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Spatial and temporal variations of the high-altitude cusp precipitation

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Abstract. Structured dispersion patterns of the ion precipitation in low- and mid-altitude cusp regions have been reported by many authors. These patterns are interpreted either as temporal features in terms of the pulsed reconnection model or as spatial changes caused by a combination of the particle velocity with the convection of magnetic field lines. It is generally expected that the spatial dispersion is predominantly observed in lower altitudes where the spacecraft crosses a wide range of geomagnetic coordinates in a short time, whereas the high-altitude spacecraft observes temporal changes because it stays nearly on the same field line for a long time.

We have analyzed one pass of the INTERBALL-1/MAGION-4 satellite pair through the high-altitude cusp and found that both temporal and spatial dispersion effects are important even in the magnetopause vicinity. The analysis of the present event shows a spatial nature of the observed dispersion in the LLBL and in the plasma mantle. We have identified two sources of a mantle precipitation operating simultaneously. Our investigations suggest that besides already reported latitudinal dispersion, the longitudinal dispersion can be observed during intervals of sufficiently high east-west interplanetary magnetic field component.

Key words. Magnetospheric physics (magnetopause, cusp and boundary layers; magnetosheath; plasma convection)

1 Introduction

Two cusps are spatially narrow regions where magnetosheath plasma of a solar wind origin can directly enter into the magnetosphere and the dayside ionosphere (Heikkila and Winningham, 1971; Smith and Lockwood, 1996). Since matter in the magnetosheath is comprised of shocked solar wind plasma, the particle composition and charge state are the same as those found in the solar wind. Over a decade after the initial cusp observation, a more precise definition of this region was developed from observations of low-altitude ion and electron precipitations (Newell and Meng, 1988). The cusp (or cusp proper) was distinguished from the cleft/low-latitude boundary layer (LLBL) and later from the mantle (Newell et al., 1991).

Several mechanisms of magnetosheath plasma entry into the magnetosphere have been suggested. These mechanisms range from impulsive penetration (Lemaire, 1985), through Kelvin-Helmholtz instability (e.g. Thomas, 1995), up to diffusion (e.g. Thorne and Tsurutani, 1991). However, as an extensive discussion in Sibeck et al. (1999) has shown, observational facts are generally consistent with magnetic reconnection being a dominant source of the cusp plasma, whereas other mechanisms can contribute to the cusp population under specific circumstances. As noted there, a unique feature of reconnection is that it requires the relevant physical processes to take place only in a narrow diffusion region, while its consequences are global: Once the interplanetary and magnetospheric field lines become interconnected, they remain connected while being convected with the solar wind, and plasma continues to enter the magnetosphere. This is in contrast to all other mechanisms that operate only locally, and their occurrence at different locations is essentially uncorrelated.

From the cusp precipitation point of view, we can distinguish two basic reconnection processes: subsolar magnetopause reconnection during southward interplanetary magnetic field (IMF) (e.g. Reiff et al., 1977) and lobe reconnection during northward IMF (e.g. Luhmann et al., 1984). If reconnection takes place equatorward of the cusp, the convective flow is antisunnward and magnetospheric open field lines are moved poleward through the cusps. In the magnetospheric tail, the field lines are reconnected again and return toward the dayside. If southward IMF increases, the flow from the nightside is not fast enough to replace the reconnected flow in the dayside and thus the magnetopause is eroded at the dayside and the cusp moves to lower latitudes (e.g. Měrka et al., 2002).

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However, if the reconnection site is poleward of the cusp, the resulting convective flow is sunward and the open field line is moved equatorward through the cusp in this case. The convective flow is slow because it opposes the fast magnetosheath bulk flow. The subsolar magnetopause position and the cusp latitude are not sensitive to reconnection rate variations during northward IMF (Newell et al., 1989; Palmroth et al., 2001).

As observed by the various spacecraft at both low and high altitudes, a cusp precipitation is often characterized by ion energy dispersion (Rosenbauer et al., 1975). During southward IMF, ion energy falls with increasing magnetic latitudes due to the convection electric field operating as a velocity filter on particles from the injection point to the observation point (e.g. Smith and Lockwood, 1996). During this IMF orientation, the high-energy ions quickly reach lower latitudes and the lower-energy ions appear later at higher latitudes. By contrast, if reconnection takes place in the tail lobes, the high-energy ions quickly reach higher latitudes, whereas the low-energy ions are convected to lower latitudes (e.g. Woch and Lundin, 1992a, b; Topliss et al., 2000) and thus the ion energy-latitude dispersion signifies the boundary of open and closed magnetic field lines. The simulation work by Onsager et al. (1993) has reproduced these observed ion dispersion relations.

An alternative approach can be found in Yamauchi and Lundin (1994). The authors analyzed the flow near the cusp and showed that the supersonic flow above the cusp, together with the outflow of ionospheric ions, can lead to the creation of a shock in the outer cusp and, consequently, to the spatial distribution of the particles according to their energy. However, this model is gasdynamic in nature and thus it cannot explain features connected with the IMF orientation.

Precipitating ions do not always follow a monotonic dispersion. Often complex structures, such as ion steps (e.g. Newell and Meng, 1991; Escoubet et al., 1992), are observed and associated with the effects of the temporal variation of the reconnection rate (i.e. pulsed reconnection; Lockwood and Smith, 1994; Lockwood and Davis, 1996) or spatial structures (e.g. patchy reconnection; Newell and Meng, 1991; Onsager et al., 1995).

