Investigation into the Spatial and Temporal Coherence of Ionospheric Outflow on January 9-12, 1997

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Abstract: Long term average ion outflow data derived from the Dynamics Explorer 1 Energetic Ion Mass Spectrometer data revealed very strong correlation between the net global ion outflow rate and measures of geomagnetic and solar activity as parameterized by the 3 hour Kp, 1 hour AE and Dst, and daily F10.7 indices. We use mass-resolved ion outflow observations from the Akebono, Polar, and FAST satellites obtained during a four day interval to assess the temporal and spatial coherence of ionospheric outflow on shorter time and smaller spatial scales. We find no relationship between locally measured ion outflow and a five minute resolution global monitor of energy exchanged between the ionosphere and magnetosphere. We discuss the implications of this result on models of the magnetosphere that include transport of ions from the ionosphere through the various regions of the magnetosphere.

Keywords: Ion outflow, Magnetosphere-Ionosphere Interactions, Space weather.

Introduction. The mass density of the magnetosphere is not constant locally or globally. Significant and variable fractions of magnetospheric plasma come from the ionosphere and the solar wind. (See Johnson, 1983, and Hultqvist, et al., 1999, for a comprehensive series of review articles on this subject.) Variation in mass density has the largest geophysical consequences in regions where the magnetic field is relatively weak, i.e. in the plasma sheet and boundary layer where the plasma and magnetic pressures are comparable in magnitude. Several investigators have noted that the time of flight of low energy ionospheric plasma to the plasma sheet is of the same order of magnitude as the average interval between substorms (e.g., Peterson et al., 2001), and that changes in mass composition in the plasma sheet could be responsible for substorm onset (e.g., Cladis and Francis, 1992). It is currently not possible to systematically investigate the geophysical consequences of variations in mass composition because of the lack of simultaneous global sampling or global models. For example, only one of the current large scale magnetospheric models attempts to calculate temporal and spatial variations of the magnetospheric ion composition (Li, et al., 2000). Near simultaneous global data coverage is, of course, not practical. The only practical way to investigate and understand the long term feedback effects thought to be associated with changes in ion outflow and mass composition is to self consistently include ion outflow in large scale magnetospheric models.

Quantitative information on ion outflow is sparse. For a recent review see Yau and André (1997). Long term average ion outflow data derived from the Dynamics Explorer (DE) 1 Energetic Ion Mass Spectrometer by Yau et al. (1988) revealed very strong correlation between the net global ion outflow rate and measures of geomagnetic and solar activity as parameterized by the 3 hour Kp, 1 hour AE and Dst, and daily $F_{10.7}$ indices. For example, Figures 1 and 2, reproduced from Yau et al. (1988) show the variation in H^+ and O^+ outflows as a function of the 3 hour K_p index (Figure 1) and a 1 hour A_E index (Figure 2). Both figures show that O^+ outflow is strongly influenced by the solar EUV radiation present at high levels of the $F_{10.7}$ solar activity index. Yau et al. (1988) have reported empirical relations of the net ion outflow as a function of these solar and geomagnetic indices. Because the DE 1 orbit was such that all latitudes and local times were covered once every 18 months, the empirical relations derived from the data in Figures 1 and 2 are not necessarily appropriate to include in magnetospheric models with higher temporal and spatial resolution.

Long term data bases of well-calibrated data from which ion outflow information can be obtained are currently available only from the DE 1, Akebono, and Polar satellites. Yau et al. (1988) and Collin et al. (1989) have independently derived empirical models of the magnitude of ion outflow averaged over the polar cap as a function of the energy exchange between the magnetosphere and ionosphere parameterized by geomagnetic and solar activity from data obtained on the DE 1 spacecraft. These parameterizations have recently been validated using data obtained on the Polar and Akebono spacecraft (Peterson et al., 2001, Cully, 2001). These papers clearly resolve and quantify the variation of global H^+ and O^+ outflow rates with magnetic and solar activity. Peterson et al. (2001) show that outflow occurs at auroral and polar cap latitudes at all local times, but is most intense near noon and midnight magnetic local times. Tung et al. (2001) also provide quantitative information about the importance of the midnight region of ion outflow using data obtained on the FAST spacecraft.

Almost no information is currently available on simultaneous spatial and temporal variations or coherence of ion outflow, although various investigators are working on the problem (e.g., Wilson et al., 2001, Stevenson et al., 2001, and Hirahara et al., 1998). Quantitative information on the spatial and temporal coherence of ion outflow is clearly required before significant progress can be made in incorporating ion outflow into global magnetospheric models. In particular we need to understand how accurately ion outflow can be characterized locally by global monitors of the energy exchange between the ionosphere and magnetosphere.

