Ionospheric Outflow:
Observational Constraints on Global Models

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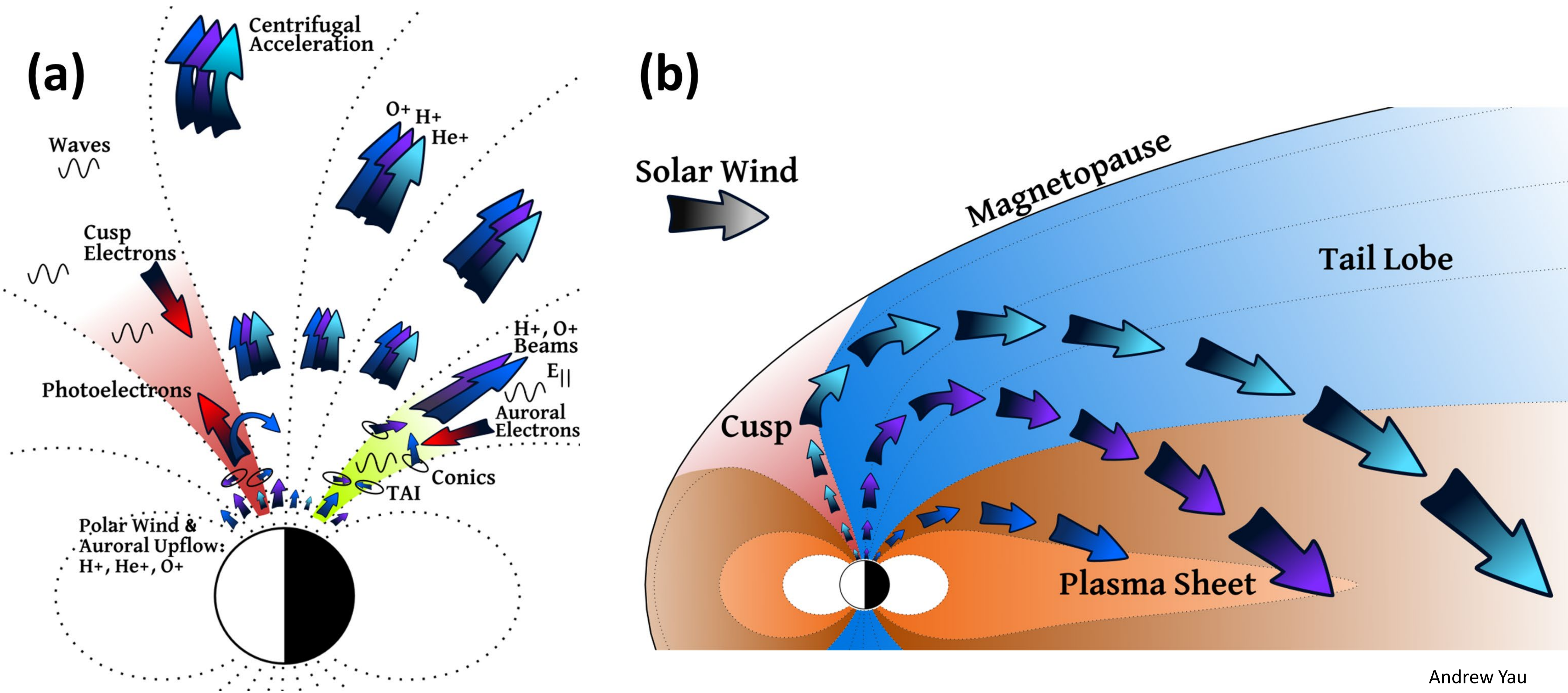
Thanks to Andrew Yau, Victoria Foss, Laila Andersson, Rob Redmon, Robin Ramstad, and Alex Glocer

Outline

- The role of ions in the magnetosphere
  - Introduction / Overview
- Examples of how to use global observations to constrain or test models
  - Upwelling and energization on the dayside
  - NO^+ chemistry as a time tag to constrain energization to 100’s of keV
  - Estimating the ionospheric fraction of magnetospheric plasma
- What I don’t know about ion outflow, but wish I did.
  - Hint: These things we will probably only learn from model trade off studies

The Big Picture



Andrew Yau

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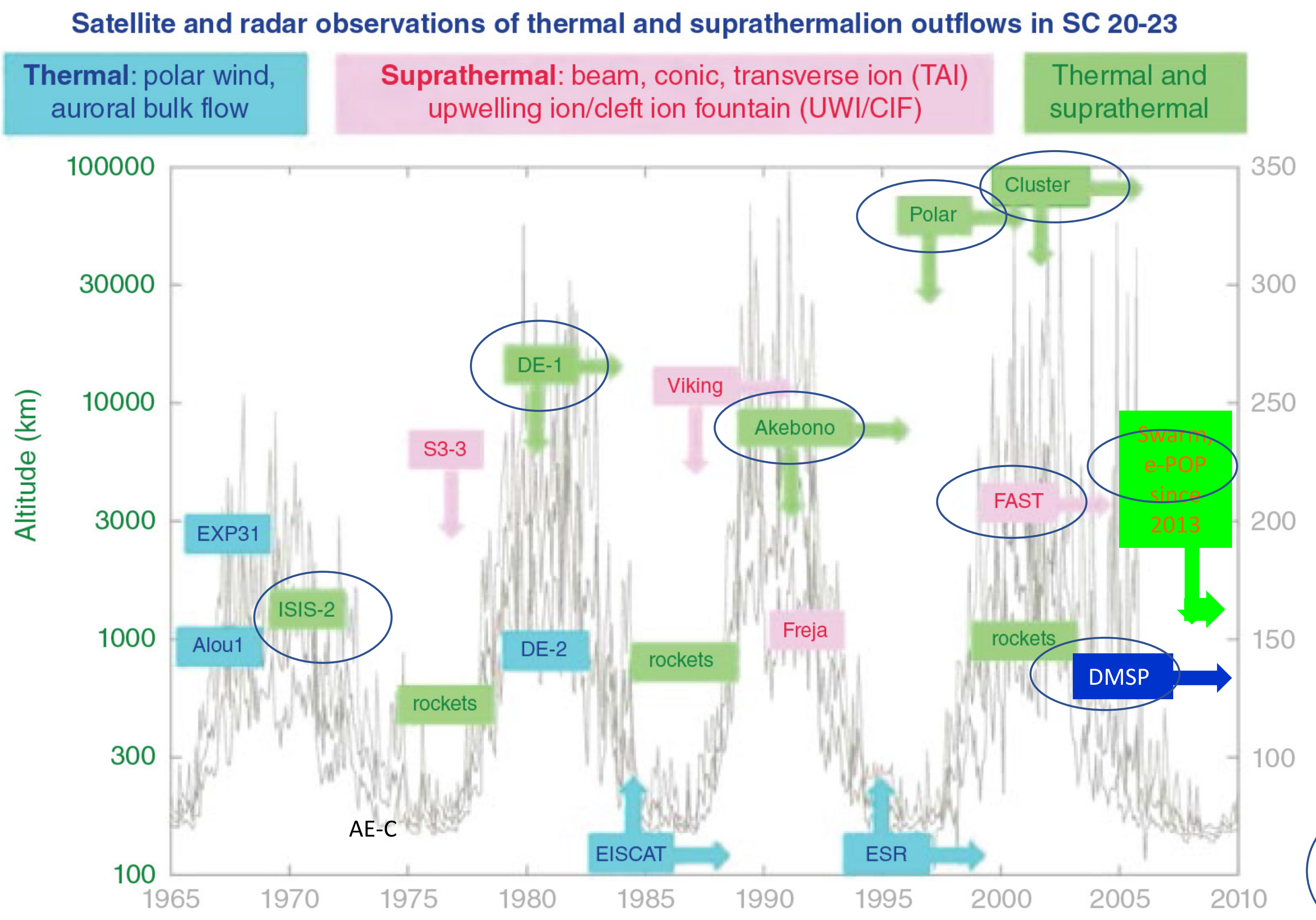
The Big Picture in Words

- Most of the energy is in the magnetic field, so it determines the large scale structure
- The solar wind and gravity determine the extent and shape of the magnetosphere
- Ions and electrons come from the solar wind and ionosphere
  - Ions are heavy and slow so they define the fine structure
  - Electrons are light and fast so they go everywhere
    - ..and electron interactions with ions create plasma waves that facilitate energy or momentum transfer between ions, electrons, and the magnetic field
    - ..and electrons make up almost all of the currents!
  - Electron and ion gyroradii (energy) matter

Thermal and Suprathermal Ion Observations



Thermal / Suprathermal

Energy transition ~ 1 eV

Gravity maters:

- Energy required for ionospheric ions to reach the plasma sheet depends on altitude
- Most Upwelling ions observed by radars in the ionosphere return to the ionosphere.

Since 2010
MMS
Van Allen Probes
Arase (ERG)
MAVEN
Mars Express
Venus Express

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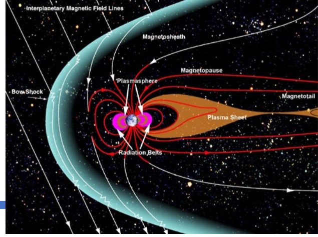
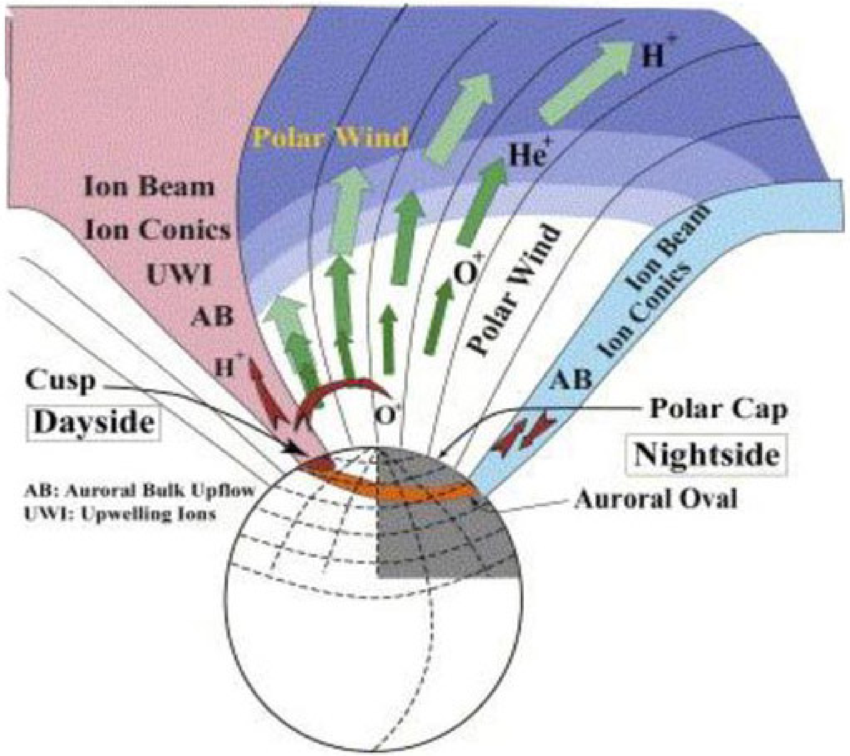
Standard view of ions in the magnetosphere



- H^+, He^+, O^+, NO^+, O_2^+ … created by Solar EUV photons, energetic electrons, and chemistry
- Energy from the solar wind drives field-aligned currents, ionospheric convection, and creates plasma waves.
- Neutral-ion interactions warm the upwelling ionospheric ions and drive them to higher altitudes
- Ambipolar electric fields created by gravity move thermal ions upward in the polar wind
- Plasma waves in the auroral plasma cavity further energize ions to > 10 eV allowing access to the distant plasma sheet.
  - This is the ‘gap’ region that is hard to observe, model/parameterize
- Inward convection energizes plasma sheet O^+ to the energies observed there.
- Warm O^+ in the outer plasma sphere become the plasma cloak
- Ignore H^+ because we can’t tell if its from the solar wind or ionosphere
- Only think about He^+ when its in the plasma sphere
- Ignore minor ions (He^+, N^+, NO^+, O_2^+ …) and thermospheric chemistry.



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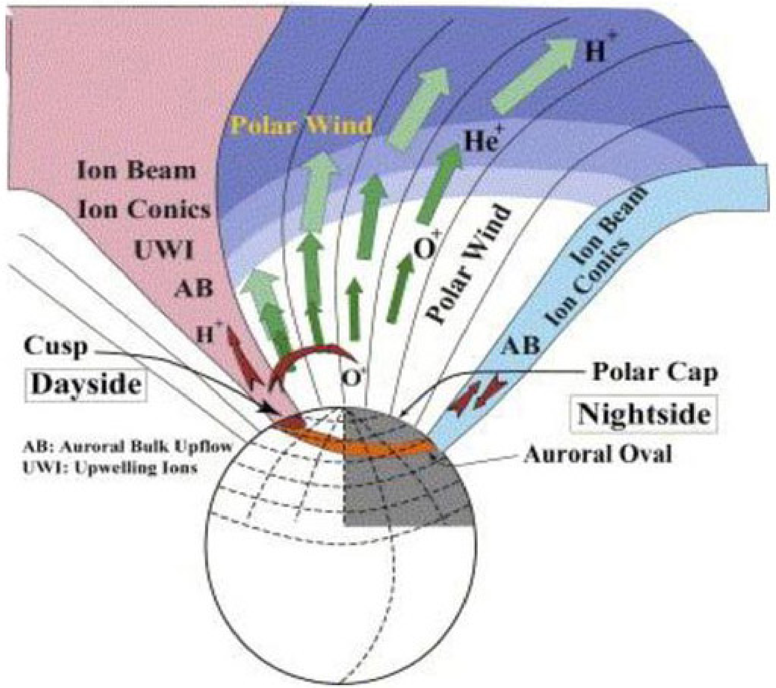
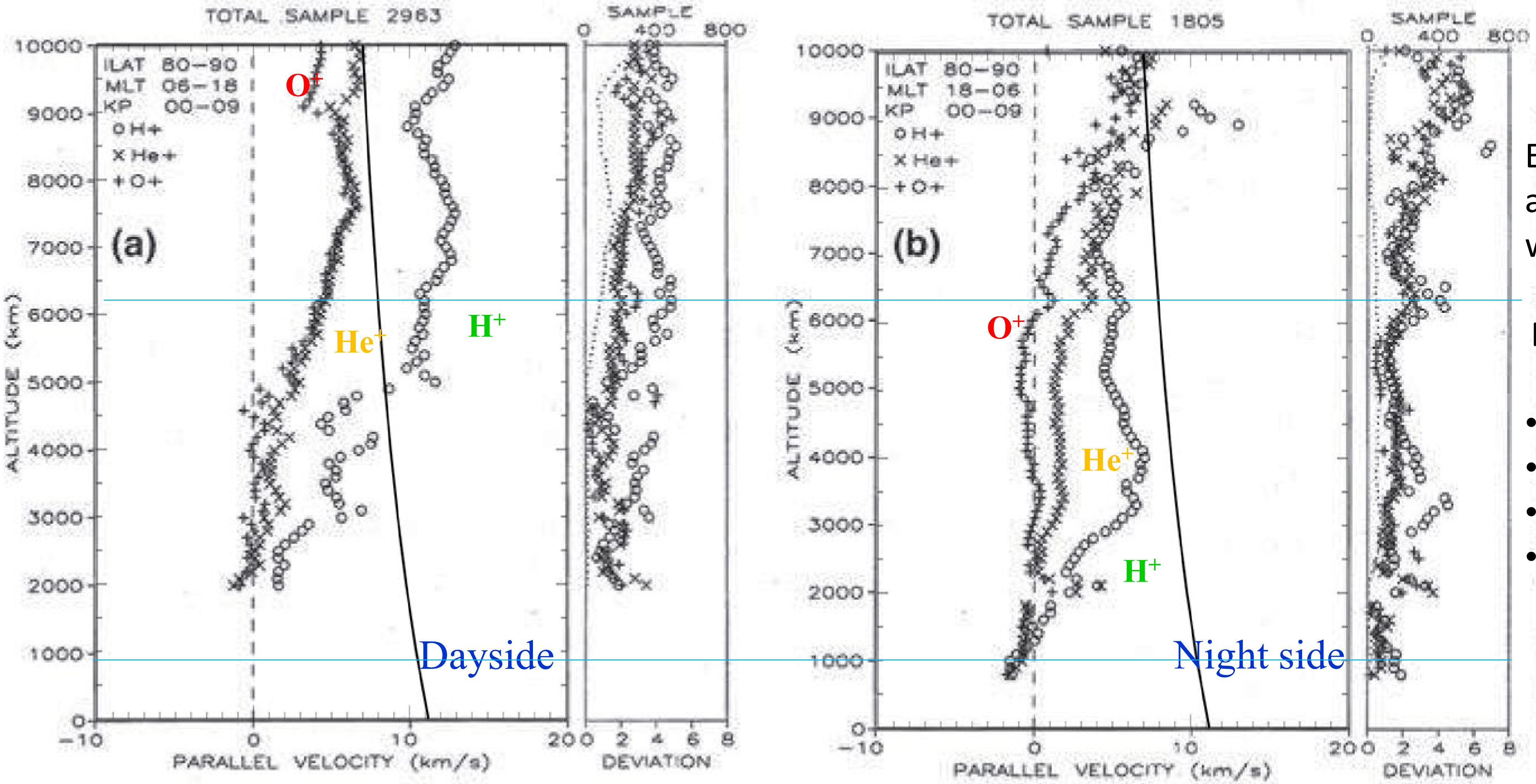
Ion Outflow



