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Reverse convection and cusp proton aurora: Cluster, polar and image observation

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Abstract

On April 21, 2001 an interplanetary CME started to interact with the magnetosphere when CLUSTER spacecraft were travelling in the cusp region. This interaction produced a strong magnetic storm ($D_{st} = 103$ nT) at Earth. Cusp proton aurora was caused by the leading phase of the CME. Cusp proton aurora generally appear during northward IMF, this paper demonstrates that they can also be triggered during southward IMF when the reverse convection has been generated by an IMF dominated Y component. The location of the cusp proton aurora shifted about 30° from dawnside to duskside when IMF B_y changed from −10 to 5 nT. The requirement to produce proton cusp aurora seems to be a reverse convection in the cusp region instead of the northward IMF (not only northward IMF, but IMF B_y is also an important parameter!).

Keywords: Proton aurora; Reverse convection and cusp; Cluster, polar, and image observation

1. Introduction

Auroral observation obtained by the Viking UV imager indicated that the discrete auroral features poleward of the cusp can exist in the northern hemisphere during periods of northward IMF (Murphree et al., 1990). Possible signatures of the high latitude reconnection have also been recognized from the dayside optical emission at 630.0 and/or 557.7 nm during the northward IMF, (Sandholt et al., 1996a,b, 1998). The auroral forms and emission positions are affected by the interplanetary magnetic field orientation. The relation between the northward IMF cusp aurora and the IMF B_x component has been examined by Oieroset et al. (1997). They concluded that the northward IMF cusp aurora could be intensified by IMF negative B_x component which is a favoured condition for the high latitude reconnection poleward of the cusp region. However, the ionosphere convection patten at the footprint of the high latitude reconnection is not so well understood. The reconnected field lines for northward IMF that map to the high-latitude side of the ionospheric footprint of the cusp are no longer constrained to be situated on the open/closed flux boundary, but can be located at higher latitude within the polar cap only (Song et al., 1999). No new open flux is created in this process. The ionospheric signature of the reverse convection during northward IMF has been indeed observed by the CUTLASS HF coherent radar in conjunction with Polar UVI observation (Milan et al., 2000).

Proton cusp aurora during northward IMF can be terminated by the IMF turning southward (Fuselier

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et al., 2002). Furthermore, a statistical study between June 5 and November 26, 2000 on the proton cusp aurora has been performed by Frey et al. (2002). They found that all 18 clear proton aurora events appeared during northward IMF periods. A huge amount of the Defense Meteorological Satellite Program (DMSP) data set has been used to examine the global auroral ion precipitation (Hardy et al., 1989, 1991; Brautigam et al., 1991). High flux ion precipitation in the cusp region for quiet time has been observed by Hardy et al. (1989, 1991). Brautigam et al. (1991) found that the hemisphere averaged ion precipitation strongly depended on the IMF orientation, and surprisingly found that both the proton precipitation energy flux and number flux are enhanced with increasing IMF B_z positive. After carefully checking the IMF B_z distribution with the K_p index, they confirmed that the enhanced global precipitation flux for an increasing northward IMF is a real effect. Even the auroral ion/electron flux ratio during northward IMF B_z (+5 nT) is 2.2 times higher than that during IMF south B_z (−5 nT).

The present study, based on multi-satellite observations tries to provide some new observations for the complex cusp dynamic process in order to understand proton aurora in the cusp region. Based on Cluster and Polar observations, this paper further demonstrates that the positive IMF B_z is not a necessary condition for the cusp proton aurora. The cusp aurora can also be produced during IMF southward when the reverse convection has been triggered.

2. Cluster and polar observations

Energetic particle data were obtained by the RAPID instrument on board the CLUSTER satellites (Wilken et al., 1997) and by the CAMMICE/MICS instrument on board the POLAR satellite. The RAPID experiment has an advanced ion spectrometer with time-of-flight (T) and energy (E) detection systems which determine the mass of incident energetic particles. The energy range is from 30 to 1500 keV. The MICS/Polar instrument is able to identify different ion species and their charge state. An ESA (electrostatic analyzer) selects ions with a particular energy-to-charge ratio (E/Q), which is followed by a velocity/energy detection system [TOF (time-of-flight)/SSD (solid state detector)]. A post-accelerating voltage is applied between the ESA and the TOF/SSD system to improve the detection efficiency for low energy particles. The energy range of MICS is from 1.2 to 426 keV/e in 32 energy channels (Wilken et al., 1992).