The purpose of this paper is to determine if the parameterization of ion outflow as a function of geomagnetic indices (e.g. Yau et al., 1988) that was successful on global spatial and 18 month temporal scales can be extended to shorter time and smaller spatial scales.

Observations.

January 9-12, 1997 was the first interval of significant geomagnetic activity for which data from instruments capable of monitoring ion outflow on the FAST, Akebono, and Polar satellites were all available. Lu et al. (1998) and others have extensively characterized the magnetosphere during this interval. In particular, Lu et al. have examined some global, high time resolution (5 min.) monitors of energy deposition into the ionosphere in terms of Joule heating and auroral precipitation, which they found are reasonably well correlated with a 5 minute A_E index they independently derived from 68 magnetometer stations located between 55 and 76 degrees magnetic latitude.

On the FAST satellite the TEAMS instrument provides mass resolved ion spectra from 1 eV to 12 keV (Klumpar et al., 2001). On the Polar satellite the TIMAS instrument provides mass resolved ion spectra over the energy range 15 eV to 33 keV (Shelley et al., 1995). On the Akebono satellite the SMS instrument provides mass resolved ion spectra from 0 to 4000 eV in two independent sensor ranges (Whalen et al., 1990). The Akebono data presented here are from the lower (0 to 70 eV) energy range. Details of the orbits of these satellites and other information about the instruments and data presented below are displayed in Table 1.

Figure 3 presents an overview of the times for which data were acquired and the positions of the three satellites for the interval from January 9, 1997, at 00:00 UT to January 13, 1997, 00:00 UT. Data intervals acquired over the southern hemisphere are indicated by negative values of invariant latitude. It is clear from Figure 3 that data were not uniformly acquired. Akebono data are not available for January 10. FAST data are not available for a large portion of January 11. As indicated in Table 1, no Akebono data were acquired in the cusp region (defined here as all invariant latitudes between 0900 and 1500 magnetic local time) and most (>60%) of the Polar data were acquired at apogee over the northern polar cap (defined here as above 75 degrees invariant latitude and not between 0900 and 1500 magnetic local time). Unfortunately only limited data is available from Akebono from the periods of the most intense magnetic activity. There were no instances where data was available when two of the satellites were magnetically conjugate.

The January 9-12 interval is useful to investigate because it includes intervals of both quiet and disturbed magnetic activity. Figure 4 presents a plot of the 5 minute resolution A_E index for the interval reported by Lu et al. (1998). In the interval of interest there are one extended and two short periods of relatively intense magnetospheric power input interspersed with extended periods of little power input (i.e., where the A_E index was below about ~50 nT).

Figure 5 presents an overview of the H^+ and O^+ outflow data acquired from Akebono/SMS, Polar/TIMAS, and FAST/TEAMS for the interval of interest as a function of the 5 minute resolution A_E index at the time of the measurements. The units of ion outflow are ions/m^2-s. All data values are normalized to 300 km for comparison with previous work (eg. Loranc et al. 1991, Yau et al., 1988). The Akebono data were derived by directly integrating observations corrected for the effects of the spacecraft potential. Data presented here from Polar and FAST are from the partial energy ranges shown in Table 1. The Polar data reported here were obtained from the product of density and velocity moments. The FAST data reported are from direct integration of observed energy-angle distributions. We have not corrected the computed fluxes for the net downward flux associated with loss cone type distributions. Peterson et al. (2001) have noted that the magnitude of influx of ions directly calculated from a distribution with a well-developed loss cone is negligible for O^+ and reduces the H^+ outflow values only a few percent.

Data points are included in Figure 5 only for measurements showing net upflowing ion flux. As noted in Table 1, there is a wide variation in the fraction of data points with upflowing flux. This value ranges from 85% for O^+ measured on Akebono to 16% for H^+ measured on FAST. Yau et al. (1988), Collin et al. (1989), and Peterson et al. (2001) reported net outflowing fluxes only for intervals where the instrumental count rates were large enough to assure that the fluxes were significantly above the level of uncertainty in the measurement. No such criteria have been applied to the data presented in Figure 5. If the requirement that fluxes exceed the standard deviation by a factor of 1.5 (the criteria used by Peterson et al.) is applied to the Polar data in Figure 5, 79% of the O^+ and 42% of the H^+ data points would be removed. With the exception of a slight reduction in the magnitude of the fluxes, the general distribution and scatter of the Polar data points satisfying the 1.5 sigma criteria (not shown) is qualitatively similar to that shown in Figure 5. The FAST and Akebono data available for this investigation did not include estimates of their statistical significance, so no such test could be made.

