

## Postprint: Energy Characteristics During Field-Aligned Electron Events in the Earth's Magnetospheric Cusp Region

**Authors:** Zhang Ziyang, Shi Jiankui, Klaus Torkar, Wang Zheng, Cheng Zhengwei

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### Abstract

Based on data from the Cluster satellite observation of a strong disturbed field-aligned electron event on September 30, 2001, in the northern hemisphere polar cusp region, this study analyzes the energy characteristics of field-aligned electrons during this event and discusses the role of field-aligned electrons in the transmission of solar wind energy to the magnetosphere and in the energy transfer process during magnetosphere-ionosphere coupling. The main research results indicate that during this electron disturbance event, both electron velocity and density exhibited strong perturbation variations, with velocity increase being a primary factor. In this event, spectral analysis within the low-energy ranges of 5~200 eV and 500~1500 eV demonstrates that the upward electron flux exceeds the downward electron flux, indicating that upward electrons primarily originate from the ionosphere, and that ionospheric upward electrons play a very active role in this event. Based on analysis of the energy characteristics of charged particles in the ionosphere, it is concluded that upward electrons of ionospheric origin were accelerated during their upward propagation in this event. Regarding the acceleration mechanism, further in-depth research is required.

### Full Text

## Study on Energy Characteristics During Field-Aligned Electron Events in the Earth's Magnetospheric Cusp Region

Zhang Ziyang<sup>1,2</sup>, Shi Jiankui<sup>1</sup>, Klaus Torkar<sup>3</sup>, Wang Zheng<sup>1</sup>, Cheng Zhengwei<sup>1</sup>

<sup>1</sup>State Key Laboratory of Space Weather, National Space Science Center, Chinese Academy of Sciences, Beijing 100190, China

<sup>2</sup>College of Information Science and Technology, Beijing Normal University, Beijing 100875, China

<sup>3</sup>Space Research Institute, Austrian Academy of Sciences, Graz, Austria, A-8042

## Abstract

Based on data from an extremely intense field-aligned electron event observed by the Cluster satellites in the northern cusp region on September 30, 2001, this paper analyzes the energy characteristics of field-aligned electrons during this event and discusses their role in the transfer of solar wind energy into the magnetosphere and in magnetosphere-ionosphere coupling processes. The main findings indicate that both electron velocity and density exhibited strong perturbations during this event, with the velocity increase being a primary factor. Energy spectrum analysis within the low-energy ranges of 5–200 eV and 500–1500 eV reveals that the upward electron flux exceeded the downward electron flux, demonstrating that the upward electrons originated mainly from the ionosphere and that ionospheric upward electrons played a highly active role in this event. Based on the energy characteristics of charged particles in the ionosphere, we conclude that the ionospheric upward electrons were accelerated during their upward propagation. The specific acceleration mechanism requires further investigation.

**Keywords:** polar cusp, field-aligned electrons, energy characteristics, ionospheric origin

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## 1. Introduction

Field-aligned electrons were first observed in the late 1960s using OGO 4 satellite data, which revealed a flux peak near a pitch angle of  $0^\circ$  for electrons with energies of 2.3 keV [1]. In observational data analysis, field-aligned electrons are often referred to as “electron beams.” Polar region field-aligned electrons can be classified as upward-moving or downward-moving based on their direction of motion along magnetic field lines [2–4]. In the 1980s, researchers analyzing S3-3 satellite observations at altitudes of approximately  $1 R_E$  over the auroral zone identified both upward and downward electron beams propagating along magnetic field lines, finding that these oppositely directed field-aligned electrons could coexist simultaneously, though with slightly different energies [5].

Early observations suggested that field-aligned electron beams had very short durations of only 1–2 seconds [6,7]. However, using data from the Intercosmos-Bulgaria-1300 satellite at an altitude of about 850 km over the auroral zone, researchers detected field-aligned electron bursts lasting approximately 40 seconds, noting that these longer-duration (10–30 s) electron bursts corresponded to spatial scales of 100–250 km [8]. Long-term continuous observations by the Cluster II satellites have provided comprehensive statistics on polar region field-aligned electron events, revealing that their duration distribution ranges from

6 to 475 seconds, with most events lasting less than 50 seconds and the most probable duration being 10–20 seconds [9].

