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Cusp Energetic Particle Events Measured by POLAR Spacecraft

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Abstract. The Charge and Mass Magnetospheric Ion Composition Experiment (CAMMICE) on board the POLAR spacecraft observed more than 70 cusp energetic particle (CEP) events in 1996. All of these events were associated with a decrease in the magnitude of the local magnetic field measured by the Magnetic Field Experiment (MFE) on POLAR. This is an important discovery, which reveals six interesting features for the CEP events: (1) They all were detected in the dayside at high latitude near apogee; (2) their energies were in excess of 2.4 MeV; (3) an individual CEP event could last for hours; (4) the event-averaged intensity of 1-200 keV/e helium was anticorrelated with the magnitude of the local geomagnetic field but correlated with the turbulent magnetic energy density; (5) the events were associated with an enhancement of the low frequency electromagnetic noise; and (6) a possible seasonal variation was found for the occurrence rate of the events with a maximum in September. The measured high charge state of helium and oxygen ions in the CEP events indicates a solar source for these particles. A possible explanation is that the energetic helium ions are energized from lower energy helium by a local acceleration mechanism associated within the high-altitude dayside cusp. These observations represent a discovery of a major acceleration region of the magnetosphere.

1 Introduction

Since the discovery of the Earth's radiation belt by Van Allen and his colleagues in 1958 (Van Allen and Frank, 1959; Yoshida et al., 1960; Van Allen, 1963), the studies of the energetic particles in the radiation belts have been extended to include the heavy ions (Krimigis and Van Allen, 1967; Fritz and Krimigis, 1969) and the isotopic species (Chen et al., 1994, 1996a,b). Kremser et al. (1995) reported an ion charge state observation with energy less than 50 keV in the mid-altitude cusp. However, those studies were limited to either near the equator or at low-mid altitude, and the behavior of the energetic charged particles in the high altitude polar cusp region remained unknown. One important question in the geospace environment has been to determine the behavior of energetic particles in the high altitude polar cusps and their relation with the outer radiation belt particles. On February 24, 1996, POLAR was launched with a 1.8×9 R_e (Earth radius) polar orbit, which had an inclination of 86 degrees and a period of 18 hours. Such polar orbits provide an excellent and unique opportunity to investigate the energetic particles in the polar cusp regions.

By definition, the polar cusps have very weak magnetic field strength and are funnel-shaped field lines that map to the day- and night-side of the magnetopause surface (Chapman and Ferraro, 1931; Reiff et al., 1977; Reiff, 1979; Marklund et al., 1990; Crooker et al., 1991). In practice, the cusp regions are identified either by a minimum in the local magnetic field (Farrell and Van Allen, 1990) or by a combination of low magnetic field strength, high plasma intensity, and the presence of broadband plasma wave noise (Fung et al., 1997; Chen et al., 1998).

The Charge and Mass Magnetospheric Ion Composition Experiment (CAMMICE) onboard POLAR was designed to measure the charge and mass composition within the magnetosphere over the energy range of 1 keV/e to 60 MeV/e, to determine the fluxes of various ion species and their relative abundances and incident charge state, to provide important information about the origins of the energetic particles, and to identify mechanisms by which these ions are energized and transported from their source populations within geospace (Chen et al., 1997, 1998).

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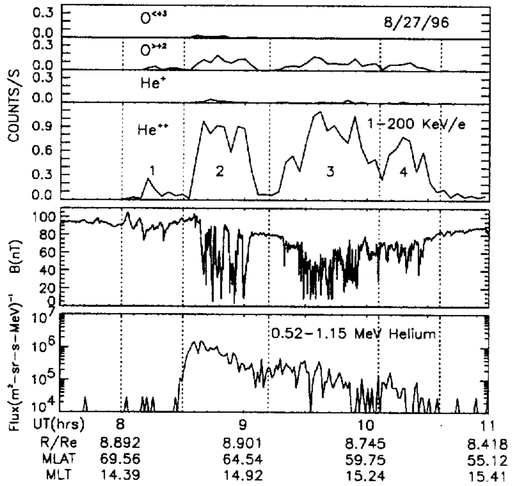

Fig. 1. The CEP events on August 27, 1996. The panels from top to bottom show the counting rates for $O^{<+3}$, $O^{>+2}$, He^{+}, and He^{++} versus time, the corresponding variation of the local geomagnetic field, and the flux of the 0.52-1.15 MeV helium, respectively, where the vertical dashed lines mark the four different regions in the events. The distance of POLAR from the Earth (in Re), the magnetic latitude (MLAT), and the magnetic local time (MLT) are shown at the bottom of the figure.

