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Relationship of upflowing ion beams and conics around the dayside cusp/cleft region to the interplanetary conditions

W. Miyake[1], **T. Mukai**[2], **and N. Kaya**[3]

[1]Communications Research Laboratory, 4-2-1 Koganei, Tokyo 184-8795, Japan
[2]The Institute of Space and Astronautical Science, Yoshinodai, Sagamihara 229-8510, Japan
[3]Kobe University, 1-1, Rokkodai, Nada, Kobe 657-8501, Japan

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Abstract. The dayside cusp/cleft region is known as a major source of upflowing ionospheric ions to the magnetosphere. Since the ions are supposed to be energized by an input of energy from the dayside magnetospheric boundary region, we examined the possible influence of the interplanetary conditions on dayside ion beams and conics observed by the polar-orbiting Exos-D (Akebono) satellite. We found that both the solar wind velocity and density, as well as IMF B_y and B_z, affect the occurrence frequency of ion conics. The energy of ion conics also depends on the solar wind velocity, IMF B_y and B_z. The ion beams around the local noon are not significantly controlled by the interplanetary conditions. The results reveal that ion convection, as well as the energy source, is important to understand the production of dayside ion conics while that of ion beams basically reflects the intensity of local field-aligned currents.

Key words. Ionosphere (particle acceleration) – magnetospheric physics (magnetopause, cusp, and boundary layers; magnetosphere ionosphere interaction)

1 Introduction

The dayside cusp/cleft region is known as a major source of ion conics (Gorney et al., 1981; Kondo et al., 1990; Thelin et al., 1990; Miyake et al., 1996), as well as low-energy upwelling ions (e.g. Lockwood et al., 1985; Yau and Andre, 1997). Various energy mechanisms and sources have been proposed (Andre and Yau, 1997). Interplanetary magnetic field and solar wind plasma conditions control the cusp geometry and dynamics of particles and fields around the cusp/cleft region (see, for example, Smith and Lockwood, 1996) and are therefore supposed to control the dayside ion energization. Fuselier et al. (2001) reported nearly instantaneous ionospheric outflow of 30 eV O^+ in response to the passage of a CME shock. The energized ions of terrestrial origin are transported to the magnetosphere and are believed to be an important source of plasma populations in the magnetotail (e.g. Chappell, 1988). Lennartsson (1995) found the ionospheric oxygen ion density in the plasma sheet to be correlated with solar wind energy flux.

Dependence of the dayside upwelling ions (with energies less than a few tens of eV) on interplanetary conditions has been reported in several literatures. Pollock et al. (1990) investigated the effects of IMF B_z on low-energy upwelling ions and found that O^+ flux and the occurrence probability is not dependent on IMF B_z. Chandler (1995), however, revealed that IMF B_z seems to have the largest effect on the downflows of O^+ ions, which are probably the return flow of dayside upwelling ions. Moore et al. (1999) reported ion heating driven by variations of the solar wind dynamic pressure when a CME hits the magnetosphere. Elliot et al. (2001) showed that the density and parallel flux of O^+ ions in the polar cap at altitudes between 5.5 Re and 8.9 Re are well correlated with the solar wind dynamic pressure and solar wind electric field ($-\boldsymbol{V} \times \boldsymbol{B}$). Low-energy ions flowing out of the ionosphere disperse according to their mass and energy as they are swept away from the source by convection. Hence, low-energy upwelling ions are under the strong influence of the interplanetary parameters (e.g. Lockwood et al., 1985; Delcourt et al., 1988).

