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Key Points:
- Cluster FAE distribution is double peaked around auroral oval at high altitude
- The distribution shows a dawn favored asymmetry in the cusp/cleft region
- The FAE durations can be 475 s which is the longest of the so far observed

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Distribution of Field-Aligned Electron Events in the High-Altitude Polar Region: Cluster Observations

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Abstract Field-aligned electrons (FAEs) are important for the energy transport in the solar wind-magnetosphere-ionosphere coupling. However, the distribution of FAEs and the concerning physical mechanism in different altitudes of the polar region are still unclear. In this paper, data from the Cluster spacecraft were used to study the characteristics of FAEs in high-altitude polar region. We selected FAE events with a flux higher than $3 \times 10^8 (cm^2\ s)^{-1}$ for our analysis. Their distribution was double peaked around the auroral oval. The main peak occurred around the cusp region (magnetic local time (MLT) 0700–1500) which leaned to the dawnside. The other peak appeared in the evening sector with MLT 2100–2300 just before midnight. The durations of the FAE events covered a wide range from 4 to 475 s, with most of the FAE events lasting less than 40 s. The possible physical mechanisms are discussed, namely, that the downward FAEs may consist of decelerated solar wind and reflected up flowing ionospheric electrons in the potential drops, whereas the upward ones may be mirrored solar wind electrons and accelerated ionospheric up flowing electrons.

1. Introduction

Field-aligned electrons (FAEs) measured by satellites in the low- and middle-altitude polar regions have been reported by multiple authors. In the low-altitude (300–1,000 km) polar region, downward and upward electrons have been measured in the auroral oval by the AE-C and AE-D spacecraft (Klumpar, 1981; Lin & Hoffman, 1979; Zanetti et al., 1981). In the middle-altitude (1 R_E) polar region, electrons simultaneously streaming upward and downward have been observed by the S3-3 satellite (Sharp et al., 1980). According to the statistics of the S3-3 data in the auroral oval, the field-aligned electrons were considered to be stable in a circumpolar zone (Collin et al., 1982).

Berko (1973) studied the field-aligned electron precipitation that was most likely to occur when particle fluxes were high. He also noticed that the field-aligned precipitation generally was a short-time duration phenomenon, rarely appearing continuously for more than 5 to 10 s according to the data from the OGO 4 satellite at an altitude of 412–908 km. The Freja TESP electron spectrometer repeatedly observed 0.05–15 s field-aligned electron events at the altitude of 1,700 km in the auroral zone (Boehm et al., 1995). The data from the Intercosmos-Bulgaria-1300 Satellite had shown that the FAEs were observed continuously for 10–30 s at altitudes of about 850 km, and the FAEs could sometimes last for 40 s (Bankov et al., 1986).

By analyzing the OGO 4 satellite data at altitudes of 412–908 km, Berko (1973) pointed out that the FAEs were distributed over the entire auroral oval with a maximum occurrence at about ILAT (invariant latitude) 70°–72.5° in the range of magnetic local time (MLT) 2200–0100(+1). Using S3-3 data obtained at low altitude (3,000–8,000 km) in the northern polar region, Collin et al. (1982) have shown that the FAEs were limited to an ILAT range within 63–81°, and the MLT distribution was double peaked in the morning and evening at MLT 0700 and 2200, respectively, and only in the northern polar region. In a statistical study on field-aligned electrons observed by Exos D (Akebono) below 10,000 km altitude, Miyake et al. (1998) showed that the field-aligned electrons were largely a dayside phenomenon. Using Viking data, Thelin and Lundin (1990) found that the FAEs were more frequent in the dawn sector than in the dusk sector at an altitude of 2 R_E in the cusp/cleft region.

The research mentioned above mostly concerns the FAEs observed in the low-altitude polar region. In general, the authors considered that the up flowing electrons were originating in the ionosphere (Gorney et al., 1985; Miyake et al., 1998; Zanetti et al., 1981). Yoshioka et al. (2000) pointed out that a fraction of the downward electrons were possibly caused by up flowing electrons drifting to the adjacent magnetic field line and being reflected back by the potential drop above the satellite. Some characteristics of the downward electrons, however, were different from those of the upward flowing electrons. This suggests an alternative path of entering the low-altitude polar region. Some authors considered that solar wind or magnetosheath electrons could be the main source for downward electrons in the cusp region (Lavraud et al., 2004; Shi et al., 2014; Smith & Lockwood, 1996), and the magnetotail electrons should be the main source for the downward electrons or precipitation in the nightside auroral oval (Barth et al., 2004; Berko & Hoffman, 1974; Crooker, 1992; Teste et al., 2007).

Some authors have studied the contribution of the FAEs to the field-aligned current (FAC). McFadden et al. (1999) considered that FAEs are the main carrier of FACs in the polar region. By calculation and comparison, Klumpar and Heikkila (1982) considered that the FAEs have a great contribution to the FAC and could be the only carrier of FACs in the polar region.

The Cluster satellites with their electron measurements provide a good opportunity to study the FAEs (Escoubet et al., 2001). Using Cluster data, some authors reported FAE events with durations less than 60 s in the dayside auroral oval (Hu et al., 2008). Some authors found heavy FAE disturbances in the cusp region (Shi et al., 2014). However, there is no report on the FAE distribution at the altitudes of the Cluster orbit.

