The Ionospheric Contribution to the Magnetospheric Plasma Population

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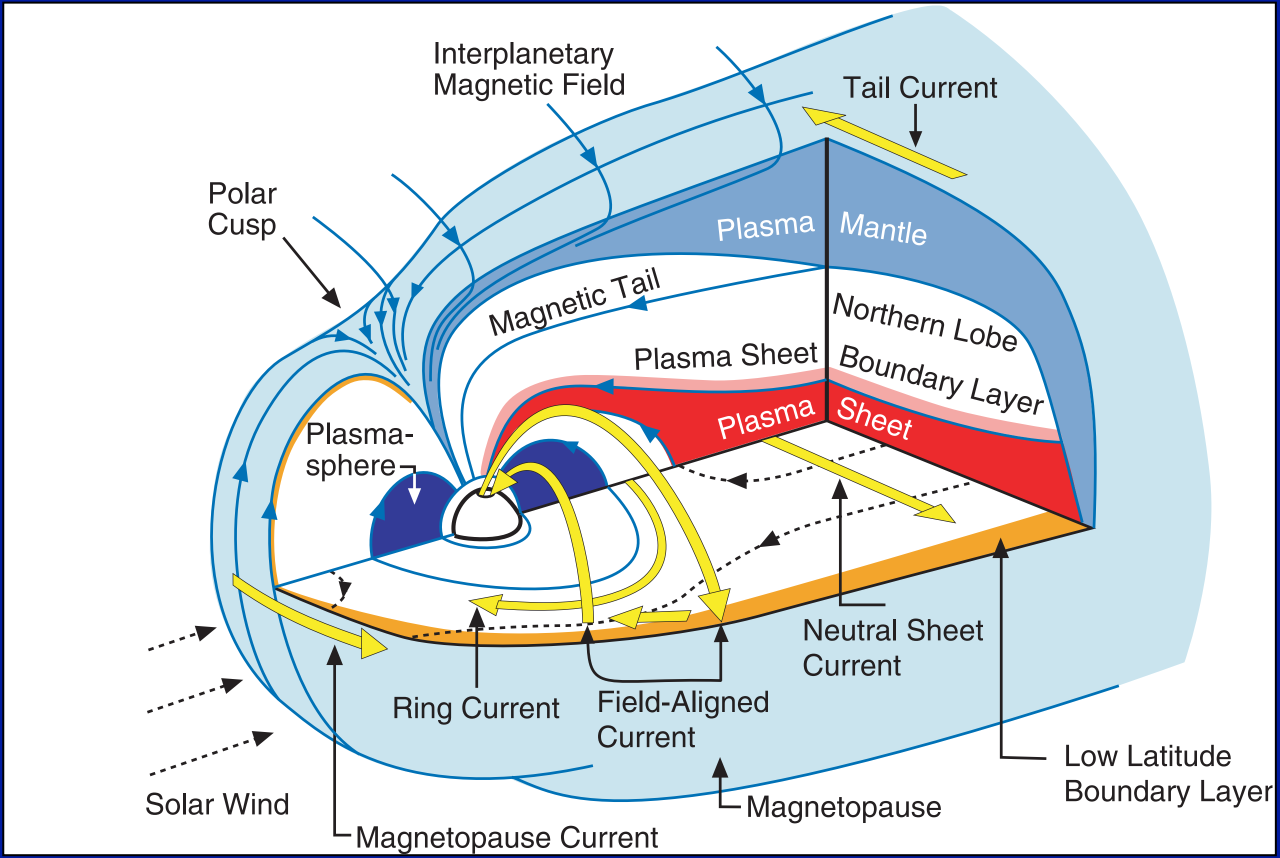
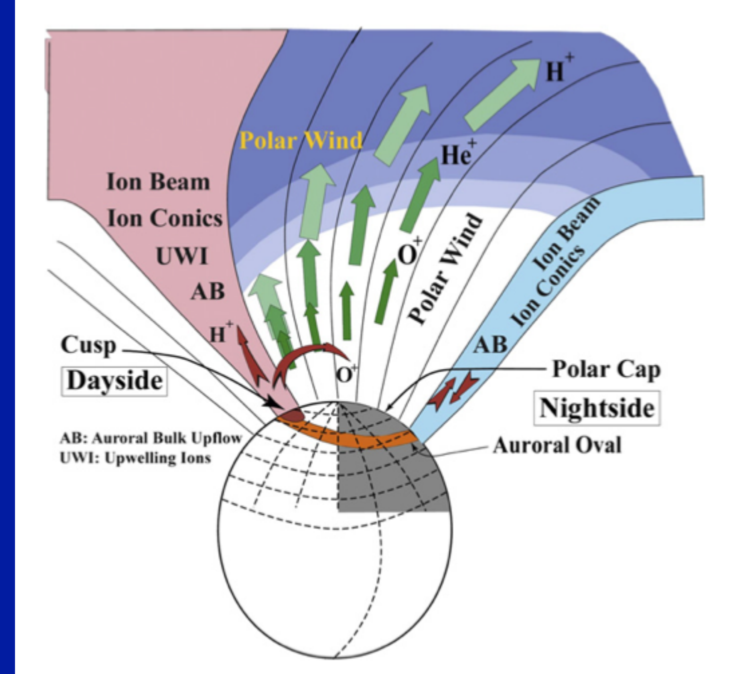
Outline

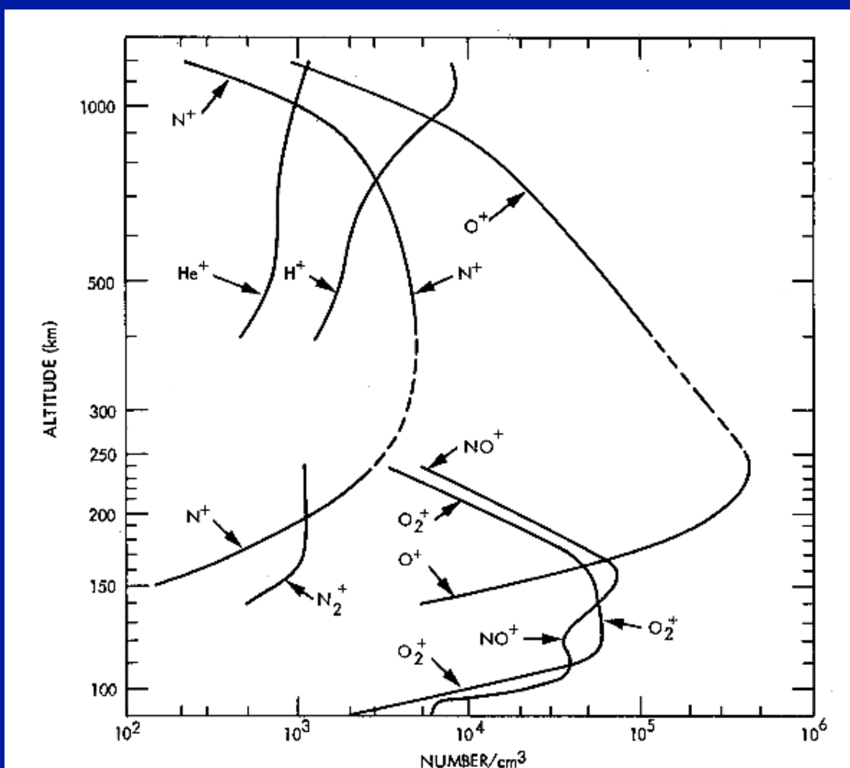
- Introduction
- Upflow and Outflow
  - Classical Polar wind escape
  - Heating and acceleration
  - EUV and activity dependence
- Transport
  - Cusp ions/cold ion beams
  - Plasma sheet
  - Inner magnetosphere
- Conclusions

- Two sources for magnetospheric plasma
  - Solar Wind (H+, He++)
    - Enters through reconnection
  - Ionosphere (H+, O+, He+)
    - Must be heated/accelerated to escape the earth's gravity

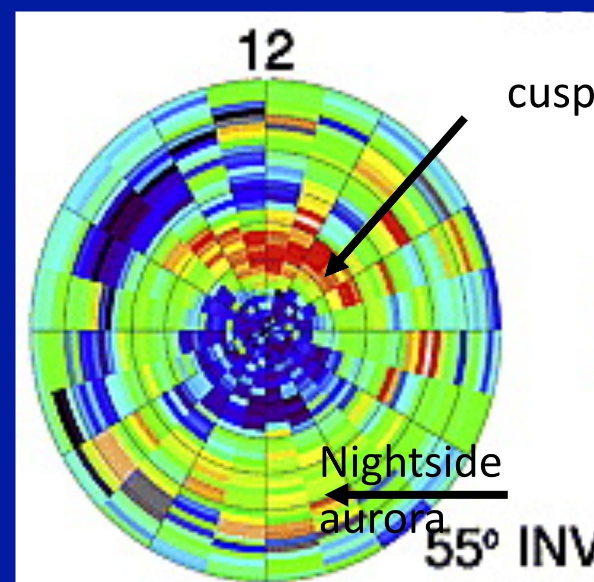


- Locations of upflow/outflow
  - Cold outflow
    - Polar cap
  - Energetic outflow
    - Dayside cusp
    - Nightside auroral region





O+ upward ion flow densities ($m^{-2}\ s^{-1}$)



Lennartsson et al, 2004

Classical Polar Wind

- First postulated by Axford et al. (1968) as an analogy to the Solar Wind –
  - the higher density ionospheric plasma would expand along open field lines to the empty magnetotail lobes
- The "classical" mechanism of escape:
  - Assume an ionosphere in hydrostatic equilibrium.
  - Ions and electrons have different scale heights due to the their different masses. The electron could escape along the field due to its lighter mass.
  - But this leads to charge separation that generates an "ambipolar electric field":

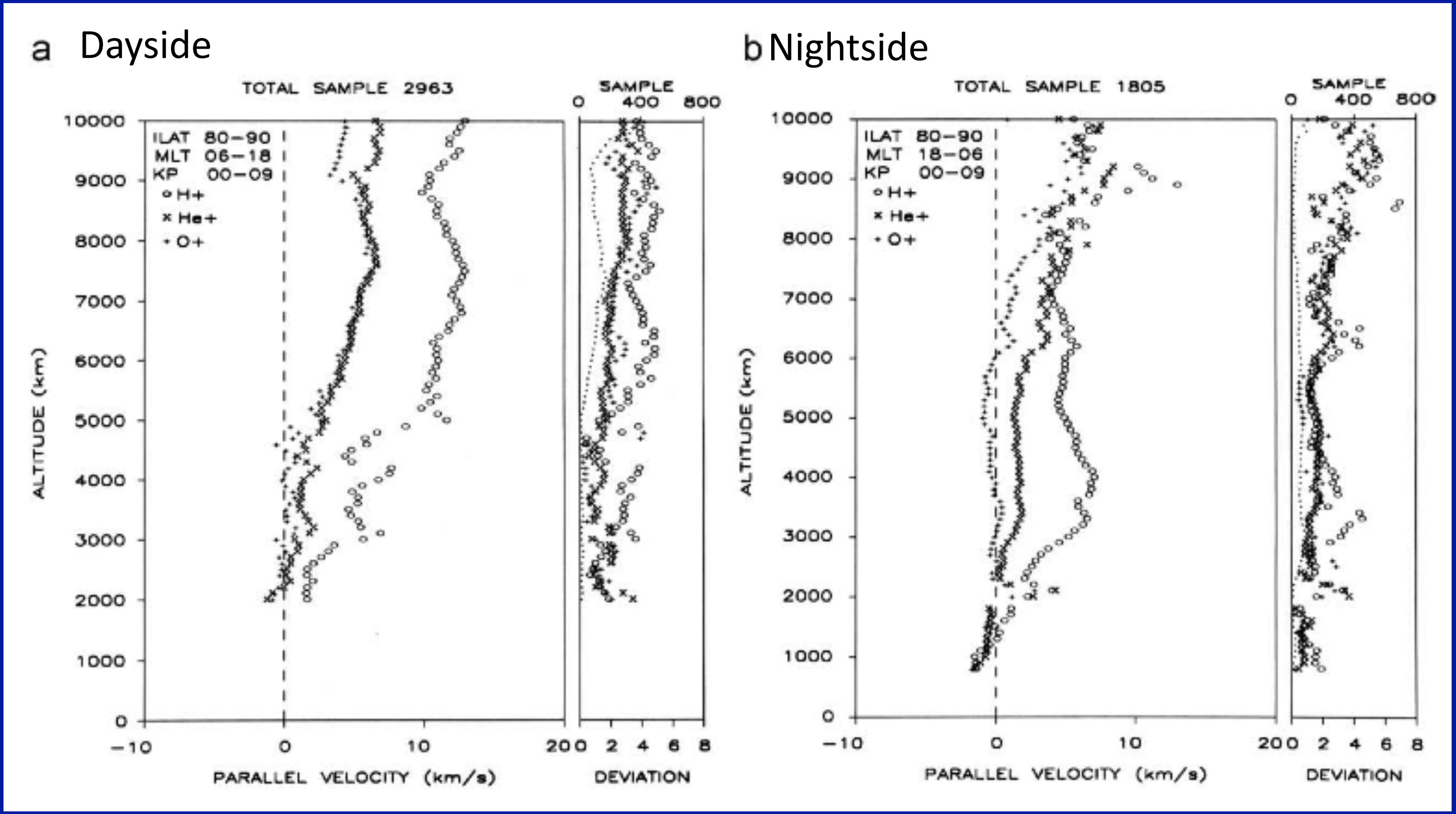
$$E = -\mu \bullet g / e \qquad \mu = \left(m_i^+ + m^-\right)/2$$

  - Because the main heavy ion is O+, the balance of forces between gravity and the upward electric field will drive the light ions (H+ and He+) up the field line.

Polar Wind

- Complications
  - The polar ionosphere is not in hydrostatic equilibrium and is time-dependent.
  - Flux tubes are convecting over the polar-cap – field-aligned outflow occurs along with this convection.
  - 3D time dependent models have been developed to simulate this outflow that give good agreement with observations (e.g. Schunk and Sojka, 1989, 1997, Schunk, 2007)

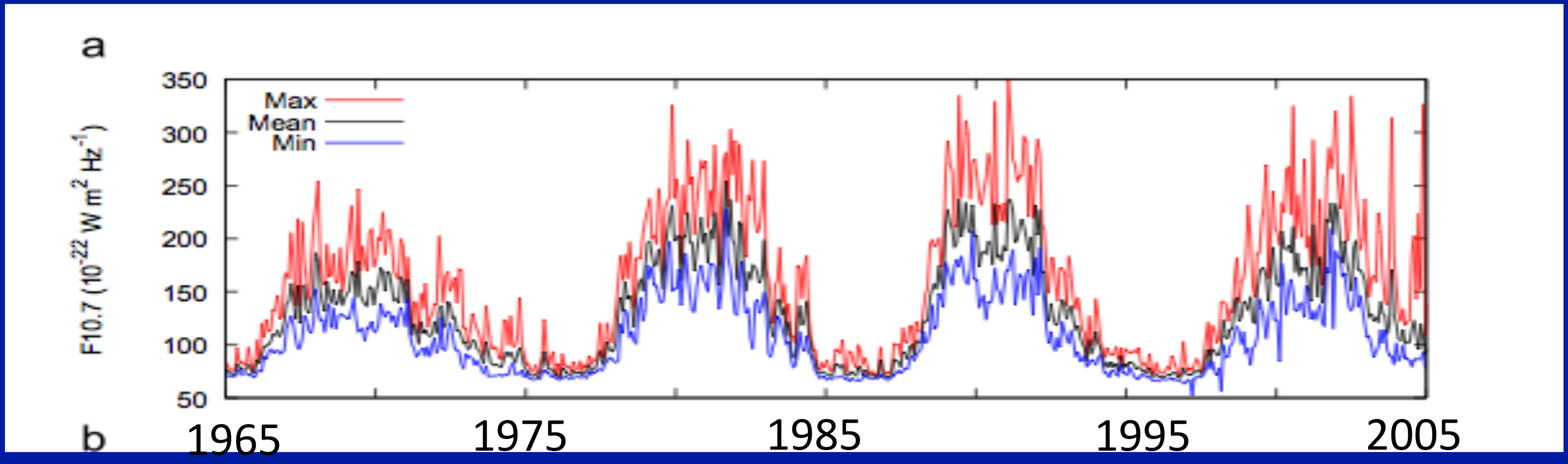
Polar Wind - Observations

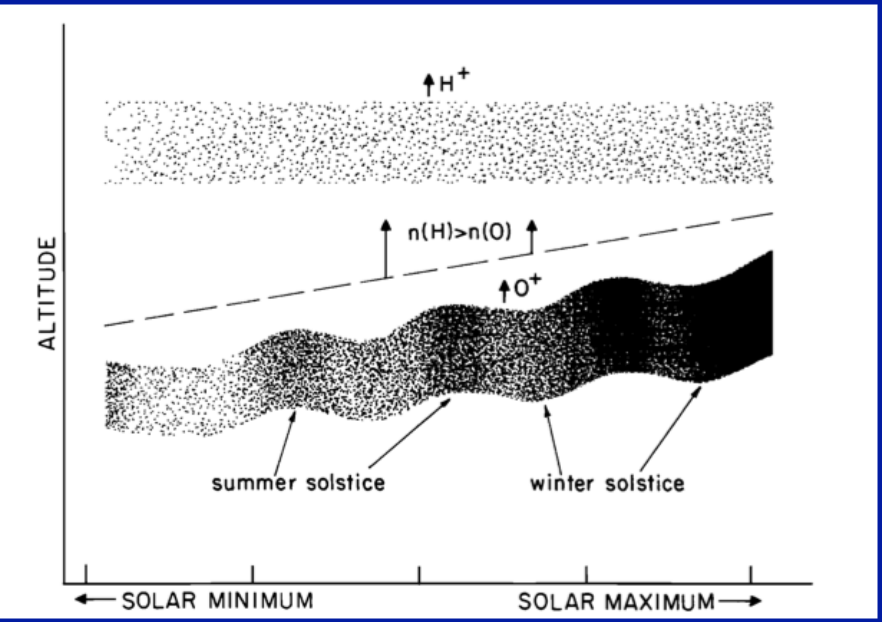


Yau et al., 2007

- Velocity increase with altitude is observed for all species.
- H+ is accelerated to the highest velocities.
- The altitude dependence varies significantly between dayside and nightside.
- One significant surprise was the amount of O+, which is not expected in the classical theory. This points to the need for more “non-classical” heating/ acceleration.

Impact of Solar EUV





- Controls overall ionization, heating, and molecular dissociation rates of the neutral atmosphere.
- EUV input changes with solar cycle, solar activity, and season
- Variations in EUV change ionospheric and atmospheric densities, composition, scale heights.

