# Observations of Ionospheric Electron Beams in the Plasma Sheet

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Electrons streaming along the magnetic field direction are frequently observed in the plasma sheet of Earth's geomagnetic tail. The impact of these field-aligned electrons on the dynamics of the geomagnetic tail is however not well understood. Here we report the first detection of field-aligned electrons with fluxes increasing at ~1 keV forming a "cool" beam just prior to the dissipation of energy in the current sheet. These field-aligned beams at ~15 $R_E$ in the plasma sheet are nearly identical to those commonly observed at auroral altitudes, suggesting the beams are auroral electrons accelerated upward by electric fields parallel ($E_{\|}$) to the geomagnetic field. The density of the beams relative to the ambient electron density is $\delta n_b/n_e \sim$ 5–13% and the current carried by the beams is $\sim 10^{-8}$–$10^{-7}$ A m$^{-2}$. These beams in high $\beta$ plasmas with large density and temperature gradients appear to satisfy the Bohm criteria to initiate current driven instabilities.

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*Introduction.*—Auroral particles are accelerated by electric fields parallel to the magnetic field direction ($E_{\|}$). Early work emphasized electrons accelerated in the downward direction into the ionosphere responsible for the auroral emissions [1]. Observations however have since shown electrons are also accelerated in the upward direction. The FAST (Fast Auroral SnapshoT) experiments have established there are two quasistatic electric field structures along the geomagnetic field direction, one that accelerates electrons downward and the other upward [2]. The energies of the accelerated electrons are typically ~1 keV and these field-aligned electrons are the source of the global auroral current system [3].

Electrons streaming along the magnetic field have been observed in the magnetosphere [4] and in the plasma sheet [5,6]. Recently, Debye scale electrostatic structures similar to those seen in the auroral potential regions have been observed in Earth's geomagnetic tail [7,8] during times when plasmas flowed at speeds of several hundred km s$^{-1}$, which sometimes can exceed the local Alfvén speed [9]. Field-aligned electrons and solitary structures can create turbulences and unstable plasma distributions in the plasma sheet. An important problem still not understood well is how the auroral processes might affect the plasma sheet dynamics, and vice versa.

This article presents the first observations of field-aligned electron beams appearing in the plasma sheet just prior to the time when the current sheet dissipates energy. The beams are nearly identical to those commonly seen at ionospheric altitudes suggesting that the electron beams we measure have been accelerated upward in the auroral potential structure. The densities of the beams are substantial, representing ~5%–13% of the total local plasma density. The maximum field-aligned current carried by the electrons is $\sim 10^{-8}$–$10^{-7}$ A m$^{-2}$. These values are consistent with the Bohm criteria for sustaining the double layer structures.

*Observations.*—The electron data used in our study are in the energy range ~0.05–26.4 keV measured by the Plasma Electron and Current Experiment on the multi-spacecraft mission Cluster [10]. Plasma Electron and Current Experiment consists of electrostatic analyzers and position sensitive microchannel plates as detectors [11]. Two analyzers are placed on opposite sides of the spacecraft (SC) to view radially outward and, as the SC spins, the field of view sweeps out the entire sky obtaining 3D distributions in one spin of the SC (4 s). The energy and angular resolutions of the two detectors are, respectively, 12.7% and 16.5% and 15° (for both).

We discuss two events, one obtained when Cluster 3 (SC3) was in the geomagnetic tail ~15 $R_E$ ($R_E$ = 6380 km) and the other when Cluster 1 (SC1) was closer to Earth at ~5 $R_E$. The macroscopic plasma parameters (velocity moments of the distribution function) characterizing the conditions under which these observations were made are summarized in Figs. 1 and 3. The magnetic field components, density and temperature, energy flux spectrograms of ions and electrons, and pitch-angle spectrograms of the electrons (~ 0.5–2.3 keV) are shown as well. The ion detector, like the electron detector, measures 3D distributions in one spin of the spacecraft [12]. All measurements are given in the geocentric solar magnetospheric (GSM) coordinate system. XGSM is positive toward the Sun, YGSM is positive toward dusk, and ZGSM completes the third component of a right-handed coordinate system. The pitch angles at 0° and 180° correspond to along and against the magnetic field direction.

