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Cause of super-thermal electron heating during magnetotail reconnection

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[1] We present a candidate mechanism for the energization of super-thermal electrons during magnetic reconnection in the Earth's magnetotail. By analyzing in-situ measurements of electron distribution functions we characterize the relative energy gain of the electrons as a function of energy, $\Delta\mathcal{E}(\mathcal{E})$. For all the events considered the high energy part of $\Delta\mathcal{E}(\mathcal{E})$ is nearly independent of $\mathcal{E}$. This is the signature of energization in an acceleration potential, $\Phi_{\|}$, which is caused by parallel electric fields in the vicinity of the reconnection region. The same acceleration mechanism is also documented for a kinetic simulation of reconnection.
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1. Introduction

[2] Magnetic reconnection [*Dungey*, 1953] plays a fundamental role in magnetized plasmas as it permits the rapid release of magnetic stress and energy through changes in the magnetic field line topology. In reconnection events associated with solar flares up to 50% of the released magnetic energy can be converted into kinetic energy of super-thermal (10–100 keV) electrons [*Lin and Hudson*, 1971; *Lin et al.*, 2003; *Holman*, 2005]. In the Earth's magnetotail reconnection is observed to cause electron acceleration up to 300 keV [*Øieroset et al.*, 2002]. Electron energization is also fundamentally important to astrophysics because the X-rays generated by super-thermal electrons provide an important window into astrophysical processes. Despite its importance the mechanism that energizes the super-thermal electrons is still not understood. A recent theoretical study shows that Fermi acceleration of electrons in contracting magnetic islands can produce power-law distributions [*Drake et al.*, 2006] seemingly consistent with those observed in the Earth's magnetotail [*Øieroset et al.*, 2002]. However, here we consider the reconnection event investigated by *Øieroset et al.* [2002] and an event including magnetic islands [*Chen et al.*, 2008]; we find that the electron energization as a function of energy, $\Delta\mathcal{E}(\mathcal{E})$, does not obey the linear scaling law, $\Delta\mathcal{E} \propto \mathcal{E}$, that is the signature of the Fermi acceleration process. Rather, for each event, the spectra of $\Delta\mathcal{E}(\mathcal{E})$ are (for all time points) consistent with energization in acceleration potentials, $\Phi_{\|}$, related to parallel electric fields in the vicinity of the reconnection regions [*Egedal et al.*, 2009].

2. Adiabatic Model for Magnetized Electrons

[3] A desirable goal in reconnection studies is to understand the dynamics of the electrons from thermal energies all the way up to relativistic energies. New insight into the behavior of the thermal electrons has been obtained through a recently derived adiabatic theory for the temperature anisotropy of the thermal electrons [*Egedal et al.*, 2005, 2008]. Given the success of this theory in accounting for electron distribution functions measured by spacecraft [*Chen et al.*, 2009; *Egedal et al.*, 2010] we here explore if the high energy limit of this model is applicable to the electron distributions at super-thermal energies. At high energies the magnetic moment is often not conserved and the theory needs to be generalized to include pitch angle diffusion. Therefore, below we summarize the original model for the thermal magnetized electrons and in the next section we consider the high energy limit including the effect of pitch angle diffusion.

[4] The model by *Egedal et al.* [2008] provides an adiabatic solution to the Vlasov equation (or Liouville's theorem) $df/dt = 0$, stating that the phase-space density of the electrons is constant along their trajectories in $(\mathbf{x}, \mathbf{v})$-space. Critical to the model is the formation of a positive acceleration potential. This potential is defined as

$$\Phi_{\|}(\mathbf{x}) = \int_{\mathbf{x}}^{\infty} \mathbf{E} \cdot d\mathbf{l}, \qquad (1)$$

where the integral is taken along the magnetic field lines, following the field lines all the way out to the ambient ideal plasma where $\mathbf{E} \cdot \mathbf{B} = 0$. Thus, $\Phi_{\|}$ measures the work done by the total electric field as an electron escapes (or enters) the reconnection region in a straight shot along a magnetic field line. Note, that in general the reconnection geometry includes out-of-plane magnetic and electric field components such that $\Phi_{\|}$ is different from the regular (in-plane) electrostatic potential [*Egedal et al.*, 2009].

