POLAR observations of properties of H^+ and O^+ conics in the cusp near ∼5300 km altitude

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Observations by the thermal ion dynamics experiment (TIDE) on POLAR are used to explore properties of low-energy ionospheric ion conical distributions at ∼5300 km altitude over the southern cusp under different interplanetary magnetic field (IMF) conditions with negative and positive B_z components. The properties are summarized as follows: (1) At the edge upstream of the convection in the cusp, the energy of outflowing ions abruptly increased from a few eV to ∼100 eV; (2) The angular distributions also abruptly changed from rammed $<\sim$5 eV polar wind distributions to ∼10-100 eV conics and the cone angles are wider for O^+ than for H^+; (3) The uppermost energy of the O^+ conics was larger than that of H^+, while the O^+ flux was lower than that of H^+; (4) The cone angles for both light and heavy ion conics were largest in the upstream region of the convection and gradually decreased in the convection direction as well as the conic energies; (5) The energization region could distribute over $>\sim 1^\circ$ in the latitudinal direction; (6) These conic signatures gradually gave way again to polar wind components further downstream of the cusp; (7) The UFI beams and conics were sometimes observed alternating, particularly for H^+, and (8) The distinct ion conic bursts often occurred multiple times, especially downstream of the cusp.

1. INTRODUCTION

The cusp/cleft region is thought the most important source of ionospheric ions transported into the polar magnetosphere and the lobe/mantle regions of the magnetotail [e.g., *Horwitz and Lockwood*, 1985; *Lockwood et al.*, 1985a, b]. Suprathermal ionospheric ions outflowing from the polar cap and the cusp/cleft regions were suggested as an important contributor to the plasma sheet content [*Chappell*, 1987, and references therein].

In the dayside auroral region, ion conics are a typical form of the upward flowing ions (UFI). The energization process acting on the thermal ionospheric ions to produce the suprathermal outflows was considered by *Moore et al.* [1985] based on Dynamics Explorer measurements, who concluded that the low-altitude transverse ion acceleration (TIA) is important for the ionospheric ion supply to the magnetosphere. *André et al.* [1990] used simulations and DE 1 observations to suggest that the heating region could be narrow in the latitudinal direction but extended in altitude. *Whalen et al.* [1991] also showed abrupt enhancement of the perpendicular heating in the cusp/cleft at 5000-7000 km altitudes. *Miyake et al.* [1993] proposed that the conics are continuously energized over a wide altitudinal range during the upward transport from the topside ionosphere.

Knudsen et al. [1994] recently reported Akebono observations of the H^+ and O^+ conics in the low-altitude cusp. They observed that the cone angles of O^+ are always larger than those of H^+. They concluded that a latitudinally narrow but altitudinally wide ("wall" like) region upstream of the cusp is the location of the predominant process energizing the ionospheric ions perpendicular to the magnetic field. They also proposed that the velocity filter effect due to the $\mathbf{E}\times\mathbf{B}$ drift after the heating could produce the overall cone angle variations in the convection direction and the mass dependence of the cone angles at a given position/time.

More recently, the suborbital mission, sounding of cleft ion fountain energization region (SCIFER [*Kintner et al.*, 1996]), provided fine-scale observations of the ionospheric ion heating. *Arnoldy et al.* [1996] reported that several narrow heating regions were repeatedly observed at altitudes of $\sim$1000-1500 km near 10 MLT. The ionospheric ions were significantly accelerated to energies of 500 eV in the perpendicular direction.

Woch and Lundin [1992] presented typical energy dispersions of the solar wind proton component penetrating into the low-altitude cusp to investigate interplanetary magnetic field (IMF) effects on the solar wind injection into the ionospheric cusp under different IMF conditions. It was evident that the solar wind injection had a significant influence on the TIAs, which suggests the importance of the relative location of the upflowing ion signatures to the solar wind injection events.

