Spatial and Temporal Coherence of Ion Outflow

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Why do we care about ion outflow and its spatial/temporal coherence?

- Ions contribute significantly to the rigidity of the magnetosphere, especially in the plasma sheet and boundary layer regions
- A significant and variable fraction of the ions in the magnetosphere comes from the ionosphere
- Travel times for O^+ and He^+ from the ionosphere to the plasma sheet are of the same order as the time between substorms

Is there a long time scale feedback from ion outflow to magnetospheric dynamics?

How do we go about proving or disproving such feedback exists?

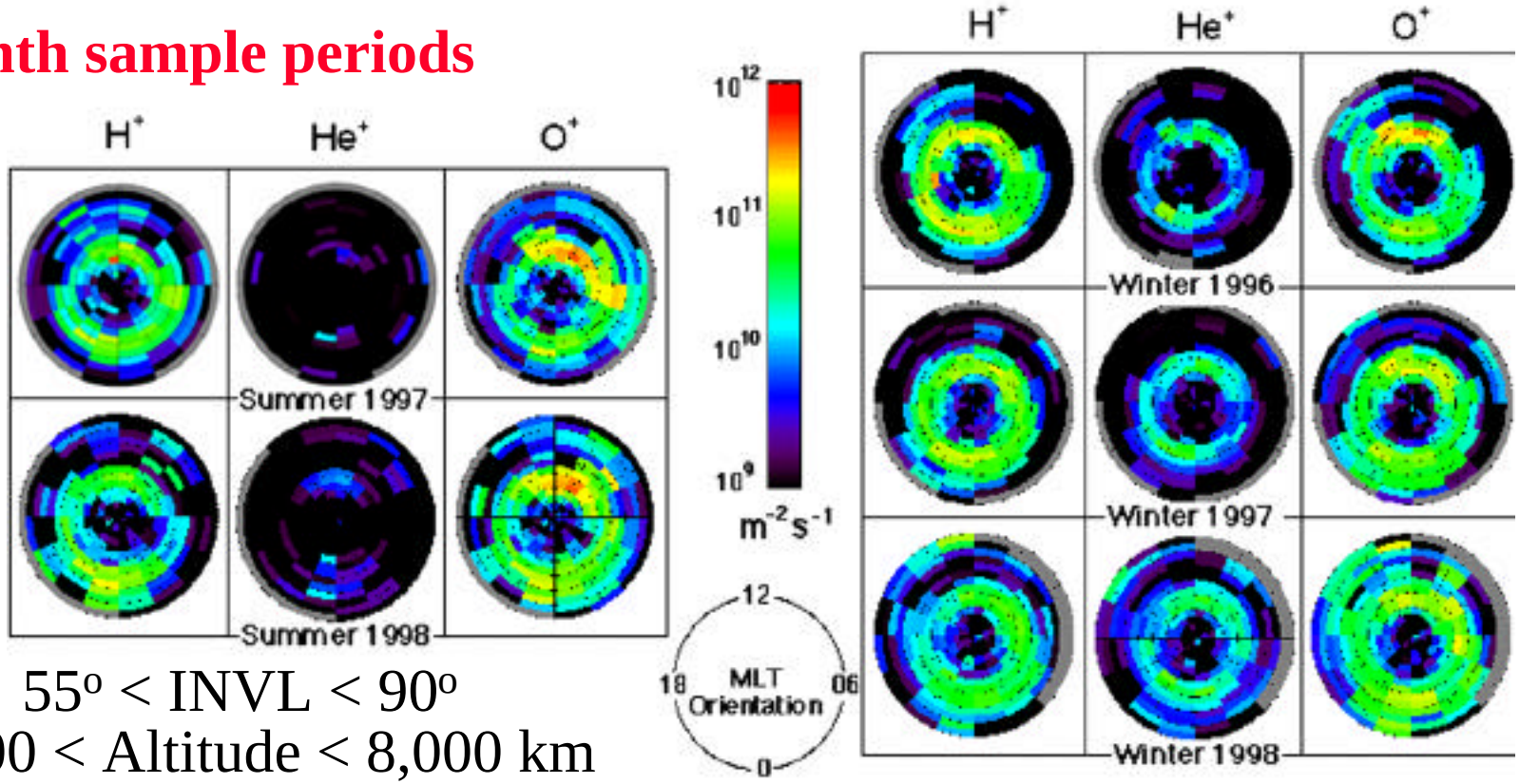
Peterson and Yau, IAGA G3.03, 2001

- It has been difficult to explore the relevance of ionospheric plasmas to long time scale magnetospheric processes because:
  - Magnetospheric convection and long travel times from the magnetosphere make it difficult to relate events in the ionosphere with events in the plasma sheet and equatorial magnetosphere.
  - **There is very little information available about the spatial and temporal coherence of plasma escape from the ionosphere!**
- Large scale magnetospheric models can provide a means to identify and quantify feedback, if any, between ionospheric outflow and geomagnetic storms and substorms.
  - **Models would be easier to build and understand if large scale coherent features in ion outflow existed and could be exploited**

Peterson and Yau, IAGA G3.03, 2001

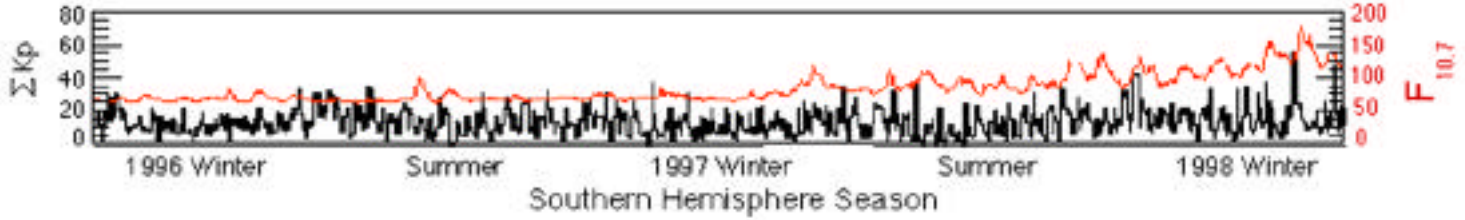
Hemispherical ion outflow rates as a function of season and species show the association with auroral zone and noon/midnight maxima

