Electron-only Reconnection in an Ion-scale Current Sheet at the Magnetopause

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Abstract

In the standard model of magnetic reconnection, both ions and electrons couple to the newly reconnected magnetic field lines and are ejected away from the reconnection diffusion region in the form of bidirectional burst ion/electron jets. Recent observations propose a new model: electron-only magnetic reconnection without ion coupling in an electron-scale current sheet. Based on the data from the Magnetospheric Multiscale (MMS) mission, we observe a long-extension inner electron diffusion region (EDR) at least 40 $d_i$ away from the X-line at the Earth’s magnetopause, implying that the extension of EDR is much longer than the prediction of the theory and simulations. This inner EDR is embedded in an ion-scale current sheet (the width of $\sim 4 d_i$, $d_i$ is ion inertial length). However, such ongoing magnetic reconnection was not accompanied with burst ion outflow, implying the presence of electron-only reconnection in an ion-scale current sheet. Our observations present a new challenge for understanding the model of standard magnetic reconnection and the electron-only reconnection model in an electron-scale current sheet.

Unified Astronomy Thesaurus concepts: Magnetic fields (994); Solar magnetic reconnection (1504); Plasma astrophysics (1261); Plasma physics (2089); Space plasmas (1544)

1. Introduction

Magnetic reconnection is a widespread important physical process that allows the rapid energy conversion of magnetic field into the plasmas, resulting in the particle’s acceleration/heating and the changing of magnetic field topology (Priest & Forbes 2000; Yamada & Ji 2010). Magnetic reconnection is frequently observed or thought to play a major role in the astrophysical and space plasmas, such as solar flares, solar and stellar coronae, solar wind, the planetary magnetosphere, the interplanetary space, the interstellar medium, neutron stars, accretion disks, astrophysical jets, galaxy clusters, and black holes (Priest & Forbes 2000; Øieroset et al. 2001; Deng & Matsumoto 2001; Lin et al. 2005; Vaivads et al. 2004; Huang et al. 2010; Yamada & Ji 2010). The crucial region of magnetic reconnection can be divided into an ion diffusion region (IDR) where the ions are demagnetized and an electron diffusion region (EDR) where both the ions and the electrons are demagnetized due to the different mass between the ion and the electron. Around or in the diffusion region, the significant phenomenon is the Hall effect that includes Hall currents, the bipolar Hall electric field pointing toward the center of the current sheet, and the Hall quadrupolar out-of-plane magnetic field because of the relative motion between the ions and the electrons (Priest & Forbes 2000; Øieroset et al. 2001; Deng & Matsumoto 2001; Lin et al. 2005; Vaivads et al. 2004; Huang et al. 2010, 2012; Yamada & Ji 2010). EDR, which is embedded in the ion diffusion region, can extend several $d_i$ along the outflow direction and develop two substructures, i.e., inner EDR and outer EDR. The inner EDR containing the X-line is the core region during the magnetic reconnection, which features intense electron currents, non-zero $E' = E + V_e \times B$, electron nongyrotropy or electron crescent distribution, super-Alfvénic electron flow, and electron dissipation $J \cdot E' > 0$, etc. (Zenitani et al. 2012; Hesse et al. 2013), while the outer EDR can extend tens of $d_i$ (where $d_i$ is ion inertial length) along the outflow direction, where the electrons remain decoupled from the magnetic field and form a super-Alfvénic outflow jet, electron nongyrotropy, strong electron currents, and $J \cdot E' < 0$ (Zenitani et al. 2012; Le et al. 2013).

The inner EDR has recently been in situ identified at the terrestrial magnetopause and in the magnetotail by the unprecedented high-resolution measurements from the Magnetospheric Multiscale (MMS) mission (Burch et al. 2016; Zhou et al. 2017, 2019; Huang et al. 2018; Torbert et al. 2018; Fu et al. 2019). The outer EDR, with energy conversion from the particles to the fields ($J \cdot E' < 0$), has been identified in the magnetosheath (Phan et al. 2007), in the magnetotail (Zhou et al. 2014), and at the magnetopause (Hwang et al. 2017). We should point out that such an outer EDR is only an electron jet with the violation of electron frozen-in condition and has a negative $J \cdot E'$. Recently, an EDR with positive energy dissipation ($J \cdot E' > 0$) extended 20 $d_i$ away from the X-line embedded in the burst ion outflow was reported in the downstream of magnetic reconnection at the magnetopause (Zhong et al. 2020).