- Before S3-3 the focus was on H^+ and He^+ in the polar wind
- Hoffman and his ISIS co-workers were limited by attitude data quality. This was a common problem on early missions. Their work around for thermal ion data was to set the O^+ vertical drift velocity to zero.
- Shelley (1977) discovered energetic O^+ precipitating and started the search for upflowing heavy thermal ions. (Their instrument was funded to look for He^{++} precipitating from the magnetosphere!)
- Subsequent observations of thermal ions on DE-1 by Chappell and his colleagues were limited by uncertainties in the space craft potential.
- It wasn't until Akebono in the 90's that a large volume of upflowing thermal ion data were available.

Akebono Polar Wind Observations



Escape velocity 11.2 km/s at the surface decreases with altitude

Escape energy at 10 km/s (~top of ionosphere)

- H^+ 0.5 eV
- He^+ 2.1 eV
- O^+ 8.4 eV
- NO^+ 15.7 eV

Abe et al., 1993a, b

o H^+ x He^+ + O^+

Data from Polar Cap. Auroral zone and cusp data are excluded

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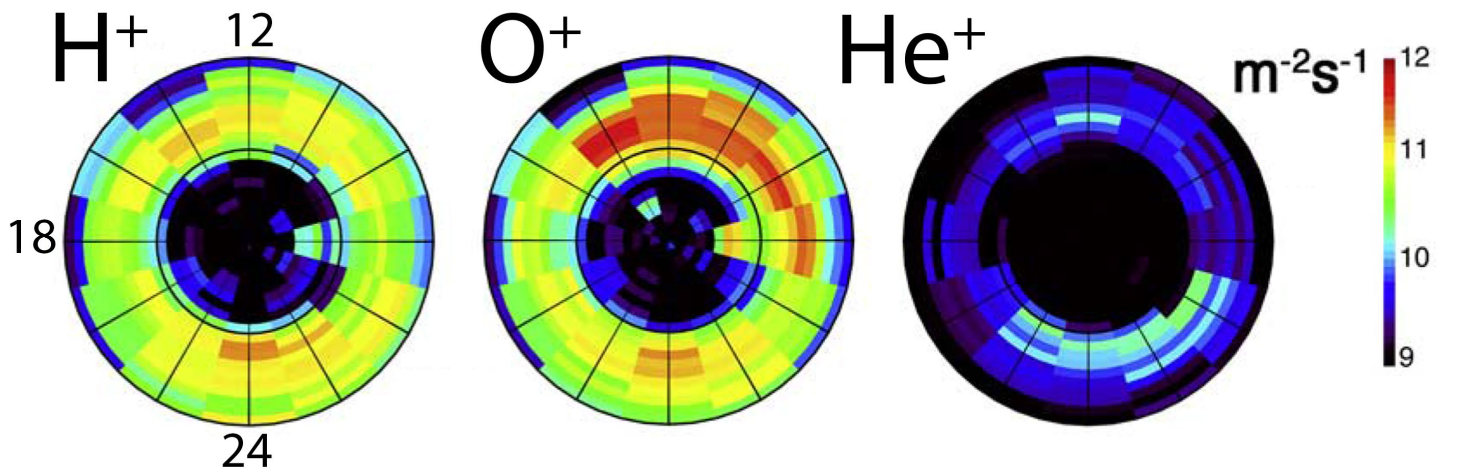
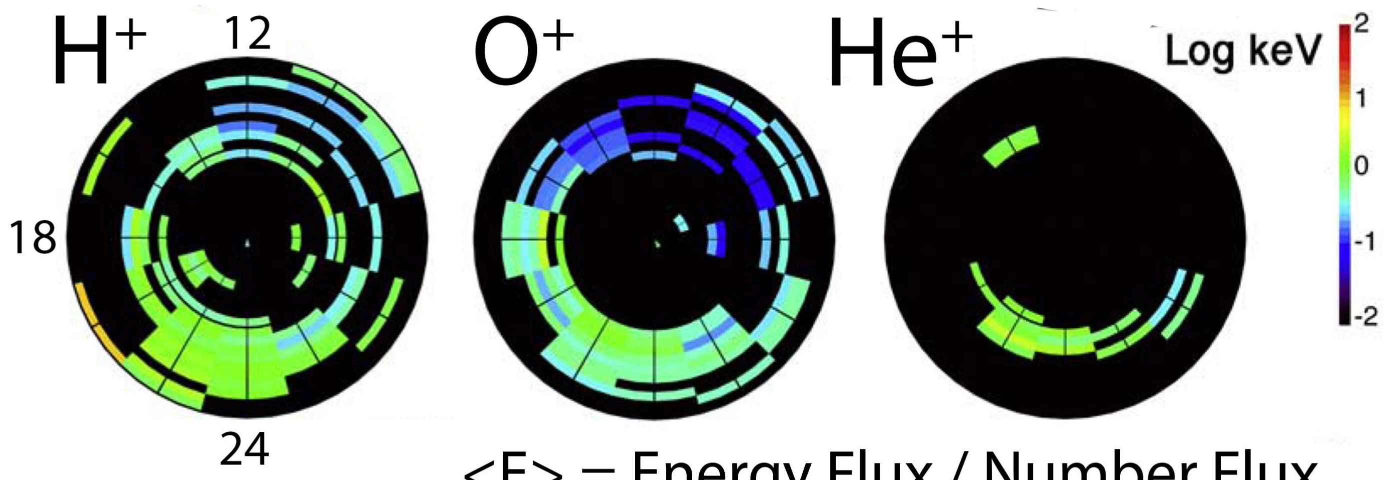
Polar Observations of Upflowing Ions at 2 R_E

The energization is:

- primarily on auroral field lines
- All local times but… concentrated near noon and midnight
- KeV energies on the nightside …. Less on the dayside
- *Is the dayside H^+ - O^+ characteristic energy difference real?*

Number flux in boundary normal coordinates



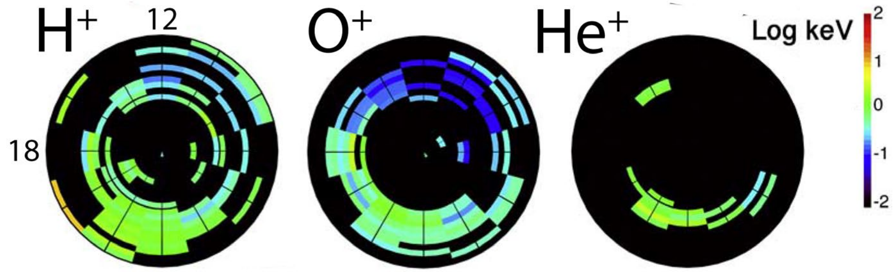


Peterson et al., 2008

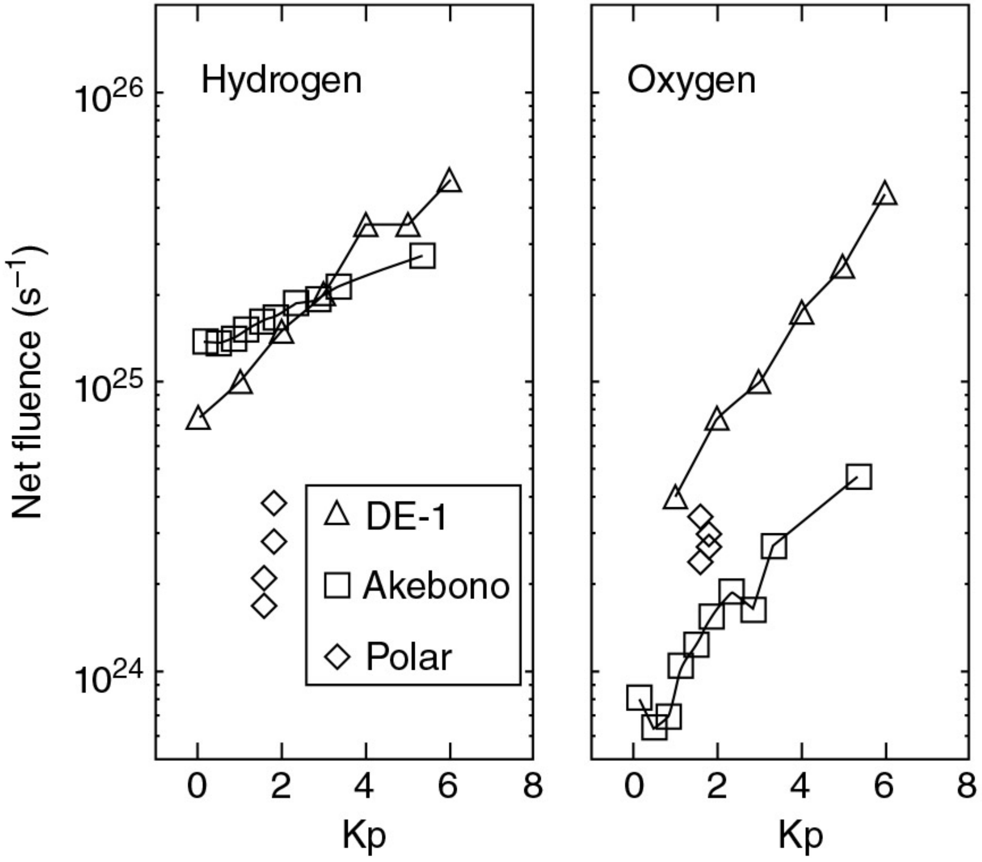
<E> = Energy Flux / Number Flux

Maybe the Devil's in the Details

	Akebono	DE – 1	Polar
Altitude (km)	6,000 – 10,000	10,000 – 16,000	6,000 – 8,000
Energy (eV)	0 – 20	10 – 24,000	15 – 33,000



<E> = Energy Flux / Number Flux



Cully et al., 1993

H^+

- The Thermal H^+ population is energized and detected by DE -1 above ~ 8,000 km
  - DE -1 misses H^+ thermal plasma at low activities
  - Akebono misses H^+ energetic plasma at high activities
  - Polar misses the H^+ thermal plasma

O^+

- Energy threshold of DE -1 is lower than that of Polar
- Lower O^+ flux observed by Polar suggests high fluxes in the lower end of the DE -1 eV range than that of Polar
- The Akebono O^+ data are consistent with this interpretation

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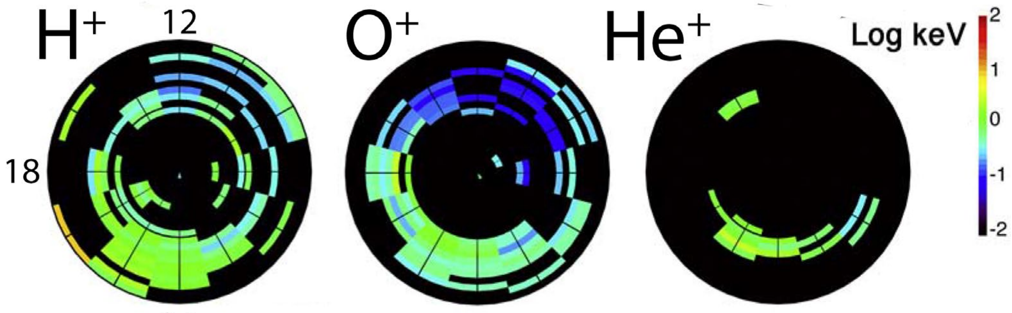
Characteristic Energies at 2 R_E

At 2 R_E geocentric > 15 eV



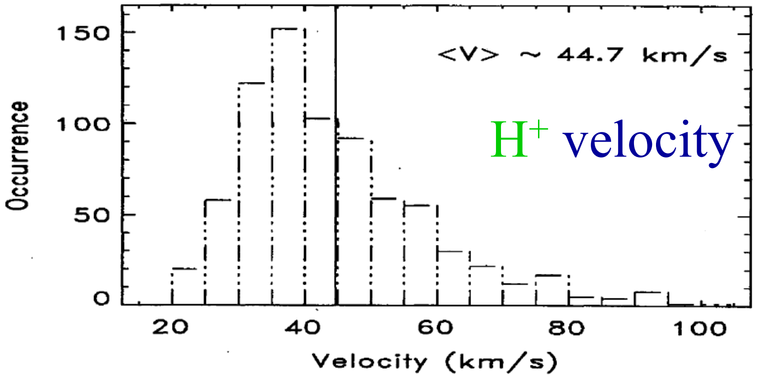
<E> = Energy Flux / Number Flux

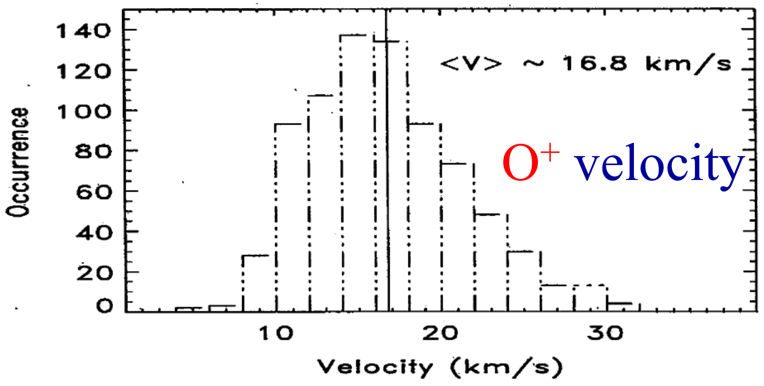
		Energy (UFI) 0.015-33 keV	Number Flux Below 15 eV (50,000)	Estimated Energy 0-33 keV
H^+	PC	0.3	99.97%	0.001
	AZ	0.56	97.0%	0.03
O^+	PC	0.19	99.1%	0.008
	AZ	0.30	63.8%	0.1
He^+	PC	0.7	99.8%	0.008
	AZ	0.6	87.1%	0.11

Peterson et al., 2008

H^+, O^+ Polar Wind Velocity on Polar

at 9 R_E geocentric (near solar min)





Su et al, 1998.