6 month sample periods



55° < INVL < 90°

6,000 < Altitude < 8,000 km

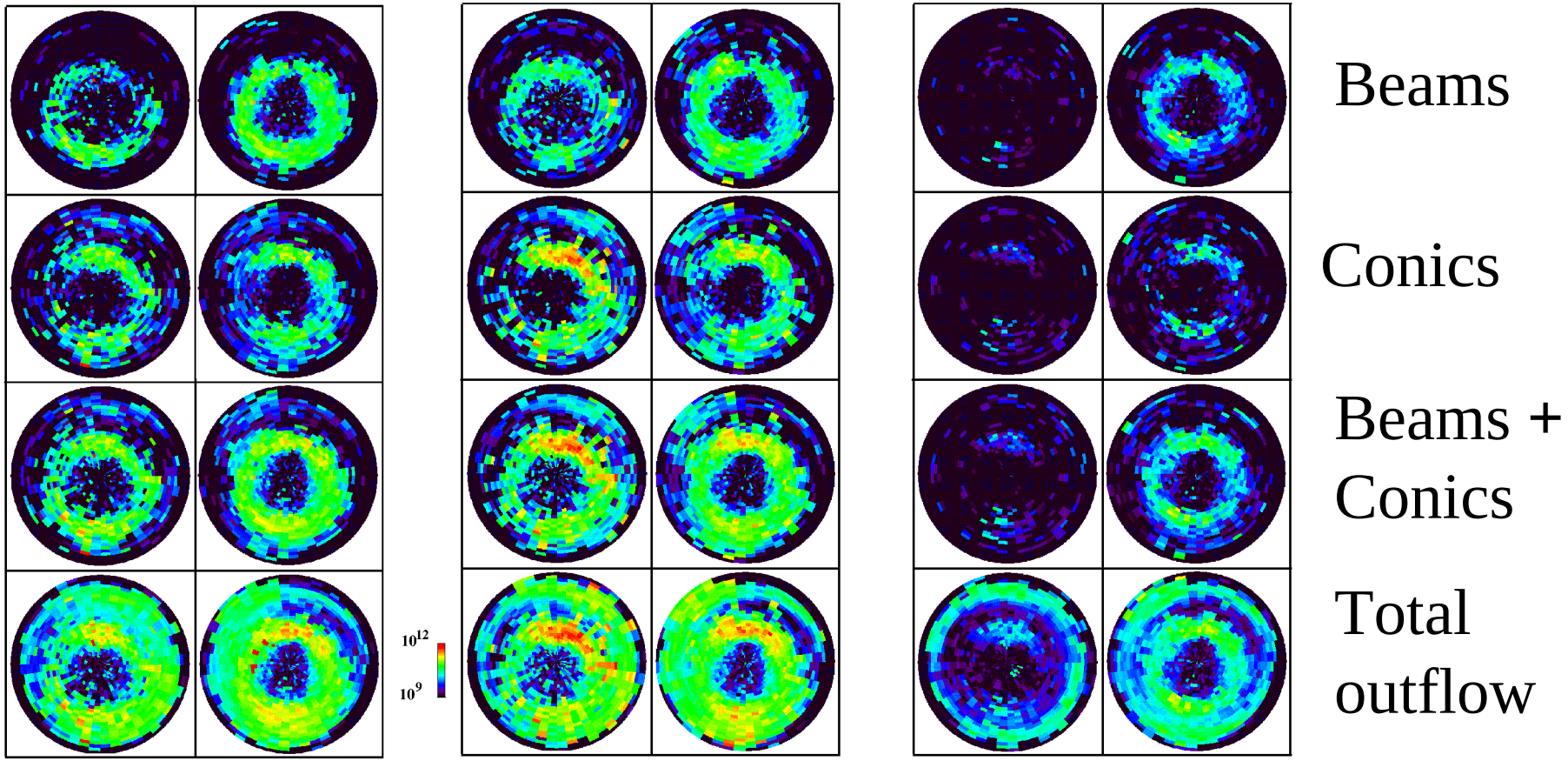


Polar TIMAS instrument, 15 eV < E/q < 33 keV, 3/96 - 12/98

Peterson and Yau, IAGA G3.03, 2001

There is a seasonal variation in acceleration processes, but the total ion outflow for H^+ and O^+ is independent of season in the **solar minimum** Polar/TIMAS data set. Winter He^+ is >2x Summer He^+ outflow.

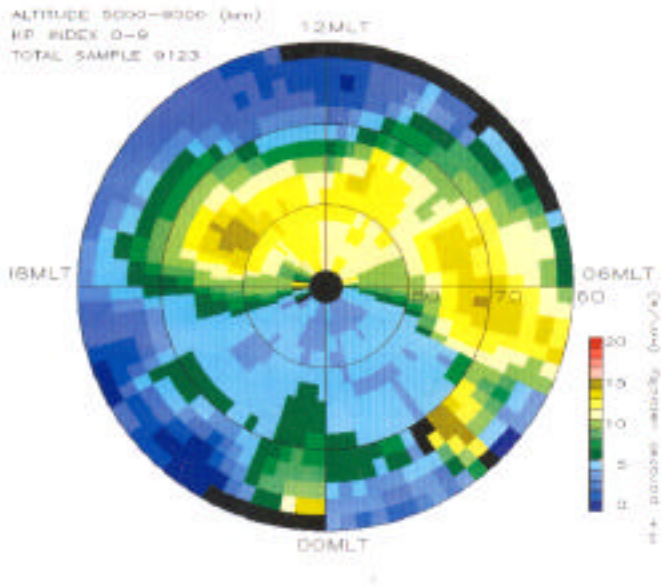
Left column - Summer **Right column - Winter**



Peterson and Yau, IAGA G3.03, 2001

A small fraction of upwelling thermal plasma from the collision dominated F region (above ~300km) can escape.

Abe and coworkers have shown the polar wind is strongly modulated by sunlight



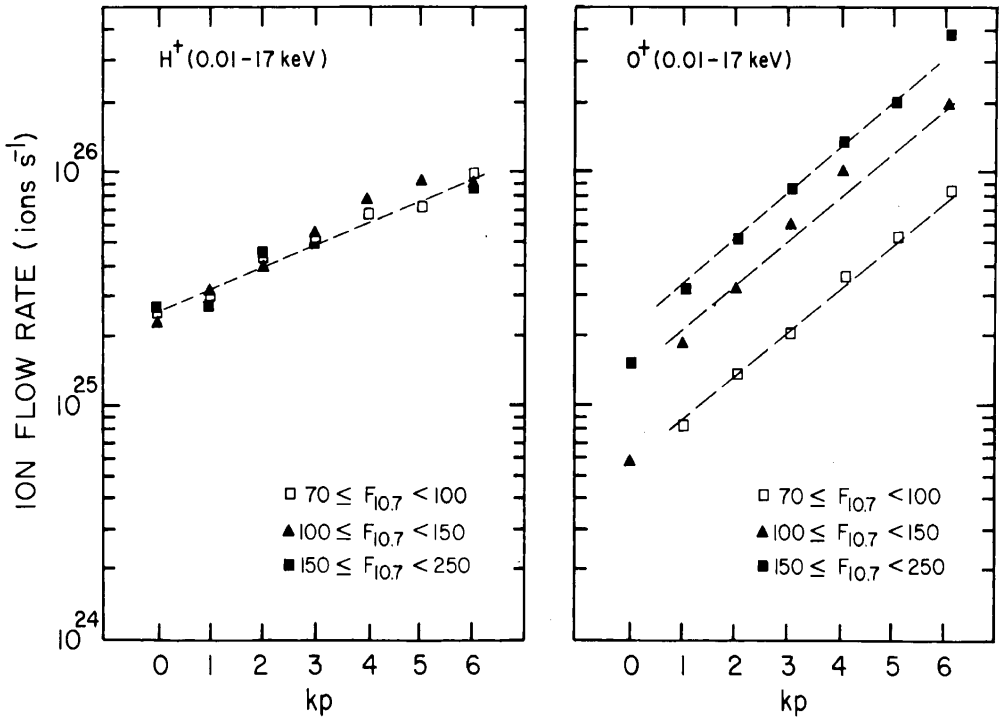
The seasonal independence of H^+ and O^+ outflow rates during solar minimum conditions observed by Polar/TIMAS suggests that

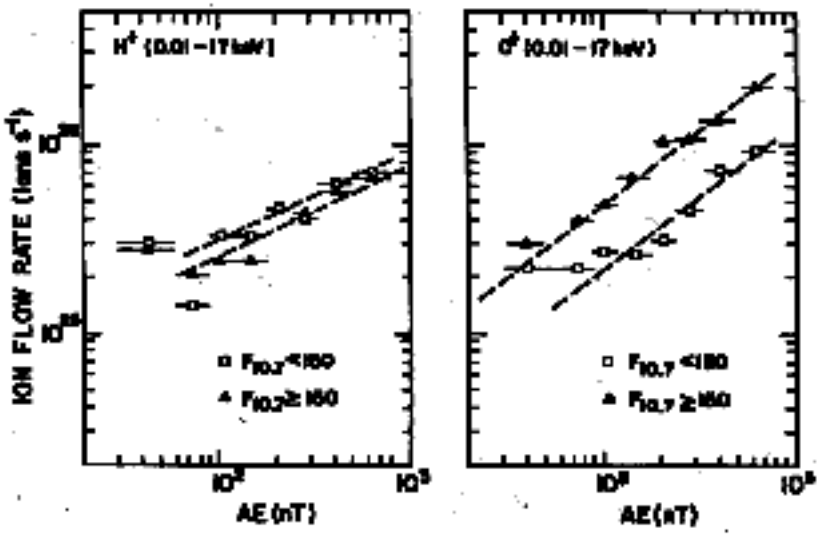
1) Outflow rates are set by conditions in the ionosphere

2) The energy of outflowing ions is set by auroral energization and acceleration processes acting above 300 km.