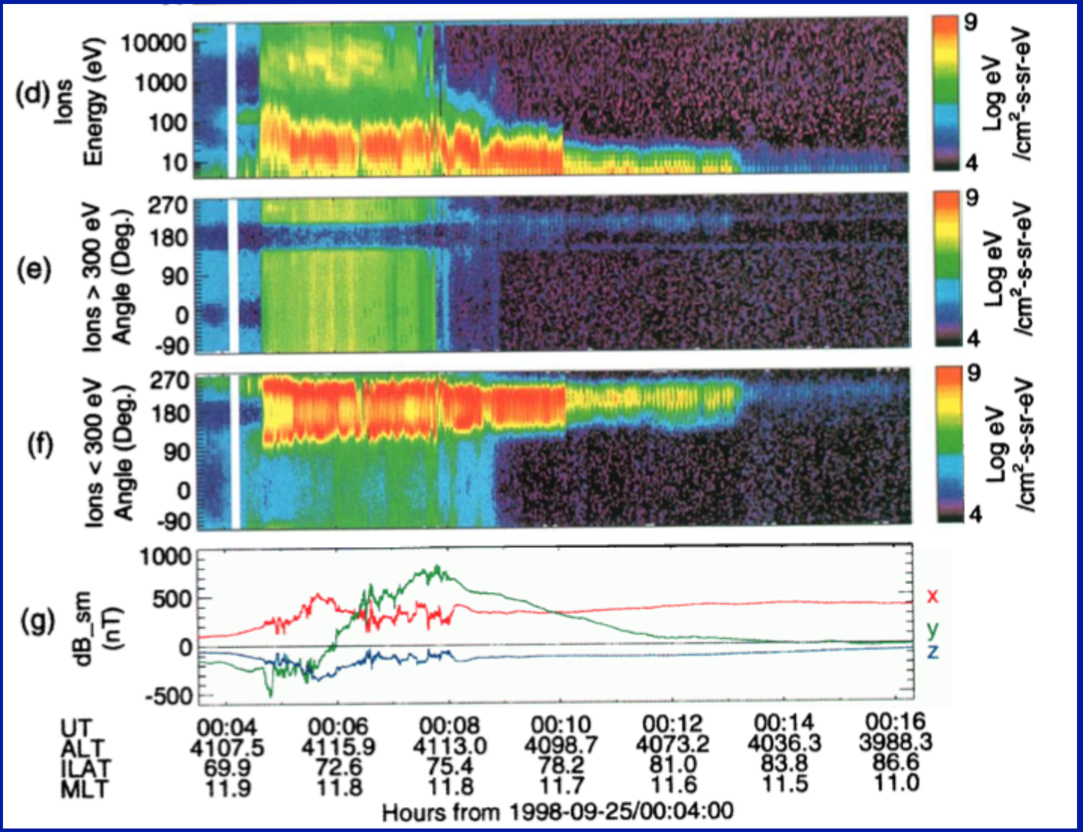
Yau et al., 1985

Other Sources of Energy Input

- Poynting flux due to reconnection on dayside
  - Results in ionospheric heating due to Joule dissipation (frictional heating between ions and neutrals, as reconnected field line is dragged).
  - The higher thermal temperature leads to a higher scale height.
  - This increases the number of ions at higher altitudes where transverse ion heating is occurring.
- Electron heating through precipitation of soft (<keV) electrons
  - Electron precipitation can directly heat the ambient plasma in the F-region ionosphere.
  - It also increases ionization, which increases the electron density.
  - The increased temperature increases the electron scale height which increased the ambipolar electric field.

Wave Acceleration

- The higher altitude cusp has broadband ELF and VLF waves.
- Ions resonant with the waves are heated perpendicular to the field.
- The mirror force then moves them up the field line, creating upflowing "conics."

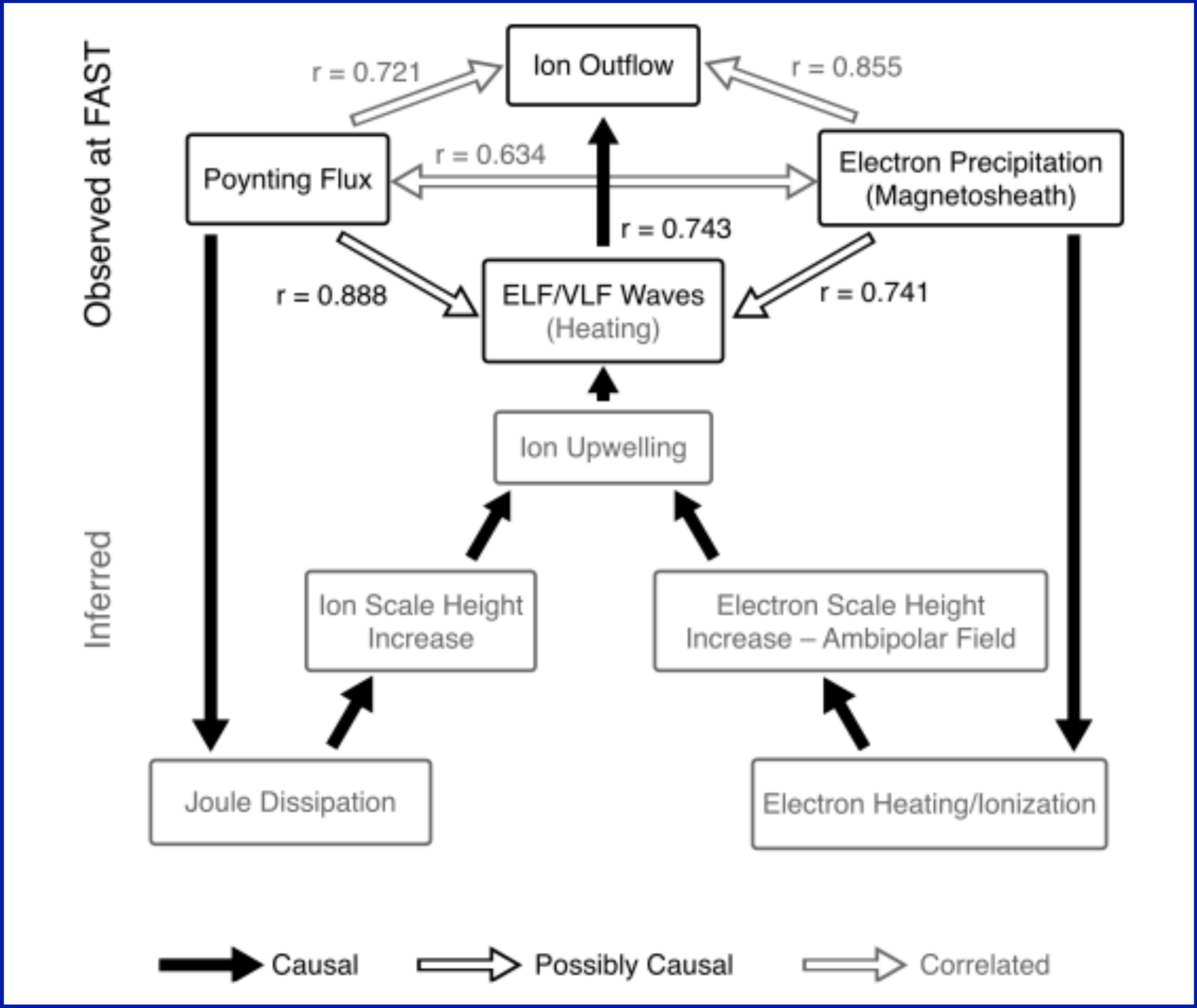


Pass through the cusp, showing perturbations in the magnetic field, and the ion conics

Strangeway et al. 2000.

For review of wave acceleration, see Andre and Yau, 1997

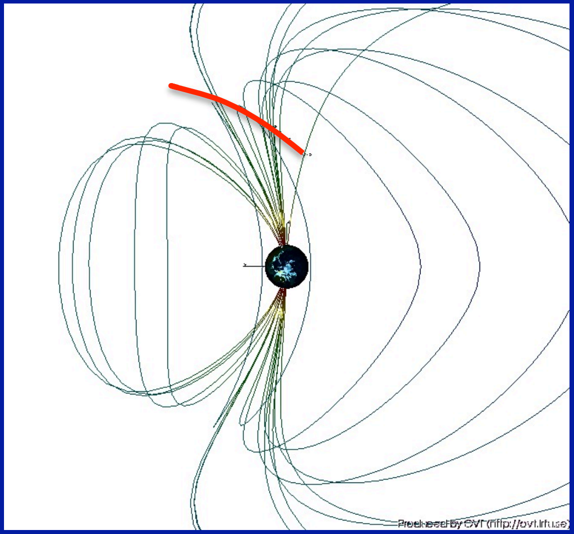
Summary of Multistep Process

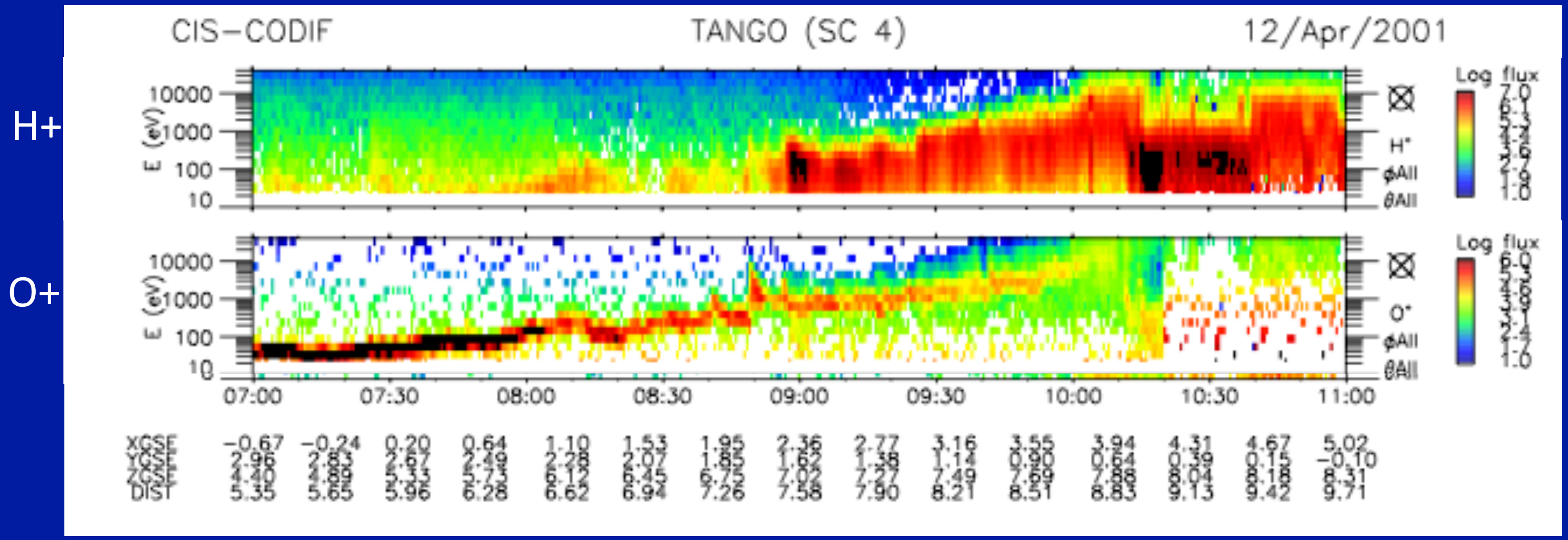


Strangeway et al., 2005

High Altitude Cusp

- O+ Ions are accelerated to >10 keV in the cusp
- Reach >1 keV between 8 and 12Re at latitudes between 75 and 90.

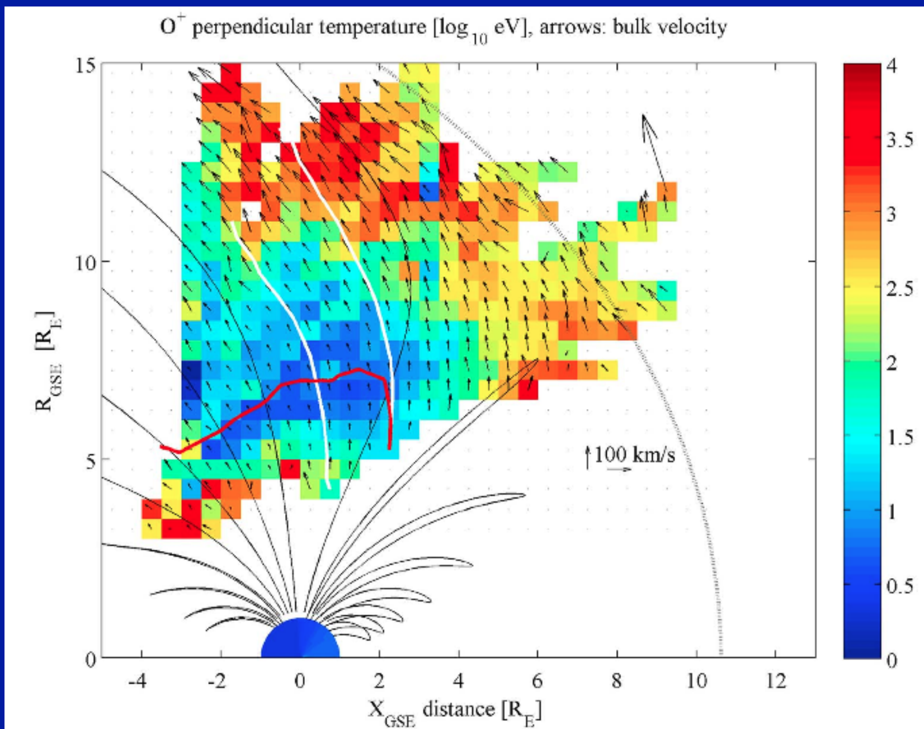




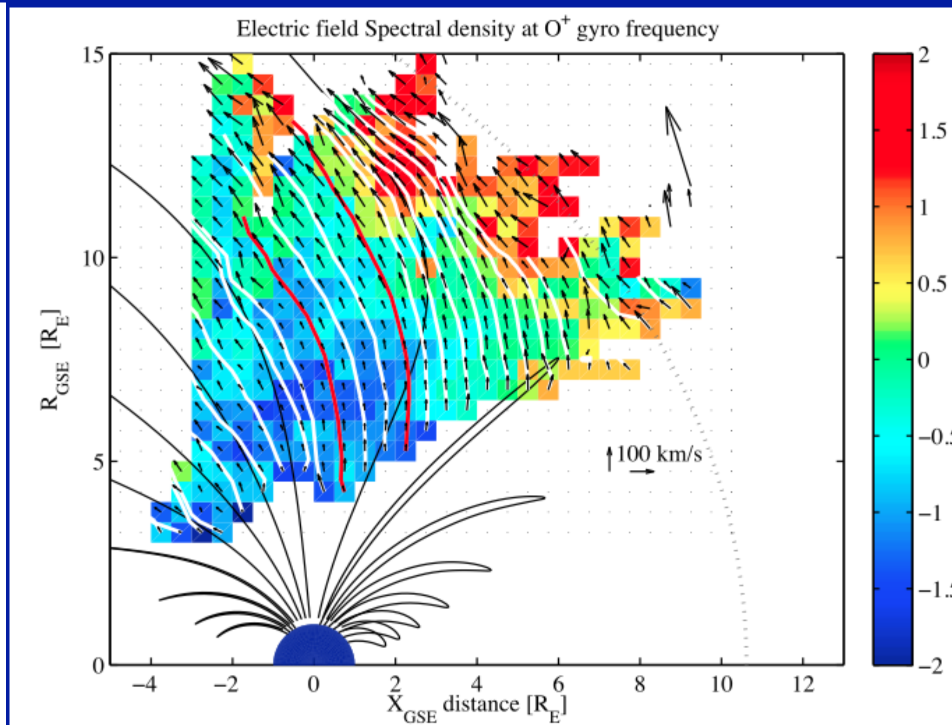
Arvelius et al. 2005

Correlation with Waves

O+ Perpendicular Temperature



Electric field spectral density at O+ gyrofrequency

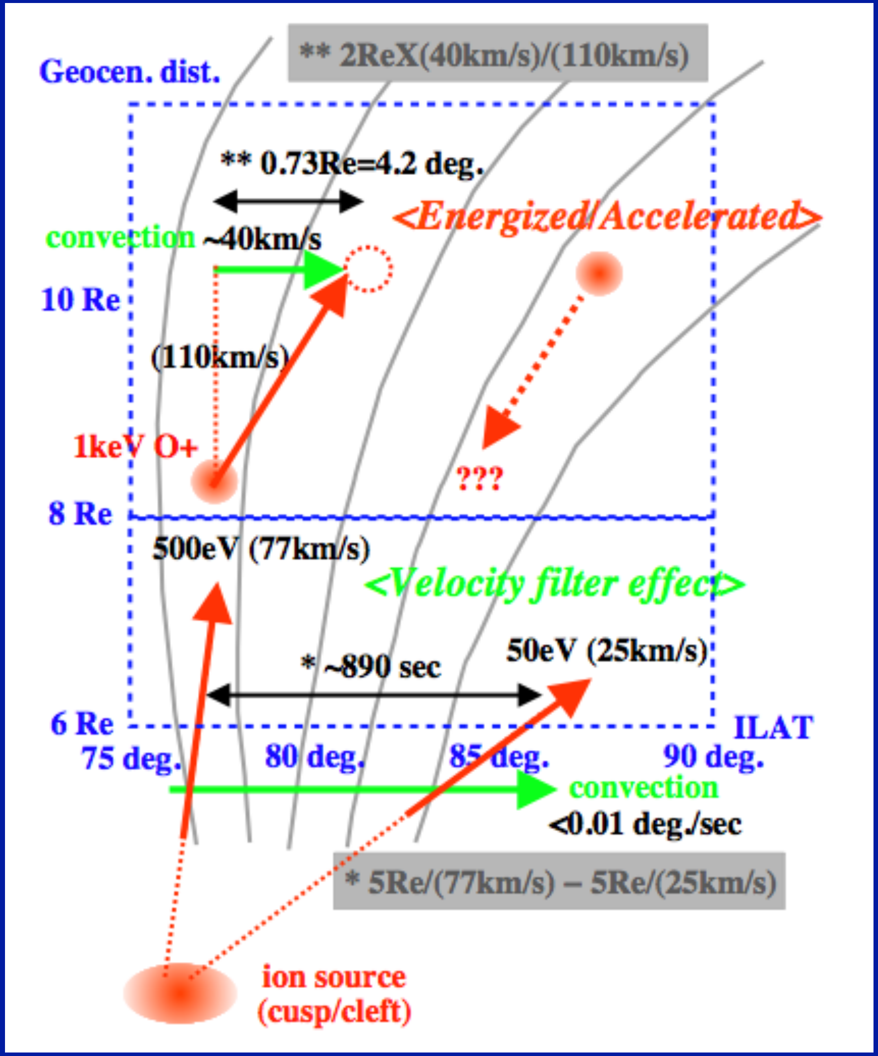


- Regions of hot O+ correlate well with location of high wave activity at the O+ gyrofrequency.

