POLAR/TIMAS observations of suprathermal ion outflow during solar minimum conditions

Revised, June 7, 2000.

W.K. Peterson[1], H.L. Collin[1], A.W. Yau[2], and O.W. Lennartsson[1]

[1]Lockheed Martin Space Physics Laboratory

Palo Alto, California, 90304, USA

[2]University of Calgary

Department of Physics and Astronomy

Institute for Space Research

Calgary, Alberta, Canada T2N 1N4

ABSTRACT: We present observations of the magnitude and variability of escaping suprathermal ions in the energy per charge range of 15eV/e - 33 keV/e. The data were obtained from the Toroidal Imaging Mass-Angle Spectrograph (TIMAS) on the POLAR spacecraft from April 1996 to September 1998 over the Earth's southern polar cap during solar minimum conditions. The net outflow rates of ionospheric ions derived from this data set are significantly different than those inferred from analysis of similar data obtained at higher altitudes from the Dynamics Explorer (DE) -1 satellite. The data present a clear picture of the seasonal variation of ion outflow as a function of solar illumination (i.e. season). We conclude that the differences between the present results and previous DE-1 estimates of the magnitude of escaping suprathermal ions can be explained by energization of the H^+ component of the polar wind above the 6,000-8,000 km altitude region where the POLAR data were acquired. We also note that seasonal variations in He^+ outflow presented here are not as large as those reported previously.

Introduction:

The ionosphere and magnetosphere are coupled by several processes with significantly different temporal and spatial scales. These processes involve large scale field-aligned currents, plasma waves, precipitating energetic particles, and ionospheric plasma outflow. In terms of energy exchanged, ion outflow is the weakest of these processes. However, because of the significant time required for ionospheric ions to reach and affect the plasma sheet, there is a possibility of long term feedback effects. It has been difficult to explore the nature of feedback mechanisms because of the limited information available about the spatial and temporal coherence and variability of plasma escape from the ionosphere. Recent reports of the seasonal modulation in the strength of upflowing auroral ion beams in the evening MLT sector [e.g. Collin et al., 1998] demonstrate the importance of quantifying seasonal variations of other parameters that might possibly affect the strength of the magnetosphere-ionosphere interaction. The only previous report of seasonal variations of ion outflow [Yau et al., 1985a], was severely restricted by the characteristics of the Dynamics Explorer (DE)-1 orbit which gave less than ideal seasonal sampling, and did not include He^+.

The composition of the magnetosphere is determined by the difference between the influx from and losses to both the solar wind and ionosphere. Quantitative information about the magnitude and variability of magnetospheric plasma sources and losses is based on data extremely limited in their spatial and temporal coverage. (See, for example, Hultqvist et al. [1999].) Yau and André [1997] have recently reviewed the published reports on the ionospheric sources of magnetospheric plasma. The majority of reports focused on identifying the nature of the outflow (i.e. ion beam or conic distribution) and the altitude dependence. Quantitative global synoptic reports of ion outflows from several years of data are available only from the Dynamics Explorer (DE) -1 satellite. Quantitative DE-1 observations of the magnitude of the flux of escaping suprathermal ions have been reported by Yau et al. [1984, 1985a,b, 1988] (H^+ and O^+) and Collin et al. [1987, 1988, 1989] (H^+, O^+ and He^+). Yau et al. [1988] and Collin et al. [1989] independently developed empirical estimates of the net outflow rates of escaping suprathermal ionospheric ions as a function of solar and magnetic activity indices. We note here, that because of features of the DE-1 orbit, information about seasonal variations of ion outflow from DE-1 is limited [Yau et al. 1985a].

The TIMAS instrument is on the POLAR spacecraft which was launched in early 1996 into a 90 degree inclination orbit with apogee and perigee 9 and 2 Earth radii (R_E) respectively. The high quality, mass resolved, energetic ion data obtained from the Toroidal Imaging Mass-Angle Spectrograph (TIMAS) [Shelley et al. 1995] and the unique orbit of POLAR provide an opportunity to independently determine properties of the ionospheric plasma source. Data from POLAR perigee passes were obtained at nearly constant altitude. In the first three years of operation, when the perigee was over the southern polar cap, outflowing ions were sampled in the 6,000-8,000 km altitude region. More importantly, POLAR perigee data are such that information about seasonal variations of ion outflow can be reliably obtained.

This paper is organized as follows: We first discuss how the data were accumulated and reduced. We then present the observed seasonal variations in the data, and calculate the net rates of escaping ionospheric ions observed at POLAR between 6,000 and 8,000 km. We then show that the rates of outflowing ionospheric H^+ we report from POLAR are significantly less than those reported by Yau et al. [1988] and Collin et al. [1989] from DE-1 data obtained at higher altitudes. We conclude that this difference can be explained by energization of the polar wind to energies detectable by the DE-1/EICS instrument above the altitude where the POLAR/TIMAS data presented here were obtained. We also make some observations regarding the seasonal variability of escaping suprathermal He^+.