This suggests that there might be some large scale spatial and temporal coherence in ion outflow that modelers can exploit

How coherent is ion outflow?





3 hour bins for K_P

1 hour bins for A_E

18 month sample period

From analysis of almost a solar cycle's worth of DE -1 mass spectrometer data Yau et al., [1988] found that a power index (A_E, K_P, D_{ST}) and a solar EUV index [$F_{10.7}$] characterized global ion outflow.

Peterson and Yau, IAGA G3.03, 2001

What do we know about **s**patial and temporal variations of ion outflow?

- **Temporal Variation**
  - Clearly resolved seasonal variation in He^+ outflow
  - Clearly resolved variation in 18 month average global outflow rates with magnetic and solar activity dependence captured in the DE 1 empirical models
- **Spatial Variation**
  - Outflow is closely associated with the Auroral Zone.
  - There are clearly defined maxima in outflow for Cusp/Cleft and Midnight MLT Regions
- *Almost no information is available on temporal variations on time scales less than a season.*
- *Some information is available on the simultaneous spatial and temporal variations (coherence) of ion outflow.*

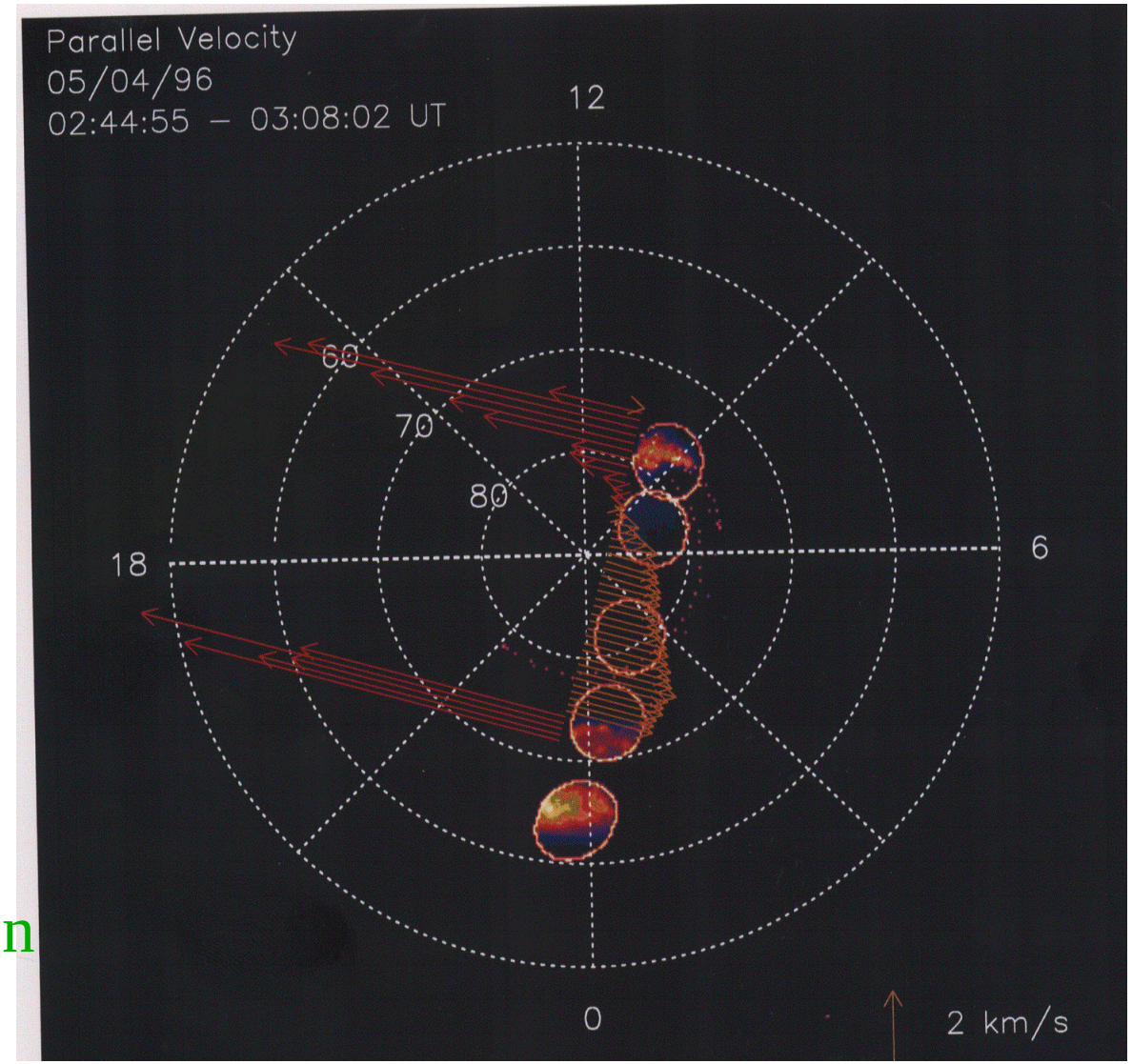
Peterson and Yau, IAGA G3.03, 2001

Stevenson et al. (to appear in JGR, 2001) have shown a strong correlation between UV emissions and upflowing O^+ for three perigee passes of the Polar satellite.

Circles enclose individual images from the Polar UVI instrument

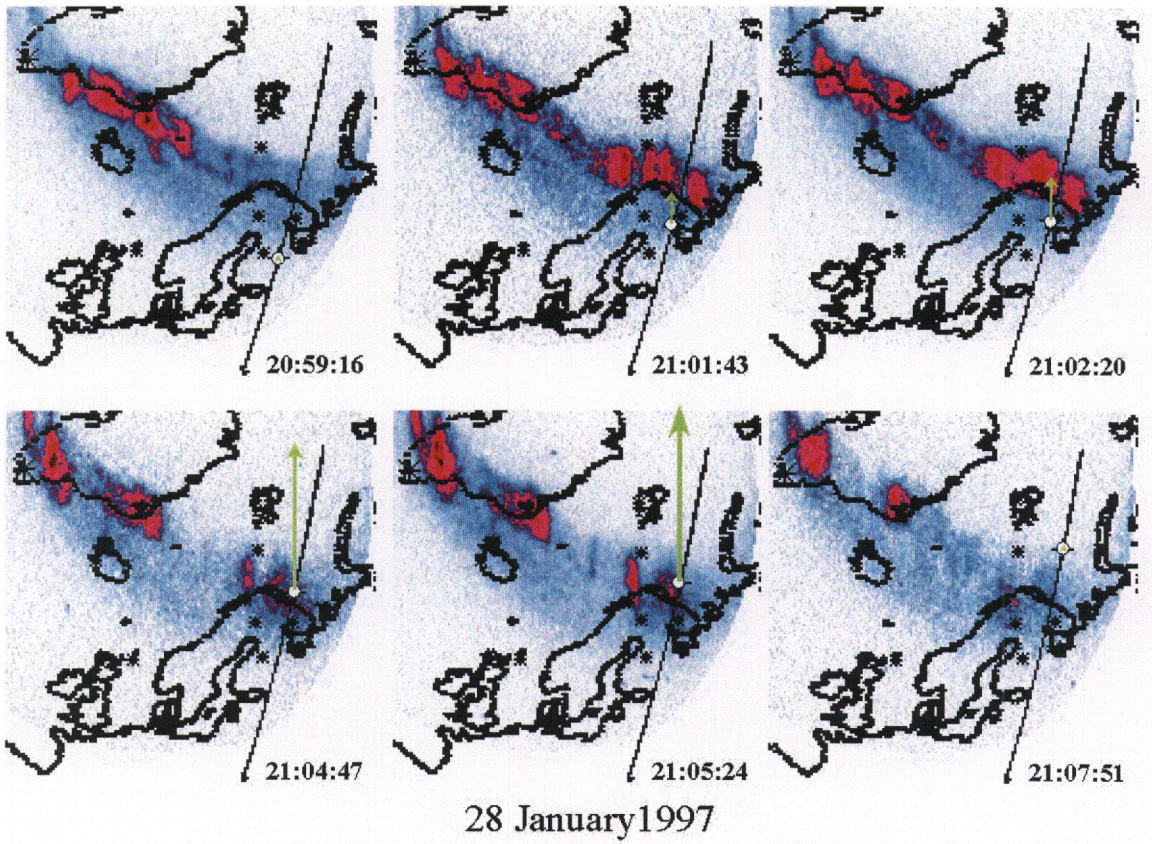
Vectors show O^+ velocity measured by the Polar/TIDE instrument.