Recent studies have presented reconnection with the burst of electron jets, but no ions were accompanied at the turbulent magnetosheath (Phan et al. 2018) and quasi-parallel shocks (Gingell et al. 2019; Wang et al. 2019), which challenges the standard model of EDR in the reconnection that the ions are ejected away from the diffusion region in the form of burst ion jets in the downstream. It is revealed that the electron-scale current sheet could also produce turbulent energy transformation and dissipation without ion participation during magnetic reconnection (Phan et al. 2018).

In this study, we report a textbook inner EDR emerging in an ion-scale current sheet (the thickness up to 4 $d_i$) at the magnetopause boundary layer, which is characterized by super-
Alfvén electron jet, electron nongyrotropy, and positive energy dissipation in a clear parallel electric field. This EDR with a thickness of $\sim 0.53 \, d_i$ is extended about 40 $d_i$ away from the X-line in the downstream of magnetic reconnection but without a burst ion outflow. Our observations demonstrate a new feature of reconnection in space, i.e., electron-only reconnection in the ion-scale current sheet, which is different from the traditional magnetic reconnection model, and challenges the previous observations as well.

2. Event Overview

The overview observations from 13:31:10 to 13:34:00 UT on 2015 September 7, when the MMS was located at $\sim [3.85,$
The magnetic field measured by the fluxgate magnetometer (FGM) instrument (Russell et al. 2016), the electric field from the electric double probe (EDP) instruments (Lindqvist et al. 2016), and the particle data measured by the fast plasma investigation (FPI) instrument (Pollock et al. 2016) on board MMS in burst mode are used in this study. MMS traveled through the first magnetosphere (positive $B_z$ in Figure 1(a), low-speed plasma flow, high temperature, and low density in Figures 1(b)–(e)), then crossed the magnetopause boundary layer, and finally entered the magnetosheath (negative $B_z$ in Figure 1(a), high-speed flow, low temperature, and high density in Figures 1(b)–(f)). These two black dashed lines mark the magnetopause boundary layer that is characterized by the mixed particles: high-energy particles from the magnetosphere and low-energy particles from the magnetosheath (Figures 1(g) and (h)). One reconnecting current sheet marked by yellow shading has the most intense
current density (Figure 1(i)), up to ~2 μA/m², which will be investigated in the rest of the paper.

Figure 2 displays the detailed observations of the current sheet from 13:32:26 UT to 13:32:28 UT. All vectors are presented in the LMN coordinate system derived by the minimum variance analysis (MVA; Sonnerup et al. 1998), where the L direction is along the magnetic field line trend, N points to the inflow direction, and the M component completes the orthogonal coordinate system. Three uniform vectors of LMN coordinates in GSE coordinates, are \( L = [0.206, -0.216, 0.955] \), \( M = [0.089, -0.975, -0.202] \), and \( N = [0.975, 0.043, 0.220] \), respectively. This crossing of the current sheet embedded in steady ion flow (Figure 2(b)) is characterized by the reversal of \( B_L \) from positive to negative (Figure 2(a)), accompanied by a bipolar signature of the \( B_M \) component relative to the guide field (\( \sim -8 \) nT; Figure 2(a)), the tripolar signature of the current \( J_L \) component (Figure 2(d)), large fluctuations in electron velocity (Figure 2(c)), and the intense electric field (Figure 2(e)). Combining the tripolar variation in \( J_L \) and the bipolar variation in \( B_M \), one can infer that MMS detected one reconnection diffusion region with the well-known Hall current and the Hall quadrupolar out-of-plane magnetic field (small guide field \( \sim -8 \) nT here). Due to the large convective ion flow \( V_i \), the convection term will dominate the electric field. Thus, the convective term \( V_i \times B \) removed from the electric field \( E_N \), i.e., \( (E + V_i \times B)_N \) is shown in Figure 2(f). One can see that \( (E + V_i \times B)_N \) has a bipolar variation from positive to negative, except one small pulse during the crossing of the current sheet, indicating that \( (E + V_i \times B)_N \) points toward the center of the current sheet. We also calculate the different terms of the general Ohm’s law. It can be seen that Hall term \( (J \times B)_N \) can well balance the

