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Energetic electron acceleration observed by MMS in the vicinity of an X-line crossing

A. N. Jaynes¹, D. L. Turner², F. D. Wilder¹, A. Osmane³, D. N. Baker¹, J. B. Blake⁷, J. F. Fennell², I. J. Cohen⁴, B. H. Mauk⁴, G. D. Reeves², R. E. Ergun¹, B. L. Giles⁶, D. J. Gershman⁵, R. B. Torbert⁷, and J. L. Burch⁸

¹Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, Boulder, Colorado, USA, ²Space Sciences Department, The Aerospace Corporation, El Segundo, California, USA, ³Department of Radio Science and Engineering, Aalto University, Helsinki, Finland, ⁴The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, USA, ⁵Los Alamos National Laboratory, Los Alamos, New Mexico, USA, ⁶NASA Goddard Space Flight Center, Greenbelt, Maryland, USA, ⁷Space Science Center, University of New Hampshire, Durham, New Hampshire, USA, ⁸Southwest Research Institute, San Antonio, Texas, USA

Abstract During the first months of observations, the Magnetospheric Multiscale Fly’s Eye Energetic Particle Spectrometer instrument has observed several instances of electron acceleration up to >100 keV while in the vicinity of the dayside reconnection region. While particle acceleration associated with magnetic reconnection has been seen to occur up to these energies in the tail region, it had not yet been reported at the magnetopause. This study reports on observations of electron acceleration up to hundreds of keV that were recorded on 19 September 2015 around 1000 UT, in the midst of an X-line crossing. In the region surrounding the X-line, whistler-mode and broadband electrostatic waves were observed simultaneously with the appearance of highly energetic electrons which exhibited significant energization in the perpendicular direction. The mechanisms by which particles may be accelerated via reconnection-related processes are intrinsic to understanding particle dynamics across a wide range of spatial scales and plasma environments.

1. Introduction

The fundamental plasma process of magnetic reconnection, which transfers vast amounts of energy from storage in magnetic fields to kinetic energy, occurs along the magnetopause as well as downstream in the magnetotail. Magnetic reconnection in the plasma environment specific to the dayside magnetopause region has been studied extensively to date, most notably with the Cluster mission [Escoubet et al., 2001], although many of the related processes from large to small scales remain a mystery. In particular, energetic electron observations resulting from dayside magnetic reconnection effects have been reported on relatively rarely [Tang et al., 2013]. Several studies have noticed an energetic electron layer residing just outside the magnetopause at high latitudes [Scholer et al., 1982, and references therein]. These observations were made near or within the polar cusp and showed notable anisotropies indicative of streaming along local field lines [e.g., Scholer et al., 1982]. This layer has been shown to be persistent in the distant tail region of the magnetopause [Baker and Stone, 1977], indicating that this is a fairly ubiquitous process. A more recent example is a study by Walsh et al. [2012] that showed field-aligned electron distributions of tens of keV appearing at the high-latitude dayside magnetopause boundary as observed by Cluster. The explanation given for this was magnetospheric plasma being "released" to the region outside the magnetosphere following the reconfiguration of field lines during reconnection. All of the studies mentioned above have reported strongly field-aligned distributions with respect to the local magnetic field.

Although the magnetotail is a very different plasma regime from the dayside magnetopause, it is useful in this case to review the multitude of studies on energetic electrons in tail reconnection that have been performed with use of Cluster, Wind, and Time History of Events and Macroscale Interactions during Substorms data [e.g., Birn et al., 2012]. Electron energization up to ~300 keV directly in the diffusion region was observed with Wind [Øieroset et al., 2002]. Unlike the streaming features seen consistently in the dayside high-energy electron observations, this study reported isotropic pitch angle distributions. Øieroset et al. [2002] noted that lower hybrid wave turbulence was recorded spanning the time of electron acceleration, but the spacecraft did not
obtain observations of higher-frequency waves for this event. Parallel electric fields, $E_{\parallel}$, in the direction of the local magnetic field have been implicated in this intense acceleration process and come in the form of phase space holes and double layers. Egedal et al. [2012] successfully reproduced Cluster observations of suprathermal electron generation using parallel electric field structures within kinetic simulations. Theoretically, this mechanism can provide energization up to hundreds of keV or even MeV [Egedal et al., 2015].

Two additional mechanisms involving magnetic islands to produced energetic electrons via reconnection have been proposed in recent years. Drake et al. [2006] performed 2-D particle-in-cell simulations that showed electron acceleration to high energy is possible through Fermi reflection with multiple “contracting” magnetic islands. Electrons can be subjected to this mechanism repetitively during the typical reconnection environment in the magnetotail. Another, slightly conflicting mechanism was put forth in Pritchett [2008]; this simulation did not show the same type of acceleration process but did find that energization up to hundreds of keV could result as a result of “converging” magnetic islands in the presence of a guide field. Both simulations have aspects that have been observed in data, and both mechanisms can potentially result in relativistic electron production from magnetic reconnection related processes.