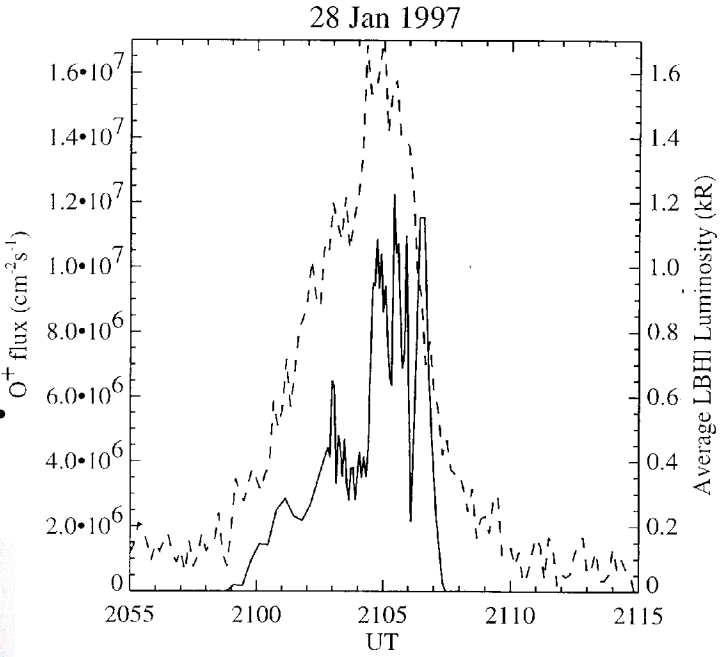
Demonstrates the spatial association of outflow with electron precipitation



Peterson and Yau, IAGA G3.03, 2001

Wilson et al. [to appear in JGR] have looked at outflowing O^+ from FAST in association with POLAR UV images for ~50 FAST orbits in January and February 1997.



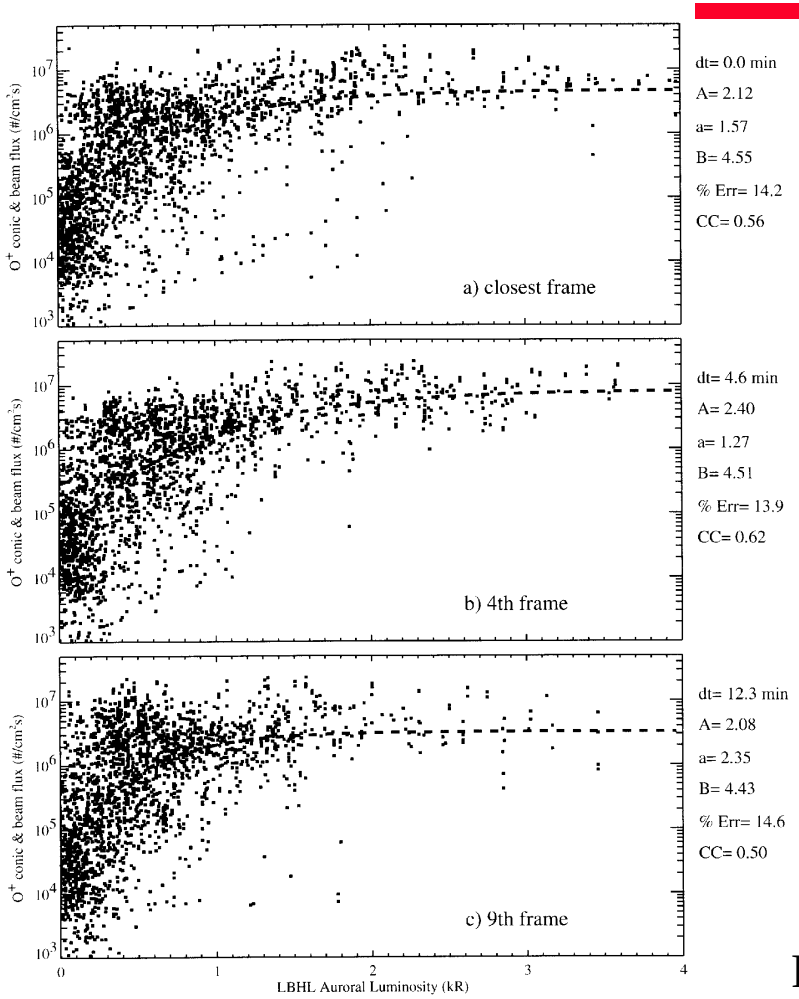


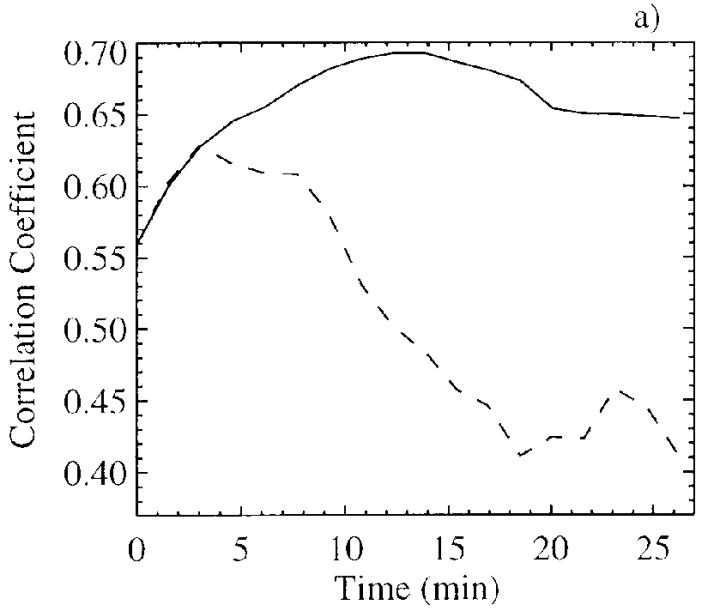
Solid line - O^+ upflowing flux

Dotted line - 5 image frame average of LBHL intensity (170 nm)

Note the time offset between emissions and O^+

Fits of O^+ outflow to time lagged image intensity have relatively poor correlation coefficients