This paper describes the distribution of the FAEs observed in the high-altitude polar region, using data from the Cluster spacecraft. The results show that FAEs are mainly distributed in the cusp region and in the nightside auroral oval. The differences of the FAE distributions between high and low altitudes are also discussed.

2. Data and Instrument

The four Cluster spacecraft have a quasi-polar orbit with an apogee at about 19.7 R_E and a perigee at about 4 R_E (Escoubet et al., 2001). Cluster crosses the polar region at an altitude of about 4–8 R_E and has the advantage of allowing studies on FAEs in the high-altitude polar region.

In this paper, we use the electron data from the Plasma Electron And Current Experiment (PEACE) covering an energy range from 0.7 eV to 30 keV and detecting electrons arriving from all directions (Johnstone et al., 1997) and magnetic field data from the fluxgate magnetometer (FGM) (Balogh et al., 2001) of the Cluster spacecraft from the years 2003 and 2004 in order to statistically analyze the characteristics of the FAEs in the high-altitude polar region. We select orbit sections in the polar region by using data at ILAT $>51°$. Moreover, we use the magnetic field data to determine whether the spacecraft is inside the magnetosphere. The data are spin averages with a time resolution of about 4 s.

As we know, the motion of electron can in general be described as a superposition of two components. One is gyromotion around the magnetic field line and the other is the field-aligned motion of the electron guiding center along the field line. Therefore, we call the electrons field-aligned electrons (FAEs) and use the field-aligned flux to do analysis on the electron characteristics. The flux is defined as the field-aligned velocity multiplied by the electron density. These quantities have been extracted from the PEACE moments data product in the Cluster Science Archive. If we calculate the FAE flux with all data, we can see (an example is given in Figure 1) that most of the time the FAE flux is very small and merged into the background noise. For this study we define an FAE event as an electron beam with a continuous field-aligned number flux above a noise threshold of $3 \times 10^8 (\mathrm{cm}^2\ \mathrm{s})^{-1}$ in magnitude which was determined empirically by checking the flux calculated from all data. For example, the red lines in Figure 1 mark the threshold of $3 \times 10^8 (\mathrm{cm}^2\ \mathrm{s})^{-1}$. All events with a flux over the upper red line or below the lower one were selected for analysis.

The duration of an FAE event is defined as the time range in which the flux continuously keeps its absolute value greater than the threshold. The FAE is called upward (or downward) FAE in accordance with its

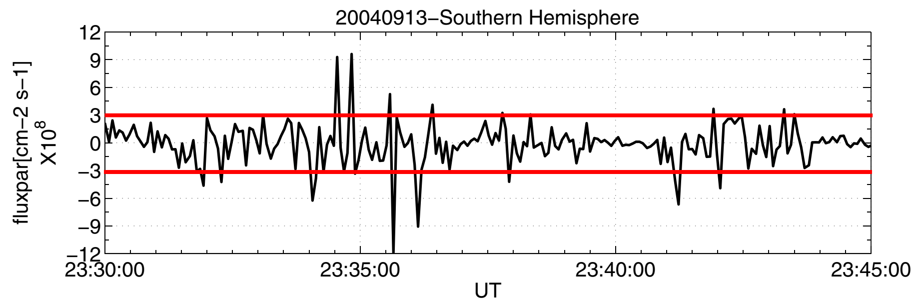

Figure 1. An example of the FAE event selection, based on data from spacecraft Cluster C3. The red lines mark the threshold.

field-aligned velocity direction relative to the Earth. The Tsyganenko T96-01 model (Tsyganenko & Stern, 1996) is used in our study.

3. Statistical Results

Data observed by Cluster in 2003 and 2004 were used for our analysis. We define a "polar region" with ILAT $>$ 51°. A total of 1,335 FAE events has been identified in the polar region, including 625 up flowing and 710 down flowing events. There were 860 (64%) and 475 (36%) events in the Southern and Northern Hemispheres, respectively.

The 1,335 FAE events covered the entire MLT range in the polar region (Figure 2a). In 2003 and 2004, the typical altitude range of the Cluster orbit in the southern polar region (4–7 R_E) was slightly higher than that in the northern one (4–6.5 R_E). However, in the Southern Hemisphere, a single trajectory covered a narrow range of MLT (1–5 h), while one trajectory covered a large range of MLT (5–15 h) in the Northern Hemisphere. Thus, one spacecraft trajectory crossed different regions.

In Figures 2b–2d, we can see that all FAE events, including the downward and upward ones, were observed in the altitude range of 4 to 7 R_E in the Southern Hemisphere, while they were observed in the altitude range of 4 to 6.5 R_E in the Northern Hemisphere.

From the first glance we can say that the FAE events were mainly concentrated around noon, and some of them were located in the premidnight sector. In detail, we can see that up flowing and down flowing electrons had similar distributions with MLT both in the Northern and Southern Hemispheres. Most of the FAE events were concentrated in the MLT range of 0700–1500 (was it around the cusp region? we will confirm it later) both for the downward and the upward events and both in the Northern and Southern Hemispheres. Also, we can see another concentration of FAE events on the evening side, in the MLT range of 1900–0100(+1), both for the downward and upward directions, both in the Northern and Southern Hemispheres.