The major objective of the Far Ultraviolet Instrument (FUV) on IMAGE is the observation of global changes in the aurora accompanying large-scale changes in the magnetosphere (Mende et al., 2000). FUV consists of the imaging channels Wideband Imaging Camera (WIC) and the dual-channel Spectrographic Imager (SI-12 and SI-13). One feature of FUV is the capability for simultaneous observation in three different wavelength regions. The IMAGE satellite is in a highly elliptical orbit of 1000 × 45,600 km altitude. The FUV consists of three imaging sub-instruments and observes the aurora for 5–10 s during every 2 min spin period (Mende et al., 2000). It is mostly sensitive to proton precipitation in the energy range of 2–8 keV, with very low sensitivity below 1 keV (Frey et al., 2002).

On April 21, 2001, the leading phase of a coronal mass ejection (CME) encountered the magnetosphere. The disturbed period was preceded by a phase of high density plasma with a peak of 40 particles cm^{-3}, the dynamics pressure reached to around 10 nPa. The subsolar magnetopause is greatly compressed to around $8R_E$ for 9 h. Between 2000 and 2400 UT both the Cluster and Polar spacecraft were travelling in the high latitude region (see Fig. 1(left)). Fig. 1(right) gives an overview of the RAPID measurements between 2100 and 2400 UT on April 21, 2001. The different panels show proton fluxes and the magnetic field components and the magnetic field magnitude in GSE coordinate system. Both Fig. 1(left) and Fig. 1(right) suggest that the Cluster spacecraft were initially travelling in the tail-lobe of the magnetosphere and then at about 2145 UT entered from the lobe into the cusp-like region. The cusp region can be easily identified by the enhanced energetic ions, together with turbulent depressed magnetic fields. As we can see from Fig. 1(right), the magnetic field in the cusp region is fluctuated a great deal more than in the adjacent boundary region.

2.1. Proton cusp aurora during both southward and northward IMF

2.1.1. Event 1: from 22:30 to 23:00 UT on April 21, 2001

Fig. 2(left) presents four consecutive SI12 images projected onto the magnetic latitude (MLAT) and magnetic local time (MLT). The colour bar on the right side indicates the proton auroral intensity. As we can see from Fig. 2(left), before 22:45 UT, the dayside cusp regions (around 12 MLT, latitude between 70° and 80°) was filled with diffuse emissions and, occasionally with visible but weak auroral spots or arcs. Between 22:45 and 22:55 UT, the cusp proton aurora which was located in the prenoon sector and around 75° in the invariant latitude greatly intensified. The dayside cusp proton aurora then diminished after 22:57 UT. The proton aurora intensification happened when the RAPID instrument observed greatly enhanced proton flux (the first panel)and the sunward plasma flow (the third panel) while the IMF was clearly southward with −3 nT and the IMF B_y was quite large, around −8 nT. The reverse convection occurring during southward IMF has been also