Data reduction

The data presented here were obtained with the Toroidal Imaging Mass-Angle Spectrograph (TIMAS) [Shelley et al. 1995]. The energy-angle distributions of the major ion species, H^+, O^+, He^+ and He^{++}, in the energy range 15 eV/e to 33 keV/e are acquired simultaneously by TIMAS every 6 second spin of POLAR. These distributions are binned onboard into various three dimensional arrays, or “data products”. A selection of these data products are transmitted to ground. Which data products are transmitted at any time depends on the operating mode of TIMAS and the available telemetry bandwidth. Usually H^+ and O^+ data products are available on every spin and He^+ on alternate spins. The instrument background count rate and data necessary to verify satisfactory instrument performance are always available. For each ion species TIMAS can produce data products with different energy, angle, and mass resolution. In this study Medium Resolution Distribution Functions (MRDF's) were used preferentially. Initial ground processing converts data products of this type to differential number fluxes, corrected for background, at each of 14 energy levels and 112 look directions which together cover 98% of the unit sphere (4 steradians). The effective field of view of each angular bin is about 22 degrees full width for this data product. Measurements are made at interleaved sets of 14 energy levels on successive spins so that the full set of 28 energy levels is sampled in two spin periods or 12 seconds. Densities and three dimensional velocity vectors for each species are calculated from moments of the three dimensional ion distributions.

The densities and velocities derived from the moments calculation contain contributions from upflowing ion beams and ion conics as well as contributions from downflowing and mirroring magnetospheric populations. A fraction of the downflowing magnetospheric component is absorbed by the ionosphere and not reflected. The net contribution of the magnetospheric component is thus a downflow. The net outflow rate or fluence of ionospheric ions can be estimated directly from the ion moments after a correction is made for the portion of the magnetospheric component that is absorbed by the ionosphere.

Schematically the calculation is: (net outflow rate of ionospheric ions) = (ion density) x (component of velocity parallel to the measured magnetic field) + (correction for the absorbed magnetospheric component). Consistent with, and as described in Yau et al. [1985a,b, 1988] and Collin et al. [1987, 1988, 1989], the correction for the magnetospheric component was made by calculating the contribution to the outflow rate which corresponds to a nominal loss cone filled with the observed downward field-aligned ion flux. Correcting for the ionospheric absorption of a fraction of the magnetospheric component resulted in a significant but not overwhelming increase in the net ionospheric outflow rate calculated for H^+, but little change in the other species. The correction is largest equatorward of the auroral zone.

A record was kept of all the 12-second intervals in which suitable data products for each species had been produced. If there was a suitable data product for any species the net outflow rates of those species and their uncertainties were recorded for that interval. The date, time, invariant latitude, magnetic local time, and altitude were also recorded for all intervals.

All available data near perigee taken between March 1996 and September 1998 were examined in a sequence of six-month periods centered approximately on the solstices, which we refer to as "seasons" hereafter for brevity, i.e. southern winter from April through September, and summer, from October through March. The precession of POLAR's orbit relative to the Sun-Earth line required six months to make a complete scan of local times. It was therefore not possible to divide the data into shorter intervals which would still have complete local time coverage. About 30,000 12 second samples were collected for each six month "season".

For calculating the hemispheric total outflow rate, the measurements were sorted into 14 2.5 degree invariant latitude bins between 55 degrees and 90 degrees and 24 one hour magnetic local time bins. No distinction was made for altitude since the altitude range sampled was not large, about 0.9 to 1.3 R_E, but the measurements were normalized to 6678 km ($1R_E$ +300km) geocentric distance (dipole approximation).

The hemispheric net ionospheric outflow rate was calculated for each ion species from the data samples collected during each six month "season". In each case the estimated significance of the net outflow value for each sample was required to be greater than one sigma. I.e. a sample with less than one sigma is included in the "sum of samples" (denominator), while the corresponding "ion outflow" is not included in the "sum of ion outflow" (numerator).

Occasionally count rates of ions, usually protons, are high enough to cause local saturation of the TIMAS microchannel plate detector. When this happens, some of the saturating ion species are missed and the count rates of other species are overestimated. These effects are exaggerated at the highest count rates and thus overestimate the outflow rate. In order to minimize this source of error a maximum count rate was set for samples which were to be used to calculate net ionospheric outflow rate. About 1.4% of all samples were rejected for this reason. The outflow rate calculated in this way was compared with the outflow rate calculated using all samples. In most cases the difference was small, about 1% for ion beams in winter, but was about 15% for conics in the summer with the difference in outflow rates predominantly on the dayside between 75 and 80 latitude. These differences can be regarded as upper limits of the uncertainty introduced by the microchannel plate saturation.

The uncertainties of the hemispheric total outflow rates were generally less than 10% except for the weakest outflows, which are mainly summer He^+. Including samples which did not meet the "one sigma" requirement increased the uncertainties, but did not significantly change the net outflow rates for ionospheric ions.