Solid line - 19 FAST orbits from February 7-11, 1997
Implied O^+ velocity 5 km/s = 2eV

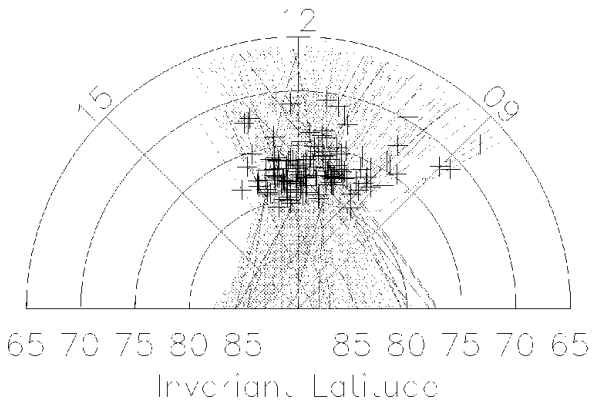
Dashed line - 31 FAST orbits from January 25-31, 1997
Implied O^+ velocity 13 km/s =15eV

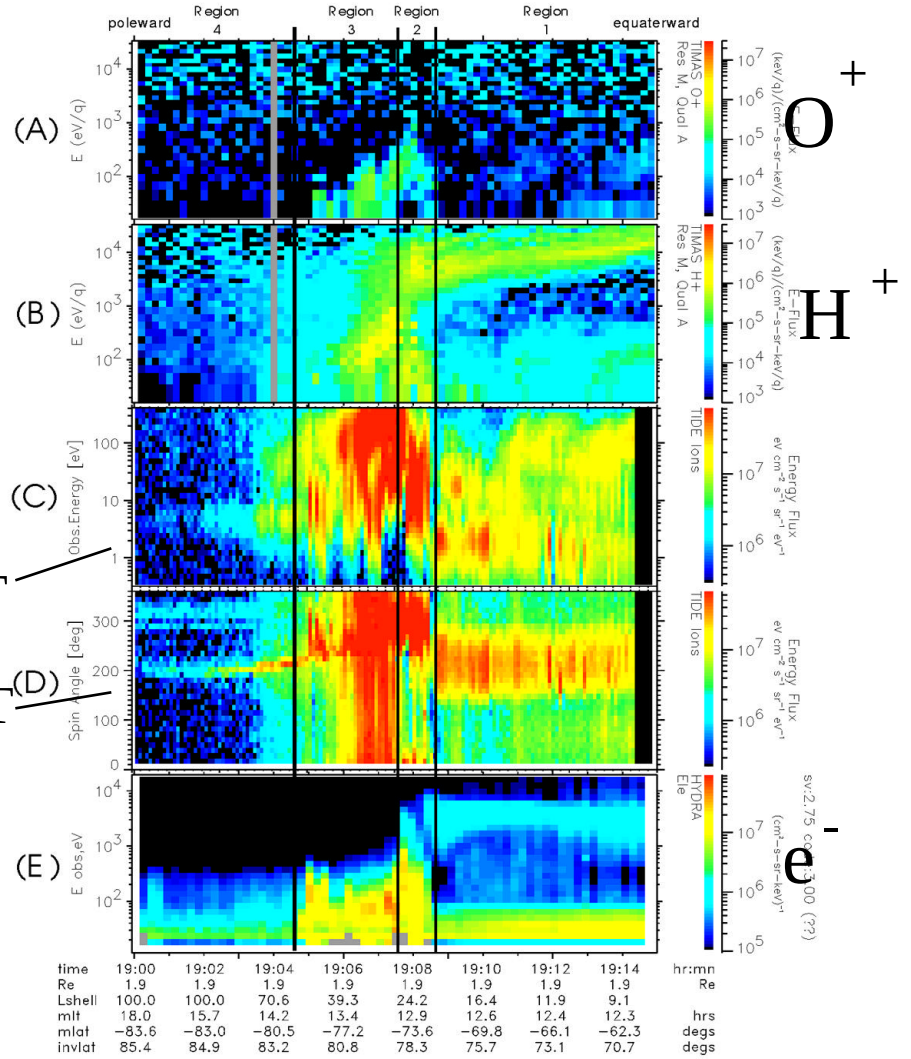
Demonstrates the variable nature of time of flight effects.

From Wilson et al., 2001.

Peterson and Yau, IAGA G3.03, 2001

Valek et al. 2001., have looked at properties of escaping O^+ as a function of location relative to the equatorward edge of the polar cusp using an automated procedure applied to data from the Polar/TIDE instrument acquired at perigee





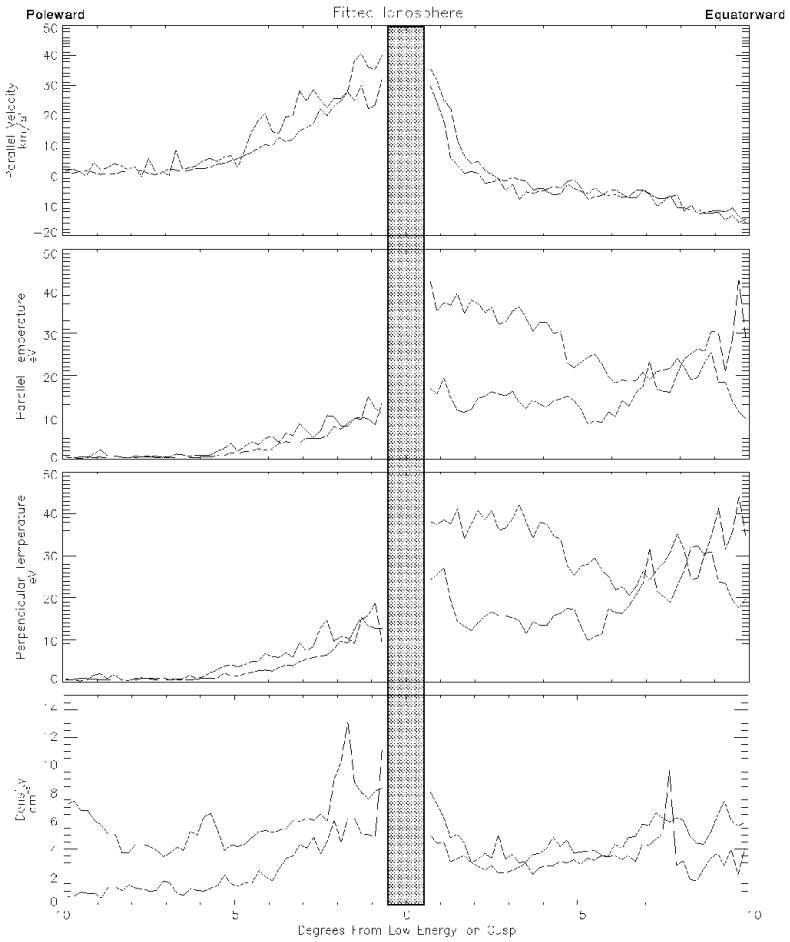
O^+

H^+

e^-

They found, as have others, that the cusp position moves as a function of IMF direction and magnetic activity

Valek et al. 2001. found:



Upflow velocity

O^+ upflow begins at equatorward edge of cusp independent of IMF direction

T parallel

T perp

O^+ upflowing plasma is hotter poleward of the cusp for IMF northward

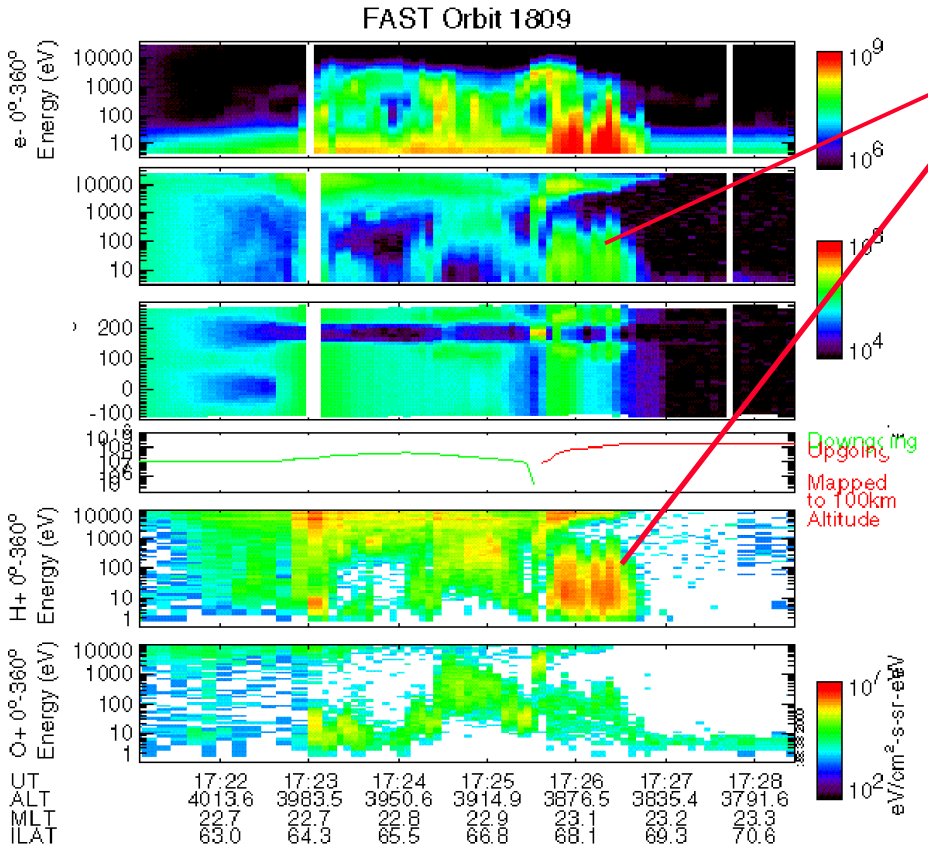
Density

O^+ Density and outflow rate from cusp region are larger for IMF southward

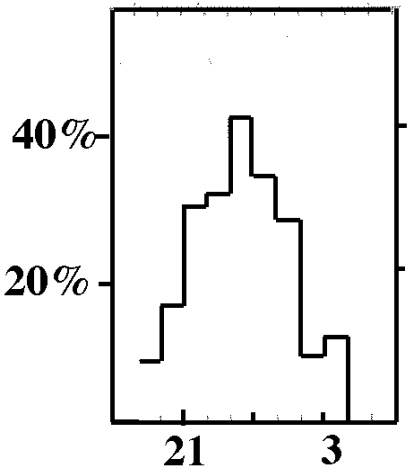
Normalized cusp position for IMF northward and southward

Peterson and Yau, IAGA G3.03, 2001

Tung et al. (JGR, 2001) found enhanced H^+ outflow associated with conics near midnight in the recovery phase of substorms.



The observed fluxes, over limited MLT range can account for a small (<10 %) fraction of the plasma sheet ion population



Distribution of events in MLT for Jan/Feb '97

Peterson and Yau, IAGA G3.03, 2001

Question:

- Is ion outflow proportional to solar wind power input over extensive or limited spatial scales?
  - **Can global ion outflow be characterized instantaneously by a single parameter?**

There are currently six operating satellites with mass spectrometers capable of monitoring ion outflow

Akebono/SMS (1989-), Polar/TIMAS(1996-), and FAST/TEAMS (1996-), 3 Cluster satellites (2000-)

Peterson and Yau, IAGA G3.03, 2001

Table 1: Orbit, Instrument, and Data parameters

	Akebono	Polar	FAST
Energy Range	0-70 eV	15 eV - 33 keV	1 eV - 12 keV
Altitude Range	275 - 10,500 km	2 - 9 Re/R	400 - 4000 km
Inclination	75°	90°	83°
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%

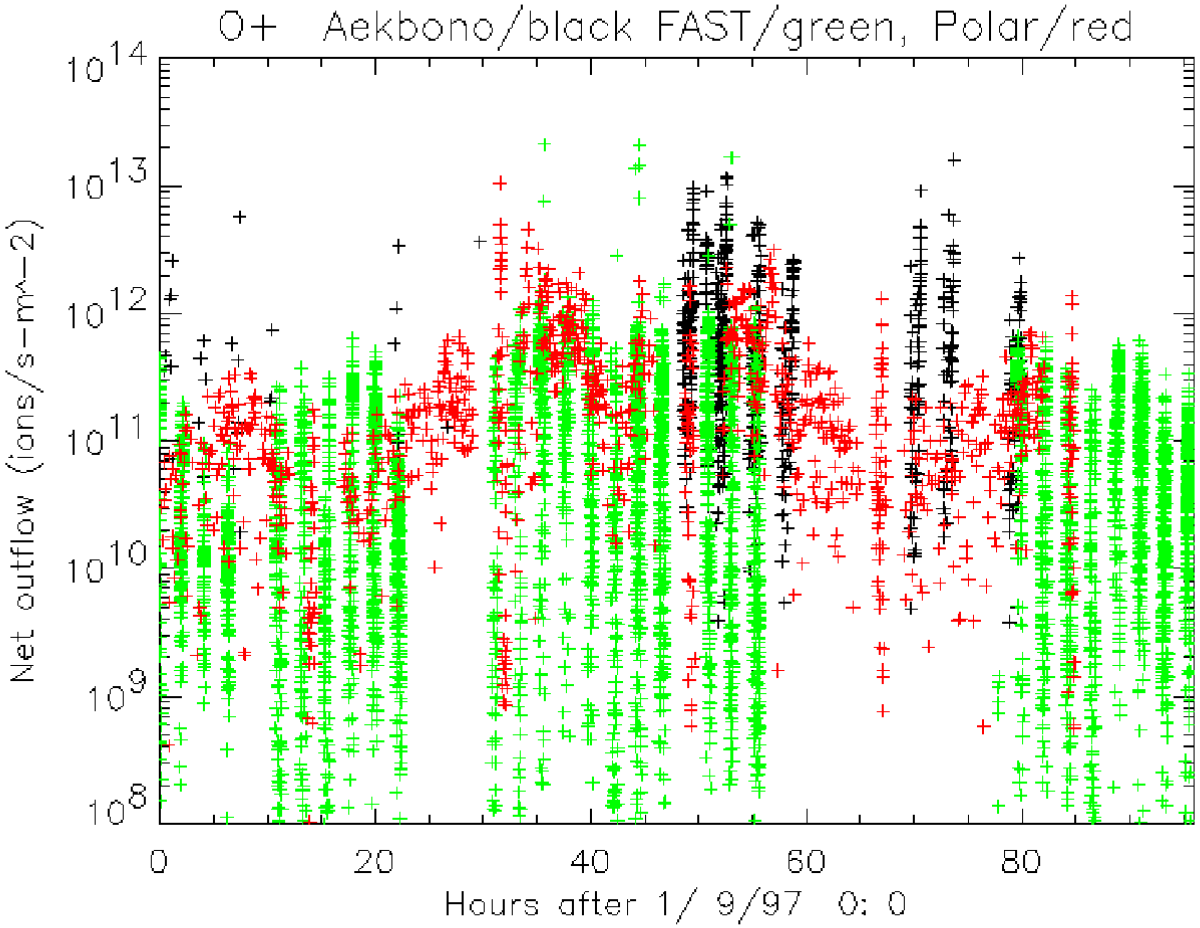
[a]Apogee
[b]Perigee
[c]09-15 MLT
[b]Invl > 75°; outside of cusp MLT range

The first time three satellites were operating during a geomagnetic event, **and subsequent quiet interval**, was in January, 1997

Peterson et al. (unpublished manuscript)have reported the lack of spatial or temporal coherence of H^+ and O^+ outflow during the period January 9-12, 1997.