Structured cusp ion-energy dispersions, known as stepped or staircase cusp ion signatures, are interpreted as temporal variations in the pulsating cusp model (Lockwood and Smith, 1994). In a recent paper, Lockwood et al. (1998) compared Polar/Hydra data with a simulation model based on pulsed reconnection, and the simulation showed that sudden steps in the ion energy occurred for upgoing and downgoing ions at the same time without any delay. The ions are on field lines that have different time histories, since reconnection and upward/downward steps are caused by moving the location of the spacecraft to field lines which were reconnected more/less recently.

On the other hand, Lockwood and Smith (1992) noted that variations in the reconnection rate are not the only way to produce ion energy steps. For example, variations of the IMF orientation may changed the degree of acceleration of the ions as they cross the dayside magnetopause or a satellite could pass from flow stream line on one X-line to stream lines from a second X-line, and this motion would appear as a step in the ion energy dispersion due to the different time history of reconnection (Lockwood et al., 1995).

Based on the Viking data, Xue et al. (1997) developed a numerical cusp ion injection model. This model has simulated the large-scale energy-latitude dispersion and the small-scale energy-pitch-angle V-signatures observed at middle altitudes. Their model also included a temporal density variation propagating along the magnetopause. The model reproduced a cusp ion structure that was similar to Viking observations, showing the overlap of two independent injections on the same field lines.

Phillips et al. (1993) interpreted cusp structures as a quasi-steady spatial structure which did not appear to be consistent with a localized merging event. Onsager et al. (1995) used two spacecraft in the dayside cusp to investigate spatial/temporal structures and interpreted ion dispersion signature as a spatial structure. Similar observations of Trattner et al. (1999) and Trattner et al. (2002a) were based on conjugated cusp crossings of INTERBALL-1/Polar and Polar/FAST, and the authors found that cusp structures appeared to be stable and unchanged for a few hours. Based on these observations, Trattner et al. (2002b) concluded that the major cusp structures during stable solar wind conditions are not the signature of pulsed reconnection, but they are explained as spatial in nature and do not convect poleward. This conclusion is consistent with long-term observations of cusp precipitation discussed in Sandahl et al. (2000) and Sandahl (2002). The authors show that the precipitation patterns observed in middle and high altitudes are steady and not too sensitive to small changes of upstream parameters. It does not necessarily mean that reconnection should be completely steady. There can be a larger spot on the magnetopause where reconnection patches replace each other due to magnetosheath fluctuations, but an observer in the distance would register nearly continuous plasma inflow. The models based on pulsed reconnection are probably applicable to pronounced changes of upstream parameters.

We are presenting a case study of a crossing of the cusp region in high altitudes which reveals that both spatial and temporal changes should be taken into account for an explanation of the observed features. Moreover, our study shows that the cusp can be supplied from two reconnection sites simultaneously.

2 Instrumentation

In this paper, we present ion observations from near the dayside high-altitude cusp crossing on 21 March 1997, using simultaneous measurements of the INTERBALL-1 and MAGION-4 spacecraft. Both spacecraft have been launched on 3 August 1995 into a highly elliptical orbit with apogee at 31 R_E and inclination 63°. The distance between the spacecraft was varying in the range of one and several thousands of km but in this particular case, the separation was ∼10 000 km. Both satellites carried a similar set of plasma and charged particle detectors. We display ion observations using the MPS/SPS plasma spectrometer on board the MAGION-4 satellite and the omnidirectional plasma detectors (VDP and VDP-S) placed on board both satellites. The ion energy spectra were measured by MPS/SPS in the energy range from 40 eV to 5 keV in several directions (Němeček et al., 1997). The VDP and VDP-S plasma experiments were intended to determine an integral ion flux vector (Šafránková et al., 1997). Further, we are using the additional measurements of magnetic fields on both MAGION-4 and INTERBALL-1 spacecraft (Klimov et al., 1997) and measurements of electron spectra (Sauvaud et al., 1997), for estimation of important boundaries.

In addition, WIND (Magnetic Fields Investigation (MFI) and Solar WIND Experiment (SWE)) data are used for solar wind context measurements (Lepping et al., 1995; Ogilvie et al., 1995). These data are provided by the International Solar Terrestrial Physics (ISTP) key parameter Web page. The SWE data was used to compute the solar wind velocity and a propagation time between both INTERBALL-1 or MAGION-4 and the WIND spacecraft, respectively.

The measurements were further supported by the observations of the DMSP F13, satellite in the auroral ionosphere. The Defense Meteorological Satellite Program (DMSP) satellites are polar-orbiting, sun-synchronous satellites with a nominal altitude of 830 km and an orbital period of 101 min. DMSP F13 which passes the cusp at the end of analyzed interval, carries the SSJ/4 auroral particle spectrometer, capable of measuring electron and ion differential fluxes with energies between 30 eV and 30 keV. The detectors are oriented toward the local zenith and provide a complete energy spectrogram once per second (Hardy et al., 1984).

