Abstract  Magnetic reconnection is a universal process where energy is transferred from magnetic fields to particles. However, it remains unclear whether this transfer of energy includes the direct energization of particles to high energies (i.e., >10s of keV). We compare the spectral indices of energetic (50–200 keV) electrons from six magnetotail electron diffusion region candidates encountered by MMS with those from “quiet-time” plasma sheet crossings to test whether energetic electron enhancements result from direct energization at/near the reconnection site or simply focusing high-energy populations that do not originate from the nearby X-line and already exist in the plasma sheet along the newly reconnected field lines. The study suggests that active reconnection can be a source of localized electron energization. However, the EDR spectra are not outside the range of those from the quiet-time plasma sheet, which surprisingly still often have very energetic (up to and beyond 200 keV) electrons present.

Plain Language Summary  Magnetic reconnection is a fundamental process in plasma physics and is hypothesized to be an efficient process to accelerate particles up to very high energies by transferring energy held in the magnetic field to the particles. Similar to how a taught rubber band can snap, releasing its latent energy—so too do magnetic fields “snap” in reconnection; as the field lines relax to their normal state, they transfer their energy to particle. This paper addresses an outstanding question of whether magnetic reconnection in fact produces high energy electrons. While many computer simulations have predicted this, most in situ observations have focused on energization at much lower energies than we look at here. However, this paper compares a handful of events very near the region where reconnection is believed to occur to a “control group” of nonactive regions not near a reconnection site and finds that the events nearest the reconnection do tend to have more energetic electrons. This provides evidence that the energetic electrons are in fact coming from the reconnection site.

1. Introduction
Magnetic reconnection is considered a fundamental universal process where energy is transferred from magnetic fields to particles (Cassak & Shay, 2012; Galeev, 1979; Nagai et al., 2013; Phan et al., 2006). However, it remains unclear whether this transfer of energy includes the direct energization of particles to high energies (i.e., 10s of keV and above). The energization of electrons from ~10 s of keV and above) have been observed in the magnetotail for decades in association with high-speed reconnection jets (Ashour-Abdalla et al., 2011; Fu et al., 2011, 2013) and substorm processes (Baker & Stone, 1976, 1977; Duan et al., 2014; Terasawa & Nishida, 1976) believed to be regulated globally by reconnection (Angelopoulos et al., 2008; Baker et al., 2002, 1996). However, there is a great uncertainty as to whether the reconnection accelerates the particles directly, by means of secondary processes that can occur substantial distances from the reconnection sites, or by associated dynamical processes unrelated to the reconnection itself. The Wind spacecraft (Ogilvie & Desch, 1997) provided the first in situ observations suggesting direct energization of electrons up to ~300 keV (the...
To date, only six potential electron diffusion regions (EDRs) have been identified by the MMS team in the magnetotail based on plasma and fields parameters. We focus on these events as they are clear flow reversals and thus, by definition, are assumed to occur in very close proximity to active reconnection sites. These events are listed in Table 1; though these events are presented in the references cited in Table 1, not all of these events are explicitly referred to as EDR candidates in those works. As can be seen from Table 1, all six of the EDR candidate events occur in the magnetotail at radial distances between 16 and 23 RE.

Generally, magnetospheric electron distributions have two components: the thermal and the nonthermal. To investigate the potential significance of electron energization at/near an X-line on the nonthermal part of the electron distribution, we chose to compare the spectral indices of the energetic (50–200 keV) electrons observed by FEEPS for these events with those from “typical, quiet-time” plasma sheet crossings (PSCs) by MMS, which we used as a baseline of energetic electrons in the magnetotail for comparison. It should be noted that although the FEEPS instruments measure electrons from 30 keV up to ~560 keV, analysis of the higher energies must account for the presence of a constant background due to cosmic rays that create an apparent local minimum near the center of the ion diffusion region traversed by the spacecraft.

The shortage of in situ observations has not hindered the theoretical study of electron energization in reconnection. In addition to the direct energization by the reconnecting electric field, multiple models have been used to present potential mechanisms that can accelerate electrons within and near reconnection sites (Birn et al., 2012; Egedal et al., 2013; Treumann & Baumjohann, 2013). Specific mechanisms proposed include: multistep energization from a combination of “surfing” along the boundary of the current sheet, followed by Speiser-like and betatron acceleration (Hoshino, 2005); guide field-retention of electrons near an X-line (Pritchett, 2005); direct energization due to a large-scale positive potential along the field line (Egedal et al., 2010); wave-particle interactions either in the reconnecting current sheet (Jaynes et al., 2016; Shinohara et al., 1998) or near the pileup region (Hoshino et al., 2001; Imada et al., 2007); and finally, Fermi-like acceleration due to either contracting (Chen et al., 2008; Drake et al., 2006) or coalescence of (Oka et al., 2010; Retinò et al., 2008) magnetic islands.