35 eV

25 eV

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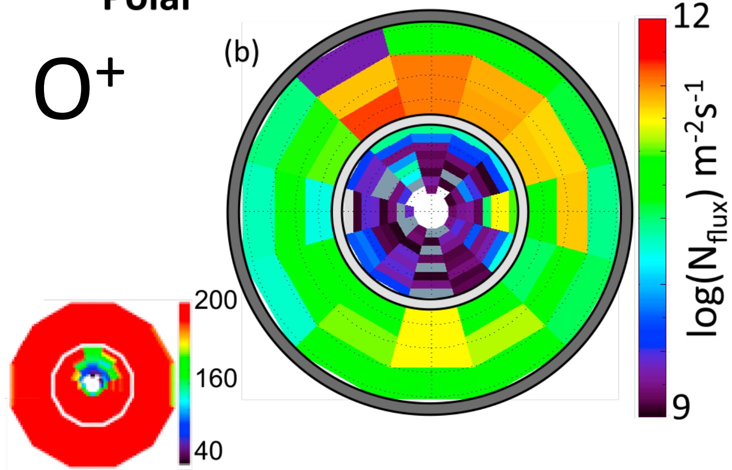
Observations of characteristic energies at 2 RE and above in the polar cap and auroral zone are few, and not easily compared.

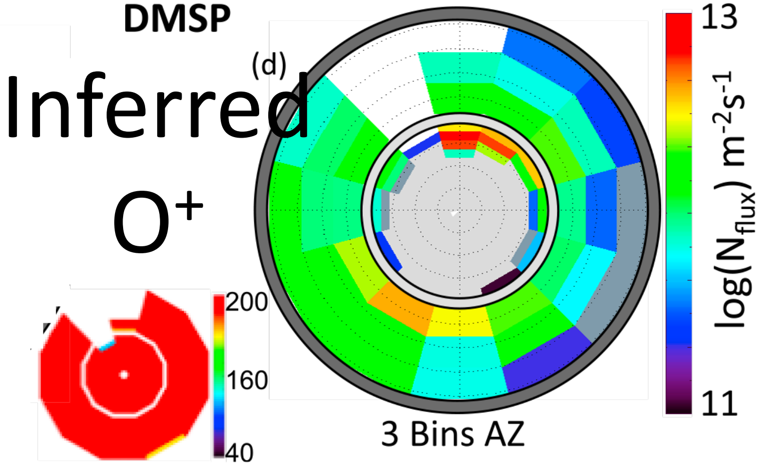
There is a significant low energy ion population at the top of the 'gap'

The Gap Region

Polar



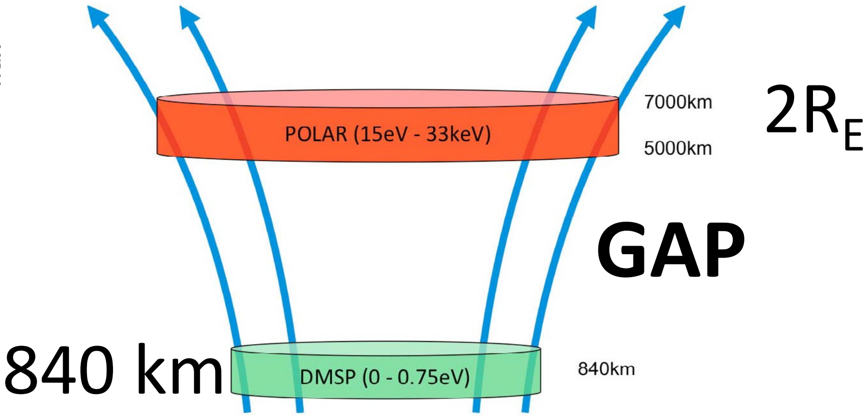
DMSP

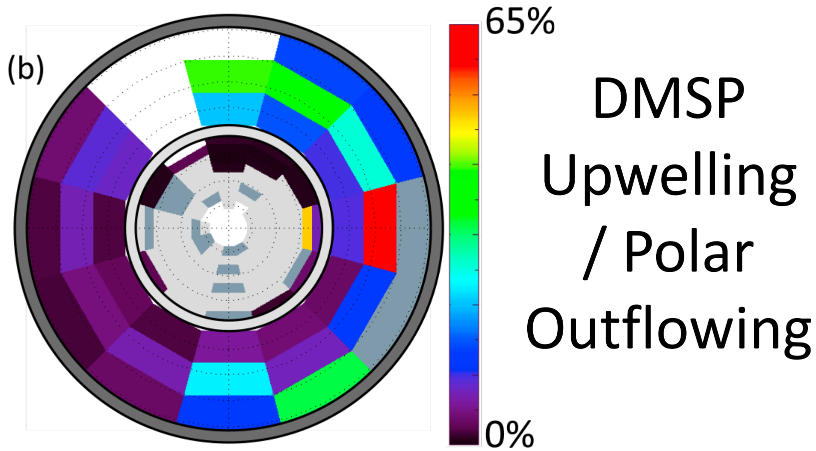


Redmon et al., 2012

Over 40 years of observations have established that many processes contribute to energization and acceleration between the ionosphere and >~ 2 R_E

- We know that most ionospheric ions are not energized and do not reach 2 R_E
- We don't know the if dominant process or even if all processes have the same efficiencies at all local times





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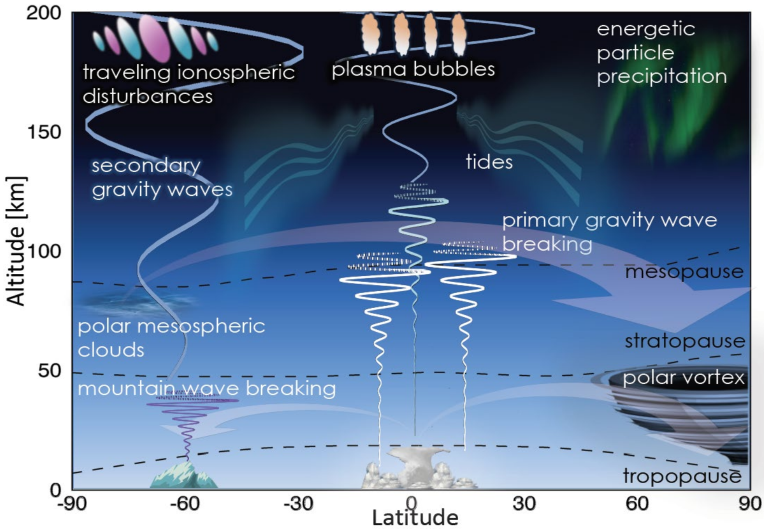
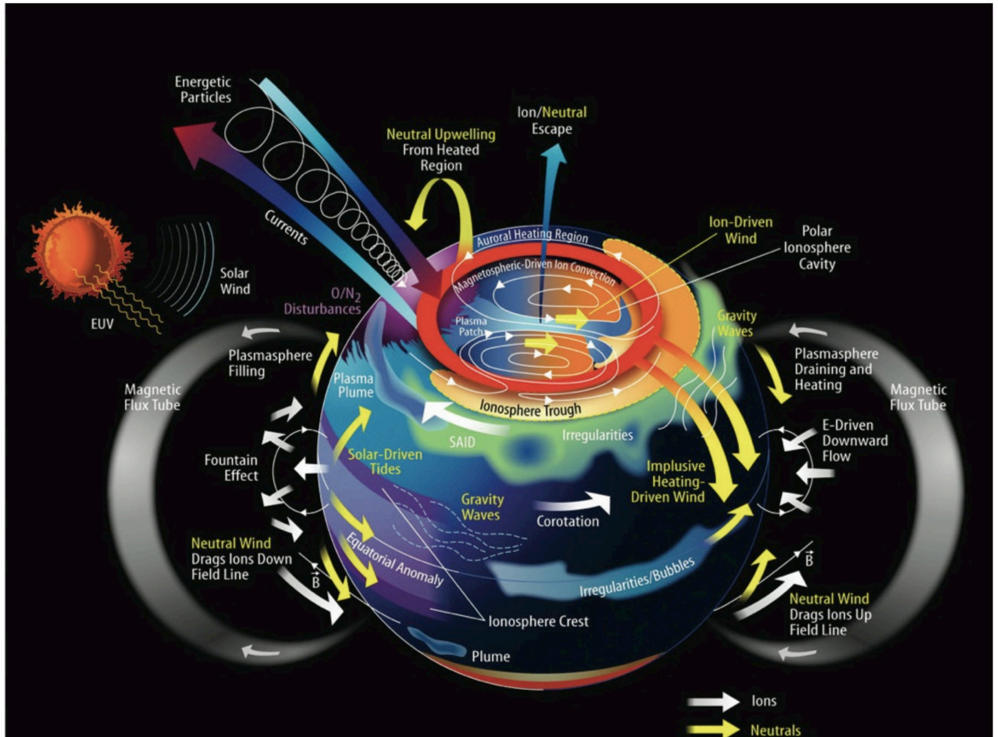
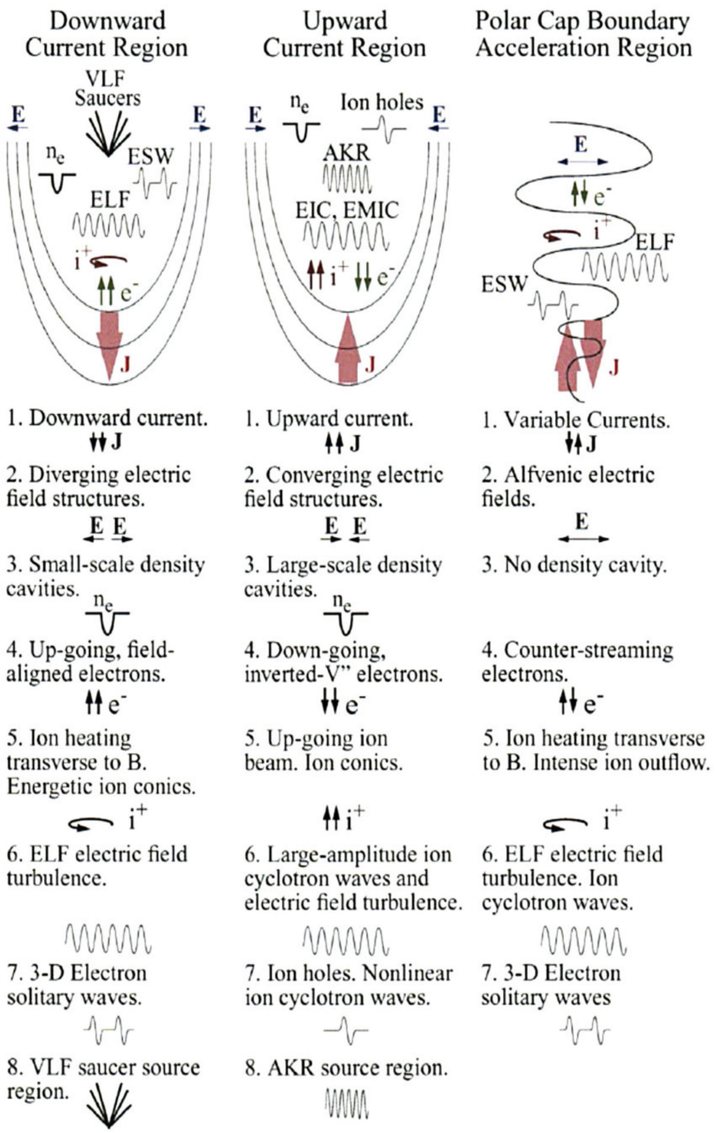
How are ions accelerated / energized?



Pushes from the thermosphere and ionosphere at all latitudes

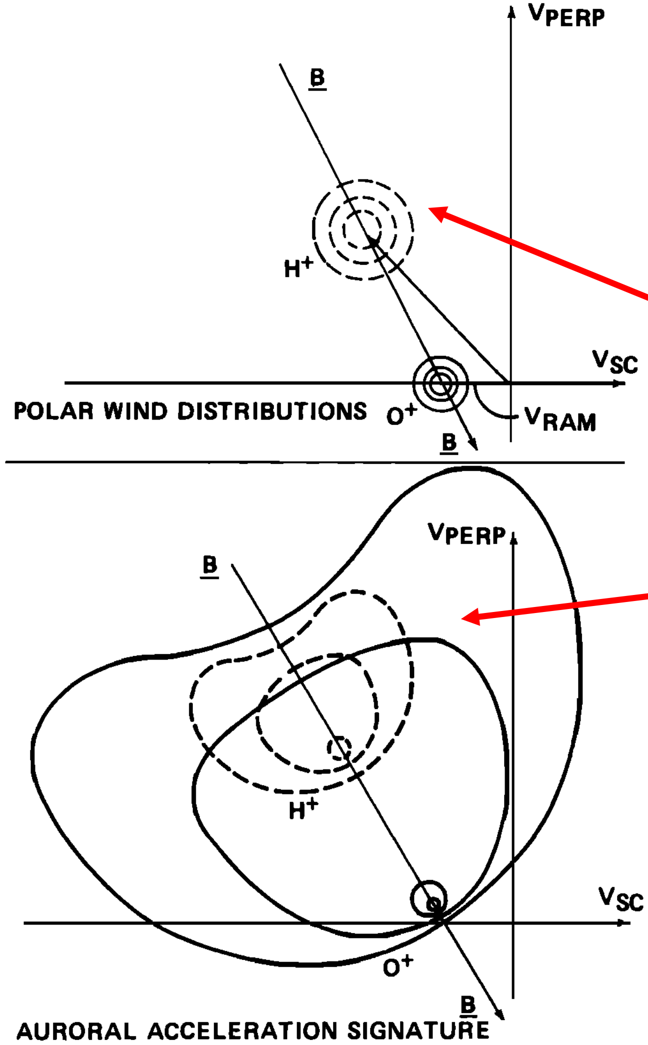


Kicks from plasma process in the gap auroral zone and polar cap field lines.