The energy of field-aligned electrons is generally on the order of eV, with maximum energies reaching the keV range [3,7]. Due to high energy thresholds on early satellites, low-energy field-aligned electrons with distinct spectral and pitch angle characteristics could not be observed. After implementing spacecraft potential control and reducing detection thresholds, field-aligned electrons have been observed in many regions of Earth's magnetosphere, including the auroral zone, cusp/cleft region, polar cap, plasmasphere, equatorial ring current region, and magnetotail plasma sheet, with different characteristics observed in different regions [10–12].

The cusp region plays a crucial role in solar wind-magnetosphere-ionosphere coupling. Solar wind energy can directly enter the magnetosphere through the cusp region and reach the ionosphere. Energy transferred from the solar wind to the magnetosphere is stored until it is released during magnetic storms and substorms, after which it is primarily dissipated in the atmosphere and ionosphere through the polar regions. Studying the characteristics of field-aligned electrons in the cusp region aids in understanding mass and energy transport and dissipation during solar wind-magnetosphere-ionosphere coupling. Consequently, researchers have conducted numerous studies on field-aligned electrons in polar regions, including the cusp region. Kintner et al. first observed upward field-aligned electrons in the southern hemisphere cusp region using Hawkeye 1 satellite data in 1978 [13], noting that the observed field-aligned electrons in the cusp region had energy peaks below 1 keV, generally concentrated in the 100–200 eV range, with fluxes between  $10^7$  and  $10^8$   $[\text{cm}^2 \cdot \text{s} \cdot \text{sr} \cdot \text{eV}]^{-1}$ . Subsequent studies have concluded that low-energy upward and downward field-aligned electrons are commonly present in the cusp region [14,15].

Ionospheric electrons typically have energies of only a few eV, yet upward electrons observed in polar regions exhibit energies ranging from tens of eV to keV levels. Therefore, electrons must undergo acceleration during their upward propagation from the ionosphere, enhancing their energy to levels detectable by satellites. Alfvén first proposed the existence of a parallel electric field acceleration mechanism along magnetic field lines above the polar ionosphere [16,17]; however, some researchers have noted that parallel electric fields alone cannot fully explain the characteristics of field-aligned electrons, suggesting that fluctuating electric fields and multiple flickering double layers [5] or wave-particle interactions may also contribute to particle acceleration [2,3].

The Cluster satellites carry electron and ion instruments capable of direct detection of field-aligned particles in polar regions. On September 30, 2001, during a magnetic storm, the four Cluster satellites observed an unprecedentedly intense field-aligned electron event while crossing Earth's cusp region. Analysis indicates that this field-aligned electron event was associated with enhanced solar wind dynamic pressure and southward interplanetary magnetic field disturbances. During this event, observed electron velocities reached 500 km/s,

electron densities reached  $75 \text{ cm}^{-3}$ , and downward electron fluxes reached  $2.10 \times 10^9 \text{ (cm}^2 \cdot \text{s)}^{-1}$ —parameters more than an order of magnitude greater than those observed by Cluster in regions outside the cusp and also more than an order of magnitude greater than those observed during quiet times [9,18].

This paper utilizes data from the intense field-aligned electron event observed by the four Cluster satellites during their crossing of the northern hemisphere cusp region on September 30, 2001, to analyze the energy characteristics of field-aligned electrons during this event and to discuss their origin and role in solar wind energy transfer to the magnetosphere and in magnetosphere-ionosphere coupling processes.

## 2. Data Sources

The Cluster II mission consists of four identical polar-orbiting satellites positioned at the vertices of a tetrahedron after orbital insertion. The Cluster orbit has an apogee geocentric distance of  $19.6 R_E$ , a perigee geocentric distance of  $4 R_E$ , an inclination near  $90^\circ$ , and an orbital period of 57 hours [19]. From July to October each year, the Cluster perigee is located in the dayside inner magnetosphere while the apogee is in the distant magnetotail. During this period, Cluster satellites cross over the polar region at altitudes of  $4\text{--}8 R_E$ , providing excellent observational opportunities for studying field-aligned electron events above Earth's polar regions.