The noontime concentrations of FAE events, in both the upward and downward directions, were in the altitude range from about 4 to 7 R_E in the Southern Hemisphere and from about 4 to 6.5 R_E in the Northern Hemisphere. Also, the evening time concentrations had a lower altitude range than the noontime concentrations both in the Northern and Southern Hemispheres.

Figure 3 shows the locations of all FAE events in the MLT-ILAT plane. The red crosses and the black circles are used to mark the upward and downward FAE events, respectively. We can see that the FAE events were mainly distributed in the latitude range of ILAT 62°–85° in the Southern Hemisphere and ILAT 65°–83° in the Northern Hemisphere, but there were different features in different directions and different MLT regions. For details, please see later in this paper.

Beside Figure 3, we perform statistical analysis of the FAE distribution in the polar region. The statistics is for the number of the FAE events and the normalized count rate of FAE events. The normalized count rate is to investigate the satellites orbit influence on the FAEs distribution and is calculated as a ratio of number of FAE events in each MLT and latitude bin to the total time of Cluster spent in that MLT and latitude bin.

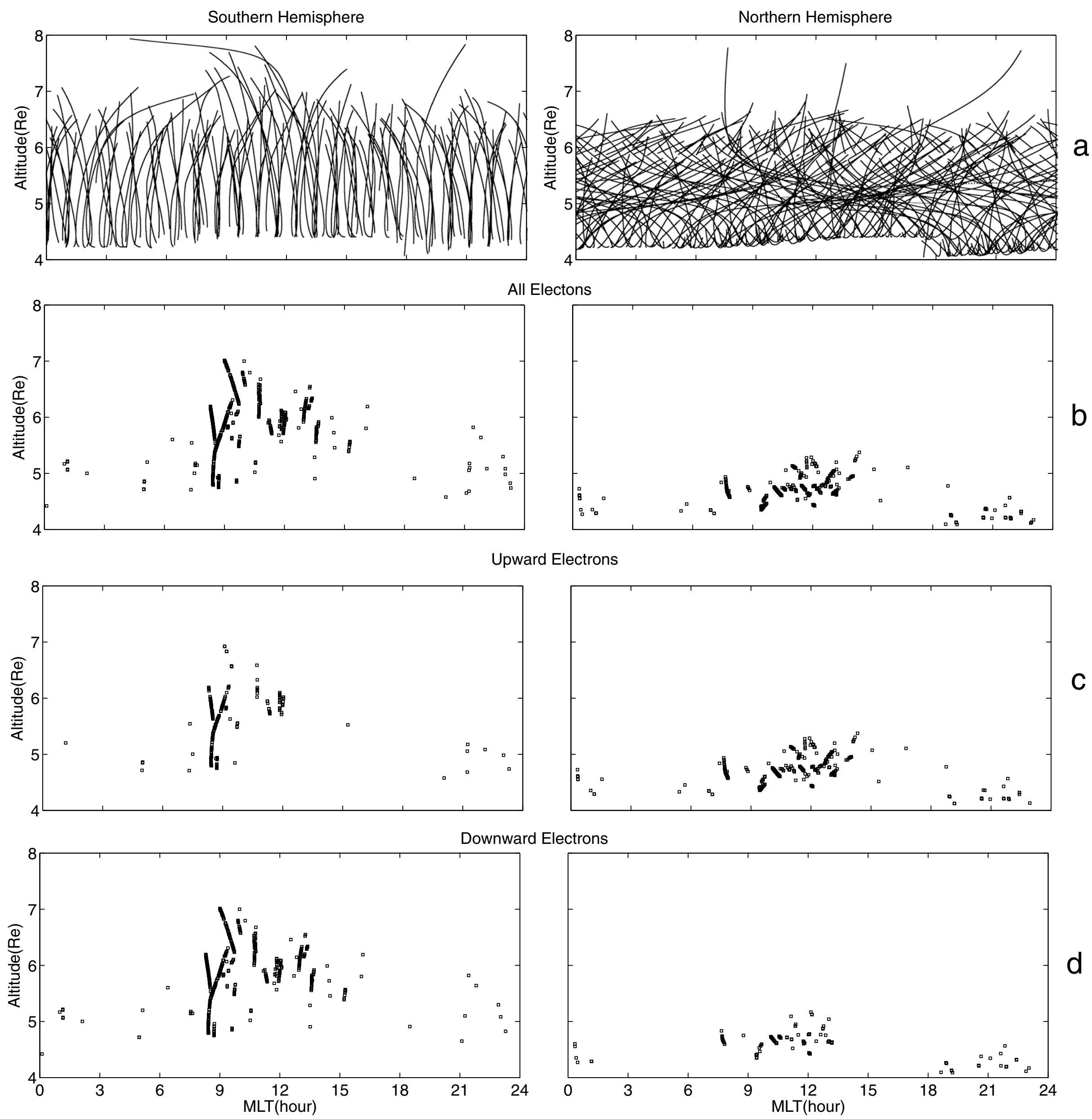

Figure 2. (a) The orbital coverage of the Cluster observation in the polar region. (b–d) The locations of all FAE events, the up flowing, and the down flowing FAE events in MLT-altitude plane both in the Southern and Northern Hemispheres, respectively.