 

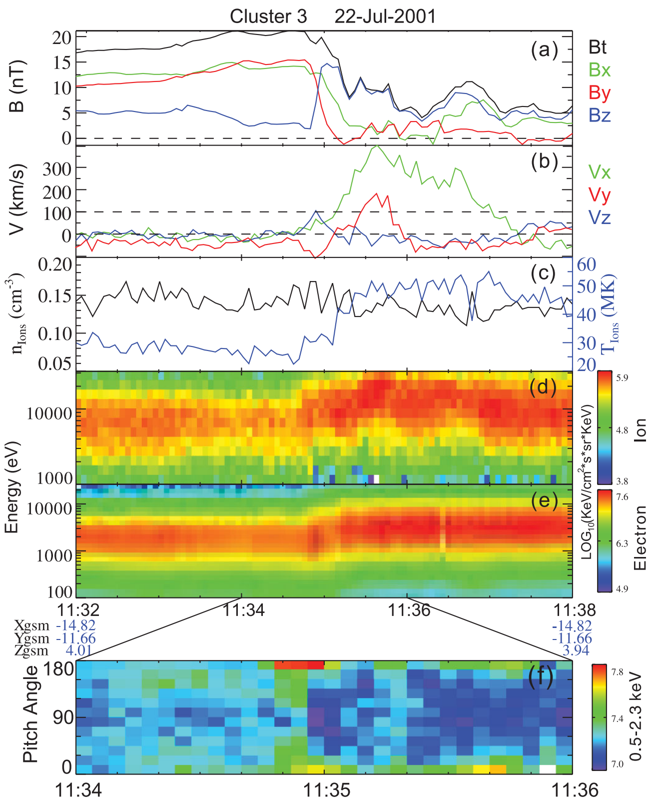


FIG. 1 (color). Summary plot of 22 July 2001. Data are shown in the GSM coordinate system. (a) Magnetic field components and the total intensity, (b) components of the average plasma speeds, (c) density (black) and temperature (blue), (d) and (e) energy flux spectrograms of ions and electrons, and (f) pitch-angle spectrograms of the electrons with energies ~0.5–2.3 keV.

*22 July 2001.*—The dynamics on this day began at ~1133 UT, with SC3 recording a small increase in $B_x$ and $B_y$ while $B_z$ decreased (Fig. 1). The maximum values attained by $B_x$ and $B_y$ at ~1134:45 UT were ~14 nT and ~15 nT, respectively, and the minimum by $B_z \sim 3$ nT. The total $|B|$ was ~22 nT, which suggests SC3 was close to the high latitude plasma sheet boundary. The energy flux spectrograms of ions (~ 1–30 keV) and electrons (~ 500 eV–6 keV) show typical behavior of plasma sheet particles and corroborate that SC3 was in the plasma sheet [panels (d) and (e)]. The slow build up of the magnetic field was observed on all four Cluster SC indicating this disturbance covered a region larger than the SC separation of 1200 km in *X-Y* and *X-Z* directions (not shown).

All three components of the magnetic field then changed abruptly at 1134:47 UT with $B_y$ decreasing to −1 nT and $B_x$ to ~3 nT. (The small value of $B_x$ indicates SC3 was near the current sheet.) The $B_z$ component increased sharply from ~3 nT to ~15 nT. This behavior is called dipolarization because the magnetic tail geometry becomes more dipolar. Dipolarizations occur when high $\beta$ plasma ($\beta \sim 0.4$) in the current sheet (CS) is abruptly "removed" by mechanisms as yet not identified, reconfiguring the magnetic topology. These current dissipations are accompanied by intense auroral activities and Earth becomes an intense radio emitter at kilometric wavelength [13].

Prior to 1134:47 UT, the plasma was relatively quiescent with $V_x$ and $V_z \sim 0$ and $V_y \sim -25$ km s$^{-1}$. Accompanying the onset of dipolarization, $V_x$ increased and reached ~400 km s$^{-1}$ at 1135:35 UT. $V_y$ changed from −25 km s$^{-1}$ to +125 km s$^{-1}$ and returned to −25 km s$^{-1}$. $V_z$ remained fairly steady throughout the period except at the beginning when it increased to ~100 km s$^{-1}$. Following the onset, SC3 encountered hotter and more intense plasma as $|B|$ decreased to ~5 nT. SC3 was then located close to the central CS where the ion plasma temperature was $T \sim 5 \times 10^7$ °K.

