ACCELERATED AURORAL AND POLAR-CAP IONS: OUTFLOW AT DE-1 ALTITUDES

A.W. Yau

Herzberg Institute of Astrophysics, National Research Council of Canada, Ottawa, Canada K1A OR6

E.G. Shelley and W.K. Peterson

Lockheed Palo Alto Research Laboratory, Palo Alto, CA 94304 U.S.A.

Abstract. Data from the Dynamics Explorer-1 Energetic Ion Composition Spectrometer (DE-1 EICS) in the period from September 1981 to May 1984 were used to determine the mass composition, magnitude, magnetic activity dependence, long-term variations, and topology (MLT-invariant latitude distribution) of energetic (0.01-17 keV/e) terrestrial ion outflow. The period coincided with the declining phase of the current solar cycle (cycle 21). At both magnetically quiet and active times, the O^+ outflow rate exhibited long-term variations which correlated with the declining solar radio flux. Overall, the O^+ outflow rate in the 1981-82 period was a factor of 2 larger than the 1983-84 rate. Any corresponding variation in the H^+ outflow rate, if present, was much smaller and not statistically significant. The O^+ ion outflow rate increased exponentially with the Kp index, the rate at very disturbed times (Kp $\geq$ 6) being 3×10^{26} ions s^{-1} at solar maximum and a factor of 30 larger than the quiet-time (Kp = 0) value. The increase in the H^+ outflow rate with Kp was more modest, the disturbed time (Kp $\geq$ 6) rate being 7×10^{25} ions s^{-1} and a factor of 5 larger than the quiet-time value. The results point to the importance of perpendicular ion acceleration processes at low altitudes.

Introduction

We present results from a statistical study based on data from the Energetic Ion Composition Spectrometer (EICS) on Dynamics Explorer-1 (DE-1), in which we determined the mass composition, magnitude, magnetic activity dependence, long-term variations, and topology of energetic (0.1-17 keV) terrestrial ion outflow. These results establish the quantitative significance of upflowing auroral and polar cap ionospheric ions (UFI) as a source of magnetospheric plasma, and reveal a number of important aspects concerning ionospheric ion acceleration processes.

The morphological characteristics of upflowing ions have been the subject of a number of studies using data on S3-3 below 8000 km [Ghielmetti et al., 1978; Gorney et al., 1981; Collin et al., 1981, 1984; Ghielmetti and Johnson, 1983] and data on DE-1 up to 23000 km [Yau et al., 1984]. The present study is a follow-on to the Yau et al. study which was focussed on the occurrence frequency distribution of upflowing ions at 8000-23300 km altitude in the auroral zone and the polar cap; the data base used in the present study is an extension of that of Yau et al.

Data

Since its launch on August 3, 1981, DE-1 has provided a unique and comprehensive data set for studying ionospheric ion acceleration. The DE-1 data set is unique in three respects: the energy range of its ion composition measurements, its period of operation relative to the solar cycle, and its orbital coverage. On DE-1, the Retarding Ion Mass Spectrometer (RIMS) measured ions in the $\lesssim$50 eV/e range, while the Energetic Ion Composition Spectrometer (EICS) measured ions up to 17 keV/e. Together, the two instruments cover the full energy range of energetic UFI. DE-1 was launched near the peak of the current solar cycle (Cycle 21), and the DE data set covers the late solar-maximum and early declining phase of the solar cycle. The DE-1 orbit has an apogee of 4.6 R_e geocentric, an inclination of 90°, and an orbit-plane local-time drift period of 12 months and a line-of-apsides drift period of 18 months.

