Observation of Nonuniform Energy Dissipation in the Electron Diffusion Region of Magnetopause Reconnection

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Abstract We use Magnetospheric Multiscale (MMS) data to investigate the energy dissipation in a magnetopause reconnection electron diffusion region (EDR) event with moderate guide field. The four MMS spacecraft were separated by about 10 km so that comparative study among spacecraft within the EDR can be implemented. Similar magnetic field and electric current properties at each spacecraft indicate the formation of a quasi-homogeneous magnetic and current structure in the diffusion region. However, we find that the energy dissipations detected by each spacecraft are still different due to the temporal or spatial effect of the out-of-plane reconnection electric field ($E_M$) within the dissipation region. Our study suggests that the nonuniform or unsteady energy dissipation in the reconnection EDR may be a universal process.

Plain Language Summary Magnetic reconnection is a fundamental physical process during which magnetic topologies are changed and magnetic energy is transferred to plasma. Although the effects and structures created by reconnection can be very large in scales, reconnection is actually triggered within a small diffusion region. In the electron diffusion region, energy dissipation is a significant issue, which needs to be investigated further. Previous studies have shown that energy dissipation can be localized and oscillatory due to plasma waves or turbulent environment. Our study shows that the energy dissipations are still nonuniform or unsteady even under diffusion region with quasi-homogeneous magnetic field and electric current structure. Thus, we suggest that the nonuniform or unsteady energy dissipation in the reconnection dissipation region is a universal process.

1. Introduction

Magnetic reconnection is a fundamental physical process during which magnetic topologies are changed and magnetic energy is transferred to plasma. It has been proposed as a key process in the transport of mass, momentum and energy of the plasma from the Sun to Earth (Dungey, 1961). Although the effects and structures created by reconnection can be very large in scales, reconnection is actually triggered within a small diffusion region. According to the collisionless Hall MHD reconnection model, the diffusion region includes an ion diffusion region (IDR) on the spatial scale of an ion inertial length, where ions are decoupled from the magnetic field and a smaller electron diffusion region (EDR), on the spatial scale of an electron inertial length, where electrons are also decoupled from the magnetic field (Hesse et al., 2001; Shay & Drake, 1998; Sonnerup, 1979). In the last few decades, the structure and physical processes in the IDR have been well illustrated by in situ observations (e.g., Dunlop et al., 2011; Eastwood et al., 2010; Fu, Cao, et al., 2013; Fu, Khotyaintsev, et al., 2013; Mozer et al., 2002; Øieroset et al., 2001; Vaivads et al., 2004).

In order to investigate the EDR, where electrons dominate the physical processes, NASA launched the Magnetospheric Multiscale (MMS) mission (Burch, Moore, et al., 2016; Burch, Torbert, et al., 2016) in 2015, which includes four identical spacecraft positioned at small spatial separations and with unprecedentedly high-resolution plasma data. At the magnetopause, where the plasma and magnetic field on two sides of the
reconnection current sheet are asymmetric, a series of EDR events have been reported based on MMS observations (e.g., Burch & Phan, 2016; Burch, Torbert, et al., 2016; Cao et al., 2017; Dong et al., 2020; Eriksson et al., 2016; Khotyaintsev et al., 2016; Lavraud et al., 2016; Norgren et al., 2018; R. Wang et al., 2017; Z. Wang et al., 2019; Webster et al., 2018; Zhong et al., 2018; Zhou et al., 2017), where many characteristics associated with the EDR have been observed, for example, a strong electron current, electron agyrotropy, a “crescent-shaped” electron velocity distribution, and strong energy dissipation. Moreover, using the First-Order Taylor Expansion (FOTE) method (Fu et al., 2015, 2016), which can accurately resolve the magnetic null position and reconstruct the magnetic topology around the spacecraft tetrahedron, direct evidence of the X-line in some of these events has also been further confirmed (Fu et al., 2019).