Figure 3. EDR successively observed by four MMS spacecraft. (a) \( L \) component of magnetic field. (b) Energy dissipation \( J \cdot E' \). (c)–(d) Electron agyrotropy using two methods: \( \sqrt{Q} \) considers the full agyrotropy with all components of the electron pressure tensor, while \( A_{\phi_e} \) only measures the components perpendicular to the magnetic field. (e) Energy gain per cyclotron period of electron \( \epsilon_e \). (f) Relative strength of electric and magnetic force in the bulk electron rest frame \( \delta_e \).
electric field \((E + V_i \times B)_N\), which means that the bipolar change of \((E + V_i \times B)_N\) is a Hall electric field caused by the Hall term. The electron velocity \(V_{el}\) and \(V_{em}\) are up to \(-300 \text{ km s}^{-1}\) and \(400 \text{ km s}^{-1}\), respectively, after subtracting the background flow, which are much larger than the local Alfvén speed \(V_A \sim 126 \text{ km s}^{-1}\), implying that MMS detected a super-Alfvénic electron flow in this diffusion region. In addition, MMS also measured one peak in electron density and the increase in electron temperature dominated by parallel temperature. It is interesting that the nonzero electric field \(E'\) in the electron frame (Figure 2(g)), the large parallel electric field (up to \(5 \text{ mV m}^{-1}\) in Figure 2(h)), and the very strong energy dissipation from the fields to the plasmas (\(J \cdot E' > 0\), up to \(7 \text{ nW m}^{-3}\) in Figure 2(k)) are observed during this crossing. All these features suggest the existence of an inner EDR in this reconnection diffusion region. It is noticeable that the ion bulk velocity at LMN coordinates does not have an obvious increase signature as Figures 1(b)–(c) shows. According to the electron motion during the time interval, the background flow is against the reconnection outflow direction (center vertical dashed line), which should cause a similar decrease of total velocity for the electrons and ions. Thus, the slight increase of ion bulk velocity in Figures 2(b) and 1(c) should be the increase of background flow, not the signature of ion outflow. Therefore, only the electron outflow is detected during the current sheet crossing, implying that this event could be categorized as electron-only reconnection.

Figure 3 shows the observations of the electron anisotropy and energy dissipation from four MMS spacecraft. It can be seen that all four MMS spacecraft captured the EDR with peaks in positive energy dissipation (\(J \cdot E' > 0\) in Figure 3(b)), agyrotropy \(\sqrt{Q}\) and \(A_0\phi_0\) (Figures 3(c)–(d)), the gain energy per cyclotron period \(e_e\) (Figure 3(e)), and relative strength of electric and magnetic force in the bulk electron rest frame \(\xi_e\) (Figure 3(f)) that are marked by four vertical dashed lines, implying that four MMS spacecraft successively crossed the EDR. One should point out that these peaks are not in the center of the current sheet (i.e., \(B_L = 0\)), but located at the positive \(B_L\) region, indicating that the inner EDR has a deflection due to the presence of a guide field, which has been predicted in the previous simulations (Le et al. 2013) and observed by the Cluster (Zhou et al. 2014). This influence can also explain that the center of the current sheet and the center of the EDR are inconsistent, as shown in Figure 2(a).

We perform the Timing analysis on the magnetic field and obtain the moving speed \(V_x \sim 234 \text{ km s}^{-1}\) along the direction \(n = [0.0288, 0.1493, 0.9884]\) in LMN coordinates. The thickness of the current sheet is estimated as \(V_x \cdot dt \sim 234 \text{ km s}^{-1} \times 0.7 \text{ s} = 164 \text{ km}, or 161 \text{ km} along the N direction (where dt is the average duration of the current sheet crossing for four MMS spacecraft), about 4 \(d_i\) or 161 \(d_i\) (\(d_i \sim 41 \text{ km}\) and \(d_e \sim 1 \text{ km}\) are the ion and electron inertial lengths, respectively, based on background ion density \(n_i \sim 30 \text{ cm}^{-3}\)). This indicates that MMS encountered a thick current sheet or an ion-scale current sheet. In addition, we notice that four MMS spacecraft successively crossed the current sheet, first MMS1, then MMS2 and MMS3, and finally MMS4; thus, we also can use the positions of the MMS to estimate the thickness of the current sheet. When MMS1 (MMS2) was in the center of the current sheet, MMS2 (MMS4) was at the edge of the current sheet; when MMS3 (MMS4) was in the center of the current sheet, MMS1 (MMS2) was at the edge of the current sheet (seen \(B_L\) in Figure 3(a)). The separations of MMS1–MMS2, MMS1–MMS3, and MMS2–MMS4 along the N direction are 67 km, 98 km, and 83 km, respectively. Thus, the thickness can be estimated as \(2 \times (67 + 98 + 83 + 83)/4 \sim 165.5 \text{ km}\) in the N direction, which is very close to the estimated thickness derived by the Timing analysis. Moreover, based on the average duration (0.095 s) of positive \(J \cdot E'\), the estimated thickness of the inner EDR along the N direction is about 22 km, i.e., \(\sim 0.54 \text{ } d_i \text{ or } 22 \text{ } d_e\).