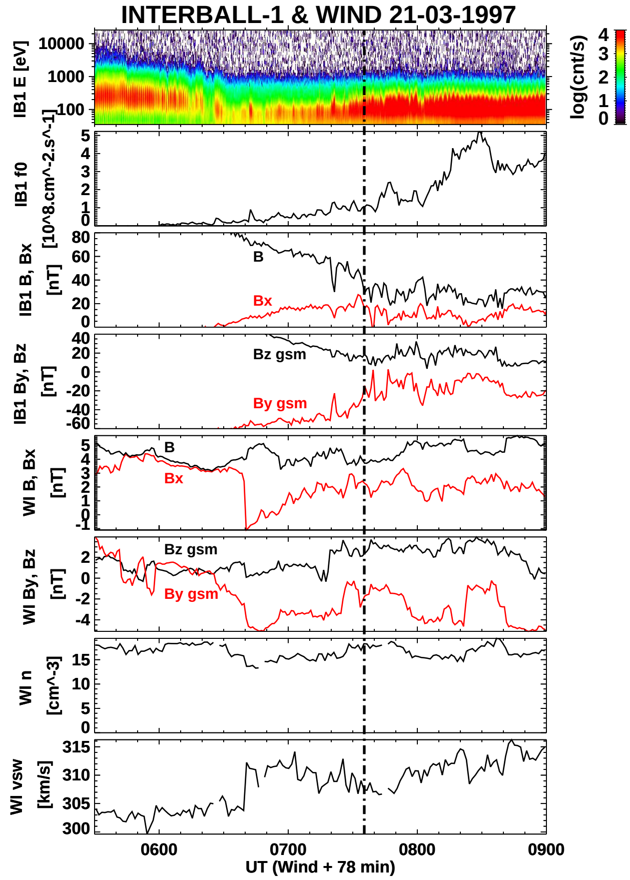

Fig. 1. Upstream conditions during the event under study (21 March 1997) measured by WIND (four bottom panels: the IMF B_X component and magnetic field strength; IMF B_Y and B_Z components in GSM coordinates; the proton density; and the X component of the solar wind velocity). The electron energy spectrograms (top panel); the ion number flux (2nd panel) and magnetic field (3rd and 4th panels) registered on board INTERBALL-1 in the LLBL and outer cusp (until 07:35 UT) and in the magnetosheath. WIND data are shifted on ∼78 min to account for a propagation time.

3 Introduction to the analyzed event

The analysis of dispersion patterns is based on observations of the MAGION-4 spacecraft made in the high-latitude high-altitude magnetosphere. The spacecraft moved from (−1, −4.5, 2) R_E to (3, −1, 9) R_E in GSM coordinates. The same regions were crossed by INTERBALL-1 approximately 70 min earlier but, unfortunately, only total currents of Faraday cups and electron energy spectra are available for the period under investigation. Supporting WIND measurements at (228, 18, 8) R_E in GSE coordinates show a low solar wind velocity (300–315 km/s) and a high number density (15–20 cm^{-3}), resulting in a dynamic pressure slightly above the average (2.6 nPa) and nearly constant during the whole investigated interval (see Fig. 1, WIND data panels. Note that the WIND data are shifted by 78 min to account for a corresponding propagation time). The IMF B_X component was positive and large until ∼06 : 40 UT when IMF turned rapidly to a nearly southward orientation. The IMF B_Y component was positive throughout the whole time interval. IMF B_Z gradually changes from strongly positive (+5 nT until 05:30 UT) to small negative values (−2 nT at 06:35 UT) and then jumps to −5 nT and is a dominant IMF component until ∼07 : 30 UT. After 07:30 UT, IMF B_Z becomes smaller but it remains negative until the end of our interval.

The high magnetic field magnitude observed by INTERBALL-1 until ∼07:15 UT (third and fourth panels in Fig. 1) suggests that the spacecraft is in the magnetosphere, whereas the fluctuating magnetic field repeating some IMF features observed after ∼07:50 UT puts the spacecraft into the magnetosheath. The electron energy spectrograms (first panel in Fig. 1) registered in the magnetosphere do not contain any high-energy population and the ion flux (in the second panel) is very low. These facts, together with the spacecraft location, lead to the conclusion that the spacecraft crossed the magnetopause in the cusp region. As Měrka et al. (2000) has shown, the magnetopause in this region is

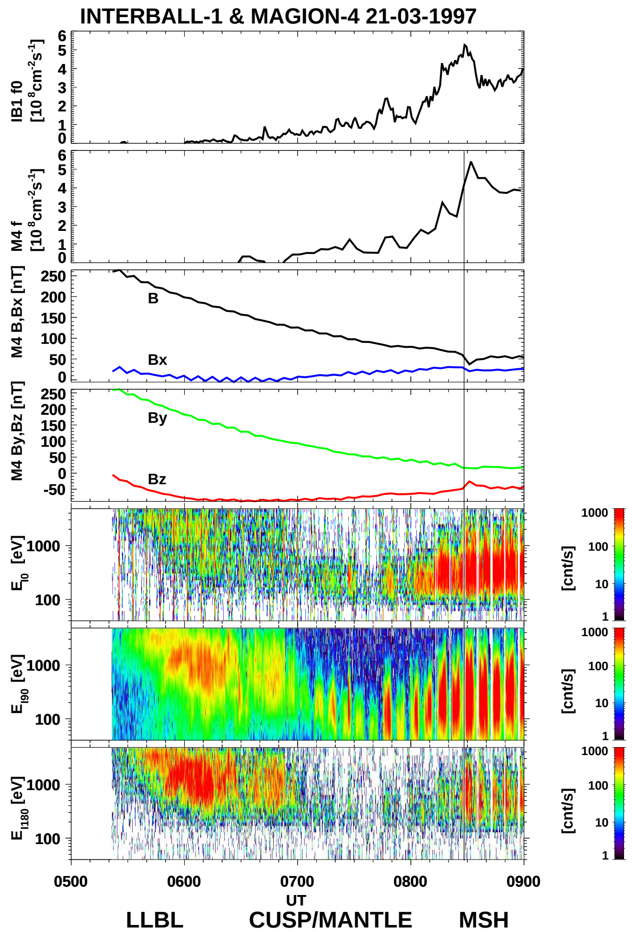

Fig. 2. MAGION-4 observations of the precipitating ions. The first panel shows the INTERBALL-1 ion flux for the sake of reference. The second panel presents the MAGION-4 ion flux and the next three panels depict ion energy spectra measured in three directions. The magnetopause crossing is distinguished by a vertical line, the identification of crossed regions is labeled in the bottom part.