There are only a few reports on the relationship between the interplanetary parameters and dayside energetic ion outflow, i.e. ion beams and conics. Thelin et al. (1990) studied the effects of IMF B_y on the occurrence frequency of dayside ion beams and conics from Viking observations and found the localized noon minimum of the occurrence frequency, which is displaced following the polarity of B_y. Miyake et al. (2000) also investigated the effects of all three components of the interplanetary magnetic field on the dayside ion conics and revealed that IMF B_y and B_z control the production of dayside ion conics. They also suggested the possibility that interplanetary magnetic field affects the dayside ion energization by means of controlling not only the energy input, but also the convection pattern. This paper is an extension of Miyake et al. (2000), including ion beams, as well

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Correspondence to: W. Miyake (miyake@crl.go.jp) as ion conics and the possible effects of solar wind velocity and density in the analysis. The purpose of the present paper is to discuss the possible causes in terms of dayside ion energization by investigating both the energy input to local ion energization region and the spatial spread of energized ions due to convection.

2 Data

The ion data for this study were acquired by the Low Energy Particle (LEP) instrument on the polar-orbiting Exos-D (Akebono) satellite, which has an initial apogee and perigee of 10482 and 272 km, respectively (Oya and Tsuruda, 1990; Tsuruda and Oya, 1991). The LEP instrument consists of two sets of E/Q analyzers and was designed to observe energy-pitch angle distributions of auroral electrons and ions. It has an energy-per-charge range of 13 eV/q–20 KeV/q for ion measurement. The energy range is divided into 29 logarithmically spaced steps and is scanned in 2 s. The pitch angle range is divided into 18 bins of 10° each in the data processing procedure (see Mukai et al., 1990 for the details of the instrument). Observation has been successfully carried out since the initial turn-on and a large data set for auroral electrons and ions has been built. In this study we used the ion data obtained from April 1989 through April 1992. Ion beams and conics were automatically identified by the algorithm used in Miyake et al. (1996) for every 16 s (see Miyake et al., 1996 for the details of the identification process and statistical characteristics of dayside ion beams and conics).

We also used 5 min averages of the interplanetary magnetic field and solar wind plasma data from IMP-8 in this study. For the analysis we selected the IMF and solar wind plasma data taken where the satellite was located upstream of the Earth in the solar wind (i.e. $X > 0$). In the 09:00–15:00 MLT (magnetic local time) range, we identified 5146 ion beams and 13541 ion conics in 16 s averaged data from the Exos-D (Akebono) satellite. The interplanetary parameters were available for 30%–40% of the upflowing ion events.

We analyze here the occurrence frequency of ion beams and conics, which is given by $f = n/N$, where n is the number of events in an Alt-IL-MLT (altitude – invariant latitude – magnetic local time) bin and N is the number of samples in each bin under a certain interplanetary condition. In this study, the number of samples means the number of all the available 16 s data in the bin, and the number of events means the number of events where ion beams and conics are identified. The statistical uncertainty is defined as $\sigma = [f(1-f)/(N-1)]^{0.5}$. The occurrence frequency in this study is integrated over the entire altitude (<10 000 km), invariant latitude (65°–85°), and MLT (9–15 h) ranges. Since the occurrence frequencies of ion beams and ion conics are increased with altitude (Miyake et al., 1996) and more data were sampled at a higher altitude due to the slow satellite motion and the wide visible range from the ground station, about 80% of the events presented here were observed in the altitude above 7000 km. No normalization of the data for altitude was made in the analysis.

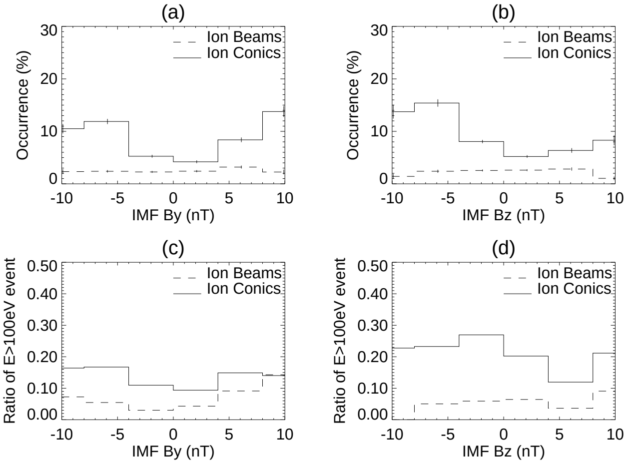


Fig. 1. Occurrence frequency of ion beams and conics as a function of **(a)** IMF B_y and **(b)** IMF B_z and ratio of the energetic (>100 eV) event to the total event number as a function of **(c)** IMF B_y and **(d)** IMF B_z. The occurrence frequency is integrated over the entire altitude (<10 000 km), invariant latitude (65°–85°), and MLT (9–15 h) ranges. The vertical bar in Figs. 1a and 1b is the statistical uncertainty.

