Remote sensing of a magnetotail reconnection X-line using polar rain electrons

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[1] We report on electron phase space distributions (PSDs) observed near the plasma sheet (PS) boundary layer (PSBL) by the Cluster electron spectrometers when the northern lobe was occupied by significant fluxes of polar rain (PR) electrons. These observations reveal the spatial structure of the electron transition layer (TL) between the polar rain electrons and the PSBL electron population accelerated during reconnection. This TL comprises overlapping spatial dispersion signatures in both energy and pitch angle, which are caused by convection of flux tubes across the magnetic separatrix during the electron time-of-flight (TOF) from the X-line combined with acceleration in the reconnection region. Analysis of this structure allows us to estimate the location of the X-line. By assuming the PSBL population arises through acceleration of the PR electrons, comparison of their PSD indicates that the electrons gain energy proportional to their initial energy. **Citation:** Alexeev, I. V., V. Sergeev, C. J. Owen, A. Fazakerley, E. Lucek, and H. Réme (2006), Remote sensing of a magnetotail reconnection X-line using polar rain electrons, *Geophys. Res. Lett.*, *33*, L19105, doi:10.1029/2006GL027243.

1. Introduction

[2] Suprathermal electrons of the solar wind strahl population can directly penetrate the magnetosphere through the open night side magnetopause. A small proportion of these particles precipitate into the polar cap ionosphere, which gave rise to this population being labeled the Polar Rain. However, most of these electrons are reflected in the high-latitude magnetic mirrors and returned to the lobes, thus forming bidirectional PR electron PSD on open magnetotail lines.

[3] The changes of the PR electron population near the boundary between open and closed magnetic field lines in the magnetotail are not as well studied as the corresponding transition of energetic protons in the PSBL. In the latter case, the proton TL often shows a specific pitch angle and energy-dependent spatial dispersion. Such a pattern is explained by the convection of flux tubes across the magnetic separatrix during the ion TOF from the X-line [see, e.g., *Elphic et al.*, 1995], known as convective filtering. Measurements of the low-energy cut-off velocities of direct (earthward) and reflected (tailward) proton beams can be used to infer the distance to the reconnection site. However, this method is rarely used in practice as the ions are generally slow and their TOF scale is comparable to or larger than the time scale of the reconnection process.

[4] Dispersion effects may also exist in the PR electron population near the magnetic separatrix. *Shirai et al.* [1997] reported Geotail observations near the PSBL which showed a narrow layer of uni-directional ~100 eV PR particles with indications of energy-dispersion. This was more clearly seen in the observations made at lower altitude by the Akebono spacecraft.

[5] In this paper, we use the Cluster observations to show that convective filtering also accounts for the complicated, but regular, spatial structure of the electron TL. For the first time, we use electron energy dispersion and pitch angle anisotropies observed within this structure to determine the location of the magnetotail X-line. Furthermore, we use analysis of PSDs recorded by the Cluster electron spectrometer PEACE [*Johnstone et al.*, 1997], to determine some of the features of the electron acceleration mechanism operating near the X-line.

2. Event Description, September 8, 2002

[6] The characteristics of an isolated substorm on September 8, 2002, which had an expansion phase starting at 21:18 UT, were considered in detail by *Sergeev et al.* [2005]. *Semenov et al.* [2005] also used Cluster data from this same event to estimate a distance to the reconnection X-line. However, their analysis is based on multi-spacecraft observations of magnetic field disturbances in the lobes, and thus differs significantly from the electron-based techniques employed here.