The pitch-angle spectrogram (panel f) shows a field-aligned electron beam (0.5–2.3 keV) at 180° pitch angle. The maximum beam intensity peaked at ~1134:47 UT just before the dipolarization and lasted for ~12 s (3 spins). At this time, SC3 was in the northern hemisphere and 180° pitch-angle corresponds to electrons coming from the earthward direction. The beam was observed within the field of view of one pixel ~15°.

The beam at ~0° was observed ~4–8 s later with diminished intensity. This time delay can be interpreted as either the time for the 180° beam to propagate to the opposite end of the field and mirror back or that the 0° electrons are coming from further down in the geomagnetic tail or the southern auroral ionosphere. The speed of 1 keV electrons is ~18 700 km s$^{-1}$, hence the time delay of 4–8 s corresponds to a distance of ~11–22 $R_E$.

The differential energy spectra of electrons from ~50–26 keV and pitch-angle distributions for a few selected energies are shown in Fig. 2. The energy spectra are for electrons with pitch-angles of 0°, 90°, and 180° (left panel). Except for the diminished intensity of the 1 keV peak at 0° as compared to 180°, the form of these energy spectra is essentially the same. The spectrum of 90° pitch angle electrons (black crosses) remained essentially unchanged compared to the spectra at earlier times before the beam was detected (not shown). The differential flux of the beam at the peak ~$8 \times 10^7$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ keV$^{-1}$ detected here is comparable to the upward going fluxes observed in the auroral ionosphere [2].

The behavior of the pitch-angle distributions for few selected energies (bottom right) is consistent with the energy spectra. We see "wings" at 0° and 180° to ~2 keV indicating the presence of field-aligned electrons. To characterize the beam, we have subtracted the mean fluxes and the beam was fit with a Maxwellian (top right). The estimated density of this beam is $\delta n_b \sim 0.05 \pm .02$ cm$^{-3}$ and using ~0.6–1 cm$^{-3}$ for the ambient density $n_e$ (estimated from the plasma frequency, not shown), $\delta n_b / n_e \sim$ 0.08–0.05. The temperature (kT) of the beam is

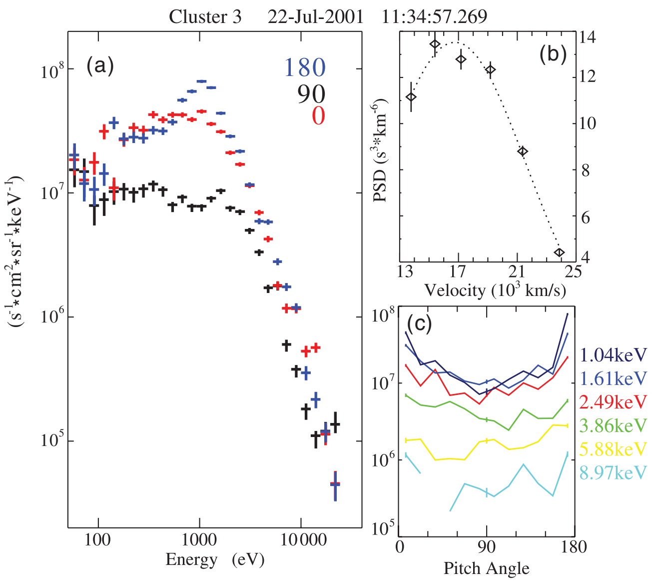


FIG. 2 (color). (a) Differential energy spectra for electrons with pitch-angles of 0°, 90°, and 180° at 1134:57. (b) Phase space density for the "beam" with a Maxwellian fit. (c) Pitch-angle distribution for selected energy channels.

$\sim$135 ± 22 eV and similar to temperatures reported [2] for the upward accelerated auroral electrons. The thermal velocity of the beam $v_b$ is $\sim 6.89 \times 10^3$ km s$^{-1}$. Since the drift speed $v_D$ of 1 keV electrons is $\sim 1.89 \times 10^4$ km s$^{-1}$, the ratio $v_D/v_b$ is $\sim$2.7. An estimate of field-aligned current carried by these electrons obtained by subtracting the electrons traveling along and against the direction of the magnetic field yielded $\sim 3 \times 10^{-8}$ A m$^{-2}$. This current was most intense when the beam developed at 1134:47 UT and it was measured on all 4 SC. The intensities were all nearly the same, but the features were different. For example, on SC2, it was bipolar and on SC4, there were two bursts (not shown).