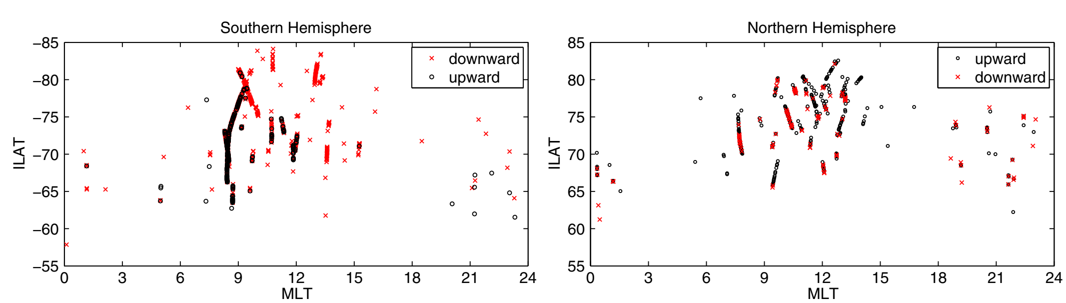

Figure 3. Distribution of the FAE events locations in the MLT-ILAT plane, the red crosses and the black circles marking the upward and downward FAE events, respectively.

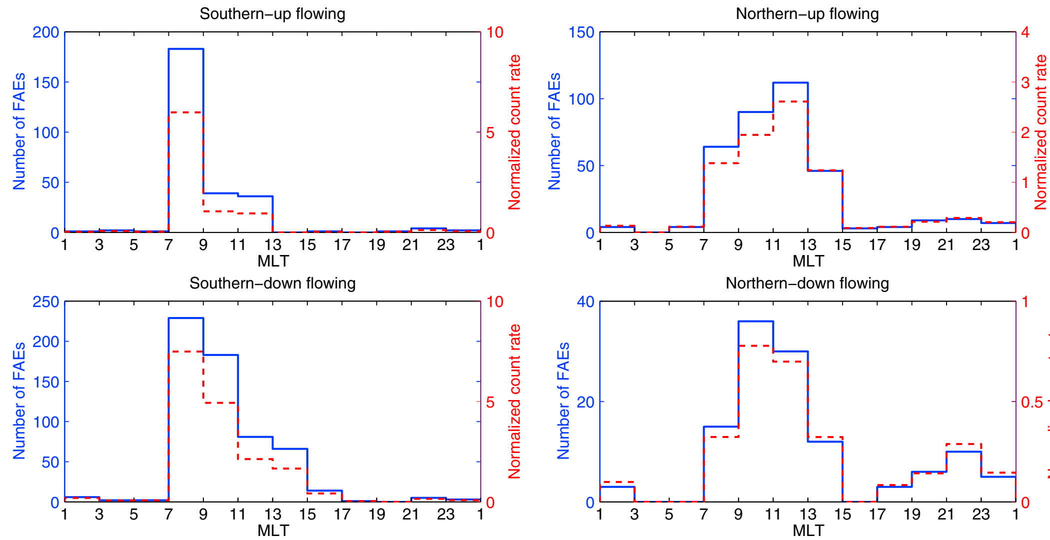

Figure 4. FAE events number (the real line with blue color) and normalized count rates (the dashed line with red color) versus MLT in upward and downward directions and in both hemispheres in 2003 and 2004.

Figure 4 illustrates the statistics on the upward and downward FAE events versus MLT in both hemispheres. The left vertical column with blue color represents the number of the FAE events, and the right vertical column with red color represents the normalized count rates of the FAE events. One can clearly see the distribution of FAE events in different MLT ranges in Figure 4.

First, from left column of Figure 4, we can see that the upward FAE events in the Southern Hemisphere on the dayside were mainly distributed in the MLT range 0700–1300 which covers the MLT range before and part of the cusp/cleft, and the downward events were mainly distributed in the MLT range 0700–1500 which covers the MLT range before and inside the entire cusp/cleft. The occurrences of both the upward and downward FAE events peak in the MLT range 0700–0090 which is before the cusp/cleft MLT range. On the dayside in the Northern Hemisphere, both the upward and the downward FAE events were mainly distributed in the MLT range 0700–1500. The upward FAE events peaked around noon at MLT 1100–1300, and the downward events had a number peak leaned to the forenoon in the MLT range 0900–1100. So we can say for both hemispheres that both the upward and downward FAE events on the daytime are mainly distributed in the MLT range which includes the cusp/cleft. There were more FAE events in the morning sector than in the afternoon.

Second, from the left column in Figure 4, we can see that, on the nightside, both in the Southern and Northern Hemispheres, both the upward and downward FAE events were concentrated before midnight and had a maximum occurrence in the MLT range 2100–2300. Both the upward and downward FAE events stood out more in the north than in the south. In the Northern Hemisphere, the downward FAE events stood out more than the upward ones.

From Figure 4, one can see that variations of the normalized count rate (red dashed line) for both upward and downward FAEs both in the Northern and Southern Hemispheres are similar to the variations of the absolute counts (blue real line). It implies that the Cluster satellites orbit influence on the distribution of the FAE events can be neglected.

From the above we can see that the MLT distribution of the FAE events (both the upward and downward ones) observed at the altitudes of the Cluster orbit was double peaked in both hemispheres. The main peak was around the cusp region and leaned toward the dawnside. The other peak was around the range of 2100–2300 in MLT.