often hardly distinguishable during periods of negative IMF B_Z. In our particular case, we think that the magnetopause crossing can be connected either with a small decrease in the magnetic field modulus at ∼07:35 UT or with a jump in the ion flux at ∼07:42 UT. The ion flux is still very low above the magnetopause because the satellite probably entered the region of a stagnant plasma (Haerendel, 1978; Dubinin et al., 2002). The following gradual increase of the ion flux until ∼08:15 UT is then connected with a crossing of the reconnection layer (Němeček et al., 2003). The flux level of the magnetosheath proper is probably reached at ∼08:15 UT. The jumps observed later are of a magnetosheath origin and correlate with IMF rotations (Šafránková et al., 2004). Although no ion energy spectra are available on board INTERBALL-1 during the investigated period, we can use flux measurements as a magnetosheath monitor after 08:00 UT.

4 MAGION-4 observations

The ion energy spectrograms recorded by three channels of the MPS/SPS device (MAGION-4) are shown in the three bottom panels of Fig. 2. The ion fluxes derived from Faraday cups on board INTERBALL-1 and MAGION-4 are given in the two top panels for reference. Both flux profiles measured by the two spacecraft moving along the same orbit (INTERBALL-1 advanced MAGION-4 by 70 min) exhibit some simultaneous changes as increase in the ion flux increases at ∼07:47 or 08:15 UT which can be attributed to the changes in the magnetosheath density above the cusp. However, these changes are small and do not mask the similarity of the overall profiles. This similarity suggests that MAGION-4 crossed a steady region and we can believe that the changes in ion spectra in the magnetosheath are of a spatial nature. The determination of the magnetopause crossing is again very difficult but the most probable candidate is the change in the magnetic field (third and fourth panels in Fig. 2) accompanied with an increase in the ion flux at ∼08:27 UT. A more precise analysis is impossible because only 3-min averages of the magnetic field and 6-min averages of the ion flux are available. However, these changes correlate with changes in ion energy spectra shown in the last three panels. The spectra were recorded by the analyzers with different view angles. The I0 channel registers tailward streaming ions, whereas I180 channel (bottom panel) measures ions proceeding toward the Sun. These two analyzers are oriented roughly along the satellite spin axis and thus their data do not exhibit any distinct spin modulation. On the other hand, the I90 analyzer is oriented nearly perpendicularly to the spin axis and scans a broad range of pitch angles during one satellite revolution. The energy range of measurements is 40 eV–5 keV, which is clearly insufficient in the first part of the interval when the satellite observes a hot ion population. The energy of this population gradually decreases. From ∼06:55 UT, a strong spin modulation in the I90 channel suggests a bulk motion of the observed ions. The decrease in the ion energy continues until ∼07:40 UT when the trend reverses and the energy becomes increasing. At ∼08:27 UT, it reaches the magnetosheath energy and the satellite crosses the magnetopause. If we compare the fluxes observed by I0 and I180 channels, we can note that the sunward flux dominates at the first part of the interval (until 07:40 UT), whereas the tailward streaming ions prevail in the second part, especially in the magnetosheath. However, MAGION-4 is in the magnetosphere (i.e. in a low-beta region) most of the time and thus the ion motion would be rather organized by the magnetic field.

We make use of the fact that the I90 channel scans nearly all pitch angles and thus we divided its measurements into several groups according to the pitch angles and computed the integral energy flux for each of these groups. The results are shown in Fig. 3. The energy flux does not depend on the pitch angle until ∼07:00 UT but a lack of the particles streaming along the magnetic field is observed later. The increase in the energy flux from 05:15 to 06:05 UT can

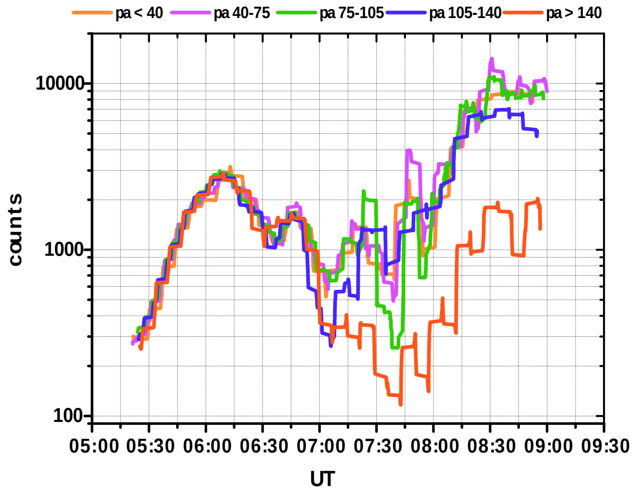

Fig. 3. Computed integral energy fluxes for different pitch angles (labeled at the top part of the figure) in the whole time interval. Data used are taken from the spectrograms in the middle panel of Fig. 2.

be partly artificial and connected with a limited energy range of our device. The general decrease in the energy flux from 06:05 to 07:00 UT is associated with the decrease in the ion energy because the ion number flux increases, as can be seen in the Faraday cup data (second panel in Fig. 2). The decrease in the ion energy is compensated by the increase in their number and thus the energy flux is roughly constant between 07:00 and 07:40 UT. A steep rise of the energy flux after 07:40 UT is connected with a simultaneous increase in both the ion number flux and ion energy.