The DE-1 orbit is extremely useful for UFI studies because not only does it cover the entire auroral zone and polar cap up to 4.6 R_e at all local times, but it also enables data sampling in all seasons of the year and repeated sampling of a given season in successive years. This is illustrated in Figure 1, in which the geographic latitude and local time of the DE-1 apogee are shown as a function of time from September 1981 to August 1984. The different circle types at the top of the figure denote the different sea-
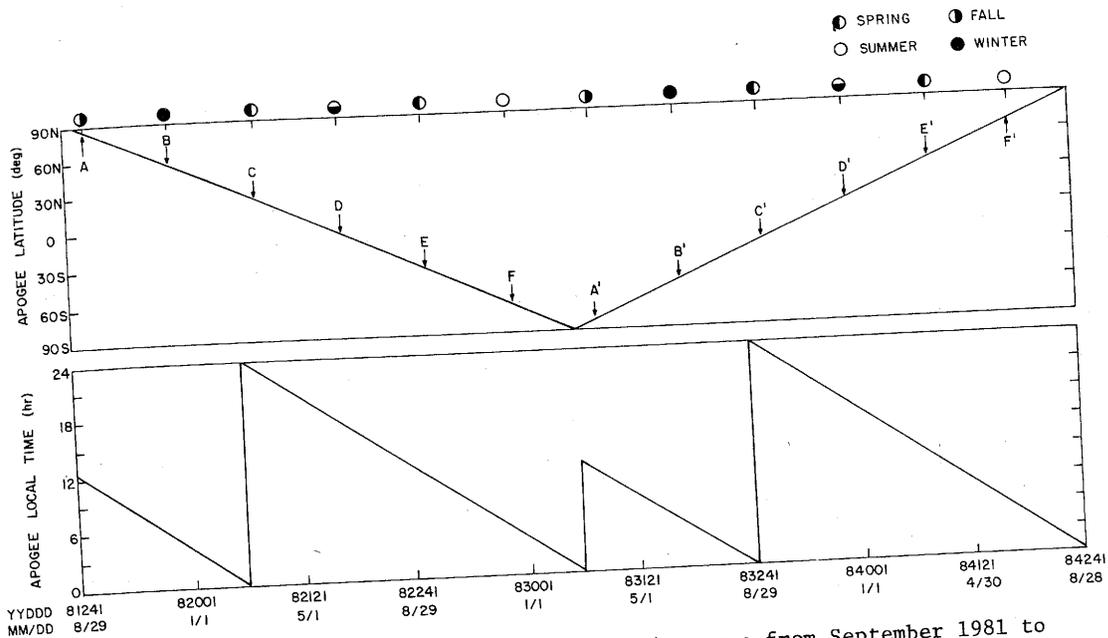
Fig. 1. Geographic latitude and local time of DE-1 apogee from September 1981 to August 1984. The identifiers indicate season of apogee data. A and A': fall equinox; B and B': winter solstice; C, C', E and E': spring equinox; F and F': summer solstice; D and D': winter in one hemisphere and summer in the other (equatorial apogee).

sons. The figure shows that the apogee latitude and local time in a given season in the first orbital cycle (the first 18 months of the mission) are revisited in the same season in the second orbital cycle. Identifiers A and A' show, for example, apogee coverage at the local-noon polar cap (83°N latitude and 1100 LT) at the northern fall equinox of 1981, and again at the southern fall equinox in 1983. Other identifier pairs show corresponding revisits of apogee latitude and local time at spring equinox (C and C', E and E'), summer solstice (F and F') and winter solstice (B and B').

The data base used in this study was acquired between September 15, 1981 and May 31, 1984. It consists of 96-s averaged integral ion fluxes of H^+ and O^+ in three energy intervals (0.01-1, 1-4, 4-17 keV) and nine pitch-angle bins. Data coverage was fairly complete at high altitude (above 16000 km, within ~1 R_e of DE-1 apogee) for all magnetic local times and invariant latitudes above 56° (auroral and polar-cap latitudes), and for all four seasons of the year. Details of the data base were described in Yau et al. [1985].

Figure 2 shows an example of UFI event during magnetically active times. The six spectrograms show H^+ and O^+ ion fluxes at 0.01-1, 1-4 and 4-17 keV, respectively, as a function of pitch-angle and time. Very intense (>10^7 cm^{-2} s^{-1} sr^{-1}) O^+ UFI fluxes at 0.01-1 keV were observed throughout the southern dayside auroral zone and appear as enhancement in the spectrogram at pitch angles which decrease with increasing altitude, from
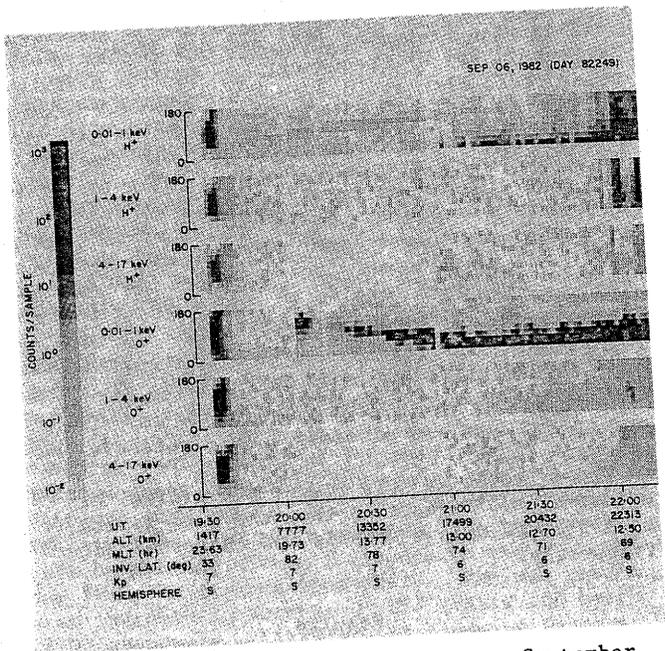