In the EDR, energy dissipation is a significant issue, which needs to be investigated further (Birn et al., 2001). Energy dissipation in the EDR is usually estimated by using nonideal energy transfer $j \cdot E'$ rate where $E' = E + v_e \times B$ is the electric field in the electron rest frame (Zenitani et al., 2011). $j \cdot E' > 0$ corresponds to the energy transfer from the field to the particles. Due to the asymmetric boundary condition at the magnetopause, the flow stagnation point is separated from the X-point and is located a little on the magnetospheric side of the separatrix (Malakit et al., 2013; Wang, Fu, Olshhevsky, et al., 2020). Recently, MMS results of magnetopause EDRs show that large dissipation could occur both around the X-point and/or in the flow stagnation region, and may be related to the prevailing guide field conditions (Genestreti et al., 2017). Energy dissipation can be localized and oscillatory due to large amplitude waves (Burch et al., 2018). Furthermore, under a large guide field, the strong parallel electric field can play an important role in energy dissipation (Ergun, Goodrich, et al., 2016) during reconnection. In a turbulent environment, numerous current filaments associated with O-lines can appear inside the diffusion region and can be responsible for energy dissipation (Fu et al., 2017). By comparing the observation results between each MMS spacecraft, Cozzani et al. (2019) reported an event with inhomogeneous current densities and energy conversion within an EDR, suggesting that an EDR can be rather structured. Although many EDR events have been reported, EDR events with a quasi-homogeneous magnetic field and current structure, however, are rarely reported, so its physical property has not been fully understood.

In this paper, we report an EDR event at the subsolar magnetopause with a moderate guide field resulting from a near-radial (normal direction of reconnection current sheet) crossing of spacecraft. The four MMS spacecraft were separated by about 10 km, which is comparable to a few electron inertial lengths ($d_i = 1.5$ km). Magnetic field and electric current properties are similar within the EDR at each spacecraft, suggesting that the magnetic field and current structure in the EDR is quasi-homogeneous. We still find that the energy dissipations detected by different spacecraft are different, due to a nonuniform out-of-plane reconnection electric field $E_{\parallel}$.  

2. Observations

In this study, we use burst mode data from the MMS mission, where the magnetic field is from the Magnetometer (Russell et al., 2016), plasma data is from the Fast Plasma Investigation (Pollock et al., 2016) and electric field is from the Electric Field Double Probe (Ergun, Tucker, et al., 2016; Lindqvist et al., 2016). All the vectors are transformed into the local magnetic normal (LMN) coordinate system, as derived from the minimum variance analysis on the magnetic field taken from 09:43:14–09:43:21 UT, where $N$ is the normal direction of the magnetopause current layer. Here the maximum, medium and minimum variance vectors in Geocentric Solar Ecliptic (GSE) coordinates are $L = (0.40, -0.04, 0.92)$, $M = (0.09, -0.99, -0.08)$, and $N = (0.91, 0.11, -0.39)$, respectively.