*23 February 2004.*—The geomagnetic disturbance level on this day was moderate and multiple injections of energetic particle events were observed [14] accompanied by electron beams. We will focus on the beam observed at $\sim$0326:40 UT when SC1 detected dipolarization of the magnetic field (Fig. 3) shown by an increase of $B_z$ from $\sim$60 to $\sim$74 nT at 0326:30 UT. (Other components, for example, $B_x$, changed smoothly and none showed the dipolarization feature.) This dipolarization event was also accompanied by increases of mean plasma flow speeds, $V_x \sim 75$ km s$^{-1}$, $V_y \sim 50$ km s$^{-1}$, and $V_z \sim -75$ km s$^{-1}$.

The ion and electron pitch-angle spectrogram shows the counter-streaming field-aligned beams at 0° and 180° pitch angles were detected simultaneously, within the 4 s time resolution of the instrument (Fig. 3, panel f). Note that the data here cannot resolve any structure faster than 4 s sampling time. Electrons of 1 keV energy streaming at $\sim 1.89 \times 10^4$ km s$^{-1}$ above the aurora starting from 2 $R_E$ would arrive at the SC in less than 1 s.

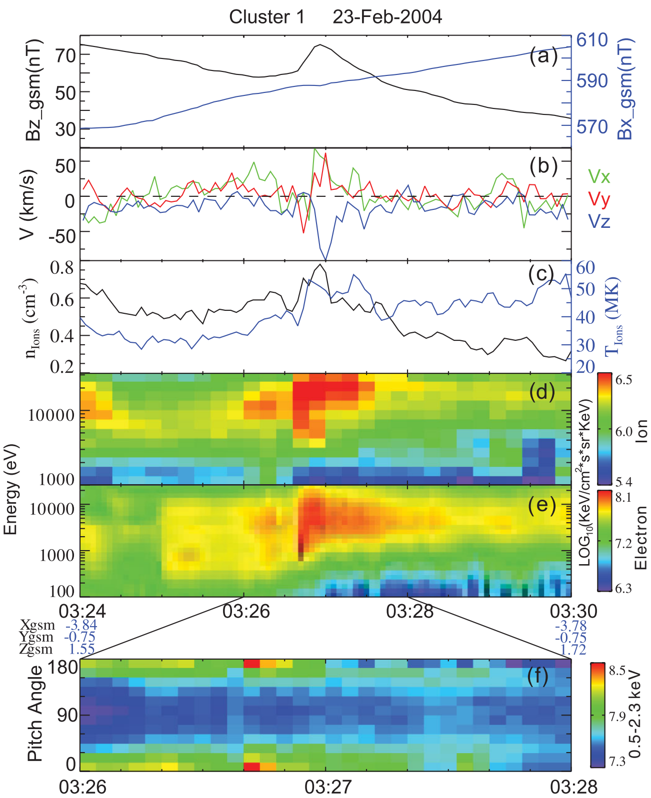


FIG. 3 (color). Summary plot of 23 February 2004. Identical format as in Fig. 1.

The left panel (Fig. 4) shows differential energy spectra of electrons from $\sim$50 eV–26 keV at 0°, 90°, and 180° pitch angles. Like the plasma sheet event, the beam energy is at $\sim$1 keV. The fluxes here were an order of magnitude higher than the fluxes in the plasma sheet. The pitch-angle distributions from a few selected energy channels (lower right) show enhancement of fluxes along 0° and 180° as in the plasma sheet with the fluxes slightly higher in 180°.

The beams close to Earth have all of the same features as the ones in the distant plasma sheet except here the beams are more intense and "cooler." The beam density determined for this event (Fig. 4, upper right) is $\delta n_b \sim 0.21 \pm 0.09$ cm$^{-3}$ and using the ambient electron density $n_e \sim 1.6$ cm$^{-3}$, we find $\delta n_b/n_e \sim 0.13$, which is slightly higher that the value in the plasma sheet. This beam had a temperature (kT) $\sim$51 ± 10 eV, yielding $v_b \sim 4.2 \times 10^3$ km s$^{-1}$ and the ratio $v_D/v_b$ is $\sim$4.5. Examination of several other beams observed close to Earth have shown similar features (not shown).

The field-aligned current determined for this event varied considerable on the 4 SC. Bipolar signatures were observed on SC2 and 4 with intensities $\sim 10^{-7}$ A m$^{-2}$ while the beams on SC 1 and 3 were unipolar and less intense, $\sim 10^{-8}$ A m$^{-2}$. These variations would be expected of localized structures of beams detected from different regions of the auroral potential structure.