Observations of outflowing ions:

Figure 1 presents data acquired between April 1, 1996 and September 31, 1998 from POLAR perigee passes reduced as described in the previous section. The data in Figure 1 show seasonal (as defined above) maps of the net outflow rate or fluence of the three major ionospheric ions. Color coded fluence values are presented from 55 to 90 degrees INVL for two summer and three winter seasons. Figure 1 also presents two line plots indicating solar and magnetic activity as a function of time (season) at the bottom. The red line indicates the daily value of the solar 10.7 radio flux index ($F_{10.7}$) which is a proxy for the intensity of the solar extreme ultra violet (EUV) flux. The black line indicates the daily sum of the planetary magnetic activity index K_P. The conditions in the first winter and summer seasons were particularly quiet. The largest geomagnetic storm in this interval, January 10-11, 1997, had a minimum hourly D_{ST} index of less than -80.

The data presented in Figure 1 have three important properties. 1) They are the most comprehensive view of escaping He^+ outflow rates yet obtained; 2) They present a clear picture of the seasonal variation of outflowing ions as a function of solar illumination (i.e. season); and 3) The net escaping ionospheric outflow rate is significantly different than that inferred from analysis of similar data obtained at higher altitudes by the Dynamics Explorer (DE) -1 satellite. We first discuss the seasonal and MLT/INVL distribution maps. This is followed by a presentation of the inferred hemispherical outflow rates.

The net outflow rates or fluence of ionospheric ions shown in Figure 1 displays, in unprecedented detail, variations by season and species in the pattern of ionospheric outflow. The most striking feature in Figure 1 is the significant asymmetry in the summer/winter observations of He^+ fluence in the auroral zone. In the two summer seasons, significant He^+ fluences in the auroral zone were seen only near noon and midnight MLT. In the winter seasons, however, significant fluences of He^+ are seen at all local times.

Table 1 presents the net outflow rates of ionospheric H^+, He^+, O^+ and their sum integrated over each set of the seasonal MLT-INVL maps shown in Figure 1. Table 1 and Figure 1 both show differences between both the total outflow rates and their INVL/MLT distributions for successive seasons with similar geomagnetic and solar activity (e.g. the southern winters and summers of ‘96 and ‘97).

The total ion outflows reported in Table 1 are significantly different than those reported from the analysis of DE-1 data acquired at higher altitudes by Yau et al. [1985a,b, 1988], and Collin et al. [1987, 1988, 1989]. The analysis presented below shows that the differences cannot be attributed to different solar and geomagnetic activity levels in the POLAR and DE-1 data accumulation intervals.

Characteristics of the DE -1 orbit and the altitude range over which ion outflow data were acquired are significantly different from POLAR. The DE -1 ion outflow data were binned as a function of altitude (16,000 to 24,000 km) as well as invariant latitude and magnetic local time. The full range of location parameters were covered once every 18 months [Yau et al. 1985a]. To calculate the net ion outflow rate of suprathermal ions under various solar and geomagnetic activity conditions, Yau et al. [1988] and Collin et al. [1989] also binned the DE -1 data into magnetic and solar activity ranges. From the binned data set they developed empirical relations relating geomagnetic and solar activity with global ion outflow rates. These DE -1 empirical relations allow us to systematically compare ion outflow rates determined from POLAR ion spectra.

The Yau et al. [1988] empirical relations were derived from a subset of data restricted to O^+ and H^+ and were derived from data in three broad energy ranges and approximate pitch angle information. Collin et al. [1987, 1988] made an independent assessment of the total ion outflow using the same algorithms and altitude restrictions used by Yau et al. The Collin et al. empirical relations [Collin et al., 1989] however, were derived from a data set that retained the full instrumental energy resolution and accurate pitch angle information and that included He^+. The empirical relations describing ion outflow derived from this independent analysis are remarkably consistent with those derived by Yau et al. Table 2 summarizes the differences in data accumulation, data sampling and data processing for the two DE-1 analyses and the POLAR data reported in Figure 1 and Table 1.

The empirical relations derived from the two independent analyses of DE -1 data are given in Equations 1-5 below. Equations 1 and 2 are derived from equations 9 and 10 in Yau et al. [1988]. They relate the expected hemispherical outflow (as opposed to global outflow characterized by equations 9 and 10 in Yau et al. [1988]) of suprathermal ions in units of sec^{-1}. Equations 3-5 are from the independent Collin et al. [1989] analysis in the same units. Here $F_{10.7}$ is the 10.7 cm solar radio flux index, which is derived from the daily solar flux at 10.7 cm measured by the Dominion Radio Astrophysical Observatory in Penticton, British Columbia, and used as a proxy for solar EUV activity. K_P is the three hourly global index of geomagnetic activity.

$$F_{O}+ = 5 \times 10^{24} \exp[(F_{10.7} - 100)/100] \exp[0.5 K_P] \quad (1)$$

$$F_{H}+ = 1.3 \times 10^{25} \exp[-2.7 (F_{10.7} - 100)/1000] \exp[0.23 K_P] \quad (2)$$

$$F_{O}+ = 8.5 \times 10^{23} \exp[0.013 F_{10.7}] \exp[0.54 K_P] \quad (3)$$

$$F_{H}+ = 1.0 \times 10^{25} \exp[0.23 K_P] \quad (4)$$

$$F_{He}+ = 1.3 \times 10^{23} \exp[0.012 F_{10.7}] \exp[0.29 K_P] \quad (5)$$

Table 3 presents the average solar and geomagnetic conditions for the five seasons of data presented above and the expected net hemispherical ion outflows calculated using equations 1-5 for these seasons. The K_P value reported is one eighth of the sum of the K_P index for the day each data point was acquired. H^+ and O^+ data in parentheses were derived using equations 1 and 2. The other numbers were derived using equations 3-5. The average in the last row is a simple average of the five seasons sampled.