Figure 1 is an overview of the magnetopause crossing for a 20 s interval around 09:43:20 UT on December 13, 2015. During this interval, MMS is located around $(11.0, 0.2, -1.0)$ Earth radii in GSE coordinates. It traveled from the magnetosphere to the magnetosheath and crossed the magnetopause boundary layer between 09:43:13–09:43:24.3 UT (as denoted between the blue and red vertical dashed lines). The magnetic field in the maximum variance direction, $B_{nc}$, changes from +52 to $-10$ nT (Figure 1a), corresponding to a magnetic shear angle of 129°. The out-of-plane guide field ($B_{\parallel}$) is about 10 nT, which corresponds to 0.5 $B_{nc}$. Here, $B_{nc} = 21$ nT is the geometric average magnetic field considering an asymmetric boundary condition, when the magnitude of the inflowing magnetosheath and magnetospheric boundary layer magnetic fields are 13
Figure 1
and 52 nT, respectively (Cassak & Shay, 2007). As MMS enters the magnetosheath, the plasma densities increase from 0.5 to 13 cm$^{-3}$ and low-energy plasma also appears in the energy spectrogram (Figures 1b, 1h and 1i). In particular, we can see a narrow strong current (up to 1.8 μA/m²) embedded in the wider current sheet a little before magnetic field reversal ($B_L = 0$) and magnetic intensity dropout (Figure 1e). From this strong current region, the rate of increase of plasma density obviously slows down (Figure 2b). This is consistent with the signature of an inflow stagnation point. Here, the current density is calculated from the plasma moment as $\mathbf{j} = \mathbf{e}_i \times (\mathbf{v} - \mathbf{v}_e)$. The lack of an ion jet indicates that the spacecraft were crossing a non-reconnecting magnetopause or crossing a reconnection EDR along a near-radial direction (Burch & Phan, 2016). Around electron jet region, the electric field is mainly in the N direction (Figure 1f). This is consistent with the predicted, unpolar, normal Hall electric field along the magnetospheric side of the separatrix in order to stop the inflow.
of magnetosheath ions during asymmetric reconnection (Pritchett, 2008). From the blue vertical dashed line, ions exhibit a dispersive distribution (Figure 1b) with bulk speeds of up to 190 km/s, mainly in M direction (Figure 1c) and an agyrotropic velocity distribution (Figure 1k). These are typical characteristics of a finite ion Larmor gyroradius effect of overshoot magnetosheath ions into the magnetosphere near the EDR (Shay et al., 2016). In this region, the electron parallel temperature \( T_e \) starts to increase corresponding to counter-streaming distribution, low energy (10–800 eV) electron populations at pitch angles 0° and 180° (Figures 1g and 1j). This kind of anisotropy is also consistent with the presence of the magnetospheric inflow region near the EDR (Egedal et al., 2011).

Figure 2 shows the detailed structures of the magnetic field, current and electric field from four spacecraft. The four spacecraft timing method, measured on peak points of the current, gives a velocity of 43.5 km/s along (0.12, 0.09, −0.99)\(_{\text{MNN}}\) relative to MMS. We see that the crossing velocity is nearly along the normal direction (N) of current sheet and its magnitude is consistent with the measured bulk plasma velocity \( V_N \) in Figure 1c, indicating the convection velocity from the timing results is consistent with the normal bulk velocity. Based on this velocity, the estimated width of main current sheet (traversed from 09:43:18–09:43:20 UT) is about 87 km and the narrow, intense current structure is about 8 km width. For reference, the ion and electron inertial length of the inflowing magnetosheath region are 64 and 1.5 km; so that the width of the whole current sheet and the narrow strong current structure are of order the ion and electron inertial scales, respectively. Figure 2c shows that the boundary normal magnetic field \( B_N \) is small, but positive (≈2 nT), which suggests that the spacecraft are located south of the X-line. Such a magnetic field corresponds to a dimensionless reconnection rate of \( \sim 0.1 \) (\( B_N / B_{\text{rec}} \), Phan et al., 2001), which is consistent with theoretical predictions (Birn et al., 2001).

Focusing on the strong current region, we find that the large current is mainly in the perpendicular direction, while the parallel component is negligible, especially for MMS 2 and 3 (Figures 2d and 2e). Figure 2f shows the dominant electric field \( E_N \) (solid), together with the N component of Hall term \( \mathbf{j} \times \mathbf{B} / ne \) (dotted) and the electron pressure gradient term \( \nabla \cdot P_e / ne \) (dashed) in the generalized Ohm’s law. The Hall term is calculated at each spacecraft, while the electron pressure gradient term is obtained from the four spacecraft method (Sonnerup et al., 1998). We do not show the ion convention term \( \mathbf{j} \times \mathbf{B} / \mathbf{B} \), because it can be neglected within the dissipation region. We see that the Hall term is larger than the electric field \( E_N \) and the deviation between them can partly be attributed to the negative electron pressure gradient term. We note that the magnitude of electron pressure gradient term estimated here should be smaller than actual value because the requirement that the spatial scale of this structure be larger than spacecraft separation is not satisfied (e.g., Dunlop et al., 2016). This non-negligible electron pressure gradient indicates that electrons are not magnetized and that the electron diamagnetic current associated with this electron pressure gradient is an important source of the large electron current (Dong et al., 2018). Figure 2g shows the scalar electron agyrotropy index \( Q_e \) of each spacecraft (Swisdak, 2016). We see a clear enhancement up to 0.05 in all the spacecraft signatures during the sampling of the strong current region. This strong agyrotropy is consistent with a crescent-shaped electron velocity distribution in the perpendicular plane (see Figure 1l), which is a typical characteristic of the electron inflow stagnation region (Burch, Moore, et al., 2016; Burch, Torbert, et al., 2016).