2 Features of CEP Events

On August 27, 1996 POLAR/CAMMICE observed an energetic particle event in the polar cusp region, which showed some unusual features and was once thought to be a special event in the polar cap (Chen et al., 1997). Now, we confirm that the event represents a new magnetospheric phenomenon, and we call it the **cusp energetic particle** (CEP) event. More than 70 CEP events were detected during 1996 (Chen et al., 1998).

An example of a CEP event is shown in Fig. 1. On August 27, 1996, at about 8:40 UT when the POLAR spacecraft was 9 Re (Earth's radius) from the Earth at $\simeq 67^o$ geomagnetic latitude (MLAT) and $\simeq$ 14.7 hours local time (MLT), the CAMMICE detected a large increase of 1-200 keV/e helium intensity (the fourth panel from top of Fig. 1) that corresponded to a large decrease in the magnitude of the local geomagnetic field (GMF) measured by the Magnetic Field Experiment (MFE) (Russell et al., 1995) on POLAR (the fifth panel from top of Fig. 1). In other words, Figure 1 suggests that the 1-200 keV/e helium intensity was anticorrelated with the field magnitude. The event lasted more than two hours (about 8.0-10.6 UT).

A closer examination of Fig. 1 indicates that there were four helium peaks that were associated with four local minima in the field magnitude and corresponded to four different regions: 8.0-8.5 UT, 8.5-9.2 UT, 9.2-10.1 UT and 10.1-10.6 UT, and they were designated as four individual CEP events. The numbers of 1, 2, 3, and 4 within the vertical dashed lines in the top panel of Fig. 1 mark the four different regions in this period. The most remarkable feature is that there is an unexpected increase of more than two orders of magnitude of the 0.52-1.15 MeV helium flux within the event period (bottom panel of Fig. 1). Figure 1 also shows that the intensity of He^{++} and $O^{>+2}$ fluxes were enhanced during the event period. The figure shows that (i) compared to He^{++}, the He^{+} was negligible; (ii) compared to $O^{>+2}$, the $O^{<+3}$ was negligible; and (iii) at 1-200 keV/e, the helium particles were the dominant heavy ions with an intensity of about one order of magnitude larger than the oxygen ions. Since solar wind particles have higher ion charge states than that of ionospheric particles (Gloeckler et al., 1986), the top four panels of Fig. 1 suggest a solar wind source for the particle fluxes in the CEP events.

The plasma wave observations inside the cusp regions have been reported previously (Kremser and Lundin, 1990; Marklund et al., 1990; Pottelette et al., 1990; Ishii et al., 1992; Peterson et al., 1993; Norqvist et al., 1996), which revealed that the extremely low frequency (about 10 Hz) electromagnetic noize was a clear indication of the cusp region. Figure 2 presents measurements by the Plasma Wave Investigation (PWI) (Gurnett et al., 1995) on POLAR of the plasma wave electric and magnetic field intensities on 8/27/96 for the same time period as shown in Fig. 1. The data are displayed as frequency-time spectrograms with electric field intensity displayed in the top panel, and magnetic field intensity displayed in the bottom panel, each color coded in blue through red according to the color bar to the right of each respective panel. The distance of POLAR from the Earth (in Re), the magnetic latitude, the magnetic local time (MLT), and the L-shell values are shown at the bottom of the figure. The important point is that there are broad bandwidth bursts of magnetic noise extending from below 5.6 Hz up to about 1 kHz which appear to correlate well with the magnetic field decreases and helium count rate increases observed in Figure 1. Electric field turbulence extending over a large frequency range of a few tens of Hz to about 10 kHz is also seen during these times. However, it is not easy to establish whether or not this turbulence is associated with the CEP events because electrostatic noise commonly observed in the polar cap is seen both preceding and following the CEP events. The low-frequency noise is observed in the range between the proton cyclotron frequency and the electron cyclotron frequency. In Fig. 2, two features of the spectrum during the CEP event are the rapid decrease in intensity with increasing frequency and the most intense emissions occurring at frequencies less than about 200 Hz. The aforementioned features for the events on 8/27/96 are also present in other events listed by Chen et al. (1998) during different days.

