Cold Plasma Source of Upflowing Ionospheric Ions in the Nightside Auroral Ionosphere

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The frequent occurrence of energetic O^+ upflowing ionospheric ions (UFI) at high altitude during auroral substorms raises the question of the cold plasma source and acceleration altitude for the O^+ ions, and their possible effects on the substorm-time plasma sheet. Ion composition observations on Akebono in the nightside auroral ionosphere reveal the significant presence of thermal-energy (a few eV) O^+ ions in the 6000–10,000 km altitude region both during and between auroral substorms. Their upward flux normalized to 2000 km altitude is about $2 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1}$. They are believed to be a significant source of cold plasma for the energetic UFI. During auroral substorms, Akebono occasionally observes molecular (N_2^+ and NO^+) upflowing ions up to ~ 60 eV, in or near regions of auroral electron precipitation up to 10,000 km altitude. This suggests the occurrence of a fast ion acceleration process in the F -region or topside ionosphere, where freshly created molecular N_2^+ and NO^+ ions are accelerated to several eV or greater within their dissociative recombination lifetime ($\sim$ a few minutes). Ground photometric observations and simultaneous particle measurements on sounding rockets confirm the presence of transversely accelerated ions (TAI) up to ~ 200 eV in the topside ionosphere (near 600 km altitude) within tens of seconds of substorm expansion onset. Such hundred-eV TAI are frequently observed on Akebono in latitudinally confined regions of the nightside auroral ionosphere down to ~ 2000 km altitude. They can reach the so-called “parallel acceleration region” at ~ 1 – $2 R_E$ altitude within a few minutes, where they are often accelerated further to keV energy and can typically reach the plasma sheet during a substorm. Their flux is an order of magnitude smaller than the thermal ion flux. They are believed to be a minor source of plasma for the energetic UFI. In contrast, the lower-energy (≤ 10 -eV) O^+ TAI are typically too slow to reach the parallel acceleration region during the substorm, as they are decelerated by gravitation or trapped by it and traverse repeatedly along the magnetic field line. Hence they constitute a possible source of quiet-time thermal ions in the parallel acceleration region. Another possible source of thermal ions in the region is the polar wind O^+ ions convected anti-sunward along the auroral oval from the dawn and dusk sectors. The thermal O^+ ions in the parallel acceleration region at ~ 1 – $2 R_E$ altitude of the nightside auroral ionosphere are believed to be the dominant source of cold plasma for energetic UFI at high altitude; they can reach the plasma sheet during a substorm, thereby modifying its composition significantly.

1. Introduction

The ion composition measurements of Shelley *et al.* (1972) were the first indication that ions of terrestrial origin might constitute a substantial component of the energetic ion population in the active-time magnetosphere. These measurements showed that precipitating O^+ flux in the 1–10 keV range sometimes exceeded the accompanying H^+ flux during magnetic storms. Since then, a number of studies have demonstrated the substantial and variable presence of O^+ fluxes in the active-time plasma sheet (Lennartsson and Sharp, 1982) and tail lobes (Sharp *et al.*, 1981).

The first direct observation of energetic (keV) auroral upflowing ionospheric ions (UFI) was provided by Shelley *et al.* (1976). On S3-3 below 8000 km altitude, Ghielmetti *et al.* (1978) found that energetic UFI occur in a zone closely associated with the statistical auroral oval, and that their occurrence frequency increases with altitude. Gorney *et al.* (1981) found that upflowing ion beams occur primarily above 5000 km. This suggests that parallel ion acceleration occurs predominantly in the so-called "parallel acceleration" region between ~ 1 and $2 R_E$ altitude.

On DE-1, Yau *et al.* (1985) reported the frequent occurrence of 100-eV O^+ UFI in the night-side auroral ionosphere. Yau *et al.* (1985) found that the heavy-to-light ion flux ratio (O^+/H^+) in UFI increases with the level of solar and magnetic activity. During magnetically active times near solar maximum, the O^+ UFI flux normalized to 2000 km altitude was about $3 \times 10^8 \text{ cm}^{-2}\text{s}^{-1}$. Collin *et al.* (1987) found that the O^+/H^+ energy ratio also changes with solar activity.