The H^+ and O^+ total outflows estimated using the Yau et al. parameterization (Eqs 1-2) are not significantly different from those determined from the Collin et al parameterization (Eqs 3-4). Both are within the uncertainties expected at the low levels of solar and magnetic activity encountered during the time the POLAR data were accumulated. However, the values in Table 3 differ from the observations summarized in Table 1.

The data in Table 4 compare and contrast the observed (season-averaged) ion outflows from Table 1 and the estimated outflow computed using the empirical relations given in equations 1-5 and summarized in Table 3. The units in Table 4 are ions/second leaving the southern hemisphere (rows 1-3) or ratios (rows 4-6). The last row reports the range of ion outflows, including the polar wind, expected over a single hemisphere under quiet geomagnetic conditions at solar minimum derived from Table 1 in the Yau and André [1997] critical assessment of the literature on ion escape. Global (i.e. from two hemispheres) ion outflows are given by Yau and André for a variety of regions and conditions. The numbers in the last row in Table 4 are the sum of ionospheric ion outflows from the auroral zone and polar cap at solar minimum, quiet geomagnetic conditions (K_P =0-2), for a single hemisphere (i.e. one half of those reported by Yau and André).

The data in Table 4 shows that the POLAR H^+ values are 10-20% of those expected from both DE -1 empirical analyses, and those for O^+ are 40-70% of the expected values. The He^+ observations are 30% larger than expected from the Collin et al. empirical analysis. Yau et al. [1988] did not estimate the He^+ outflow. The significance of these differences is discussed below.

Discussion

The data from the POLAR/TIMAS instrument presented above provide a previously unavailable comprehensive seasonal overview of the composition and magnitude of escaping suprathermal ionospheric plasma. They also provide a measure of net ionospheric outflow rates independent of those obtained from the Dynamics Explorer -1 (DE -1) satellite. The data in Table 4 demonstrate that the net escaping outflow rate of suprathermal ions inferred from the analysis of POLAR data is significantly different than that inferred from the analysis of DE-1 data.

The absolute calibration of the response of the POLAR/TIMAS instrument to H^+ fluxes cannot account for the differences shown in Table 4. Extensive work is currently underway to refine the absolute calibration with the help of observed mass spectral line shapes. Preliminary indications are that there will be no more than a 10% correction. In addition, derived flux and density values of H^+ dominated plasmas are generally consistent with those independently derived from POLAR/HYDRA [e.g. Trattner et al., 2000] and POLAR/TIDE [e.g. Huddleston et al., 2000]. The POLAR/TIMAS relative calibration of H^+ and O^+ was established prior to launch [Shelley et al., 1995] and verified on-orbit using the mass spectral data products [e.g. Lennartsson et al., 2000]. Finally, The uniformity of 6-month seasonal outflow values reported in Table 1 shows that temporal variations in the absolute calibration and the relative H^+/O^+/He^+ calibrations are not significant.

Yau and André [1997] evaluated the net ionospheric ion outflow rate measurements from DE-1/EICS in comparison to other independent estimates from Akebono/SMS and DE-1/RIMS [e.g. Abe et al., 1996, Chappell, 1988, Pollock, et al., 1990]. They presented a range of expected H^+ and O^+ ion outflow rates, including the contribution from the polar wind under various geomagnetic and solar activity conditions from both hemispheres. The outflow rates in the last row of Table 4 are the expected range of hemispherical suprathermal ion outflows at high (up to DE-1 apogee) altitude during solar-minimum, geomagnetic quiet conditions, under which the POLAR/TIMAS data reported here were acquired.

The O^+ outflow observed by POLAR is within the range of values expected by Yau and André. The H^+ outflow observed on POLAR is significantly below the expected value. One of the unanswered questions raised by Yau and André [1997] is: “What fraction, if any, of the thermal plasma remains un-energized up to very high altitudes, and therefore may have evaded detection so far?” Yau and André approached the question of estimating the relative importance of the polar wind by separately estimating the net ion outflow rates from the auroral zones and polar caps. We follow their example here. Table 5 presents estimates of total and regional (as defined in the caption to Table 5) outflows from Yau and André [1997, Table 1] appropriate to the solar and geomagnetic conditions encountered by POLAR (i.e. solar minimum and magnetic activity characterized by the K_p index near 2). Table 5 also restates total ion outflows reported here and sums over specific regions in the INVL-MLT maps as indicated in the caption.