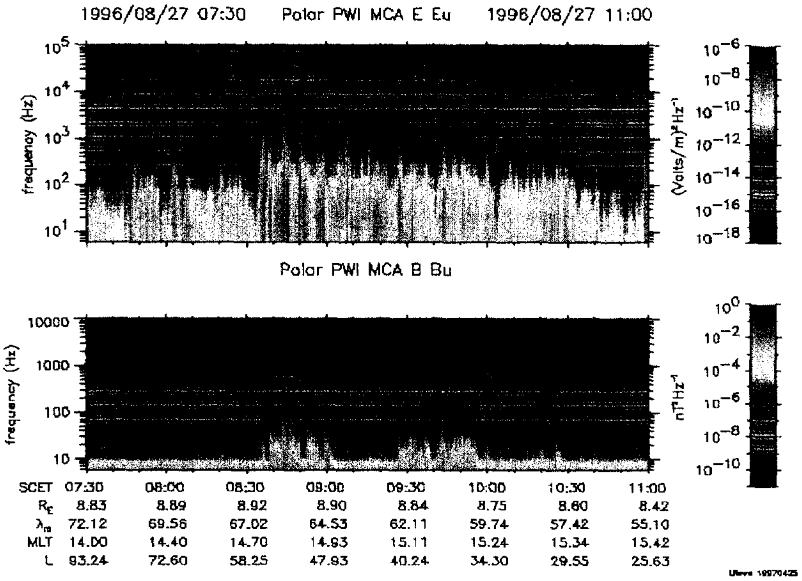

Fig. 2. Frequency-time spectrograms of the plasma wave electric field intensity (top panel) and magnetic field intensity (bottom panel) on August 27, 1996. The intensities are color coded in blue through red according to the color bar shown to the right of each respective panel. The distance of POLAR from the Earth (in Re), the magnetic latitude, the magnetic local time (MLT), and the L-shell values are shown at the bottom of the figure. Broadbanded electric and magnetic field turbulence is seen during the four periods of interest shown in Fig. 1.

3 Magnetospheric Positions and Seasonal Variations of CEP Events

Figure 3 exhibits the event-averaged positions of the CEP events in the magnetosphere with plots of MLT versus MLAT (panel a) and MLAT versus R/Re (panel b) in polar coordinates. In panel (a), the four dashed circles from inside to outside indicate the MLAT positions from 80° to 50°, respectively. In panel (b), the dashed circles represent the distance of POLAR from the Earth (in Re). Panel (a) reveals that the CEP events were observed in the dayside. Both panels in Fig. 3 also reveal that the CEP events spanned more than 20 degrees in geomagnetic latitude, which is different from the expectation of the low altitude cusp where it is observed to be only about four degrees wide, or less, in latitude (e.g., Menietti and Burch, 1988; Marklund et al., 1990; Yamauchi et al., 1996), but is comparable with the high altitude cusp results (Haerendel et al., 1978; Lundin, 1985; Fung et al., 1997; Sandahl et al., 1997; Zhou et al., 1997). The other two interesting features are that the CEP events extended more degrees in latitude in the afternoonside than that in the morningside, and that there was a 14-MLT peak of the CEP events. According to low altitude observations (Lundin et al., 1995), it is actually reasonable to have extra acceleration at 14 MLT due to a solar wind induced boundary layer polarization. All CEP events were observed at radial distances greater than 7 Re.

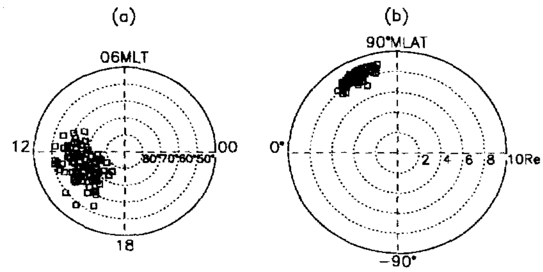

Fig. 3. The event-averaged positions of the CEP events in the magnetosphere with MLT versus MLAT (panel a) and MLAT versus R (panel b) in polar coordinates. In panel (a), the four dashed circles from inside to outside indicate the MLAT positions from 80° to 50°, respectively; while in panel (b), the dashed circles represent the distance of POLAR from the Earth (in Re, Earth's radius).