The thermal ion dynamics experiment (TIDE) onboard the POLAR satellite is able to measure fully three-dimensional velocity distribution functions of thermal and suprathermal ion composition typical in the ionosphere and the magnetosphere with high time and angular resolutions. The fine energy resolution and wide energy range sampled by TIDE enable us to investigate precise distributions not only of the upflowing ionospheric ions but also of the solar wind component. We devote this paper to presenting recent observational results concerning energization processes and transport of the ionospheric ions observed in and near the cusp by TIDE onboard POLAR.

2. DATA SOURCES

We present the TIDE data obtained in the southern hemisphere near perigee ($\sim$5300 km). TIDE has seven identical sensors, each of which consists of two portions: an energy analyzer using an electrostatic mirror and a retarding potential analyzer, and a mass spectrometer using a time-of-flight technique [*Moore et al.*, 1995]. The combination of the wide field of view (157.5°) and the satellite spin motion realizes the measurement of fully three-dimensional velocity distributions of major ion species (H^+, He^{2+}, He^+, O^+, and some molecular ions) with high angular resolution (11.25°×22.5°). The energy range of the data shown here is 0.1-300 eV/q divided into 16 steps on a logarithmic scale. The time resolution is 6 s, the same as the spin period.

The key parameter data obtained by the magnetic field instrument (MFI [*Lepping et al.*, 1995]) and the solar wind experiment (SWE [*Ogilvie et al.*, 1995]) onboard the Wind satellite are briefly described to indicate the IMF conditions before and during the POLAR cusp observations.

3. OBSERVATIONS

We present two observations of the upflowing ions in cusp under different IMF conditions in Plate 1. The first observation was for southward IMF conditions, and the second for northward IMF conditions, according to observations by the Wind satellite. At southern perigee, POLAR always crossed the cusp from higher to lower latitudes during April 1996.

3.1. Event 1: Southward IMF

POLAR crossed the low-altitude cusp during 0429-0432 UT on April 12, 1996. If the approximately 20-minute time lag of the solar wind arrival between the Earth and Wind is taken into account, the z component of IMF was southward (~ -2.5 nT) on the average, although the x and y components were also significant ($+6$ and -5 nT, respectively).

Plate 1a shows PES (polar angle in abscissa, energy in ordinate, spin angle in color code) chromograms of H^+ and O^+. The abscissa of the overall plots is universal time (UT in hours and minutes), and the ordinate is energy (in electron volts: eV) on a logarithmic scale. Each bin separated by short tick marks shows a polar angle-energy spectrogram for a spin. The spin angles in which the largest ion fluxes were detected are indicated by a color code wheel, as shown at the middle top. The fluxes are expressed by brightness in the left-side portion of the color code wheel.

An intense solar wind proton injection was seen in the high-energy range ($>$50 eV/q), and the energy dispersion is consistent with the antisunward convection in the cusp under southward IMF condition [e.g., *Woch and Lundin*, 1992]. Namely, the proton energy was highest in the upstream region of the cusp because of a velocity filter effect due to $\mathbf{E}\times\mathbf{B}$ drift. The fluxes colored by white suggest no dependence on the polar angle, which means that the solar wind component was isotropic. A vertical purple line embedded in each bin indicates the loss cone position in the upward direction. Sudden decreases of fluxes seen at the middle-energy range of the energy dispersion were due to the instrumental sensitivity variations. Unfortunately, the TIDE data for a spin of 0431:41-0431:47 UT were not available, as displayed by gray areas.

At energy ranges lower than those of the solar wind component, H^+ and O^+ fluxes are seen. There are several important characteristics seen in these spectrograms: The energies of the O^+ conics were higher than those of the H^+ conics, and the energy variations for both ions were largest toward the injection region for the solar wind component, especially before 0431 UT. In the upstream portion of the cusp (that is, near the equatorward edge during 0431-0432 UT), the O^+ energy was particularly steady for about 30 s within the energy range 5-100 eV/q. On the other hand, the energies of the H^+ conics varied more rapidly, although this is somewhat indefinite since the H^+ fluxes partially overlapped the solar wind components at higher energies. Also, in the downstream portion of the cusp before 0431 UT, the energy variation of the O^+ conics was generally gradual as compared with that of H^+. Throughout the cusp observation, the flux of the H^+ conics was equal to or frequently larger than that of O^+. The important properties of the outflowing ions are schematically shown in Figure 1.

