Measurement of the Magnetic Reconnection Rate in the Earth’s Magnetotail

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Abstract In the Earth’s magnetotail, magnetic reconnection releases stored magnetic energy and drives magnetospheric convection. The rate at which magnetic flux is transferred from the reconnection inflow to outflow regions is determined by the reconnection electric field \( E \), which is often referred to as the unnormalized reconnection rate. To better quantify the efficiency of reconnection, this electric field \( E \) is often normalized by the characteristic Alfvén speed and the reconnecting magnetic field. This parameter is generally called the normalized or dimensionless reconnection rate \( R \). In this paper, we employ a two-dimensional fully kinetic simulation to model a magnetotail reconnection event with weak geomagnetic activity (<200 nT of the AE index) observed by the Magnetospheric Multiscale (MMS) mission on 11 July 2017. We obtain \( R \) and \( E \) from direct measurements in the diffusion region and indirect measurements of the rate at the separatrix using a recently proposed remote sensing technique. The measured normalized rate for this MMS event is \( R \approx 0.15 \), consistent with theoretical and simulation models of fast collisionless reconnection. This corresponds to an unnormalized rate of \( E \approx 2 \)–3 mV/m. Based on quantitative consistencies between the simulation and the MMS observations, we conclude that our estimates of the reconnection rates are reasonably accurate. Given that past studies have found \( E \) of the order \( \approx 10 \) mV/m during strong geomagnetic substorms, these results indicate that the local \( E \) in magnetotail reconnection may be an important parameter controlling the amplitude of geomagnetic disturbances.

1. Introduction

Magnetic reconnection is a key process in collisionless plasmas that converts magnetic energy to plasma kinetic and thermal energies through a rapid change of magnetic field topology. At the Earth’s magnetopause, for example, this process produces efficient transport of solar wind energy into the magnetosphere along the reconnected field lines. In the Earth’s magnetotail, this process releases the stored magnetic energy and excites global geomagnetic disturbances leading to the aurora substorms (e.g., Dungey, 1961). The topology change during this process occurs in a small-scale region surrounding the reconnection X-line where plasmas are decoupled from the magnetic field. This so-called diffusion region is known to have a multiscale structure based on the ion and electron scales (e.g., Shay et al., 1998), which can be described by the generalized Ohm’s law (e.g., Kuznetsova et al., 1998; Pritchett, 2001),

\[
E = E + \mathbf{U}_e \times \mathbf{B} = E + \mathbf{U}_i \times \mathbf{B} - \frac{1}{en} \mathbf{J} \times \mathbf{B} = -\frac{\nabla P_e}{en} - \frac{m_e}{e} \frac{d\mathbf{U}_e}{dt},
\]

where \( E \) and \( \mathbf{B} \) are the electric and magnetic fields, respectively, \( \mathbf{U}_e \) and \( \mathbf{U}_i \) are the ion and electron bulk velocities, respectively, \( \mathbf{J} \) is the current density vector, \( P_e \) is the electron pressure tensor, \( E \) is the elementary charge, and \( m_e \) is the electron mass and \( n \) is the number density. Considering a 2-D situation in which reconnection develops in the x-z plane, the reconnection process is sustained by the y component of the electric field. In the outer diffusion region called the ion diffusion region (IDR), only the ions are decoupled from the magnetic field and the Hall term \( \mathbf{J} \times \mathbf{B}/en \) is dominant, while in the inner diffusion region called the electron diffusion region (EDR), the electrons are also decoupled from the field and \( E_y > 0 \) (e.g., Hesse & Winske, 1998; Nakamura, Nakamura, & Hasegawa, 2016; Pritchett, 2001).
Thus, the reconnection electric field, often referred to as the normalized rate, the rate at which the magnetic flux is transferred from the inflow region into the diffusion region to change the field line connectivity. In this paper, the reconnection electric field is also referred to as the unnormalized reconnection rate. In addition to this unnormalized rate, the rate \( R = \frac{V_{in}}{V_{Ab}} \) which is generally called the normalized (or dimensionless) reconnection rate, is also a key parameter that defines how efficiently the topology change in the reconnection process occurs. Here \( V_{Ab} \) is the ion Alfvén speed based on the background reconnecting field strength \( B_b \) and the upstream density. In theoretical discussions of reconnection physics, the normalized value is most commonly used, since it represents the most meaningful dimensionless measure of the rate. Assuming \( B_{in} \sim B_b \) and \( V_{out} \sim V_{Ab} \), the normalized reconnection rate can be approximately written by using the unnormalized rate \( (E_r \sim V_{in} B_m) \) as

\[
R = \frac{V_{in}}{V_{Ab} B_b} \frac{E_r}{V_{out} B_b}.
\]

This equation indicates that the unnormalized rate \( E_r \) is sensitive to the normalized rate \( R \) and the upstream value of the magnetic field \( B_b \) and, to a lesser degree, the density \( n \). The main focus of this paper is to obtain both the normalized and unnormalized reconnection rates in a magnetotail reconnection event observed by the Magnetospheric Multiscale (MMS) spacecraft on 11 July 2017, which was first reported by Torbert et al. (2018).

The Geospace Environmental Modeling magnetic reconnection challenge (Birn et al., 2001) compared various simulation models from the magnetohydrodynamic to fully kinetic models. Birn et al. (2001) suggested that in collisionless plasmas, the decoupling of ion and electron dynamics (i.e., the Hall effect) commonly facilitates fast reconnection with a normalized rate of the order 0.1. Recent kinetic simulations also demonstrated that fast reconnection with \( R \sim 0.1 \) even occurs in regimes where the Hall effect is negligible (e.g., Liu et al., 2014). More recently, Liu et al. (2017, 2018) modeled the normalized reconnection rate as a function of the exhaust opening angle near the diffusion region. Unlike the traditional Sweet-Parker scaling (Parker, 1957; Sweet, 1958), the normalized rate with a large opening angle is limited by the force-balance imposed at the inflow and outflow regions. Their simple model predicts that the fast normalized rate has an upper bound value \( \sim 0.1 \), and the rate remains the same order over a wide range of the exhaust opening angle; this could explain this nearly universal value of the fast rate. Assuming \( B_{in} \sim B_b \) and \( V_{out} \sim V_{Ab} \) (i.e., \( R \sim V_{in} / V_{Ab} \sim B_{out} / B_b \)). Cluster observations of \( V_{in} \) and \( B_{out} \) near the IDR at the magnetopause were used to demonstrate that the normalized rate was indeed of the order 0.1 (e.g., Fuselier et al., 2010; Phan et al., 2001; Vaivads et al., 2004).

MMS was launched on 12 March 2015 to explore microscale reconnection physics in the Earth’s magnetosphere, particularly focusing on the electron-scale physics (Burch, Moore, et al., 2016). The initial science phase of this mission targeted the dayside magnetopause, where asymmetric reconnection occurs between the magnetosheath and the magnetosphere. The second phase, which started on March 2017, targeted the near-Earth magnetotail, where nearly symmetric reconnection occurs (Fuselier et al., 2014). In the initial phase, the high-resolution observations by MMS successfully identified the EDR at the magnetopause (e.g., Burch, Torbert, et al., 2016; Genestreti, Varsani, et al., 2018). By optimizing local coordinates of the EDR crossing event reported by Burch, Torbert, et al. (2016), Hasegawa et al. (2017) inferred the reconnection electric field from the convection electric field \( -\mathbf{U}_r \times \mathbf{B} \) as \( E_r \sim 0.4 \sim 1.0 \text{ mV/m} \), which corresponds to the normalized rate \( R \sim 0.11 \sim 0.25 \) based on the local \( V_{Ab} B_b \) around the EDR crossing interval. In another EDR crossing event by MMS, Chen et al. (2017) reported that the normalized rate was estimated to be \( R \sim 0.1 \) based upon a direct measurement of the out-of-plane electric field (i.e., \( E_r \)) near the EDR and the observed upstream value of \( V_{Ab} B_b \).