The solid lines shown on each panel in Figure 5 are plots of the functions $4 \times 10^{10} \times A_E^{0.4}$ (for H^+) and $2 \times 10^{10} \times A_E^{0.8}$ (for O^+). The functional form and constants were chosen to provide a common basis to intercompare data both within Figure 5 and with the empirical ion outflow model of Yau et al. (1988). Comparison of the relative position of these lines with the scatter plotted data in Figure 5 shows systematic variations in the absolute magnitudes of the outflowing ion fluxes observed on the three platforms. We note that there were no Akebono observations from the cusp region, which is characterized by large fluxes of escaping O^+ at all levels of magnetic activity, included in the data presented here. The fluxes reported from Polar and Fast have not been corrected for the effects of a non zero spacecraft potential and do not include the lowest energies . The values of the outflowing fluxes from Akebono are consistent with those reported by Abe et al. (1993a,b, 1996). The Polar fluxes reported in Figure 5 are slightly higher than those reported by Peterson et al. (2001) because no statistical criteria were used to select data. The Polar fluxes shown in Figure 5 are also, on average, slightly higher than those obtained from FAST. We do not consider the differences between Akebono, Polar, and FAST fluxes shown in Figure 5 significant, because of systematic differences in the regions sampled, uncertainties in the relative instrumental calibrations, and altitude dependent energization of the polar wind as discussed by Peterson et al. (2001).

The most important feature in Figure 5 is the magnitude of the variation of outflowing fluxes recorded at similar levels of geomagnetic activity. We attempted to reduce the scatter in the data by considering time of flight effects and variations in characteristic ion outflow by region. Specifically, we examined the H^+ and O^+ fluxes from the three platforms by region (cusp, auroral zone, and polar cap) and found the amount and magnitude of scatter was similar to that in Figure 5. For example, Figure 6 presents data obtained in the auroral region (defined here as the region below 75^o invariant latitude, and not between 09 and 15 hours magnetic local time) with no delay between the time of observation and the time associated with the five minute resolution A_E index. Figure 7 presents the same data that is in Figure 6, but includes the time delay between the ionosphere and the various satellite altitudes assuming a constant velocity of 10 km/s for both H^+ and O^+. We also examined the H^+ and O^+ fluxes from the three platforms as a function of the 5 minute resolution A_E index at times corrected for time of flight from the ionosphere at constant velocities of 1, 10, and 100 km/s by region. These results of this revealed scatter similar to that shown in Figures 5, 6, and 7.

Discussion:

The data presented in Figures 5, 6, and 7 were assembled to address the question: How spatially and temporally coherent are the fluxes of escaping ionospheric ions? In particular: How well can ion outflow be characterized locally by global monitors of the energy exchange between the ionosphere and magnetosphere?

The only existing models of ion outflow are the parameterizations of global ion outflow by Yau et al. (1988) and Collin et al. (1989). These empirical models were derived assuming that global energy parameters such as A_E and Kp are directly related to local measurements of ion outflow. These investigators sorted local measurements of ion outflow data obtained from DE -1 over the full range of solar activity in the last solar cycle into a global model organized by invariant latitude, magnetic local time and solar and magnetic activity indices. They independently determined that the global outflow of H^+ was proportional to $A_E^{0.4}$ and the global outflow of O^+ was proportional to $A_E^{0.8}$. The proportionality factors used to generate the solid lines in Figures 5, 6, and 7 are those appropriate for low solar activity conditions encountered in January 1997.

The scatter in the magnitudes of outflowing fluxes at low and moderate activity levels (i.e., $A_E <$ 500 nT) is about 4 orders of magnitude for all three platforms. There is little data available from Akebono and Polar at higher levels of activity, but there is no indication that the magnitude of the scatter is significantly less above 500 nT than below. As described above, we have examined sub-sets of the data from the cusp, auroral zone, and polar cap, and in a framework adjusted to correct for the time of flight for low energy ions to reach the various satellites. The scatter in the ion outflow fluxes was not significantly reduced when the data were examined in this way.

Figures 5, 6, and 7 show that significant and variable intensity fluxes of O^+ and H^+ are escaping the ionosphere at all levels of activity from all regions of the auroral and polar ionosphere. In fact, the limited data presented here suggest larger fluxes of H^+ than predicted by the Yau et al. [1988] empirical relations leaving the ionosphere at the lowest levels of magnetic activity. The larger data sets assembled by Yau et al. and Collin et al. clearly show that, on average and globally, the rate of ion outflow increases with both magnetic and solar activity. The data in Figures 5, 6, and 7 illustrate the large degree of variability in ion outflow.

