2e), lead to a large, positive, non-ideal energy conversion \(j \cdot E'\), where \(E' = E + V_e \times B\) is the electric field in the electron frame. The \(j \cdot E'\) reaches up to +40 nW/m\(^3\) as seen in Figure 2j, implying conversion of field energy into plasma energy (Zenitani et al., 2011). Furthermore, Figure 2k shows the scalar agyrotropy index \(\sqrt{Q}\) as defined by Swisdak (2016), and we see an enhancement of \(\sqrt{Q}\) of up to 0.07 during this interval, which is a clear indication of agyrotropy.

Below the time series, Figures 2l–2o display two 2-D cuts of the electron velocity distribution functions at 30 ms intervals in the plane parallel and perpendicular to the magnetic field. The electron crescent distribution in the parallel plane appears first at 17:15:19.996 UT (Figure 2l) and then in the perpendicular plane at 17:15:20.026 UT (Figure 2o). This type of distribution has recently been explained as resulting from mean-dering electron motion within the electromagnetic field structure of the EDR (Burch et al., 2016; Egedal et al., 2016; Hesse et al., 2014).

3. Summary and Discussion

In this letter, we present a direct observation of an unmagnetized electron signature, beside the leading edge of an ion-scale flux rope FTE observed by MMS, which we interpret as evidence of a secondary reconnection EDR. The whole magnetopause crossing process is presented schematically in Figure 3b: (1) Before crossing the MSP boundary of the reconnection layer, bistreaming electrons, a finite ion Larmor gyroradius effect of overshoot MSH ions, and a clear intrusion of the ion outflow jet into the MSP inflow region indicate that the spacecraft is located downstream but not far from primary X-line. (2) Then the MMS spacecraft cross the MSP boundary (electron edge), characterized by positive \(E_n\) and strong current, and enter into the reconnection exhaust region with southward ion outflow. (3) Before the spacecraft encounters the ion-scale flux rope, a secondary reconnection EDR is observed by MMS4, which is characterized by strong electron current and electron jet reversal, a normal aligned Hall electric field, an unmagnetized electron population with crescent distribution, a large parallel electric field, and strong energy dissipation. (4) Beside the EDR, a flux rope with...
a force-free structure and a scale size of approximately 3d, was observed. Subsequently, MMS crosses the MSH boundary of reconnection layer and enters into the MSH.

Flux ropes of different scales are commonly observed in the magnetopause boundary layer. Our in situ observation of secondary reconnection beside a flux rope provides the opportunity to better understand the creation and evolution of the flux rope in the exhaust region (Dong et al., 2017). In simulations, flux ropes can either be created around the primary reconnection region due to an instability of the current sheet (e.g., Drake et al., 2006) or created in the exhaust region directly (Lapenta et al., 2015). Our observation here supports the view that flux ropes can be created and evolve in the reconnection exhaust region. We cannot exclude the possibility that flux ropes are created around the primary reconnection region, however, and are ejected from this with the reconnection outflow. In this case, secondary reconnection in the exhaust region can still explain the evolution of its size and magnetic flux.

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