Bagenal et al, 2014; adapted from Carlson et al., 1998

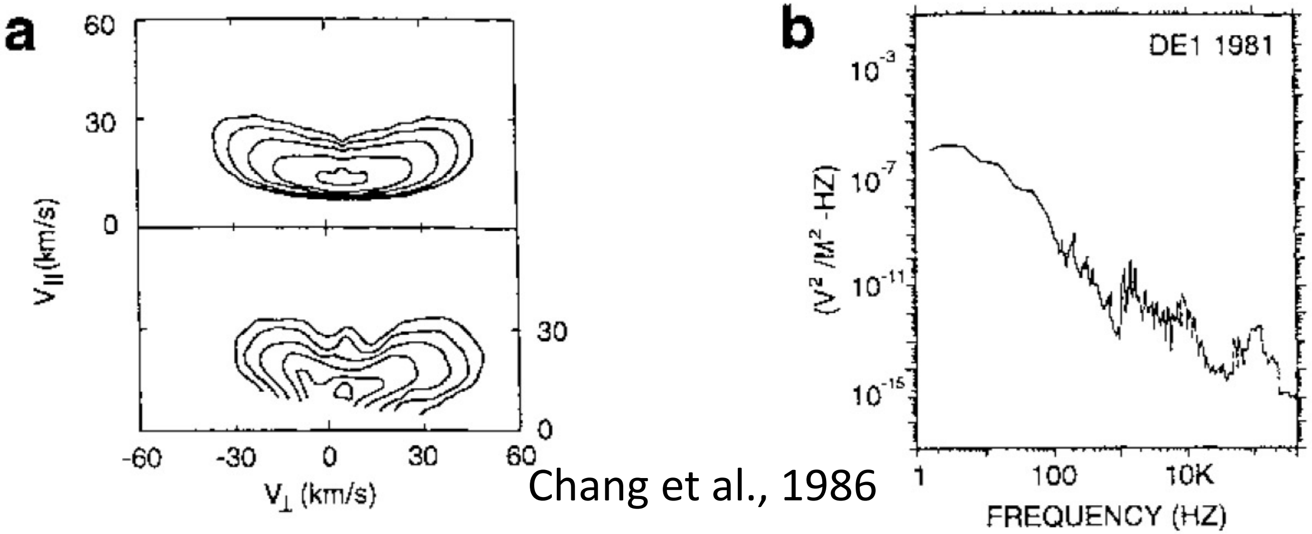
Resonance Heating: A cautionary tale



Moore et al., 1985

Beams and Conics

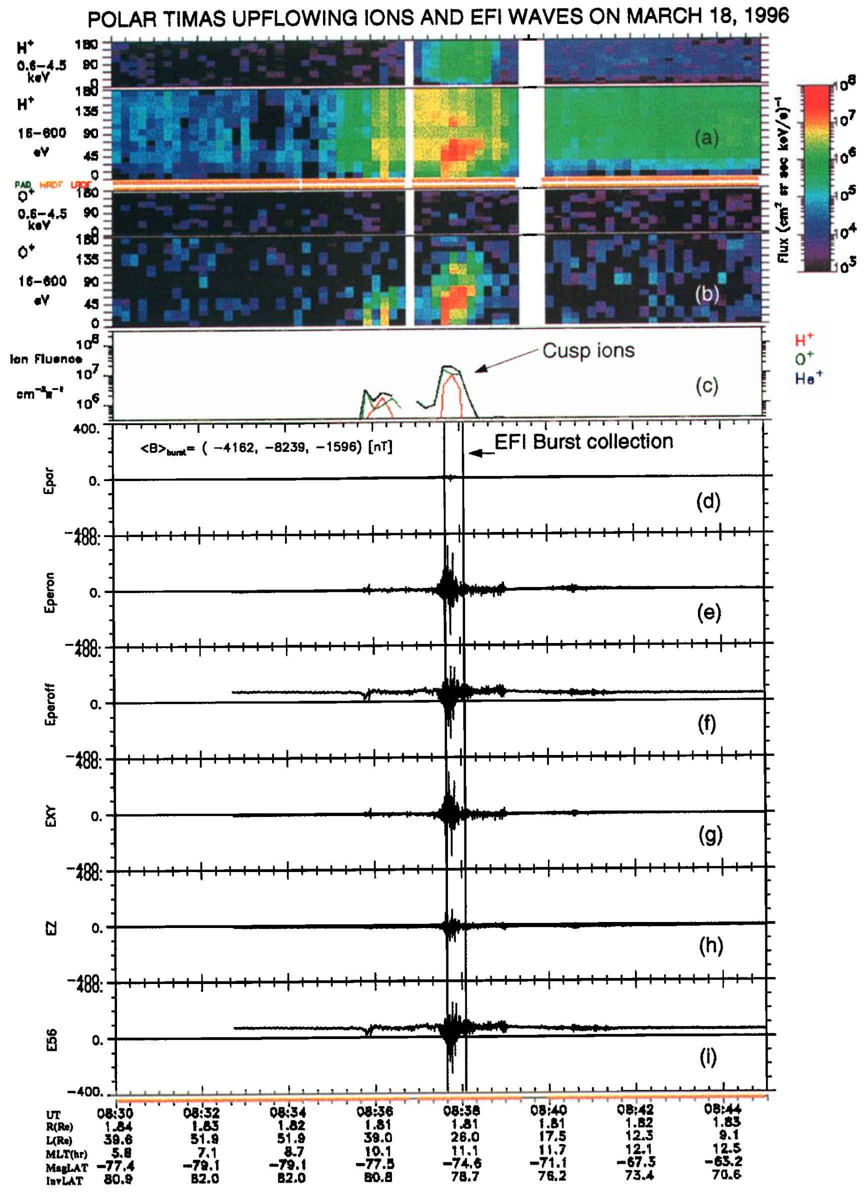
a) Ion distribution on an auroral field line from DE -1
b) Simultaneous broadband electric field power spectrum in the spacecraft frame



Chang et al., 1986

- Assuming the local plasma waves are in gyroresonance with the ions, Chang et al., presented a formula relating the perpendicular energy of the O^+ conic distribution to the electric field power spectral density at the O^+ gyrofrequency

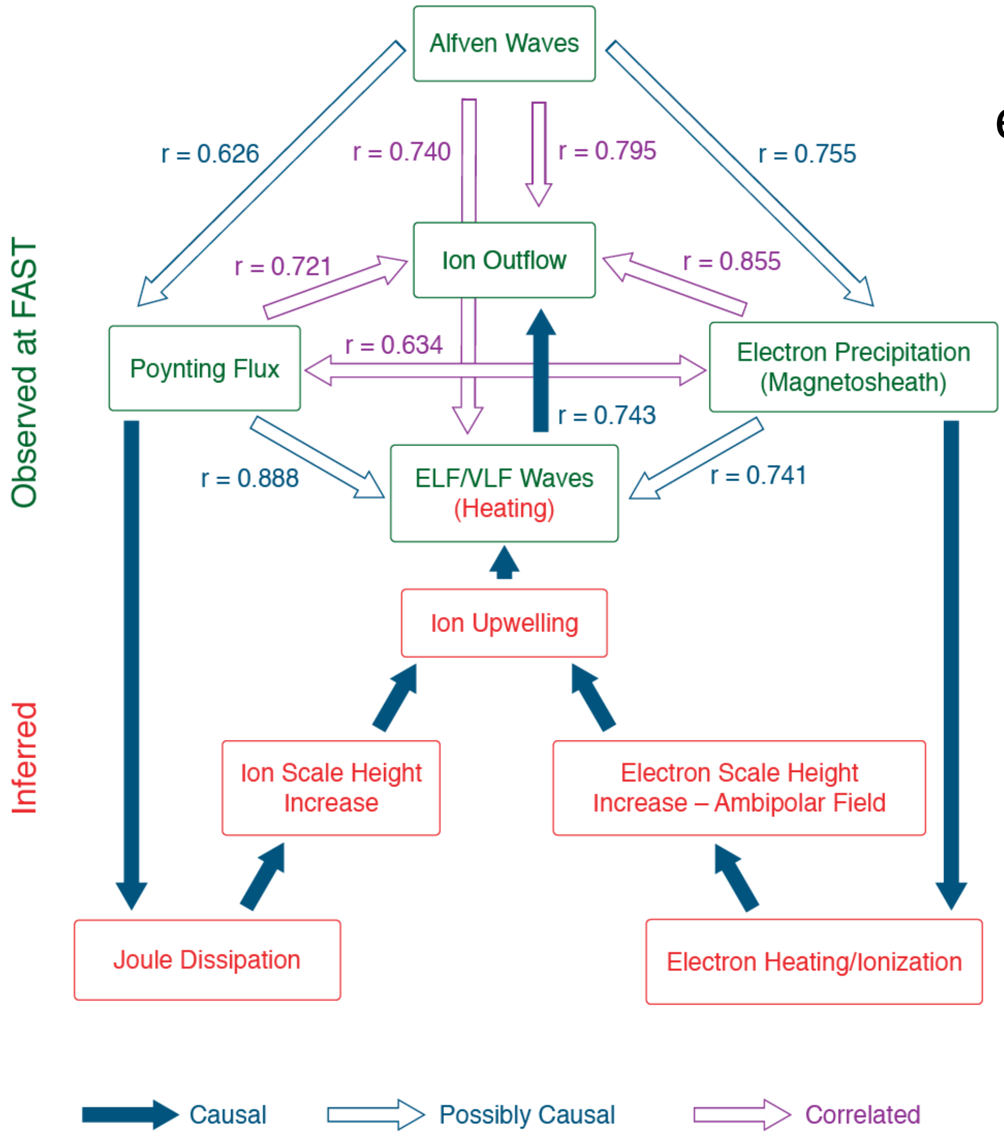
But ion heating is more complicated than that!



Angelopoulos et al., 2000

- The Chang et al., relation gives heating rates and perpendicular temperatures much larger than observed.
  - The work around is to say that only 10% of the wave power has left-hand polarization and actually interacts with the ions.
- Burst mode electric field data from many Polar events showed that the wave properties were such that they could not gyro resonate with O^+
- The O^+ is heated locally so there has to be a local electric field transferring the energy.
  - Density Structures, Turbulence, Other wave modes, ….
- Need MMS cadence observations from at least two satellites in the 'gap' to resolve

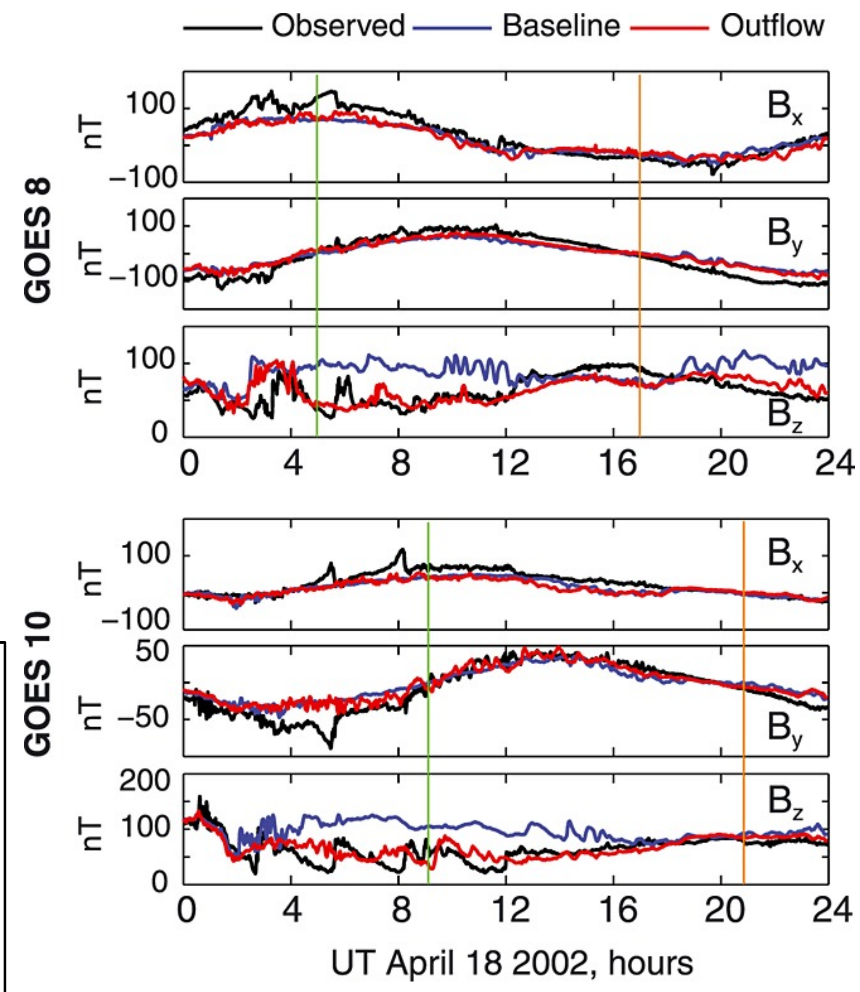
Parameterize: Energy In *vs* Ions Out.



Strangeway et al., 2005,

This approach to energization in the 'gap' region in a global MHD model provided key insights to the formation of sawtooth oscillation in the geomagnetic tail

This approach is informative but has difficulty reproducing the observed global MLT distribution of ion outflow.



Brambles et al., 2013

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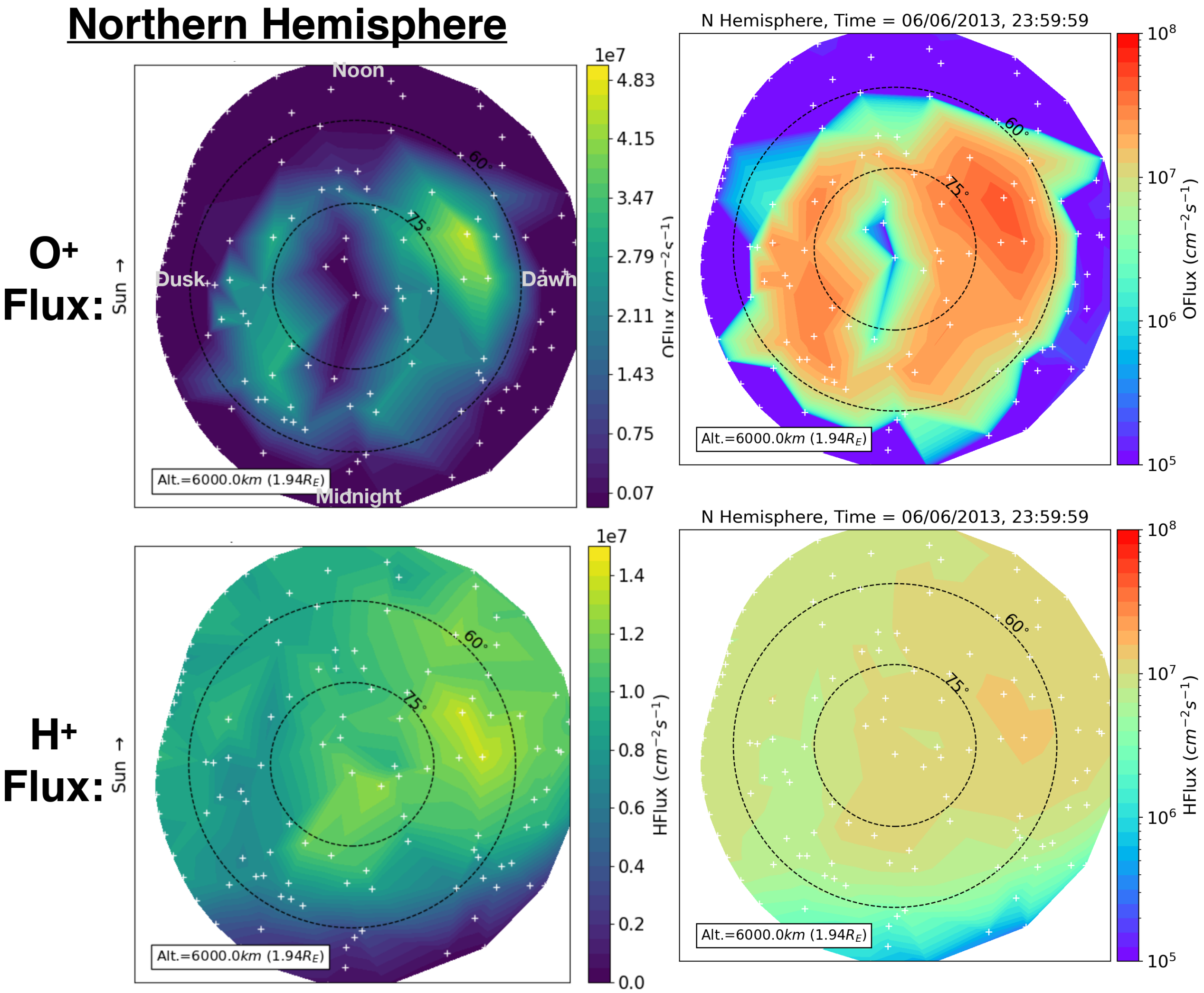
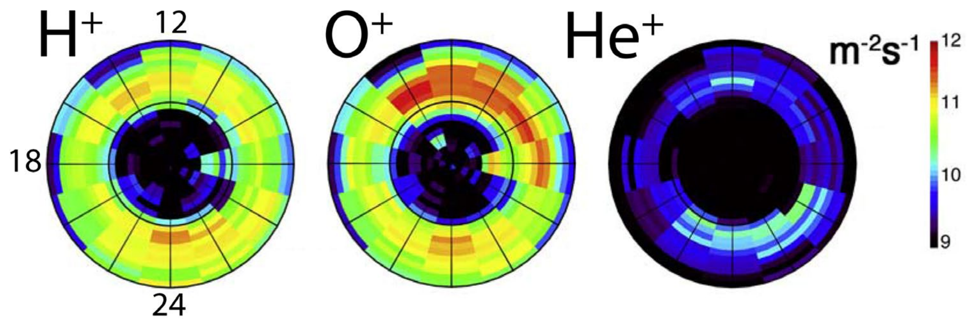
Global models are getting better in the gap



Linear color bar (left) and log color bar (right)

Glocer et al, JGR under review.