The trajectory of the MMS crossing the reconnection region is illustrated in Figure 4. In order to determine where the EDR is, we...
identify the separatrix and the center of the EDR using $B_M - B_E = 0$ (where guide field $B_E \sim -8$ nT) marked by three vertical dashed lines in Figure 2. The EDR extension slightly deviates from the center of current sheet due to the presence of a guide field (Le et al. 2013). The distance between two separatrices and the center of the EDR is estimated as 33 km and 55 km, respectively, based on the Timing analysis, contributing to $\sim 2 d_i$ width between two separatrices. Given the hypothesis that the separatrices are straight lines start from the X-line as well as the magnetic field lines being parallel to the separatrices nearby, one can obtain the cone angle of the spacecraft crossing point at separatrices from the following equation: $\tan \theta \sim \frac{\delta}{D} \sim \frac{b_y}{b_e}$, where $\delta$ is the distance between the separatrix and the center of EDR, $D$ is the extension of EDR from the X-line. The cone angle $\theta$ can be derived by the magnetic field in the $L$ and $N$ directions at the intersection of the trajectory of MMS and the separatrices. Thus, the cone angles $\theta$ are $\sim 1.19^\circ$ and $\sim 1.94^\circ$ corresponding to the lower and upper crossing points at separatrices, respectively (shown in Figure 4). Based on the triangle theory, the extension length of the EDR is estimated to 1604 and 1621 km away from the X-line resulting from the distance as 33 and 55 km between the center of the EDR and the lower and upper separatrices, respectively. Roughly, therefore, the EDR extension from the X-line in the downstream is at least $\sim 40 d_i$, which is the first time there has been in situ observation of an inner EDR for such a long extension in space. In addition, the average reconnection rate $R = 0.021 \sim 0.034$, calculated by the equation given in Liu et al. (2017) and Nakamura et al. (2018), consistent with the previous predictions and observations (Xiao et al. 2007; Liu et al. 2017; Chen et al. 2019; Zhong et al. 2020).

3. Conclusion

Thanks to the unprecedented high-resolution data from the MMS mission, an inner EDR is successfully and definitely identified at the magnetopause (Burch et al. 2016; Zhou et al. 2017) and in the magnetotail (Huang et al. 2018; Torbert et al. 2018; Chen et al. 2019; Zhou et al. 2019) by electron nongyrotropy or electron crescent distribution, strong energy dissipation $J \cdot E > 0$, super-Alfvénic electron flow, parallel electric field, and electron demagnetization, etc. In addition, an outer EDR with electron demagnetization and a super-Alfvénic outflow jet is also identified in the magnetosphere (Xiao et al. 2007; Chen et al. 2019). In the present study, we identify a reconnection diffusion region with a well-defined Hall electro-magnetic field and Hall current at the magnetopause boundary layer. Further analysis shows that the EDR embedded in this diffusion region has a long extension, at least $\sim 40 d_i$ away from X-line in the downstream within the ion-scale current sheet (4 d_i). This EDR does not belong to the outer EDR, but is consistent with the signatures of the inner EDR. Recently, Phan et al. (2018) have shown an electron-only reconnection in electron-scale current sheets. However, it is surprising that there is not a burst ion outflow (Figure 2(b)) even in such a thick ion-scale current sheet as in our case, implying that this inner EDR occurs during electron-only magnetic reconnection in an ion-scale current sheet. This implies that energy transformation and dissipation without ion participation during magnetic reconnection could also occur in an ion-scale current sheet, like in an electron-scale current sheet. Our observations reveal a new feature of an EDR in magnetic reconnection, which challenges the understanding of standard EDR in magnetic reconnection and recent electron-only reconnection in an electron-scale current sheet, and gives new pictures for the magnetic reconnection. The event presented in this study could be the textbook for identifying the details of an electron-only-type magnetic reconnection. Recently, the possible mechanisms of electron-only reconnection formation have been proposed. It is suggested that electron-only reconnection is the early phase of an ion-scale reconnection (Wang et al. 2020). Meanwhile, the strong external driver (Lu et al. 2020) could also be the reason for electron-only reconnection. There is still doubt, about the applicability of these mechanisms on the ion-scale current sheet circumstances. It should be tested through simulations in the future. Our results could also shed new light on the fundamental understanding of the reconnection process in astrophysical and space plasmas.

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