In the nightside auroral ionosphere, the frequent occurrence of O^+ -dominated energetic UFI (Yau *et al.*, 1985) at high altitudes (>8000 km) raises the question of the cold plasma source for the O^+ UFI. On S3-3, Sharp *et al.* (1977) interpreted the observed ion conics as ions which were transversely accelerated at lower altitudes (~ 5000 km) and then spiralled upward along the magnetic field as a consequence of adiabatic invariance. Assuming that the thermal-energy O^+ ions originated at the altitude of transverse acceleration, this interpretation would require an ambient O^+ density in the ~ 5000 -km altitude region that is orders of magnitude larger than expected values based on typical topside ionospheric scale height considerations. Ion conics and TAI up to hundreds of eV were previously observed at lower altitudes: down to 2000 km on S3-3 (Gorney *et al.*, 1981), at 1400 km on Isis-1 and -2 (Klumpar, 1979), and between 500 and 1000 km on sounding rockets (Whalen *et al.*, 1978; Yau *et al.*, 1983). However, mass composition information was not available from these measurements. Thus, the source of cold O^+ plasma for the energetic UFI at high altitude remains an open question.

Abe *et al.* (1993) recently studied the characteristics of the thermal plasma in the polar ionosphere between 2000 and 10000 km altitude, using the thermal ion composition measurements from the Akebono suprathermal mass spectrometer (SMS). Their study was concentrated in the latitude region above 80° , and represented the first comprehensive statistical study of the polar wind above 4000 km altitude. Abe *et al.* (1993) found that in the high-altitude polar cap poleward of the auroral oval, low energy (a few eV) upflowing ions were regularly observed and were typically characteristic of the polar wind, in that they were field-aligned, and had temperature below 1 eV, and parallel ion velocities which varied inversely with the ion mass. In the present study, we concentrate our analysis of the Akebono SMS data on the thermal ion flow in the parallel acceleration altitude region in the nightside auroral ionosphere.

Detailed description of the SMS instrument and its operations was presented elsewhere (Whalen *et al.*, 1990). In this study, we present data acquired by SMS in its fast and mass scan modes. In its fast scan mode, SMS was programmed to sample thermal and suprathermal ions every other spin (8 s). In the thermal measurements, its retarding potential analyzer (RPA) rapidly stepped through 8 voltage steps in the -0.1 to 16.3 V range relative to the spacecraft ground every 64 ms, and it sampled 4 mass steps every 256 ms, typically H^+ , He^+ , O^{++} and O^+ . In the suprathermal ion measurements, typically 4 or 8 energy-per-charge steps in the range of 0.1 – 4 keV are sampled. In the mass scan mode, a 64-point ion mass per charge spectrum in the 0.9 – 64 AMU/q range was obtained every 1 s at a fixed RPA or suprathermal ion energy per charge setting, resulting in an 8-point angular spectrum for each of the 64 sampled mass steps per spin.

2. Observations

Data from SMS in the period of February to September 1990 and that of March to November 1991 were used in the present analysis. Data in the thermal fast scan mode were used to determine

Fig. 1. Averaged H^+ (crosses) and O^+ (diamonds) thermal ion flux, observed at 6000–9000 km on Akebono in the midnight sector (21–03 MLT) sector and normalized to 2000 km altitude under southward IMF conditions ($B_z \leq -0.5$ nT) as a function of invariant latitude.

the spin-plane component of the parallel ion velocity $v_{\parallel}$ and the ion density n_i , following the procedure presented in Watanabe *et al.* (1992) and Abe *et al.* (1993). Since the local magnetic field is nearly parallel to the spacecraft spin plane, $v_{\parallel}$ is a good estimate of the parallel ion velocity. The ion density, n_i , was not been corrected for perpendicular (convection) drift and the spacecraft potential, and is believed to be lower limit estimates.

Figure 1 shows the averaged upward ion flux of thermal H^+ and O^+ ions at 6000–9000 km altitude in the midnight sector (21–03 MLT), at times of southward interplanetary magnetic field (IMF) as a function of invariant latitude. The flux was derived as the product of the averaged upward ion velocity and ion density, and was normalized to a reference altitude of 2000 km (by the ratio of magnetic field at the reference and measurement altitudes, respectively) in order to facilitate comparison with flux measurements at other altitudes. For both H^+ and O^+ , the largest flux was about 10^8 $\text{cm}^{-2}\text{s}^{-1}$, and was observed near 66° , the lowest invariant latitude at which data were available. The flux is believed to be a lower estimate since the ion density was likely to be an underestimate. In comparison, the observed fluxes in the other magnetic local time sectors (not shown) were peaked at higher invariant latitudes (typically above 75°). In selected orbit passes, the angular distribution of the observed ion flux was fitted to that of a drifting Maxwellian to obtain an estimate for the ion temperature. For both ion species, the ion temperature in all local time sectors was found to be typically 0.2–0.3 eV. Thus, the observed H^+ and O^+ ions in Fig. 1 are believed to be the cold (thermal-energy) plasma population in the parallel acceleration region of the nightside auroral ionosphere.