The last two rows in Table 5 show the ratio of the ion outflow expected from the analysis of Yau and André [1997] relative to those reported here. The absolute values of the ratios depend strongly on the different INVL/MLT regions defined as auroral zone and polar cap noted in the Table caption. The important information in the last two rows of Table 5 is that the H^+ and O^+ ratios are similar (25 and 17) in the auroral zone but significantly different (100 and 30) in the polar cap. Note that the expected auroral/polar cap ratio in Yau and André is similar for H^+ and O^+ (3.5 vs. 3.0). The POLAR observations reported here show this ratio to be significantly different for H^+ and O^+ (14.4 vs. 5.3). The difference between the polar cap and auroral zone regions is, of course, that the relative contribution of the polar wind to the rate of escaping ions is relatively more important in the polar cap. Another way to look at the relative importance of the thermal polar wind component of escaping ions is presented in Table 6.

Table 6 shows explicitly that the sum of the thermal outflow estimate from Akebono and the energetic outflow observed on POLAR in the 6,000 to 8,000 km range is directly comparable to the outflow rate derived from DE -1 data using eqn's 1-5 above. As noted in Table 2, the DE -1 data on which eqn's 1-5 are based was obtained in the altitude range 16,000 to 24,000 km, and at energies in the range 10eV-17keV. It is important to note that the polar wind data available for the Yau and André analysis and used in the estimate in the first row of Table 6 were lower-limit estimates obtained at solar maximum, as solar minimum data were not yet available.

We interpret the data in Table 6 and the difference in ratios reported in Table 5 and noted above to imply that the POLAR observations do not include the very significant flux of low energy H^+ ions associated with the polar wind. This conclusion implies that a substantial fraction of the polar wind is accelerated to energies within the DE-1/EICS energy range between these two altitude ranges. In the paragraph below, we summarize the other observational evidence in the literature supporting this conclusion.

Abe et al. [1993, 1996] report that the polar wind velocity increases significantly in the altitude range between 6,000 and 10,000 km, i.e. within and above the region of the POLAR observations reported here. Reports of the occurrence probability of ion beams and conics based on data from the DE -1 EICS instrument show an increased probability of detecting an ion beam or conic above 16,000 km [Yau et al., 1984, 1985a,b, Kondo et al., 1990, Peterson et al., 1992, 1995]. Kondo et al. [1990] showed that, at low levels of magnetic activity (defined as $K_p < 3^+$), and for energies less than 1 keV, the probability of encountering an H^+ or O^+ ion beam at 20,000 km was more than twice that at 8,000 km. Peterson et al. [1995] showed that the upward flux associated with O^+ conics was ~5 times higher at 20,000 km than at 8,000 km. The same study showed that the flux associated with He^+ conics was significantly lower and nearly independent of altitude. Miyake et al. [1993, 1996] confirmed the increase of conic energy with altitude using data from Akebono.

Escape of O^+ from the ionosphere is significantly impeded by both gravity and an accidental charge exchange mechanism with neutral hydrogen [Moore, 1980]. Energy added to the ionosphere by solar and magnetic activity only partially overcomes these barriers. Several studies [e.g. Peterson et al., 1993, and Lu et al. 1992] have shown that additional energy has to be transferred to O^+ above the ionosphere to account for observed outflow rates. At what altitude(s) and how that energy is added is a topic of current research. The data presented above seem to suggest that there is little or no thermal O^+ above 8,000 km. We caution the reader that it is not possible to reach this conclusion from the data presented here because, as noted above, the estimates of the O^+ polar wind flux reported in Table 6 are lower-limit estimates that were obtained at solar maximum.

We did not expect to find the significant, mass dependent, difference in ion outflow rates discussed above when we designed the data analysis reported here. We note that the POLAR satellite obtains considerable data at higher altitudes in the northern hemisphere and that a systematic investigation of escaping fluences from the northern hemisphere could be used to affirm or refute the conclusion above. The methods and tools developed for this study will have to be significantly modified to process data from POLAR apogee into a form that can be compared with the results presented here.

Seasonal variations of ion outflow:

Recent reports of the seasonal modulation in the strength of upflowing ion beams in the evening MLT sector [e.g. Collin et al., 1998] show the importance of quantifying seasonal variations of other parameters that might possibly have an affect on the strength of the magnetosphere/ionosphere interaction. The data presented in Figures 1 and Table 1 provide a previously unavailable comprehensive seasonal overview of the composition and magnitude of escaping ionospheric ions. These data indicate summer/winter ratios of the net ionospheric outflow rates for H^+, He^+ and O^+ of 0.9, 0.4, and 1.0 respectively. The only previous report of seasonal variations of ion outflow [Yau et al., 1985a] was severely restricted by the characteristics of the DE-1 orbit which gave less than ideal seasonal sampling and did not include the third major ionospheric ion, He^+.

The significant seasonal variations in He^+ outflow is not unexpected. Hoffman and Dodson [1980] reported nearly an order of magnitude in seasonal variations in the thermal (<5 eV) upflowing He^+ ion fluxes at 1400 km. In particular they reported the peak He^+ flux was 2×10^7 and the averaged summer value was 1.5×10^6 in units of $(cm^2\text{-s-sr})^{-1}$. The reason for the summer/winter variation in He^+ outflow is that the helium neutral concentration at the exobase is significantly (20 to 30 times) greater in winter than summer [Mauersberter et al., 1976]. The variation in the neutral He density has been captured in the MSIS model [Hedin, 1987]. The summer/winter He^+ outflow ratio reported here is significantly lower than that reported by Hoffman and Dodson [1980]. We note that the fluxes Hoffman and Dodson reported are from a few representative months of data centered on solstice. The 0.4 summer/winter ratio of escaping suprathermal He^+ reported here was obtained during 30 months of solar minimum conditions and 6 month “seasons” centered on solstice.