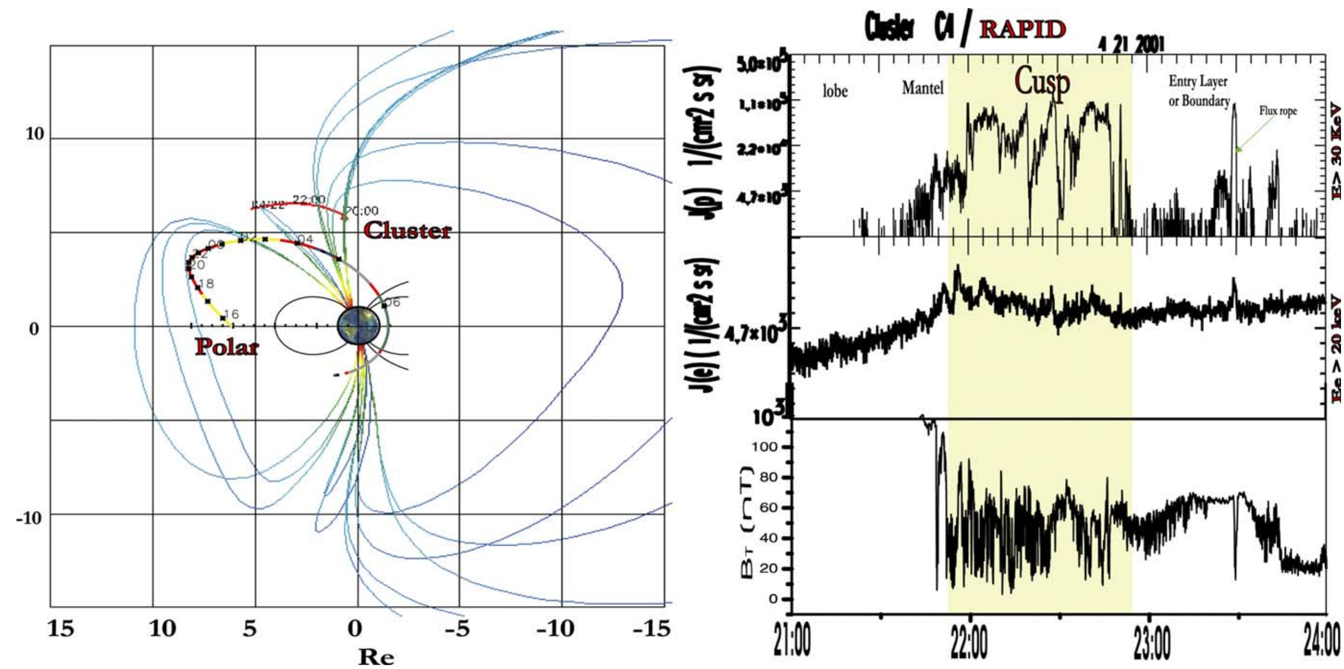

Fig. 1. Noon–midnight cut of the Cluster and Polar trajectory through the Tsyganenko magnetic field model (Tsyganenko and Stern, 1996) for April 21, 2001. Only one Cluster satellite is shown since the separation is too small. An overview plots of Cluster data between 2100 and 2400 UT on April 21, 2001 is shown on the right. From the top the panels show: the proton flux, and the magnetic field components and the total magnitude in the GSE coordinate system recorded by the RAPID and FGM instruments.