[7] On this day the Cluster orbit lay close to the X–Z GSE plane and the spacecraft were at a distance of $X_{GSM} = -16\ R_E$ in the magnetotail. The spacecraft were arranged in a tetrahedron with a maximum separation of ~4700 km. An overview of the period of interest is presented in Figure 1, which shows an energy-time spectrogram of the earthward field-aligned electrons detected by Cluster 3 (Figure 1a), the three components of the magnetic field vector (Figures 1b–1d) measured by the FGM magnetometer [*Balogh et al.*, 2001], the proton density (Figure 1e) and X-component of velocity (Figure 1f) measured by the CIS-CODIF ion spectrometer [*Réme et al.*, 2001]. In Figures 1b–1f, we show the data from all four spacecraft, employing the standard Cluster colors for each trace (C1-black, C2-red, C3-green, C4-blue). Before 21:36 UT, all four spacecraft were located in the northern lobe (B_X strongly positive), sampling a PR electron population with

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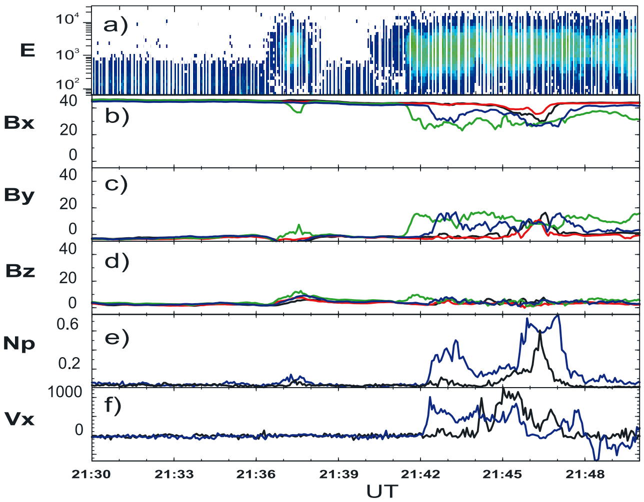

Figure 1. PEACE electron spectrometer data for electrons moving earthward along the magnetic field from spacecraft 3. (a) Three components (GSE) of the FGM magnetic field for (b–d) the four spacecraft, (e) CIS CODIF plasma density, (f) and Vx (GSE) component of the proton velocity.

temperature ~90 eV. However, suprathermal electrons were also observed by PEACE with energies up to ~1500 eV. The PR had symmetrical field-aligned and anti-field-aligned components and was continuously observed while the spacecraft remained in the lobe. At ~21:36 UT, spacecraft C3, C4, and later C2, in the order of their increasing Z_{GSM} coordinate, briefly encountered the PSBL for a period of <1 minute. Later at 21:42 UT all four spacecraft crossed the PSBL (in the order C3, C4, C2, C1) and entered the PS proper, where the PR population was replaced during the PSBL crossing by hotter and denser electrons. Inside the PS, the CIS instruments detected fast, field-aligned, earthward proton flows with velocities up to 1000 km s^{-1} which is consistent with a reconnection-related outflow jet from an active magnetotail X-line located tailward of the spacecraft.

[8] We first concentrate here on the structure of the electron TL between the lobe and plasma sheet regions. Figure 2 presents PEACE data from C3 for the transient (Figure 2a) and main (Figure 2b) PSBL encounters observed at ~21:37 and ~21:41 UT respectively. Each of the sub-panels presents a pitch angle versus time spectrogram for selected electron energy channels (6 channels from 70 eV to 1.2 keV in panel (a) and 6 channels from 74 eV to 2.3 keV in (b), as indicated on the left of each sub-panel).

[9] At each TL encounter, as the spacecraft moved from the lobe towards the PS, PEACE initially detects a burst of 1–10 keV unidirectional, field-aligned, earthward-moving electrons. This is shown in Figure 2b in energy channels 1.1 and 2.3 keV, the vertical line "1" marks the Earthward electron beam at energy 2.3 keV. Corresponding reflected tailward-moving (anti-parallel) electrons appear 8–20s later (for energy channel 2.3 this is shown by line "2"). Simultaneously, the PR electrons start to diminish, showing both energy-dispersion and anisotropy. This is evident in Figure 2 (Figures 2a and 2b in the lower energy bands), where both higher-energy PR electrons disappear first and those direct earthward (0° pitch angle) disappear before those reflected (180°). Upon exit from the PSBL at the end of the transient encounter, these electrons reappear in the reverse order.