Plate 1b shows two PSE (polar angle in abscissa, spin angle in ordinate, energy in color code) chromograms of H^+ and O^+, displaying the angular distributions of the largest fluxes of ions among all energy steps. The energy can be roughly estimated from the color code wheel shown at the top of Plate 1; the lowest energy ($<$0.3 eV/q) is indicated by red, the highest ($>$100 eV/q) by blue, and the intermediate ($\sim$10 eV/q) by green. During the interval when the energy of the O^+ conics did not change significantly, there were no significant variations in the pitch angle distributions either (see the interval marked by red underlines at 0431:20 UT). This may imply that the satellite crossed above a latitudinally-wide O^+ heating region. Because the satellite velocity perpendicular to the magnetic field direction was $\sim$7.4 km/s, the roughly-estimated width of the O^+ heating region would be at least 133 km.

In the mantle downstream of the cusp during 0430-0430:30 UT, the O^+ energy was still enhanced, in contrast to that of H^+. It is likely that the O^+ conics observed in the mantle were not locally energized but were transported from the cusp proton injection site. On the other hand, the H^+ energy rapidly decreased with increasing latitude. Because the H^+ velocity was higher than that of O^+, the H^+ conics might escape to high altitudes along close-by field lines before being convected very far poleward from the energization region.

As seen in Plate 1a, poleward in the cusp, TIDE observed a large amount of the H^+ and O^+ polar wind, although they might contain some low-energy residual of the conics at higher latitudes due to the convection effect [*Gurgiolo and Burch*, 1982] or some small heating processes was still active in the polar cap near the cusp. The pitch angle distributions evolved from the complete conic signatures through asymmetric distributions enhanced in the satellite-ram direction as reported by *Giles et al.* [1994] to the polar wind components. The pitch angle evolution from the polar wind to the conics was more abrupt at the equatorward edge of the cusp than in the poleward region, as observed by other satellites and rockets [e.g., *André et al.*, 1990; *Knudsen et al.*, 1994; *Arnoldy et al.*, 1996].

In Plate 1c, we present velocity distributions of upflowing ions in the plane containing the local magnetic field direction during three intervals (from the top, mantle, pure cusp, and at lower latitudes than the cusp), as indicated by red underlines or arrows in Plates 1a-b. As seen in the middle plot of Plate 1c, the cone angle of O^+ conics was larger than that of H^+. Figure 2 shows an example of the pitch angle distributions of H^+ and O^+ during this interval. The O^+ distribution had a peak at $\sim$55°, whereas the peak for H^+ was at $\sim$40°. The wider cone angle for O^+ is also evident from Plate 1b. That is, the circular distributions in the PSE chromograms and the holes at the centers of the distributions were larger for O^+

than for H^+.

3.2. Event 2: Northward IMF

During the event 2 on April 15, 1996, the IMF was strongly northward ($B_z \sim +6$ nT). The energy dispersion of the solar wind protons observed in the energy range more than 50 eV/q was consistent with an equatorward convection for such northward IMF conditions, as seen in Plate 1d. The characteristic energy of the dispersion decreased gradually and monotonically with decreasing latitudes during 0234:30-0236:30 UT.

The characteristic O^+ energy was nearly constant during the interval 0234:40-0236:10 UT, and the pitch angle distributions of O^+ changed from nearly transverse features to the upflowing conic features at $\sim$0235 UT. The energy variation of the H^+ conics was more abrupt than that of O^+. It is also noted that the characteristic O^+ energy was slightly higher that that of H^+ during 0235-0236 UT. These results imply that the energization rates and/or the influence of the transport at and below the satellite altitude are different between H^+ and O^+. For example, it is likely that the O^+ ions could be energized more efficiently since the frequencies of plasma waves accelerating the ionospheric ions transversely would be closer to the gyro frequency of O^+ than for H^+. Inferring from the gradual energy variation of O^+, the energization region of O^+ may be wider in altitude and latitude than that of H^+.