Nilsson et al. 2012

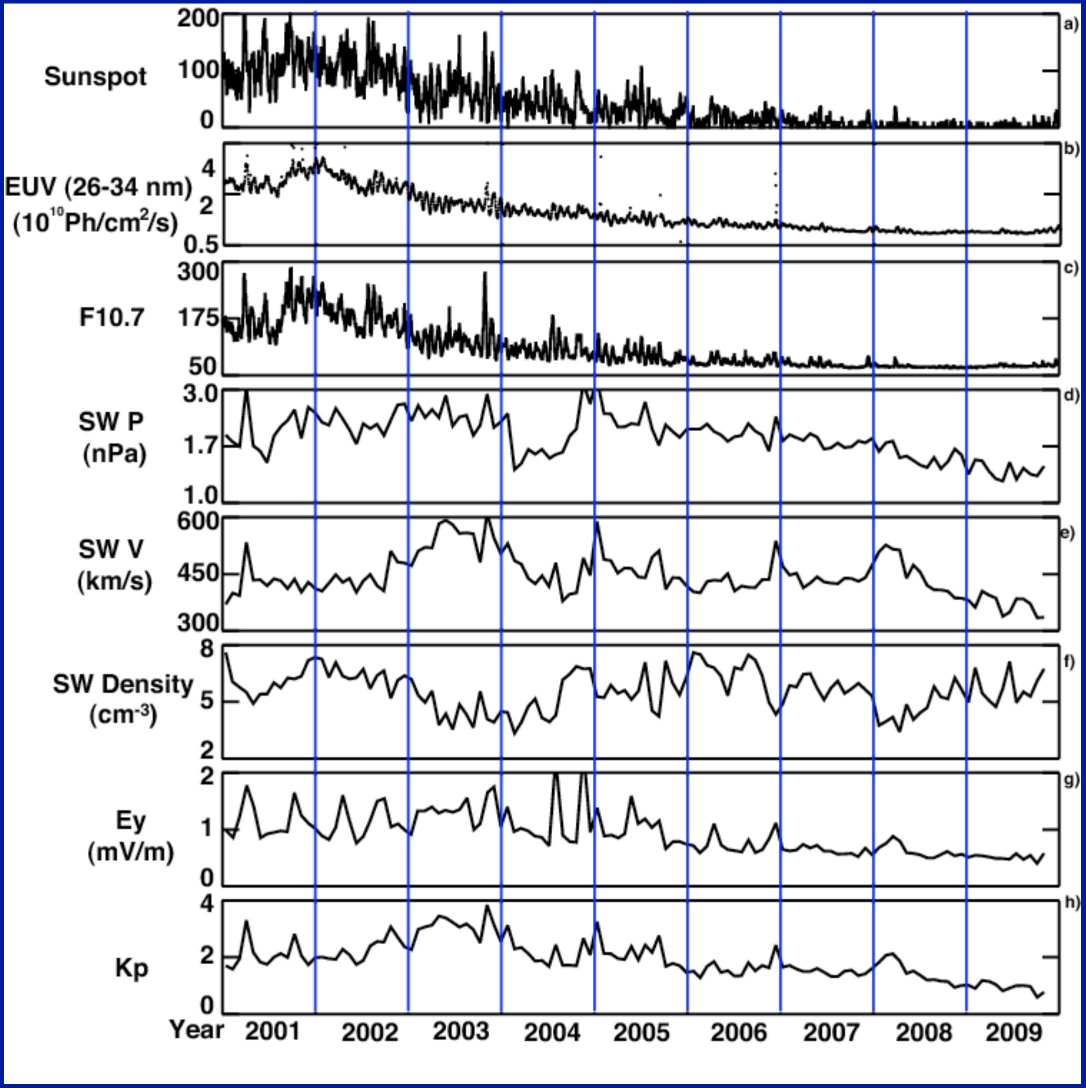
Cusp acceleration

- O+ ions which exit the cusp at low altitudes end up over the polar cap and in the lobe
- O+ ions with energies/ trajectories that bring them higher in the cusp undergo significant further acceleration, likely due to wave heating.
- These ions are mixed with the entering magnetosheath ions, creating a population that is mixed solar wind and ionospheric that moves into the mantle.



Arvelius et al. 2005, Nilsson et al. 2006,2012

Solar Cycle and Activity Dependence

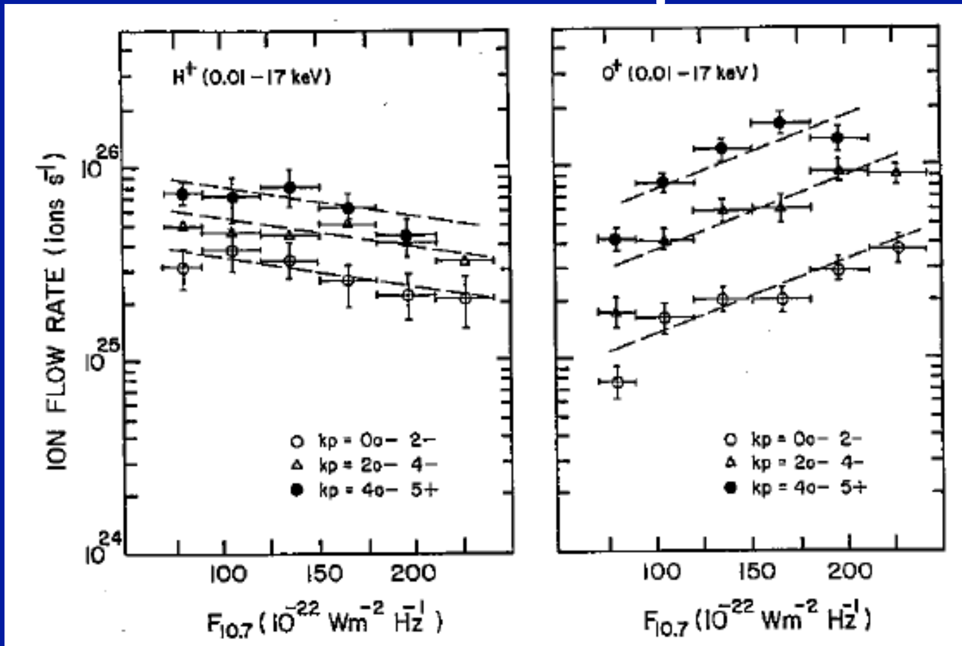


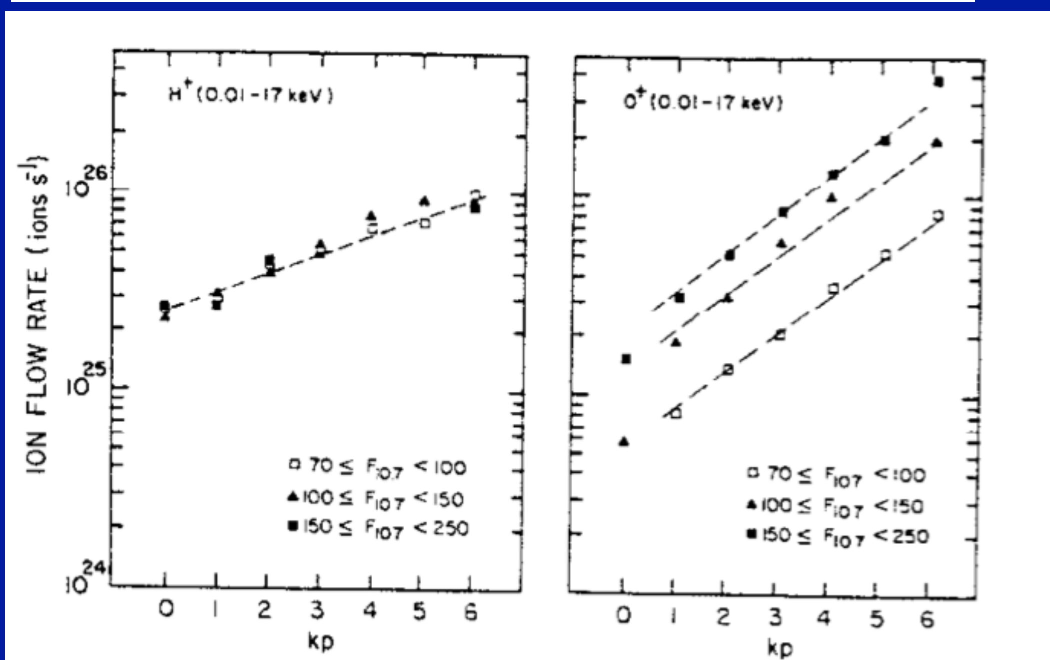
- We have shown that EUV varies with solar cycle
- Magnetospheric activity also decreases toward solar minimum.
- The change in energy input to the ionosphere significantly changes the amount of outflow.

Liao et al. 2012

Outflow dependence

DE Measurements
.01-17 keV
~3-4 Re altitude



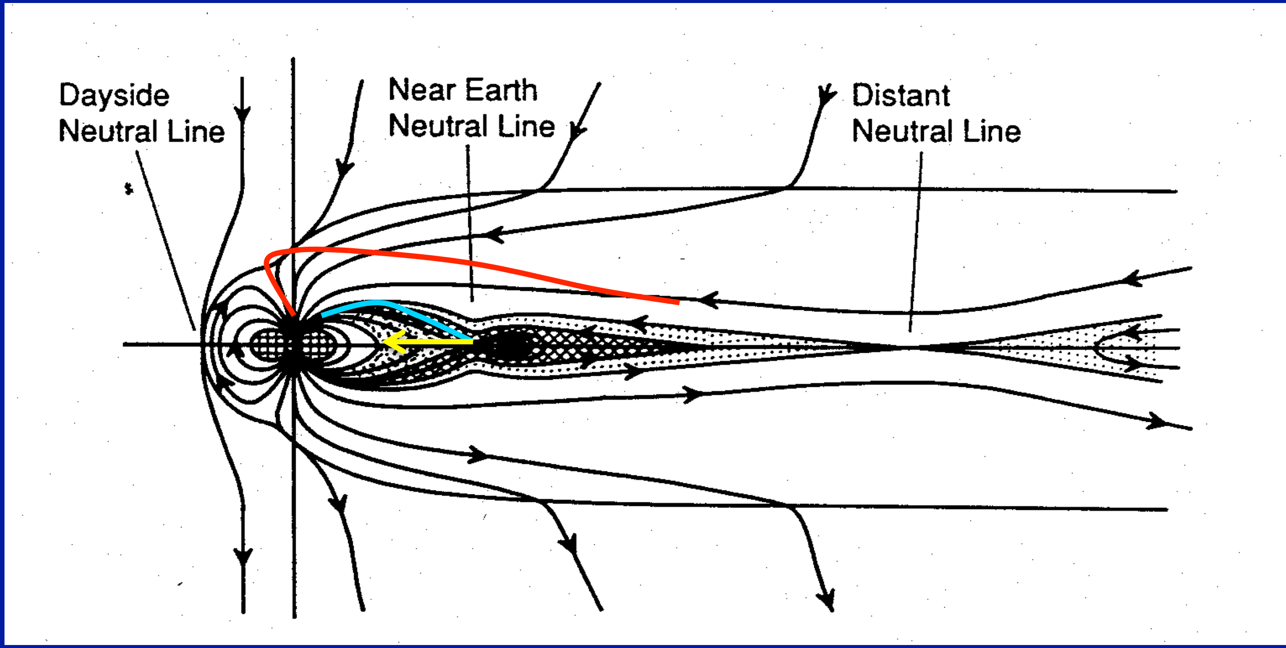


- Slight Decrease in H+ outflow with F10.7 (proxy for EUV input)
- Factor of 5 increase in O+ outflow with F10.7
- Factor of 4 change in H+ with Kp.
- Factor of 20 change in O+ with Kp

Yau et al., 1988

Transport of O+

- The ionospheric outflow from the dayside cusp is convected through the lobes to the plasma sheet
- Outflow from the nightside auroral region has direct access to the plasma sheet
- From the plasma sheet, the ions are convected earthward to the inner magnetosphere.
- The composition in the different regions depend on both the source and the transport to that region.



Geomagnetic Mass spectrometer (Chappell et al. 1987)

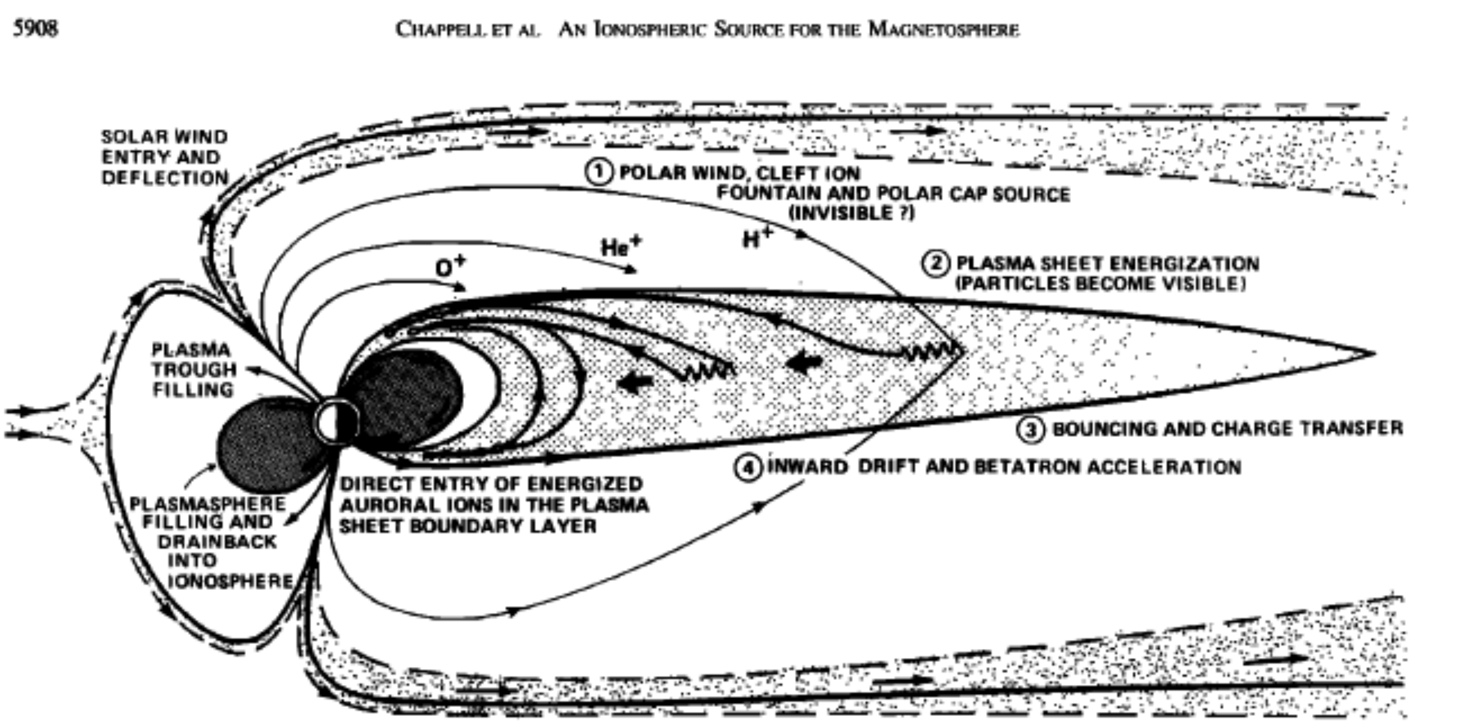
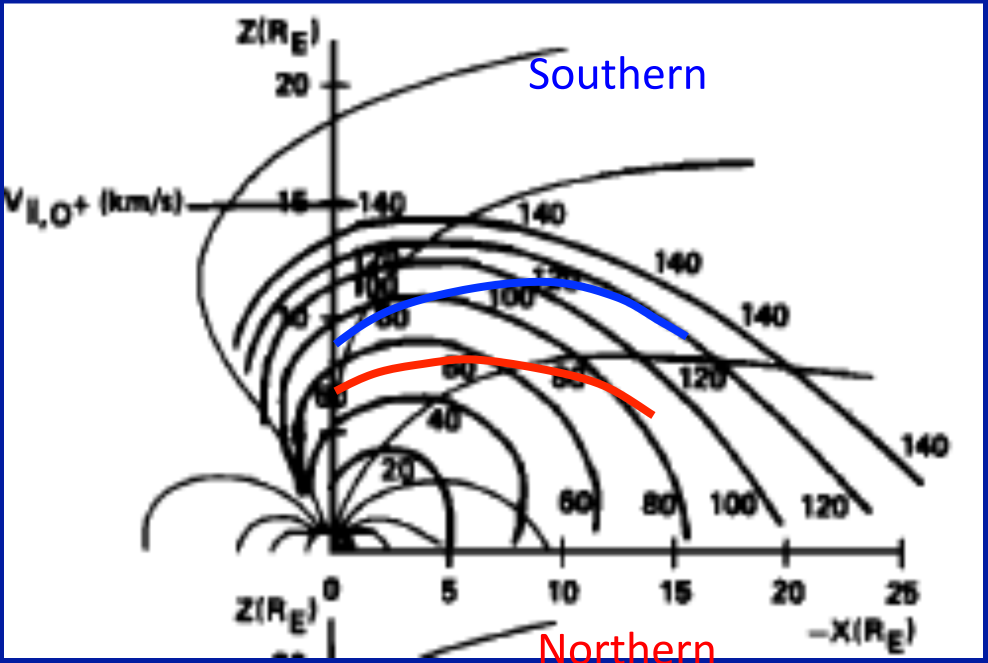


Fig. 4. An illustration of the filling processes through which the ionosphere populates the different plasma regions of the magnetosphere. The arrows indicate the flow directions of the ions as they move from the ionosphere into the plasmasphere, plasma trough, and plasma sheet. The thicker lines in the plasma sheet indicate that the cold plasma is being energized.

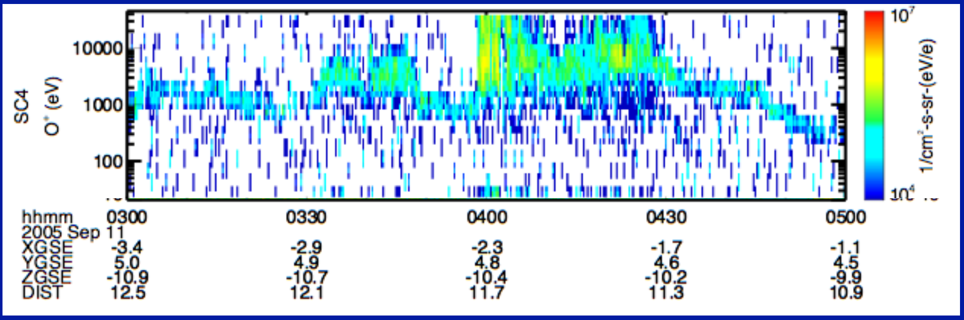
- Ions with the same energy are separated by mass, due to their different velocities parallel to the field.