More recently, in the second phase of the MMS mission, Torbert et al. (2018) first reported an EDR crossing event in the magnetotail on 11 July 2017, in which the reconnection electric field \( (E_r) \) within the EDR was directly observed in the range about 1–2 mV/m. In this MMS event on 11 July 2017, since the MMS spacecraft crossed the magnetotail current sheet very gradually, it is difficult to know the exact upstream value of \( V_{Ab} B_b \).
On 11 July 2017, the MMS spacecraft crossed the electron inertial scale (δe scale) EDR in a magnetotail reconnection process (Torbert et al., 2018; G18) with high time resolution burst-mode ion (150 ms) and electron (30 ms) measurements (Pollock et al., 2016), magnetic fields (Russell et al., 2016), and electric fields (Ergun et al., 2016; Lindqvist et al., 2016; Torbert et al., 2016). Figure 1 shows the overview of this event on 11 July 2017 during 22:30–22:40 UT. Figure 2 shows zoomed-in views of an interval around 22:34 UT, during which the spacecraft crossed the EDR as first reported by Torbert et al. (2018). All data are displayed in local LMN coordinates, in which G18 found that the reconnection rate could be calculated with a relatively small uncertainty. These coordinates were obtained by minimum variance analysis (MVA; Sonnerup & Scheible, 1998) of the electron bulk velocity \( V_e \) during the local \( V_{\text{e,flow}} \) reversal interval between 22:34:02 and 22:34:04 UT (see the vertical line in Figure 1 and zoomed-in views in Figure 2). Hereafter, we refer this method to obtain LMN coordinates as MVA–\( V_e \) coordinates and corresponds to the direction of the local reconnection outflow jet. \( N \) (\([0.2651, 0.3074, 0.9139]\) in GSM) is obtained by the minimum variance direction of \( V_e \) and corresponds to the direction of the local reconnection outflow jet. \( M \) (\([0.1749, 0.9168, -0.3591]\) in GSM) closes the right-hand coordinate system and corresponds to the out-of-plane direction. The \( L \), \( M \), and \( N \) directions correspond to the \( x \), \( y \), and \( z \) directions in the simulation shown in this paper. See G18 for more details of these coordinates, as they discuss the accuracy of MVA–\( V_e \) by comparing with other possible methods to obtain local coordinates.

In this event, the spacecraft were in a near-Earth \((X_{\text{GSM}} = -21R_E)\) lobe region in the southern hemisphere until 22:32 UT (Figure 1) and then encountered tailward-flowing high-speed \((V_{\text{IL}} < -400 \text{ km/s})\) ion jets (Figure 1g). Subsequently, at around 22:34 UT, the spacecraft encountered an ion flow reversal (Figure 1g) with a very short interval (approximately a few seconds) of a much higher-speed \((|V_{\text{e,flow}}| \sim 10,000 \text{ km/s})\) electron flow reversal in the \( L \)-direction accompanied by a strong out-of-plane electron flow \((V_{\text{e,flow}} \sim -20,000 \text{ km/s})\); Figures 2b and 2e). The \( B_z \) component varied from about \(-10\) to \(-12 \text{ nT}\) in the lobe region (see the time before 22:32 UT in Figure 1a) to almost \(-2\) to \(0 \text{ nT}\) near the electron flow reversal point (see the time around 22:34 UT in Figure 1a and Figures 2a and 2d). This indicates that the spacecraft were close to the EDR during the electron flow reversal \((\sim 22:34 \text{ UT})\). During this electron flow reversal, only MMS3, which was located about \(10–15 \text{ km north}\) (in the \( N \) direction) of other three spacecraft, observed the \( B_z \) reversals just after the \( B_y \) reversal (see the time at 22:34:02–22:34:03 UT in Figure 2a), while the other three spacecraft only observed the negative \( B_z \) values during this interval (see Figure 2d). This indicates that only MMS3 crossed the current sheet center near the EDR.

This paper is organized as follows. Section 2 describes the overview of the MMS event on 11 July 2017 and the details of the simulation model based on the MMS event. Section 3 presents the overview of the simulation results and the comparisons between the virtual observations from the simulation and the MMS observations. Based on the comparison between the virtual observations and the MMS observations in the reliable coordinates, this paper further confirmed the reliability of the rates obtained from both the direct measurements within the EDR and the remote estimations using recently proposed remote sensing techniques for the normalized rate (Liu et al., 2017) and the unnormalized rate (T. K. M. Nakamura et al., 2018).

2. Model

2.1. Overview of MMS Observations

On 11 July 2017, the MMS spacecraft crossed the electron inertial scale (δe scale) EDR in a magnetotail reconnection process (Torbert et al., 2018; G18) with high time resolution burst-mode ion (150 ms) and electron (30 ms) measurements (Pollock et al., 2016), magnetic fields (Russell et al., 2016), and electric fields (Ergun et al., 2016; Lindqvist et al., 2016; Torbert et al., 2016). Figure 1 shows the overview of this event on 11 July 2017 during 22:30–22:40 UT. Figure 2 shows zoomed-in views of an interval around 22:34 UT, during which the spacecraft crossed the EDR as first reported by Torbert et al. (2018). All data are displayed in local LMN coordinates, in which G18 found that the reconnection rate could be calculated with a relatively small uncertainty. These coordinates were obtained by minimum variance analysis (MVA; Sonnerup & Scheible, 1998) of the electron bulk velocity \( V_e \) during the local \( V_{\text{e,flow}} \) reversal interval between 22:34:02 and 22:34:04 UT (see the vertical line in Figure 1 and zoomed-in views in Figure 2). Hereafter, we refer this method to obtain LMN coordinates as MVA–\( V_e \) coordinates and corresponds to the direction of the local reconnection outflow jet. \( N \) (\([0.2651, 0.3074, 0.9139]\) in GSM) is obtained by the minimum variance direction of \( V_e \) and corresponds to the direction of the local reconnection outflow jet. \( M \) (\([0.1749, 0.9168, -0.3591]\) in GSM) closes the right-hand coordinate system and corresponds to the out-of-plane direction. The \( L \), \( M \), and \( N \) directions correspond to the \( x \), \( y \), and \( z \) directions in the simulation shown in this paper. See G18 for more details of these coordinates, as they discuss the accuracy of MVA–\( V_e \) by comparing with other possible methods to obtain local coordinates.
2.2. Simulation Settings

In this paper, we performed a simulation that models the above MMS event on 11 July 2017 at around 22:34 UT. The simulation was performed on the MareNostrum 4 machine, using the fully kinetic particle-in-cell code VPIC (Bowers et al., 2008, 2009). The simulation performed in this paper is 2–1/2 dimensional in the $x$-$z$ plane and started from a simple 1-D Harris type current sheet with a weak guide field. The initial magnetic field and the corresponding number density are set up as

$$B_x(z) = B_b \tanh(z/L_0), \quad B_y = B_g \quad \text{and} \quad n_i(z) = n_{0i} \text{sech}^2(z/L_0) + n_{bi},$$

where $B_b$ is the background reconnecting magnetic field component, $B_g$ is the initial uniform guide field, $n_{0i}$ is the Harris density component, $n_{bi}$ is the background density, and $L_0$ is the half-thickness of the initial current sheet. Although it is difficult to know the exact Harris and background parameters from the MMS