We conclude that the variability shown in Figure 5 is a direct reflection of spatial and temporal variations in ion outflow. This conclusion is based on the fact that we were unable to reduce the scatter in data plots of ion outflow as a function of A_E by considering data from specific regions (i.e. cusp, polar cap and auroral zone) or by assuming a uniform velocity for all escaping ions. Our observations are consistent with the ion outflows being spatially and temporally not as coherent as electron precipitation.

The variability of the intensity and spatial distribution of precipitating electrons into the ionosphere, and especially their filamentary and sheet-like nature, is well documented by the rapid variations in auroral optical emissions. Because the physical processes accelerating electrons into the ionosphere are not the only processes necessary to extract thermal ions from the ionosphere, the lack of large scale spatial and temporal coherence in the ion outflow could not be predicted from existing observations. There are, however, some recent results that suggest some spatial organization in ion outflow. Wilson et al. (2001) have looked at particle distributions acquired on the FAST spacecraft simultaneously with auroral intensities observed by the UVI instrument on Polar at the foot of a magnetic field line passing through the FAST spacecraft. They showed that the data were most easily interpreted by including a variable time delay between the time of FAST observations and UVI image. The interpretation of the Wilson observations is complicated by the coarse spatial resolution of the UVI imager. Nevertheless, they report a weak correlation between the ion outflow observed on FAST and the intensity of the auroral emission at the foot of the field line sampled by FAST. They show that the best fit of the data is obtained by using a different time delay between the FAST and UVI observations for each sub set of data.

The data presented and discussed above show that the simple global parameterization suggested by Yau et al. (1988) does not adequately capture the spatial or temporal variability of ion outflow. Clearly there is a need to organize ion outflow observations in relation to auroral features as suggested by Wilson et al. (2001). Since global optical observations of auroral emissions are limited, we suggest that reporting ion outflow in a coordinate system keyed to dynamic geophysical features such as field aligned current intensity and direction may organize the data as well or better than UV emission data. Peria et al. (2000) have shown that it is possible to cast large scale data bases easily in such a coordinate system. Another approach to capture the variability in ion outflow that could also be used with a larger data set is to adapt the technique used to characterize global energy input from sporadic measurements of electron precipitation (e.g., Foster et al. 1986) to ion outflow observations.

Conclusion:

The data we have examined from three satellites from the 4 days in January, 1997, show that ions leave the ionosphere at all levels of geomagnetic activity. Furthermore our results show that the correlation of global ion outflow with magnetospheric energy exchange reported by Yau et al. (1988) and confirmed by Collin et al.(1989), Peterson et al. (2001) and Cully (2001) only applies to the global average ion outflow. The over four order of magnitude variation in the local outflow rates at all levels of geomagnetic activity shown in Figures 5, 6, and 7 illustrate that the fine temporal and spatial variation observed in auroral optical emissions extends to ion outflow. We infer that the short time and spatial scale variation of ion outflow must be included in any large scale model of the magnetosphere that attempts to include effects of micro and meso scale variations in magnetospheric mass density.

Acknowledgments. Work at the University of Colorado was supported by NASA Grant NAG 10967. Work at Lockheed was supported by NASA contracts NAS-5-30302 and NAS5-31283. Work at HAO/NCAR was supported by the NASA SEC Guest Investigator Program. Work at the University of Calgary was supported by the Natural Science and Engineering Council Canada and the Canadian Space Agency.