3. Analysis

[10] The similarity of the transient and the main PSBL encounters and reverse order of changes on the entry and exit, as is observed by several or all of the Cluster spacecraft, shown in the previous section, supports the conclusion that both the observed anisotropy and energy-dispersed variations are caused by the traversal through a stable spatial structure which moves up and down with respect to the spacecraft.

[11] The motion of the spacecraft with respect to this layered structure may be caused by the motion of the separatrix itself, due to the active reconnection process or by plasma convection which moves the plasma with frozen magnetic field towards the PS. Generally these velocities do not cancel each other and the separatrix with its attached electron TL can generally be expected to be in motion with respect to the spacecraft. We test quantitatively the consistency of the observed distributions with the predictions of a model of the convective filtering mechanism.

[12] In this model the form of the electron PSD observed by a spacecraft at a certain point within the TL is determined by TOF effects acting on an electron as it moves from the acceleration point in the vicinity of the X-line to the spacecraft location. On magnetic field lines inside this

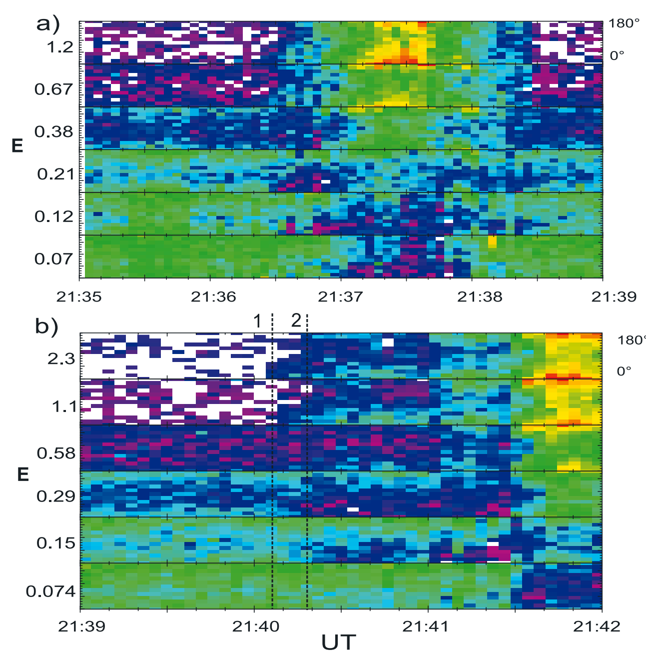

Figure 2. (a) Cluster 3 PEACE spectrogram for the transient PS encounter. Figure 2a contains six panels representing electrons in different energy ranges with the central energy indicated on the left in keV. Each panel contains a pitch angle distribution with 180° electrons appearing at the top, and 0° electrons at the bottom; (b) PEACE electron spectrogram of the main PS encounter from the Cluster 3 spacecraft, with format similar to Figure 2a. Vertical lines show the time of appearance of parallel (1) and anti-parallel (2) electrons of 2.3 keV energy.

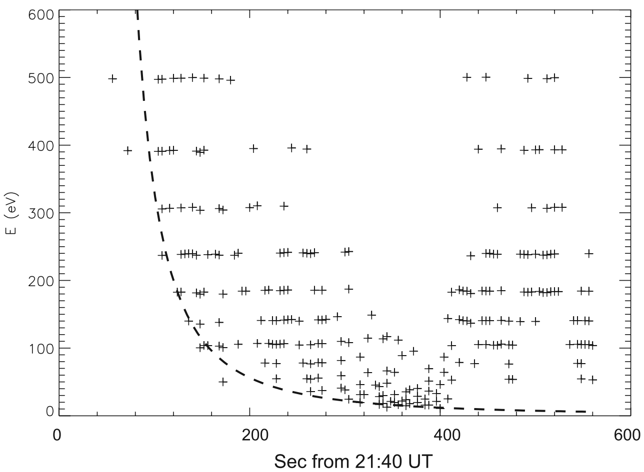

Figure 3. Energy dispersion of the earthward parallel polar rain electrons. Crosses show points where PEACE detected 0 counts; the dashed curve shows the theoretical best fit curve for the electron switch-off energy dispersion.