![Figure 1. Overview of the event observed by the Magnetospheric Multiscale (MMS) spacecraft during the interval 22:30–22:40 UT on 11 July 2017. The plots show the MMS3 observations of (a) three $LMN$ components of the magnetic field, (b and c) energy spectra for ions obtained from EIS (>45 keV) and FPI (<30 keV) instruments, (d) ion and electron number densities, (e and f) parallel and perpendicular components of electron and ion temperatures, and (g and h) three $LMN$ components of the ion and electron bulk velocities. The $LMN$ coordinates are employed to better understand the local reconnection physics around the time (~22:34) when the spacecraft crossed the electron diffusion region as marked by the vertical line. The $L$, $M$, and $N$ directions correspond to the $x$, $y$, and $z$ directions in the simulation shown in this paper. See G18 for more details of the $LMN$ coordinate descriptions. For the FPI ion data, the background noise due to energetic electrons is subtracted using a correction method introduced in Nakamura et al. (2017).](image-url)
observations, we roughly inferred the ion and electron densities and temperatures during the downstream interval around 22:32–22:33 UT ($n_i$$\sim$0.08–0.1 cm$^{-3}$, $T_i$$\sim$4,000–5,000 eV, and $T_e$$\sim$1,000–1,500 eV) as the current sheet (Harris) components (see the time before 22:32–34 UT in Figures 1d–f). We also estimated the minimum densities near the EDR at $\sim$22:34 UT and the interval with a sudden $V_{ix}$ depression at $\sim$22:33:30 UT ($n_i$$\sim$0.03 cm$^{-3}$, $T_i$$\sim$1,000–2,000 eV, and $T_e$$\sim$300–1,000 eV) as the background plasma assuming that the central reconnection region had already been filled with background plasmas. Regarding the magnetic field, we inferred $B_x$ ($\sim$12 nT) in the lobe region (see the time just before 22:32 UT in Figure 1a) as $B_0$. These inferred values roughly satisfy the pressure balance ($P_{ei}$$\sim$0.064–0.1 nPa and $P_{eb}$$\sim$0.08–0.11 nPa). We set up the initial density and temperature ratios based on these values as $n_i/n_e = 3.0$, $T_i/T_e = 3.0$, $T_i/T_\text{eb} = 3.0$, and $T_e/T_\text{eb} = T_e/T_\text{eb} = 3.0$. The guide field is set to be $B_0 = 0.03 B_0$, which roughly corresponds to the values of $B_{by}$$\sim$0.25–0.5 nT at $B_x = 0$ crossings observed by MMS3 during 22:34:02–22:34:03 UT (see Figure 2a). Although these values may be different from the real current sheet and background values (e.g., the downstream values with finite $B_x$ were different from the exact values at the current sheet center, the density should decrease, and the temperatures should increase near the $X$-line from the background values), the quantitative consistencies between the virtual observations in this simulation and the MMS observations shown in sections 3 and 4 justify the adequacy of these initial values. $L_0$ is set to be 0.6$d_{i0}$, where $d_{i0}$ is the ion inertial length based on $n_0$. The ratio between the electron plasma frequency and the gyrofrequency is set to be $\omega_{pe}/\Omega_e = 2.0$. The ion-to-electron mass ratio is $m_i/m_e = 400$. The system size based on $d_{i0}$ is set to be $L_x \times L_z = 120d_{i0}\times 40d_{i0} = 2,400d_{i0}\times 800d_{i0} = 14,400 \times 4,800$ cells with a total of $1.4 \times 10^{11}$ superparticles, which minimizes the effects from the simulation boundaries during the simulation times shown in this paper. The boundary conditions are periodic along the $x$-direction, with conducting walls along the $z$-direction. A weak initial magnetic field perturbation is added at the center of the simulation domain according to $\delta B = \mathbf{z} \times \nabla \Phi$, where $\Phi = -0.02 B_0 \sin (x/L_0) \cos (z/L_0)$, such that reconnection starts near the center of the simulation domain $x = 0$.

3. Simulation Results

3.1. Overview of the Simulation Results

Figure 3a shows the time evolution of the peak reconnection outflow speed for ions and the unnormalized reconnection rate ($E_\text{r}$) measured at the $X$-line by $\partial A_y/\partial t$ (red) and $E_y$ (blue). After the onset of reconnection at $t$$\sim$30$\Omega_e^{-1}$, both the outflow speed and the reconnection rate rapidly increase. The reconnection rate reaches the maximum value $E_\text{r}$$\sim$0.1$V_{অbd}B_0$ at $t$$\sim$40$\Omega_e^{-1}$. After saturating, the rate maintains a nearly constant value in the range $E_\text{r}$$\sim$0.06–0.09$V_{অbd}B_0$. Figures 3b–3d show the time evolution of ion outflow jets after the
saturation of the reconnection rate. The $d_i$-scale thickness of the ion outflow jets expands in the $x$-direction (10–40$d_{i0}$) at a speed comparable to the ion Alfvén speed based on $B_x$ ($\sim 1.5V_{Ai0}\sim 0.9V_{Aib}$). Figures 3e–3g show the time evolution of electron outflow jets near the $X$-line at around $t\sim 50\Omega_i^{-1}$. The $d_e$-scale thickness of the electron outflow jets also expands in the $x$-direction (20–50$d_{e0}$), although the expansion speed is much smaller than the electron Alfvén speed based on $B_x$ ($\sim 0.010V_{Ae0}\sim 0.006V_{Aeb}$) and even smaller than the ion Alfvén speed based on $B_x$ ($\sim 0.2V_{Ai0}\sim 0.12V_{Aib}$). The size of the central electron flow reversal region, which corresponds to the EDR, is not significantly changed with time in this steady reconnection phase as seen in past fully kinetic simulations with sufficiently large system sizes (e.g., Karimabadi et al., 2007; Shay et al., 2007). These multiscale reconnection signatures ($d_i$-scale ion outflow jets accompanied by $d_e$-scale electron outflow regions) are roughly consistent with the observed signatures (minute-scale ion jets accompanied by second-scale electron jets) by the MMS shown in Figures 1 and 2.

3.2. Virtual Observations

To directly compare the simulation and the MMS observations, we performed virtual observations in the simulation focusing on the electron flow reversal interval shown in Figure 2. To determine the paths of the virtual probes, we first examined $B_z$ ($B_y$ in the simulation) observed by MMS3 shown in Figure 2a, which roughly indicates the distance of the spacecraft from the current sheet center (i.e., the $N$ or $z$ coordinate), and made a modeled $B_x$ curve shown in Figure 4. We then chose a virtual probe path
For orbit 2t, we consider the time evolution—that is, the horizontal axis in Figure 4 corresponds to the simulation time. We assume that the probe moves at a constant speed in the x-direction, which corresponds to the X-line retreat motion in a real magnetotail situation. Based on multipoint timing analysis, Torbert et al. (2018) estimated the motion of this MMS X-line event was about 170 km/s, which is roughly 1/8 of the ion Alfvén speed $V_{Alfven}$ based on $n_0 = 0.03$ cm$^{-3}$ and $B_0 = 12$ nT. In this paper, we take $1/8V_{Alfven}$ as the probe motion speed in the $x$-direction. To determine the start point of the path, we set the time when the probe crosses the $x$ coordinate of the X-line $x = 30d_{eo}$ (i.e., the $p_1$ point in Figure 4) as $t = 50\Omega_i^{-1}$. Then, we compute all $z$ coordinates corresponding to all time points before and after $t = 50\Omega_i^{-1}$ (i.e., determine the full path of the orbit 1t). Subsequently, we compute the path of orbit 2t, whose $z$-coordinates are $\Delta z = 0.83d_{eo}$ smaller than orbit 1t. The paths of these orbits are plotted in Figure 3f, and the virtual observation results of the magnetic and electric field and electron bulk flow velocity along the paths are shown in Figures 5a–5f. The results are in quantitative agreement with the MMS observations normalized by $n_0 = 0.03$ cm$^{-3}$ and $B_0 = 12$ nT (compare with Figure 2), particularly on (i) the Hall $B_y$ ($B_{yo}$) peak before the $B_z$ ($B_{zo}$) reversal for both orbits, (ii) the electron flow (current) peak in the $y$ ($M$) direction near the $B_z$ ($B_{zo}$) reversal for both orbits, (iii) the stronger Earthward ($+V_{ex}$) flow (outflow jet) and weaker tailward flow for both orbits, (iv) the weak positive $B_y$ ($B_{yo}$) for orbit 1s (MMS3) and the weak negative $B_y$ ($B_{yo}$) for orbit 2s (MMS1) after the $B_z$ ($B_{zo}$) reversal, (v) the negative to positive $E_y$ ($E_{yo}$) reversal for both orbits and the stronger positive $E_y$ ($E_{yo}$) reversal only for orbit 1s (MMS3), and (vi) the almost constant $E_x$ ($E_{xo}$) through the interval for both orbits. These quantitative consistencies strongly indicate that the present simulation accurately reproduces the electron-scale structures near the X-line during this MMS event and that the relative paths through the electron-scale structures of orbit s are similar to the real paths of the MMS spacecraft. The consistencies also indicate the adequacy of the background parameters ($n_0=0.03$ cm$^{-3}$ and $B_0=12$ nT) we used in the simulation.