In order to resolve the spacecraft position relative to the X-line, we perform the FOTE method (Fu et al. 2015, 2016) to reconstruct magnetic field structure at 09:43:19.55 UT, where the small calculated error (see Figure S1) suggests reliable reconstruction results. Figures 2i and 2j show the magnetic field topology around X-line and the position of each spacecraft in both three-dimensional coordinates and a two-dimensional projection. In order to view the topology better, a new coordinate system \( (e_1, e_2, e_3) \), where \( e_1 = (0.97, 0, -0.24) \), \( e_2 = (0, 1, 0) \) and \( e_3 = e_1 \times e_2 = (0.24, 0, 0.97)_{\text{MNN}} \) is adopted. We can see that \( e_1, e_2, \) and \( e_3 \) correspond roughly to L, M, N, respectively. The tetrahedron with the solid lines shows the MMS location at 09:43:19.55 UT, where MMS locates on the southward and slightly on the magnetosheath side of the X-line, which is consistent with above conjecture from the magnetic field and electron velocity. The nearest spacecraft, MMS3 is about 13 km from the X-point. The tetrahedron with dashed lines in Figure 2j shows that the predicted position at the time the strong current region is encountered by MMS1/MMS4, using an estimated time shift from the solid position, where the black arrow indicates the direction of the spacecraft motion. The order in which the four spacecraft cross the magnetospheric side of the separatrix in the reconstruction
result is generally consistent with the observation result. In terms of the MMS array sequence, MMS2 passes through first, then MMS1 and MMS4 pass through simultaneously and MMS3 passes through last.

From Figures 2a–2g, we find that the magnetic field, current structure, normal electric field and electron agyrotropy at each spacecraft are almost the same except for the time lag (simply convecting), which indicates that this reconnection EDR is quasi-homogeneous and time stationary during the short period, at least around the local region MMS crossed. The energy dissipation \( \mathbf{j} \cdot \mathbf{E}' \) during the strong current region, however, shows different results between each spacecraft (Figure 2h), that is, MMS2 and MMS3 show similar positive values (3 and 3.8 nW/m\(^2\)), while MMS1 and MMS4 show small negative values. These pairs of similar results rule out a possible stochastic uncertainty caused by the electric field. In this event, the dissipation region seems to be only located around electron stagnation point and it is absent near the magnetic field reversal region.