The data used in this paper are from the four Cluster II satellites (C1, C2, C3, and C4). Electron detection data are obtained from the Plasma Electron And Current Experiment (PEACE) instrument [20], which covers an energy range of  $0.7 \text{ eV}\text{--}30 \text{ keV}$ . Magnetic field data are obtained from the Fluxgate Magnetometer (FGM) [21]. All data have a time resolution of 4 seconds.

On September 30, 2001, between 14:10 and 15:10 UT, the four Cluster satellites formed an elongated tetrahedral configuration in space, with the C3 satellite trailing behind the other three. The satellites successively crossed the northern hemisphere cusp region at a geocentric altitude of approximately  $4.5 R_E$ . During this period, the four Cluster satellites observed the largest spatial-scale, temporal-scale, and most intense field-aligned electron disturbance event to date at an altitude of about  $4.5 R_E$  above the cusp region [18].

[Figure 1: see original paper] shows a schematic diagram of the four satellites' orbital projections in the X-Z plane during the period 14:10–15:10 UT on September 30, 2001. The four differently colored line segments represent the projected trajectories of the four satellites: black, red, blue, and green correspond to C1, C2, C3, and C4, respectively. The arrow end of each segment corresponds to 14:10 UT, while the tail end corresponds to 15:10 UT. As shown in Figure 1, during 14:10–15:10 UT, the four Cluster satellites crossed the northern hemisphere cusp region at different times and spatial positions, in the order C4, C2, C1, and C3. The distance between C1 and C2 was 1000 km, between C1 and C4 was 1800 km, between C2 and C4 was 1000 km, and C3 was approximately

12,000 km from the other three satellites.

Researchers have established criteria for identifying cusp crossings based on observed parameter variations: the magnetic field strength must decrease by more than 1 nT relative to the background field with associated disturbances; proton and electron densities must increase abruptly and exceed  $5 \text{ cm}^{-3}$ ; electron temperature must change significantly; and  $\text{He}^{++}$  ions must be present with densities exceeding  $0.5 \text{ cm}^{-3}$  [22,23]. Following these criteria and incorporating actual Cluster observations, we determined that the cusp crossing intervals for the Cluster satellites on September 30, 2001, were 14:20–14:32 UT (C1), 14:20–14:32 UT (C2), 14:58–15:02 UT (C3), and 14:18–14:32 UT (C4). During these crossings, all four satellites observed clear decreases in total magnetic field strength with disturbances, abrupt increases in electron density (reaching a maximum of approximately  $110 \text{ cm}^{-3}$ ), and increases in electron temperature (reaching a maximum of approximately 130 eV). These characteristics satisfy the established criteria for cusp crossings [22,23].

### 3. Data Analysis Results and Discussion

Early researchers referred to electrons observed near a pitch angle of  $0^\circ$  as field-aligned electrons. In reality, due to the presence of magnetic fields and the charge carried by electrons, nearly all electrons in magnetized regions undergo gyromotion around magnetic field lines while simultaneously moving parallel to them, and thus can be considered field-aligned electrons [18].

[Figure 2: see original paper] presents the time series of electron field-aligned velocity, density, and field-aligned flux observed by the C3 satellite during its crossing of the northern hemisphere cusp region on September 30, 2001, during a major magnetic storm. Between 14:10 and 15:10 UT on that day, the C4, C2, C1, and C3 satellites successively crossed the northern hemisphere cusp region, all observing intense field-aligned electron disturbance events with significant perturbations in field-aligned electron flux.

As shown in Figure 2, the C3 satellite observed dramatic disturbances in electron field-aligned velocity, density, and flux during its cusp crossing. C3 first detected downward electrons, followed by upward electrons with extremely strong flux. At 14:58 UT, when C3 entered the cusp region, it observed a sharp increase in electron density with disturbed, downward-directed velocities reaching a maximum of 500 km/s. At 15:00 UT, electron density reached its maximum value of  $75 \text{ cm}^{-3}$ , nearly 20 times greater than that observed before C3 entered the cusp region. At this time, the downward flux also increased to its maximum value of approximately  $2.10 \times 10^9 \text{ (cm}^2 \cdot \text{s)}^{-1}$ . At 15:00:30 UT, C3 observed the electron velocity transition from downward to upward, after which the electron density decreased rapidly but remained at relatively high values; the upward velocity and upward flux were not yet large. At 15:02 UT, the upward velocity reached its maximum value of 1200 km/s, while electron density also reached a peak of approximately  $42 \text{ cm}^{-3}$ , and the upward flux reached its maximum

value of  $4.70 \times 10^9 \text{ (cm}^2 \cdot \text{s)}^{-1}$ . Subsequently, the electron field-aligned velocity decreased sharply, and the electron field-aligned flux began to decrease. After exiting the northern hemisphere cusp region, the observed field-aligned electron parameters returned to their pre-cusp levels.