Fig. 2. Spectrograms of EICS data on September 6, 1982 between 1930 and 2210 UT, when Kp was 6-7. Data are 96-s averages and binned into nine 6-7. pitch-angle bins. Ordinate of spectrograms is pitch angle; 0° is away from the ionosphere in the southern hemisphere. Note the upflowing O^+ ion beams in the 0.01-1 keV channel in the 0°-20° bin between 2100 and 2210 UT.

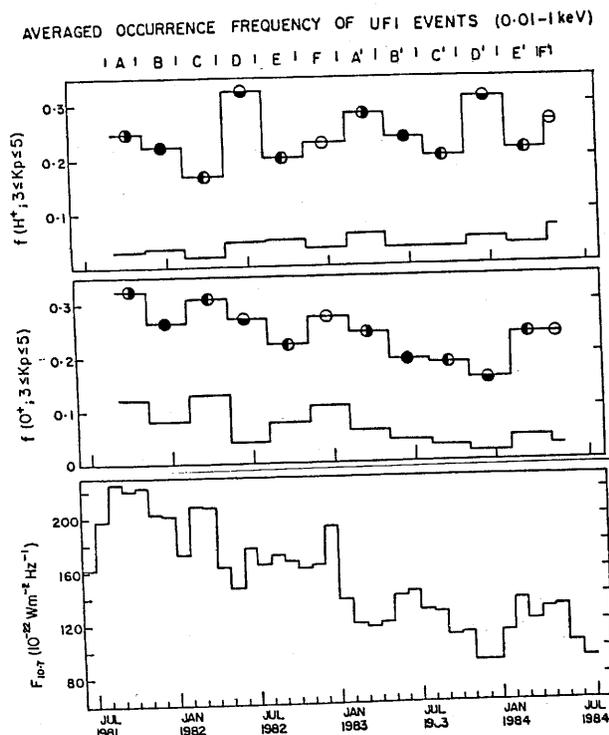AVERAGED OCCURRENCE FREQUENCY OF UFI EVENTS (0.01-1 keV)

Fig. 3. Averaged occurrence frequency of UFI events during magnetically active times (Kp = 3-5) between September 1981 and May 1984. (a) H^+ frequency, (b) O^+ frequency, (c) monthly mean solar radio flux at 10.7 cm. Histograms marked by circles indicate frequency of events with $>10^6$ cm^{-2} s^{-1} sr^{-1} fluxes; unmarked histograms refer to frequency of events with $>10^7$ fluxes. Different circle types denote different seasons of apogee data sampling. Solid circles: winter; open circles: summer; semi-open circles on the left: fall; semi-open circles on the right: spring; semi-open circles on top: equal winter-summer (equatorial apogee) coverage.

$\lesssim 90°$ at ≈ 13000 km to $<20°$ above 17500 km. The upward ion flux was at least 2 decades above the downward flux.

The features in this figure are typical of active-time O^+ events in that they are generally more intense than H^+ events and that they occur frequently.