In order to investigate the specific reason for different dissipations, we show the detailed current, electric field and energy dissipation information of each spacecraft in Figure 3. The currents between each spacecraft are very similar and are mainly in the L and M directions during the dissipation region, while the N component can be neglected (Figures 3b–3d). This indicates that different dissipation is caused by the electric field, especially the L and M components of electric field. Figures 3e and 3f show the electric field \( E_L \) and \( E_M \) components in magnetopause rest frame, with a data sample rate of 8,192 s\(^{-1}\) and Figures 3g and 3h show the nonideal electric field (\( E'_L \) and \( E'_M \)). Figures 3i–3k show the L and M components and total energy dissipation, respectively. Here the \( \mathbf{v}_e \times \mathbf{B} \) term at each spacecraft has a similar value due to the similar magnetic field and current structure. Thus, the different \( \mathbf{E}' = (\mathbf{E} + \mathbf{v}_e \times \mathbf{B}) \) values depend entirely on total electric field \( \mathbf{E} \). We see that the electric field \( E_L \) at each spacecraft is small or positive during the encounter with the dissipation region (Figure 3e). Under the influence of positive \( v_{eM}B \) component, the \( E_L \) for all the spacecraft has a positive value and therefore creates a positive dissipation component \( j_L E'_L \) from the positive current \( J_L \) (Figures 3b, 3g and 3i). A different condition occurs for the out-of-plane electric field \( E_M \), where the values at MMS1 and MMS4 remain positive, whereas the values at MMS2 and MMS3 turn negative during dissipation region encounter (Figure 3f). The similar results of MMS1 and MMS4, together with their simultaneous crossings, ensure the reliability of electric field measurement. Thus, \( E_M \) remains under similar conditions due to the small value of \( (\mathbf{v}_e \times \mathbf{B})_M \). Different \( E_M \) creates different dissipation results from \( j_M E'_M \), that is, MMS2 and MMS3 are positive, while MMS1 and MMS4 are negative (Figure 3j). A negative dissipation from \( j_M E'_M \) then makes the total dissipation \( \mathbf{j} \cdot \mathbf{E}' \sim j_L E'_L + j_M E'_M \) negative overall and the positive dissipation from \( j_M E'_M \) increases the total overall positive value. Above all, different positive and negative values of energy dissipation are related to the \( E_M \). When \( E_M \) is negative, which is consistent with the predicted direction of reconnection electric field, the total energy dissipation is positive, that is, that energy is transferred from magnetic field to particles.

### 3. Discussion and Summary

By combining the detailed relative position of each spacecraft (Figure 4), we can investigate the reason for the different energy dissipation rates and the role of the out-of-plane electric field \( E_M \) in the dissipation region. The current sheet (blue shaded region) is located in the LM plane and the crossing velocity is nearly along the N direction. In the N direction, MMS1 and MMS4 have nearly the same positions along N, MMS2 and MMS3 are positioned 9 and −7 km relative to MMS1. This configuration is consistent with the crossing sequence and time interval of each spacecraft. In the plane of current sheet (LM plane), we see that the locations of MMS2 and MMS3 are very close together, while MMS1 is nearer MMS2/MMS3 in the L-direction and MMS4 is near MMS2/MMS3 in the M-direction. One explanation of the temporal effects is that the negative electric field \( E_M (E'_M) \) is unsteady and disappears when MMS1/MMS4 cross the current sheet. Such unsteady magnetic reconnection was previously suggested in Cluster observations (Fu, Cao, et al., 2013; Fu, Khotyaintsev, et al., 2013) and recently confirmed in MMS observations (Wang, Fu, Olshhevsky, et al., 2020; Wang, Fu, Vaivads, et al., 2020). Another possible explanation for the variations across the spatial array is that \( E_M (E'_M) \) follows a highly localized three-dimensional distribution and does not have enough extent in the L and M directions for MMS4 and MMS1 to observe it. Previous simulation and observational results have indicated that the EDR can extend and be divided into inner and outer regions, with positive and negative energy dissipations, respectively (Chen et al., 2016; Hwang et al., 2017; Karimabadi et al., 2007; Zenitani
et al., 2011). We note that in these previous interpretations, different values of the energy dissipation are due to the different directions of nonideal reconnection electric fields $\mathbf{E}_M^\prime \times \mathbf{B}$, while the value of electric field $E_M$ remains stable. In our case, MMS1/MMS4 and MMS2/MMS3 may have crossed the outer and inner regions of EDR, in turn. However, the different values of $\mathbf{E}_M^\prime \times \mathbf{B}$ are due to a changing value of $E_M$, while $\mathbf{V}_e$ and $\mathbf{B}$ remain similar between each spacecraft.