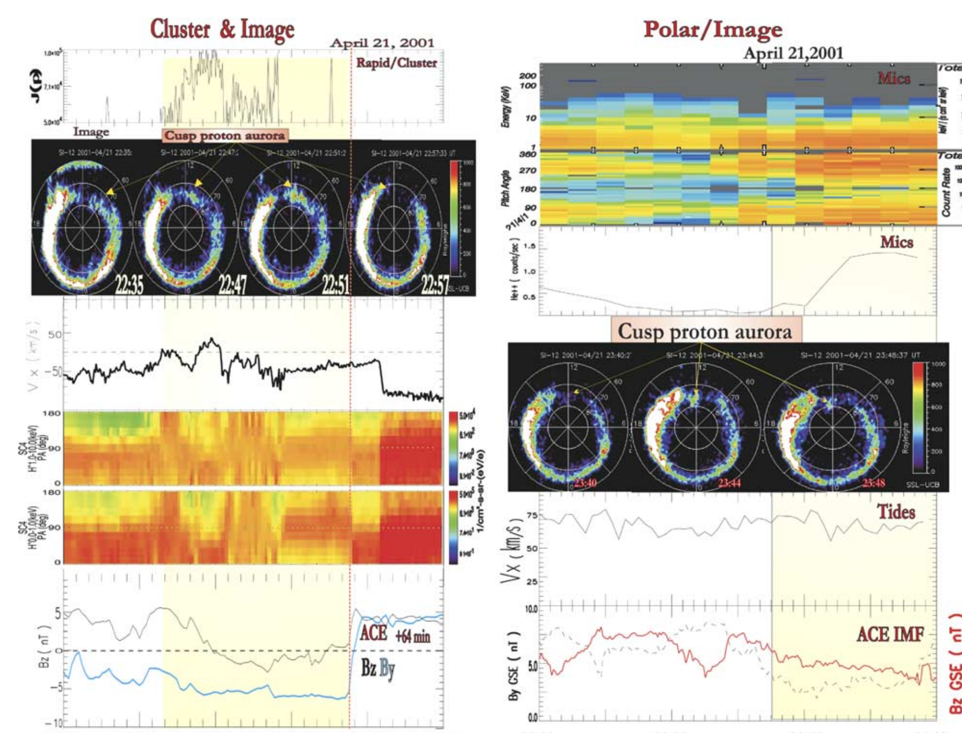

Fig. 2. Summary plots for two cusp proton aurora events: (1) from 22:30 to 23:00 UT on April 21, 2001 (left); and (2) from 23:00 to 24:0 UT on April 21, 2001 (right). From the top the panels show: Integral energetic ion fluxes; consecutive proton auroral images taken by IMAGE FUV/SI12 from 2235 to 2257 UT. Images are projected onto the MLT-MLAT plane, and the magnetic field components obtained by ACE in the lagrange point(L1) in GSE coordinate system. The timing of ACE magnetic field data has been shifted 59 min assuming a change in the interplanetary reach to Cluster location is propagating at solar wind speed.

previously observed. Lu et al. pointed out that a significant sunward flow would appear near the polar cap boundary for southward IMF as long as $|B_y|$ was greater than $|B_z|$.

Farrugia et al. (1989) established a formula to evaluate the delay between a change in the IMF impinging upon the satellite and its effects reaching the ionosphere within the radar or optical field-of-view. The time delay between Cluster and IMAGE $T_{ci} \approx 6$ min is the time lag for the change to reach the ionosphere accordingly. This is simply estimated as a single Alfven wave travel time from the magnetospheric cusp to the ionosphere.

2.1.2. Event 2: from 23:00 to 24:0 UT on April 21, 2001, Northward IMF

Before 22:40 UT, the dayside cusp region was filled with diffuse emissions and occasionally visible but ,weak auroral spots or arcs, see Fig. 2(right). After 22:40 UT, the proton aurora in the dayside cusp region (12 MLT, latitude between 70° and 80°) began to brighten as shown in Fig. 2(right). It is worth mentioning that the high latitude proton cusp aurora in this case was shifted to the post-noon sector (around 13 MLT) and to higher latitude (towards 80°). The proton aurora intensified when the Polar/MICS instrument observed greatly enhanced energetic ion flux (the first three panels in the Fig. 2(right)) and Polar/TIDE instrument observed the sunward plasma flow (the fourth panel) whereas the IMF was clearly northward with +3 nT. Proton cusp aurora that appeared during northward IMF is consistent with previous observations (Fuselier et al., 2002; Frey et al., 2002).

It is worth pointing out that the MLT location of proton aurora in the cusp is strongly affected by IMF B_y. As we can see from Fig. 2, when IMF B_y was around −10 nT, the location of proton aurora was located on the dawnside around 10.5 MLT (Fig. 2(left)). When the IMF B_y changed to + 4 nT, the proton aurora was shifted to the duskside around 12.4 MLT (Fig. 2(right)). This is in agreement with the predication of an empirical formula (Frey et al., 2002), MLT = 11.8 + 0.127 IMF B_y.

3. Discussion

The observed cusp proton aurora can be explained in the framework of the high latitude reconnection process. As shown in Fig. 3(right), during periods of extended northward IMF, magnetospheric convection cells confined to open field lines in the tail lobes were proposed as a possible consequence of a northward IMF merging at the magnetopause with the southward tail lobe field lines poleward of the cusps. The convection in the high latitude boundary layer region is sunward and this has been coined as "Reverse Convection" (Crooker, 1992). The magnetic field and plasma signatures of the high latitude reconnection have been reported previously by Gosling et al. (1991) and Kessel et al. (1996). Particle precipitations at lower altitudes caused by the northward IMF reconnection at the high latitude has been documented by Viking observation (Woch and Lundin, 1992). During such a process, the solar wind particles can also be accelerated and injected at the magnetopause, producing further precipitation from the boundary layer down to polar ionosphere to generate the observed cusp proton aurora as shown in Fig. 2. Previous studies suggested that the reverse convection would appear not only during northward IMF, but it could also be an phenomenon for the IMF southward case