The detail analysis of dispersion patterns seen in Fig. 2 is presented in Fig. 4. Since a clear low-energy cut-off is not observed, Fig. 4 shows maxima of differential energy flux in different directions with respect to the magnetic field. This plot reveals that the decrease in the ion energy, observed until 07:40 UT is not continuous but several injection-like structures can be identified. The peak energy decreases from 2 keV to 0.9 keV at 06:20 UT. A more detail analysis of the data shows that the decrease in the ion energy which is fitted by a straight line in the bottom panel, probably proceeds in several steps. This suggests (Lockwood and Smith, 1994; Trattner et al., 2002b) a changing reconnection rate which is probably connected with changes in the IMF direction.

At ∼06:22 UT, the energy of precipitating ions jumps up to 2 keV. The following decrease is more rapid, the energy falls from 2 keV to 200 eV during ∼10 min. A problem of the analysis of this particular injection is that the spacecraft spin period (approximately 6 min) is rather long and comparable with the duration of an aforementioned energy decrease. However, the I180 analyzer (bottom panel in Fig. 2) is not affected by the spacecraft spin. It monitors the particles with ∼90° of the pitch angle and observes the same decrease, as shown in the middle panel of Fig. 4. The generally lower energies observed during this injection, near 90° of a pitch angle (middle panel in Fig. 4) in comparison with

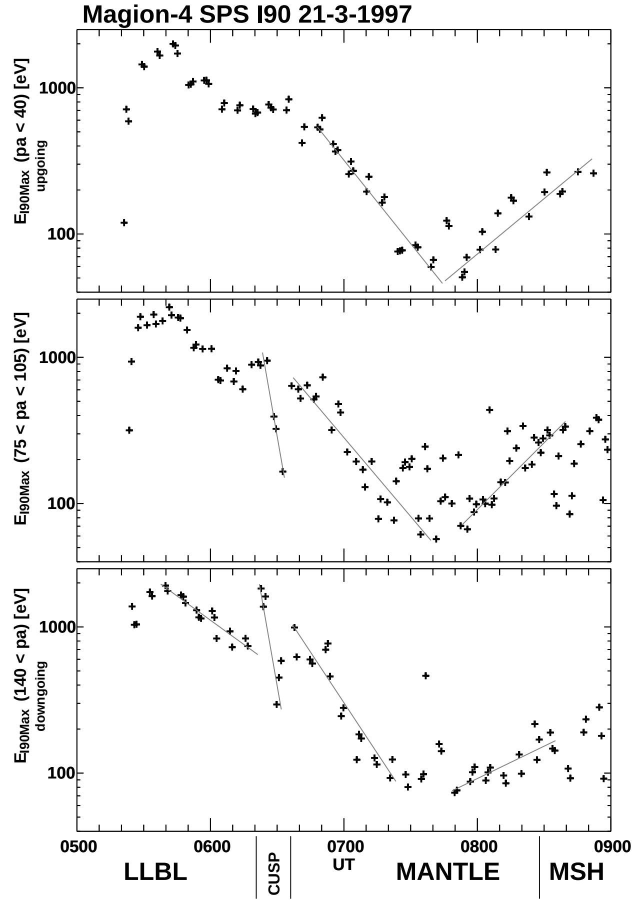

Fig. 4. The maxima of differencial energy fluxes in different directions with respect to the magnetic field.

the downgoing population, are probably a combination of the sampling and fast energy decrease because the analyzer registered first downgoing and then perpendicular ions. A more detailed analysis of the data shows that the decrease in the ion energy, which is fitted by a straight line in the bottom panel, probably proceeds in several steps. This suggests (Lockwood and Smith, 1994; Trattner et al., 2002b) a changing reconnection rate which is probably connected with changes of the IMF direction.

At ∼06:35 UT, the energy again jumps up to ∼1 keV and then slowly decreases toward the low-energy limit of the device (∼40 eV). The minimum is reached at 07:45 UT. The following increase has a similar slope and is stopped by the magnetopause crossing. These features are clearly seen in the top panel of Fig. 4 because the ions are generally upgoing (see Fig. 3) and thus the data from other directions shown in the two bottom panels are rather noisy. Nevertheless, a comparison of top and bottom panels in the figure reveals lower energies of downgoing population. This difference is connected with a time of flight effect because the path of upgoing ions is significantly longer and thus only faster ions can be observed on the same field line.