3 Results

Figure 1 shows the occurrence frequency of ion beams (broken line) and conics (solid line) in the 09:00–15:00 MLT range as a function of IMF B_y (Fig. 1a) and IMF B_z (Fig. 1b) and the ratio of energetic (>100 eV) events to the total event number as a function of IMF B_y (Fig. 1c) and IMF B_z (Fig. 1d). The vertical bar in Figs. 1a and 1b is the statistical uncertainty. The occurrence frequency indicates the fraction of time interval of the event occurrence. Upflowing ions are almost always present around the dayside auroral region whenever the satellite traverses the region. Therefore, the occurrence frequency of upflowing ions here represents the spatial area occupied by upflowing ions in the integration range (65°–85° invariant latitude and 09:00–15:00 MLT), rather than the time interval of the event. The ratio of energetic event to the total event number, on the other hand, indicates the intensity of the local ion energization. The energy of ion beams is defined as the energy of the field-aligned peak of ion flux, while that of ion conics is the maximum energy observed of conical ion distributions.

As reported in Miyake et al. (2000), both the IMF B_y and B_z components control the dayside ion conics, which are more frequently observed and more energetic when the magnitude of B_y is large and B_z is negative, though there might be an increase in energy input during a strongly northward B_z period. There is a coupling between the spiral angle of IMF and solar wind velocity. As shown later in Fig. 3, both the occurrence frequency and the ratio of the energetic event

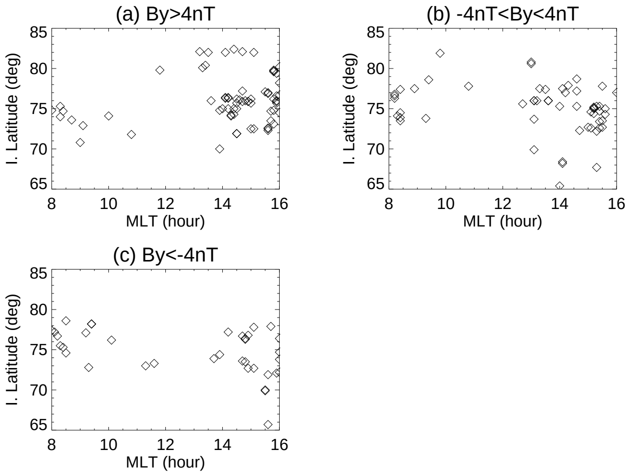


Fig. 2. Location of energetic (>100 eV) ion beam event in MLT-I.Lat coordinate when IMF B_y is **(a)** strongly positive, **(b)** nearly zero, and **(c)** strongly negative.

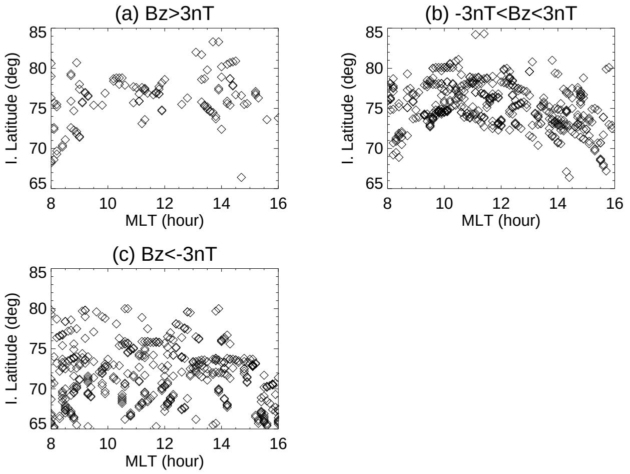


Fig. 3. Location of energetic (>100 eV) ion conics event in MLT-I.Lat coordinate when IMF B_z is **(a)** strongly positive, **(b)** nearly zero, and **(c)** strongly negative.