Figure 2 shows the variations of the upward ion flux with the magnetic Kp index. As in the previous figure, the flux was normalized to 2000 km altitude. The fluxes in the dusk, midnight, and dawn sectors are shown in dotted, solid, and dashed curves, respectively. For both ion species, the data were averaged over the 6000–9000 km altitude and 60° – 75° invariant latitude

Fig. 2. Averaged H^+ (crosses) and O^+ (diamonds) thermal ion flux, observed at 6000–9000 km and 60° – 75° invariant on Akebono in the midnight (21–03 MLT; solid curves), dawn (03–09 MLT; dashed curves), and dusk (15–21 MLT; dotted curves) sectors, and normalized to 2000 km altitude, as a function of Kp index.

region. The O^+ flux generally increases by a factor of 3–5 as Kp increases from 2 to 6 in both the dawn and dusk sectors, but does not appear to vary much with Kp in the midnight sector. In comparison, the H^+ flux exhibits a more modest increase with Kp at quiet and moderately active times (Kp below 4), and decreases with increasing Kp at active times (Kp above 4) in all three MLT sectors. Overall, the O^+ flux is comparable to the H^+ flux at active times, but is generally smaller than the H^+ flux at quiet times. To the extent that the Kp index represents an approximate measure of auroral activity (substorm) level, Fig. 2 suggests a moderate (factor of 2–3) increase in the cold plasma O^+/H^+ ratio in the auroral acceleration region during auroral substorms.

During periods of sustained auroral activities, the SMS occasionally observed significant fluxes of molecular upflowing ions in the auroral ionosphere (Yau *et al.*, 1993). Figure 3 shows an ion mass spectrum observed in a molecular upflowing ion event on January 22, 1990 in an apogee pass (8700–9500 km altitude). The Kp index was 3^+ at this time, and had been above this level for most of the preceding 24 hours. Akebono was traversing the northern auroral zone near local midnight (23.1–23.7 MLT). Intense precipitating electron fluxes in the 1–10 keV range were observed between 73° and 74° invariant, and between 69° and 70° invariant. Molecular ions, composed predominantly of N_2^+ , were encountered immediately equatorward of the two regions of energetic electron precipitation.

Figure 3 shows the measured ion mass spectrum at 2134:33 UT, when molecular ions were encountered. It shows the ion count rate in the upward field line direction. The mass peaks at 1, 4, 8, 16, and 28 amu/ q indicate the presence of H^+ , He^+ , O^{++} , O^+ , and N_2^+ , respectively. The spectral width of the N_2^+ peak was ~ 0.12 (FWHM) and was significantly broader than that of the He^+ and O^+ peaks (FWHM ~ 0.07), reflecting the presence of a smaller but nevertheless non-negligible component of the NO^+ ions in addition to N_2^+ ions. The difference between the

Jan 22, 1990 EXOS-D

Fig. 3. Count rate of measured ions in the upward field line direction as a function of ion mass per charge, in molecular upflowing ion event on January 22, 1990 at 2134:33 UT. (a) 0–60 eV ions; (b) 5–60 eV ions. The H^+ , He^+ , and O^+ rates in (a) and (b) are essentially identical, indicating these ions were predominantly below 5 eV in the spacecraft frame. The N_2^+ rate in (a) is about twice that in (b), indicating that the observed N_2^+ ions were predominantly above 5 eV.

upper and lower panels in Fig. 3 provides an estimate of ions above 5 eV in the spacecraft frame. This is because the lower panel includes only data from detector counter “2” which is sensitive to all ions below 60 eV, whereas the upper panel includes in addition data from detector counter “1” which is insensitive to ions below 5 eV. The fact that the H^+ , He^+ , and O^+ count rates in the two panels are essentially identical indicates that these ions were predominantly below 5 eV in the spacecraft frame. The fact that the N_2^+ count rate in the upper panel is about twice that in the lower panel indicates that a substantial fraction of the observed N_2^+ ions were in the 5–60 eV range.