layer, it is also possible to observe PR electrons whose TOF from the X-line is longer than the time elapsed since the reconnection of that field line. These electrons are unaffected by the change of topology of the field line and thus maintain their original parameters. More generally, the electron PSD on a given field line inside the TL is determined by the time T elapsed since that magnetic field line underwent reconnection and by the distance S_L to the X-line itself. Under certain assumptions we can find the time T for the field line which passes through the spacecraft location inside the TL. At a particular time t it is related to the spacecraft motion with respect to plasma and magnetic separatrix. Here we use a simple 2D model of the transition layer, assuming that plasma convects towards the neutral sheet and that the magnetic separatrix moves in the opposite direction due to the ongoing reconnection process. Also we assume that the X-line acts steadily on the scale of the observed TL crossings (~2 minutes). In this case time T can be expressed in the following way:

$$T(t) = t - T_0 = (t - t_0)(1 - V_c/V_s) = k(t - t_0), \qquad (1)$$

where T_0 is the time at which the field line underwent reconnection, t_0 is the time the spacecraft crossed the magnetic separatrix, and V_c and V_s are the plasma convection velocity and the velocity of the separatrix with respect to the plasma. Note that in this case we do not use direct information about velocities V_c and V_s, but instead derive the factor k from the observation of the separate time delays between the detection of the switch-off of direct (at time t^+)and reflected (at time t^-)electrons of the same energy:

$$k = \frac{2T_b}{t^- - t^+}, \qquad (2)$$

where T_b is the electron TOF from the spacecraft to the mirror point, which may be calculated using the *Tsyganenko* [1995] magnetic field model under the assumption of adiabatic electron motion. We calculated the coefficient k, using observed delays between switch-on of direct and reflected accelerated electrons with energies from 1.2 keV to 4 keV: for this case we found that k = 0.26 ± 0.02. Due to the relatively low time resolution of the data, this error in k is the main source of errors in all subsequent calculations.

[13] We then proceed to determine the distance to the X-line, using the observed energy dispersions in time, which we interpret as an effect of the spacecraft crossing a time-stationary electron TL. The TOF of an electron with parallel velocity V from the reconnection site to the spacecraft is $T = S_L/V$. Hence, taking into account the time scale k, the time delay between switch-off of parallel Earthward electrons with velocities V_1 and V_2 is:

$$t_1 - t_2 = \frac{S_L}{k}\left(\frac{1}{V_2} - \frac{1}{V_1}\right), \qquad (3)$$

which is similar to formulas, used in the analysis of velocity dispersed ion beams [see e.g., *Takahashi and Hones*, 1988].

[14] Figure 3 indicates the times, marked by crosses, at which the PEACE instrument returned zero counts for the direct, Earthward-moving parallel electrons as a function of energy from ~10 eV to ~500 eV during the TL crossing by C1. A best fit of the modelled curve (described by equation (3)) above to the earliest times of zero count at each energy is also displayed. The relatively good quality of this fit suggests that the initial assumption of constancy of the coefficient k during this crossing is quite good in this case. This best fit curve corresponds to a distance to the X-line S_L = 29 R_E.