Results

Figure 3, adapted from Yau et al. [1985], shows the averaged occurrence frequencies of H^+ and O^+ upflowing ions below 1 keV at moderately active times (3- $\leq$ Kp $\leq$ 5+) in the twelve 91-day periods (seasons) identified in Figure 1. In panels a and b, the histograms marked by circles are occurrence frequencies of events with $>10^6$ $(cm^2$ s $sr)^{-1}$ fluxes; the unmarked histograms show

the portion of events with $>10^7$ $(cm^2$ s $sr)^{-1}$ fluxes. Panel c shows the monthly mean 10.7 cm solar radio fluxes at 1 A.U. in the 91-day periods. The O^+ UFI frequency displays a continual trend of overall decrease. In contrast, no long-term trend of decrease is apparent in H^+ UFI. The September 1981 - August 1984 period coincided with the early declining phase of the present solar cycle, when $F10.7$ decreased from a high of 222 (x 10^{-22} Wm^{-2} Hz^{-1}) in September 1981 to a low of 93 in November 1983. The long-term trend of decreasing O^+ occurrence frequency is found to correlate with the solar radio flux, with the O^+/H^+ ratio peaking near solar maximum. Its short-term variation also appears to track the corresponding variation in the solar flux.

In both H^+ and O^+, the outflow was dominated by (over 90 percent) <1 keV ions. Figure 4 shows the active-time (Kp = 3-5) upward O^+ ion flux $<J_n>$ at 0.01-1 keV and 1000 km reference altitude, as a function of invariant latitude for the four MLT sectors. Triangles denote the 81-82 data, circles the 83-84 data. In both periods, the upward ion flux peaked near 78° invariant in
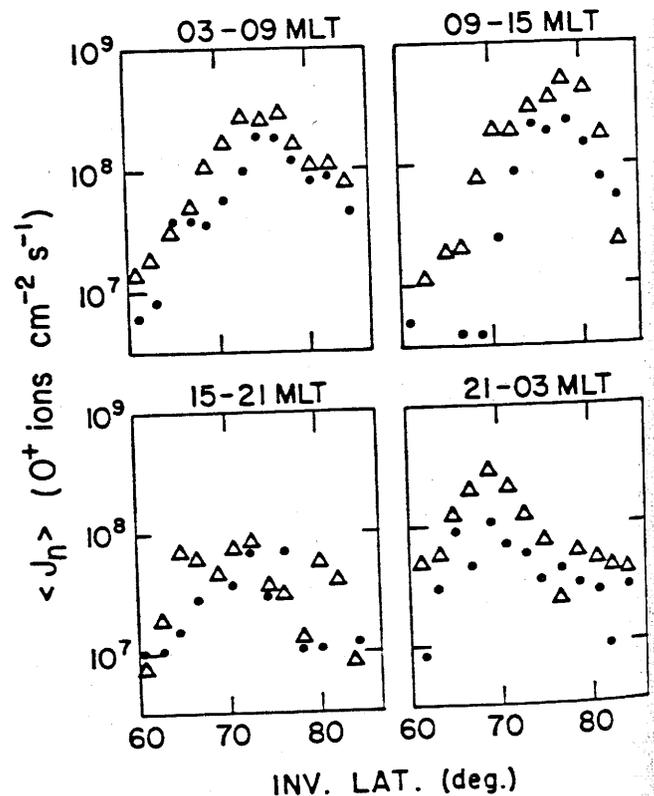

INV. LAT. (deg.)

Fig. 4. Active-time (Kp = 3-5) upward O^+ ion fluxes at 0.01-1 keV normalised to a reference altitude of 1000 km, as a function of invariant latitude at different MLT sectors. Triangles: September 1981 - January 1983 data; dots: February 1983 - May 1984 data.
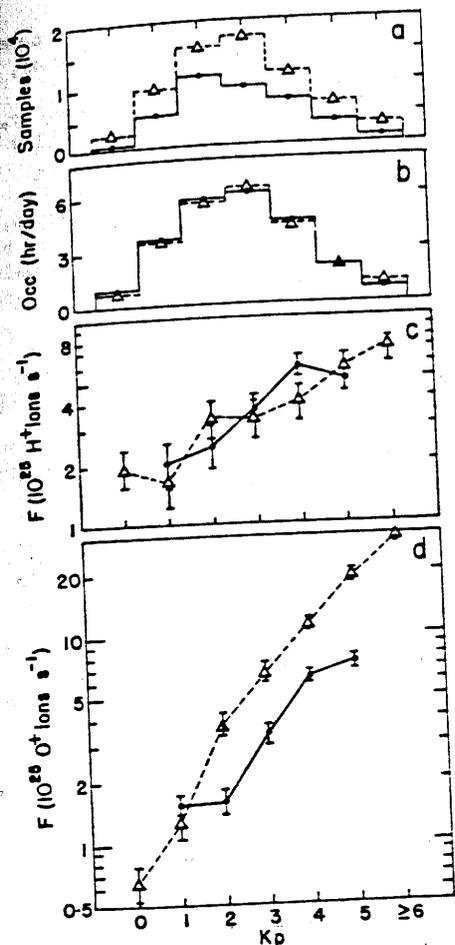
Fig. 5. H$^+$ and O$^+$ outflow rates at 0.01-1 keV as a function of Kp. Triangles: September 1981 – January 1983 data; dots: February 1983 – May 1984 data. (a) data sampling distribution, (b) Kp occurrence frequency distribution, (c) H$^+$, and (d) O$^+$ outflow rates.