At 0235:34 UT, the pitch angle distributions of the H^+ conics abruptly changed from conical to field-aligned, and after several seconds the distribution showed wide ($\sim 60^\circ$) cone angle again, as displayed in Plate 1e (see the PSE chromograms indicated by three red arrows). Plate 1f shows the velocity distributions during the three satellite spins. As seen in the middle subpanel of H^+, the H^+ distribution consists of an almost field-aligned component. The characteristic energy was several eV/q, and there was no large difference between the energies for the conics and the beams. After one satellite spin (6 s) the field-aligned component evolved back to the conical form. *Liu et al.* [1994] reported that the alternating occurrence of low-energy H^+ beam and conic features on the nightside was related to upward field-aligned current density. Also in the cusp, the field-aligned current may have a significant influence on the pitch angle distribution of the upflowing H^+ ions. On the other hand, the pitch angle variation of the O^+ conics was not as clear as that in H^+, as seen in the successive O^+ plots.

Also observed in this event were the repeated TIAs at $\sim$0236:40 and $\sim$0237:15 UT, as shown schematically in Figure 1. The SCIFER results also showed that there were multiple heating walls in the cleft region [*Arnoldy et al.*, 1996]. These results imply that the structure of the heating sources and spatial distributions is more complicated than perhaps previously indicated [*Knudsen et al.*, 1994; *Watanabe et al.*, 1995].

4. DISCUSSION

The TIDE observations presented here suggest that the energization of the ionospheric ions occurs presumably along the field lines where highest-energy solar protons are injected. Moreover, the heating regions were observed to be quite structured. It is also noteworthy that the cone angles of the O^+ conics were wider than those of H^+ for most of the intervals. *Knudsen et al.* [1994] proposed a heating wall model to explain the pitch angle distributions and variations. On the other hand, the latitudinal energy variations imply that the heating rates for H^+ and O^+ ions could be different and dependent on altitude, which may be associated with the differences of the energies, pitch angle distributions, and their latitudinal variations. We consider that the heating region of the ionospheric ions may be distributed more widely in the altitudinal direction in the upstream region of the cusp than in the downstream region. It is also possible that the gravitational effect would be more significant for the heavy ion (O^+) conics.

With respect to the fluxes of UFI conics, the TIDE data showed tendencies that are not inconsistent with the data from DE 1 and Akebono. On the other hand, the energy of O^+ is larger than that of H^+ in the TIDE observations. In Freja results from lower altitudes ($<$2000 km), the peak energy of O^+ was comparable to or slightly smaller than that of H^+, while the flux of O^+ was larger than that of H^+ [e.g., *Norqvist et al.*, 1996].

The differences of the energies and fluxes between the TIDE data and these Freja results may imply that the O^+ ions could be continuously accelerated further at higher altitudes than for H^+. This scenario would lead to wider cone angles for the O^+ conics than for H^+. It is also possible that a cool component of H^+ ions at altitudes higher than the O^+-dominated region would continuously contribute to the H^+ conic population and that the heating rate for H^+ would be smaller than for O^+. This would explain the higher H^+ flux than that of O^+ above 5000 km. Some observations by Akebono and DE 1 also implied that the H^+ fluxes were higher than those for O^+ [*Peterson et al.*, 1993; *Watanabe et al.*, 1995].

Solar activity and/or seasonal variations may also be involved in the explaining the differences in these results, as discussed by *Yau et al.* [1984] and *Moore et al.* [1996]. The indices of sunspot number and $F10.7$ show that the solar activity decreased during the periods of the Freja observations in February and March 1994 and the POLAR observations.

In the mantle downstream of the direct cusp proton injection, the low-velocity O^+ ions could be transported from the active heating region upstream in the cusp, and so, the energy decrease for the O^+ fluxes would be more gradual than for H^+, because of the velocity filter effect. Within the upstream direct injection site, both ion species would be energized over $>\sim 1^\circ$ of latitude because the energies and the pitch angle distributions of H^+ and O^+ showed no noticeable variations for several spins, as described in the observation section.