[15] The polar rain electrons provide a stable source population which may populate the plasma sheet following acceleration by reconnection and subsequent Fermi-betatron acceleration on contracting reclosed field lines. This can be effectively used to determine some properties of the acceleration process provided by magnetic reconnection. Thus we compare the PSD distributions of two populations of earthward-moving electrons, both moving parallel to the magnetic field direction in this case and assuming that they remain parallel to the field during the acceleration process. For practical purposes, we average the PR PSDs from C3 over two minutes prior to the PS encounter. We also average the PSDs for the accelerated population observed by C3, using two different methods. First, we take an average over the period between the first detection of the direct accelerated electrons and the first detection of the reflected electrons. The resulting PSD thus represents only electrons which have undergone an acceleration process near the X-line. The second method averages the PSD over the entire interval between the first detection of the accelerated population and the first detection of the PSBL-like bidirectional electron PSDs of higher fluxes. These PSD distributions of field-aligned, earthward electrons of the PR and accelerated population are presented in Figure 4a.

[16] In the absence of particle scattering, according to the Liouville theorem the PSD is conserved along particle trajectories. Hence, the distribution of the accelerated field-aligned electrons F_a is related to the PR parallel electrons distribution F_{pr} by a simple relationship:

$$F_a(E_a(E_{pr})) = F_{pr}(E_{pr}) \qquad (4)$$

Since we know F_a and F_{pr}, we can use this relation to reconstruct some details of the acceleration mechanism,

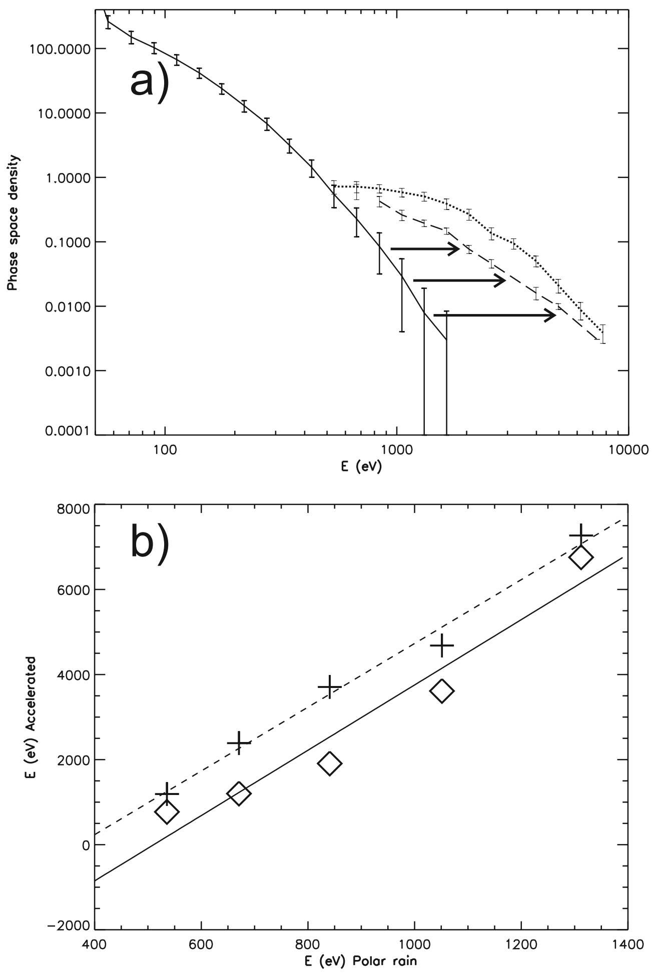

Figure 4. (a) Phase space density distributions of field aligned (earthward) electrons. The solid line is for the original polar rain, the dotted line indicates the average across the entire TL, and the dashed line is for the electrons coming directly from the acceleration site. Arrows show the Liouville mapping. (b) Mapping of the accelerated (vertical axis) and original (horizontal axis) polar rain electron PSDs. Crosses represent the mapping of the accelerated electron PSD obtained by averaging across the entire electron TL, while diamonds represent the mapping obtained by averaging the PSD of only those electrons coming directly from the acceleration site. The straight lines show the results of linear best fits to the data.

represented by an energy space mapping: $E_a = E_a(E_{pr})$. Such mappings are reconstructed using equation (4) for both methods of F_{pr} averaging described. Our results are presented in Figure 4b. Note that both mappings are well described by the linear law $E_a \sim 7.5 \times E_{pr}$, rather than a simple shift of the PSD in energy space. Note also that these mappings reflect an absence of electrons with energies below ~400 eV in the accelerated electron population.