For orbit 2s, the probes move through the simulation domain by a constant speed in the $+x$-direction at the fixed time $t = 50\Omega_i^{-1}$ (i.e., the horizontal axis in Figure 4 corresponds to the $x$ coordinate). Here we assume that the reconnection process is in a perfectly steady phase and we can neglect the time evolution of the reconnection structures near the EDR (i.e., the probe crosses the structure fast enough to neglect the time evolution of the structure). To determine the paths, we first set the $p_0$ point in Figure 4 as $x = 30d_{eo}$, which is the $x$ coordinate of the X-line as shown in Figure 3f. Then we determine the spatial extent of the horizontal axes in Figure 4 (i.e., determine the full path of the orbit 1s) by setting the $p_1$ point as $x = 42d_{eo}$, which is where the $|V_{ex}|$ value reaches the half of the $|V_{ex}|$ peak as seen in the real MMS3 data in Figure 2b. Finally, we can compute all $z$ coordinates corresponding to all $x$ coordinates by matching the $B_y$ profile. The path of orbit 2s is nearly identical to orbit 1s but has $z$ coordinates that are $\Delta z = 0.83d_{eo}$ smaller than orbit 1s. The paths of these orbits are plotted in Figure 3f, and the virtual observation results of the magnetic and electric field and electron bulk flow velocity along the paths are shown in Figures 3e–3g. Note that due to the limit of computer resources, the time resolution of these time-dependent virtual observations is only $\Delta t = 1\Omega_i^{-1} = 400\Omega_e^{-1}$. Nevertheless, the overall variations are well resolved and the results are in quantitative agreement with the MMS observations as well as the results for orbit s on the above six points (i)–(vi). This indicates not only that the relative paths through the electron-scale structures of orbit t are also similar to the real MMS paths but also that the observed reconnection process was in a roughly steady state during the observation interval as assumed for orbit s. In the next section, based on these consistencies between the simulation and observations, we estimate both of the normalized and unnormalized reconnection rates of this MMS reconnection event using various methods particularly focusing on the comparison between the
orbit 1s and the MMS3 (and orbit 2s and the MMS1) observations. The results in the next section will be summarized in section 5.1 and Figure 9.

4. Measurements of the Reconnection Rates

4.1. Direct Measurements of the Normalized and Unnormalized Reconnection Rates

Figures 6b–6d show the paths of orbits 1s and 2s in the simulation domain near the EDR with color plots of $B_y$, $E_y$, and $E_z$. In these orbits, the probes first cross the $x < 0$ and $z < 0$ side of the positive Hall field region, which corresponds to the IDR, and then enters the positive $E_y$ region, which corresponds to the EDR. After crossing the EDR, both probes stay near the neutral sheet ($z = 0$) in the outer EDR, where $E_y$ is negative. During the outer EDR interval, only orbit 1s (corresponding to MMS3) slightly crosses the neutral sheet. It is notable here that the peak $E_y$ value in the EDR is expected to be balanced with the nearly uniform $E_y$ value around the whole diffusion region (IDR and EDR), which corresponds to the unnormalized reconnection rate (i.e., the reconnection electric field $E_r$). Thus, it is expected that we can directly obtain the unnormalized rate of this reconnection process from the direct measurements of the electric field during the EDR crossing.

Figure 7 shows the virtual observation plots for orbit 1s (left) and the real MMS3 observation plots (right). The low density ($\sim n_b$) seen in both simulation and observation plots (see Figures 7a and 7i) indicates that the orbit 1s and the MMS3 (and orbit 2s and the MMS1) observations. The results in the next section will be summarized in section 5.1 and Figure 9.

![Figure 5](example.png)

**Figure 5.** Virtual observations of the EDR crossing, made along the virtual probe paths of orbits (a–c) 1s, (d–f) 2s, (g–i) 1t, and (j–l) 2t shown in Figure 3. The plots show three xyz (corresponding to LMN in the MMS observations) components of the (top) magnetic field, the (middle) electron bulk flow velocity, and the (bottom) electric field.
spacecraft was located in the region filled with the background plasma during this event. The parallel temperature anisotropy is seen in both simulation and observation plots (see Figures 7b and 7j) during the interval of a large $E_x$ (see Figures 7g and 7o as well as Figure 6d for simulation). This indicates adiabatically trapping of the inflowing electrons and the resulting energization by the ambipolar parallel electric field as predicted in past kinetic studies (e.g., Egedal et al., 2013; Le et al., 2016). Past kinetic studies also predicted that the electrons entering the EDR gain a significant amount of energy by the positive $E_x^r$ within the EDR (e.g., Le et al., 2016; Zenitani et al., 2011). The clear positive $E_x^r$ peak and the corresponding positive $\mathbf{J}_x \cdot \mathbf{E}$ ($\mathbf{J} \cdot \mathbf{E}$ in this case) peak seen in both simulation and observation plots (Figures 7f, 7h, 7n, and 7p) indicate the crossing of the EDR where the energy conversion was ongoing as predicted. The peak $E_x^r$ values in both simulation and observation plots reach the nearly constant $E_x$ values during the observed intervals (Figures 7f and 7n). The constant $E_x$ value (corresponding to $E_x^r$ in the simulation) is consistent with the simulated unnormalized reconnection rate measured at the X-line shown in Figure 3a ($E_x^r$=0.085V_{Ab}B_0). Considering this consistency between $E_x$ obtained from orbit 1s and the exact $E_x$ at the X-line, as well as the many quantitative consistencies between orbit 1s and MMS3 as shown above, the observed $E_x$ value averaged over the EDR crossing interval in Figure 7n ($E_x^r$=2.54 ± 1.07 mV/m) could reflect the unnormalized reconnection rate of this MMS event. In a similar procedure, the directly observed $E_x$ in orbit 2s and MMS1 are obtained as $E_x^r$=0.084 ± 0.026V_{Ab}B_0 and $E_x^r$=3.00 ± 0.70 mV/m, respectively, as displayed in Figures 9a and 9b. Note that the observed $E_x$ values shown in this paper were calculated in the spacecraft frame. As examined in G18, since the $(\mathbf{v} \times \mathbf{B})_\parallel$ term due to the relative motion of the X-line and the spacecraft is negligible if the X-line speed is of the order $10^4$ km/s (given the average $B_0$ is of the order $10^{-3}$ nT), $E_x$ in the spacecraft frame is nearly identical to that in the X-line frame.