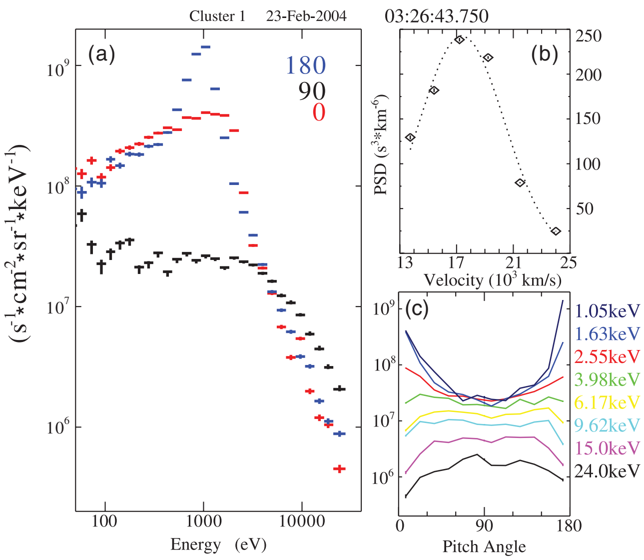


FIG. 4 (color). Differential spectra and pitch-angle distributions of electrons for the event on 23 February 2004. Identical format as in Fig. 2.

*Discussion.*—Plasmas in the vicinity of the current sheet are complicated with multicomponent populations that include unidirectional and counterstreaming electron beams. The streaming electrons have been interpreted in terms of the CS dynamics and/or reconnection processes [5,15,16]. The observations that the beams can arrive in the plasma sheet prior to dipolarization are important and indicate that the auroral process and the plasma sheet are dynamically coupled. However, our observations have not provided information on the dipolarization process, which remains unknown.

A rough estimate of the height of the ionosphere where the beams originate can be obtained by assuming these electrons keep their energy and first invariant constant. Noting that the ratio of the energy perpendicular $W_\perp$ and parallel $W_\parallel$ at the observation point with $B = 20$ nT is $W_\perp/W_\parallel = \tan^2 7.5° = 0.017$, the magnetic field at the mirror point is $B = 1196$ nT. The T96 [17] and international geophysical reference field models show the corresponding altitude of the mirror point is $\sim$17 000 km, indicating the streaming 1 keV electrons came from a height of $\sim 2.7\ R_E$ in the auroral ionosphere.

A random sampling of plasma sheet events shows the field-aligned beams are usually observed near boundaries with large temperature and density gradients when the CS dissipates energy. The beams are fairly intense with $\delta n_b/n \sim 0.05$–$0.1$, current $\sim 10^{-8}$ to $10^{-7}$ A m$^{-2}$ and the drift velocity of the beam $v_D \sim 1.8 \times 10^4$ km s$^{-1}$ is much larger than the thermal spread of the beam, $v_b \sim 10^3$ km s$^{-1}$. These values can be used to examine the Bohm criteria for producing double layers [18].

We find that in the plasma sheet, $m_e V_b^2 \sim 3 \times 10^{-9}$ ergs and $kT_e \sim 2.2 \times 10^{-10}$ ergs, satisfying one of Bohm's criteria by an order in magnitude. The other Bohm criterion for the current to sustain double layers $J_c > ne(2kT_e/m_e)^{1/2}$ is also satisfied: the current at the peak of the beam is $J_c \sim 10^{-7}$ A m$^{-2}$, which is larger than $ne(2kT_e/m_e)^{1/2} = 1 \times 10^{-10}$ A m$^{-2}$. These observations support the idea that the solitary waves observed in the plasma sheet are possibly produced locally by instabilities involving strong currents and double layers [7,8,19].

The beams we detected were also accompanied by wide band electrostatic (ES) waves, which are unresolved ES solitary structures of double layers [20]. Moreover, we observed fluctuations of electromagnetic fields at frequencies between the electron cyclotron and lower hybrid frequencies for ES waves and below the electron cyclotron frequency for the electromagnetic waves. Nearly monochromatic waves have been found in the Earth's magnetotail as far as $-90\ R_E$ [21,22].

A kinetic simulation has shown double layers could be produced in the ionosphere by strong currents [23]. A similar simulation has not yet been performed in the plasma sheet. The results reported here can be used as inputs in kinetic simulations to validate if double layers are a possible source of electrostatic solitary waves observed in the plasma sheet.

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