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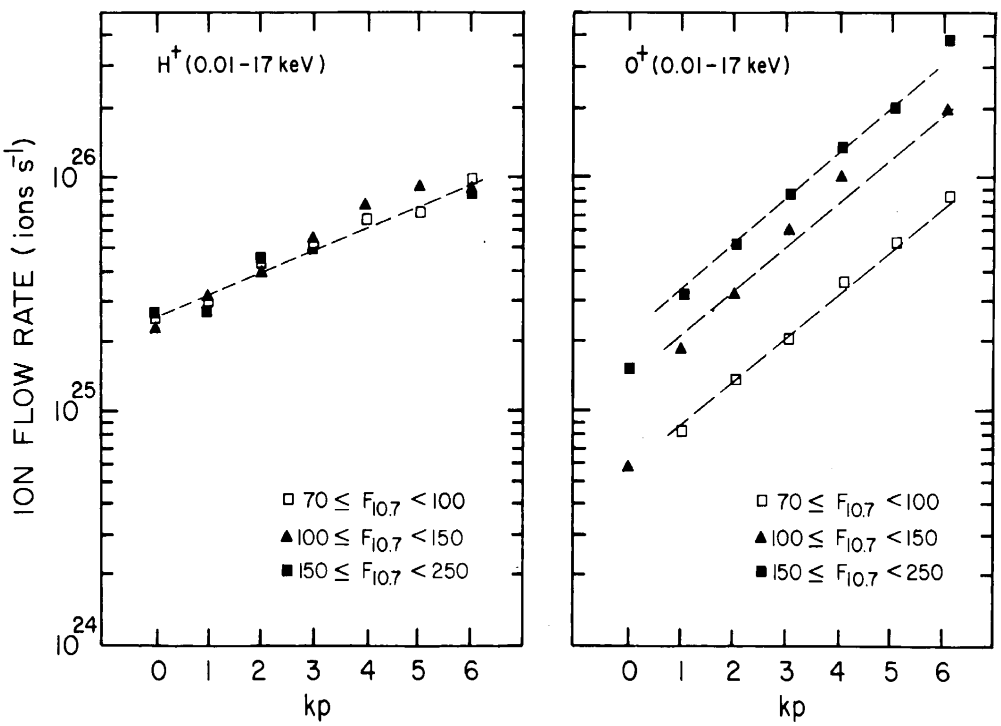

Fig 1 Total ion outflow from both hemispheres as a function of the magnetic index K_p and solar activity index F_{107} derived from six years of data from the Dynamics Explorer 1 Energetic Ion Composition Spectrometer (EICS). Reproduced from Yau et al. (1988)

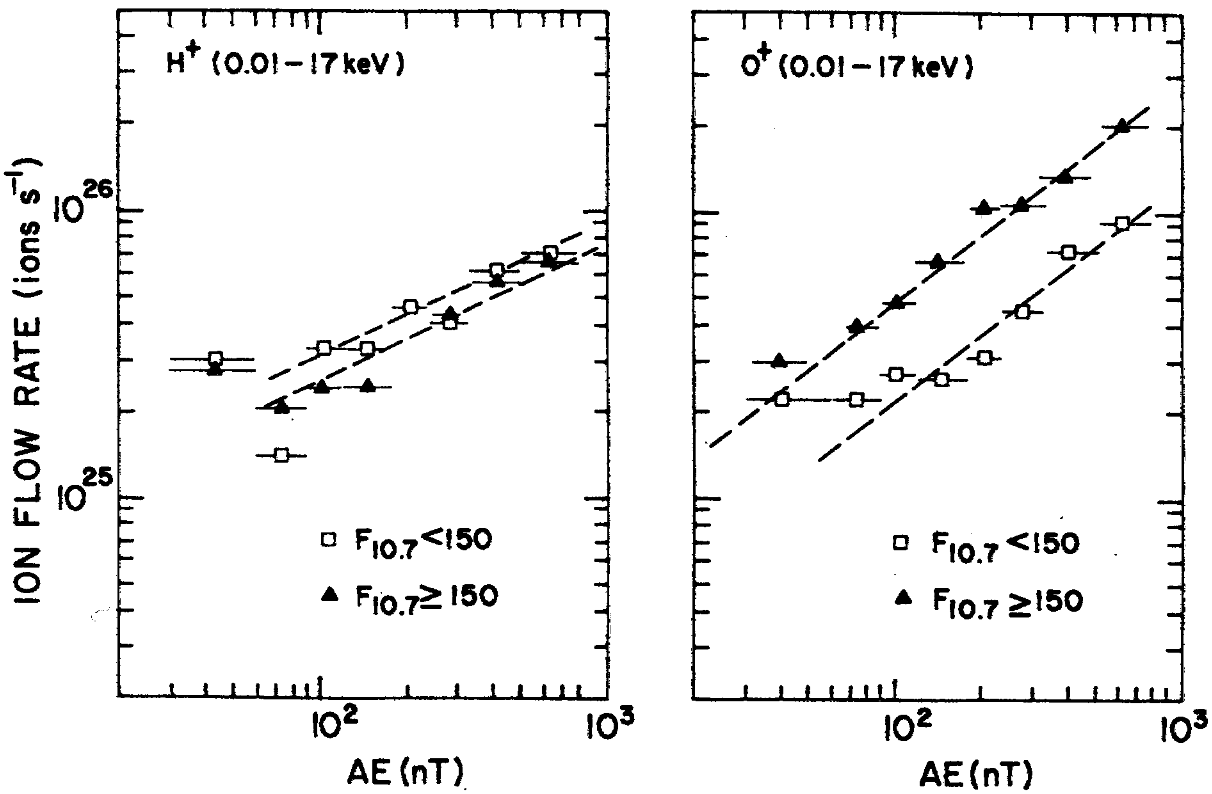

Fig. 2 Total ion outflow from both hemispheres as a function of a one hour resolution magnetic index A_E and solar activity index F_{107} derived from six years of data from the Dynamics Explorer 1 Energetic Ion Composition Spectrometer (EICS). Reproduced from Yau et al. (1988). Note than at the time the data were published availability of the AE index was limited. The number of data samples in the average shown here is significantly less than the average shown in Figure 1.