Although the electric field in the magnetospheric inflow region has large-amplitude oscillations which may be related to electrostatic wave structures, $E_M$ and $E_M^\prime$ become stable near the dissipation region, especially the nonideal electric field $E_M^\prime$ (Figures 3g and 3h). Furthermore, the time intervals of negative $E_M (E_M^\prime)$ in MMS2 and MMS3 correspond to the encounter with the dissipation region. This indicates that the appearance of negative $E_M (E_M^\prime)$ is associated with a small dissipation region rather than a background disturbance.
As an important parameter, the reconnection rate, as determined by external magnetic field configuration or the physical process in internal diffusion region is a matter of concern (Liu et al., 2017). Due to the nonuniform reconnection electric field ($E_M$), calculating the overall reconnection rate associated with reconnection electric field seems difficult. However, we can try to use the maximum value of electric field in the dissipation region to estimate the instantaneous reconnection rate. The dimensionless reconnection rate is equal to normalized reconnection electric field obtained from the inflow Alfvén speed and magnetic field ($\frac{E_{rec}}{V_{A,in}B_{in}}$). For a magnetopause with asymmetric boundary conditions, the scaled inflow Alfvén speed in the magnetosphere and magnetosheath, respectively (Cassak & Shay, 2007). For the maximum peak reconnection electric field of $E_M = 1.28$ mV/m in MMS2, the calculated dimensionless reconnection rates are ~0.29, which is slightly larger than the result calculated by external magnetic field $B_0 / B_{rec}$ above and theoretical predictions of Birn et al. (2001). If we consider that only the maximum value of the reconnection electric field is used in the calculation, this larger value compared to the overall reconnection rate is reasonable. Our results suggest that the reconnection electric field in the EDR is rather unsteady or nonuniform due to spatial or temporal effect, which makes it difficult to calculate the overall reconnection rate by in situ measurements, while the reconnection rate calculated by external magnetic field configuration is more reliable.

It is worth noting here that we find the accuracy of the measured electric field data is sufficient for our analysis. First, the plasma moment data is reliable, as can be confirmed by the similar results obtained for the current density from both four-spacecraft plasma moments and from the magnetic field, via the curlometer (Dunlop et al., 2018). Figure S2 shows that small deviations occur only for the central peak and close to 09:43:20 UT where the current sheet scales are smaller than the spacecraft separation. Second, cross-calibration between the electric field data and the plasma moment data can be implemented (as carried out by Torbert et al., 2016). Near the magnetosheath region, such as for times from 09:43:20.8 UT, $E'$ should be almost zero, and this is true for our results (Figures 3g and 3h, where values remain <~0.5 mV/m). We therefore conclude that this level of error may affect the specific value calculated above, such as energy dissipation and reconnection rate, in only a small way without affecting the conclusion of this paper.

In summary, we have investigated the localized energy dissipation $j \cdot E'$ around the EDR by using four-spacecraft measurements at the magnetopause. The finite Larmor gyroradius effect of ions; a bi-streaming distribution of electrons in the magnetospheric inflow region; strong current on electron scales; a crescent-shaped electron velocity distribution, and no ion outflow jet, all indicate that MMS crossed the EDR along a near-radial direction. This is further confirmed by the reconstruction of the FOTE method. A similar magnetic field and electric current behavior, observed by all four spacecraft, indicates the formation of a quasi-homogeneous magnetic field structure in the diffusion region. However, the energy dissipations are
nonuniform due to either a temporal or spatial effect from the out-of-plane reconnection electric field $E_M$. Thus, our study suggests that the nonuniform or unsteady energy dissipation in the reconnection dissipation region is a universal phenomenon, even under diffusion region with quasi-homogeneous magnetic field and current structure. This makes it difficult for estimating the overall energy dissipation around the EDR by in situ measurements.

Data Availability Statement
For MMS data visit https://lasp.colorado.edu/mms/sdc/public/.

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