As seen in Figures 3a and 6a, the maximum ion outflow speed (roughly corresponding to $V_{out}$) reaches 0.5V_{Ab} at $t = 50\Omega_e^{-1}$ in the simulation, which is roughly consistent with the ion Alfvén speed $V_{Alb}$ based on the density ($n_0 + n_l$) in the downstream region. This means that the plasma sheet flux tubes in the outer IDR (i.e., the whole diffusion region) had not yet been flushed out and the ion outflow speed $V_{out}$ is still controlled by the plasma sheet density in this locally steady phase at $t = 50\Omega_e^{-1}$.

Hence, the simulated normalized reconnection rate measured at the X-line and from the orbits 1s and 2s can be estimated as $R \sim E_x^r/V_{out}B_0 = E_x/V_{Alb}B_0$≈0.085±0.017, 0.174±0.051, and 0.169±0.052, respectively, as plotted in Figure 9c. Notice that as seen in Figure 3a, the outflow speed in the simulation gradually increases after reaching around $V_{out}$=0.5V_{Ab} ($V_{Alb}$ for $n = n_0 + n_l$). The depletion of the local density around the diffusion region by the inflowing low-density lobe plasma during reconnection may cause this increase. However, this increase of $V_{out}$ saturates after $t = 60-70\Omega_e^{-1}$ in the simulation likely due to the periodic boundary effect (Figure 3a). We expect that $V_{out}$ could get closer to $V_{Alb}$ if the boundary effect was negligible, although past kinetic simulations demonstrated that the peak $V_{out}$ is often below (i.e., does not exactly reach) $V_{Alb}$ (e.g., Liu et al., 2012). Since the spacecraft missed the center of the downstream region of ion outflow jets where the $B_l$ component would be close to zero, we cannot know the exact $V_{out}$ from the MMS observations. Thus, we estimate the observed normalized reconnection rate by assuming $V_{out}$ in the range between 0.5V_{Ab}≈7.55 km/s for $n_0 = 0.03$ cm$^{-3}$ and $B_0 = 12$ nT and $V_{Alb}$≈1,510 km/s, and the results for $V_{out}$ = 0.5V_{Ab} ($R$=0.280 ± 0.115 for MMS3 and $R$=0.330 ± 0.077 for MMS1) and $V_{out}$ = $V_{Alb}$ ($R$=0.140 ± 0.059 for MMS3 and $R$=0.165 ± 0.039 for

Figure 6. (a) Color plot of $V_{ix}$ with the in-plane magnetic field lines at $t = 50\Omega_e^{-1}$ (the same as Figure 3c) and the cut of $U_{ix}$ at $z = 0$. (b–d) Zoomed-in views of $B_y$, $E_y^r$ ($E_r$), and $E_z$ plots with the in-plane field lines and in-plane electron bulk flow vectors. The paths of orbits 1s and 2s are plotted in Figures 6b–6d.
MMS1) are displayed in Figure 9d. The results show that the rate normalized by \( V_{Aib} \) is reasonably consistent with the value obtained from the simulation (\( \sim 0.17 \)), which indicates that \( V_{out} \) during this MMS event was close to \( V_{Aib} \) (i.e., the downstream region may already be broadly filled with the lobe plasmas). As we will show in the next subsection, the remotely estimated normalized rate of this event (\( \sim 0.15 \)–0.2) also agrees well with the rate normalized by \( VAib \). The flatter density variation in the diffusion region in the MMS3 observation than in the virtual observation for orbit 1s (compare Figures 7a and 7i) may also support that \( V_{out} \sim V_{Aib} \) during this MMS event.

It should be noted here that the \( EM \) (i.e., out-of-plane) value in observations can vary depending on the accuracy of the coordinate system in which it is evaluated. Our companion paper G18 compares different coordinate systems during the EDR crossing interval of this MMS event and estimates the magnitude of errors on the normalized reconnection rate (\( EM/VAibBb \)) for each system. They found that the simulated rate agrees with the observed rate for the MVA-\( V_e \) method (the one employed in this paper) better than with the rates for other coordinates. They also confirmed this by applying the MVA-\( V_e \) method.
to the virtual observation data of orbit 1s and found that the difference of the reconnection rate between $E_y$ and $E_b$ (i.e., the error from the coordinates for the MVA-$V_e$ method) is less than 20%, which is smaller than the instrumental errors ($\sim$30%). These results confirm the adequacy of the comparisons between $xyz$ components in the present simulation and the observed MVA-$V_e$ based $LMN$ components as demonstrated above. The consistency of the peak values of $\mathbf{J}_e \cdot \mathbf{E}$ and $\mathbf{J}_b \cdot \mathbf{E}$ ($U_{\alpha\beta}\mathbf{E}_{\alpha\beta}$) in the simulation and the MVA-$V_e$ based observation (see Figures 7h and 7p) also indicates the adequacy of the orientation of the $M$ axes and the corresponding $E_r$ obtained by the MVA-$V_e$ method. Thus, the direct observations of the normalized and unnormalized reconnection rates shown in this section would be reasonably reliable. See G18 for more details of the direct observations of the reconnection rates by MMS. In the next two subsections, we further confirmed the reliability of these rates even from remote estimations at the reconnection separatrix located near the edge of the EDR.

### 4.2. Remote Measurements of the Normalized Reconnection Rate

Recently, Liu et al. (2017) proposed a theory showing that the normalized reconnection rate $R$ is described by the exhaust opening angle $\theta$ near the diffusion region (IDR) as the following equation:

$$R = \frac{E_f}{V_{Ab}\bar{B}_0} = \tan \theta \left(\frac{1 - \tan^2 \theta}{1 + \tan^2 \theta}\right)^{1/2} \sqrt{1 - \tan^2 \theta}$$

(3)

Here $R$ is the rate normalized by $B_0$ and the local Alfvén speed $V_{Ab}$ based on the density measured at the edge of the IDR. As discussed in section 4.1, this local Alfvén speed could increase toward $V_{Ab}$ from $V_{A0}$ after the density around the IDR is depleted by the inflowing low density plasmas from the lobe. As suggested in Liu et al. (2017), the opening angle $\theta$ in equation (3) corresponds to the angle of the reconnection separatrix line in the $x$-$z$ plane just outside the IDR edge. If the size of the EDR is negligible compared to the size of the IDR, this angle would correspond to the aspect ratio of the whole diffusion region (i.e., the separatrix line would connect straight to the center of the diffusion region from outside of the diffusion region). Indeed, the opening angle of the separatrix line in the simulation is nearly constant from the outside of the IDR to the edge of the EDR as seen in Figures 6a and 6c (see the field line angles near the white lines). As shown in Figure 6c, the angle of the separatrix line near the EDR, which would correspond to $\theta$ in equation (3), is about 12.5°. By substituting this angle into equation (3), the normalized reconnection rate in the simulation can be predicted as $R = 0.186$, which is reasonably consistent with the rate measured at the $X$-line ($R\sim 0.17$). This consistency indicates that the angle of the separatrix line near the EDR edge is useful to predict the normalized reconnection rate in this MMS event. Note that with this small observed angle of 12.5°, the prediction of equation (3) is similar to the classical Sweet-Parker scaling (Parker, 1957; Sweet, 1958) $R = \tan \theta = 0.22$. However, equation (3) has included the correction limiting the rate in the large opening angle limit, which is not considered in the Sweet-Parker model.