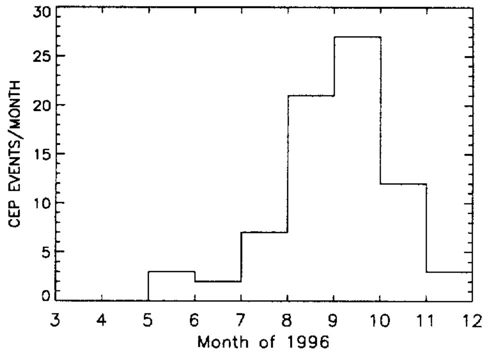

Fig. 4. The monthly CEP events during 1996.

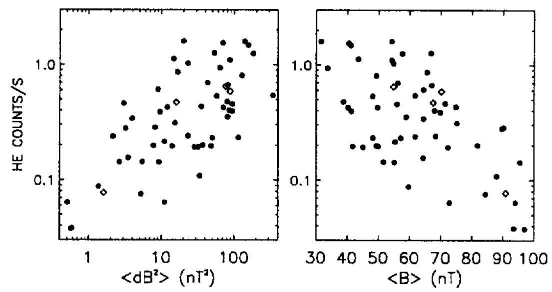

Fig. 5. Event-averaged counting rate of the 1-200 keV/e helium versus two different local GMF parameters: $< dB^2 >$ (left panel) and $< B >$ (right panel), where $< >$ represents event average and $dB = B_{i+1}$ - B_i. The four open squares represent the four events on 8/27/96.

The CEP events also exhibit possible seasonal variations. Figure 4 is a histogram showing the distribution of the monthly CEP events during 1996. A peak value of 27 events was measured in September. Before ascribing this to a seasonal variation, one needs to examine the POLAR's orbit effect. Those POLAR orbits with R > 7 Re, 7 hours < MLT < 17 hours, and 45° < MLAT < 80° are found as the region where a CEP event may be detected. If POLAR spends less time in such a region, one would expect to observe fewer events. This is the case before May 1996, which may explain why no CEP events were observed during March and April. However, this is not the case after May 1996. Information from POLAR orbits indicates that there were ample opportunities for POLAR to pass through the dayside cusp region during June to December periods (Chen et al., 1998). Therefore, the variation of the CEP event occurrence rate during June to December, 1996 was not an orbit effect. Another effect is the time variation of the solar activity (like the coronal-hole structure) that will make superficial seasonal effect if one looks at only a one-year data. More years data are needed to study the seasonal effect.

4 Relationships of He Intensity with GMF

The local magnetic fields play an important role in organizing the measured energetic helium intensities. Figure 5 associates the event-averaged counting rate of the 1-200 keV/e helium with two different local GMF parameters: $< dB^2 >$ (left panel) and $< B >$ (right panel), where $< >$ represents event average and $dB = B_{i+1}$ - B_i from 6 seconds resolution field data. The four open squares are the four events on 8/27/96. The event-averaged method was used to reduce the irregular and random fluctuations and to analyze the statistical properties. Figure 5 reveals that the 1-200 keV/e helium intensities were best organized by $< dB^2 >$ (left panel), and that there was an anti-correlation between 1-200 keV/e helium intensities and the event-averaged (mean) field (right panel). The least squares fits give a correlation coefficient of 0.692 for the left panel and -0.596 for the right panel.

5 Discussion

Axford (1970) has suggested that ions can be directly injected into the polar regions from the magnetosheath and subsequently accelerated, and Bird (1975) discussed a mechanism for the capture of solar wind ions and their subsequent trapping. While it is clear that the high charge state ions originated from the solar wind, the injection and trapping mechanisms for these ions remain unknown. The extremely low frequency electromagnetic waves that are observed during the CEP events are similar to the lion roars observed in the magnetosheath (Tsurutani et al., 1982). The generation mechanism of the wave has been a hot topic in the cusp studies (Kremser and Lundin, 1990; Marklund et al., 1990; Pottelette et al., 1990; Ishii et al., 1992; Peterson et al., 1993; Norqvist et al., 1996; Andre and Yau, 1997). The lion roars that were detected close to the magnetopause were generated by the cyclotron instability of anisotropic thermal electrons when the local plasma critical energy falls to values close to or below the electron thermal energy, 25 eV, as a result of decreases in B, or conversely, in high beta (10-25) regions. The lion roars are terminated by increases in the ambient magnetic field magnitude and consequential increases in the local plasma critical energy to values greater than 100 eV (Tsurutani et al., 1982). In the present study, the magnetic field turbulence, in association with the decreases in magnetic field and increases in helium count rates, may be an indication of plasma injection from the magnetosheath through high latitude reconnection. Panel 5 (from top) of Figure 1 suggests that a strong diamagnetic cavity can be produced at high latitude in the polar cusp. The anti-correlation between 1-200 keV/e helium intensities and the event-averaged (mean) field in the right panel of Fig. 5 is consistent with the existence of a diamagnetic cavity.