The presence of significant molecular ion flux at high altitude (above 8000 km in this case) is indicative of their energization in the F -region or topside ionosphere. At auroral latitudes, molecular ions are created by electron impact ionization. In order to escape from the ionosphere in detectable quantities, they must acquire their escape energy in a time short compared with the local dissociative recombination lifetime, which is of the order of 5 minutes in the F -region and topside ionosphere (Yau *et al.*, 1993). It is important to note that the potential energy of a

molecular N_2^+ or NO^+ ion (28 or 30 AMU/q) at 1 R_E altitude is about 10 eV. Therefore, the observed molecular ions in Fig. 3 must have been energized to above 15 eV within a few minutes. In other words, the observation points to a fast ion energization process in the F -region or the topside ionosphere during active aurora. This is consistent with the evidence of fast ionospheric ion feeding to the inner magnetotail (Daglis and Axford, 1995).

In the nightside auroral ionosphere down to 2000 km, Akebono frequently encounters regions of transverse ion acceleration, in which the observed ions are accelerated at 90° pitch angles to ~ 100 –200 eV (Whalen *et al.*, 1991). The region of acceleration is latitudinally confined, and is often less than 100 km. Transversely accelerated ions (TAI) have previously been observed below 1000 km altitude during auroral substorms (Whalen *et al.*, 1978; Yau *et al.*, 1983). Figure 4 shows the morphology of a large, multiple, pre-midnight auroral substorm at Churchill, Canada, on February 15, 1985, in which hundred-eV TAI were observed near 600 km altitude. The substorm consisted of a series of three distinct brightening and poleward expansion phases over a period of about 40 minutes. The three lower panels show the ground magnetograms. The three activation phases (expansion and brightening) of the substorm are clearly visible in the negative excursions of the X -magnetogram near 0510, 0521, and 0537 UT. The upper panel shows the integrated optical auroral emission intensity at $5577\text{\AA}$ along the line of sight from a meridian scanning photometer. The intensity is shown as a function of time and elevation angle: 0° corresponds to the northeast horizon (52° azimuth), 180° the southwest horizon, and 90° the zenith at Churchill.

The auroral form was visible on the southern horizon before the onset of the substorm, and started to brighten in the east at 0507:30, reaching a peak intensity of 50–75 kR. It expanded poleward shortly thereafter (at 0509:30), reaching the zenith at 0510:15, receding rapidly equatorward, forming a NW-SE oriented multiple arc system to the south. The X -magnetogram displayed a 150 nT negative bay during this poleward expansion. Then, at 0519:00, the multiple arc system began to brighten, and expanded poleward at 0520:40. The X -magnetogram showed a 200-nT negative bay during this poleward expansion. The auroral form continued its poleward motion at 0529:00, and started to break up at 0530:30. In the ensuing 5 minutes, its intensity dropped to below 10 kR. Then, at 0536:50, the third poleward expansion and brightening occurred, reaching a peak intensity in excess of 200 kR. At this time, the X -magnetogram showed a -200 nT excursion, and the Z -magnetogram showed a 500 nT negative bay.

Figure 5 shows the measured ion and electron data from the MARIE sounding rocket, from 0535 to 0542 UT during the last of the three expansion phases and immediately preceding it. In and near the region of auroral electron precipitation during the substorm, transversely accelerated ions (TAI) up to 300 eV were observed in the 500–600 km altitude region during the expansion phases. The instrument complement on the MARIE rocket and the detailed characteristics of the observed TAI were presented earlier (Kintner *et al.*, 1986). Panel (a) and (b) show the precipitating ion flux at 47–366 eV in the 0° – 90° pitch angle range and the corresponding flux in the upgoing hemisphere (90° – 120° pitch angles), respectively. Panel (c) and (d) show the more energetic components (0.89–22.9 keV) of the ion fluxes. Panel (e) shows the precipitating auroral electron flux. The measured data were obtained from electrostatic analyzer ion and electron spectrometers which stepped through 16 energy steps and sampled a range of pitch angles as the rocket payload spinned and precessed. From the measured data, the pitch angle and energy distributions for both the ions and the electrons were subsequently reconstructed, and used to derive the integrated fluxes shown in the figure.