Electron field-aligned flux is determined by both electron density and field-aligned velocity. Based on the observed variations in field-aligned electron velocity, density, and flux during the Cluster cusp crossing on September 30, 2001, we can see that the perturbations in electron field-aligned flux are closely related to perturbations in both electron density and velocity: the variation trend of electron field-aligned flux resembles that of electron field-aligned velocity, indicating that velocity plays a crucial role in determining the flux variation trend. However, during the period 14:59–15:00:30 UT, the rapid increase in electron density made density an important contributor to the electron field-aligned flux.

Increased velocity leads to increased energy of charged particles. During this observed field-aligned electron disturbance event, the electrons carried significantly enhanced energy. [Figure 3: see original paper] shows the electron energy spectra at different pitch angles in two low-energy ranges (5–200 eV and 500–1500 eV) observed by the PEACE instrument on Cluster during the field-aligned electron enhancement event on September 30, 2001. The C3 satellite did not obtain electron spectral data before 14:23 UT due to instrument issues, resulting in a blank display. The different color bars on the right side of each panel represent the magnitude of electron energy flux.

As shown in Figure 3, all four Cluster satellites observed enhanced electron energies across the full pitch angle range for both 5–200 eV and 500–1500 eV electrons during their cusp crossings, indicating that electron fluxes at different pitch angles within the cusp region were greater than those outside the cusp. During satellite entry into the cusp region, the increase in 5–200 eV electron flux was much greater than that in the 500–1500 eV range, demonstrating that the enhanced electron flux in the cusp region consisted primarily of low-energy electrons. Low-energy charged particles mainly originate from the ionosphere and often undergo acceleration during upward propagation [13,24]. This indicates that ionospheric charged particles played a highly active role in this cusp field-aligned electron disturbance event during the magnetic storm. Additionally, in the 5–200 eV electron spectrogram, the energy flux at a pitch angle of  $180^\circ$  (i.e., upward electrons) was significantly greater than that at other pitch angles, further confirming that these low-energy electrons were moving upward along magnetic field lines from the ionosphere. Since ionospheric charged particles have energies of only a few eV, while Figure 3 shows electron energies in the 5–200 eV range, this demonstrates that ionospheric electrons were accelerated during their upward propagation.

Figure 3 also shows that in the 500–1500 eV electron spectrogram, the energy fluxes at pitch angles of  $0^\circ$  and  $180^\circ$  were both significantly greater than those at other pitch angles, with different spectral characteristics for downward and upward electrons. Solar wind particles can directly enter the magnetosphere

through the cusp region along magnetic field lines, even reaching ionospheric altitudes. The downward electrons (pitch angle  $0^\circ$ ) observed in the 500-1500 eV spectrogram should primarily originate from the solar wind, indicating that solar wind electrons constitute a major component of the observed electrons in this energy range.

The upward electrons observed at a pitch angle of  $180^\circ$  in the 500-1500 eV range have two possible sources: ionospheric electrons and reflected solar wind electrons. Ionospheric electrons with energies as high as 500-1500 eV indicate that upward electrons from the ionosphere underwent substantial acceleration. Proposed acceleration mechanisms for electrons during upward propagation from the ionosphere include parallel electric fields along magnetic field lines above the ionosphere [16,17], fluctuating electric fields and multiple flickering double layers [5], and wave-particle interactions [2,3]. All these mechanisms can accelerate electrons to varying degrees. The specific acceleration mechanism for the field-aligned electrons observed in this event requires further investigation.

Electrons undergoing upward or downward motion along magnetic field lines also execute gyromotion. Consequently, electron energy can be divided into two components: energy parallel to the magnetic field and energy perpendicular to the magnetic field, with the perpendicular component including both gyromotion energy and drift energy perpendicular to the magnetic field lines.