Recently, new in situ observations from the Magnetospheric Multiscale (MMS) mission (Burch, Moore, et al., 2016) have revolutionized the understanding of magnetic reconnection providing high-resolution, multipoint in situ measurements of reconnection events. Though several electron-scale studies of reconnection have shown evidence of electron energization, at times even up to 10s of keV energies (Burch, Torbert, et al., 2016; Torbert et al., 2018), few studies have focused on the significance of high-energy (>30 keV) particle energization (Ergun et al., 2020). In particular, the study of potential particle energization resulting from magnetic reconnection was a critical science objective for the MMS Energetic Particle Detector (EPD) investigation (Mauk et al., 2016). The investigation includes the Energetic Ion Spectrometer (EIS; Mauk et al., 2016) and Fly’s Eye Energetic Particles Spectrometer (FEEPS; Blake et al., 2016) instruments. The analysis presented here primarily focuses on energetic electron observations obtained by the FEEPS instruments. This study examines whether very high energy (10s of keV and above) electrons are accelerated via (a) direct energization from processes during reconnection events or (b) simple redirection/focusing of energetic populations that already exist in the plasma sheet.

### 2. Observations

To investigate the potential significance of electron energization at/near an X-line on the nonthermal part of the electron distribution, we chose to compare the spectral indices of the energetic (50–200 keV) electrons observed by FEEPS for these events with those from “typical, quiet-time” plasma sheet crossings (PSCs) by MMS, which we used as a baseline of energetic electrons in the magnetotail for comparison. It should be noted that although the FEEPS instruments measure electrons from 30 keV up to ~560 keV, analysis of the higher energies must account for the presence of a constant background due to cosmic rays that create a “minimum ionizing” peak near ~300 keV. The lowest energy (30 keV) FEEPS electron channel was also disregarded throughout this study because this channel often contains significant noise due to its proximity to the detectors’ discriminator threshold.

An automated identification routine was employed using the following criteria to identify the PSC events: (1) the MMS spacecraft were required to be in the magnetotail, defined as \( X_{\text{GSE}} < -7.5 \) RE and instrument’s highest energy channel) in an ion diffusion region in the deep (60 RE) terrestrial magnetotail (Øieroset et al., 2002). These measurements found that the spectral index (i.e., \( \gamma \), where electron phase space density \( \text{PSD} \propto E^{-\gamma} \)) had an apparent local minimum near the center of the ion diffusion region traversed by the spacecraft.

The shortage of in situ observations has not hindered the theoretical study of electron energization in reconnection. In addition to the direct energization by the reconnecting electric field, multiple models have been used to present potential mechanisms that can accelerate electrons within and near reconnection sites (Birn et al., 2012; Egedal et al., 2013; Treumann & Baumjohann, 2013). Specific mechanisms proposed include: multistep energization from a combination of “surfing” along the boundary of the current sheet, followed by Speiser-like and betatron acceleration (Hoshino, 2005); guide field-retention of electrons near an X-line (Pritchett, 2005); direct energization due to a large-scale positive potential along the field line (Egedal et al., 2010); wave-particle interactions either in the reconnecting current sheet (Jaynes et al., 2016; Shinohara et al., 1998) or near the pileup region (Hoshino et al., 2001; Imada et al., 2007); and finally, Fermi-like acceleration due to either contracting (Chen et al., 2008; Drake et al., 2006) or coalescence of (Oka et al., 2010; Retinò et al., 2008) magnetic islands.

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### Table 1

| Magnetotail EDR candidate | Radial distance |
|---------------------------|----------------|
| 2017-05-28/04:00:50 (Rogers et al., 2019) | 22.7 RE |
| 2017-06-17/20:24:07 (Huang et al., 2018) | 22.6 RE |
| 2017-07-03/05:26:51 (Chen et al., 2019) | 18.0 RE |
| 2017-07-11/22:34:02 (Torbert et al., 2018) | 22.3 RE |
| 2017-07-26/07:03:40 (Ergun et al., 2018) | 24.8 RE |
| 2017-08-10/12:18:33 (Zhou et al., 2019) | 16.1 RE |