[5] In the model it is assumed that the magnetic moment, $\mu = mv_{\perp}^2/(2B)$, is conserved and that the incoming electrons in the ambient plasma are characterized by an isotropic distribution $f_0(\mathcal{E})$. In the limit where the electron thermal

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speed is much larger than the inflow speed to the reconnection region an approximate solution to $df/dt = 0$ is obtained

$$f(\mathbf{x}, \mathbf{v}) = \begin{cases} f_0(\mathcal{E} - e\Phi_{\|}), & \text{passing} \\ f_0(\mu B_\infty), & \text{trapped} \end{cases}. \quad (2)$$

Thus, the model includes the non-linear response due to electrons trapped in electric and magnetic fields. This response dominates at thermal energies, which has been verified using fully kinetic simulations [*Lê et al.*, 2009] (an example of a trapped electron trajectory is given in section 4).

3. Approximation for *f*($\mathcal{E}$), Valid With and Without Pitch Angle Diffusion

[6] Again, the model summarized above takes μ as an adiabatic invariant. Meanwhile, for electrons in the Earth's magnetotail the relatively large Larmor radii at super-thermal energies cause the invariance of μ to break down. As such, in the magnetotail the electron distributions are typically isotropic for energies above 20 keV [*Øieroset et al.*, 2002]. For the present study we will therefore explore the behavior of the 1D pitch angle averaged distribution $f(\mathcal{E}) = \int\int f(\mathcal{E}, \Theta, \phi) \sin(\Theta) d\Theta d\phi / 4\pi$. Using the results above, in this section we obtain an approximate form for $f(\mathcal{E})$ which is applicable both with and without pitch angle diffusion.

[7] In kinetic simulations of guide-field reconnection even the most energetic electrons often remain magnetized throughout the simulation domain and equation (2) applies [*Lê et al.*, 2009]. For energies $\mathcal{E} > \alpha e\Phi_{\|}$ the majority of the electrons are passing. Here α is a dimensionless constant ($1 < \alpha < 2$) which depends on the geometry of the reconnection region. We can therefore expect that the pitch angle averaged distribution $f(\mathcal{E})$ approaches the passing part of equation (2), $f(\mathcal{E}) \simeq f_0(\mathcal{E} - e\Phi_{\|})$. In other words, we expect the super-thermal electrons to acquire a fixed energy gain $\Delta\mathcal{E} \simeq e\Phi_{\|}$ which is independent of their final energy $\mathcal{E}$.

[8] Still considering the case without pitch angle diffusion, for $\mathcal{E} < \alpha e\Phi_{\|}$ most of the electrons are trapped. As discussed by *Egedal et al.* [2008, 2009] their energy gain is less than $e\Phi_{\|}$ and it is controlled by the action integral $J = \oint v_{\|} dl$ in the bounce motion as they enter the reconnection region. Provided the bounce motion is sufficiently rapid J is an adiabatic invariant. The shortening of the bounce orbits inside the reconnection region therefore leads to an energy gain proportional to the parallel energy $\mathcal{E}_{\|}$. Thus for $\mathcal{E} < \alpha e\Phi_{\|}$ we expect an average energy gain $\Delta\mathcal{E}$ nearly proportional to $\mathcal{E}$.

[9] We now consider the case of super-thermal electrons ($\mathcal{E} > \alpha e\Phi_{\|}$) where pitch angle diffusion is important. The pitch angle diffusion basically "turns off" the magnetic trapping and ensures that all electrons with $\mathcal{E} > \alpha e\Phi_{\|}$ can enter and escape the reconnection region rapidly along the field lines. Thus, during the transit of a super-thermal electron the field lines are nearly static. Furthermore, we notice that pitch angle diffusion does not change the electron energy and because the pitch angle diffusion is random the distribution function must be isotropic $f = f(\mathbf{x}, \mathcal{E})$. With these observations the simplified Vlasov equation reads $0 = df/dt \simeq \partial f/\partial \mathbf{x}\, \partial \mathbf{x}/\partial t + \partial f/\partial \mathcal{E}\, \partial \mathcal{E}/\partial t$ with $\partial \mathcal{E}/\partial t = e\mathbf{E} \cdot \partial \mathbf{x}/\partial t$ and $\partial \mathbf{x}/\partial t \simeq v_{\|}\mathbf{B}/B$. After integration we find $f \simeq f_0(\mathcal{E} - e\Phi_{\|})$, which is identical to the passing part of equation (2). Therefore, the main consequence of the pitch angle diffusion is to eliminate the anisotropy associated with magnetic trapping.