In this manuscript, we report on observations of energetic electrons up to $\sim 100$ keV observed simultaneously with whistler-mode waves and broadband electrostatic waves during an X-line crossing in the vicinity of a magnetic reconnection site. A key question to be answered from the observations presented here, and future collaborations with simulation, is: what is the role of reconnection in energetic particle production at the dayside magnetosphere boundary?

2. Data and Instrumentation

This study takes advantage of the high-fidelity data now available from NASA’s Magnetospheric Multiscale (MMS) mission [Burch et al., 2015], launched in March 2015. The four, identically outfitted MMS spacecraft were launched in highly elliptical orbits designed to gather in situ measurements while crossing the magnetopause boundary region during two consecutive sweeps of the dayside magnetosphere in the first phase of the nominal mission lifetime. The apogee of the tetrahedron formation during this stage is approximately $\sim 12$ R$_E$. The suite of particle and field instruments on board each of the MMS spacecraft offer state-of-the-art measurements of the plasma environment with appreciably high time and energy resolution to observe the fundamental processes that take place during magnetic reconnection. These include the primary instrument used in this paper, the Fly’s Eye Energetic Particle Spectrometer (FEEPS) [Blake et al., 2015] within the Energetic Particle Detector instrument suite [Mauk et al., 2014]. Data from additional instruments, the Fast Plasma Investigation (FPI) [Pollock et al., 2016] and the FIELDS instrument suite [Torbert et al., 2014], were used to support the analysis presented.

The FEEPS instrument is capable of measuring all-sky snapshots (nearly 360°) of electron intensity from $\sim 30$ to 600 keV every 0.33 s in burst mode, as shown in this study. Using local magnetic field measurements, pitch angle distributions at differential energies can be obtained at this same cadence. From the FIELDS suite, we use data from (1) the fluxgate magnetometer (FGM) [Russell et al., 2014], (2) the electric field double probe (EDP) [Ergun et al., 2014; Lindqvist et al., 2014], and (3) the search coil magnetometer (SCM) [Le Contel et al., 2014] to investigate the magnetic field context and wave spectral characteristics observed during this event. FGM measures DC magnetic fields at resolutions up to 128 Hz, while EDP and SCM sample electric and magnetic field waveforms respectively, at up to >8 kHz resolution.

3. Observations of Accelerated Particles

The observations for this event were obtained during a region of interest time period on 19 September 2015, while MMS spacecraft were located at about 10.7 R$_E$. Figure S1 in the supporting information shows the trajectory of this orbit and the location of the spacecraft (green dot) at 10:00 UT. Based on the Shue et al. [1998] model of the magnetopause location, MMS was residing at the boundary for this event, which is confirmed using the in situ data. The solar wind was relatively quiet, with a flow speed persisting near 420 km/s, and $AE$ was only moderate, remaining near 600 nT (Figure S2). A modest value of $-47$ nT was reached around 8:30 UT by the $Dst$ index in a nonstorm disturbance on this day. An overview of the event, including thermal electron and ion spectra, temperatures, and densities, along with magnetic field and waves data, is shown in Figure S3.

During the period of time focused on for this event, 10:02:00–10:13:00 UT, the four MMS spacecraft originated in the magnetosheath and subsequently traversed a reconnection jet reversal, ending up skimming the
Figure 1. Overview of electron dynamics during the event; (a) Omnidirectional averages of electron intensity from ~30 to 300 keV on MMS 1 and MMS 2 FEEPS instruments, in an energy spectrogram format; (b) Electron energy flux spectrogram from FPI on MMS 2 covering ~10 eV–30 keV; (c) Magnetic field data from MMS 2 in GSM coordinates.

separatrix region for the ensuing ~5 min. The spacecraft make several very brief (< 20 s) excursions into the magnetosphere side of the exhaust jet, returning back into the boundary layer each time during the interval from ~10:06 to 10:09. The plasma and field data support this scenario [Wilder et al., 2016].