*Note that three separate EDR candidates were identified within 60 s of this event.*
20 R_E < Y_{GSSE} < 20 R_E; (2) magnetic field and plasma requirements were enforced to ensure that the spacecraft were close to the plasma sheet, specifically that |B_z| > |B_x|, |B_y|, B_x < 1 nT, and β_{avg} ≥ 1 (Burin des Roziers et al., 2009); (3) a minimum event time duration was set at least 6 s; (4) “quiet-time” crossings were selected based on requirements that the maximum of the AE index from the preceding 3 hr (AE*; Meredith et al., 2004) be <300 nT and any events with fast flows (|v_{x, ion_avg}| ≥ 100 km/s; Kiehas et al., 2018) were removed. Overall, these criteria resulted in the list of 133 crossings presented in the supporting information Table S1 (henceforth referred to as PSC_{all}), which occurred at distances between 11.6 and 24.9 R_E downtail. This complete PSC_{all} list was then down-selected to only include those crossings which occurred at radial distances between 16 and 23 R_E—the same range spanned by the EDR candidate events. This resulted in the dataset of 28 quiet-time PSCs to be used in this study (PSC_{16–23}). The average duration of the PSC_{16–23} events is ~200 s (σ = 198 s). For this reason, each EDR event was analyzed in this study using a 200-s window centered on the times listed in Table 1.

3. Analysis and Discussion

To analyze the variation in the spectral index of the energetic electrons between the EDR and PSC_{16–23} events, representative spectra are needed to be selected for each of the events. FEEPS has 2.5-s resolution in survey mode and captures multiple spectra throughout each of the events. Initial analysis of the spectra during these events found that simply taking the average of these spectra within any given event artificially inflated the resultant spectra in a fashion that was not truly representative of the spectra observed throughout the event. Figure 1a shows the average (i.e., average intensity observed in each energy channel) with error bars showing the standard deviation of the fluxes at that energy, as well as the 25%, 50%, and 75% flux spectra for each EDR candidate event. (b) Comparison of the “max flux spectra” (i.e., maximum flux observed in each energy channel) for the PSC_{16–23} (cyan) and EDR candidate (individually colored) events. The dashed cyan line shows the “average max flux spectra” (i.e., average of all maximum fluxes observed in each energy channel) for the PSC_{16–23} events; the gray line shows the five-count level of the FEEPS instruments.

Figure 1. (a) Comparison of the average flux spectra (i.e., average flux observed in each energy channel) with error bars showing the standard deviation of the fluxes at that energy, as well as the 25%, 50%, and 75% flux spectra for each EDR candidate event. (b) Comparison of the “max flux spectra” (i.e., maximum flux observed in each energy channel) for the PSC_{16–23} (cyan) and EDR candidate (individually colored) events. The dashed cyan line shows the “average max flux spectra” (i.e., average of all maximum fluxes observed in each energy channel) for the PSC_{16–23} events; the gray line shows the five-count level of the FEEPS instruments.
otherwise noted, the PSC16–23 data are from MMS–2, and the EDR data are the average across MMS–1,–2, and–3 (denoted as “MMS–X”); MMS–4 data are excluded because sunlight contamination due to foil damage in the FEEPS detectors results in a very poor angular coverage on that spacecraft.

Visual comparison of spectra from the EDR and PSC16–23 events in Figure 1b finds that four out of six of the EDR events (colored by event) appear to have harder spectra than the overwhelming majority of the PSC16–23 events (cyan). However, we note that with or without the presence of an EDR, most spectra show significant intensities at relativistic energies (i.e., hundreds of keV), as predicted previously (Pritchett, 2005). It is clear that most of the EDR events (five out of six) have intensities at energies >50 keV well above the average for the PSC16–23 events (dashed cyan line).

For direct comparison to previous results, including those of Øieroset et al. (2002), we also present the spectra in phase space density (PSD) in Figure 2. The PSDs \( f \) are calculated from the intensities \( J \) using the equation \( f = J/p_{\text{rel}}^2 \), where \( p_{\text{rel}} \) is the relativistic momentum \( (p_{\text{rel}} = \gamma m_{\text{e}} v) \). Note that the energy dependence of the relativistic corrections used in calculating the PSDs do slightly alter the shape of the spectra relative to the intensities.

To quantitatively compare these “max intensity spectra,” a power law fit \( J(E) = J_0 E^{-\gamma} \) was calculated, where \( J \) is the electron intensity and \( E \) is the energy, to determine the spectral indices \( \gamma \). One additional criterion was added to ensure that each event had sufficient counts to accurately determine the spectral index: the spectrum must have at least three energy channels with five or more counts. All six EDR events easily met this criterion, but the PSC16–23 data set was reduced to only 21 events with valid spectral fits. Furthermore, any energy channels with less than five counts were not included in the fit.