[10] Meanwhile, for ($\mathcal{E} < \alpha e\Phi_{\|}$) the electrons remain trapped and a detailed understanding of $\Delta\mathcal{E}$ in the presence of pitch angle diffusion may only be possible through numerical simulations. While a comprehensive analysis of this electron class is beyond the scope of this manuscript, the spacecraft data below suggest that $\Delta\mathcal{E} \propto \mathcal{E}$ (like the case for the magnetized electrons with $\mathcal{E} < \alpha e\Phi_{\|}$).

[11] In summary, for the pitch angle averaged distribution function with and without pitch angle diffusion, we expect $f(\mathcal{E}) \simeq f_0(\mathcal{E} - \Delta\mathcal{E})$ where

$$\Delta\mathcal{E}(\mathcal{E}) \simeq \begin{cases} \mathcal{E}/\alpha, & \mathcal{E} < \alpha e\Phi_{\|} \\ e\Phi_{\|}, & \mathcal{E} > \alpha e\Phi_{\|} \end{cases}. \quad (3)$$

Here the factor $1/\alpha$ for $\mathcal{E} < \alpha e\Phi_{\|}$ is included to make the expression of $\Delta\mathcal{E}$ continuous. The value of α (typically $1 < \alpha < 2$) is controlled by the geometry of the reconnection region and the level of pitch angle diffusion.

[12] We emphasize that equation (3) is only an approximation and it will only be valid if the energization by $\Phi_{\|}$ dominates all other acceleration processes. In particular, for geometries including magnetic islands, the model only accounts for the energization external to the island where the field lines reach the ambient plasmas such that $\Phi_{\|}$ is defined.

[13] In the limit where $\mathcal{E} \gg \alpha e\Phi_{\|}$ the energy gain predicted by equation (3) is $\Delta\mathcal{E} \simeq e\Phi_{\|}$, independent of $\mathcal{E}$. This fact allows us to distinguish acceleration by $\Phi_{\|}$ from other possible processes energizing the electrons. As an example, when electrons are energized by interactions with waves typically it is only the resonant electrons which move at the phase-velocity of the wave that significantly change energy. Inevitably, this leads to a strong dependence of $\Delta\mathcal{E}$ on $\mathcal{E}$. Another example is Fermi acceleration of electrons in contracting magnetic islands [*Drake et al.*, 2006]. This acceleration mechanism is also based on the action integral $J = \oint v_{\|} dl$ being an adiabatic invariant such that a reduction in the length $\oint dl$ around the island causes a proportional increase in $v_{\|}$. Thus, the change in energy is proportional to the particle energy, $\Delta\mathcal{E} \propto \mathcal{E}$. Importantly, in Fermi acceleration there is no cutoff energy (like $\alpha e\Phi_{\|}$) limiting the acceleration at high energies.

4. Kinetic Simulation Results

[14] To illustrate the role of $\Phi_{\|}$ in energizing super-thermal electrons we first examine results of an open boundary particle-in-cell simulation including 2×10^9 particles in a domain $xy = 3072 \times 3072$ cells $= 569\ c/\omega_{pe} \times 569\ c/\omega_{pe}$. The simulation is translationally symmetric in the z-direction and is characterized by the following parameters: $m_i/m_e = 360$, $T_i/T_e = 2$, $B_{\text{guide}} = 0.5\ B_0$, $\omega_{pe}/\omega_{ce} = 2.0$, background density $= 0.30\ n_0$ (peak Harris density), $v_{th,e}/c = (\sqrt{T_e/m_e})/c = 0.20$, and an initial current sheet width of about $0.4\ c/\omega_{pi}$. An in-depth description of the simulation model is given by *Daughton et al.* [2006]. Note that the time slice considered does not include any magnetic islands and Fermi acceleration is therefore not expected here.

[15] We consider the fields observed at the single time slice of Figure 1, during a time interval without significant