of ion conics correlate positively with the solar wind velocity. Large magnitude of IMF B_y generally corresponds to low velocity. Therefore, the influence of IMF B_y on ion conics is expected to be more significant when we remove the coupling effect.

Ion beams show little dependence on IMF. Most of the ion beams in this region have energies below 100 eV. The ratio of the energetic ion beam event is, however, higher at the large magnitude of B_y in Fig. 1c. Figure 2 shows the location of the energetic (>100 eV) ion beam event in MLT-I.Lat coordinate when IMF B_y is strongly positive (Fig. 2a), close to zero (Fig. 2b), and strongly negative (Fig. 2c). We extended the MLT range presented in the figure for the purpose of identifying clearly the major source of energetic ion beams. As shown in Fig. 1, the occurrence frequency of ion beams in the dayside region is small and the ratio of the energetic event is also small, so that the event number of energetic ion beams is very small. Energetic ion beams are predominantly observed on the evening side and most of the ion beams near the local noon have low energy. The more energization during a large B_y period probably takes place on the morning and/or evening sides, which is attributed to the global region-1 and region-2 current system. Iijima and Potemra (1982) reported that the current density of dayside region-1 system increases with the magnitude of B_y. There is no significant enhancement of the energetic ion beams near the local noon.

Low-energy upwelling ions have little dependence on IMF B_z except for the latitudinal distribution (Pollock et al., 1990; Elliott et al., 2001). We examine further the location of energetic ion conics in the 09:00–15:00 MLT range, summarized in Fig. 1d. In Fig. 3, we plot the location of the energetic (>100 eV) ion conics event in MLT-I.Lat coordinate when IMF B_z is strongly positive (Fig. 3a), nearly zero (Fig. 3b) and strongly negative (Fig. 3c). When B_z is negative, the location is extended toward low latitudes for the entire dayside region. Energetic ion conics are observed over the wide MLT range and concentrate on neither the morning nor the evening side, which is different from the case of ion beams. Therefore, we conclude that IMF B_z does not enhance a single source like the morning side region-1 current, but affects dayside ion conics over the wide range of MLT.

Figure 4 shows the occurrence frequency of ion beams (broken line) and conics (solid line) in the 09:00–15:00 MLT range as a function of solar wind velocity (Fig. 4a) and solar wind density (Fig. 4b) and the ratio of the energetic (>100 eV) event to the total event number as a function of solar wind velocity (Fig. 4c) and solar wind density (Fig. 4d). Ion conics are more frequently observed and more energetic when the solar wind velocity is large (Figs. 4a and 4c). There might be a small increase in the occurrence frequency of ion conics with the solar wind density, while the ratio of energetic conics decreases with the solar wind density.

We should take into account the anti-correlation of the solar wind velocity and density to interpret the results. The average velocity is 616 km/s for the density of 0-4 /cc and is 432 km/s for 12-16 /cc during the analysis period. Therefore, the anti-correlation of the solar wind velocity and density explains the decrease in the ratio of the energetic event with increasing solar wind density. The ratio is probably controlled mostly by the solar wind velocity alone. Ions are more energetic when the solar wind velocity is large. In spite of the anti-correlation of the velocity and density, on the other hand, there is a slight increase in the occurrence frequency with increasing solar wind density. The results suggest that the local ion energization is not intensified but the area of upflowing ion conics is more widely spread when the solar wind density is large.