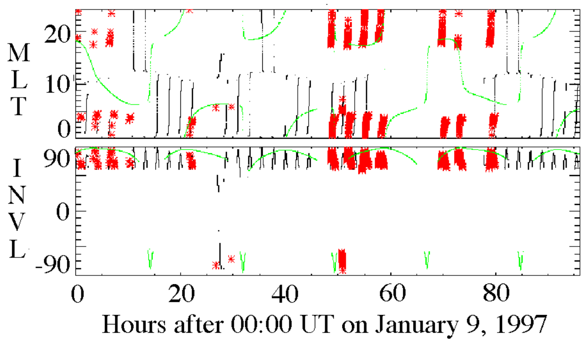

Figure 3: Location in Magnetic Local Time (MLT, top) and Invariant Latitude INVL, bottom) of Akebono (asterisk), Polar (light dotted line)and FAST (solid line) for the 96 hours for which the data presented in Figure 3 were collected.

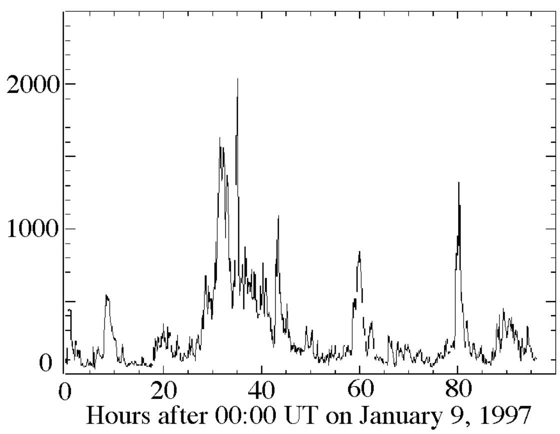

Figure 4: Value of the 5 minute A_E index as a function of time for the interval of interest. Adapted from Lu et al. (1998).