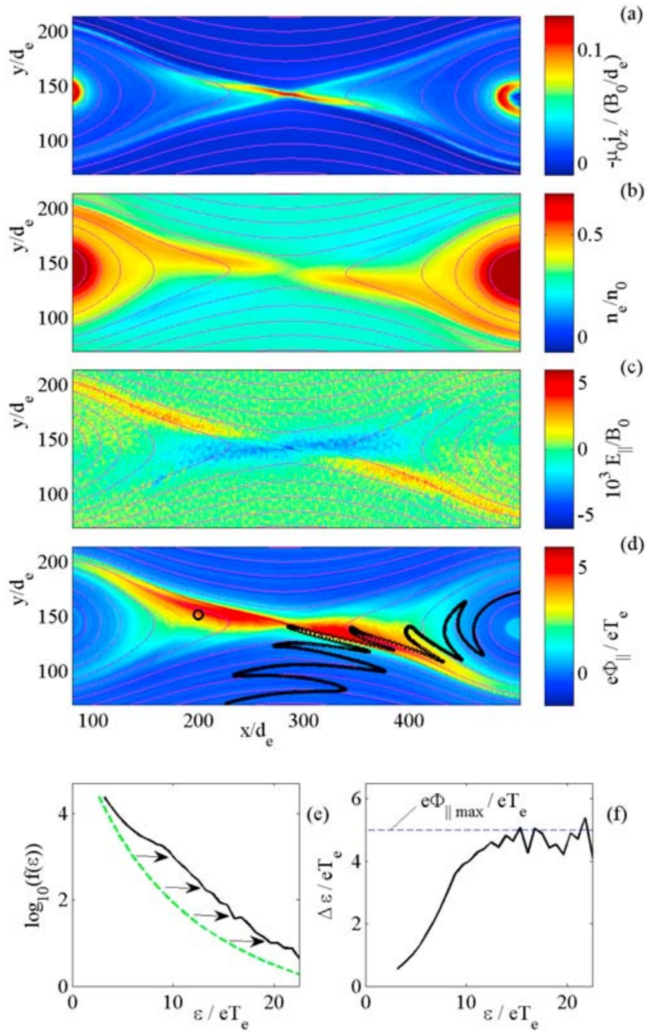

Figure 1. (a–d) Color contours of j_z, n, $E_{\|}$ and $\Phi_{\|}$. The overlayed contours of Ψ coincide with magnetic field lines. (e) Electron distributions observed at the point marked by a black circle in Figure 1d, while the green dashed line is $f_0(\mathcal{E})$ at the simulation boundary. The arrows indicate the energy gains as inferred by the Liouville mapping. (f) The energy gain $\Delta\mathcal{E}$ as a function of $\mathcal{E}$ for the point marked in Figure 1d.

evolution in the profiles. These asymmetric profiles are typical for simulations with a moderate guide magnetic field. As seen in Figure 1c inside the reconnection region finite values of the parallel electric field $E_{\|}$ develop. As evident in Figure 1d, because the integral in equation (1) is over relatively large length scales, the magnitude of $\Phi_{\|}$ becomes significant. Figure 1d also provides an example of a trapped electron typical of the thermal electrons in the reconnection region. These only sample short sections of the field lines and as described above only obtain a fraction of $e\Phi_{\|}$ in energy gain.

[16] To quantify the electron energization in the kinetic simulation we consider Figure 1e. Here the black line is $f(\mathcal{E})$ obtained from the particle data within the small regions ($3d_e \times 3d_e$) marked by the black circle in Figure 1d where $e\Phi_{\|} \simeq 5T_e$. The dashed green curve is the distribution function of incoming electrons at the simulation boundary $f_0(\mathcal{E})$. The arrows illustrate how the energy gain $\Delta\mathcal{E}(\mathcal{E})$ of the Liouville mapping is determined as the horizontal distance between $f_0(\mathcal{E})$ and $f(\mathcal{E})$ [*Alexeev et al.*, 2006].

[17] Mathematically, $\Delta\mathcal{E}$ can be determined by inverting the distribution $f_0(\mathcal{E})$ of incoming electrons yielding $\mathcal{E}_0(f)$. The change in energy is then simply evaluated as

$$\Delta\mathcal{E}(\mathcal{E}) = \mathcal{E} - \mathcal{E}_0(f(\mathcal{E})). \quad (4)$$

Results of applying equation (4) are given in Figure 1f, where $\Delta\mathcal{E}$ is shown for the distribution in Figure 1e. For sufficiently large energies, $\mathcal{E} > 2e\Phi_{\|}$, the curve of $\Delta\mathcal{E}(\mathcal{E})$ matches the representative value of $e\Phi_{\|}$. This shows that for the present simulation it is direct acceleration by $\Phi_{\|}$ that is responsible for the energization of the electrons.