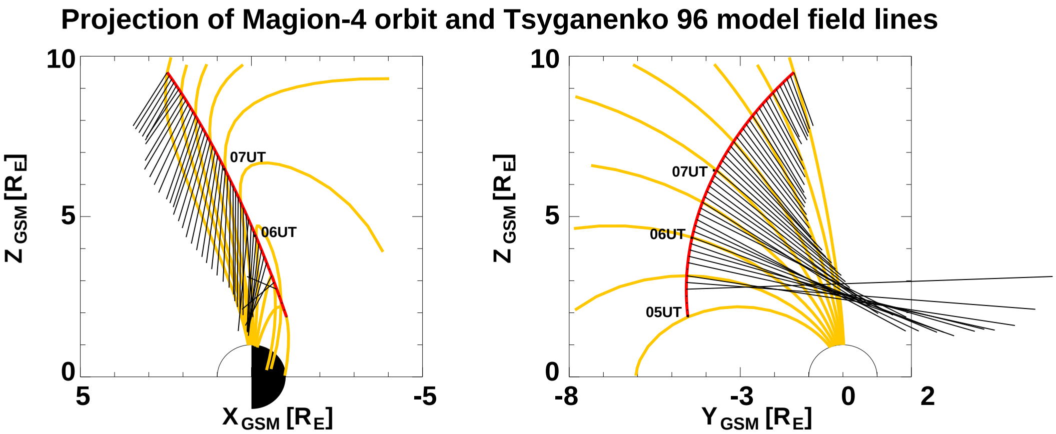

Fig. 5. Projections of the MAGION-4 orbit into the X-Z (left part) and Y-Z (right part) planes according to the Tsyganenko model. The abscissas show the magnetic field vector as measured by MAGION-4 each 5 min.

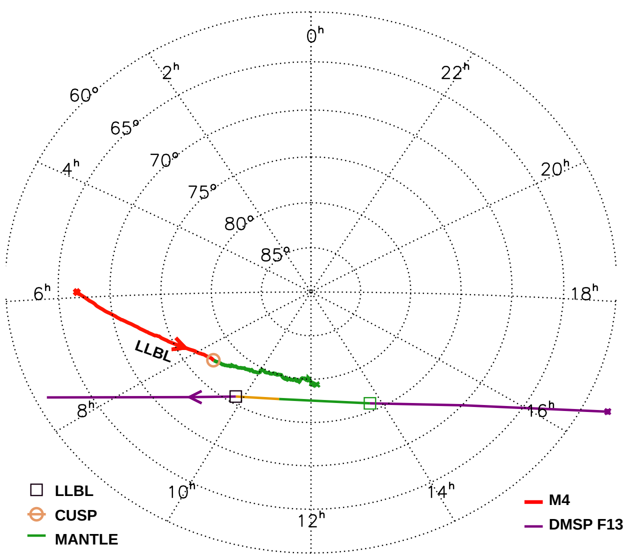

Fig. 6. Footprints of the MAGION-4 and DMSP F13 orbits. The crossed regions are labeled with different symbols and colors.

Figure 5 combines the MAGION-4 magnetic field with the Tsyganenko 1996 model (Tsyganenko and Stern, 1996). The figure shows the projections of the MAGION-4 orbit into the X-Z and Y-Z GSM planes, respectively, together with the projections of running MAGION-4 magnetic field vector. The model field lines which intersect the MAGION-4 orbit are drawn each 30 min; 6-min average of the measured magnetic field are shown as abscissas along the spacecraft orbit. One can note a good agreement of model and measured magnetic field directions in the Y-Z plane (right panel). The same fact is true for the X-Z plot (left panel) until ∼07:00 UT but the model slightly underestimates the X component later. The good agreement of model and measured fields allows us to conclude that MAGION-4 started on closed field lines in the dawn flank and gradually moved toward the local noon to open field lines poleward of the cusp proper.

The features observed by MAGION-4 can be projected to the low-altitude auroral region and compared with observations of the DMSP satellite. To find a spacecraft in an appropriate location, we have mapped the MAGION-4 orbit along Tsyganenko model field lines onto the Earth's surface. The mapping is shown in Fig. 6, together with the closest DMSP F13 pass which occurred at ∼08:55 UT, i.e. ∼20 min after the MAGION-4 magnetopause crossing. Taking into account the uncertainty of the magnetic field model, one can note an excellent conjunction of the spacecraft. The mean velocity of precipitating particles is low and the spacecraft separation is ∼10 R_E and thus DMSP observes plasma entering the cusp region approximately at the time of the MAGION-4 magnetopause crossing.

The standard DMSP plot of precipitating particles in Fig. 7 exhibits very similar features to those observed by MAGION-4 and presented in Fig. 2. The only difference is in the direction of motion of the spacecraft: MAGION-4 moves from the dawn to dusk sector but DMSP F13 proceeds in the opposite direction, and spatial features are thus reversed in time series of measurements. The decrease in the ion energy toward the local noon is observed in a morning sector where the precipitation is classified as the LLBL population. The V-shaped dispersion patterns are observed in the mantle region between 11 and 12 MLT. Earlier (i.e. in afternoon MLTs), the energy of mantle precipitation is nearly constant but we have no MAGION-4 observations at these local times. The energies observed by DMSP F13 are a little higher than those of MAGION-4. It is probably caused by the fact that DMSP is orbiting equatorward of MAGION-4 and the IMF has a significant southward component and thus one would expect higher energies at the equatorial edge of the cusp (Onsager et al., 1995).