Another important point is that the helium energy in the CEP events can be greater than 2.4 MeV (not shown). As mentioned before, the local magnetic fields play an important role in organizing the measured energetic helium intensities. During aforementioned CEP event times, the D_{st} index showed rather geomagnetically "quiet" period. Since D_{st} is a measure of the mechanism that drives magnetic storms, and the CEP events are not correlated to D_{st}, the storm-time ring current mechanism is not the one that energizes these particles. The magnetopause acceleration mechanism (Woch and Lundin, 1992) cannot account for the CEP events also. In addition, no comparable flux was observed by the WIND spacecraft for the CEP event period. The other possibility is the bow shock that accelerates the low energy solar wind particles to a higher energy, which may account for the ions below 200 keV in the CEP events. However, for $>$ 600 keV ions, the GEOTAIL data indicated that during solar quiet periods the bow shock showed no significant affect on these energetic ions, and the $>$ 600 keV ion flux was less than 10^2 particles/(m^2-sr-s-keV) either before the bow shock in the upstream or after the bow shock in the magnetosheath. All evidence suggests a local acceleration region; that is, the energetic helium ions are energized from lower energy helium by a local acceleration mechanism associated with the high-altitude dayside cusp. Therefore, the CEP events constitute a new temporarily confined charged particle population that was controlled by some local accelerating and confining mechanism (Chen et al., 1997).

The conversion of magnetic energy to plasma energy through reconnection and acceleration by induction electric fields has been suggested for some time as a means to accelerate particles. There have been no *in situ* observations to provide the detail information for investigating such energy conversion and acceleration mechanisms at the high altitude polar cap until the launch of the well-instrumented POLAR spacecraft. In Figure 5, since the $< dB^2 >$ term is proportional to the turbulent magnetic field energy density, the correlation between 1-200 keV/e helium counting rates and the $< dB^2 >$ in the left panel may be interpreted to mean that the turbulent magnetic energy density is converted into the helium ion's kinetic energy. This seems to point to a resonant or an induction electric field acceleration mechanism for the 1-200 keV/e helium ions. The acceleration mechanism for MeV helium is either different from that for 1-200 keV/e helium or greater than that by which the former are energized.

Data from CAMMICE reveal that this quasi-trapped population may always be present in the cusp regions, what varies is its intensity. The CEP events may be related to the large (more than two orders of magnitude) increases observed in the MeV charged particle flux in the outer radiation belt. These observations represent a discovery that the high-altitude dayside cusp is a major acceleration region of the magnetosphere.

6 Summary and Conclusions

The Charge and Mass Magnetospheric Ion Composition Experiment (CAMMICE) on board the POLAR spacecraft observed 75 CEP events in the polar cusp regions in 1996. All of these events were associated with a decrease in the magnitude of the local magnetic field measured by the Magnetic Field Experiment (MFE) on POLAR. Our principal conclusions are the following: (1) They were detected in the high-altitude dayside polar cusp; (2) an individual event could last for hours, and the measured helium ion energies were up to and always exceeding 2.4 MeV; (3) the intensity of 1-200 keV/e helium was anticorrelated with the magnitude of the local geomagnetic field but correlated with the turbulent magnetic energy density; (4) the events were associated with magnetic field turbulence in the frequency range between the proton cyclotron frequency and electron cyclotron frequency; (5) a possible seasonal variation was found for the occurrence rate of the events with a maximum in September, and the observed high charge state of helium and oxygen ions in the CEP events indicates a solar wind source for these particles; (6) a possible explanation is that the energetic helium ions are energized from thermalize magnetosheath helium by a local acceleration mechanism associated with the high-altitude dayside cusp. These observations represent a discovery of a major acceleration region of the magnetosphere.

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