We begin by showing an overview of the electron dynamics and magnetic field during this event, including the Omni-averaged FEEPS energy spectrogram (Figure 1a) covering ~44 keV to 600 keV, the FPI electron energy spectrogram (Figure 1b) covering 10 eV to 30 keV, and the FGM magnetic field (Figure 1c) in GSM coordinates. Starting at 10:02:00 UT, there is very little intensity seen in the FEEPS electron data at all energies. Around 10:03:45 UT, the intensity begins to increase at lower energies, while the spacecraft traverses a jet reversal. Beginning at 10:06:30, the intensities increase by up to an order of magnitude; this is followed by several such similar periods until the activity tapers off after 10:10:00 UT. This notable 10:06–10:10 interval occurs, while the spacecraft are primarily within the boundary layer region, which is identified by the thermal plasma electron and ion spectra.

Figure 2 illustrates the detailed electron dynamics by plotting the intensities in pitch angle distribution (PAD) format over time. FEEPS PADs are shown for two electron channels: 53 keV (Figure 2a) and 108 keV (Figure 2b). At the crossing time of the reconnection exhaust/jet reversal (near 10:04 UT), there is a field-aligned distribution observed, particularly in the lower energy. This same feature can be seen again around 10:11:30 UT, when the spacecraft is fully within the exhaust region once more. The presence of particles near 180° signifies...
a field-aligned flow in the direction antiparallel to the magnetic field. From 10:06 to 10:10 UT, the PADs narrow and broaden, changing between a 90° peaked distribution and a largely isotropic distribution; no asymmetric or field-aligned distributions are observed. The most intense peaked distributions occur near ∼10:07:50 UT and ∼10:08:40 UT.

**Figure 2.** Pitch angle distribution versus time plots for (a) 53 keV and (b) 180 keV electrons as observed by FEEPS/MMS-2, where color indicates intensity. Concurrent spectrograms for (c) electric and (d) magnetic fields where color indicates power spectra density. “A” and “B” refer to times used to create Figure 3.
Figure 3. Energy spectra from FEEPS measurements (MMS 1, TOP unit, sensor ID 12) showing spectra at the most perpendicular pitch angles (solid circles) and the most field-aligned pitch angles (open circles) from a time before the accelerated particles are observed (blue) and a time during the period of energization (red).

Also during this time, VLF waves in the whistler-mode frequency range are observed with regularity in both the electric and magnetic field power spectra (Figures 2c and 2d). To better show the whistler-mode frequency domain, the electron cyclotron frequency, $f_{ce}$, and half $f_{ce}$ are labeled as white lines through the power spectral density plots. Here $f_{ce}$ is obtained from the locally measured magnetic field, $B$, as $f_{ce}[\text{Hz}] = 28 \times B[\text{nT}]$. The whistler-mode band is typically defined as spanning $0.1 - 1.0 f_{ce}$ and covers 400 Hz to 2 kHz for this specific wave interval. Curiously, the whistler-mode waves in this event sit straddling $0.5 f_{ce}$, whereas they are more often observed in two distinct bands, upper and lower, falling on either side of $0.5 f_{ce}$ with a gap in power directly at $0.5 f_{ce}$. For this interval, the waves appear only within the boundary layer and are not seen in the magnetosphere proper during the brief excursions across that boundary.

Additionally, broadband electrostatic waves can be seen occurring at the same time as the whistler-mode waves. They extend from very low frequencies through to the VLF range and are apparent primarily in the electric field spectra (Figure 2c) although they can have an electromagnetic component at lower frequencies. The significance of both of these wave modes on particle energization will be discussed in the next section.

It should be noted here that these whistler-mode waves contain a nonlinear component clearly seen in the parallel component of the electric field with amplitudes up to 20 mV/m; this observation is detailed in Wilder et al. [2016].

Line plots of the FEEPS energy spectra are shown in Figure 3, to illustrate the overall energization that took place during the event. The sensor used to make these observations is electron sensor ID 12, on the TOP FEEPS unit of MMS 1. It was chosen due to the range of pitch angles covered during this interval. The blue traces are taken from a 10 s average centered around 10:02:43 UT, before the acceleration is observed, and the red traces are obtained from an 8 s average centered on 10:08:44 UT, after the acceleration took place. The solid circle lines indicate pitch angles near 90°, or as close as a FEEPS detector could come during this period; the open circle traces are taken from lower pitch angles. These time selections are noted at the top of Figure 2 by the blue letter A (“before”) and the red letter B (“after”). The lower energies are clearly enhanced between the before and after spectra, by up to an order of magnitude, but the higher energies above 100 keV are also intensified. The after spectra also demonstrate a more peaked PAD, meaning that the acceleration occurs more efficiently in the direction perpendicular to local $B$.
The event studied here is not an isolated event. During several other similar events, we see electron enhancements along with intense power at both VLF frequencies and within the frequency range that comprise time domain structures in the electric field (not shown). These observations beg further study and comprehensive modeling to tease out the precise sequence of events that leads to this energization, though we discuss some of the possibilities in the next section.