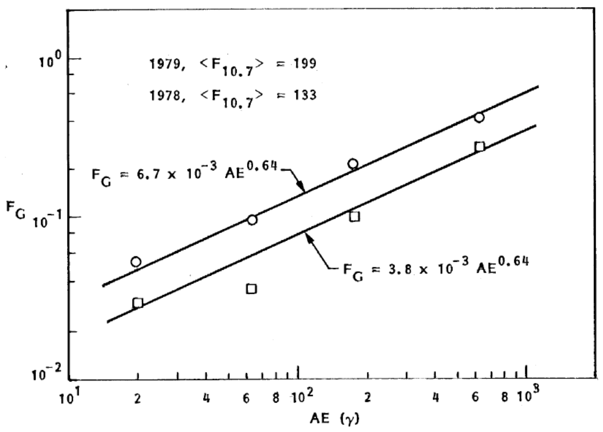
Glocer et al. model….

- Feeds the gap region with a polar wind model
- Uses a hybrid pic model with monte carlo collisions on specific field lines
- Follows the field lines in time
- And much much more

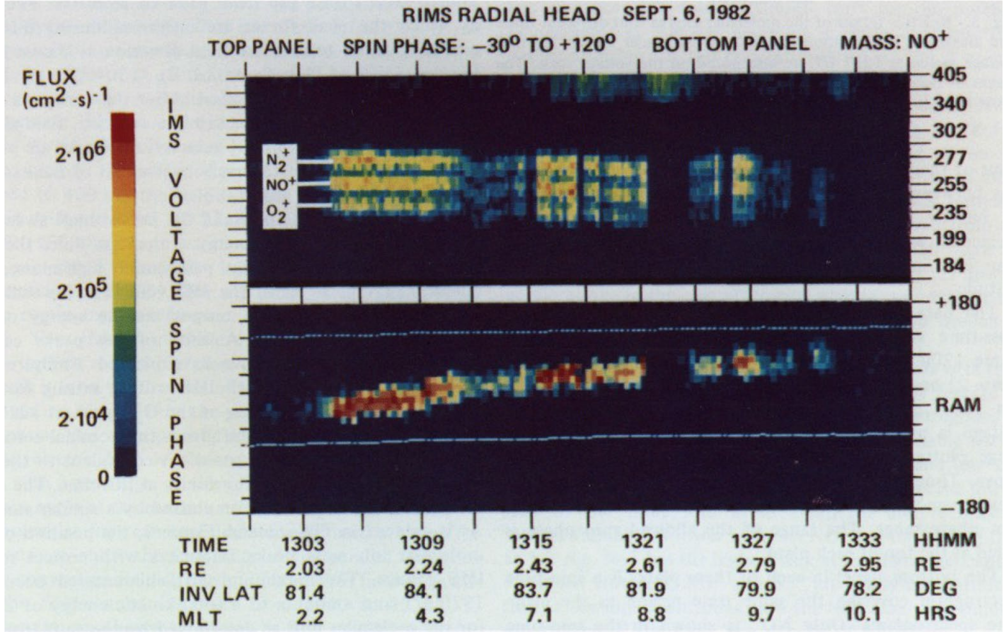
They don't match the average MLT distribution well, but …

Testing Models:
Three obscure global observations:

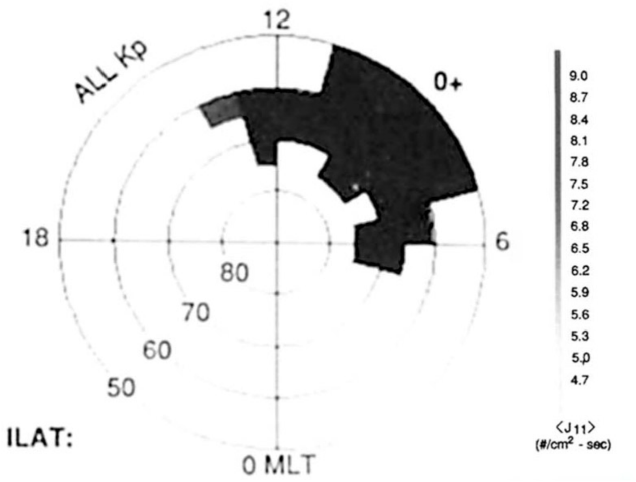
- Dawnward bias in O^+ outflow
- Molecular ions as tracers
- Contribution of solar wind plasma to the magnetosphere



Shelley, et al., 1986



Craven et al, 1985



Pollock et al., 1990

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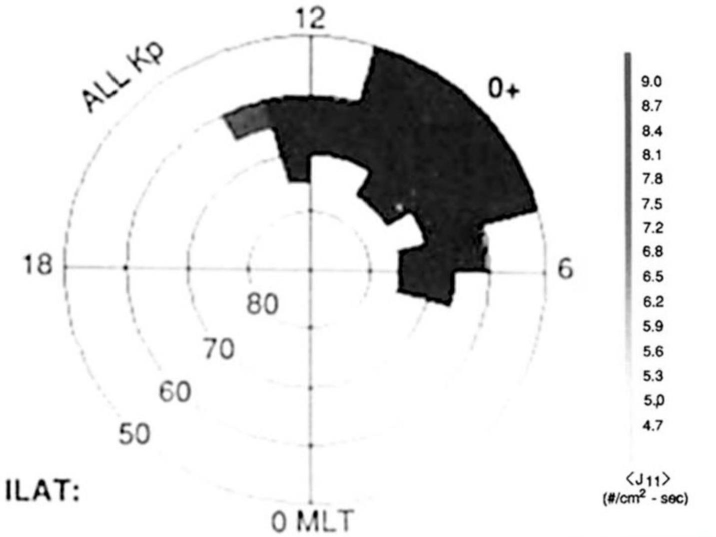
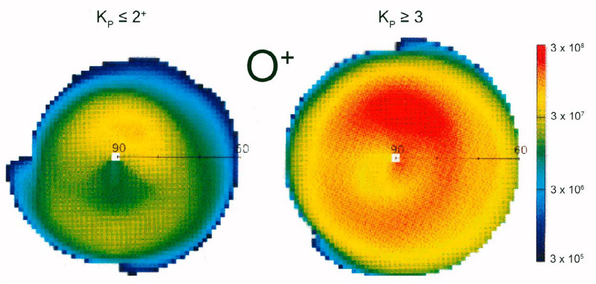
Dawnward bias in O^+ outflow

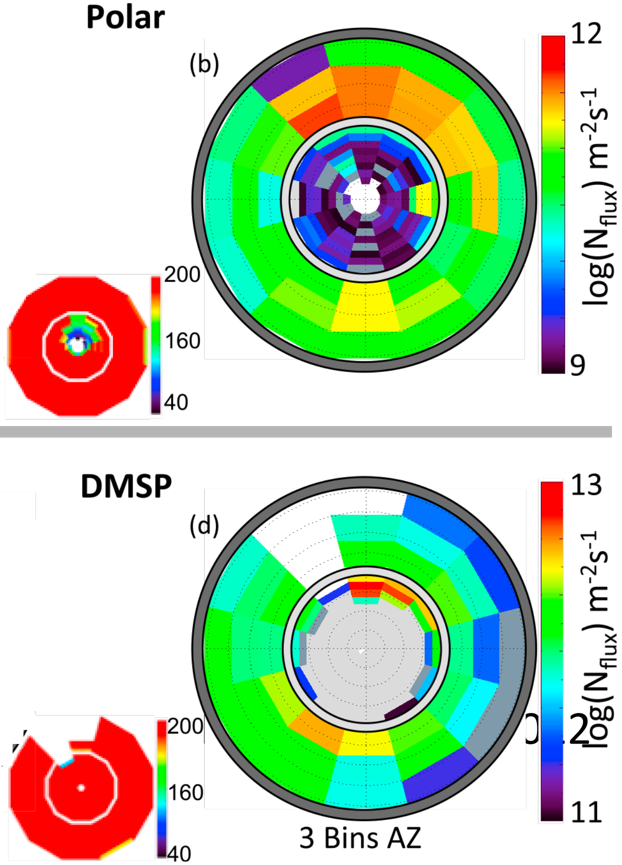
Dynamics Explorer -1



Pollock et al., 1990



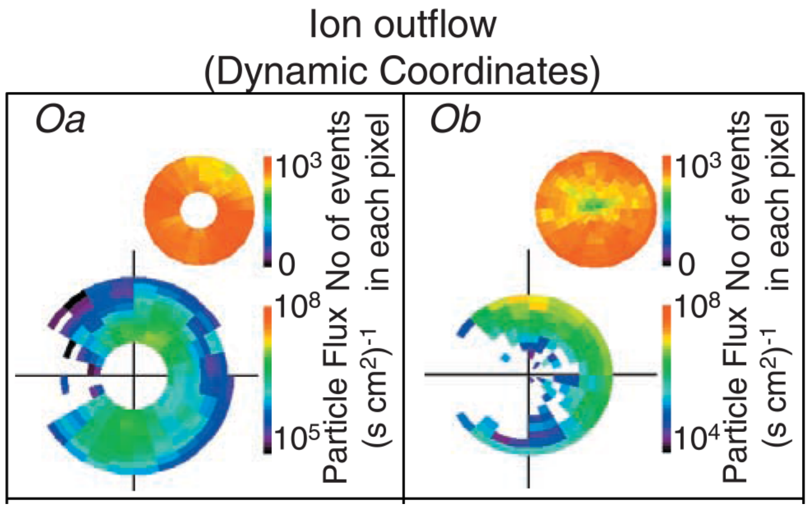
Redmon et al., 2012b



Redmon et al., 2012a

MLT distribution, especially for low energies, is biased dawnward independent of IMF B_Y on DE -1, Polar, Fast, not AZ DMSP, ….

Fast



Andersson et al., 2004

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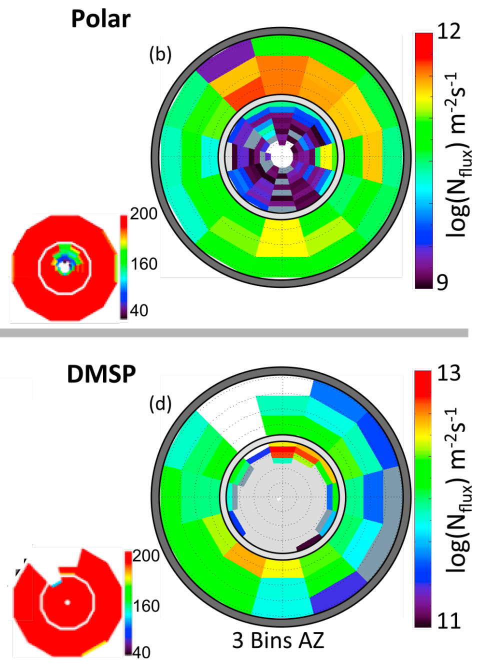
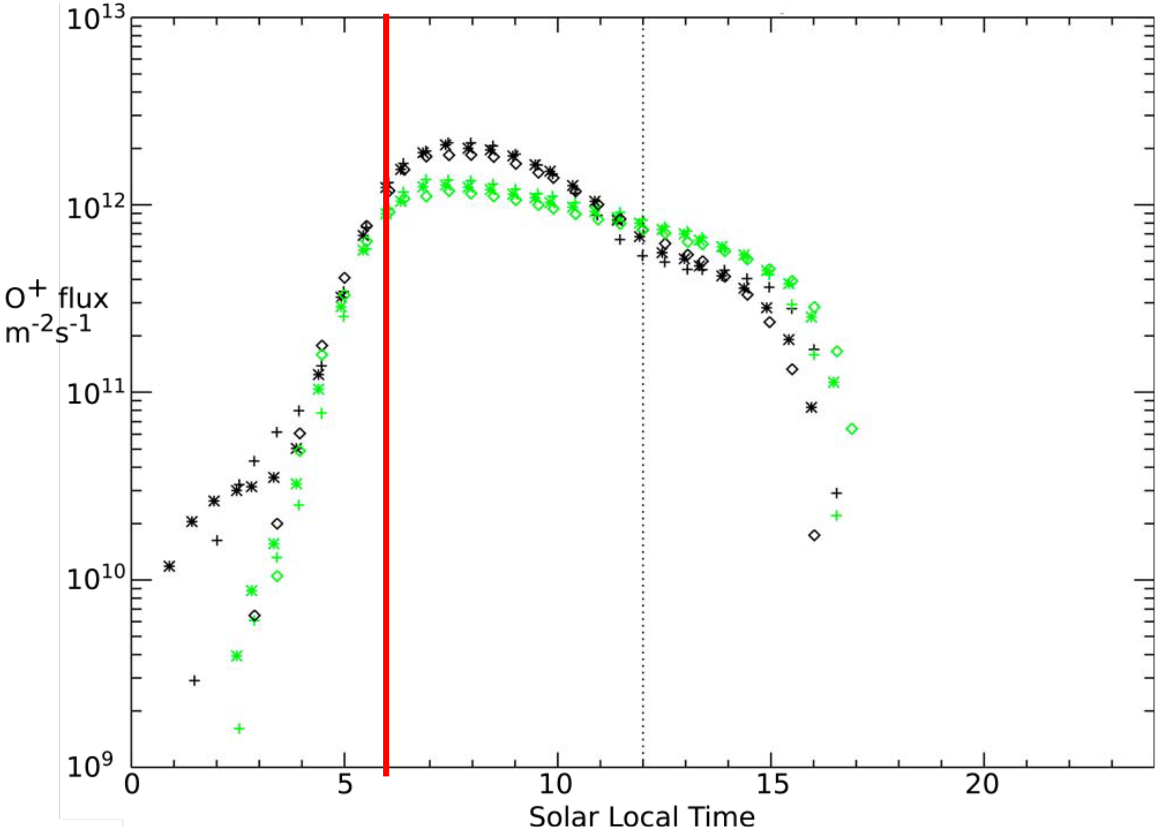
Upwelling O^+ is maximum near dawn

- The rapid onset of field-aligned upward O^+ flux associated with sunrise was one of the first results of systematic radar observations from Millstone Hill, (Evans 1975).