Tail Lobe Ion Spectrometer - Cusp Outflow Horwitz (1986)

- Ions of the same species with different energies are separated by their velocity.
- For this large convection case, ~1 keV O+ reaches the 20 Re plasma sheet.
- For these reasons, what we often observe over the polar cap and in the lobe are tailward streaming mono-energetic O+



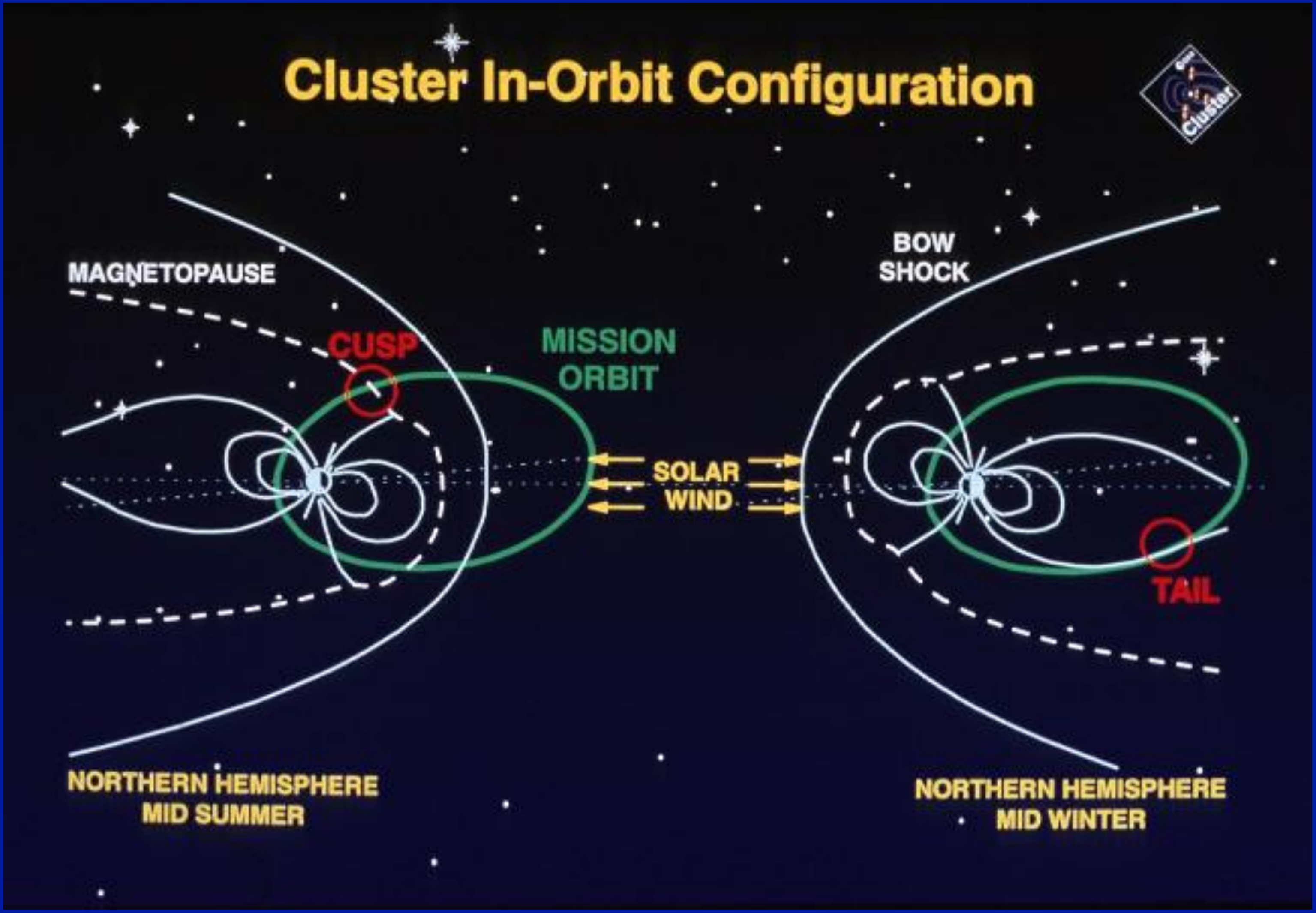
O+



Contours of equal velocity for O+ ions transported from the cusp. The combination of parallel motion and convection causes the velocity filter effect. This example is for large convection field - 100 mV/m

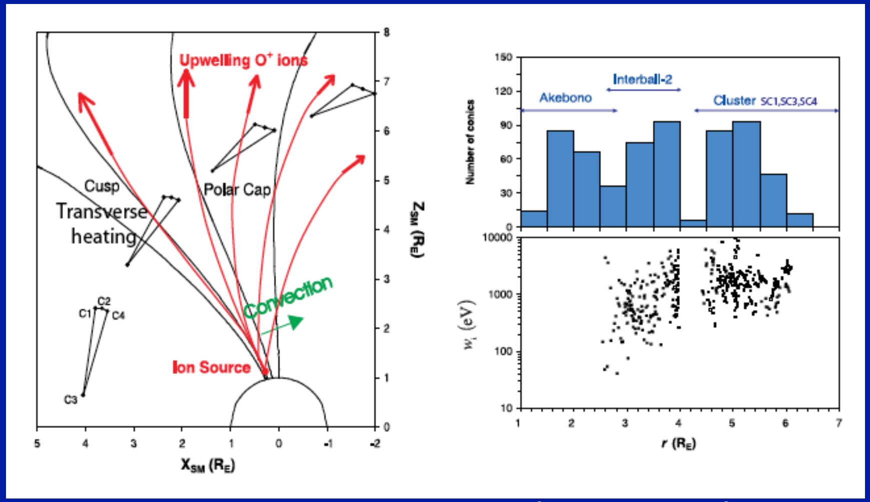
1 keV O+ = 110 km/s

Cluster Mission

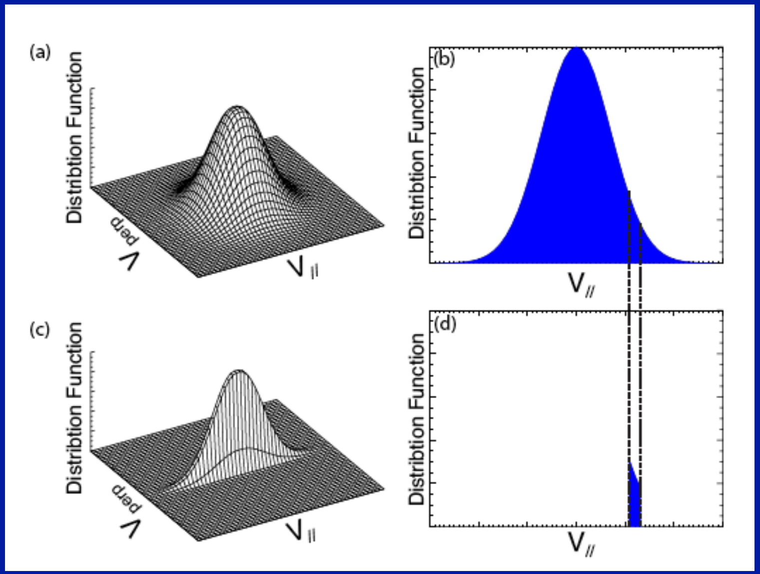


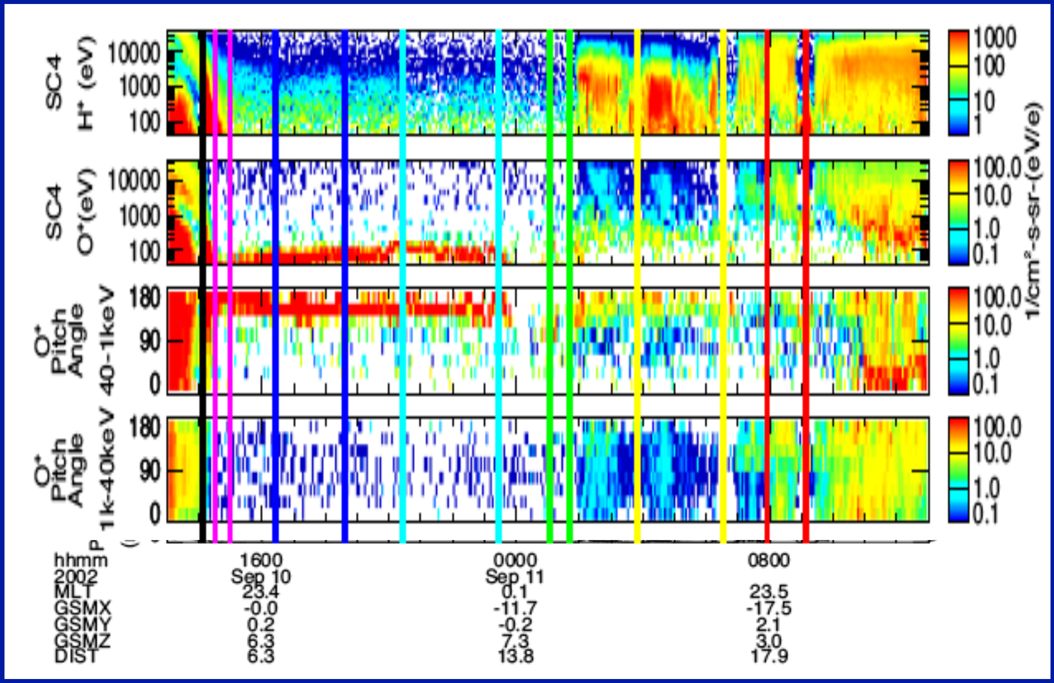
Cusp outflow and Velocity filter

- Ions are heated transversely in the cusp.
- What emerges from the cusp are ions with a broad range of energies.
- Because of the combination of parallel motion and convection, at any one place over the polar cap and in the lobe, we only see one narrow slice.



Bouhram et al.2004



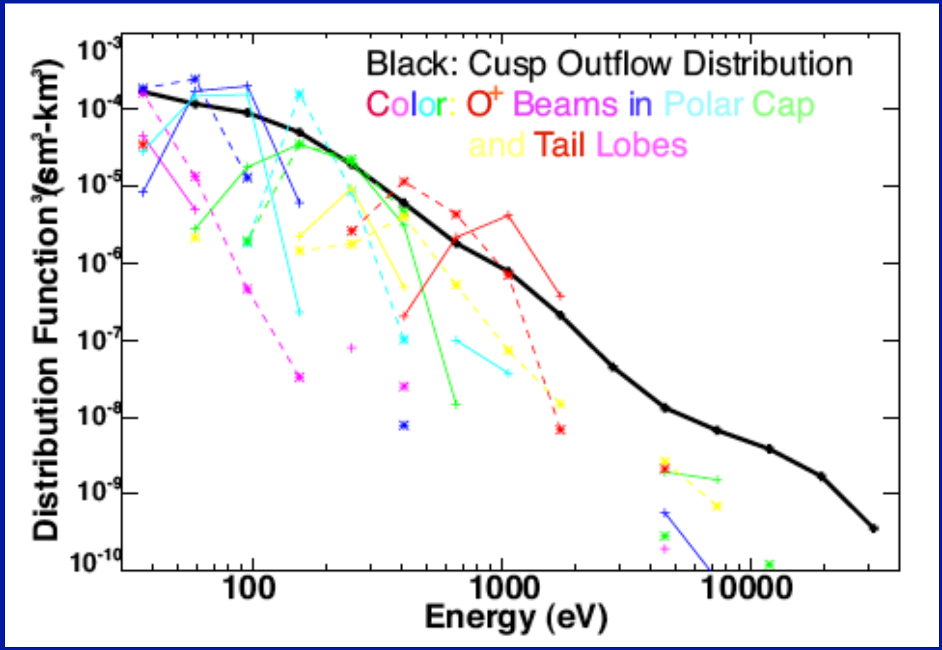


Case Study

- Here we pick one time period where we get a good measure of cusp outflow, and then track the beam as we move over the polar cap and into the lobe.
- We select a number of times to measure the spectrum

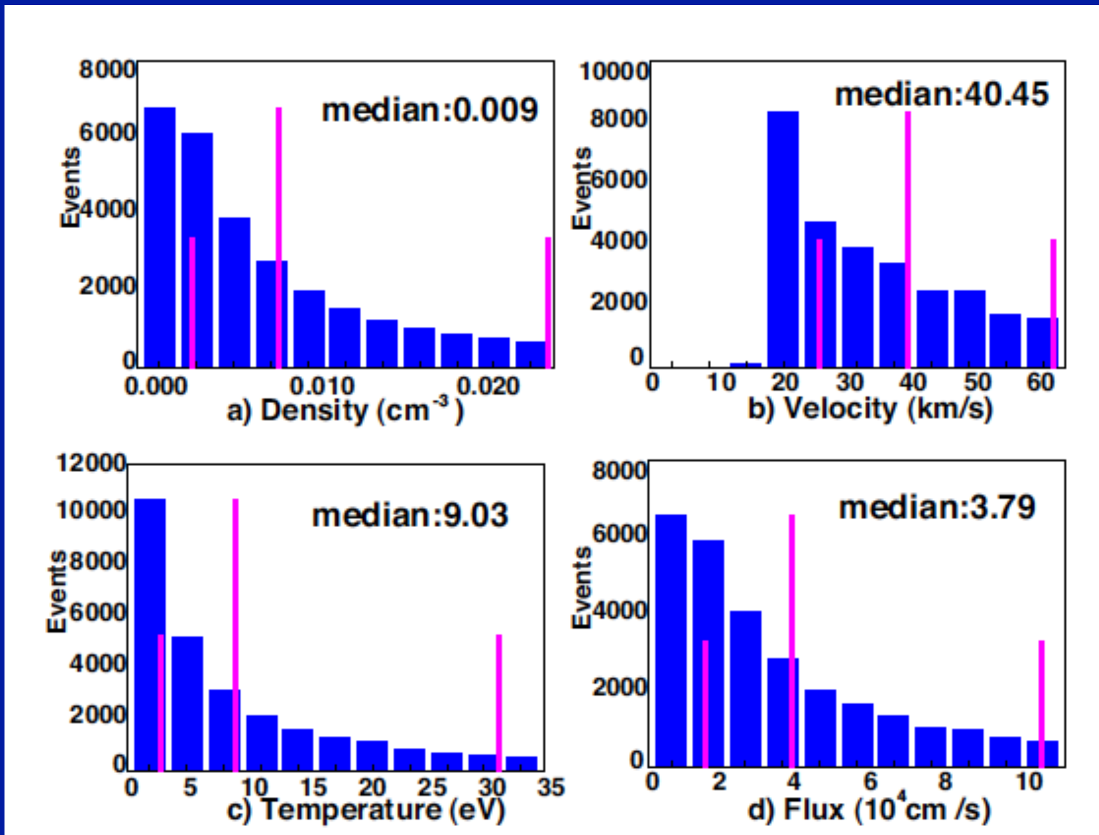
Liao et al., 2011

- We compare the cusp outflow *f* with *f* from the individual beams.
- We find that the beams generally fall within the envelope - no strong evidence for acceleration along the transport path.
- Good confirmation of velocity filter.

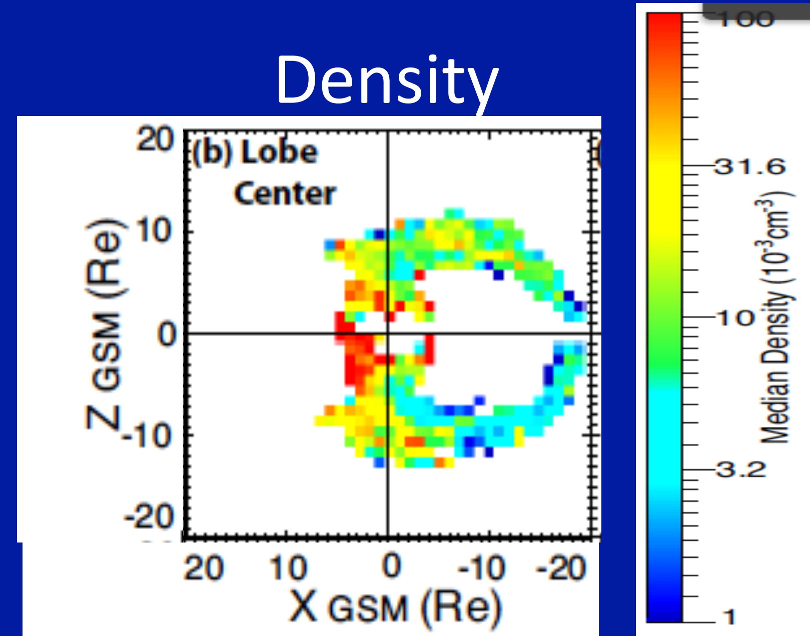


(normalized to 300 km)