The hemispherical net outflow rates of ionospheric H^+ and O^+ show no significant summer/winter modulation. Variation of the MLT/INVL distribution of suprathermal ionospheric ion outflow rates for all major ionospheric species are seen in Figure 1 both between summer/winter and successive seasons. These features are both interesting and significant. They are, however, beyond the scope of this paper.

Conclusions:

We have examined data obtained by the TIMAS instrument from POLAR perigee passes from April 1, 1996 to September 31, 1998. In this report we have focused on the total outflow rates of suprathermal ionospheric ions and their seasonal variability. We conclude from our analysis:

1) The differences between the net outflow rates of suprathermal ions presented here and previous DE-1 estimates can be explained by, and are consistent with, energization of the H^+ component of the polar wind above the 6,000-8,000 km region where the POLAR data were acquired.

2) The seasonal variations in He^+ outflow presented here are not as strong as those obtained nearly 40 years ago from the ISIS satellite and reported by Hoffman and Dodson [1980].

We did not expect to find the significant, mass dependent differences in ion outflow rates. We therefore did not design our study to examine variations in ion outflow rates as a function of ion energy, altitude or energization mechanism (i.e. ion beams or conics). Clearly such studies are indicated in view of the results presented here.

Acknowledgments: The analysis reported here would not have been possible without the leadership and dedication of Ed Shelley. The work was supported by NASA contract NAS5-30302, NASA grant NAG5-8043, NSERC grant OGP0183733, and internal Lockheed Martin funds. W.K.P. thanks Dan Baker and the staff at LASP for their hospitality.

References:

Abe, T., B.A. Whalen, A.W. Yau, S. Watanabe, E. Sagawa, and K. Oyama, Altitude profile of the polar wind velocity and its relationship to ionospheric conditions, *Geophys. Res. Lett., 20*, 2825, 1993.

Abe, T., S. Watanabe, B.A. Whalen, A.W. Yau, and E. Sagawa, Observations of polar wind and thermal ion outflow by Akebono/SMS, *J. Geomag. Geoelectr., 48*, 319, 1996.

Chappell, C.R, The terrestrial plasma source: A new perspective in solar-terrestrial processes from Dynamics Explorer, *Rev. Geophys, 26*, 229, 1988.

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, 1987

Collin, H. L., W. K. Peterson, J. F. Drake and A.W. Yau, The helium components of energetic terrestrial ion upflows: their occurrence, morphology, and intensity, *J. Geophys. Res., 93,* 7558, 1988.

Collin, H.L., W.K. Peterson, A.W. Yau, and E.G. Shelley, An empirical model of ionospheric ion output as a function of solar EUV and magnetospheric activity, presented at the IAGA meeting, unpublished manuscript, 1989.

Collin, H.L., W.K. Peterson, O.W. Lennartsson, and J.F. Drake The seasonal variation of auroral ion beams, *Geophys. Res. Lett., 25,* 4071. 1998.

Hedin, A.E. MSIS-86 thermospheric model, *J. Geophys. Res. 92*, 4649, 1987.

Hoffman, J.H. and W.H. Dodson, Light ion concentrations and fluxes in the polar regions during magnetically quiet times, *J. Geophys. Res. 85*, 626, 1980.

Huddleston, M.M., C.J. Pollock, J.S. Pickett, M.P. Wuest, T.E. Moore, and W.K. Peterson, Toroidal ion distributions observed at high altitudes equatorward of the cusp, *Geophys. Res. Lett., 27*, 469, 2000.

Hultqvist, B., M. Oieroset, G. Paschmann, and R. Treumann (Eds.) Magnetospheric Plasma Sources and Losses, Kluwer Academic Publishers, 1999. Also published as a series of articles in *Space Science Reviews*, vol. 88, 1999.

Kondo, T., B.A. Whalen, A.W. Yau, and W.K. Peterson, Statistical analysis of upflowing ion beam and conic distributions at DE 1 altitudes, *J. Geophys. Res. 95*, 12091, 1990.

Lennartsson, O.W., H.L. Collin, A.G. Ghielmetti, and W.K. Peterson, A statistical comparison of the outflow of N_2^+, NO^+, and O_2^+ molecular ions with that of atomic O^+ ions using Polar/TIMAS observations, to appear in the *Journal of Atmospheric and Solar Terrestrial Physics*, 2000.

Lu, G., P.H. Reiff, T.E. Moore, and R.A. Heelis, Upflowing ionospheric ions in the auroral region, *J. Geophys. Res. 97*, 16855, 1992.