5. Magnetotail Data from Cluster

[18] To explore which acceleration process dominates during reconnection in the Earth's magnetotail we apply equation (4) to electron data measured in situ by several spacecraft missions. First, in Figure 2a we consider electron data from the RAPID instrument on Cluster 3. This data was obtained in a reconnection event on 1 October 2001, where bursts of super-thermal electrons were observed inside magnetic islands. In fact, the spikes in the electron data seen at $t = -48$ s and $t = 50$ s occurred simultaneously with the magnetic signatures of magnetic islands [*Chen et al.*, 2008].

[19] The distributions at the time points marked by vertical dashed lines in Figure 2a are given as a function of $\mathcal{E}$ in Figure 2b. The observations at $t \simeq 25$ s were acquired in the lobe plasma characteristic of the inflow region for this reconnection event; we apply this data as a direct measurement of $f_0(\mathcal{E})$. Additional values of f_0 at lower energies are obtained from the PEACE instrument (not shown) such that when inverting $f_0(\mathcal{E})$ we obtain $\mathcal{E}_0(f)$ for a sufficient range in *f*.

[20] Based on the knowledge of $\mathcal{E}_0(f)$ and by applying equation (4) to the blue, red and green traces of Figure 2b we obtain the three spectra of $\Delta\mathcal{E}(\mathcal{E})$ shown in Figure 2c. For the data obtained at $t = -68$ s we find $\Delta\mathcal{E} \simeq 20$ keV for all energies. The red and blue data points in Figure 2c correspond to locations inside magnetic islands. Here the inferred values of $\Delta\mathcal{E}$ reach about 40 keV and 70 keV, respectively. The black dashed lines are the spectra of $\Delta\mathcal{E}$ predicted by equation (3), which agrees well with the observed forms of $\Delta\mathcal{E}(\mathcal{E})$.

[21] For the considered event we have carried out the above analysis on the RAPID data from the three other Cluster spacecraft. This yielded results similar to those shown in Figure 2. The nearly flat spectra of $\Delta\mathcal{E}$ observed when $\mathcal{E} > 1.25\ \Delta\mathcal{E}$ by the four Cluster spacecraft should be contrasted with the $\Delta\mathcal{E} \propto \mathcal{E}$ spectra expected for Fermi acceleration for all energies. Therefore, our analysis does not support the interpretation that Fermi acceleration played an essential role for this event. Instead the detailed spectra of $\Delta\mathcal{E}$ suggest that the energization process was dominated by an acceleration potential acting on the super-thermal electrons as they reached the reconnection region and entered the magnetic islands.

6. Magnetotail Data from Wind

[22] Next, we carry out an analysis for the reconnection event encountered by Wind on 1 April 1999 in the deep

(60 R_E) magnetotail. This event is particularly interesting because it includes enhancements in the observed electron fluxes for the entire energy range of the electron analyzer all the way up to 300 keV. Figure 3a shows the time evolution of the electron distribution as measured by the four highest energy channels. These data are a subset of the electron data presented in Figure 1 by *Øieroset et al.* [2002]. Wind was found to be inside the ion diffusion region between 07:45 and 8:05 UT. Meanwhile, the data observed about two hours later (between 9:50 and 10:00 UT) correspond to the lobe plasma surrounding the plasma sheet.

[23] In Figure 3b we present the electron distributions as a function of $\mathcal{E}$ measured in the lobe and at three locations gradually approaching the ion diffusion region. We use the values of f observed in the lobe as the direct measurement of the incoming electron distribution, $f_0(\mathcal{E})$, which then is inverted yielding $\mathcal{E}_0(f)$ representative of this event. By applying equation (4) to the remaining distributions in Figure 3b we obtain the spectra of $\Delta\mathcal{E}(\mathcal{E})$ shown in Figure 3c. The maximum values, $\Delta\mathcal{E}_{max}$, of each spectrum smoothly increases from about 30 kV to 150 kV as the diffusion region is approached.

[24] The black dashed lines in Figure 3c represent predictions by equation (3) which again agree well with the observations. Thus, the smoothly evolving data set is fully consistent with electron energization in an acceleration potential, $\Phi_{||}$ which increases in strength as the reconnection site is approached.

[25] For additional reconnection events observed by the Cluster mission on 21 August 2002 and by THEMIS 3 on 7 February 2009 we have carried out the analysis of the energy gain spectra, $\Delta\mathcal{E}(\mathcal{E})$. For all the events studied the shapes of $\Delta\mathcal{E}(\mathcal{E})$ are similar to the two events presented above. The spectra of energy gains consistently flat for $\mathcal{E} > 1.5\Delta\mathcal{E}$ are strong evidence that the super-thermal electrons in the Earth's magnetotail are energized by $\Phi_{||}$.