Figure 8a shows the virtual observation plot for orbit 1s of $|B_x/B_z|$, which corresponds to the angle of the in-plane field lines along the probe path. The vertical line in the left plots in Figure 8a shows the crossing point of the separatrix line where the field line angle is 12.5°. Figure 8b shows the values from the following $f_r$ as a function of the field line angle ($|B_x/B_z|$) along the probe path,

$$f_r \left(\frac{|B_x|}{|B_z|}\right) \approx \left[\frac{|B_x|}{|B_z|} \frac{1 - \left(\frac{|B_x|}{|B_z|}\right)}{1 + \left(\frac{|B_x|}{|B_z|}\right)}\right]^{1/2} \sqrt{1 - \left(\frac{|B_x|}{|B_z|}\right)^2}$$

(4)

Note that along with the separatrix line where $|B_x/B_z| = \tan \theta$, equation (4) corresponds to $R$ (i.e., equation (3)) as marked in Figure 8b. The first vertical line in the left plots in Figure 7 is the same point of the separatrix crossing as the vertical line in the left plots in Figure 8. As seen in Figures 6c and 7f and 7h, the separatrix crossing point corresponds to the edge of the EDR where the sign of $E_y$ changes from negative to positive and $\mathbf{J}_e \cdot \mathbf{E}$ starts increasing. In addition, as seen in Figure 8c, $V_{+x}$ and $V_{-x}$, which roughly correspond to the outflow and inflow components, start decreasing and increasing after the separatrix crossing, respectively. Similar features to these virtual observation results of orbit 1s near the separatrix line can be seen in the MMS3 observations. Figures 8e and 8f show $|B_x/B_z|$ and $f_r$ for MMS3. The vertical line on the right-most plots in Figure 8 and the first vertical line in the right-most plots in Figure 7 show the times when
\[ \tan^{-1}\left(\frac{|B_z|}{|B_x|}\right) = 12.5^\circ \] was determined. Similar to the simulation, this crossing time of \( \tan^{-1}\left(\frac{|B_z|}{|B_x|}\right) = 12.5^\circ \) corresponds to the crossing time of the edge of the EDR where the sign of \( E_y \) changes and \( J \cdot E \) starts increasing as well as the time where \( V_{\perp L} \) and \( V_{\perp N} \) start decreasing and increasing, respectively. In addition, other values such as \( V_{\perp L} \), \( E_x \), \( E_z \), and the electron temperature anisotropy at this crossing time are well consistent with the simulated values (compare the values near the first vertical line in the left and right plots in Figure 7). These consistencies strongly indicate a separatrix crossing by MMS3 with angle \( \tan^{-1}\left(\frac{|B_z|}{|B_x|}\right) = 12.5^\circ \), as also seen in the simulation. Thus, the normalized reconnection rate in this MMS event can also be predicted to be close to \( R = 0.15 - 0.2 \), which is consistent with the result from the direct observations for \( V_{out} \approx V_{\perp L} \) shown in section 4.1.

4.3. Remote Measurements of the Unnormalized Reconnection Rate

T. K. M. Nakamura et al. (2018) recently proposed a remote sensing technique to infer the unnormalized reconnection rate from in situ spacecraft observations of the separatrix boundary. In this technique, the unnormalized rate is estimated by calculating the increment of the reconnected magnetic flux that crosses the separatrix. When the location of the separatrix boundary is moving relative to the spacecraft location, the normalized rate can be estimated from a sequential observation of the boundary by more than two spacecraft along with the following equation,

\[ E_r \sim - (V_{\text{sim}} - V_c) \times B_{L,N}. \]  

Here \( V_{\text{sim}} \) is the timing velocity for the boundary observation, and \( V_c \) is the convection velocity of the field lines. Using this formalism, we can remotely estimate the unnormalized reconnection rate \( E_r \) from the difference between the timing velocity and the convection velocity at the separatrix boundary (i.e., from the velocity of the boundary motion in the frame of the magnetic field convection).

As seen in Figures 3e–3g, the location of the separatrix boundary near the EDR relative to the X-line (i.e., the field line structures around the vicinity of the X-line) changes only slightly even though the reconnection process continues. Hence, it can be said that the timing velocity \( V_{\text{sim}} \) of the separatrix crossing near the EDR...
would be the order of the spacecraft velocity relative to the X-line (or the X-line velocity relative to the spacecraft). As shown in Torbert et al. (2018), during this MMS event, this X-line velocity was estimated as $\sim -170 \text{ km/s}$ in the $x$-direction and $\sim -70 \text{ km/s}$ in the $z$-direction, leading to less than 0.1 mV/m of the contribution from the $-(V_{\text{sim}} \times B)_y$ term in equation (5). On the other hand, Figures 8c and 8g show the $x$ ($L$) and $z$ ($N$) components of the convection velocity $V_c$ for the virtual observation and the MMS3 observation, respectively. In both simulation and observation, $V_{c,x}$ ($V_{c,l}$) is of the order of $-0.1V_{Aeb}$ ($\sim 10^{-7} \text{ km/s}$) and $V_{c,z}$ ($V_{c,n}$) nearly equals to zero, leading to more than 1 mV/m of the contribution from the $V_c \times B_y$ term in equation (5), which is more than one order of magnitude higher than the $V_{\text{sim}}$ contribution. Thus, the spacecraft velocity ($V_{\text{sim}}$) would be negligible for the estimation of the unnormalized rate in this MMS event. In other words, the normalized reconnection rate ($E_r$) can effectively be estimated only from $(V_c \times B)_y$ of a single spacecraft in this MMS event.

As shown in Figures 8d and 8h (and Figures 9a and 9b), the estimated unnormalized reconnection rates are $E_r \sim 0.10 \pm 0.03V_{\text{Aeb}}B_y$ (for $V_c = V_{\text{EB}} = (E \times B)/B^2$) and $0.07 \pm 0.02V_{\text{Aeb}}B_y$ (for $V_c = V_{\text{Eb}}$) in the simulation and $E_r \sim 2.0 \pm 0.5 \text{ mV/m}$ (for $V_c = V_{\text{EB}}$) and $2.1 \pm 0.5 \text{ mV/m}$ (for $V_c = V_{\text{Eb}}$) in the observations, which are roughly consistent with the results from the direct observations shown in section 4.1. Note that the flux convection velocity $V_c$ was taken as $V_{\text{EB}}$ in T. K. M. Nakamura et al. (2018), which focused only on the region outside the diffusion region where nonideal terms in the generalized Ohm’s law can be negligible (i.e., $E^\parallel \sim 0$). In this paper, we also take $V_{c,z}$ and compare the results with the case for $V_{\text{EB}}$ (see red and magenta lines in Figures 8d and 8g as well as Figures 9a and 9c). As mentioned in section 4.2, the nonideal terms are roughly negligible (i.e., $E^\parallel \sim 0$) near the separatrix in both the simulation and observations. In such a situation with $E^\parallel \sim 0$, both $V_{\text{EB}}$ and $V_{c,z}$ should approximately equal to $V_e$ (e.g., Liu & Hesse, 2016). Indeed, in both the simulation and observations, the estimated unnormalized rates for both $V_{\text{EB}}$ and $V_{c,z}$ are close to the values directly obtained within the EDR, although the rates for $V_{c,z}$ are somewhat closer to the directly observed values than those for $V_{\text{EB}}$ (see Figures 9a and 9b). This difference between the results using $V_{\text{EB}}$ and $V_{c,z}$ could result from a small finite $E^\parallel$ ($E_{\text{mi}}$) value seen at the separatrix (Figures 7f and 7n) and/or different instrumental errors between $V_{\text{EB}}$ (i.e., errors for the field data) and $V_{c,z}$ (i.e., errors for the plasma data).