The positive correlation of the occurrence frequency and the solar wind velocity means that the area of ion conic event increases with the solar wind velocity. We see the expansion of the ion conic region in Fig. 5, which shows the location of the ion conics event in MLT-I.Lat coordinate when the so-

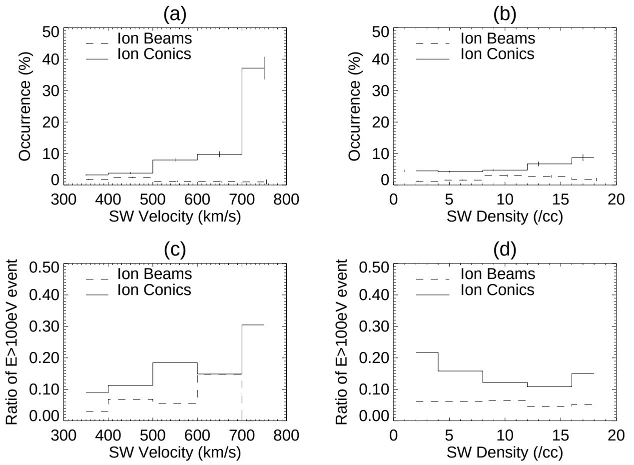


Fig. 4. Occurrence frequency of ion beams and conics as a function of **(a)** solar wind velocity and **(b)** solar wind density and ratio of the energetic (>100 eV) event to the total event number as a function of **(c)** solar wind velocity and **(d)** solar wind density. The occurrence frequency is integrated over the entire altitude (<10 000 km), invariant latitude (65°–85°), and MLT (9–15 h) ranges. The vertical bar in Figs. 4a and 4b is the statistical uncertainty.

lar wind velocity is large (Fig. 5a) and small (Fig. 5b), and that of the ion beam event when the solar wind velocity is large (Fig. 5c) and small (Fig. 5d). Many satellite orbits are discernible in Fig. 5a, which means that ion conics are observed continuously in a wide area along the satellite orbit. Ion conics during a period of small velocity (Fig. 5b) as well as ion beams (Figs. 5c and 5d) are observed in a short segment of the orbit. Although it takes time for the satellite to traverse the region, the orbital segments in the figure visualize the global extension of ion conics, which evokes an instantaneous image.

Knudsen et al. (1994) presented a polar cusp heating wall model which explains well the spatial variation of ion conics with the poleward $\boldsymbol{E} \times \boldsymbol{B}$ convection in the cusp/cleft region. The heating wall is extended not only along the field line but also longitudinally. The poleward convection spreads upflowing ions in an extended area.

Ion beams show no dependence on solar wind plasma parameters, except for a possible increase in the ratio of the energetic event in Fig. 4c. We investigate further where the possible increase comes from. Figure 6 shows the locations of energetic (>100 eV) ion conics (Figs. 6a and 6b) and beams (Figs. 6c and 6d) when the solar wind velocity is large (>500 km/s) and small (<400 km/s).

The source of energetic ion beams is still located in the evening side and there is no increase in energetic ion beams around the local noon, even when the solar wind velocity is large. Therefore, the possible increase in energetic ion beams with increasing solar wind velocity (Fig. 4c) should come from the evening side, presumably associated with the region-1 upward current system. On the other hand, energetic ion conics are increased with the solar wind velocity at all the local times including the local noon.

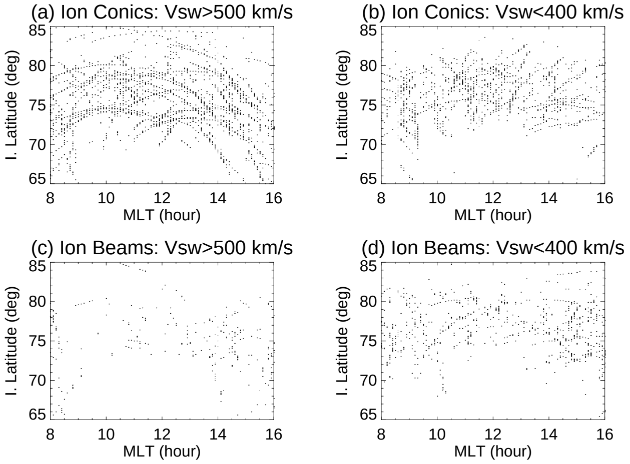


Fig. 5. Location of ion conics event in MLT-I.Lat coordinate when solar wind velocity is **(a)** large and **(b)** small, and that of the ion beam event when the solar wind velocity is **(c)** large and **(d)** small.