Peterson and Yau, IAGA G3.03, 2001

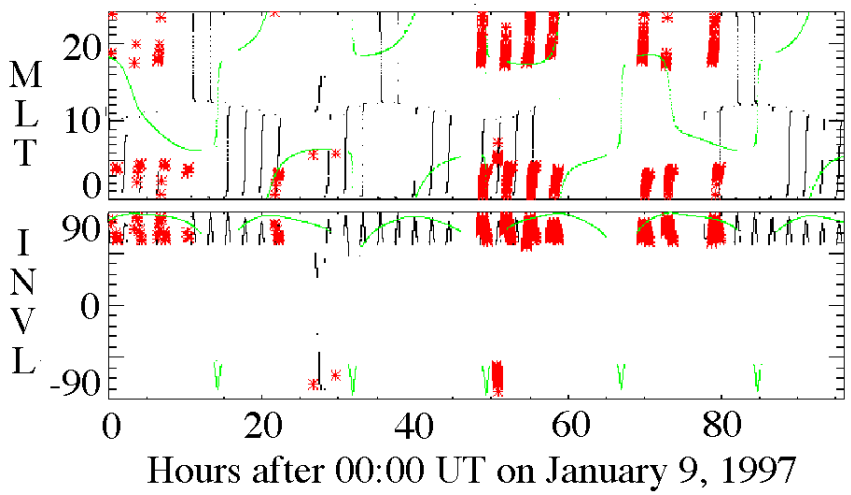
January 9-12, 1997

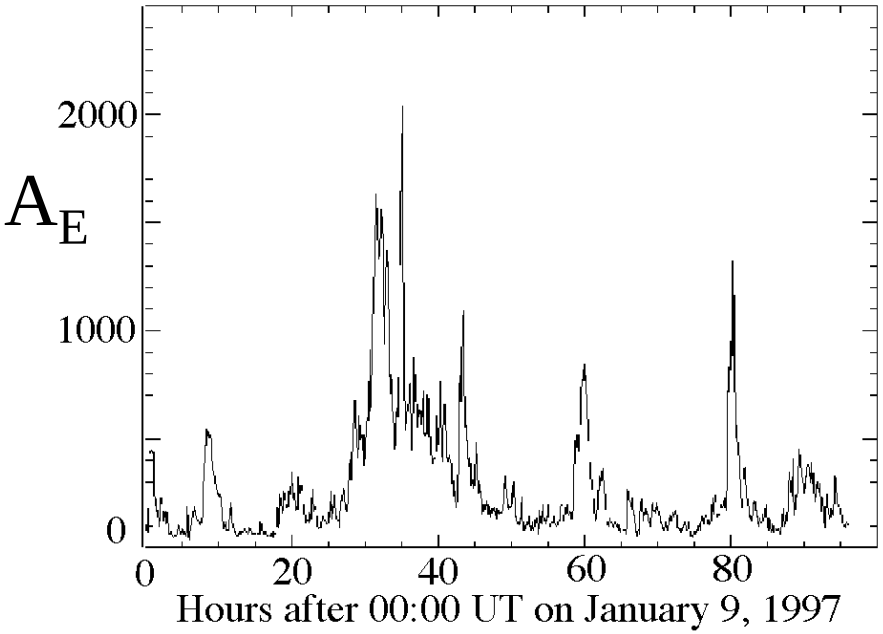


Upward O^+ fluxes observed by **Akebono**, **FAST**, and **Polar** normalized to 300 km.

Peterson and Yau, IAGA G3.03, 2001

FAST, **Akebono**, and **Polar** **(note change in colors)**





Interval is mostly quiet with periods of activity at various levels

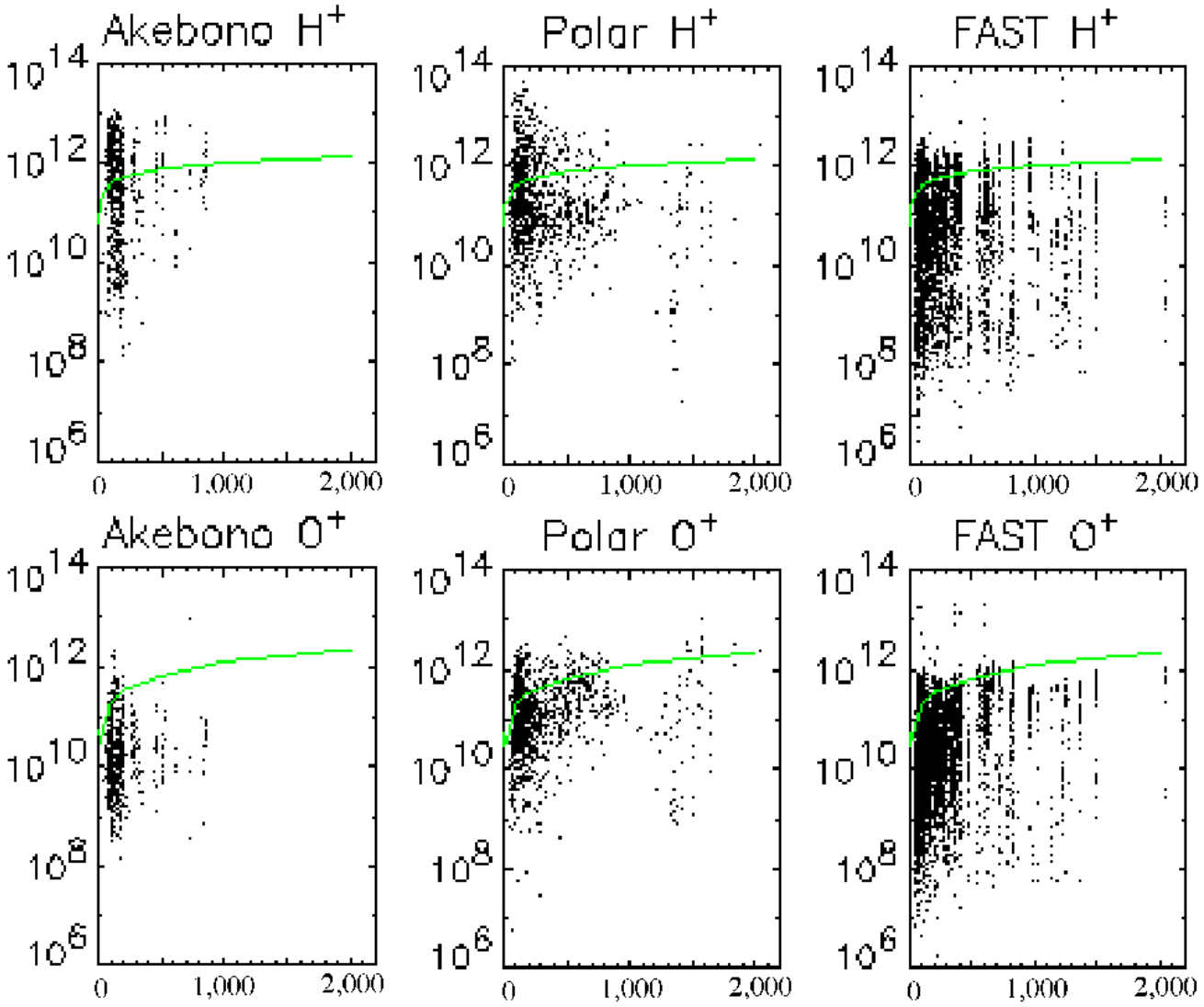
No magnetic conjunctions during this interval.