Auroral images from an image-intensified all-sky television camera at Churchill showed the onset of the poleward expansion at 0536:50. The aurora propagated eastward into the scanning photometer's field of view by 0537:00; cf. Fig. 4. Intense hundred-eV H^+ TAI were first observed near 0537:14, within seconds of the onset of the expansion. In the ensuing 30 seconds, the observed data were characterized by a distinct absence of energetic precipitating electrons (in

Fig. 4. Top panel: Integrated auroral intensity at 5577 Å observed by ground meridian scanning photometer at Churchill, Canada, on February 15, 1985, during an auroral substorm with multiple expansions in which hundred-eV transversely accelerated ions (TAI) were observed near 600 km altitude. A scan angle of 0°, 90°, and 180° corresponds to the NE (52° azimuth) horizon, the zenith, and the SW (272° azimuth) horizon, respectively. Bottom panels: X, Y, and Z-components of the ground magnetogram.

panel e). Also, the hundred-eV ion flux (panel b) was more than two orders of magnitude larger than the corresponding precipitating flux (panel a). This indicates that the observed ions originated from the ionosphere, and were not a mirroring population. During this time, the rocket payload traversed a horizontal distance of 16 km in a nearly perpendicular direction to the auroral form. The electron data therefore indicate that the observed TAI were as much as 10–15 km beyond the region of electron precipitation. Extremely intense ion fluxes were encountered from 0538:07 to 0538:12, when the ion spectrometers were saturated whenever they were stepping through the lowest energy steps (below 500 eV) and sampling the 90°–120° pitch angles. The saturation resulted in spurious counts (in panels c and d) in the higher energy measurements in the subsequent spectrometer stepping cycle. The intense TAI persisted until 0540:20, and their

Fig. 5. Observed ion and electron fluxes from the MARIE rocket on February 15, 1985, during an auroral substorm with multiple expansions near midnight (~ 0 MLT). (a) 47–366 eV ions 0° – 90° pitch angles. (b) 47–366 eV ions at 90° – 120° pitch angles. (c) 0.89–22.9 keV ions at 0° – 90° pitch angles. (d) 0.89–22.9 keV ions at 90° – 120° pitch angles. (e) 0.048–23.7 keV electrons at 0° – 90° pitch angles.

flux was in the 10^6 to 10^7 $\text{cm}^{-2} \text{s}^{-1}$ range.

Detailed pitch angle analysis showed that the TAI peaked near 105° at 0537:14 (895 km altitude), and near 90° – 95° between 0539:40 and 0540:20 (651 to 555 km altitude). Assuming that the observed hundred-eV TAI at 0537:14 were injected at 600 km altitude (topside of the TAI source region) and then spiralled upward along the magnetic field, their transit time from

the source to the observation altitude may be estimated. For 100-eV H^+ ions, the transit time would be ~ 12.5 s. Also, a peak pitch angle of 110° would be expected at the observation altitude, compared with the observed value of 105° . Given the approximate nature of the analysis, the ions have been injected at $\sim 0537:02$, within ~ 15 seconds after the onset of the optical auroral expansion and brightening at $0536:50$. The data therefore confirm the occurrence of fast ion acceleration in the topside ionosphere at the onset of substorm expansion, as inferred from observations of molecular upflowing ions at high altitude (cf. Fig. 3).

3. Summary and Discussion

We have presented ion composition observations of thermal and suprathermal ions from the Akebono suprathermal mass spectrometer (SMS) in the nightside auroral ionosphere. These observations showed that:

1. In the parallel acceleration region near $1 R_E$ altitude, thermal H^+ and O^+ ions are frequently present. Their upward flux normalized to 2000 km altitude is about $10^8 \text{ cm}^{-2} \text{ s}^{-1}$ (Fig. 1).
2. The O^+/H^+ ratio of the upward thermal ion flux increases with the magnetic Kp index. The O^+ flux is smaller than the H^+ flux at quiet times, but is comparable to the latter at active times (Fig. 2).
3. The occasional presence of molecular upflowing ions in the $1-R_E$ altitude region indicates the occurrence of fast ion energization in the F-region or topside ionosphere during periods of sustained auroral activity (Fig. 3).