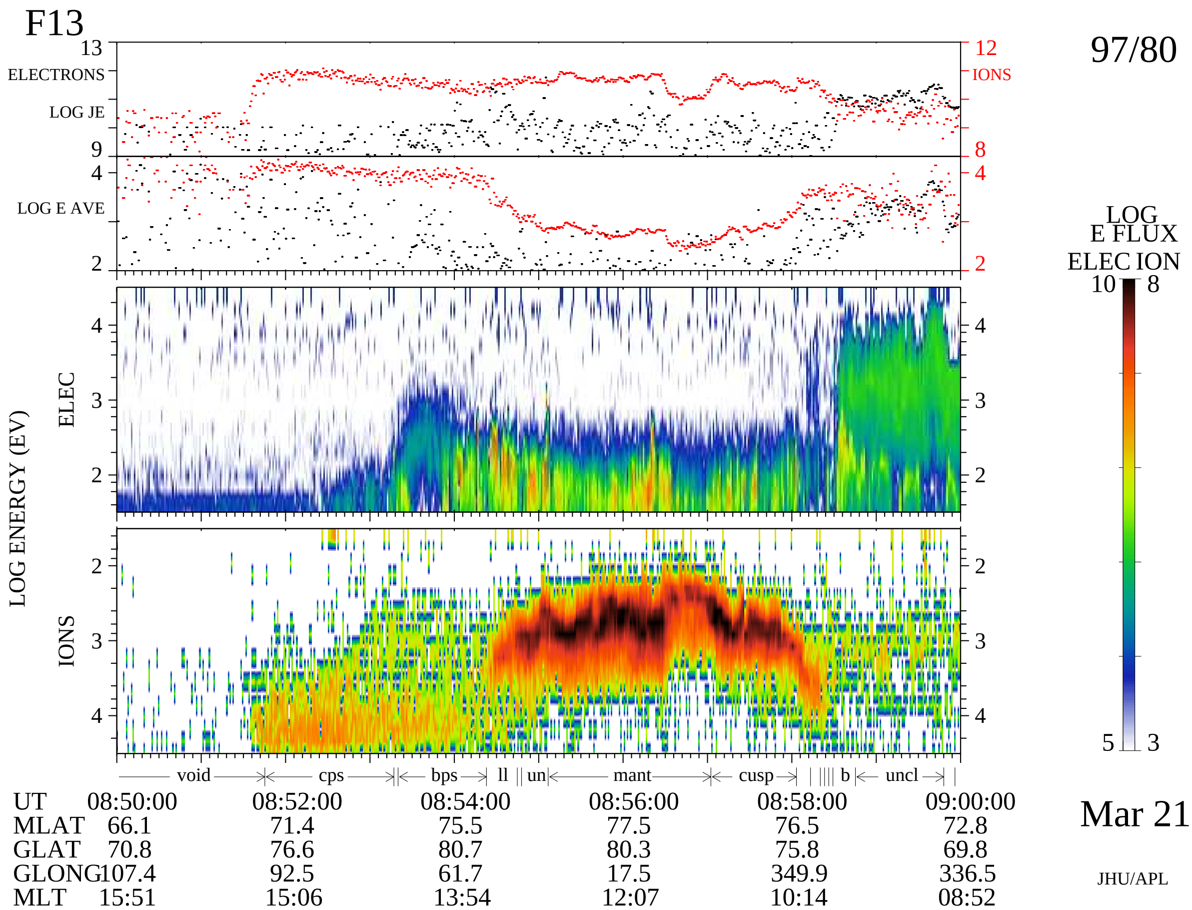

Fig. 7. Ion and electron energy spectrograms measured by DMSP F13 (adapted according to http://sd-www.jhuapl.edu/Programs/).

5 Discussion

The first feature to be pointed out is the MAGION-4 LLBL observations between 05:30 and 07:00 UT, and corresponding DMSP observations around 08:58 UT. The pitch-angle distribution in Fig. 3, as well as the MAGION-4 location shown in Fig. 5, suggest that the LLBL is on dayside closed field lines. Since the IMF pointed northward at the beginning of the investigated interval, we can expect that the LLBL is formed by multiple reconnection proceeding tailward of the cusp (e.g. Song and Russell, 1992; Němeček et al., 2003). However, the IMF has a significant B_Y component which is even more important after 06:00 UT when values of B_Y and B_Z become comparable. The drawing in Song and Russell (1992) is oversimplified for such a case. The magnetic field geometry is too complicated to be illustrated by a simple sketch of IMF B_Y. Nevertheless, the analysis shows that the field line reconnected on the dusk side in the Northern Hemisphere would convect sunward (consistently with the IMF direction) and thus it can reconnect again on the dawn side in the Southern Hemisphere. This new magnetospheric field line is longer and significantly tilted with respect to the standard magnetospheric field. Magnetic tension would turn this line toward the magnetospheric orientation and the released energy would drive the magnetospheric convection. This convection should replace the magnetic flux which is removed from the tail part and convected magnetic field lines pull the trapped plasma around the magnetosphere. The combination of the $\boldsymbol{E} \times \boldsymbol{B}$ drift and longitudinal convection will lead to the dispersion with particles of higher energies located deeper in the magnetosphere and at earlier local times.

This explanation can be applied to the MAGION-4 LLBL observations until 06:20 UT. A new injection was observed between 06:22 and 06:30 UT. The duration of this event is short and thus a temporal origin of the observed dispersion cannot be excluded. We suggest that this change in the precipitation patterns is connected with the IMF rotation observed by WIND. IMF turned from northward to southward orientations and, as Šimůnek et al. (2003) pointed out, more reconnection sites operating simultaneously can supply the precipitation during such an IMF rotation because subsolar reconnection connected with the new IMF orientation starts earlier than before reconnection tailward of the cusp is terminated. They found that the time required for a setting of a new equilibrium state can be as long as 20 min. Since the cusp moves equatorward in reaction to the IMF's turn southward (Měrka et al., 2002), MAGION-4 observes a new dispersion. The highest energies are seen first because the

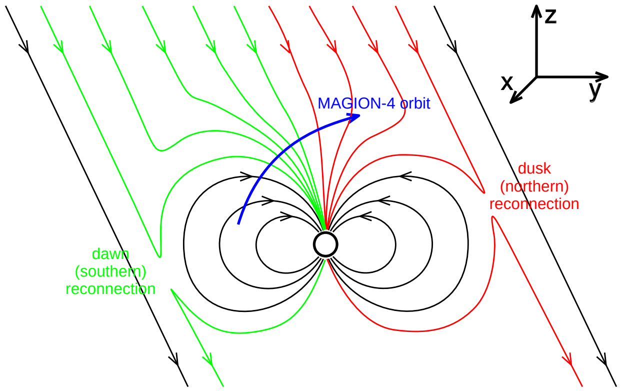

Fig. 8. A sketch of a magnetospheric topology during the investigated event in the time interval when IMF B_Z is negative.