Comparison of the calculated spectral indices between the two data sets is presented in Figure 3. This shows histograms of the calculated spectral indices for each data set using both intensities (3a) and PSD (3b). The calculated spectral indices for each of the six EDR events are shown separately for MMS–1 (black hatching), MMS–2 (red hatching), MMS–3 (green hatching), and average from across MMS–1–3 (i.e., MMS–X; blue hatching) versus those for the PSC16–23 events (cyan). The average spectral index values for the EDR events are slightly lower (i.e., harder) than those for the PSC16–23 events using both intensities (EDRs: 3.88, PSC16–23: 4.02) and PSDs (EDRs: 4.45, PSC16–23: 4.70).

The small number of EDR candidate events makes it difficult to make any statistically significant conclusion regarding the energization of energetic electrons in magnetic reconnection. However, the clear clustering...
of the spectral indices calculated for the six EDR candidates presented here—and their relative hardness (i.e., lower spectral index) compared to those of the larger PSC16–23 data set—suggest that the EDR events tend to have a more significant population of energetic particles, corresponding to harder energy spectra. If true, this larger population of energetic (say $\gtrsim 100$ keV) electrons is most reasonably assumed to result from local energization associated with the active reconnection site (Ergun et al., 2020, 2018). It should be noted that the spectral indices observed for these EDR cases by FEEPS are significantly lower (i.e., harder) than the 4.8 to 5.7 range reported for an ion diffusion region at 60 RE by Wind (Øieroset et al., 2002), but they generally agree with recent analysis of reconnection-driven turbulence observed by MMS (Ergun et al., 2020). However, it must be noted that the calculation of PSD in the Øieroset et al. analysis did not take into account relativistic corrections, which are significant at the energies being considered (e.g., 20% correction at 100 keV). These energy-dependent corrections significantly alter the shape of the spectra and the resulting spectral index, which provides further evidence that the plasma sheet is an effective accelerator of relativistic electrons. Furthermore, though not shown, analysis of the evolution of the spectral indices for the FEEPS spectra within the vicinity (±30 s) of the candidate EDRs (and the assumed nearby X-line) found no minimum in proximity to the EDR. Although the previous Wind results found evidence of a source of energetic electrons within the ion diffusion region (Øieroset et al., 2002), these results suggest that the source is not within the (much smaller) EDR (Ergun et al., 2018).

Examination of the distributions of the spectral indices for the PSCs can lead one to further conclusions. For example, the fact that the spectral indices of even these PSC16–23 events do occasionally have much harder spectra (equal to or harder than the EDR events) suggests that (a) direct energization (i.e., reconnection) is happening somewhere locally—perhaps at a very small-scale (see companion paper by Turner et al., 2020)—despite the relatively quiet global state of the magnetosphere; (b) that these higher energy electrons are being generated by reconnection in the very distant magnetotail and are being transported through the plasma sheet, as previously suggested (Øieroset et al., 2002); or (c) such energization occurs with processes not directly related to reconnection. No clear trend was seen when the spectral indices of the six EDR candidate events were sorted by radial distance.

Figure 3. Distribution of the calculated spectral indices for the PSC16–23 events (cyan) measured by MMS-2, as well as those for the six EDR candidate events observed by MMS-1 (black), 2 (red), 3 (green), and the average of MMS-1-3 (i.e., “MMSX”; blue hatching).
4. Conclusion

This paper analyzes the spectral indices of energetic electron distributions for six magnetotail EDR candidate events observed by MMS compared to a data set of 28 quiet-time plasma sheet crossings from the same tail region. Although there are too few EDR candidates to perform statistically robust analysis, the results presented here consistently find up to and above 400 keV energetic electrons in these events and generally significantly harder spectra than the comparator quiet-time plasma sheet crossings. This suggests that these energetic electrons are coming from a local source, which we assume is related to active reconnection (Ergun et al., 2020). However, the plasma sheet crossing events show that very energetic particles do exist even in the quiet-time plasma sheet, which may simply be sourced by distant, but globally less significant, reconnection sites or to processes not directly related to reconnection. Hopefully, future observations will reveal more EDR candidate events, which will enable statistical considerations of electron energization by reconnection. Future studies should also consider electron distributions measured in all the ion diffusion regions and reconnection jets events observed by MMS.

Data Availability Statement

All MMS data presented here are Level 2 and can be retrieved from the MMS Science Data Center (https://lasp.colorado.edu/mms/sdc/public/).

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