Akebono did not sample the cusp region

Significant data gaps in Akebono and FAST data

Peterson and Yau, IAGA G3.03, 2001

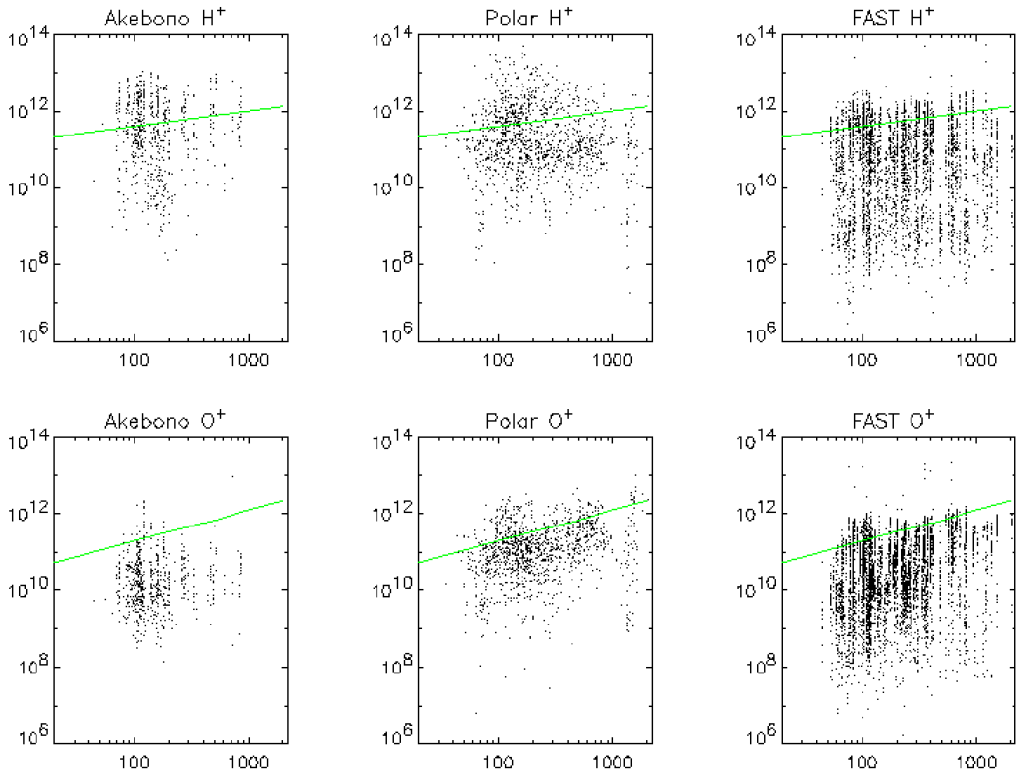
Ion outflow (m^{-2}-s^{-1}) Vs A_E



- A_E calculated from 68 magnetometers at 5 minute resolution.
- Absolute values show lower fluxes at FAST as expected.
- Scatter of data points at all levels of activity and all locations is very large!

Green lines are expected outflow from Yau et al., 1988

Peterson and Yau, IAGA G3.03, 2001



Plotting the data in log-log format shows the observed dependence on A_E is consistent with the Yau et al. prediction, **but ....they are also consistent with many other exponents!**

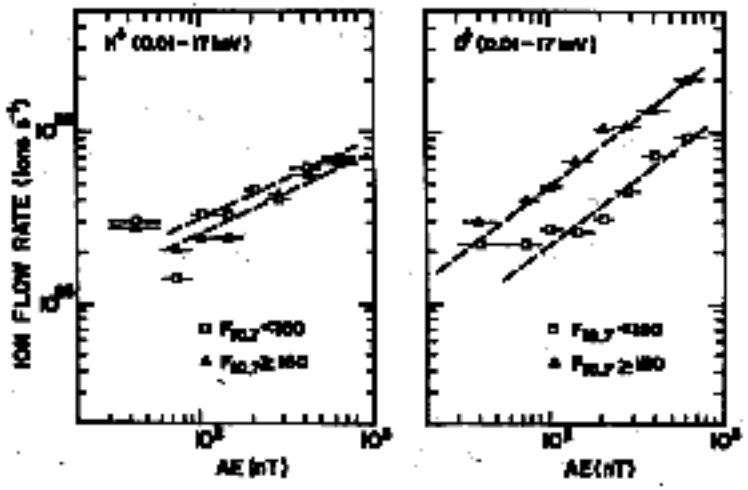
Green lines are expected outflow from Yau et al., 1988

Peterson and Yau, IAGA G3.03, 2001

We have also considered:

- Outflow from specific source regions
  - cusp, polar cap, auroral zone
- Time delay from 300 km to observation point of:
  - 1, 10, 100 km/s
  - no time delay

We have found no better fits (i.e. correlation) in any of these subsets of the data.



Yau et al., 1988

Why do we see so much more scatter in this data set than in the 18 month average data set from DE 1 reported by Yau et al.

Peterson and Yau, IAGA G3.03, 2001

The Aurora, and therefore upflowing ions are dynamic in space and time.

- There are large scale features of the aurora that are commonly seen in long term average satellite data.
  - Such as the Feldstein auroral oval and Ijima and Potemra field aligned current patterns.
- These large scale features are not generally seen in high time resolution data because auroral arcs are essentially narrow filaments that, on average, fill the auroral oval.

Peterson and Yau, IAGA G3.03, 2001

- Yau et al. examine average fluxes in INVL/MLT/ALT bins accumulated over 18 month accumulation intervals Vs. 3 hr K_P and 1 hr A_E and D_{ST} indices. They found large scale features.
- Our data set used instantaneous measurements from large regions (cusp, polar cap, auroral zone) Vs. 5 minute A_E index. We did not find the coherence reported by Yau et al.
- Casting the outflow data in boundary oriented coordinates (i.e. relative to the polar cap boundary) will improve the correlation.
  - Such an effort is expensive.
  - Funds have been requested for the analysis.

Conclusions (1):

- **Global** Ion outflow has been shown to be
  - **Constant by season** at solar minimum (no data for solar max)
  - **Coherent in 18 month bins**
    - Magnetic activity parameterized by A_E
    - Solar activity parameterized by $F_{10.7}$
  - **Not coherent (i.e. organized) in one day bins** by a single parameter such as A_E on day time scales.
- There is a suggestion that if the outflow data were in boundary oriented coordinates, outflow from selected regions might be organized by a parameter such as A_E on day time scales.

Peterson and Yau, IAGA G3.03, 2001

Conclusions (2):

- **Global** Ion outflow has been shown to
  - Have seasonal variations in energy and angular distributions
  - Be **spatially** organized by
    - Magnetospheric region (cusp, az, polar cap etc.)
    - Local Time
    - Auroral arcs visible in EUV
      - i.e. electron precipitation regions.
  - Have intense impulses of outflowing H^+ in the midnight region associated with substorms.
  - Have slightly more O^+ outflowing from the cusp region during intervals of southward IMF.

Peterson and Yau, IAGA G3.03, 2001

Conclusions (3):

- **Localized** Ion outflow has been shown to
  - Have spatial and temporal variations comparable to variations in the intensity of precipitating electrons
- **Finally**:
  - We have shown here that there is no quick and dirty way to parameterize global ion outflow instantaneously using a single parameter such as A_E.
    - Inclusion of ion outflow effects in large scale models will require some way to account for (parameterize) the spatial and temporal variability.
      - Possibilities include organizing ion outflow data in field-aligned or boundary based coordinate systems.