We have also checked the ILAT of the FAE events locations in two different MLT ranges. Figures 5 and 6 depict the ILAT ranges of the dayside and nightside FAE concentrations, respectively. The left vertical column with blue color represents the number of the FAE events, and the right vertical column with red color represents

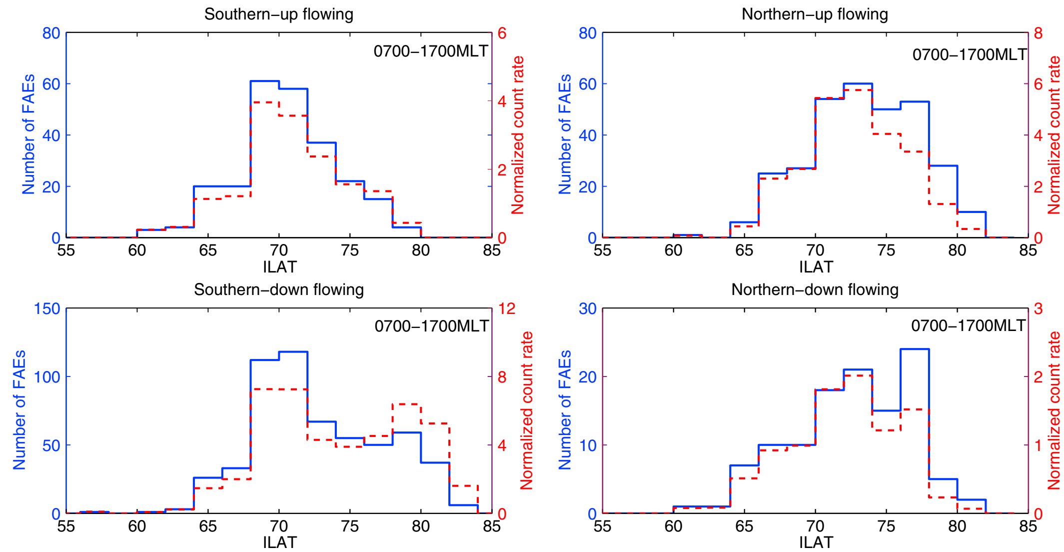

Figure 5. ILAT distributions of the upward and downward electron events in the Southern and Northern Hemispheres in the MLT range 0700–1700. The blue real line represents the number of the FAE events, and the red dashed line represents the normalized count rates of the FAE events.

the normalized count rates of the FAE events. Figure 5 is for the ILAT of the FAE events in MLT 0700–1700, and Figure 6 is for MLT 1900–0300(+1).

From Figure 5 we can see that for the dayside cases in the Southern Hemisphere the upward FAE events are mainly distributed at ILAT 60°–80° and the downward ones at ILAT 63°–84°. Both the upward and downward FAEs had peak numbers around ILAT 70°. In view of the MLT range shown in Figure 4 we can say for the Southern Hemisphere that both the upward and downward FAE events were mainly distributed around the cusp/cleft on the dayside but leaned to forenoon. For the dayside cases in the Northern Hemisphere we can see that both the upward and downward FAE events were mainly distributed at ILAT 65°–82° and had a peak around ILAT 73°. In view of the MLT range shown in Figure 4 we can say for the Northern

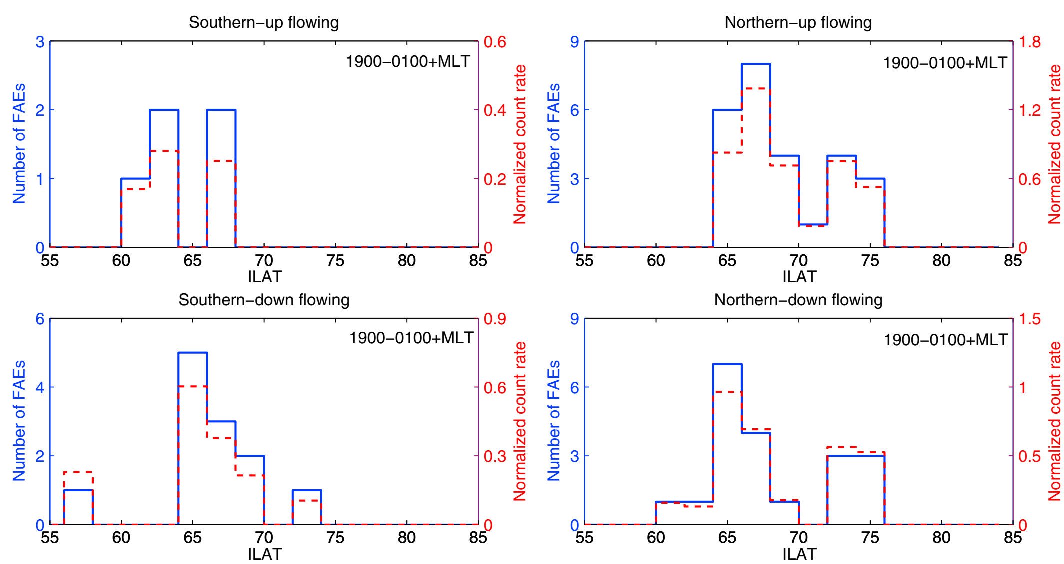

Figure 6. ILAT distributions of the upward and downward electron events in the Southern and Northern Hemispheres in the MLT range 1900–0100(+1). The blue real line represents the number of the FAE events, and the red dashed line represents the normalized count rates of the FAE events.