Mauersberger, K.D., D.C. Kayser, W.E. Potter, and A.O. Nier, Seasonal variation of neutral thermospheric constituents in the northern hemisphere, *J. Geophys. Res, 81,* 7, 1976.

Miyake, W., T. Mukai, and N. Kaya, On the evolution of ion conics along field lines from EXOS-D observations, *J. Geophys. Res. 98*, 11127, 1993.

Miyake, W., T. Mukai, and N. Kaya, On the origins of the upward shift of elevated (bi-modal) ion conics in velocity space, *J. Geophys. Res., 101*, 26961, 1996.

Moore, T.E., Modulation of terrestrial ion escape flux composition, *J. Geophys. Res., 85*, 2011, 1980.

Peterson, W.K., H.L. Collin, M.F. Doherty, and C.M. Bjorklund, O^+ and He^+ restricted and extended (bi-modal) ion conic distributions, *Geophys. Res. Lett., 19*, 1439, 1992.

Peterson, W.K., A.W. Yau, and B.A. Whalen,Simultaneous Observations of H^+ and O^+ Ions at two Altitudes by the Akebono and Dynamics Explorer -1 Satellites, *J. Geophys. Res., 98*, 11177, 1993.

Peterson, W.K., H.L. Collin, M.F. Doherty, and C.M. Bjorklund, Extended (bi-modal) ion conics at high altitudes, Space Plasmas: Coupling Between Small and Medium Scale Processes, Geophysical Monograph #86, M. Ashour-Abdalla, T. Chang, and P. Duesenbery (Eds.), American Geophysical Union, pg. 105, 1995.

Pollock, C.J., M.O. Chandler, T.E. Moore, J.H. Waite Jr., C.R. Chappell, and D.A. Gurnett, A survey of upwelling ion event characteristics, *J. Geophys. Res*, *95*, 18969, 1990

Shelley, E. G., A. G. Ghielmetti, H. Balsiger, R. K. Black, J. A. Bowles, R. P. Bowman, O. Bratschi, J. L. Burch, C. W. Carlson, A. J. Coker, J. F. Drake, J. Fischer, J. Geiss, A. Johnstone, D. L. Kloza, O. W. Lennartsson, A. L. Magoncelli, G. Paschmann, W. K. Peterson, H. Rosenbauer, T. C. Sanders, M. Steinacher, D. M. Walton, B. A. Whalen and D. T. Young, The Toroidal Imaging Mass-Angle Spectrograph (TIMAS) for the POLAR mission, *Space Science Reviews, 71*, 497, 1995.

Trattner, K.J., S.A. Fuselier, W.K. Peterson, S.-W. Chang, R. Friedel, and M.R. Aellig, Origins of energetic ions in the cusp, submitted to *J. Geophys. Res.*, March, 2000.

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, 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, 1985a.

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, 1985b.

Yau A.W., W.K. Peterson, and E.G. Shelley, Quantitative Parameterization of Energetic Ionospheric Ion Outflow, in Modeling Magnetospheric Plasma, Geophysical Monograph 44, American Geophysical Union, Washington, DC. pg. 211, 1988.

Yau A.W. and M. André, Sources of ion outflow in the high latitude ionosphere, *Space Sci. Rev. 80, 1*, 1997.

FIGURE CAPTION:

Figure 1: Top: Maps of southern hemisphere net outflow rate of ionospheric H^+, He^+ and O^+ as a function of invariant latitude and magnetic local time. Invariant latitude runs from 55 degrees to 90 degrees in 2.5 degree steps and magnetic local time is in hour steps. The fifteen maps show color coded net upward fluence in units of ions $(m^2\text{-s})^{-1}$ for two summer and three winter "seasons" (6-month intervals centered approximately on the summer and winter solstices). Bottom: Line plots of the daily sum of planetary K_p index values (black) and solar radio flux index, $F_{10.7}$, (red) for the interval over which the data were acquired.

TABLES and Table Titles

Table 1.

	Fluence			
	H^+	He^+	O^+	Total
Summer:				
1997	2.8×10^{24}	4.5×10^{23}	2.7×10^{24}	5.6×10^{24}
1998	1.7×10^{24}	4.2×10^{23}	3.4×10^{24}	5.2×10^{24}
Winter:				
1996	3.8×10^{24}	7.4×10^{23}	3.0×10^{24}	7.0×10^{24}
1997	2.1×10^{24}	8.2×10^{23}	2.4×10^{24}	4.7×10^{24}
1998	1.7×10^{24}	1.8×10^{24}	3.5×10^{24}	5.9×10^{24}

Table 1. Net outflow rates or fluence of ionospheric ions and their sum (total) from each season presented in Figure 1. The units are ions per second. Note that the rates are not global; they are from one hemisphere.

Table 2

	DE-1 (Yau et al.)	*DE-1 (Collin et al.)*	*POLAR (This report)*
Energy -Range	0.01-17 keV	0.01-17 keV	0.015 - 33 keV
# energy bins	3	32	28
Angular -resolution	~20^o	15^o	22^o
Altitude (km)	16,000-24000	16,000-24,000	6,000-8,000
Average K_P	3^+	3^+	2^-
Range of K_P	0-9	0-9	0-7
Average $F_{10.7}$	~120	~120	84
Range of $F_{10.7}$	40-300	40-300	70-190

Table 2. Properties of the ion outflow data bases from DE -1 [Yau et al., 1988, Collin et al. 1989] and POLAR [reported here].