the noon sector. In the midnight sector, the flux peaked at lower invariant latitude (near 70°) and was smaller by a factor of 2. The corresponding quiet-time (Kp = 0-2) distribution was qualitatively similar but smaller in magnitude. Overall, the flux was above a factor of 2 higher in 81-82 than in 83-84.

Figure 5 displays the 0.01-1 keV H$^+$ and O$^+$ outflow rates in the 81-82 (triangles) and 83-84 (circles) periods as a function of Kp. In addition it shows the distributions of data sampling and Kp occurrence. In both periods, data sampling was very adequate for the intermediate Kp conditions (Kp between 1 and 5), and was in proportion to the Kp occurrence distribution. Also, the Kp occurrence distributions in the two periods are very similar. In 81-82, Kp was ≤2, 3 to 5, and ≥6 in 41, 54 and 5 percent of the time. The data distribution in the three Kp ranges was 42, 53 and 5 percent, respectively.

In 83-84, the corresponding Kp occurrence distribution was 43, 53 and 4 percent, and the data distribution was 45, 51 and 4 percent, respectively. The apparent lack of dependence of Kp on solar cycle was puzzling in view of the fact that large magnetic storms (Dst << -100 nT) were limited to the near solar maximum period, and that the Kp index is a composite indicator of both magnetic storms and substorms.

For a given Kp condition, the O$^+$ outflow rate was higher in 81-82 than in 83-84 by a factor of 2. In contrast, the H$^+$ outflow rates in the two periods were equal within statistical error. The higher O$^+$ rate in 81-82 is attributed to the long-term variations of O$^+$ UFI occurrence which are correlated with variations in the solar flux (see Figure 3).

The O$^+$ outflow rate increased exponentially with Kp by a factor of ≈30 from ≈1 x 10^{25} ions s^{-1} at Kp = 0 to ≈3 x 10^{26} ions s^{-1} at Kp ≥ 6 in 81-82. Empirically, F(Kp) ∝ exp(0.56 Kp).

Summary and Discussions

At both magnetically quiet and active times, the outflow rate of upflowing O$^+$ ionosphere ions exhibits appreciable long-term variations which are correlated with the solar flux. In comparison, the variation in the H$^+$ outflow rate, if present, is much smaller and not statistically significant. The O$^+$ outflow rate is highly dependent on magnetic activity, as measured by the Kp index, and increases exponentially by a factor of 30 from Kp = 0 to Kp = 6. The corresponding increase of the H$^+$ rate with Kp is much more modest, being a factor of 5.

The qualitative similarity between the geomagnetic and solar activity dependences of UFI may be understood in terms of atmospheric and ionospheric scale height considerations. At times of increased geomagnetic activity, ion and neutral temperatures rise, as a result of ionospheric and atmospheric heating. The resulting increase in scale height effectively lifts O$^+$ to higher – ion acceleration – altitudes, thereby facilitating O$^+$ ion acceleration. The increased scale height also shifts the O$^+$-H charge exchange to higher altitude, and effectively reduces the overall probability of removal of low-altitude O$^+$ by charge-exchange, thereby increasing their probability of survival to (and hence occurrence at) high altitude. At the same time, the increase in scale height has little influence on the light H$^+$ ions from the topside ionosphere. The net result is an increase in intense O$^+$ UFI events and overall O$^+$ abundance. Likewise, at times of increased solar EUV flux (which is correlated with the F$_{10.7}$ radio flux), increased atmospheric heating occurs, resulting in increase in scale heights at the lower ionosphere and ultimately increase in O$^+$ UFI abundance at high altitude.