Dawn

Redmon et al., 2012a

FLIP Model runs in the Auroral zone at DMSP altitude

- Black with a neutral wind model
- Green without a neutral wind

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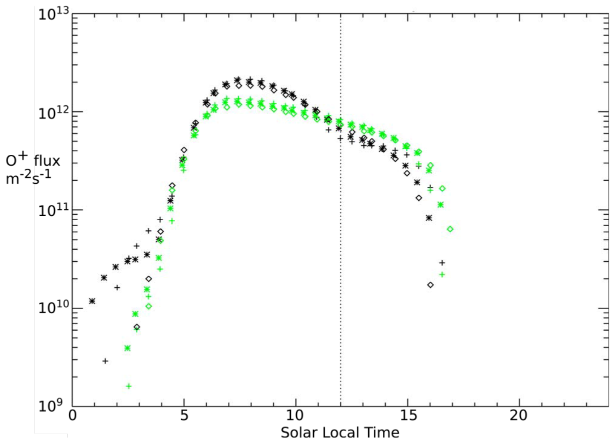
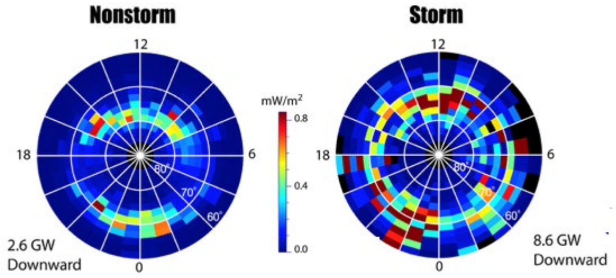
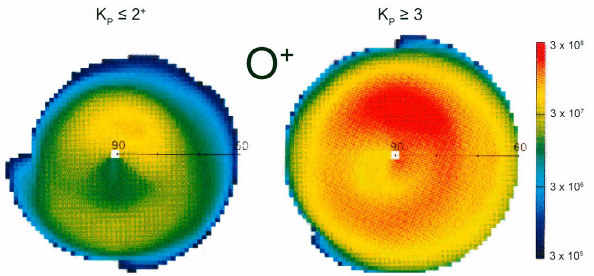
Dawnward shift resolved

- Source of upwelling O^+ peaks shortly after dawn
- Source of energy heating the O^+ at and above the ionosphere comes from magnetospheric reconnection which peaks near noon in the cusp region.
  - The IMF B_Y component is known to move the cusp dawnward/duskward
  - Redmon et al., 2010 show that this effect is small compared to the observed shift.
- Model study shows that the magnitude of the shift is
  - Larger during geomagnetic quiet times
  - Smaller during active geomagnetic times





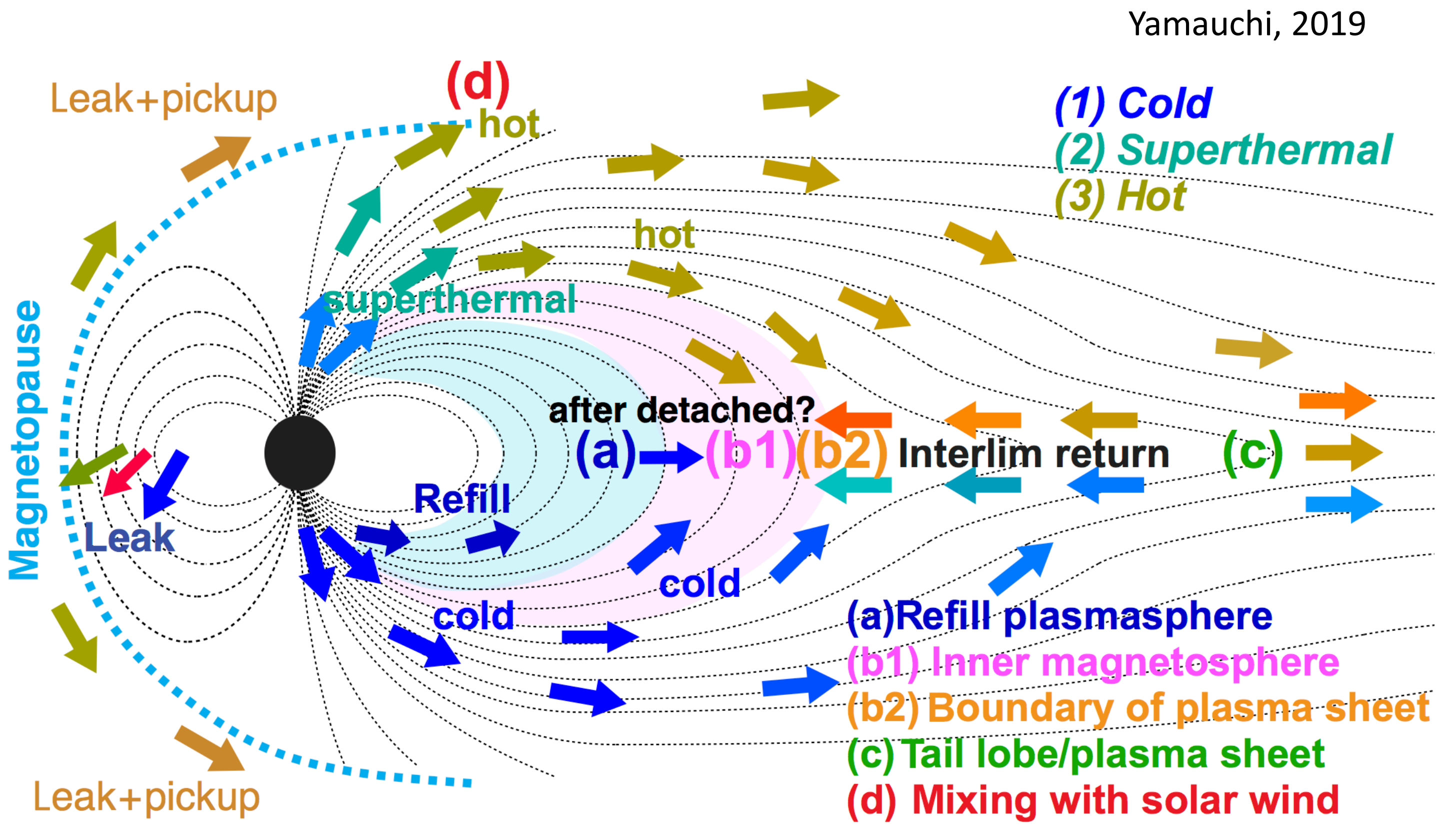


Molecular Ions: Are They Time Tags?

O^+ and molecular ions are observed in the plasma sheet with energies > 100 keV

- How?
- Where ?
- How fast?

do they acquire this energy?

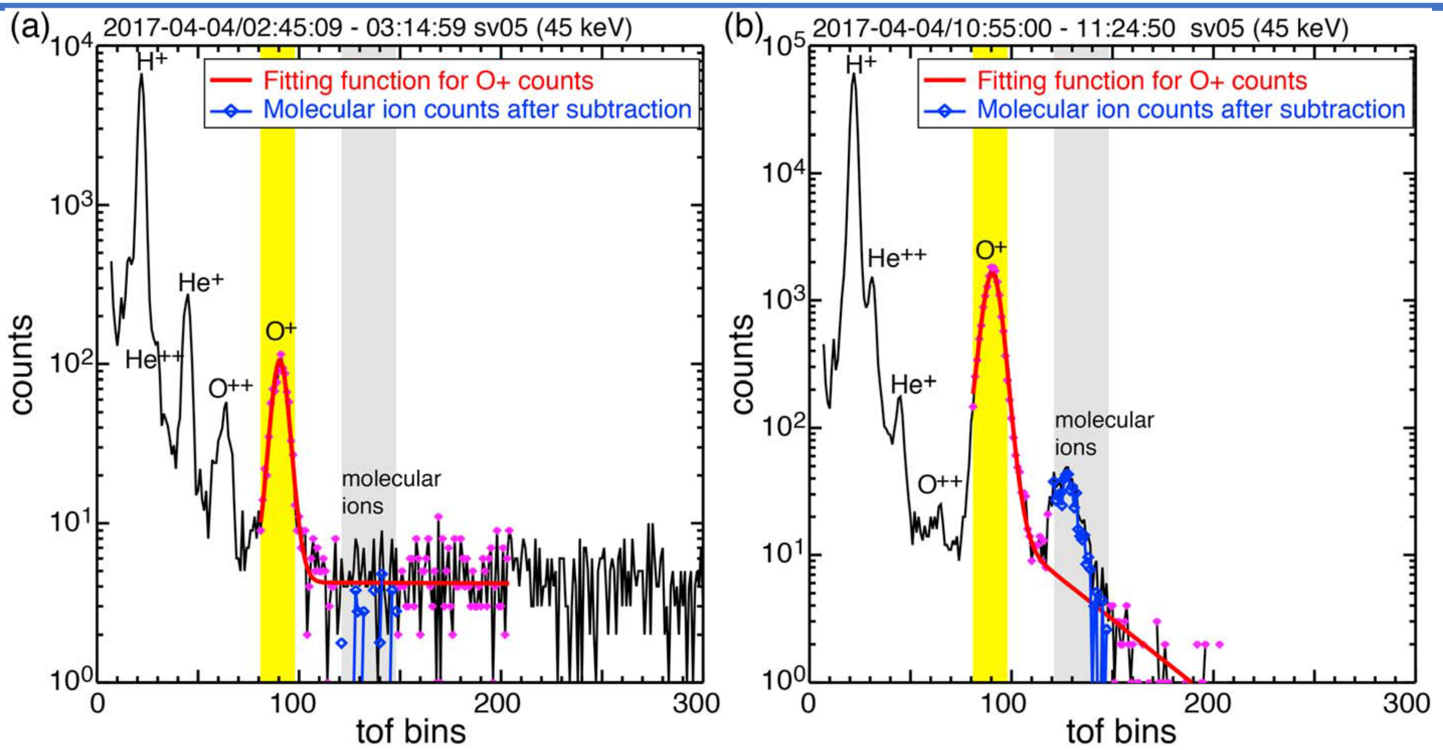


Can near simultaneous observations in the ionosphere of thermal and in the plasma sheet of energetic molecular ions put strong constraints on large-scale magnetospheric models?

Energetic Molecular Ions in the Magnetosphere

Have been observed for over 40 years

- > 10 keV on AMPTE, ISEE, GEOTAIL, Polar, ARTIMIS, and Arase (ERG)



Seki et al., 2019

30 minute averages from the ~45 keV energy bin in the inner magnetosphere before (left) and at Dst minimum (right) of a small geomagnetic storm from Arase (ERG).

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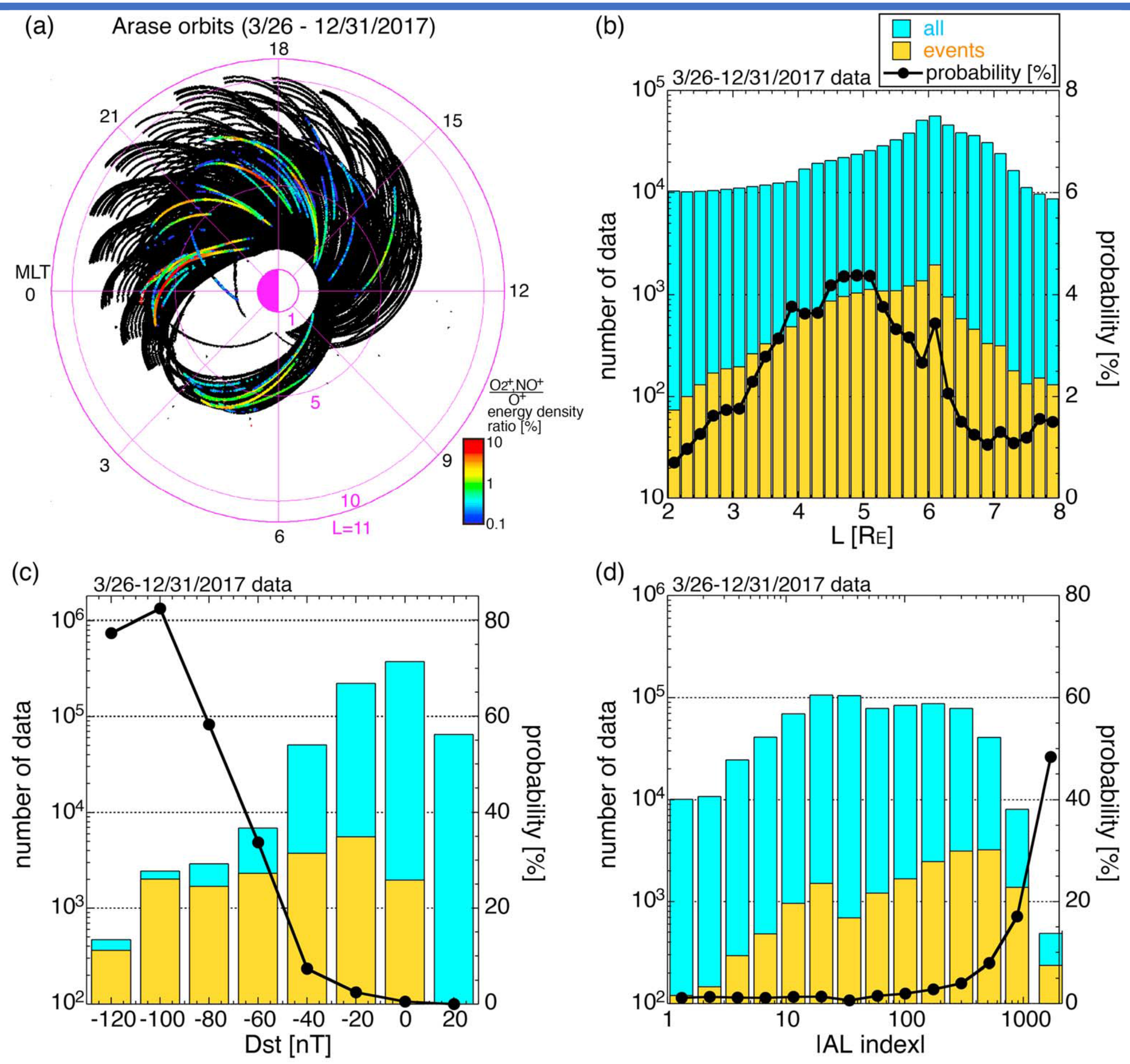
Energetic Molecular Ions are Common

- Energetic Molecular ions were previously reported only during the most intense geomagnetic storms ($D_{ST} < -100$)
- The Arase data show that they are observed during periods of modest geomagnetic activity
- What about the ionospheric source?