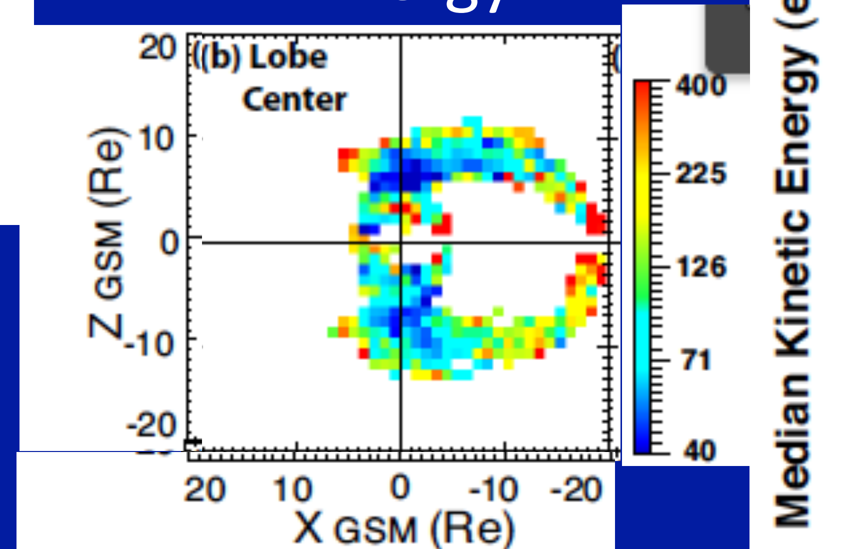
Statistics of O+ Lobe Beams



Density



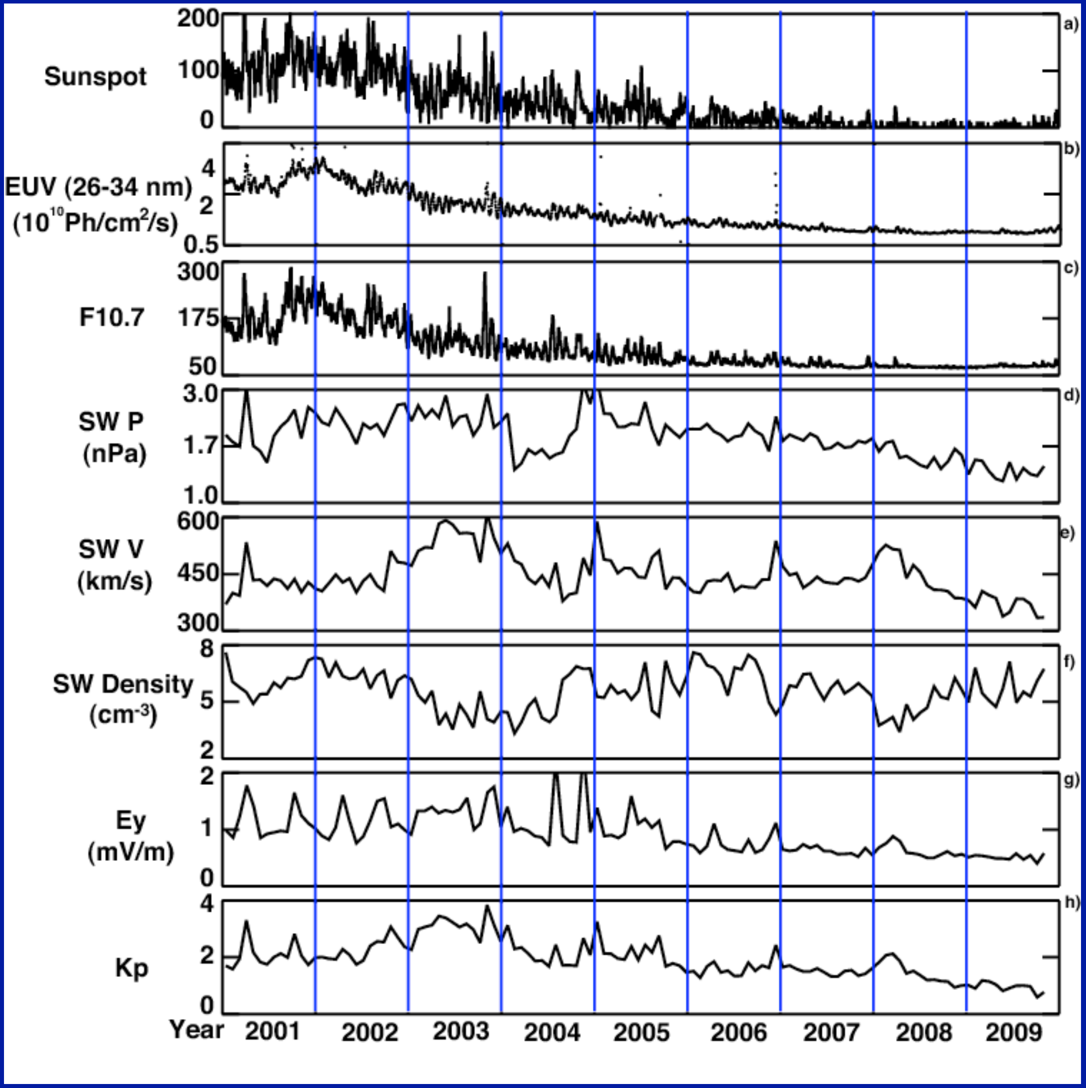
Energy



Liao et al., 2011

- Energy (velocity) increases with distance.
- Temperature low due to velocity filter (upper limit if in 1 energy channel)

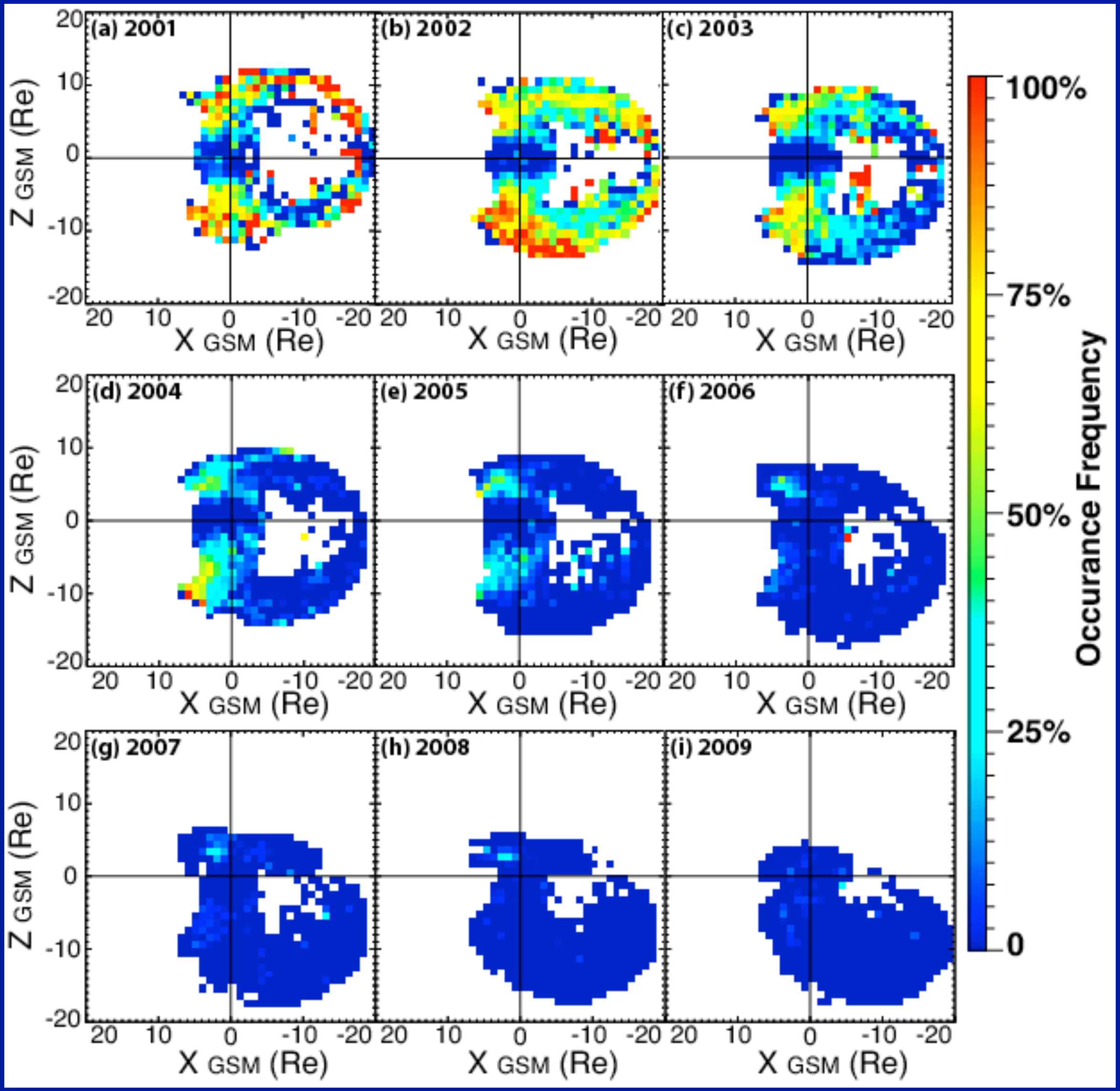
Solar Cycle Trends



- Cluster launched into solar maximum, and then experienced the extended solar minimum.

Liao et al. 2012

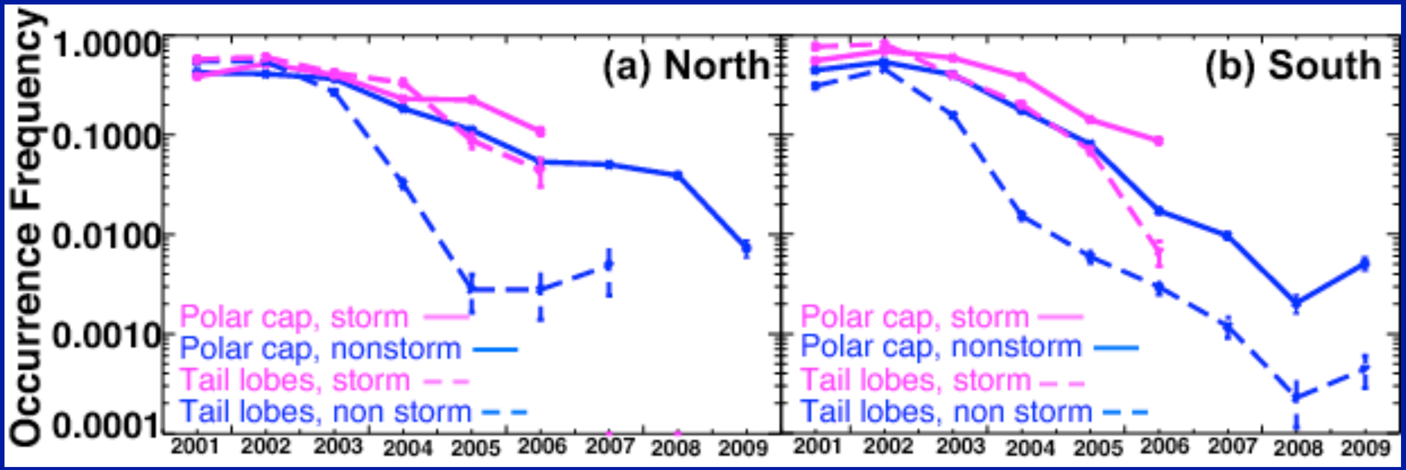
Transport from Cusp to the Plasma Sheet

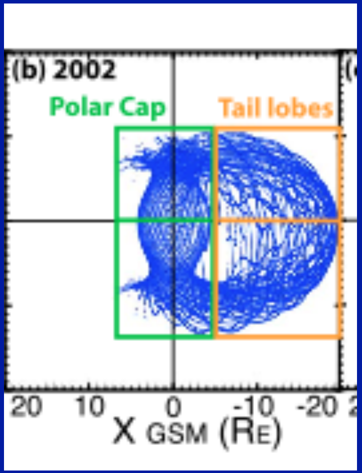


- The occurrence of O+ beams in the lobe decreased precipitously with the solar cycle.
- The decrease is most significant in the lobes.

Liao et al. 2012

Solar Cycle Effect on O+ Transport



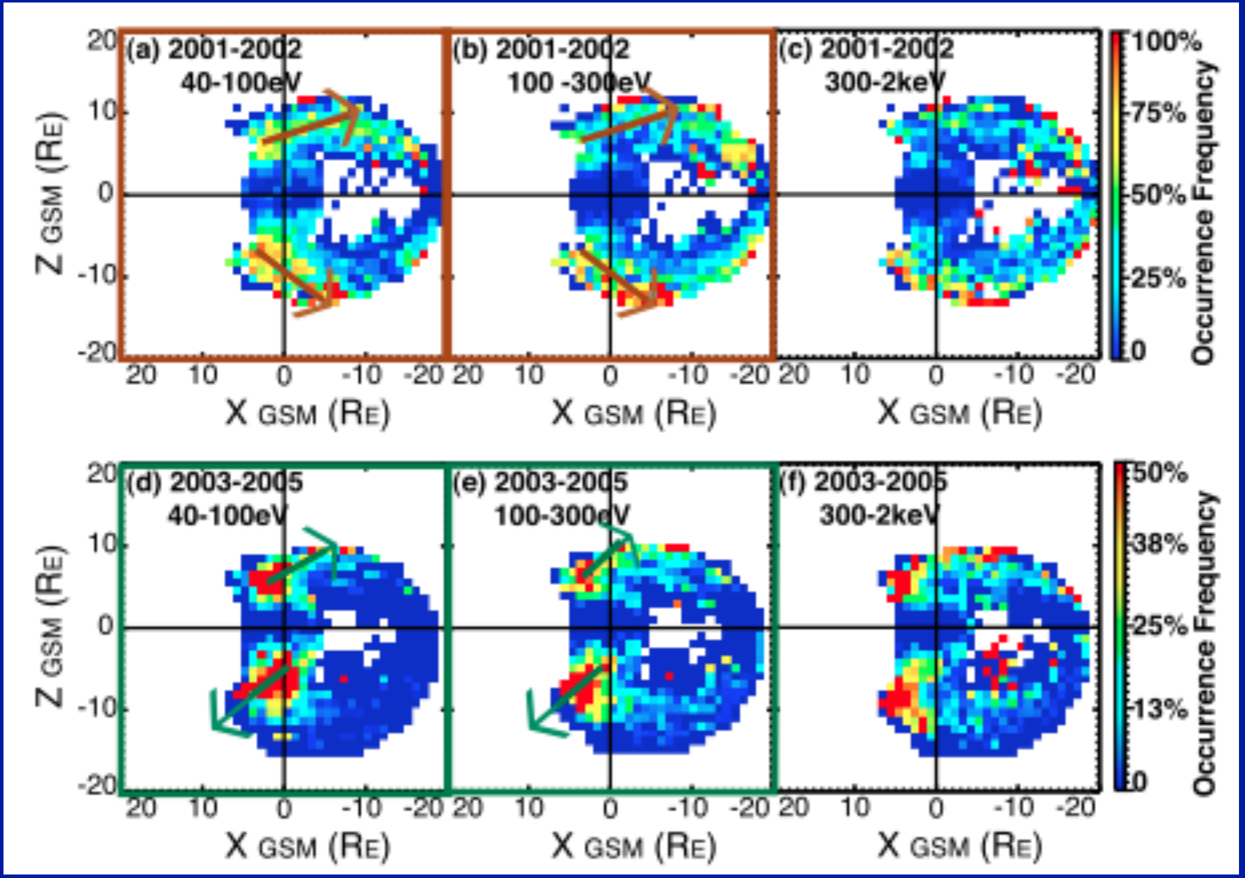


- The decrease in the polar cap distribution is consistent with the decrease in the cusp outflow source.
- The significant drop in the lobes, compared to the polar cap may be due to:
  - Change in outflow spectrum, with fewer high energy ions
  - Reduced flux of outflow bringing the lobe beams below threshold.
  - Changes in the transport path no longer bring the beams to the near-earth plasma sheet.
- Detailed analysis showed that the first two explanations could NOT explain the observations

Liao et al. 2012

Solar Cycle Effect on O+ Transport

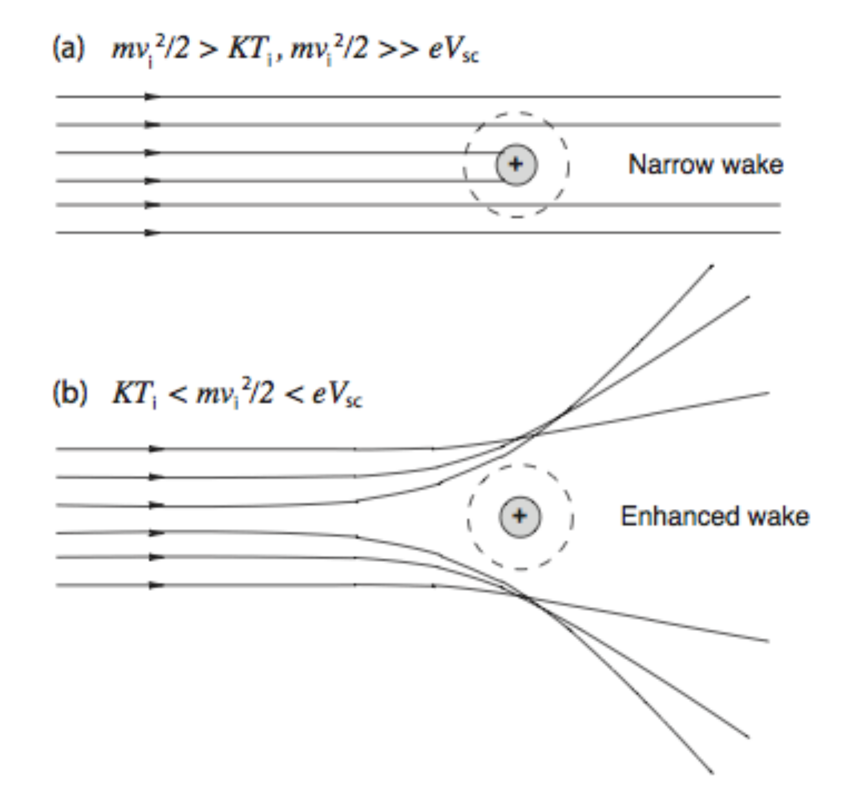
- The spatial distribution of the beams does indicate a change in transport.
- As the solar cycle declines, the beams are observed moving upward in the cusp, with less convective motion to the tail.
- These ions would then get further accelerated and be transported to the distant tail.
- Thus we would expect a very little O+ to reach the mid-tail plasma sheet during solar minimum.