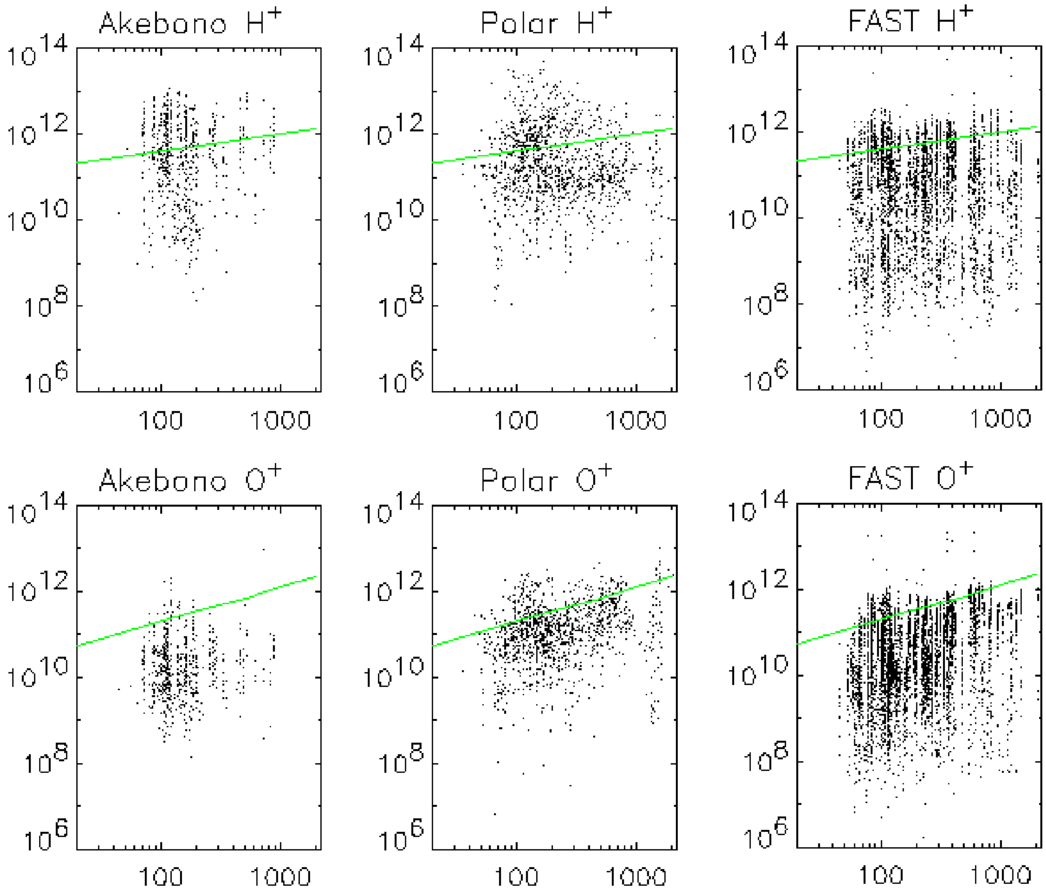

Figure 5. Upward flowing fluxes observed during the January 9-12, 1997 interval . H^+ (top row) and O^+ (bottom row) fluxes acquired from Akebono/SMS (left most pair), Polar/TIMAS (center pair) and FAST/TEAMS (right most pair). The fluxes observed in all magnetospheric regions are plotted as a function of the 5 minute resolution A_E index at the time of the measurements. The units of ion outflow are ions/m^2-s and range from 10^6 to 10^{14}. All data values are normalized to 300 km. The solid lines were derived from global models of ion outflow as discussed in the text.

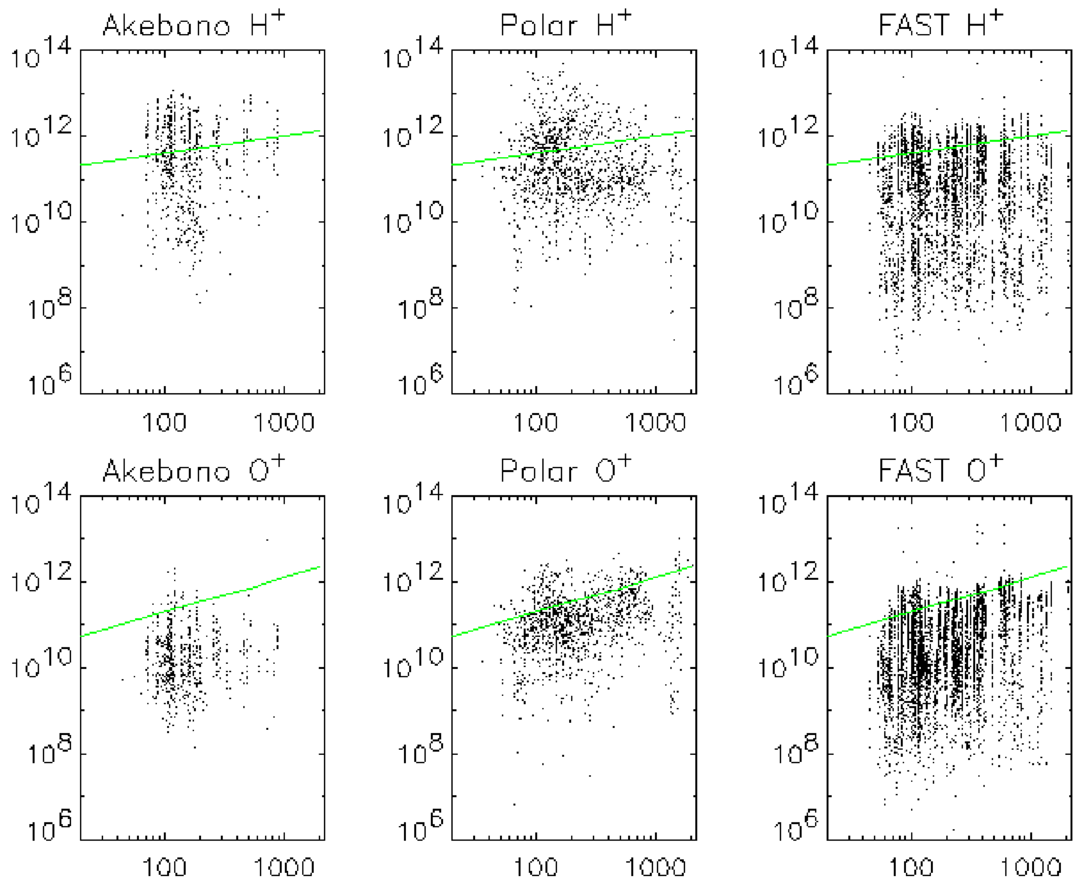

FIG 6. Upward flowing fluxes from the auroral zone as a function of the 5 minute resolution A_E index at the time of the measurements. The format and units are identical to Figure 5. The solid lines were derived from global models of ion outflow as discussed in the text.