Seki et al., 2019

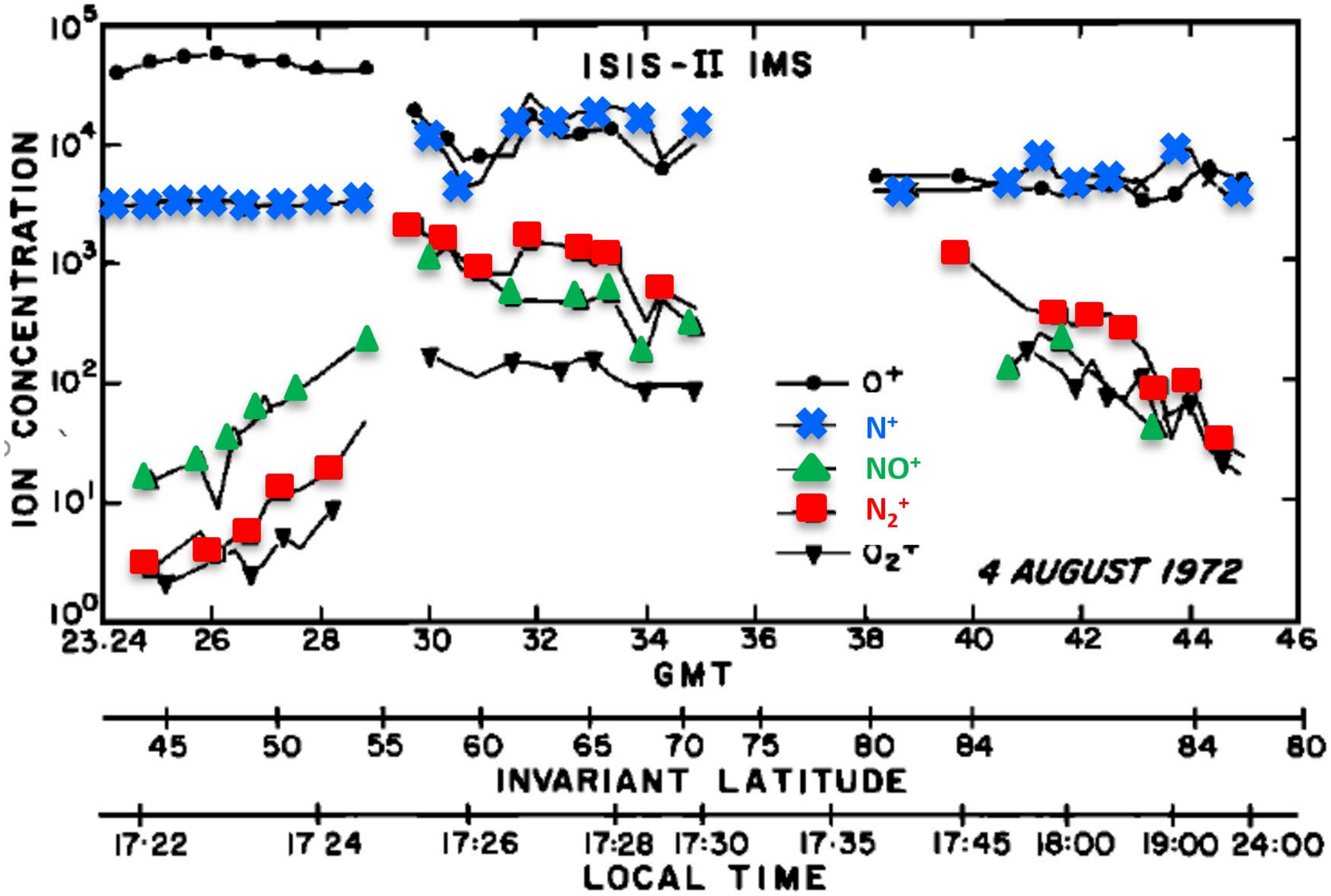
This presentation is being recorded

Molecular Ions: Ionospheric Source

Have been observed for over 40 years

- < 100 eV on ISIS-2, AE-C, DE -1, Akebono, Polar, and *e-POP*
- Akebono detected them during extended (>9 hrs) of moderate (K_P =3) activity (Yau et al., 1992)
- *e-POP* is more sensitive

During the August 1972 magnetic storm, Hoffman et al., 1974



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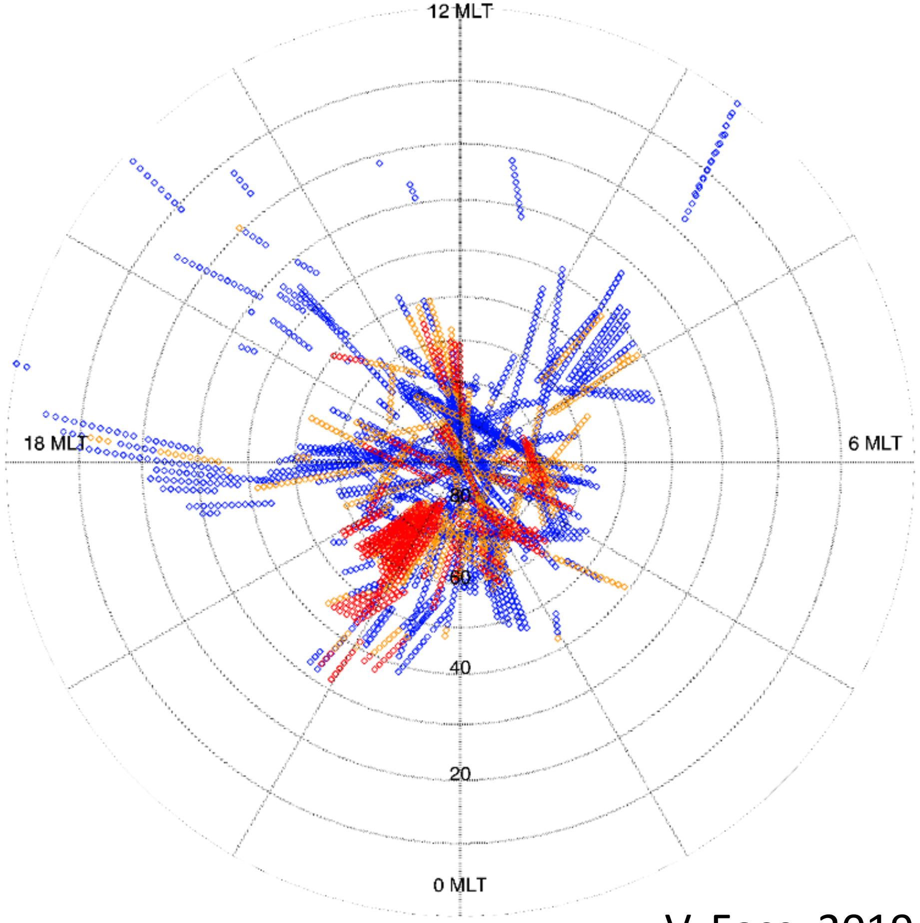
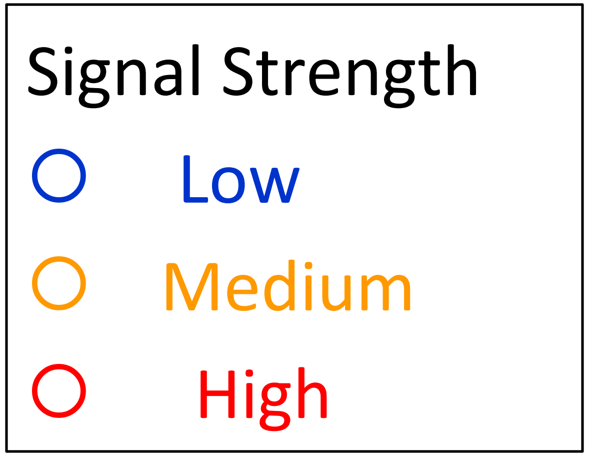
Preliminary *e-POP* results

Latitude vs MLT of Molecular ion events observed on *e*-POP

- ~6-10% occurrence
- Flowing both upward and downward
- High signal events more common in pre-midnight sector
- Molecular ions are seen with enhanced N^+ ions



V. Foss, 2019



Can we use Molecular Ions as Time Tags?

Can near simultaneous observations in the ionosphere of thermal and in the plasma sheet of energetic molecular ions put strong constraints on large-scale magnetospheric models?

- **NO**, new observations from Arase and *e*-POP show that they are too common, both in time and space, for time tags from single events observed from satellites with repeat sampling times of ~hours to be meaningful

But ....

- Near simultaneous observations from multiple cube-sats below ~1,500 km at several MLT's and in the plasma sheet could.

OR

- Analysis of average global maps of molecular ion data from *e*-POP and Arase could provide new, stronger, constraints perhaps better than those obtained using O^+ alone.

How important is the solar wind source?

Density ~ 10 / cm^3
Kinetic energy 400 km/s = ~ 1 keV H+
Thermal energy ~10^5 Kelvin = ~10 eV

Kinetic energy converted to thermal at the bow shock. At the subsolar point mostly thermal, on the flanks mostly kinetic

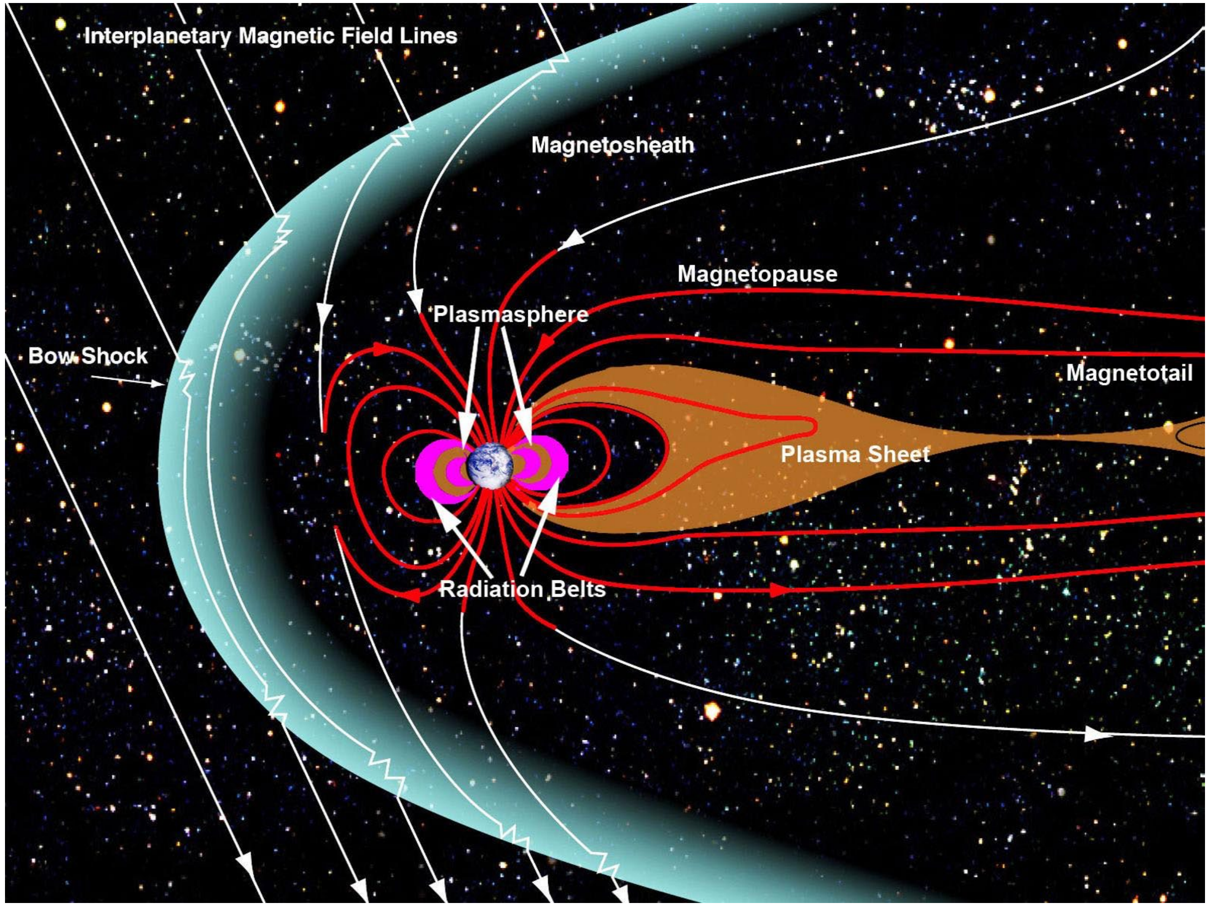
Composition
H^+ / He^{++}/ O^{5+} O^{6+} O^{7+} /
96% / 4% / 0.1% /

Source Strength: 10^{25}- 10^{26} ions/s
Hill (1974)

Energy Input:

$$E_{in} = 3.78 \times 10^7 n^{0.24} V^{1.47} B_T^{0.86} \left[\sin^{2.70}(\theta/2) + 0.25\right]$$

Wang et al., 2014



Geogenic and Heliogenic Plasma in the Magnetosphere

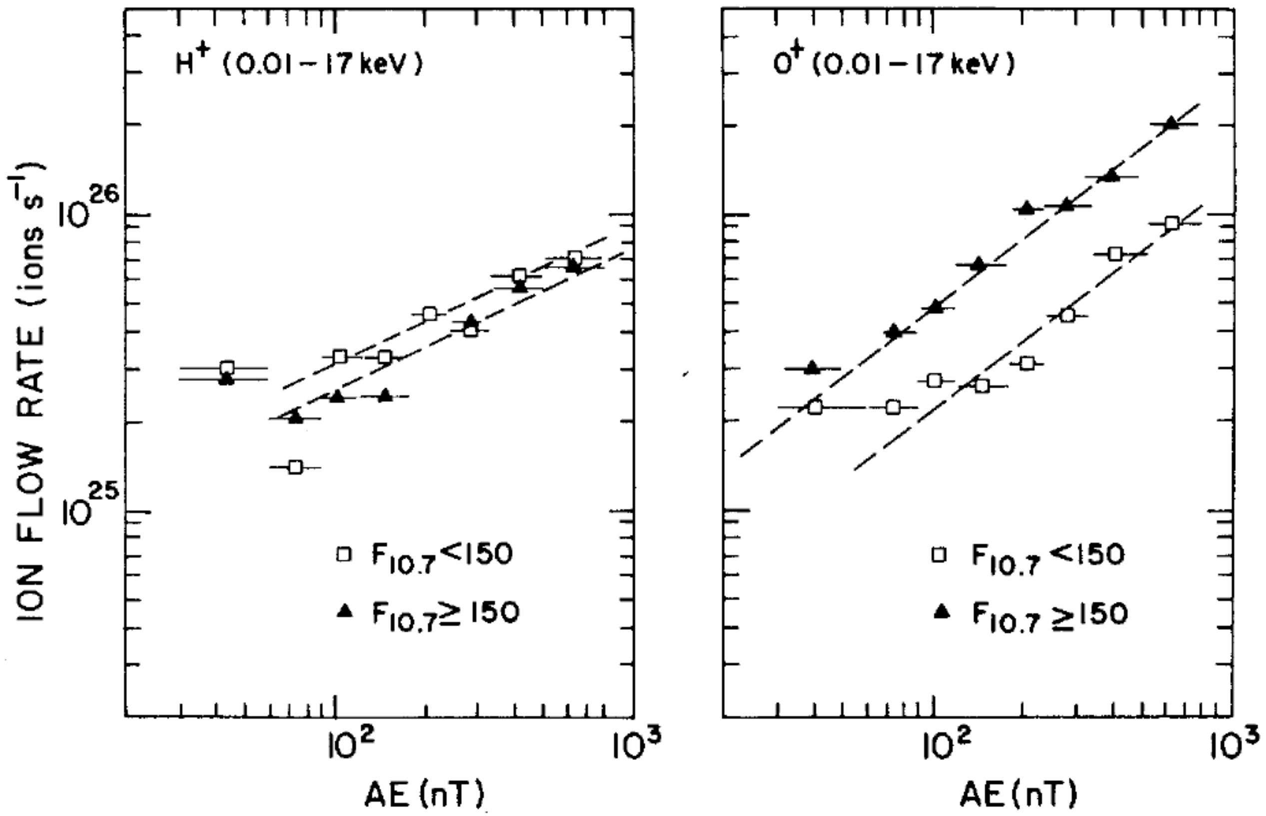
Geogenic (of Earth origin) H^+ and O^+

Heliogenic (of Solar origin) H^+

Assume H^+/O^+ ratio is constant for specific values of the magnetic activity parameter AE and the Solar activity parameter $F_{10.7}$

$$F_{O^+}(AE, F_{10.7}) = 4.2 \times 10^{25} \exp[+1.0 \times 10^{-2} (F_{10.7} - 100)](AE/100)^{0.8} \quad (11)$$

$$F_{H^+}(AE, F_{10.7}) = 4.3 \times 10^{25} \exp[-2.7 \times 10^{-3} (F_{10.7} - 100)](AE/100)^{0.4} \quad (12)$$