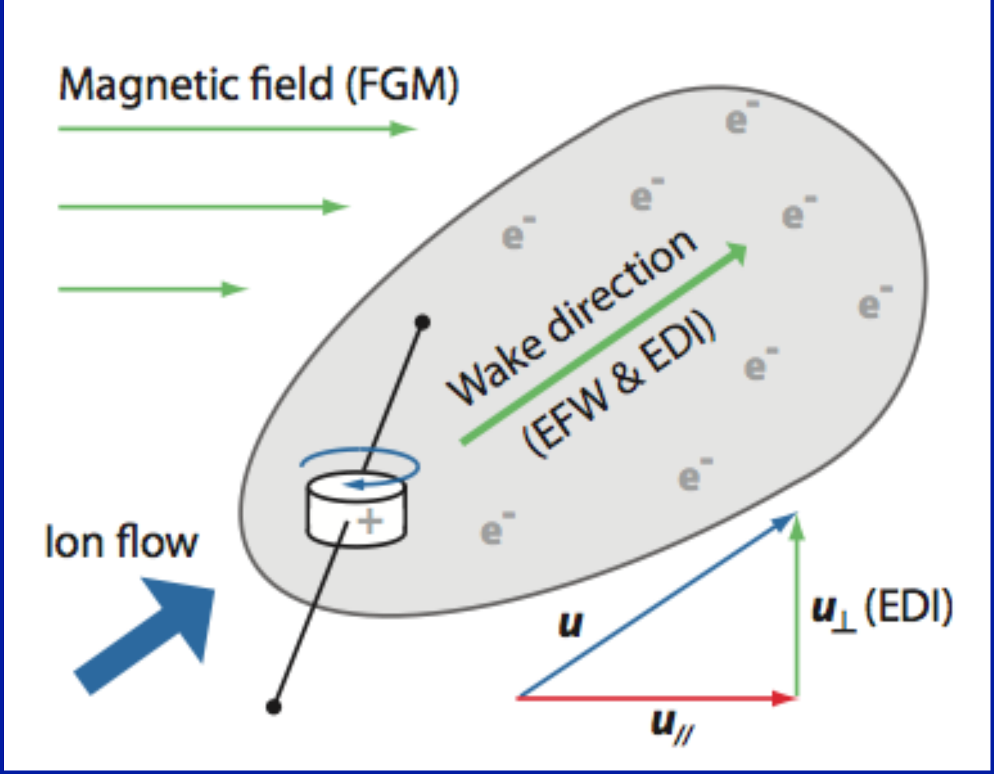


Liao et al. 2012

"Hidden" lobe population

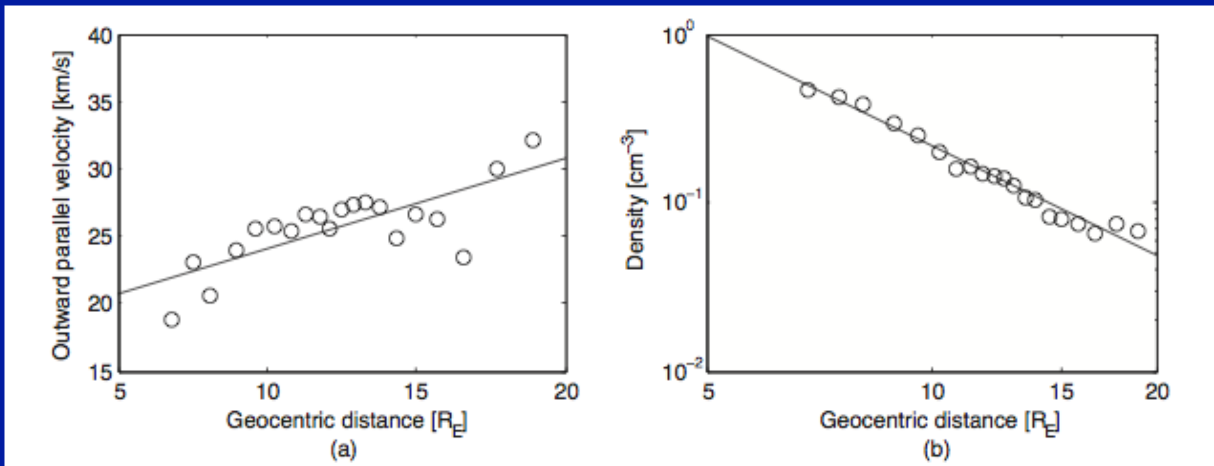
- Very low energy ions difficult to measure due to spacecraft charging in lobes.
- New method uses wake created by ions moving around the charged spacecraft to get velocity.
- S/C potential can be used to derive density.

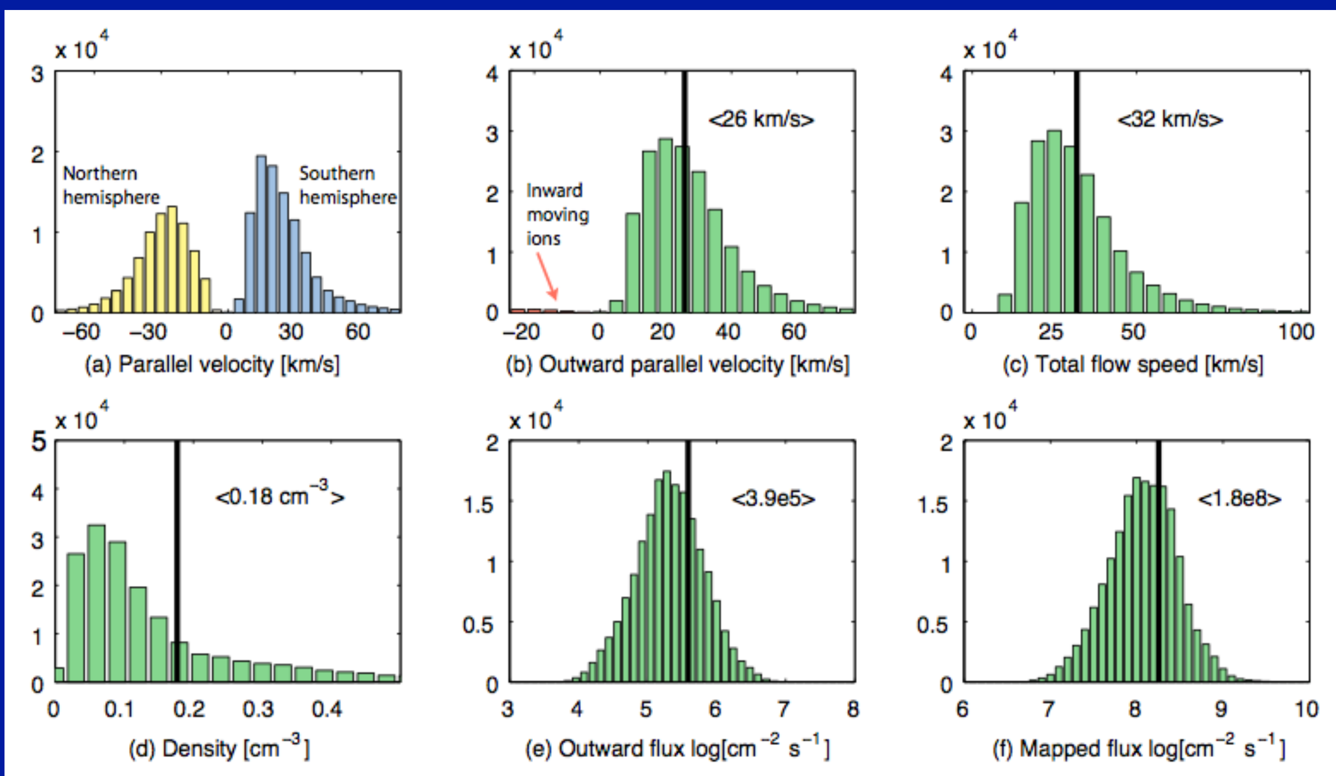




Engwall et al. 2009

“Hidden” Population Statistics

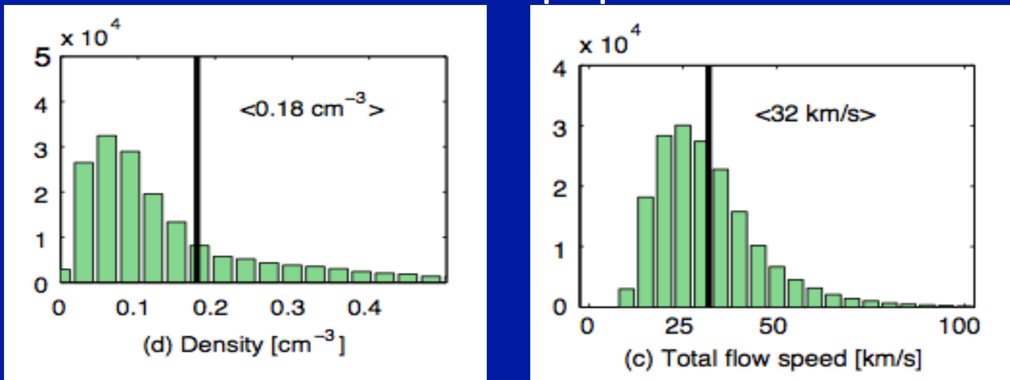




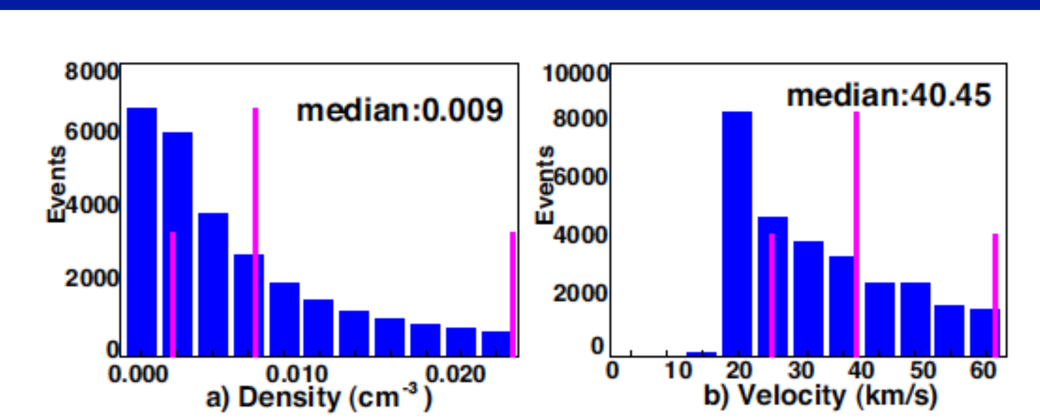
- Shows velocity increase and density decrease with radial distance
- Mean velocity is 32 km/s, but range is limited due to method.

O+ Beams and “cold” H+ population

H+ “hidden” population



O+ Beams

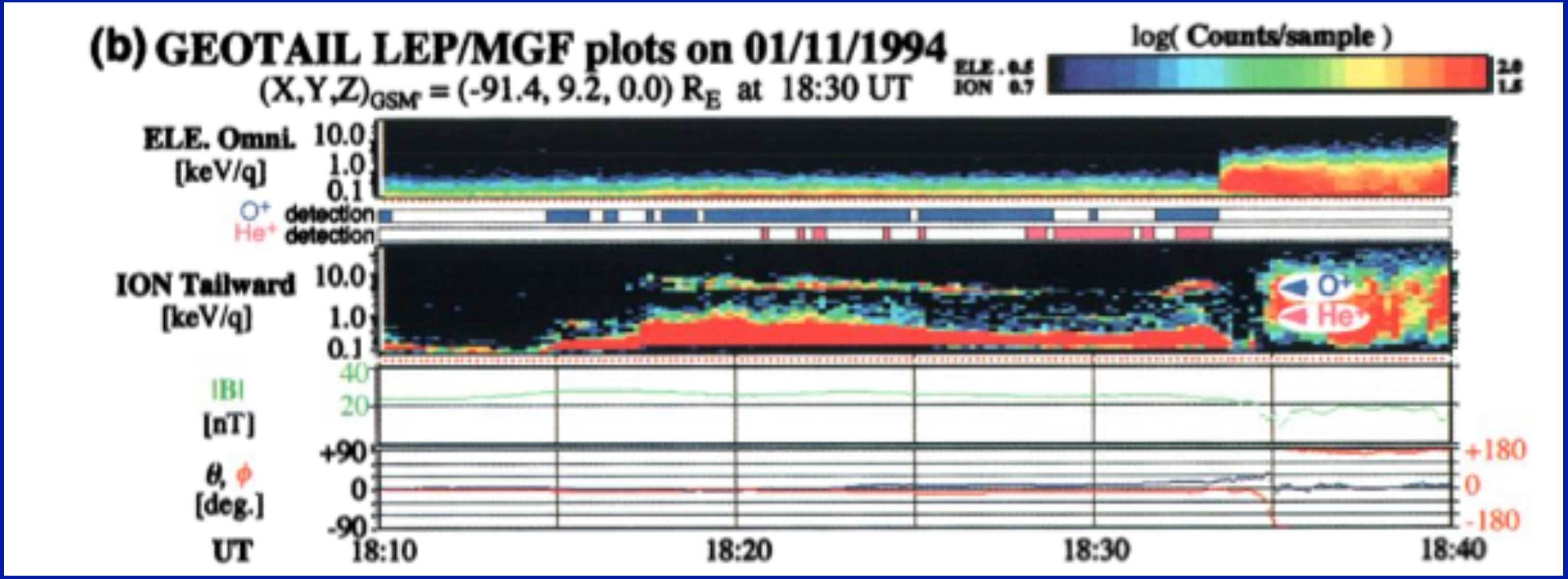


V(km/s)	H+ Energy (eV)	O+ Energy (eV)
10	0.52	8.26
20	2.07	33.06
25	3.23	51.65
30	4.65	74.38
40	8.26	132.23
50	12.91	206.61

- Both are covering the same ~ velocity ranges, within the limitations of their methods
  - CODIF can’t measure the H+ due to its low energy (<40 eV)
  - Wake method can’t measure O+ because higher energy not affected by S/C potential.
- Both show similar spatial velocity and density dependence, consistent with “velocity filter effect”.
- The low temperature is also consistent with velocity filter – only a particular velocity slice reaches a particular location.
- Conclusion: These are likely H+ and O+ transported together from the same source – most likely the cusp.

Geotail COB Work

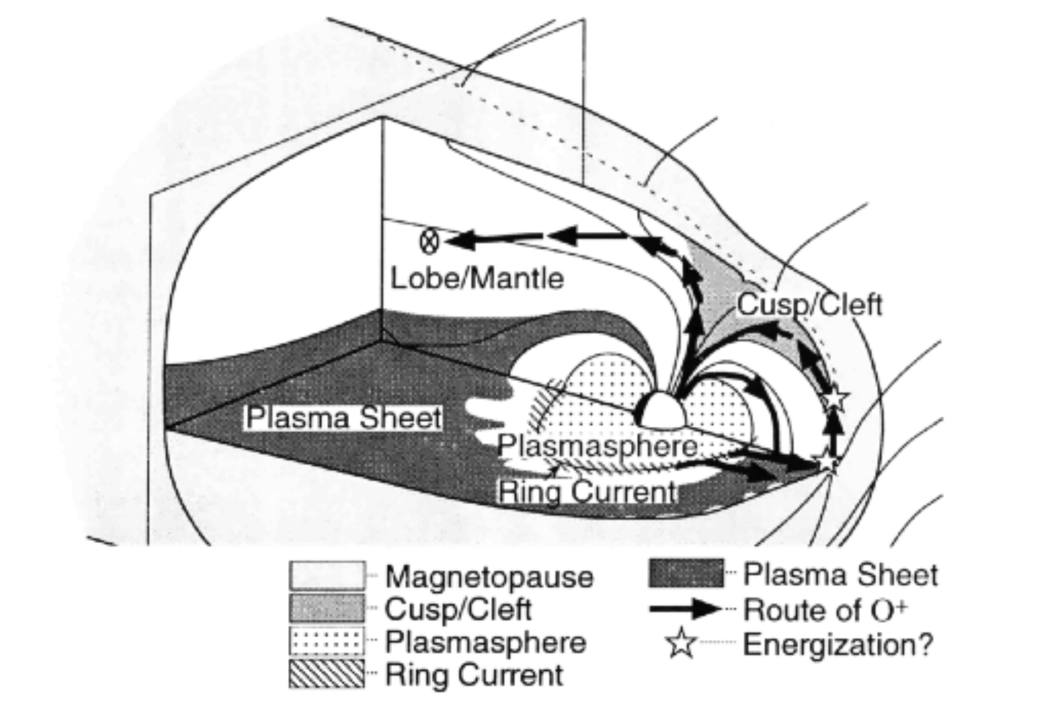
- Geotail observed the cold O+ beams in the distant tail, up to 220 Re.
- Observational Characteristics
  - Ionospheric (O+ and He+) ions coexist with solar wind ions (H+ and He++) moving at ~the same velocity.
  - Mean velocity increases with distance
  - Flux is too high to be explained by velocity filter effect on low-altitude cusp outflow.
  - Occurrence is positively correlated with Kp.



Hirahara et al., 1996, Seki et al. 1998a,1998b, 2000,2002

Geotail COB Work

- Possible sources
  - Additional energization of dayside polar outflows
  - Circulation of upward flowing ions from the nightside aurora
  - Dayside magnetospheric equatorially trapped populations, through reconnection.

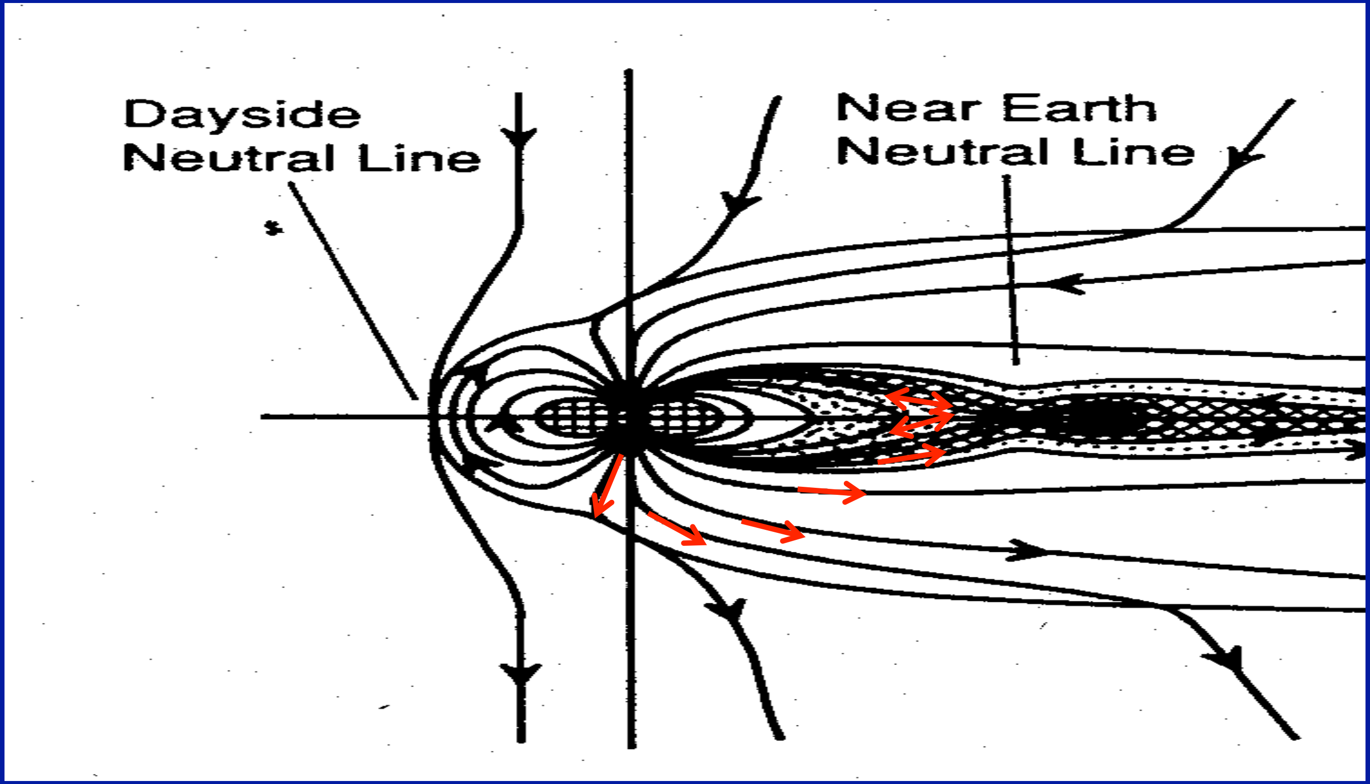


Seki et al. 2000

Seki et al. 2000, 2002 in particular investigated the third option, and found that the fluxes of dayside precipitating ions were consistent with the beams.