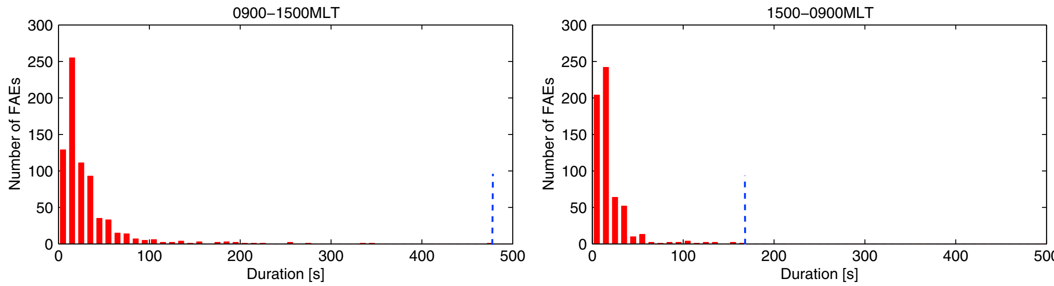

Figure 7. The distribution of durations of FAE events (left) around cusp/cleft and (right) elsewhere. The dashed line indicates the maximum durations.

Hemisphere that both the upward and downward FAE events were also mainly distributed around the cusp/cleft on the dayside but leaned to morning sector.

From Figure 5, one can see that variations of the normalized count rate of FAE events for both upward and downward FAEs both in the Northern and Southern Hemispheres are similar to the variations of the absolute counts of the FAE events. It implies that the Cluster satellites orbit influence on the FAEs distribution can be neglected.

We can also see that the ILAT of the FAE event number peak in the Northern Hemisphere was higher than that in the Southern Hemisphere for both the upward and downward FAEs. But for the normalized count rates of the FAE events, the peak values were near the same in all cases in Figure 5. From both absolute number and normalized count rate of the FAE events, we note that the downward FAE in both hemispheres seems to have other peaks at ILAT 75°–82°. It needs to be further studied.

From Figure 6, we can see that the FAE events on the nightside were less frequent than those on the dayside, but their number is still sufficient to obtain some distribution information. For the nighttime Southern Hemisphere (in the left two panels), the upward FAE events were mainly distributed at ILAT 60°–68° and the downward ones at ILAT 64°–74°. In view of the MLT range shown in Figure 4, we can say that both the upward and downward FAE events were mainly distributed around the auroral oval on the nightside but leaned to foremidnight. For the Northern Hemisphere (in the right two panels), the upward FAE events were mainly distributed at ILAT 65°–76° and the downward FAE events at ILAT 60°–76°. In view of the MLT range shown in Figure 4, we also can say that both the upward and downward FAE events were also mainly distributed around the auroral oval on the nightside but also leaned to foremidnight.

From Figure 6, one can see that all variations of the normalized count rate of FAE events in each panel are similar to the variations of the absolute counts of the FAE events. It implies that the Cluster satellites orbit influence on the FAEs distribution can be neglected.

Thus, we conclude that in the polar region at the altitude of the Cluster orbit the MLT distribution of the FAE events was double peaked in both the Southern and Northern Hemispheres. The main peak was in the daytime, and the other one was in the nighttime. In the daytime, the FAE events were mainly concentrated in the cusp/cleft region leaned to forenoon both for the upward and downward events in both hemispheres. In the nighttime, the FAE events mainly concentrated in the auroral oval but leaned to foremidnight, both for the upward and downward directions and in both hemispheres.

We have also studied the distribution of the FAE event durations. The shortest FAE duration was 4 s, and the longest reached 476 s. The longer the duration, the fewer the FAE events were. Most FAE events lasted for less than 40 s. In the duration range of 12–18 s, the FAE events had a peak occurrence at about 497 events, which was about 37% of the total.

However, the duration distribution of the FAE events in the cusp/cleft region was different from that in the other region which is indeed in the aroural oval (see Figure 7). It can be seen that in both regions the number of FAE events decreased with duration. In the cusp/cleft region about 85% of the FAE events lasted less than 40 s, compared to about 97% in the other region. The longest duration of the FAE events was 476 s in the cusp/cleft and 164 s in the other region in the aroural oval.

Table 1
The FAE Distribution at Different Altitudes

Altitude (S/C)	Authors (year)	FAE distribution
419–908 km (OGO 4)	Berko (1973)	In auroral oval mainly in MLT 2200–0100 with ILAT 70°–72.5°
3,000–8,000 km (S3-3)	Collin et al. (1982)	Only for the Northern Hemisphere, double peaked at MLT 0700 and MLT 2200, 63°–81°
Below 10,000 km (Exos D)	Miyake et al. (1998)	Dayside concentration
2 R_E (Viking)	Thelin and Lundin (1990)	Around the cusp/cleft, dawnside sector $>$ duskside sector
4–7 R_E (Cluster)	This paper	Both hemispheres, double-peaked MLT 0700–1500 with ILAT 60°–80° and MLT 1900–0100(+1) with ILAT 60°–76°

The durations of FAE events for the upward and downward directions both in the Northern and Southern Hemispheres have been studied. The results show that the durations were nearly identical in both hemispheres.