We have also presented ground photometric and simultaneous in-situ particle observations, which showed transverse ion acceleration to hundreds of eV near 600 km altitude in and near regions of auroral electron precipitation within ~ 20 seconds of the onset of auroral substorm expansions (Figs. 4 and 5). The flux of these hundred-eV TAI was on the order of 10^6 – $10^7 \text{ cm}^{-2} \text{ s}^{-1}$. Whalen *et al.* (1991) observed the frequent occurrence of ions transversely accelerated to hundreds of eV in latitudinally confined regions of the nightside ionosphere down to ~ 2000 km altitude during auroral substorms.

On DE-1 above $3.5 R_E$ altitude, Yau *et al.* (1985) found that energetic (hundred-eV and keV) auroral upflowing O^+ ion flux increases significantly during active times. In the midnight sector (21–03 MLT), the peak flux is at 68° invariant, and is about $3 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1}$ when normalized to 2000 km altitude. The upward thermal O^+ ion flux observed by Akebono in the “parallel acceleration region” near $1 R_E$ altitude is similar in magnitude and invariant latitude distribution. It represents a significant source of cold plasma for the energetic UFI at higher altitude.

The fact that the thermal O^+ ions are regularly present in the parallel acceleration region at quiet times suggests that they are available for energization at the onset of a substorm. Therefore, if they are accelerated to hundreds of eV or greater, they are capable of reaching the inner plasma sheet within the time scale of a substorm (~ 1 hr).

Hundred-eV O^+ TAI originating from the topside ionosphere at the onset of a substorm can reach the parallel acceleration region within a few minutes, and can likewise reach the plasma sheet during a substorm. However, their upward ion flux is an order of magnitude smaller than the thermal ion flux in the parallel acceleration region. Therefore, their contribution as a cold plasma source to the energetic UFI at high altitude is believed to be small in comparison.

Because of gravitation, lower-energy (≤ 10 -eV) TAI from the topside ionosphere are typically too slow to reach the parallel acceleration region during a substorm. Instead, they are likely to be trapped (or at least decelerated) between the topside ionosphere and some higher altitude. As they repeatedly traverse back and forth along the magnetic field line, they represent a source of thermal ions at high altitude, where they have near zero kinetic energy. A statistical study of

these low-energy TAI at low altitude is needed to determine their possible importance as a source of thermal-energy plasma at higher altitude.

An alternative source of thermal ions in the parallel acceleration region is the polar wind O^+ ions from the dawn and dusk sectors. Abe *et al.* (1993) found that O^+ ions constitute a significant component of the sunlit polar wind. On the dayside, the O^+ polar wind ion acquires a parallel ion velocity of 1–4 km/s above 5000 km. In comparison, the ion convection velocity at auroral latitudes is typically ~ 1 –2 km/s at ionospheric altitudes, and is predominantly anti-sunward along the auroral oval (i.e., the tangential component of the convection velocity is large compared with the perpendicular component to the oval). Thus, the transit time of the polar wind O^+ ions from the dawn or dusk sector to the midnight sector is typically ~ 1 hr, and the vertical distance traversed is about 0.5–1 R_E . Thus, O^+ polar wind ions originating from the 5000-km altitude region in the dawn and dusk sector can possibly convect to the parallel acceleration region in the nightside auroral ionosphere. A quantitative analysis of the three-dimensional velocity of the polar wind ions is needed to ascertain this possibility.

The regular presence of thermal O^+ ions in the parallel acceleration altitude region of the nightside auroral ionosphere strongly suggests that they are the dominant source of cold plasma for energetic UFI at high altitude, and that they can reach the plasma sheet during a substorm, thereby modifying its composition significantly. A number of authors have discussed the possible influence of the resultant plasma sheet mass loading on the dynamics of the substorm (Baker *et al.*, 1982; Daglis and Axford, 1995). On the other hand, Lennartsson *et al.* (1993) argued against such influence on the basis of their ISEE-1 data. The effect of upflowing ionospheric ions on the dynamics of the substorm remains a controversial question.