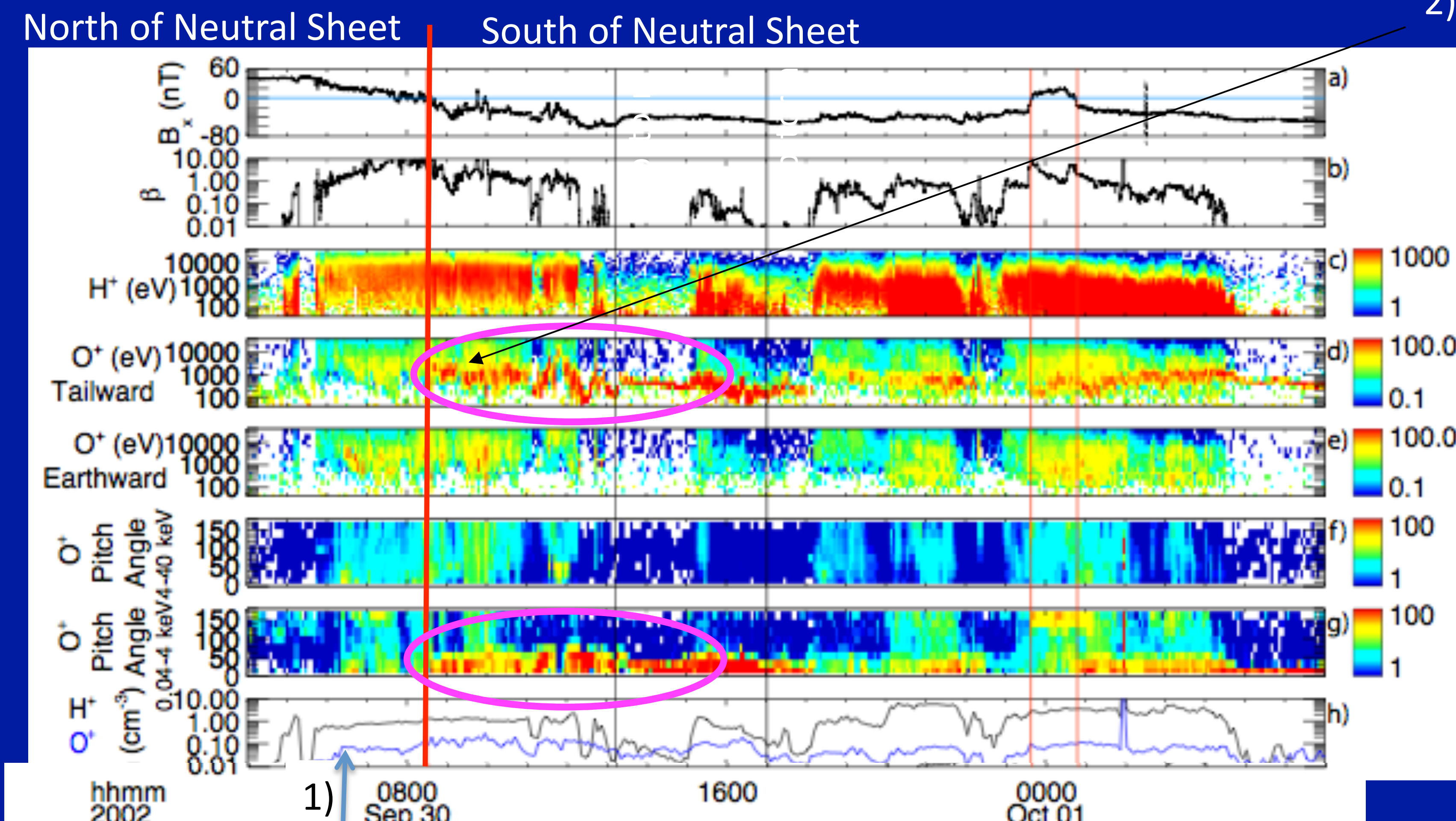
However, the new results from Cluster (Nilsson et al., 2012) showing high altitude cusp acceleration makes the first possibility most likely.

Transport into the Plasma Sheet



- Outflow from the cusp is on the lobe field lines.
- When reconnection occurs, the O+ that was on an open, lobe field line, is now on a closed, plasma sheet field line.
- If the radius of curvature is too small the ions will be scattered/isotropized as they cross the neutral sheet.
- For a larger radius of curvature, some may continue along the field.
- As they convect in, they will be heated.

Storm-time Plasma Sheet pass

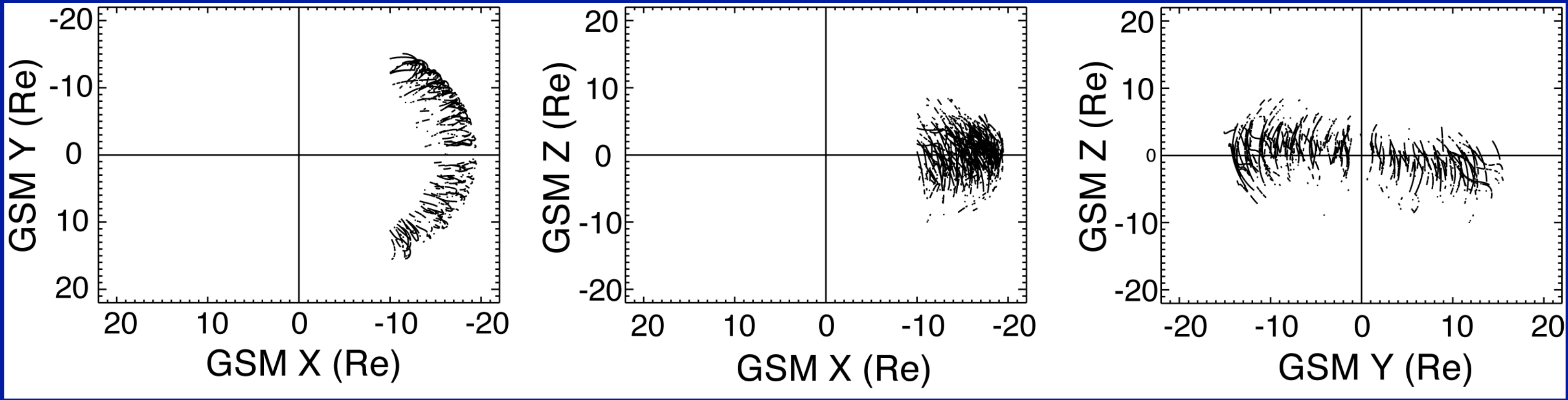


1) The O+ first increases at 6:20, with no strong field-aligned beam
2) Once the S/C crosses the neutral sheet, the strong tailward field-aligned population is clear.
3) This population continues as the spacecraft moves in and out of the lobe

Kistler et al. 2010

Solar Cycle Effect on Plasma Sheet

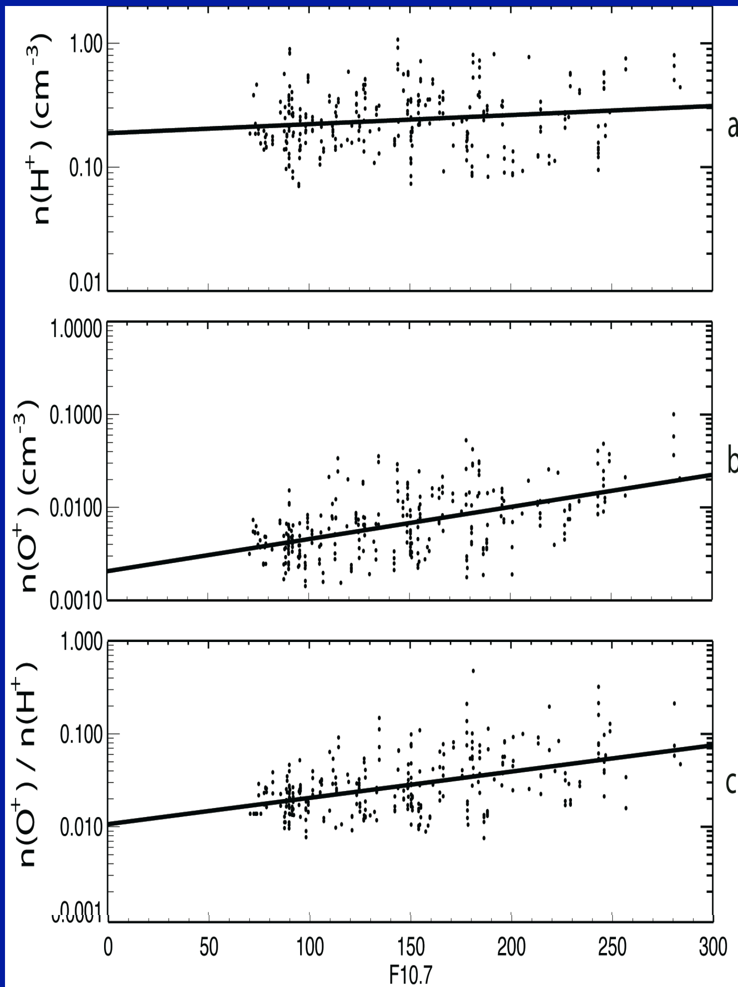
Time Period: CLUSTER "Tail seasons" (mid July to end of October) from 2001 to 2005.
Measurements: CIS/CODIF instrument from S/C 4.
Energy Range: 1 – 40 keV
Inner plasma sheet selection criteria:
- The plasma beta is greater than 1;
- The distance is greater than 15 Re.



Mouikis et al. 2010

F10.7 Dependence

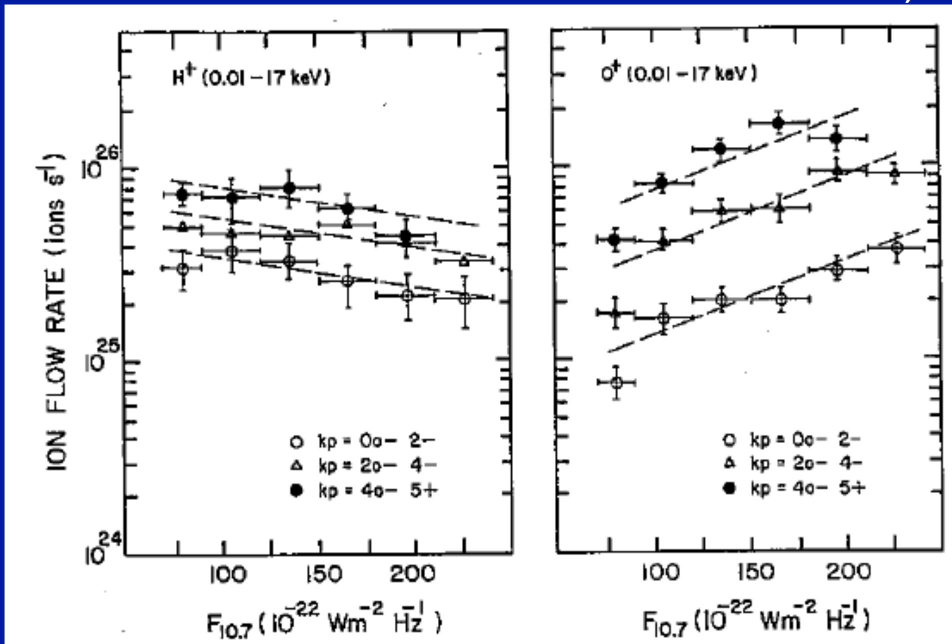
Central Plasma Sheet



F10.7

Auroral Outflow

Yau et al., 1988



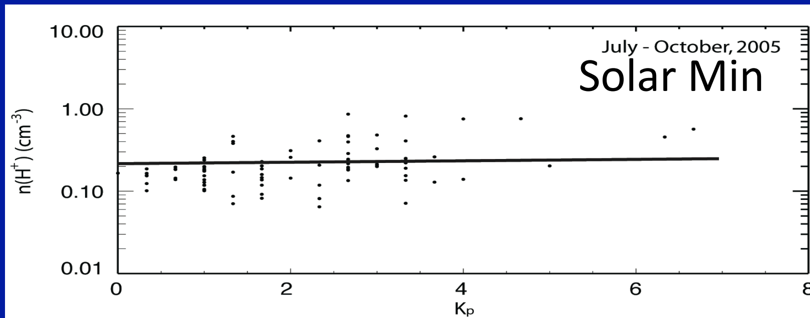
- While H+ ionospheric Outflow decreases with F10.7, the plasma sheet H+ density remains ~the same.
  - PS has mixed source – solar wind also plays a significant role
- O+ auroral outflow increases by x4, while the density in the plasma sheet increases by x8.
  - This is consistent with the plasma sheet increase reflecting both the increased source and increased transport at solar max.

Mouikis et al. 2010

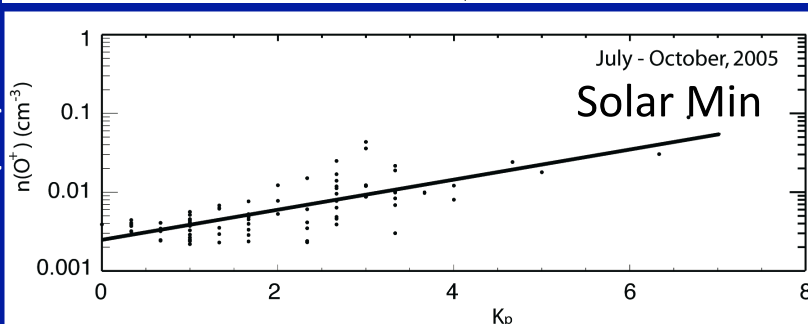
Kp Dependence

Central Plasma Sheet

n(H^+)

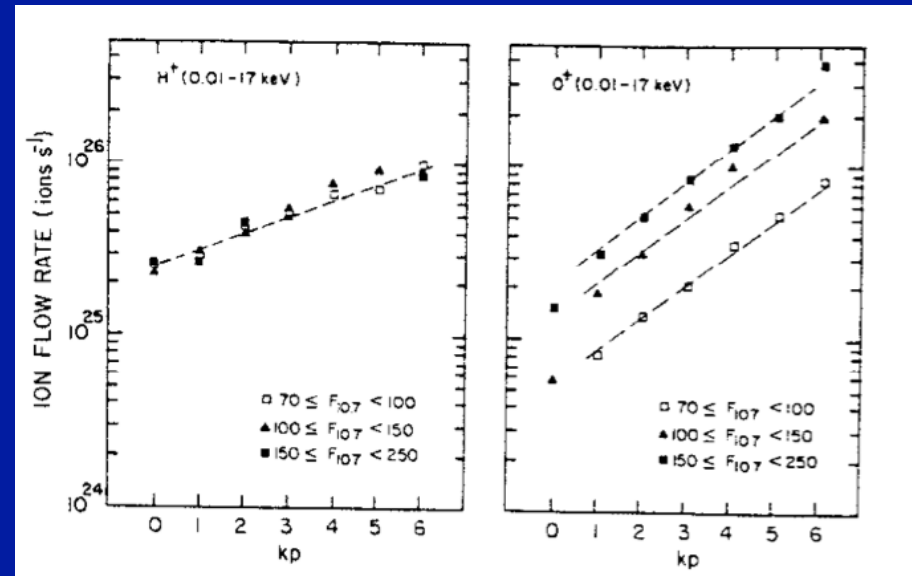


n(O^+)



Mouikis et al. 2010 Kp

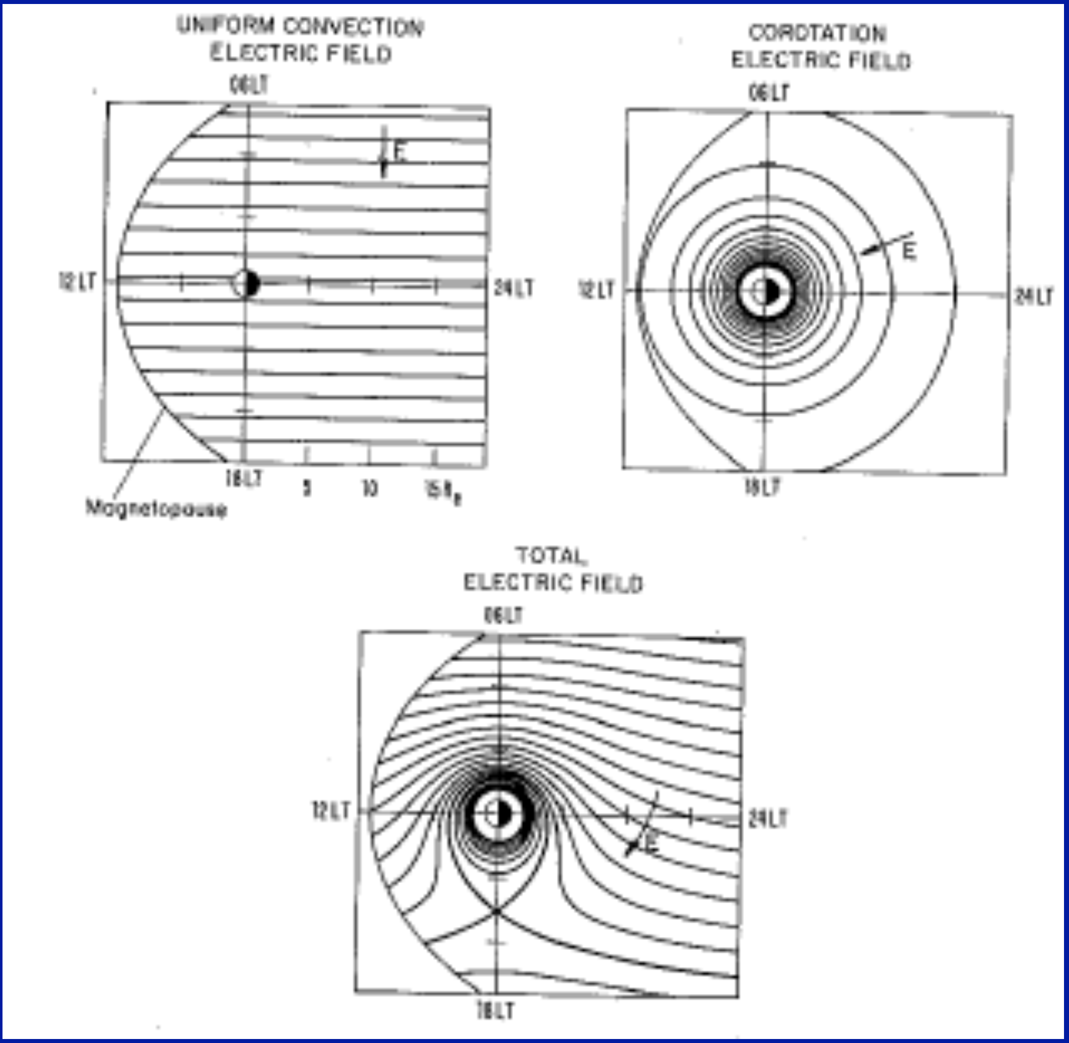
Auroral Outflow



Yau et al., 1988 Kp

- While H+ ionospheric outflow increases with Kp, the plasma sheet H+ density remains ~the same.
  - PS has mixed source – solar wind also plays a significant role
  - As H+ dominates the pressure in the PS, pressure balance also effects the density.
- O+ ionospheric outflow and O+ density in the plasma sheet both increase by x15.
  - This implies that the O+ increase in the plasma sheet with Kp is mainly a source effect. Somewhat surprisingly, transport is not playing a strong role.