4. Discussion

In this paper, we perform a statistical study on the distribution of FAE events on the Cluster orbit (4–7 R_E). The result shows that the FAE events had two maxima, for both the northern and southern polar regions and for both the upward and downward directions. The main one was around the cusp/cleft but leaning to the dawnside. The other one was around the midnight auroral oval but leaning to forenoon. Previous authors have statistically studied the field-aligned electrons distribution with other satellite data in the lower altitude polar region. The results are not totally identical. Table 1 shows a comparison of the FAE distribution at different low altitudes reported by previous authors with that in this paper.

The result reported by Berko (1973) with data from OGO 4 in the low-altitude range of 419–908 km showed that the FAEs were mainly distributed only in the midnight auroral oval with MLT 2200–0100 and ILAT 70°–72.5°, which is consistent with our result on the nightside. The result reported by Miyake et al. (1998) with Exos D data at the altitude of 10,000 km showed that the FAE had a dayside maximum. They did not show further detail. However, this is also consistent with our result that the main concentration of the FAE events is around the cusp/cleft. With Viking data at the altitude of 2 R_E, Thelin and Lundin (1990) reported that the FAEs were distributed around the cusp/cleft and there were more FAE events in the dawnside sector than that in the duskside sector. It is also consistent with our result for the dayside that the FAE concentration was leaning toward dawn. Using S3-3 data in the low-altitude range of 3,000–8,000 km in the polar region, Collin et al. (1982) have given the FAE distribution only for the northern polar region without identifying the upward or downward direction. Their result showed that the FAEs were limited to a range of ILAT within 63°–81°, and the MLT distribution was double peaked in the morning at MLT 0700 and in the evening at MLT 2200, which is well consistent with our result that the FAE had two maxima on the Cluster orbit at the altitude range of 4–7 R_E, but our result is valid both for the Northern and Southern Hemispheres and both for the upward and downward FAEs. Indeed, because of the satellite orbit limitation, the researchers sometimes could not get a full distribution of the FAEs in the whole polar region. Cluster with its orbit advantage provides a very good opportunity to investigate the FAEs in the both polar regions and with both upward and downward FAEs. Even though, we still can see that, according to the all authors mentioned above, the FAE events in the polar region are different at different altitudes.

In comparison between our results and those of other authors, we can say that from low-altitude to high-altitude polar region, the FAE events are mainly concentrated in the auroral oval and have a double-peaked distribution. However, the altitude dependence of the FAE events needs to be further investigated. The difference between our and Collin's results might be attributed to the difference in altitude. The solar wind mirror point, the parallel electric field or field-aligned potential drops, and the wave-particles interaction at different altitudes do have influences on the FAE distribution.

The downward FAEs can consist of decelerated solar wind or be formed by the up flowing electrons which have drifted to an adjacent magnetic field line and are reflected back by the potential drop above the satellite (Yoshioka et al., 2000). The upward FAEs could be accelerated ionospheric electrons or mirrored solar wind electrons. For the downward FAEs, if they are decelerated solar wind electrons, they will be decelerated further while down flowing due to the gradually increasing magnetic field. If they are originally upward electrons, reflected by the potential drop above the satellite, the reflection points of energetic electrons with different energy will be at different altitudes. Therefore, the observed downward FAE distribution will be different at different altitudes. For the upward FAEs, if they originate from the ionosphere, they should be accelerated in their transportation phase. If they are mirrored solar wind electrons, because the mirror points should be located below the spacecraft, the properties of the upward electrons at different altitude will also be different. That is why our results of the spatial distribution at high altitude are different from other authors' results at lower altitudes. On the nightside, the FAE distribution should be associated to the particles dynamics in the magnetotail. The bursty bulk flows, magnetic field dipolarization fronts during substorms, and the field-aligned electric fields in the auroral acceleration regions all should have an important role for the nightside FAE events.

We should note that during substorm processes there will be more high-energy particles. So the flux for these particles might be low (due to relatively low number density) and the kinetic energy flux might be high when compared to nonsubstorm intervals. The study of the properties and distribution of the field-aligned kinetic energy fluxes will be left for future work.

To consider the solar wind interaction with the magnetosphere, the spatial distribution of the FAE events in the polar region may depend on the solar wind and IMF conditions, as they can influence the physical processes generating field-aligned currents. Because of the special properties of cusp/cleft, solar wind particles can directly enter to the magnetosphere through cusp/cleft. Different physical mechanisms may be responsible for generating FAE events, such as the plasma vortices in the low-latitude boundary layer (LLBL) at the magnetopause due to the Kelvin-Helmholtz instability (KHI). The magnetic reconnection at high latitudes can also generate FAE fluxes and ion fluxes in the polar region (Nykyri et al., 2004; Nykyri, Otto, et al., 2006). The magnetic reconnection in the magnetotail can also produce FAEs in the nightside polar region. The vortices created at the earthward boundary of the flow breaking regions, as well as the pressure gradients (Johnson & Wing, 2015), can influence the nightside properties of the FAE events. On the other hand, the magnetosphere-ionosphere coupling processes, especially the up flowing electrons originating from the ionosphere, can also affect the spatial distribution of FAE events. The IMF orientation (i.e., the inward or outward Parker Spiral) should have a key role for the dawn-dusk asymmetries and the spatial distribution of the FAE events. During Parker Spiral IMF KHI can occur both at the LLBL (Moore et al., 2016; Nykyri, Grison, et al., 2006) favoring the dawn flank (Nykyri, 2013) and at the high latitudes (Hwang et al., 2012; Ma et al., 2016). The dependence of FAEs under different solar wind and IMF conditions will be left for future studies with more statistics.