On the basis of PROGNOZ-7 data, Hultqvist [1983] provided convincing arguments that the energetic O$^+$ ions observed at PROGNOZ-7 altitude originate from a narrow altitude region in the

lower ionosphere (below 1000 km). Moore [1980, 1984] examined the effect of O^+-H charge exchange on accelerated O^+ flux from low altitude, and its dependence on neutral atmospheric composition and temperature. Moore concluded that perpendicular energization of several eV below the cross-over altitude would be necessary for the upgoing O^+ ions to overcome charge-exchange and to reach high altitude, and that the O^+ outflow should increase with increased neutral atmospheric temperature. Perpendicular ion acceleration at low altitudes (below 1000 km) has been observed previously on the ISIS-1 and -2 spacecraft [Klumpar, 1979] and on sounding rockets [Whalen et al., 1978; Yau et al., 1983]. The present result is consistent with the argument of Hultqvist [1983] and points to the importance of low-altitude ion acceleration processes in understanding ionospheric ion acceleration at high altitudes.

Young et al. [1982] found marked O^+ density increase in the (outer) ring current with geomagnetic activity; the increase in the H^+ density was small. Young et al. found that $O^+/H^+ \propto \exp(0.17\ Kp)$ for 0.9-16 keV ions in the ring current. The corresponding ratio in UFI outflow, from Figure 5 above, is proportional to $\exp(0.30\ Kp)$. Since the Kp index is a quasi-logarithmic measure of magnetic disturbance, the exponential increase of the O^+/H^+ ion composition ratio in both UFI and ring current in this dependence reflects not only the source and sink relationship between the two on a long time-scale, i.e., that the ring current is the storage depot of the outflowing ions, but also that the ring current accommodates on a relatively short time scale the changing dynamics of the auroral ion outflow.

In conclusion, the acceleration of O^+ UFI is modulated by the atmospheric scale height, which increases with increasing solar activity (EUV flux). As a result, O^+ UFI occurrence frequency and outflow rate increase at solar maximum. In contrast, there is no significant solar-cycle variations in H^+ UFI occurrence and outflow. UFI is O^+-dominant near solar maximum and comparable in H^+ and O^+ near solar minimum.

References

Collin, H.L., R.D. Sharp, E.G. Shelley, and R.G. Johnson, Some general characteristics of upflowing ion beams over the auroral zone and their relationship to auroral electrons, J. Geophys. Res., 86, 6820-6826, 1981.

Collin, H.L., R.D. Sharp, and E.G. Shelley, The magnitude and composition of the outflow of energetic ions from the ionosphere, J. Geophys. Res., 89, 2185-2194, 1984.

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.

Ghielmetti, A.G., and R.G. Johnson, Variations in the occurrence frequency of UFI events from July 1976 to April 1979, Trans. Amer. Geophys. Union EOS 64, 807, 1983.

Gorney, D.J., A. Clarke, D. Croley, J.F. Fennell, J. Luhmann, and P. Mizera, The distribution of ion beams and conics below 8000 km, J. Geophys. Res., 86, 83-89, 1981.

Hultqvist, B., On the origin of the hot ions in the disturbed dayside magnetosphere, Planet. Space Sci., 31, 173-184, 1983.

Klumpar, D.M., Transversely accelerated ions: An ionospheric source of hot magnetospheric ions, J. Geophys. Res., 84, 4229-4237, 1979.

Moore, T.E., Modulation of terrestrial ion escape flux composition (by low-altitude acceleration and charge exchange chemistry), J. Geophys. Res., 85, 2011-2016, 1980.

Moore, T.E., Superthermal ionospheric outflows, Rev. Geophys. Sp. Phys., 22, 264-274, 1984.

Whalen, B.A., W. Bernstein, and P.W. Daly, Low altitude acceleration of ionospheric ions, Geophys. Res. Lett., 5, 55-58, 1978.

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., B.A. Whalen, W.K. Peterson, and E.G. Shelley, Distribution of upflowing ionospheric ions in the high-altitude polar cap and auroral ionosphere, J. Geophys. Res., 89, 5507-5522, 1984.

Yau, A.W., P.H. Beckwith, W.K. Peterson, and E.G. Shelley, Long-term (solar-cycle) and seasonal variations of upflowing ionospheric ion events at DE-1 altitudes, J. Geophys. Res., 90, 6395-6407, 1985.

Young, D.T., H. Balsiger, and J. Geiss, Correlations of magnetospheric ion composition with geomagnetic and solar activity, J. Geophys. Res., 87, 9077-9096, 1982.