4. Discussion

Here we examine several possible explanations for the observations of high-energy acceleration near the reconnection site reported on within this Letter.

Parallel electric fields as found in broadband electrostatic waves have been shown, at least theoretically, to be able to energize thermal electron populations up to very high energies [e.g., Egedal et al., 2015], and have been found to be ubiquitous at sharp plasma boundaries [Malaspina et al., 2015]. These structures are present in the event shown here: could they provide the acceleration mechanism? Mozer et al. [2016] found evidence in MMS data of these electric field structures accelerating electrons via Fermi reflection near an X-line up to ~200 eV, which is far below the energies relevant here. Again, such a process creates strongly field aligned distributions as well. These wave structures are known to produce up to 100 keV electrons in the inner magnetosphere [Mozer et al., 2015], providing the “seed population” for the relativistic radiation belt. However, the waves we observe here have different characteristics and only appear to give energization up to a few hundred eV in preliminary simulations (A. Osmane, personal communication, 2016).

Another mechanism is cyclotron resonance between VLF waves and electrons. In a quasi-linear treatment of diffusion theory, the rate of diffusion depends on a cold plasma parameter denoted as follows:

$$\alpha_c = \frac{f_{ce}^2}{\omega_{pe}^2} \propto B_0^2 N_0$$ (1)

where $f_{ce}$ is the electron gyrofrequency, $\omega_{pe}$ is the electron plasma frequency, $B_0$ is the local magnetic field in nanotesla, and $N_0$ is the local electron number density in cubic centimeter [Summers et al., 2007a]. Thus, $\alpha_c$ is increased as $N_0$ decreases, and energy diffusion becomes more effective [Summers et al., 2007b]. In the relatively low density of the boundary layer (<5 cm$^{-3}$), the diffusion rates increase and act more broadly over pitch angles. This is certainly a possibility in the case we present, since the spacecraft are moving in and out of a region, without knowing how long the VLF waves have been able to act upon the particles.

A final theory is a two-step process, as has been theorized to explain suprathermal acceleration near reconnection in the magnetotail [Hoshino et al., 2001; Imada et al., 2007]. A first step occurs in the diffusion region, and a second step happens downstream in the exhaust, although by what mechanism is still not clear. Perhaps, this is an amalgamation of the mechanisms discussed above, and the second step is indeed wave-particle interactions. Could this effect be at work in the dayside magnetopause region in a similar fashion to the nightside? There is indication, at least from tail reconnection observations, that the acceleration process for the lower energy part of the electron distribution is entirely different from the process that accelerates the high-energy portion of greater than tens of keV [Asano et al., 2008]. Thus, reconnection may play a key, though unique, role in energization of the high-energy tail of the initial electron population. More analysis of reconnection parameters is necessary to investigate these mechanisms fully. Using the full capabilities of MMS, it will be possible to obtain such characteristics as current sheet thickness for various events and quantitatively explore the relationship between energetic electrons and reconnection.

The source of energetic particles in the inner magnetosphere has been a long-standing question. These hundreds of keV electrons serve as a starting point for local wave-particle interactions to act on and are a crucial piece of the process that ultimately creates the relativistic radiation belt population [Jaynes et al., 2015]. Any mechanism by which 50 keV to hundreds of keV electrons are efficiently produced would be significant toward the understanding of overall electron acceleration to very high energies. Are these energetic electrons seen in the boundary layer eventually transported to the Earth’s ring current region? We have FEEPS evidence of dispersive, bidirectional, field-aligned electron injection signatures (termed “microinjections”) far out in the duskside magnetosphere, presumably drifting eastward from a source region at or near the dayside magnetopause [Fennell et al., 2016]. It is possible that these particles originated in an event very much like the one described in this paper and that it may be a common occurrence. Fennell et al. [2016] comment on this very possibility: that perhaps the microinjections observed are generated at the magnetopause region and form...
the basis for a portion of the source/seed population required to enhance the relativistic outer radiation belt. Furthermore, the myriad processes by which tens of keV electrons are produced during tail reconnection (electrons that can then be injected closer to Earth and seed the radiation belt region) are still under investigation. Whistler waves local to the reconnection region which then accelerate lower energy electrons up to 100 keV, as recounted in this letter, may contribute to the overall tail acceleration picture as well.

More work on this subject is imminent, with the high-resolution comprehensive data available from the ongoing MMS mission. The use of the four closely spaced MMS spacecraft will be able to observe the detailed evolution of the plasma waves for events such as these, when flying through the source region. Finally, simulations of the scenarios discussed here, using in situ plasma and fields parameters, are needed to bring closure to the mechanism behind this fascinating observation.

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