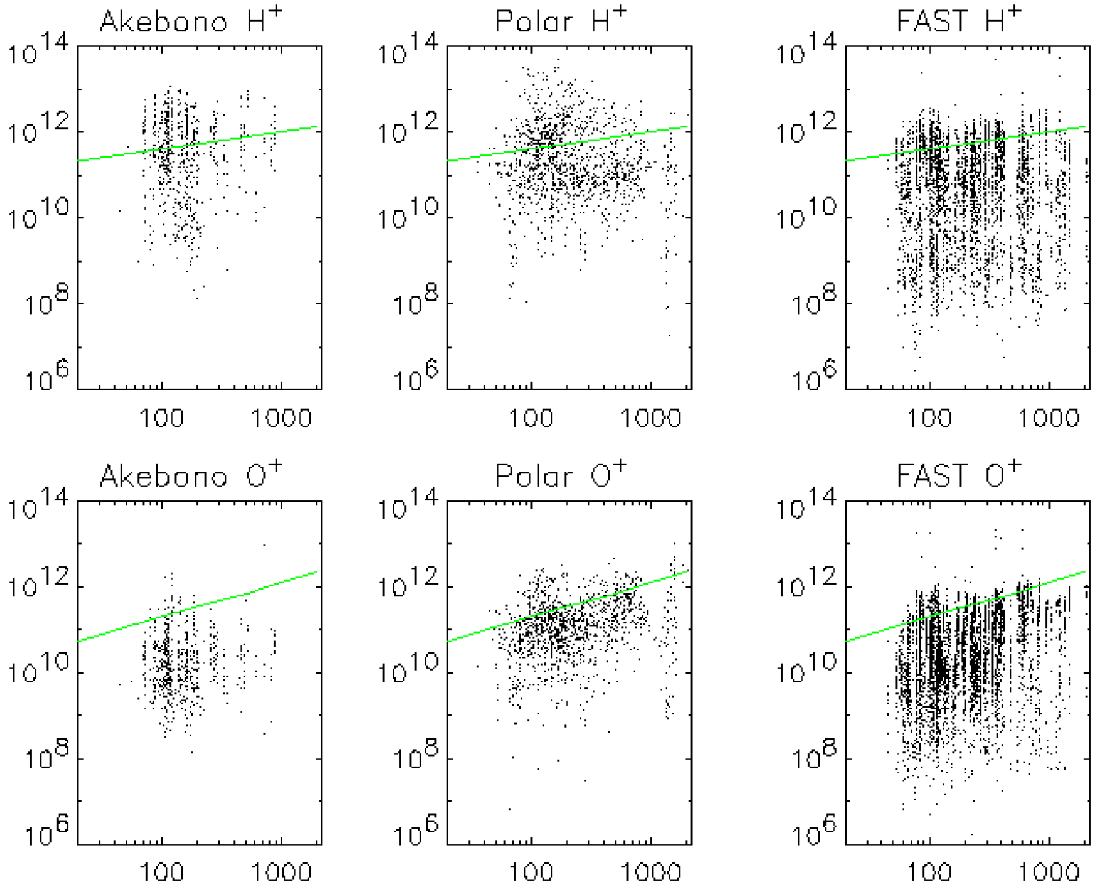

Fig 7. Upward flowing fluxes from the auroral zone as a function of the 5 minute resolution A_E index at a time before the measurements calculated by assuming a constant ion velocity of 10 km/s from 300 km altitude to the satellite at the time of detection. The format and units are identical to Figure 5. The solid lines were derived from global models of ion outflow as discussed in the text.

Table 1: Orbit, Instrument, and Data parameters

	Akebono	Polar	FAST
Energy Range	0-70 eV	15 eV - 33 keV	1 eV - 12 keV
Perigee - Apogee	275 - 10,500 km	2 - 9 Re/R	400 - 4000 km
Inclination	75^{o}	90^{o}	83^{o}
Data interval	8-16 s	192 s[a] 12 s[b]	5 - 20 s
Data samples			
Total	916	1725	7306
Cusp[c]	0%	8%	31%
Polar Cap[d]	37%	63%	34%
Upward			
O^+	85%	71%	48%
H^+	50%	71%	16%

[a]Apogee
[b]Perigee
[c]09-15 MLT
[d]Invl > 75^{o}; outside of cusp MLT range