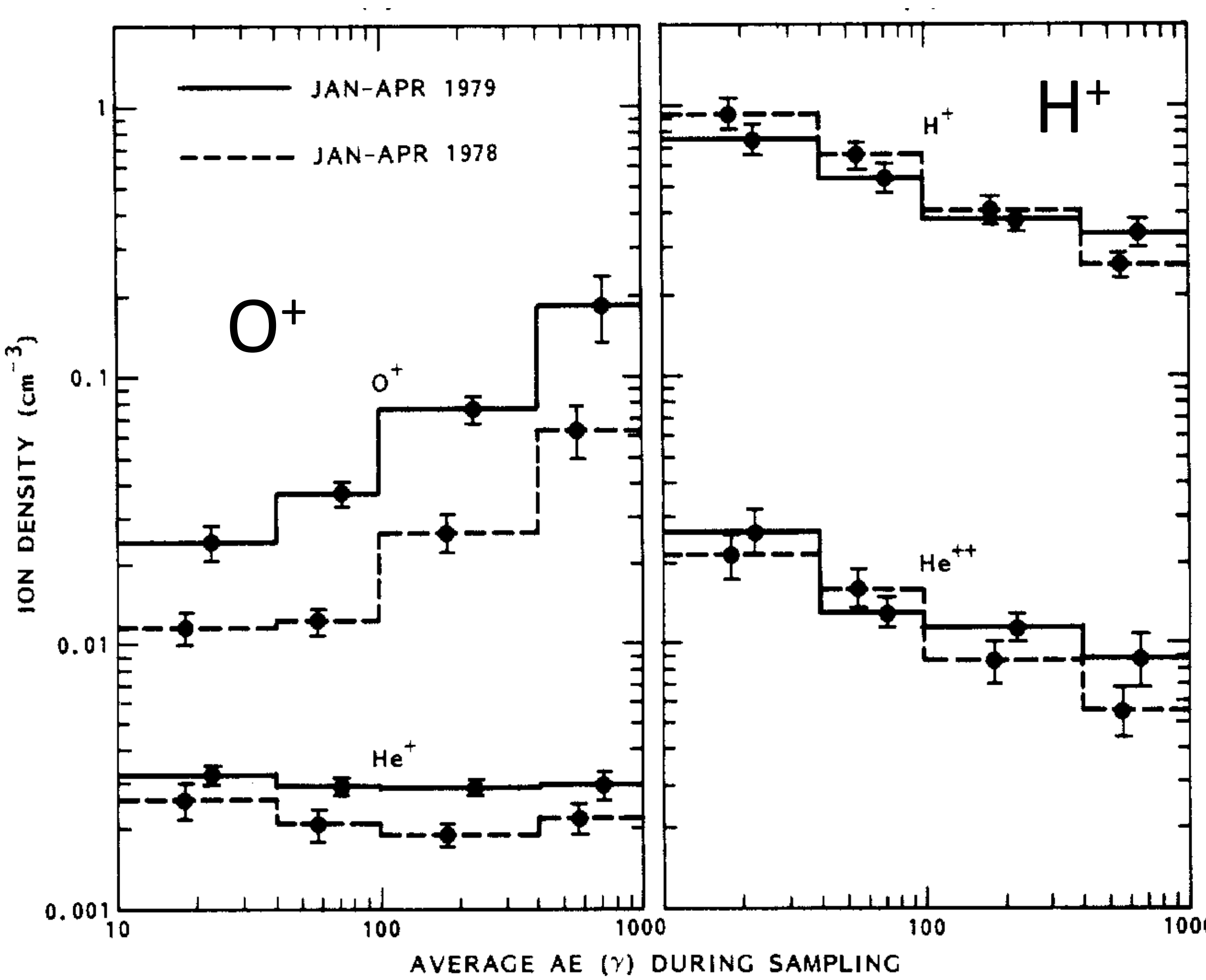


Yau et al., 1988

Plasma Sheet Observations from ISEE -1

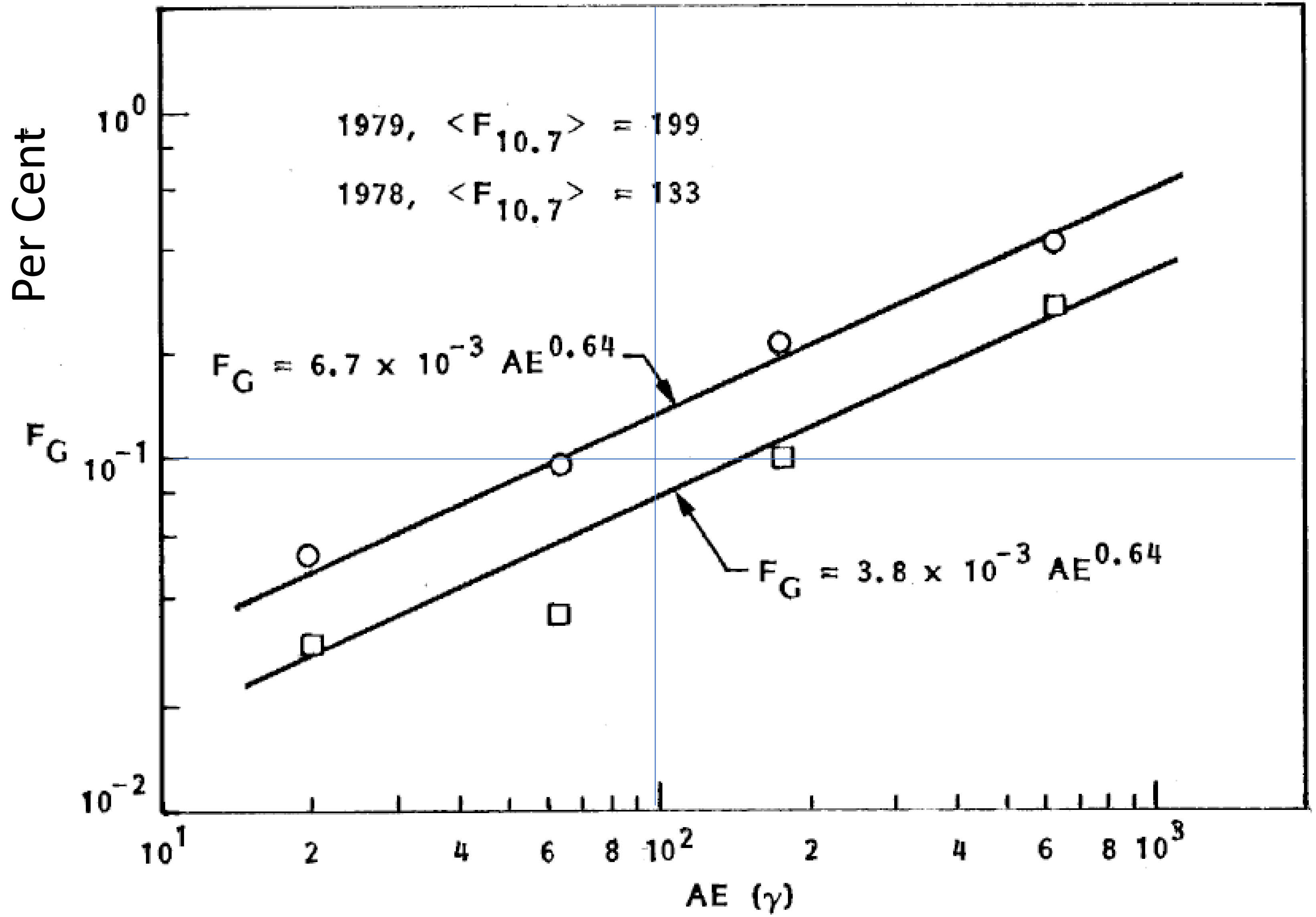
Plasma sheet H^+ and O^+ densities as a function of AE for the 1979 and 1978 ‘tail’ seasons.

- Assume constant plasma sheet volume
- H^+/O^+ ratio constant for specific values of the magnetic activity parameter AE and the Solar activity parameter $F_{10.7}$
- Effective $F_{10.7}$ Indices
  - <$F_{10.7}$ 1978> = 133
  - <$F_{10.7}$ 1979> = 199



Lennartsson, 1987

Estimate of Geogenic content



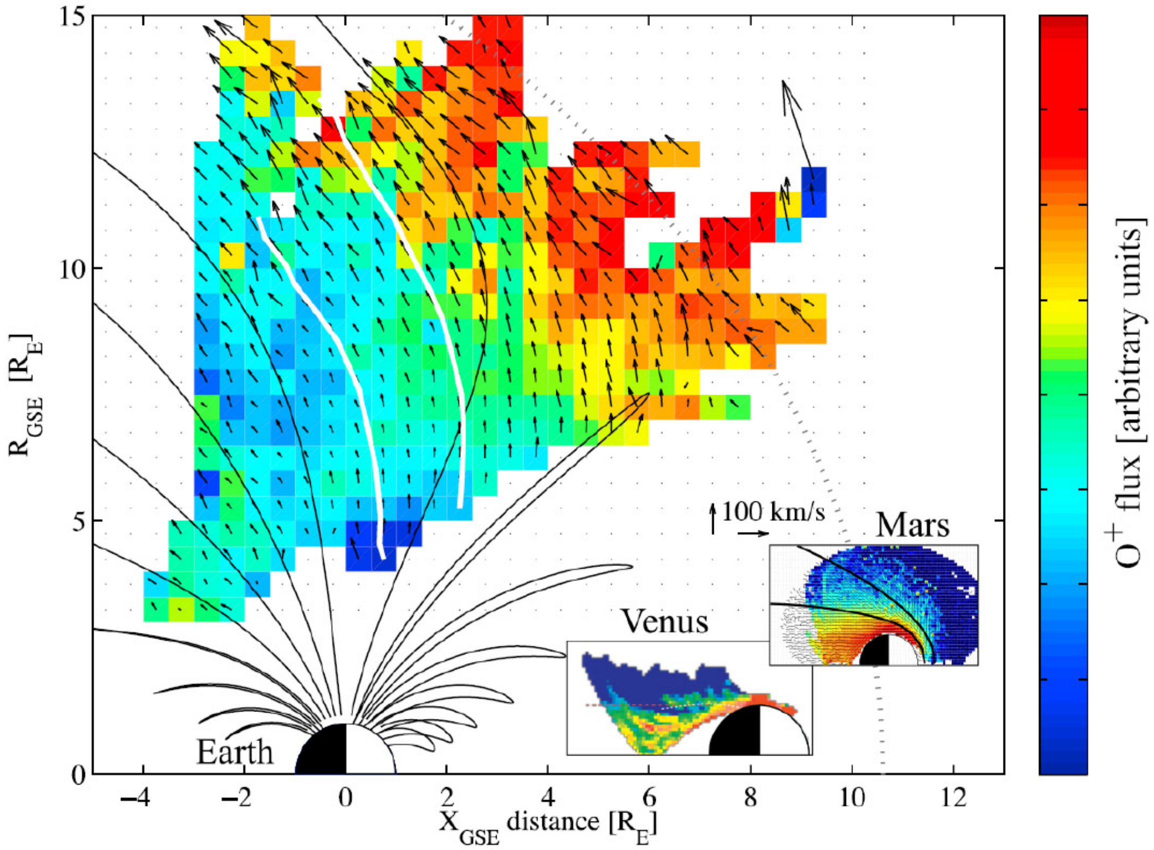
Predicts that at solar minimum, magnetic quiet times, the ionosphere makes a negligible contribution to the plasma sheet!

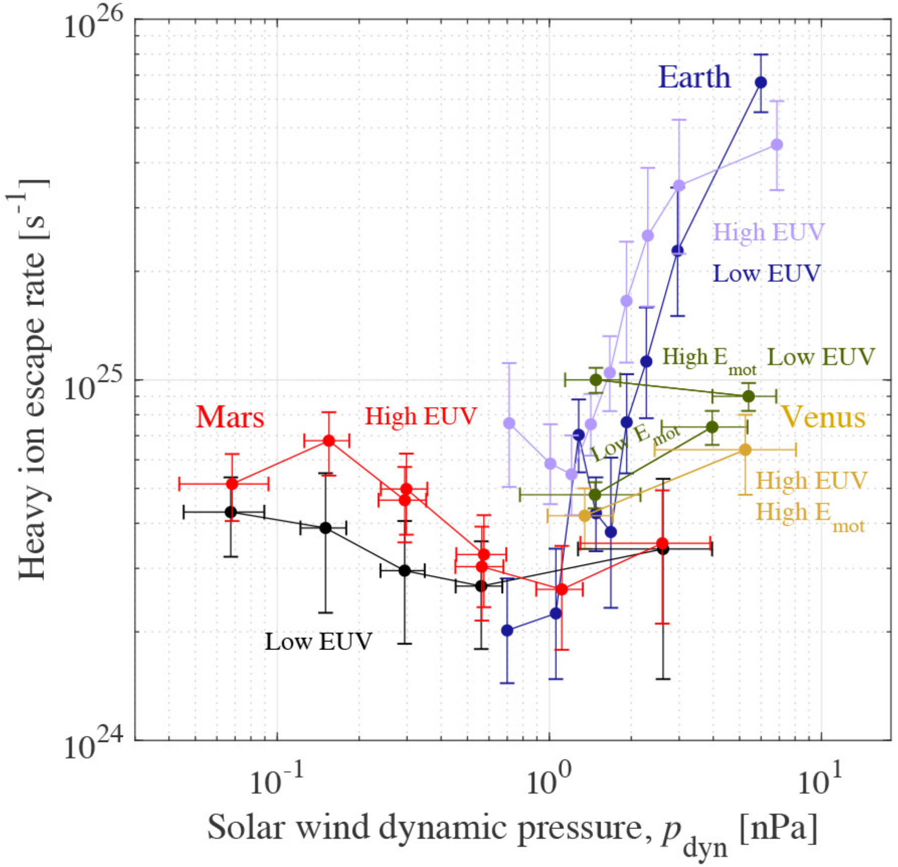
Global models should all provide insight into the geogenic content of various regions of the magnetosphere.

Shelley, et al., 1986

Out of this world thoughts

Atmospheric escape data from Earth, Mars, and Venus will be used in the new Magnetic fields, Atmospheres, and the Connection to Habitability (MACH) Science Center.

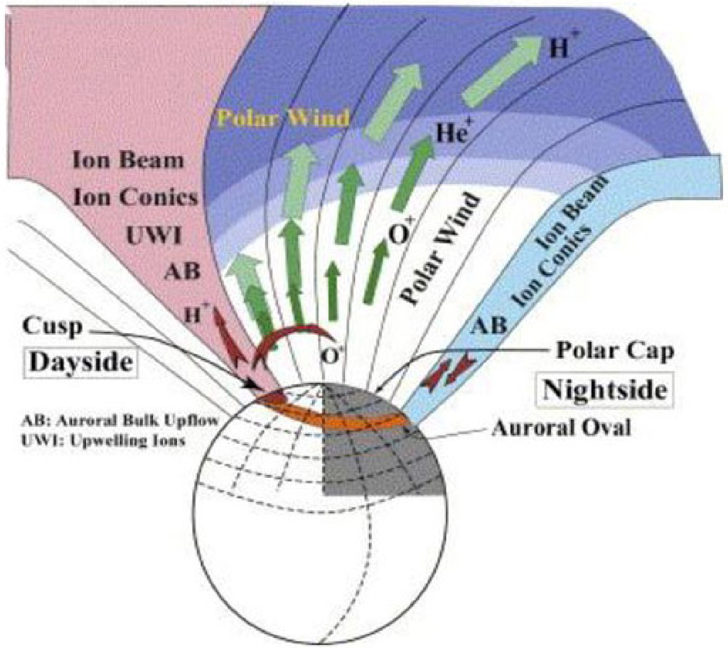




Ramstad and Barabash 2020, SSR under review

What I Want to Know about Ion Outflow

- I'd like to see the chemistry associated with molecular ion formation and transport incorporated into at least one large scale model of plasma sheet H^+, O^+, and NO^+ densities compared to data!
- Aurorae are filamentary. Large scale models of them are still not.
  - I'd like to see model results that attempt to address the consequences of the filamentary nature of auroral plasma and associated acceleration processes.
  - *Why not boundary coordinates in models?*
- Attempts have been made to sort out the relative importance of energization mechanisms in the 'gap' region, but there is still no overall consensus. We need:
  - **New mission(s)**: a large set of multi-point observations of auroral plasma using instruments with the capabilities of those on MAVEN, MMS, and RBSP.
  - **New analysis**: of existing satellite and rocket data



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