[Figure 4: see original paper] shows the temporal variation of total electron energy calculated from all energy channels of the electron spectra observed by the four Cluster satellites during the field-aligned electron enhancement event on September 30, 2001. As shown in Figure 4, the total electron energy observed before entering and after exiting the cusp region was very small and exhibited no significant disturbances. In contrast, the total electron energy observed within the cusp region was much higher and accompanied by large perturbations.

As shown in Figure 4, during this event, the maximum total electron energy observed by C1 in the northern hemisphere cusp region reached 620 eV, C2 observed a maximum of 2000 eV, C3 observed the highest total electron energy of up to 3800 eV, and C4 observed a maximum of 2500 eV. These data demonstrate that electrons observed in the northern hemisphere cusp region during this event carried very high energies in the energy transfer process, including energy transferred from the solar wind to the magnetosphere and from the magnetosphere to the ionosphere. Detailed aspects of this energy transfer require further investigation combined with other observational data.

The above analysis shows that cusp electrons originate from both the ionosphere and the solar wind. Although electrons from the ionosphere have relatively low energies, they undergo acceleration during upward propagation. Electrons from the solar wind have higher energies, indicating direct energy transport of solar wind electrons through the cusp region. Therefore, the cusp region represents an important area in solar wind-magnetosphere-ionosphere coupling processes.

#### 4. Discussion

Generally, both upward and downward field-aligned electrons in Earth's polar regions have two sources. Observed downward field-aligned electrons may be solar wind electrons directly entering the cusp region or reflected ionospheric upward electrons under the influence of potential drops above the polar region. Upward electrons may originate from the ionosphere or be reflected solar wind electrons under the action of magnetic mirror forces. Ionospheric electrons are characterized by low energies and often undergo acceleration during upward propagation. In this study, we investigate field-aligned electrons by combining their energy characteristics with their direction of motion, allowing qualitative determination of their origin. The results show that upward electrons in this event primarily originated from the ionosphere. However, accurately determining the contribution of different sources to this field-aligned electron event requires multi-point measurements and more comprehensive investigation.

Analysis of Cluster satellite data from September 30, 2001, shows that electrons from the ionosphere underwent acceleration. Alfvén proposed a parallel electric field acceleration mechanism along magnetic field lines above the polar ionosphere [16,17]; however, some researchers have noted that parallel electric fields alone cannot fully explain the characteristics of field-aligned electrons, suggesting that fluctuating electric fields and multiple flickering double layers can also accelerate charged particles [5], while others have shown that wave-particle interactions can accelerate charged particles [2,3]. The specific acceleration process for the field-aligned electrons observed in this event requires investigation using multiple instruments and analytical techniques.

During a major magnetic storm on September 30, 2001, the Cluster satellites observed the most intensely disturbed field-aligned electron event to date in the northern hemisphere cusp region. Using data from the PEACE and FGM instruments on the four Cluster satellites during their crossing of the northern hemisphere cusp region, this paper analyzes the energy characteristics of field-aligned electrons during this event, investigates their origin, and discusses their role in solar wind energy transfer to the magnetosphere and in magnetosphere-ionosphere coupling. The main results are as follows: The extremely high field-aligned electron flux density observed by Cluster resulted from both electron velocity and density increases. In this event, both velocity and density increased, but the velocity increase was the primary factor producing high field-aligned electron flux. Generally, downward field-aligned electrons have two sources: solar wind electrons directly entering the cusp region and reflected ionospheric upward electrons under potential drops. Upward electrons also have two sources: solar wind electrons reflected by magnetic mirror forces and accelerated ionospheric electrons. Energy spectrum analysis of electrons in the low-energy ranges of 5–200 eV and 500–1500 eV observed by the Cluster PEACE instrument indicates that in this event, the upward electron flux exceeded the downward electron flux in the low-energy range, demonstrating that upward electrons originated mainly from the ionosphere and that ionospheric upward electrons played

a highly active role. Based on the energy characteristics of electrons in the ionosphere, we conclude that ionospheric upward electrons were accelerated during their upward propagation in this event. The acceleration mechanism requires further investigation.

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