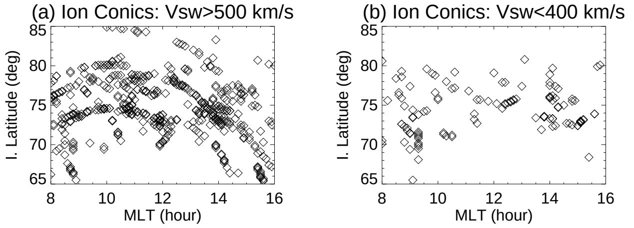
4 Discussion

It is revealed that the occurrence frequency of dayside ion conics are controlled by most of the interplanetary parameters; IMF B_y and B_z, solar wind velocity and density, while that of dayside ion beams shows little dependence on them. The difference in the occurrence frequency between ion beams and conics is basically interpreted in terms of the location of the upflowing ions generated in the polar convection pattern.

Ion conics are energized in a heating wall extended longitudinally, as well as along the field line. The heating wall is located in the midst of the poleward convection (Knudsen et al., 1994). The energized ions spread away from the heating wall to the downstream. The occurrence frequency represents the spatial area occupied by the upflowing ions. Therefore, the occurrence frequency of ion conics is quite dependent on the interplanetary parameters controlling the dayside convection.

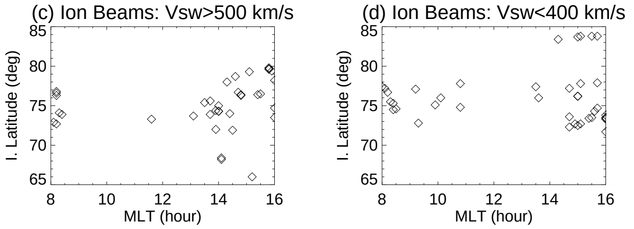
The occurrence frequency of ion conics is positively correlated with the solar wind density. It is also attributable to the convection enhancement. The dynamic pressure of the solar wind is believed to affect the momentum input to the polar ionosphere and is controlled by both the solar wind velocity and density.

Ion beams are associated with the upward field-aligned potential drop in the upward current regions and hence, with the negative divergence of the electric field. The field-aligned potential drop is developed at the center of the vortex of the convection (e.g. Lyons, 1992) and the ion beams are remain on the same flux tube, at least in the Exos-D altitude range (<10 000 km). The enhanced convection never spreads ion beams to the adjacent flux tubes.



(a) Ion Conics: Vsw>500 km/s

(b) Ion Conics: Vsw<400 km/s



(c) Ion Beams: Vsw>500 km/s

(d) Ion Beams: Vsw<400 km/s

Fig. 6. Locations of energetic (>100 eV) ion conics (upper panels) and beams (lower panels) in MLT-I.Lat coordinate when the solar wind velocity is large (left) and small (right).

The ratio of the energetic event indicates the intensity of the local energy of ion conics, and is dependent on IMF B_y, B_z, and solar wind velocity. Miyake et al. (2000) discussed the IMF control of ion conics and pointed out two possible causes. One is the increased energy input and the other is the residence time of ions in the energy region under the poleward convection. Since the enhanced convection moves ions faster and decreases the residence time of ions in the energy region, the result on the solar wind velocity means that the increase in the energy input for a large solar wind velocity is quite significant. The increase in the energy input surpasses the effect of enhanced convection, washing ions away from the energy region.

It is an interesting point that the occurrence frequency of ion conics slightly increases with the solar wind density, but the ratio of energetic event decreases. It might be interpreted in terms of the difference between the driving force of ion convection and the energy input to ion energization region.