5. Summary and Discussion

5.1. Summary

In this paper, we compared high-resolution MMS observations of a magnetotail reconnection event on 11 July 2017 with virtual observations from a 2-D fully kinetic simulation of this MMS event. Based on the comparison, we obtained reliable values for both the normalized and unnormalized reconnection rates around the EDR crossing interval of this event. The quantitative consistencies of the profiles of the magnetic and electric fields and the electron bulk flow between the virtual and real MMS observations as seen in Figures 2, 5,
and 7 confirmed the adequacy of the simulation model as well as the paths of the virtual observation probes, which crossed the EDR as suggested by Torbert et al. (2018). The reconnection rates obtained from the simulation and observations are summarized in Figure 9. The unnormalized rate (the reconnection electric field $E_r$) measured at the X-line in the simulation is $E_r \sim 0.085 V_{\text{mag}} B_0$. The direct measurements of the electric field within the EDR for the virtual observations ($E_r \sim 0.085 V_{\text{mag}} B_0$) are similar to the value measured at the X-line. Since $V_{\text{out}} \sim 0.5 V_{\text{mag}}$ in the simulation, these simulated unnormalized rates can be transformed to the normalized rates as $R E_r / (V_{\text{out}} B_0) \sim 0.17$. The direct measurements of the unnormalized rates for the MMS observations are $E_r \sim 2.5$–3 mV/m. By assuming that $V_{\text{out}} \sim V_{\text{mag}}$ (i.e., dense initial plasma sheet plasmas have been almost flushed out from the reconnection region), these observed rates can be transformed to the normalized rates as $R \sim 0.14$–0.17, which are close to the simulated value. See our companion paper G18 for more details of the accuracy of these direct measurements of the rates by the MMS spacecraft. In addition to the direct observations, by identifying the separatrix lines in the virtual and MMS observations and employing recently proposed remote sensing techniques along the separatrix for the normalized rate (Liu et al., 2017) and the unnormalized rate (T. K. M. Nakamura et al., 2018), we estimated both the normalized ($R \sim 0.186$ for both the virtual and MMS observations) and unnormalized ($E_r \sim 0.07$–0.11 $V_{\text{mag}} B_0$ for the virtual observations and $E_r \sim 2$–3 mV/m for the MMS observation) rates from the observations at the separatrix near the edge of the EDR, both of which are also close to the direct observations within the EDR for both the virtual and MMS observations. These consistencies among the inferred rates at the X-line, the rates obtained from the direct measurements of $E_r'$ within the EDR, and the remotely estimated rates at the separatrix strongly indicate (i) that the reconnection rates of this MMS event are presumably close to the directly and remotely obtained ones ($R \sim 0.15$–0.2 for the normalized rate and $E_r \sim 2$–3 mV/m for the unnormalized rate), (ii) that the reconnection outflow speed may be close to $V_{\text{out}}$–$V_{\text{mag}}$, and (iii) that the remote sensing techniques employed in this paper are practically useful to quantitatively infer the reconnection rates along the separatrix boundary.

5.2. Relation to Global Geomagnetic Activities

From a macroscopic point of view, it has been suggested that the fast reconnection whose normalized rate is of order 0.1 may universally occur to sustain various explosive phenomena in collisionless plasmas such as the solar flare and geomagnetic substorms (e.g., Parker, 1973). For example, in the Earth’s magnetotail, using typical lobe magnetic field strength of the order $B_0 \sim 10$ nT, a half-thickness of the lobe region of the order $L \sim 10^5$ km and time scale of the substorm expansion phase of the order $\Delta t \sim 10^3$ s (e.g., McPherron, 1970), a typical global flux transfer rate, which corresponds to a global unnormalized reconnection rate, can roughly be estimated to be of the order $B_0 L / \Delta t \sim 1$ mV/m. Considering a typical lobe Alfvén speed of the order $V_{\text{mag}} \sim 10^3$ km/s (i.e., $V_{\text{mag}} B_0 \sim 10$ mV/m), a typical global normalized rate can roughly be estimated to be of the order 0.1 (e.g., Cassak et al., 2017). The results of this paper indicate that the fast reconnection whose normalized rate is of order 0.1 ($R \sim 0.15$–0.2 as shown in Figure 9) may really occur in the Earth’s magnetotail under typical $V_{\text{mag}} B_0$ conditions of the order 10 mV/m ($\sim 18$ mV/m for $n_0 \sim 0.03$ cm$^{-3}$ and $B_0 \sim 12$ nT as shown in section 3). However, note that it is difficult to know from the MMS observations of this event alone whether the fast rate, which was estimated only for the EDR crossing interval, was sustained for a sufficient period of time ($\sim 10^3$ s) as to consume the lobe field and cause the global flux transfer. For example, the macroscopic signature of the ion flow reversal seen during 22:32 UT–22:39 UT in Figure 1g may indicate that the reconnection process itself continued at least for 5–10 min. However, small-scale variations such as the repeated detection of the flux rope-like magnetic field variations seen in Figure 1a during 22:35–37 UT may indicate a nonsteady evolution of the reconnection process, which may affect the local or global flux transfer rate.

T. K. M. Nakamura et al. (2018) recently applied the same remote $E_r$ sensing technique (as employed in section 4.3 of this paper) to an MMS event in which the spacecraft observed reconnection signatures propagating along the separatrix boundary while crossing the plasma sheet boundary layer (PSBL) in the near-Earth ($X_{\text{GSM}} \sim 7 R_E$) magnetotail as reported by R. Nakamura et al. (2017, 2018). In their paper, the unnormalized reconnection rate was estimated as $E_r \sim 15$ mV/m, which is remarkably higher than the above typical rate of the order 1 mV/m as well as the rate of the MMS event studied in this paper ($E_r \sim 2$ mV/m). As discussed in T. K. M. Nakamura et al. (2018), since the unnormalized reconnection rate can be written by the normalized rate $R$ and the upstream $V_{\text{mag}} B_0$ as $E_r \sim RV_{\text{mag}} B_0$, assuming that $R \sim 0.1$ even in the PSBL event, the estimated high unnormalized rate could be caused by a large $V_{\text{mag}} B_0$. Such large $V_{\text{mag}} B_0$ conditions could be caused, for
example, by the externally added magnetic flux in the magnetotail (e.g., Birn & Hesse, 2007) resulting from a global magnetospheric convection (e.g., Hsu & McPherron, 2003; Pritchett, 2005). It is notable that the observation time interval of the above PSBL event was in the middle of the expansion phase of an intense substorm with an AE (auroral electrojet) index of \(\sim 1,000\) nT as shown in Nakamura et al. (2017), while the interval of the event shown in this paper was in the middle of a very weak increase of the AE index to \(\sim 200\) nT. Similarly, past ground-based observations demonstrated by tracing the open/closed field boundary in the ionosphere that the unnormalized rate of magnetotail reconnection under strong geomagnetic disturbances was estimated to be of the order 10 mV/m (e.g., Blanchard et al., 1997). These results indicate a positive correlation between the local unnormalized reconnection rate and the amplitude of the geomagnetic disturbances. In other words, the unnormalized reconnection rate, which corresponds to the increase rate of the reconnected flux in the near-Earth region, could be a key parameter to control the amplitude of geomagnetic disturbances. A future statistical approach would be important for better understanding of these relations between the local unnormalized reconnection rate (and the correlated upstream \(V_{\text{AibBb}}\) conditions) and the geomagnetic disturbances.

5.3. Effects of Three Dimensionality

Torbert et al. (2018) analyzed electron velocity distribution functions and other related parameters obtained from three-dimensionally separated four MMS spacecraft and showed no significant variations in the three-dimensional (i.e., \(M\)) direction. In addition, G18 performed a dimensionality analysis based on the magnetic field gradients obtained from MMS multipoint field data (Rezeau et al., 2018) and confirmed that the field
Finally, it should be noted that from the distance between the tailward edge of the outer EDR to the EDR center as shown in Figure 6b. More detailed results of this event were too small to be resolved. The consistencies between the present 2-D simulation and the MMS observations shown in this paper also support these observational results and indicate that the three-dimensionality along the spacecraft orbits near the EDR crossing interval of this MMS event is so weak to be negligible. Recent 3-D kinetic simulations with high ion-to-electron mass ratios ($m_i/m_e > 250$) have indeed demonstrated such a weak three-dimensionality near the EDR in cases of weak (Lapenta et al., 2015) and zero (Nakamura, Nakamura, Baumjohann, et al., 2016; Zeiler et al., 2002) guide field, while some other 3-D kinetic simulations with lower mass ratios in antiparallel (Fujimoto & Sydora, 2012) and strong guide field (Daughton et al., 2011; Nakamura, Nakamura, Narita, et al., 2016) cases demonstrated more turbulent features in the three-dimensional direction. To confirm the effects of the three dimensionality in this MMS event more directly, we additionally performed a 3-D fully kinetic simulation with the same parameter setting as the 2-D run mainly analyzed in this paper except for a reduced system size ($L_x \times L_y \times L_z = 48d_{e0} \times 6.7d_{e0} \times 20d_{e0} = 2,880 \times 400 \times 1,200$ cells with a total of $2.8 \times 10^{11}$ superparticles) and slightly smaller $m_i/m_e (=256)$ and $\omega_{pe}/\Omega_e (=1.25)$.