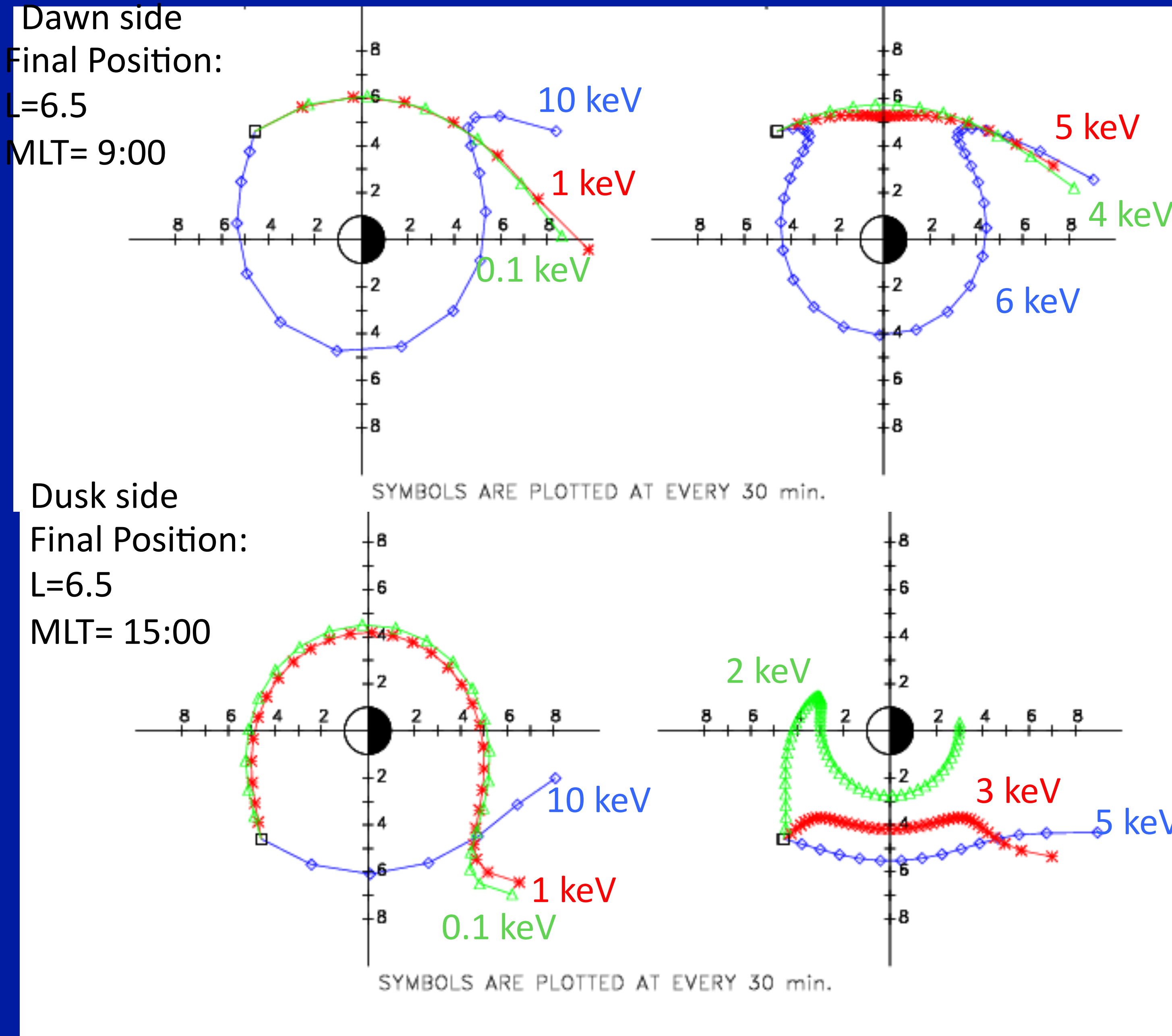
Transport to the Inner Magnetosphere



- Low energy ions are dominated by the ExB drift, and so follow co-rotation eastward
- Higher energies start to move westward due to the gradient and curvatures drifts.
- Cross-over point is at ~1-10 keV, right in the energy range of interest.

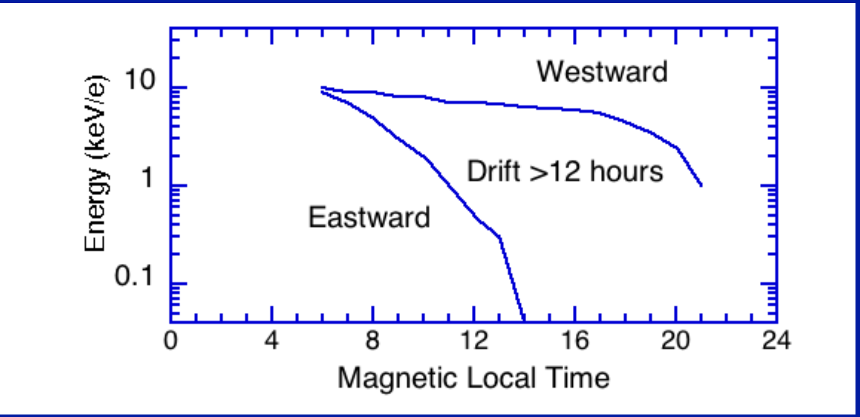
(From Lyons and Williams, 1984)

Sample Particle Trajectories

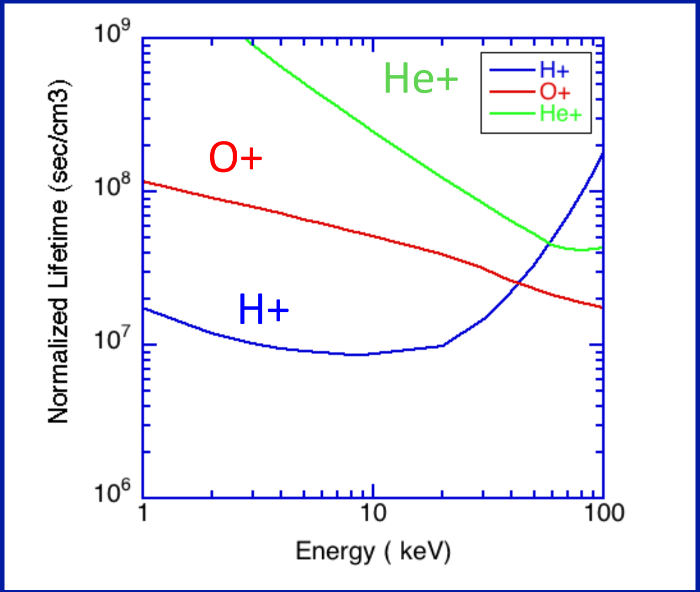


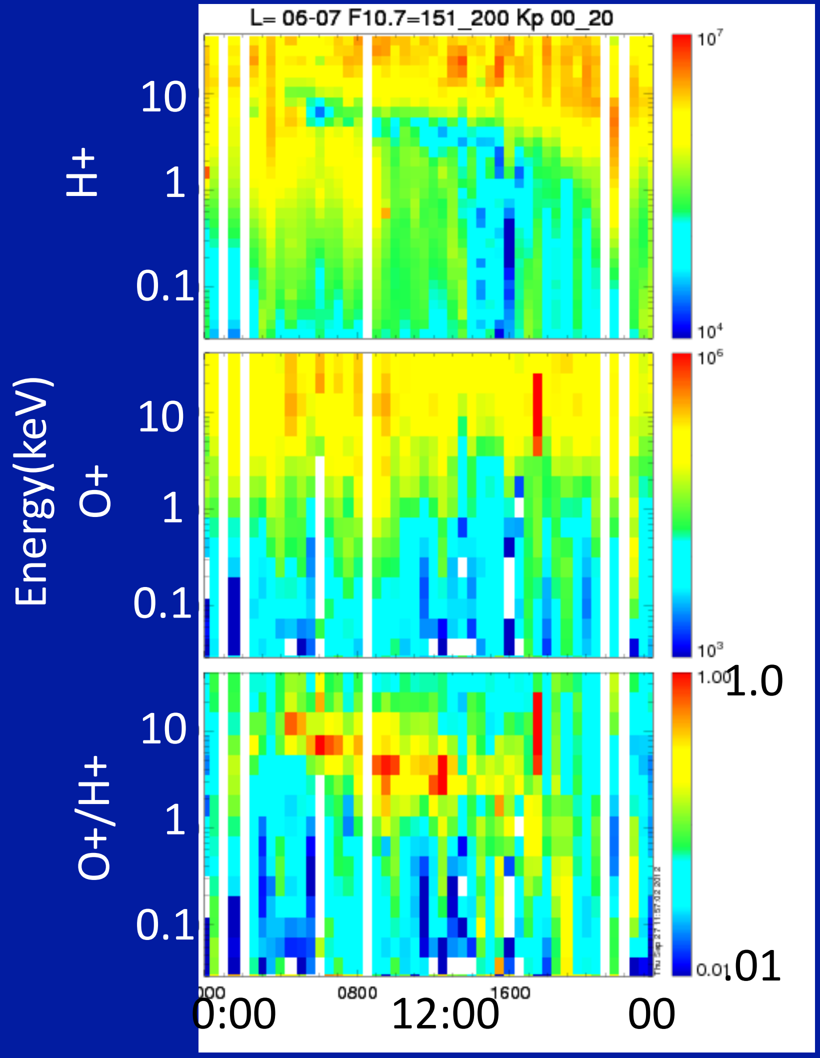
Spectral Features Resulting from Drift and Charge Exchange

Schematic Spectrum



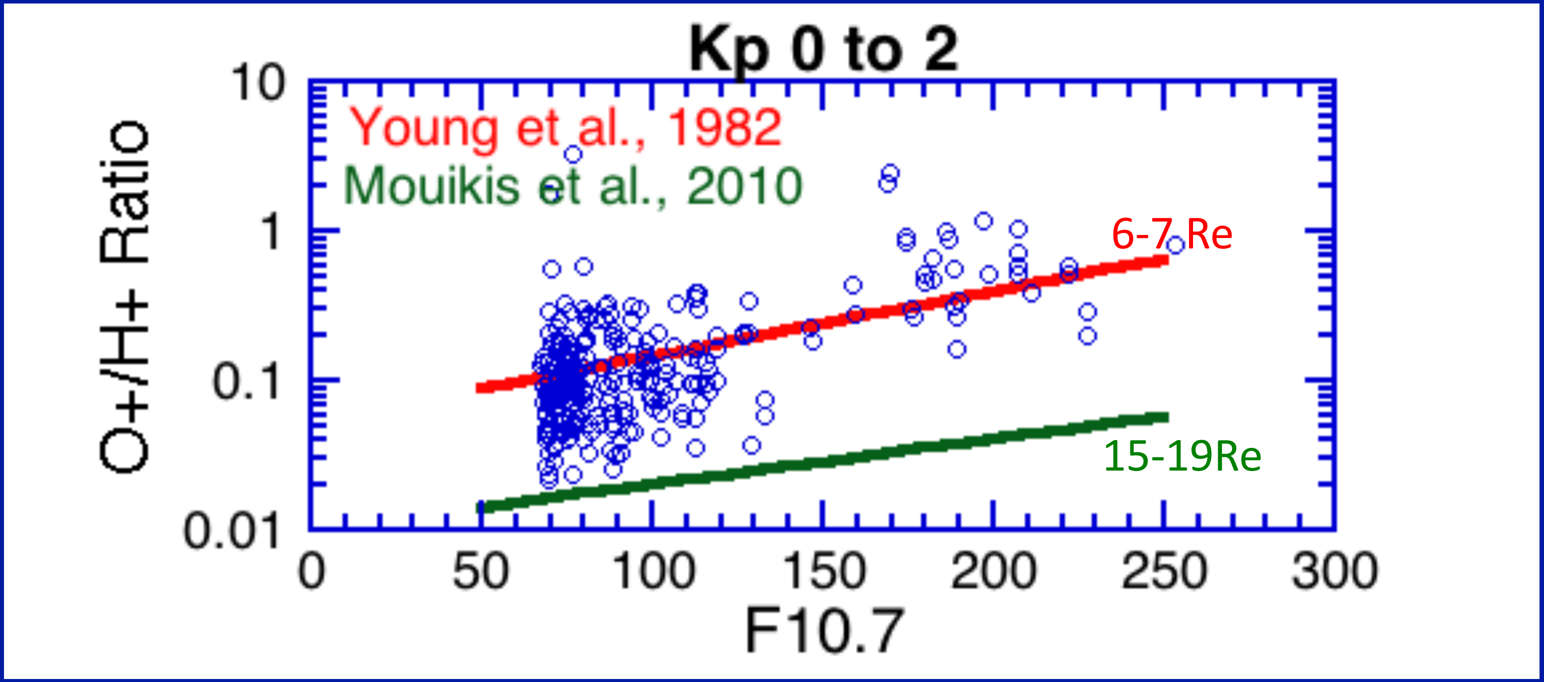
Charge Exchange Lifetimes





Magnetic local time

O+/H+ ratio vs F10.7

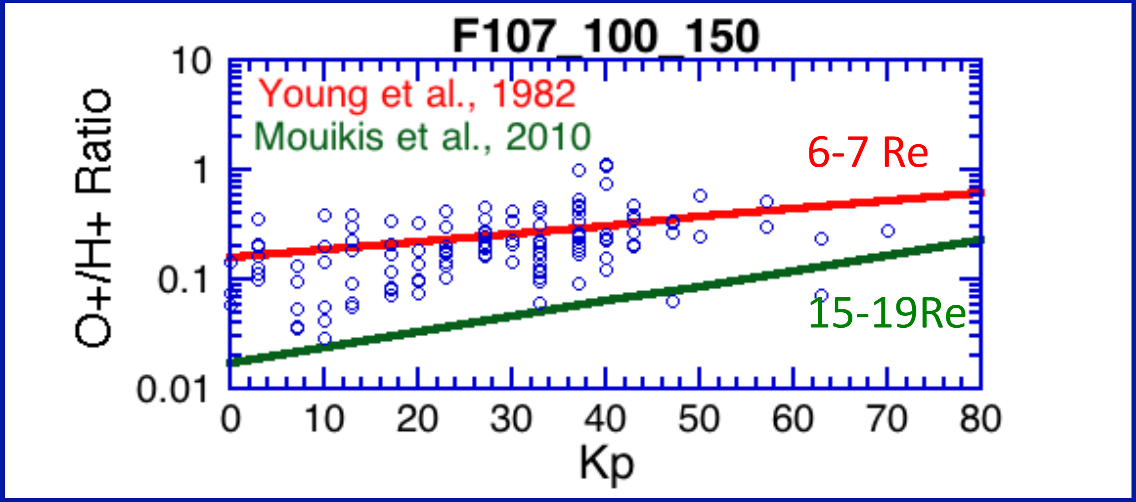


- The Young et al., 1982 F10.7 dependence agrees well with the Cluster results..
- There is ~ factor of 10 increase in the O+/H+ ratio from 15-19 RE to 6-7 Re. This implies there is significant additional entry of O+ inside 15 Re.

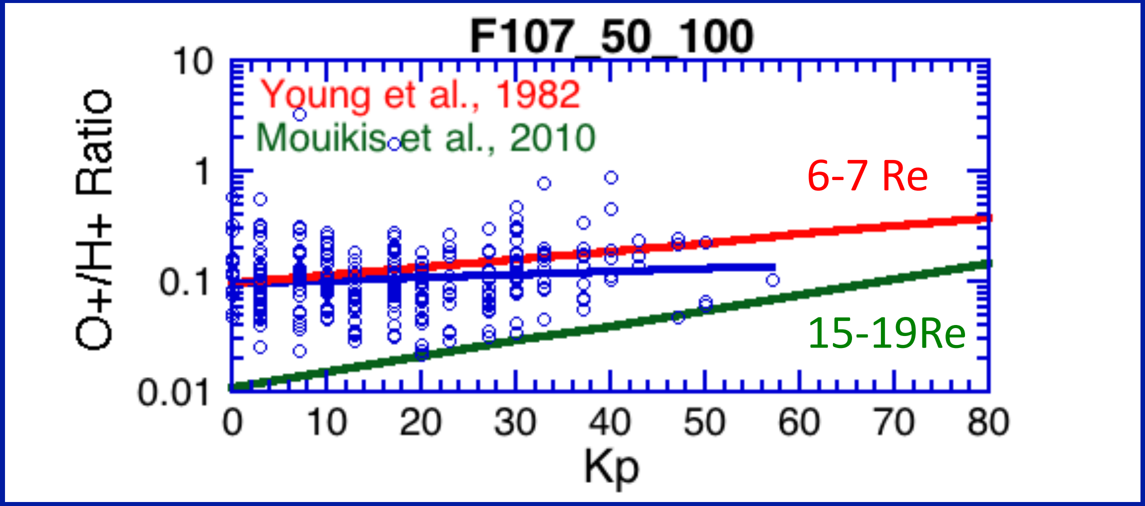
See Poster #56, G. Wang, for details

O+/H+ dependence on Kp

Medium F10.7



Low F10.7



- Because the H+ is also increasing with Kp, the O+/H+ ratio does not increase as much as O+ alone.
- For low F10.7, there is almost no increase with Kp.
- Again, we see a radial dependence, with higher O+/H+ at 6-7Re than at 15-19 Re.

See Poster #56, G. Wang, for details

Summary

- Ionospheric ions escape the ionosphere through a multistep process of heating and acceleration.

- Transport from the cusp is modulated by the velocity filter/mass spectrometer effect, so the ions in the polar cap/lobe are predominantly mono-energetic beams, and we observe "energetic" O+, and not H+.

- Cusp ions enter the plasma sheet through reconnection.

- Auroral ions have direct access to the plasma sheet, and there is evidence that their contribution is large inside 15 Re.

- Transport into the inner magnetosphere is mainly through adiabatic drifts, and the effects of species dependent loss processes are important in determining the composition.

- In all locations, both the effects of EUV (F10.7) and magnetic activity (Kp) strongly impact the composition. The source population (outflow) and the transport (convection) both change with solar cycle and solar activity, affecting the composition throughout the magnetosphere.

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