Lennartsson (1995) found that the density of 0.1 to 16 keV O^+ ions in the plasma sheet is well correlated with both the electromagnetic and kinetic energy flux of the solar wind. The electromagnetic energy flux is $Esw^2/\mu_o V$, where $Esw = -|\boldsymbol{V} \times \boldsymbol{B}|$ and the kinetic energy flux is $nmV^3/2$. In either case, the energy flux increases with increasing solar wind velocity, coinciding with our results. The kinetic energy flux is also proportional to the solar wind density, but its V^3 dependence and the anti-correlation between the solar wind velocity and density are supposed to reverse the relationship with the solar wind density. Although the terrestrial sources of the plasma populations in the plasma sheet are still controversial and ion conics over the dayside cusp/cleft region are not necessarily the source of these O^+ ions, the similarity of the dependence on the solar wind plasma conditions should be noted.

Elliott et al. (2001) found that the density and parallel flux of low-energy O^+ ions in the polar cap are well correlated with the solar wind dynamic pressure and electric field, and concluded that the ions originate in the dayside cusp/cleft region. Despite the difference in energy, their results are almost equivalent to ours for ion conics, with the exception that no significant influence of IMF B_z was found for low-energy upwelling ions (see also Pollock et al., 1990). Multi-step processes of ion energized (e.g. Andre and Yau, 1997) may account for the difference.

Ion beams show no increase in the ratio of the energetic event around local noon with IMF and solar wind plasma parameters, though they seem to be affected around the evening side region-1 current. Iijima and Potemra (1982) showed that region-1 field-aligned current in the dayside region is well correlated with IMF B_y and the solar wind dynamic pressure. Liou et al. (1998) reported that the afternoon auroral energy deposition rate is larger during a large B_y period.

The field-aligned potential drop around the local noon is not very developed, even when the solar wind velocity is large and the energy input for producing ion conics is so increased. The field-aligned potential drop is required to supply the charge carriers to the field-aligned current. No increase in the potential drop means either no significant increase in the field-aligned current density or high field-aligned conductivity around local noon.

Although broad-band ELF waves are asserted to be responsible for the energy of dayside ion conics (Norqvist et al., 1998; Andre and Yau, 1997), the energy source of the waves themselves is not yet identified. If the local field-aligned current is responsible for the generation of the ELF waves, then the field-aligned conductance around local noon should be large enough to supply charge carriers to the field-aligned current without developing a large field-aligned potential drop. The current must be closed, so that an increase in the downward current, in which energetic ion conics are often observed (Carlson et al., 1998), implies the increase in the upward current in which ion beams are present.

An alternative energy source of ion conics was proposed from Viking observations (Lundin and Hultqvist, 1989; Lundin et al., 1990). Low-frequency electric field fluctuations propagating down along the field line from the magnetosphere are able to accelerate ions, even up to several tens of keV (Hultqvist, 1996). Matsuoka et al. (1993) reported that low-frequency electric field fluctuations are frequently observed around the cusp/cleft region and are interpreted as Alfvén waves propagating down from the magnetosphere. The relationship between the low-frequency electric field fluctuations and the interplanetary parameters, however, has not yet been studied and remains for future studies.

5 Conclusions

We examined the possible influence of the interplanetary conditions on ion beams and conics around the dayside cusp/cleft regions. The solar wind velocity and density, as well as IMF B_y and B_z, affect the occurrence frequency of ion conics. The energy of ion conics also depends on the solar wind velocity and the magnitude of IMF B_y and the polarity of IMF B_z. The dependence of the occurrence frequency of ion conics is interpreted in terms of both the energy input to the ion energy region and the convection spreading conic ions downstream.

The ion beams around local noon are not significantly controlled by the interplanetary conditions. The results reveal that more parameters and physical processes should be taken into account to understand the production of ion conics, than rather ion beams, which basically reflects the intensity of local field-aligned currents.

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