The results of this 3-D run in a nearly steady reconnection phase are summarized in Figure 10. As shown in Figures 10a–10c, the $E'_y$ structure near the EDR is almost laminar, while much stronger $E'_y$ fluctuations are visibly seen along the downstream separatrix boundary where the relatively stronger density jump across the boundary exists, as also seen in past 3-D fully kinetic simulation with a smaller system size (Zeiler et al., 2002). The $E'_y$ fluctuations develop mainly in the direction perpendicular to the magnetic field approximately in the $y$-direction, as shown in the red and blue surfaces in Figure 10a. As shown in Figure 10d, the dominant wavelength of these $E'_y$ fluctuations is of the electron-inertial scale based on the background density ($k_yd_{e0}^{-1}$) or the hybrid scale based on the downstream temperatures ($k_y (p_0/n_0)^{0.5}d_{e0}^{-1}$). This wavelength range is roughly close to the unstable range of the longer wavelength electromagnetic lower-hybrid drift instability (Daughton, 2003). The electric field fluctuations in a similar wavelength range were also seen along the magnetosphere-side separatrix in recent 3-D fully kinetic simulations of asymmetric magnetopause reconnection (Le et al., 2017, 2018). Notice that the electron-to-ion scale fluctuations seen in Figure 10 appear only near the separatrix region as shown in Figure 10f, while larger scale but much weaker fluctuations are seen near the outer EDR. As discussed in Nakamura, Nakamura, Baumjohann, et al. (2016), this weak three-dimensionality near the EDR could be because, in the steady phase of reconnection, the hot and dense plasmas originally located near the diffusion region have already been convected to the downstream region. The dynamics of this evolved and steady type of symmetric reconnection produce a weaker and stronger density and temperature gradients near the $X$-line and in the downstream region, respectively. These 3-D simulation results predict that the three dimensionality is quite small for the spacecraft paths focused in this paper to obtain the reconnection rates that are in the range from the southern and tardyward edge of the outer EDR to the EDR center as shown in Figure 6b. More detailed results of this 3-D run focusing on the small-scale fluctuations along the separatrix will be reported in the near future.

5.4. Some Remarks on Future Work

Finally, it should be noted that from the distance between the $B_z$ and $B_y$ reversals for orbit 1s ($p_0$ and $p_1$ points in Figure 5a), $\sim 12d_{e0} - 7d_{e0}$ (~200 km for $n_0 = 0.03$ cm$^{-3}$), and the duration between $p_0$ and $p_1$ for MMS3 (Figure 2a), ~0.4–0.5 s, the motion speed of the virtual probes for orbit s in the $x$-direction can presumably be estimated as 400–500 km/s, which is roughly two times faster than the observed value reported in Torbert et al. (2018). Figure 11 shows the virtual observation results for a new virtual probe path (orbit 1s), which is the same as orbit 1s except that the orbit in the $x$-direction is half the extent (i.e., half the motion...
speed in the x-direction) of the orbit 1s. Notable differences between orbit 1s and orbit 1s’ are seen especially in the outflow jet (\(V_{\text{ex}}\)) component (compare Figures 5b and 11c). For the tailward jet (before the p0 point), a step-like stronger \(V_{\text{ex}}\) enhancement is seen in orbit 1s’, since the path of orbit 1s’ goes into the middle of the outer EDR around the first weak \(B_x\) interval at \(x \sim -10d_{\text{E}}\) in Figure 11a. On the other hand, for the earthward jet (after the p0 point), \(V_{\text{ex}}\) at the first \(B_x\) reversal (the p1 point) for orbit 1s’ is less than half of that for orbit 1s, since the p1 point for orbit 1s’ locates closer to the X-line. This weaker \(V_{\text{ex}}\) for orbit 1s’ leads to a smaller \(V_{\text{ex}}B_x\), which allows \(E_z\) to go back to positive after the second \(B_x\) reversal only for orbit 1s’ (compare Figures 5c and 11d). This negative-to-positive \(E_z\) variation after the p1 point for orbit 1s’ is similar to the MMS3 observation (compare Figures 2c and 11d). However, the enhancement of the strong tailward jet (negative \(V_{\text{ex}}\)) at \(x \sim -10d_{\text{E}}\) for orbit 1s’ is inconsistent with the MMS3 observation in which no significant jet enhancement around the first weak \(B_x\) interval was seen (see at \(t \sim 0.5\) s in Figures 2b). Namely, the structures of the electron outflow jets before and after the p0 point for the MMS3 observation were closer to those for orbit 1s and orbit 1s’, respectively. This indicates that the spacecraft motion relative to the X-line and/or the spatial scale (or the amplitude) of the outflow jets may not be constant during this MMS EDR crossing event. Although this study focuses only on the time interval before the p0 point during which the MMS observations agree well with the virtual observations for orbit s, such time evolution effects may be required for more detailed discussions on the EDR and the outer EDR structures.

6. Conclusions

We have performed a large-scale 2-D fully kinetic simulation of an MMS magnetotail reconnection event with a weak geomagnetic disturbance (less than 200 nT of the AE index) on 11 July 2017. By referring to the \(B_x\) (\(B_x\) in the simulation) variation near the EDR crossing interval in the MMS observation, we performed virtual observations in which the virtual probes move in the simulation domain to reproduce the \(B_x\) variation. The virtual observation results are quantitatively consistent with the MMS observations normalized by the background density (\(n_B \sim 0.03\) cm\(^{-3}\)) and reconnecting field strength (\(B_B \sim 12\) nT), which are employed to set up the simulation. Based on the consistencies, we obtained both the normalized reconnection rate (\(R\)) and the unnormalized reconnection rate (corresponding to the reconnection electric field, \(E_z\)) from both the direct measurements of the electric field within the EDR and the remote estimations at the separatrix boundary using recently proposed remote sensing techniques. The rates obtained from both the direct and remote observations (\(R \sim 0.15\)–0.2 and \(E_z \sim 2\)–3 mV/m) are indeed consistent with the simulated rates measured at the X-line. Details of the observation part of the direct measurements of the rates are described in our companion paper G18. The obtained normalized rate strongly indicates that fast reconnection with a normalized rate of the order \(R \sim 0.1\) really occurred in the magnetotail during this MMS event. Considering past ground-based observation studies (e.g., Blanchard et al., 1997) and a recent study of another MMS event (T. K. M. Nakamura et al., 2018) in both of which the unnormalized rate under strong geomagnetic disturbances was estimated to be of the order \(\sim 10\) mV/m, the weaker unnormalized rate under the weaker geomagnetic disturbance shown in this paper indicates that the local unnormalized reconnection rate in the magnetotail reconnection process may be a key parameter to control the amplitude of geomagnetic disturbances. An additional 3-D fully kinetic simulation of this MMS event demonstrated that the three-dimensionality is negligible near the EDR, as suggested in Torbert et al. (2018) and G18 from the multipoint analyses of the MMS data observed near the EDR crossing interval of this MMS event.

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