The heating regions were localized to the cusp region, but the latitudinal width estimated in our observations could be larger than those proposed by *Knudsen et al.* [1994] and *Watanabe et al.* [1995].

5. SUMMARY

The upflowing ionospheric ion signatures consisting of H^+ and O^+ observed by TIDE in the cusp at $\sim$5300 km show several common features for the different convection patterns: sunward convection under northward IMF conditions and antisunward under southward IMF. UFI conics under sunward convection conditions have been frequently reported on the basis of observations from DE 1, Viking, and Akebono [e.g., *André et al.*, 1988; *Watanabe et al.*, 1995]. While the two cases shown here were obtained under different IMF conditions, the variations of the conic signatures were both consistent with the directions of the actual plasma convection.

The general properties seen in the POLAR observations are as follows. Enhancements of the energies and cone angles of the conics were abruptly observed at the edge most upstream of the convection in the cusp where the highest-energy magnetosheath protons were precipitating into the ionosphere, and the conic energies were the highest there. In other words, the polar wind component was abruptly energized and transformed into the conics at the upstream edge of the cusp, and the widest cone angle distributions were observed. The cone angles of the O^+ conics were wider than those of H^+ for most of these intervals. Also, the cone angles for these conics gradually decreased in the convection direction. The energies of the conics decreased as well as the energy of the high-energy proton precipitation of magnetosheath origin. The latitudinal decrease of the O^+ characteristic energy was more gradual than that for H^+. The low-energy conic distributions in the downstream region gradually returned to the polar wind characteristics. The energy enhancements of the conics were observed repetitively during a cusp crossing. These results are consistent with those previously reported by, for instance, *Knudsen et al.* [1994], *Watanabe et al.* [1995], and *Arnoldy et al.* [1996].

Finally, we summarize our new results from the POLAR observations.

1. The O^+ conics were more energetic than the H^+ conics, while the flux of O^+ was lower than those of H^+.

2. The energies of the conics remained high for $>$130 km latitudinal distance.

3. The cone angles, particularly for the H^+ conics, sometimes suddenly decreased as the distribution became nearly field-aligned at the cusp injection site, and then soon recovered to conics downstream within 0.2° of latitude. This corresponding folding of the O^+ conics was more gradual than that of H^+.

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Figure 1. Schematic pictures summarizing the general properties of H^+ and O^+ seen in Events 1 and 2.

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Figure 2. The phase space densities of (a) H^+ and (b) O^+ from multiple channels and spin sectors of TIDE versus the corresponding pitch angles calculated in the plasma convection frame moving perpendicular to the magnetic field.

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Plate 1. From the top, PES and PSE chromograms and velocity distribution functions for low-energy H^+ and O^+ ions observed by TIDE in the southern low-altitude cusp are shown for the interval of April 12 (a-c) and April 15 (d-f) in 1996. PES chromograms (a and d) are energy-time (E-t) diagrams consisting of energy-polar angle bins, and PSE chromograms (b and e) show variations of the angular distributions. The scales of the ion energies and fluxes are logarithmic, as indicated by ordinates, or color code and the brightness level at the middle top. In the two types of chromograms, universal time (UT, in hours and minutes), geocentric altitude (km, in kilometers), magnetic local time (MLT, in hours), and invariant latitude (ILAT, in degrees) of POLAR are shown. The red horizontal lines or vertical arrows along the abscissas indicate the intervals of the velocity distribution functions (c and f) displayed below the chromograms. In each of the distribution contour plots, the rightward and upward directions in each subpanel correspond to field-aligned upward direction and perpendicular direction closest to the satellite ram motion, respectively. The origins of the Earth and satellite frames are shown by white and thin black crosses and tick marks, respectively, while the bulk center of the low-energy upflowing ions from moment result is located at the thick cross and tick mark. We assume that the satellite potential was 1.5 volts throughout.

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