Table 3

Average Solar and Geomagnetic Conditions	*Season*	*Expected Net Ion Outflow Rate (Hemisphere-sec)$^{-1}$*		
$\mathbf{F_{10.7}/K_P}$		H^+	He^+	O^+
72.9 / 1.8	Summer ‘97	1.5 (2.0) x 10^{25}	5.5 x 10^{23}	5.8 (9.4) x 10^{24}
94.6 / 1.6	Summer ‘98	1.4 (1.8) x 10^{25}	6.7 x 10^{23}	6.9 (10.5) x 10^{24}
71.9 / 1.8	Winter ‘96	1.5 (2.0) x 10^{25}	5.4 x 10^{23}	5.7 (9.3) x 10^{24}
79.5 / 1.6	Winter ‘97	1.4 (1.9) x 10^{25}	5.6 x 10^{23}	5.7 (9.0) x 10^{24}
121.2 / 2.1	Winter ‘98	1.6 (1.9) x 10^{25}	1.1 x 10^{24}	1.3 (1.8) x 10^{25}
88 / 1.8	**Average**	1.5 (1.9) x 10^{25}	6.8 x 10^{23}	0.74 (1.1) x 10^{25}

Table 3. Expected net ionospheric ion outflow rates from the southern hemisphere determined from equations 1-5 using the average solar and geomagnetic conditions in column 1. Values from equations 1 and 2 are in parentheses; values from equations 3,4, and 5 are not.

Table 4:

		H^+	He^+	O^+	H^+ / O^+
1	Observations	2.4×10^{24}	8.5×10^{23}	3.0×10^{24}	0.8
2	Collin(eqns 3-5)	1.5×10^{25}	6.8×10^{23}	7.4×10^{24}	2.0
3	Yau (eqns 1-2)	1.9×10^{25}	-	1.1×10^{25}	1.7
4	Collin/Obs	6.3	0.8	2.5	-
5	Yau/Obs	8.5	-	3.7	-
6	Collin/Yau	0.8	-	0.7	-
7	Yau and André	$1.2\text{-}1.8 \times 10^{25}$	-	$2.5\text{-}6.0 \times 10^{24}$	2-7

Table 4. Comparison of the rate of escaping ionospheric ions in units of s^{-1} from various sources. Row 1-POLAR observations reported here. Row 2-derived using eqns 3-5. Row 3-derived using eqns 1-2. Rows 4-6 - ratios as indicated. Row 6-7 derived from a review of the literature by Yau and André [1997]. The range of rates reported by Yau and André correspond to those expected when magnetic activity as indicated by K_P is in the range 0-2.

Table 5:

	H^+	He^+	O^+
Observations			
Total	2.4 x10^{24}	8.5 x 10^{23}	3.0 x 10^{24}
Evening AZ[a]	5.6 x10^{23}	1.2 x 10^{23}	2.6 x 10^{23}
Polar Cap[b]	3.9 x 10^{22}	1.3 x 10^{22}	5.0 x 10^{22}
AZ/Cap	14.4	9.5	5.3
Yau and André			
Total	1.8 x 10^{25}	-	6.0 x 10^{24}
Auroral[c]	1.4 x 10^{25}	-	4.5 x 10^{24}
Polar Cap[d]	4.0 x 10^{24}	-	1.5 x10^{24}
Auroral/Cap	3.5	-	3
Expected/Observed			
Auroral Zone	25	-	17
Polar Cap	100	-	30

Table 5. Net hemispherical outflow rates for ionospheric ions in units of s^{-1} and ratios of outflows from various regions, independent of season, compared to values reported in a recent review by Yau and André [1997]. The values from Yau and André are the upper limit of the quiet-time estimates which correspond to magnetic activity characteristic of the POLAR data set. Auroral zone and polar cap regions indicated by superscripts in the table are defined as follows: a) 1800<MLT<2400 and 65<INVL<75; b) INVL> 80^o ; c) INVL<76^o; d) INVL>75^o.

Table 6:

		H^{+} $(10^{25}\ s^{-1})$	O^{+} $(10^{25}\ s^{-1})$
1	Polar Wind	2.7-3.7	1.3-1.9
2	Suprathermal Observations	0.5	0.6
3	Row 1 + Row 2	3.2-4.2	1.9-2.5
4	Derived from DE -1 models	3-4	1.5-2

Table 6. Global ionospheric ion outflow rates in the units indicated. Row 1 -expected polar wind flux at solar maximum from Yau and André [1997]. Row 2 - twice the hemispherical outflow rates reported in Table 4. Row 3-the sum of Rows 1 and 2. Row 4-derived from Rows 2 and 3 of Table 4. Note that the polar wind data in Row 1 was estimated from Akebono/SMS data obtained at solar maximum. Data from Akebono appropriate for solar minimum are not yet available.

POLAR/TIMAS Outflow Rates