4. Discussion and Conclusions

[17] The similarity of electron behavior detected by each Cluster spacecraft during each PS entry/exit on September 8, 2002, allows us to conclude that a stable electron TL existed on the boundary of the PS at that time. The time-energy dispersion of the parallel and anti-parallel electrons of both the PR and accelerated electron populations observed inside this layer is produced by the spacecraft motion across this layer, whose spatial structure is the result of TOF-based convection filtering effects. By considering switch-off times of different electron populations, we estimate the location of this X-line to be ~45 R_E from the Earth. This is larger than the distance of 29–31 R_E estimated by *Semenov et al.* [2005] for the same event. However, their estimation is based on analysis of magnetic field perturbation waveforms measured by Cluster ~20 minutes earlier, when the spacecraft was in the North lobe. Thus this apparent discrepancy may be simply consistent with the tailward motion of the reconnection region during the late substorm.

[18] The thickness of the observed electron TL should increase with distance from the associated reconnection site. In the distant tail this can be substantial compared to the global structure of the plasma sheet. Recently *Manapat et al.* [2006] presented a statistical study of electron beams on the lobe/PS interface in the distant tail and confirmed the frequent appearance of strong field-aligned electron beams directed toward the reconnection region at low-energies (a few tens to a few hundred eV). This is consistent with our findings in this polar rain study (i.e., tailward PR beam in the inner part of the transitional layer). Manapat et al. also suggested that these low-energy beams are somehow formed by the reconnection process, even if they are observed very far from the reconnection site, although they did not specify the process by which this could occur. In this paper we have shown that convection filtering of the lobes electron population in the vicinity of the magnetic separatrix leads to anisotropy of the electron distributions in the TL: only the tailward part of the velocity space is populated by polar rain electrons. Taking into account that at the same time no significant ion fluxes have been observed there, it indicates that the TL contains Earthward electron electric current, which may possibly contribute to the formation of quadruple magnetic perturbations (sometimes referred to as the Hall effect) at a large distance from the reconnection site.

[19] A new result from this work is the reconstruction of the electron acceleration near the X-line. The linear fits in Figure 4b imply energy space mappings of the following form: $E_a = 7.7(E_{pr} - 506)$ eV for electrons coming directly from the acceleration site, and $E_a = 7.5(E_{pr} - 368)$ eV, obtained from averaging the accelerated PSDs across the entire electron TL. The latter estimate would include electrons which have bounced several times between the mirror points. Since the coefficient in the right hand part of these equations is approximately the same, we suggest that the main acceleration takes place while these electrons are near the X-line, rather than later in the downstream region as a result of acceleration during magnetic field line contraction. Note also that the main acceleration process is described by the linear law: thus faster particles obtain more energy than slow ones during this process. However, this cannot be simply a Fermi-like acceleration as a result of the large-scale contraction of the magnetic field lines, since the effect appears in the electrons at the edge of the TL which have not had time to perform multiple journeys to the ionospheric

mirror points and back. Thus we find almost the same acceleration factor for both direct and multiply-bounced particles.

[20] A second prominent result of this mapping is the absence of low-energy electrons in the accelerated population, reflected in the negative term on the right hand side of the mapping equations. This is consistent with loss of energy associated with overcoming an electrostatic barrier, which prevents low-energy PR electrons reaching the acceleration site. This may be due to a field-aligned component of the polarization electric field which may appear near the collisionless reconnection site as a result of decoupling between ion and electron motions [e.g., *Hoshino*, 2005]. This electrostatic field thus moderately slows the faster PR electrons, but completely blocks electrons with energies less than ∼400 eV.

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