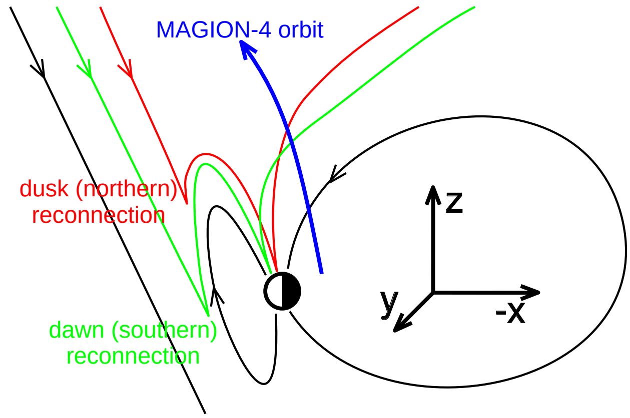

Fig. 9. Schematic drawing of latitudinally separated reconnected field lines.

satellite first encounters the equatorward edge of the cusp region. The injection adds downgoing ions to the trapped population which was already on newly open field lines and thus the downgoing population slightly prevails (Fig. 3) during this event. The whole region is crossed in approximately 10 min, in accord with the suggestions of Šimůnek et al. (2003).

The last part of the time interval (between 06:40 and 08:30 UT) was attributed to the crossing of the plasma mantle because the upgoing ion population prevails in this region (Fig. 3). The most distinct feature of this region is the V-shaped dispersion. The satellite moves in the vicinity of the magnetopause from dawn toward the local noon and the region is formed by the IMF having significant southward and duskward components. This IMF orientation would lead to two antiparallel merging sites (e.g. Trattner et al., 2002b; Němeček et al., 2003) which will be shifted toward dawn (dusk) in the Southern (Northern) Hemisphere, as is illustrated in Fig. 8. The field lines from the southern reconnection site cross the MAGION-4 orbit and we can observe the classic dispersion where the higher energies are observed on field lines closer to the source, i.e. dawnward. The reversal of the dispersion slope observed at ∼07:40 UT thus suggests that MAGION-4 starts to move toward the (new) source of the particles. We assume that this source is reconnection proceeding on the dusk side northward of the equator. MAGION-4 proceeds toward this reconnection site until it reaches the magnetopause.

The magnetic tension and magnetosheath flow push reconnected field lines from both reconnection sites toward the local noon. Since they cannot cross each another, they should by separated latitudinally, as is demonstrated in Fig. 9. We would like to point out that this scenario supports findings of Měrka et al. (2002), that the increasing IMF B_Y component leads to splitting of the cusp region into two spots which are separated longitudinally, and findings of Wing et al. (2001), who show the latitudinal splitting of the cusp location during intervals of a significant IMF B_Y component.

The Merka et al. (2002) paper is based on statistical processing of outer cusp observations, and they suggest two plasma sources as a possible explanation of a gap in cusp observations near the local noon. Wing et al. (2001, 2004) used the model predicting two sources (reconnection sites) and documented the results of the model by several DMSP passes through the cusp region. The latitudinal separation of two cusps in these data is not clearly seen, usually only a broader latitudinal width is recorded.

Our analysis shows that MAGION-4 moves first away (from 06:30 to 07:45 UT) and then toward (from 07:45 to 08:27 UT) the source of the precipitating plasma. Since the upstream conditions were sufficiently stable, we cannot expect a significant (from dawn to dusk) motion of the reconnection site and thus the only explanation is that two reconnection sites operate simultaneously and result in two precipitation streams separated longitudinally as well as latitudinally.

6 Conclusions

Our study of one pass of the INTERBALL-1 and MAGION-4 spacecraft across the LLBL/mantle region reveals a surprising stability of sources of the cusp precipitation during a long interval of a changing IMF orientation (Sandahl et al., 2000). A detailed study of dispersed precipitation has shown that:

- The spacecraft observed the LLBL and plasma mantle at high altitudes, from 5 R_E to the magnetopause, in the northern dawn sector (from 06:00 to 12:00 MLT), despite the positive IMF B_Y.

- The LLBL population was trapped on closed field lines and its energy decreased gradually as the satellite moved from dawn toward the local noon. Since the LLBL plasma was observed on closed field lines, the observed dispersion is a spatial feature.

- The LLBL was crossed again due to reconfiguration of a region after the IMF B_Z rotation. The observed dispersion patterns are consistent with a formation of the cusp during southward IMF.
- The V-shaped dispersion observed in the plasma mantle suggests the presence of two sources of the precipitations (two different reconnection sites). These sources are projected onto different longitudes and latitudes of the auroral oval.
- The duration of observed dispersion patterns in the plasma mantle excludes their temporal origin.
- A motion of the plasma responsible for the observed longitudinal dispersion is consistent with magnetospheric convection in the analyzed case.

Our investigations have shown that the process of the cusp formation is more complex than usually expected. It is controlled by external conditions, as well as by an internal state of the region given by its history.

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