The solar wind interaction with the magnetosphere can result in the geomagnetic field disturbance. We have also studied occurrence and absolute maximum flux value of the FAE events versus the geomagnetic activity index *AE* and *Kp*. The results show that both the occurrence and the absolute maximum flux were increasing with both *AE* and *Kp* increasing. It indicates that the more active the geomagnetic field, the easier the FAE events were formed and the stronger the FAE events were.

Berko (1973) reported that the field-aligned electron precipitation appeared as generally having short time duration of 5 to 10 s according to the data obtained from the OGO 4 satellite at altitudes of 412–908 km. The Freja TESP electron spectrometer has repeatedly observed 0.05–15 s field-aligned electron events at an altitude of 1,700 km in the auroral zone (Boehm et al., 1995). Our results, with Cluster observations at altitudes of 4–7 R_E in the polar region, show that the duration of FAE events extended from 4 to 476 s around the cusp/cleft and from 4 to 164 s in the other region in the arourал oval, in both hemispheres. Most FAE events had durations of less than 40 s, about 97% in the auroral oval and 85% in the cusp/cleft region. The duration of the FAE events observed with Cluster was longer than that reported by previous authors with other satellites in the lower altitude polar region. We can conclude that the lower the altitude is, the shorter the FAE events duration will be. There are two reasons for this conclusion. One is that atmospheric density will increase, and hence, the atmospheric absorption for the electrons will be stronger with lower altitude, and the duration of downward FAEs will be shorter and the number of the FAE events will be smaller. The other reason is that electrons are indeed moving in the magnetic flux tube, and the observed FAE events are also a local phenomenon, not only a temporal one. At lower altitude, the magnetic field will be stronger and magnetic tubes will be smaller; thus, the satellites will cross the magnetic flux tubes faster and the observed duration of FAE events will be shorter. We note that the duration of FAE event is a convolution of space and time effects. Therefore, we could not know the exact duration of the FAE events with the moving satellite. We can only use it to make a comparison with other satellite observations at other altitudes and can understand some properties of FAEs in different altitude regions. The exact duration of each FAE event needs to be further studied.

McFadden et al. (1999) considered that FAEs are the main carrier to FACs in the polar region. Klumpar and Heikkila (1982) considered that the FAEs could be the only carrier of FACs in the polar region. In our statistics, the selected FAE events had a flux higher than $3 \times 10^8 (\text{cm}^2\ \text{s})^{-1}$ which corresponds to field-aligned current density of $2 \times 10^2\ \mu\text{A}\ (\text{cm}^2)^{-1}$. The FAC at the altitude of the Cluster orbit is in the order of $10^2\ \mu\text{A}\ (\text{cm}^2)^{-1}$ (Shi et al., 2014). This shows that the FAEs in the events were the main carrier to the FACs at the altitude of the Cluster orbit in the polar region in both hemispheres.

5. Summary

We perform a statistical study on the distribution of FAEs at the altitude of the Cluster orbit in the polar region. The data are from the PEACE and FGM instruments on board the Cluster spacecraft in the years 2003 and 2004. We divide the FAEs into upward and downward ones both in the Southern and Northern Hemispheres. The typical altitude range of the Cluster orbit in the southern polar region (4–7 R_E) was slightly higher than that in the northern polar region (4–6.5 R_E). We select the FAE events which had a flux greater than $3 \times 10^8 (\text{cm}^2\ \text{s})^{-1}$ for the analysis.

The results show that the FAE distribution is double peaked around auroral oval at high altitude (Cluster orbit). The main peak was in the dayside, and the other was in the nightside. The dayside peak was around the cusp/cleft region but had a dawn-favored asymmetry (MLT 0700–1500), which was valid for both upward and downward FAEs and both in the Southern and Northern Hemispheres. This is different from other authors' results for the low-altitude polar region. The nightside peak was in the MLT range 1900–2300, which was also valid for both upward and downward FAEs and both in the Southern and Northern Hemispheres and matches other authors' results regarding the low-altitude region. Our study is the first one to give FAE distributions in the polar region at the altitude of the Cluster orbit.

The FAE durations covered a large range from 4 to 476 s in the daytime to 164 s on the nightside. For both the upward and downward FAEs in the cusp, the duration of most FAE events was less than 40 s, which is longer than that observed by satellites in the low- and middle-altitude polar region. Finally, the FAE events had a flux higher than $3 \times 10^8 (\text{cm}^2\ \text{s})^{-1}$ which corresponds to field-aligned current of $2 \times 10^2\ \mu\text{A}\ (\text{cm}^2)^{-1}$, which shows that the FAEs were the main carrier of FACs at the altitude of the Cluster orbit in the polar region in both hemispheres.

The physical mechanism of FAEs is also discussed in this paper. The solar wind deceleration and mirroring at different altitudes and ionospheric up flowing electron acceleration and reflection at different altitudes might be the reason for the differences in spatial distribution and duration of FAEs at different altitudes. However, further study is still needed.

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