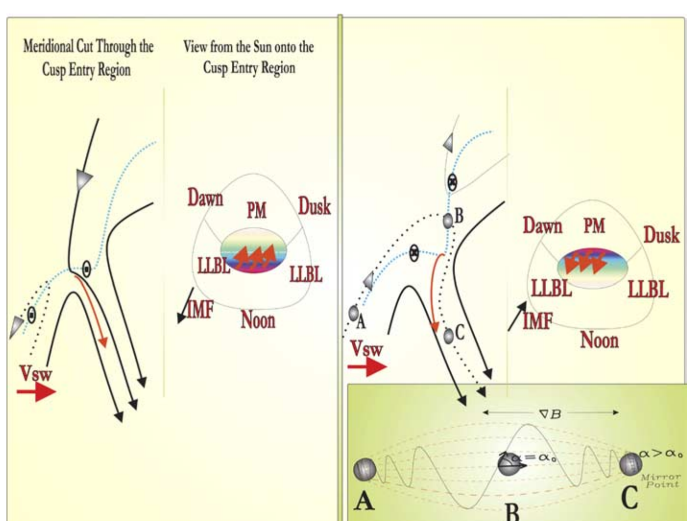

Fig. 3. A diagram of possible scenario of the cusp particle entry inferred from Cluster and Polar observation. The left for IMF southward, and the right for northward IMF.

(Coley et al., 1987; Nishida et al., 1993). A significant sunward flow (which is an indicator for the high latitude merging) near the polar cap boundary has indeed been observed during southward IMF ($-B_z$) when $|B_y|$ was greater than $|B_z|$ (Lu et al., 1994). This is consistent with our observations in event 1 (Fig. 2(left)). The sunward flow for a pure Y-directed IMF has been confirmed by a MHD simulation study by Crooker et al. (1998).

A possible scenario of the cusp ions precipitating into polar ionosphere is shown in Fig. 3. The merging process may occur in the favoured hemisphere (north) and subsequently the reconnected field line, which is still open at one end, is draped over the magnetopause and is further compressed by the solar wind dynamic pressure with the maximum intensity occurring at the subsolar region. In this way, the initial merging point B would be a local minimum magnetic field (see the bottom of Fig. 3). This newly formed geometry allows the ions to be trapped in the local minimum region. Those trapped particles may be further accelerated by the turbulent magnetic field, and pitch angle scattering leads to those trapped protons being precipitated into the polar ionosphere to cause the proton aurora. This is also consistent with the long term DMSP observations. High flux ion precipitation in the cusp region for quiet time has been observed by Hardy et al. (1989, 1991) which implies northward IMF condition. Brautigam et al. (1991) found that the hemisphere averaged ion precipitation strongly depended on the IMF orientation and further found that both the proton precipitation energy flux and number flux are enhanced with increasingly positive IMF B_z. Even the auroral ion/electron flux ratio during northward IMF ($B_z + 5$ nT) is 2.2 times higher than that during IMF southward (B_z -5 nT).

4. Summary and conclusion

Since the discovery of the cusp (Heikkila and Winningham, 1971), the cusp has remained an important, challenging, and interesting magnetospheric region to study. Magnetosheath solar wind particles via this region are expected to have direct access to the magnetosphere. Some of these particles precipitate into the ionosphere to cause the aurora in the footprint of the cusp, whereas others will mirror and drift tailward into the plasma mantle and further be convected into the tail plasma sheet.

To cause proton aurora in the cusp, the following condition is needed: a reverse convection in the cusp region. The location of the cusp proton aurora has exhibited a strong dawn–dusk asymmetry moving 30° (2 MLT) from dawnside to duskside when IMF B_y changed from -10 to 5 nT. It is highly likely that most of the precipitation protons are provided by the shocked solar wind but they may also be partly provided by the tail plasma sheet particles because of a minimum magnetic field existing off the equator in the high latitude dayside region of the magnetosphere (e.g., Tsyganenko magnetic field model). Energetic protons are easily trapped in the cusp region (peak at 90° pitch angle) by a reverse convection geometry. Reverse convection can appear in the case of southward IMF when the IMF B_y is larger than the B_z component. Strong turbulent magnetic fields observed in the cusp region maybe responsible for particle pitch angle scattering which leads to the trapped energetic protons precipitating into the atmosphere to produce the cusp proton aurora.

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