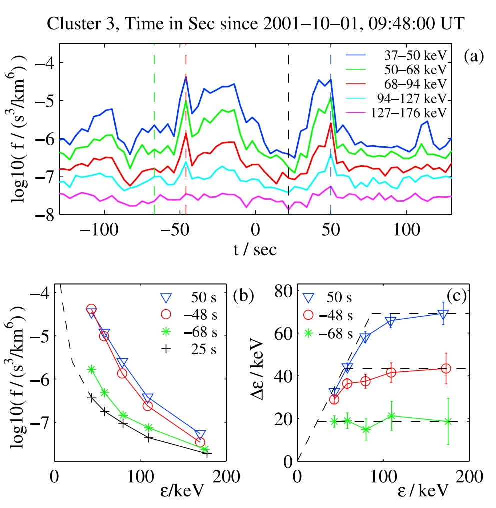

Figure 2. (a) Electron phase-space densities from the RAPID measurement on Cluster 3. (b) Electron distribution observed at separate time points. The data at $t = 25$ s is taken as the distribution of incoming electrons, $f_0(\mathcal{E})$. (c) Spectra of $\Delta\mathcal{E}$ for three separate points in time. The black dashed lines represent equation (3), evaluated with $\alpha = 1.25$ and Φ/keV = {19, 43, 69}.

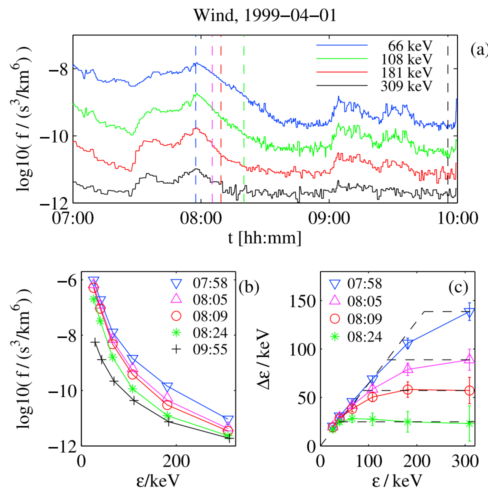

Figure 3. (a) Electron phase-space densities from the Wind spacecraft. (b) Electron distribution observed at separate time points (the data is average over two minutes to reduce noise). The data at t = 09:55 is the lobe distribution of incoming electrons, $f_0(\mathcal{E})$. (c) Spectra of $\Delta\mathcal{E}$ for four separate points in time. The black dashed lines represent equation (3), evaluated with $\alpha = 1.55$ and Φ/keV = {25, 57, 99, 139}.

7. Summary and Discussion

[26] The acceleration mechanism by $\Phi_{||}$ for the two events presented here (and the two other events we have studied) is different from acceleration in models where only the reconnection electric field is considered. This is because the acceleration by $\Phi_{||}$ includes contributions not only from the reconnection electric field but also the in-plane electric fields that develop self-consistently. Our acceleration mechanism is therefore not limited to a directed beam of electrons that travels along the reconnection X-line.

[27] Although the spectra of $\Delta\mathcal{E}(\mathcal{E})$ are similar for the events, there are still important differences to be discussed. The events encountered by Cluster (and THEMIS 3) at about $20R_E$ lasted only a few minutes and the spatial extent of $\Phi_{||}$ appears to be confined to the ion diffusion region. The localized structure of $\Phi_{||}$ will limit the number of electrons that can be energized by $\Phi_{||}$ [*Egedal et al.*, 2009]. In contrast, the event encountered by Wind in the deep magnetotail (60 R_E) lasted several hours indicating that here $\Phi_{||}$ is non-localized reaching well beyond the ion diffusion region. The large spatial extent of $\Phi_{||}$ is consistent with a much larger number of electrons being energized by direct acceleration in the associated parallel electric fields. Thus, the present analysis of the Wind observations implies that a large scale acceleration potential, $\Phi_{||}$, can develop. As called for by the observations on the sun, such a large scale potential structure could be important for the energization to 10–100keV of a large volume of electrons. The mechanisms that cause a localized $\Phi_{||}$ to develop are now understood [*Lê et al.*, 2010], but more work is still needed to account for the large scale potential inferred from the Wind observation.

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