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REFERENCES

- Abe, T., B. A. Whalen, A. W. Yau, R. E. Horita, S. Watanabe, and E. Sagawa, EXOS D (Akebono) Suprathermal Mass Spectrometer observations of the polar wind, *J. Geophys. Res.*, **98**, 11191–11203, 1993.
- Baker, D. N., E. W. Hones, Jr., D. T. Young, and J. Birn, The possible role of ionospheric oxygen in the initiation and development of plasma sheet instabilities, *Geophys. Res. Lett.*, **9**, 1337–1340, 1982.
- Collin, H. L., W. K. Peterson, and E. G. Shelley, Solar cycle variation of some mass dependent characteristics of upflowing beams of terrestrial ions, *J. Geophys. Res.*, **92**, 4757–6762, 1987.
- Daglis, I. and W. I. Axford, Fast ionospheric response to enhanced activity in geospace: ion feeding of the inner magnetotail, *J. Geophys. Res.*, **100**, 1995 (in press).
- Ghielmetti, A. G., R. G. Johnson, R. D. Sharp, and E. G. Shelley, The latitudinal, diurnal, and altitudinal distributions of upward flowing energetic ions of ionospheric origin, *Geophys. Res. Lett.*, **5**, 59–62, 1978.
- Gorney, D. J., A. Clarke, D. Croley, J. F. Fennell, J. Luhmann, and P. F. Mizera, The distribution of ion beams and conics below 8000 km, *J. Geophys. Res.*, **86**, 83–89, 1981.
- Kintner, P. M., J. LaBelle, W. Scales, A. W. Yau, and B. A. Whalen, Observations of plasma waves within regions of perpendicular ion acceleration, *J. Geophys. Res.*, **13**, 1113–1116, 1986.
- Klumpar, D. M., Transversely accelerated ions: an ionospheric source of hot magnetospheric ions, *J. Geophys. Res.*, **84**, 4229–4237, 1979.
- Lennartsson, W., and R. D. Sharp, A comparison of the 0.1–17 keV/e ion composition in the near equatorial magnetosphere between quiet and disturbed conditions, *J. Geophys. Res.*, **87**, 6109–6120, 1982.
- Lennartsson, W., D. M. Klumpar, E. G. Shelley, and J. M. Quinn, Experimental investigation of possible geomagnetic feedback from energetic (0.1 to 16 keV) terrestrial O^+ ions in the magnetotail current sheet, *J. Geophys. Res.*, **98**, 19443–19454, 1993.
- Sharp, R. D., R. G. Johnson, and E. G. Shelley, Observation of an ionospheric acceleration mechanism producing energetic (keV) ions primarily normal to the geomagnetic field direction, *J. Geophys. Res.*, **82**, 3324–3328, 1977.

- Sharp, R. D., D. L. Carr, W. K. Peterson, and E. G. Shelley, Ion streams in the magnetotail, *J. Geophys. Res.*, **86**, 4639–4648, 1981.
- Shelley, E. G., R. G. Johnson, and R. D. Sharp, Satellite observations of energetic heavy ions during a magnetic storm, *J. Geophys. Res.*, **77**, 6104–6110, 1972.
- Shelley, E. G., R. D. Sharp, and R. G. Johnson, Satellite observations of an ionospheric acceleration mechanism, *Geophys. Res. Lett.*, **3**, 654–656, 1976.
- Watanabe, S., B. A. Whalen, and A. W. Yau, Thermal ion observations of depletion and refilling in the plasmaspheric trough, *J. Geophys. Res.*, **97**, 1081–1096, 1992.
- Whalen, B. A., J. R. Burrows, A. W. Yau, E. E. Budzinski, A. M. Pilon, I. Iwamoto, K. Marubashi, S. Watanabe, H. Mori, and E. Sagawa, The suprathermal ion mass spectrometer (SMS) for the Akebono (EXOS-D) spacecraft, *J. Geomagn. Geoelectr.*, **42**, 511–536, 1990.
- Whalen, B. A., S. Watanabe, and A. W. Yau, Thermal and suprathermal ion observations in the low altitude transverse ion energization region, *Geophys. Res. Lett.*, **18**, 725–728, 1991.
- Yau, A. W., B. A. Whalen, A. G. McNamara, P. J. Kellogg, and W. Bernstein, Particle and wave observations of low-altitude ionospheric ion acceleration events, *J. Geophys. Res.*, **88**, 341–355, 1983.
- Yau, A. W., E. G. Shelley, W. K. Peterson, and L. Lenchyshyn, Energetic auroral and polar ion outflow at DE 1 altitudes: Magnitude, composition, magnetic activity dependence, and long-term variations, *J. Geophys. Res.*, **90**, 8417–8432, 1985.
- Yau, A. W., B. A. Whalen, C. Goodenough, E. Sagawa, and T. Mukai, EXOS-D (Akebono) observations of molecular NO^+ and N_2^+ upflowing ions in the high-altitude auroral ionosphere, *J. Geophys. Res.*, **98**, 11205–11224, 1993.