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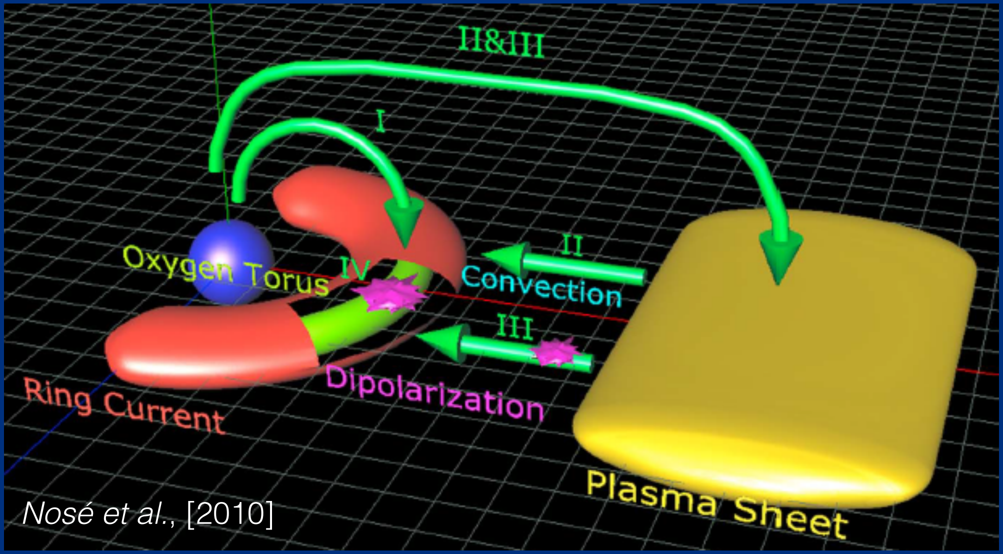
APPLIED PHYSICS LABORATORY



Matina Gkioulidou, A. Y. Ukhorskiy, S. Ohtani, D. G. Mitchell, K. Takahashi, H. E. Spence, J. R. Wygant, C. A. Kletzing

Outflow off the Beaten Path:

Low-energy (<keV) O^+ outflow directly into the inner magnetosphere

Why do we care about <keV O^+ in the inner magnetosphere

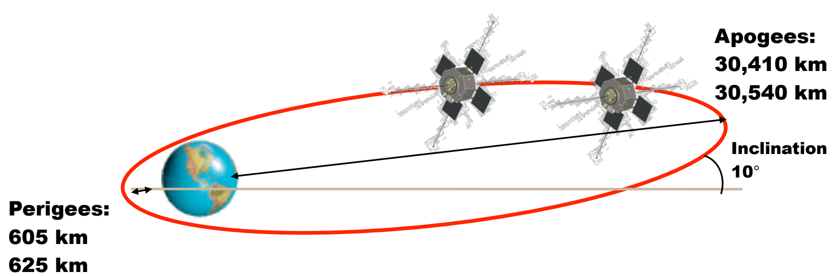
- It slows down the dayside magnetic reconnection, affecting the Solar Wind – Magnetosphere coupling [*Borovsky et al.*, 2013].
- Thermal O+ torus can be locally accelerated to 10s of keV (ring current) energies due to dipolarizations inside 6.6 R_E [*Nosé et al.*, 2011; 2014].
- ***Heavy ion mass loading is crucial for plasmapause and plasmasphere density studies. Mass loaded densities (as opposed to H^+ density profile) are important for accurate location of the plasmapause, which, in turn, is necessary for meaningful calculation of the field line resonance radial frequency profiles of ULF waves in the plasmasphere [Fraser et al., 2007].***
- Its existence is a manifestation of energy and mass exchange within the coupled inner magnetosphere - ionosphere system.

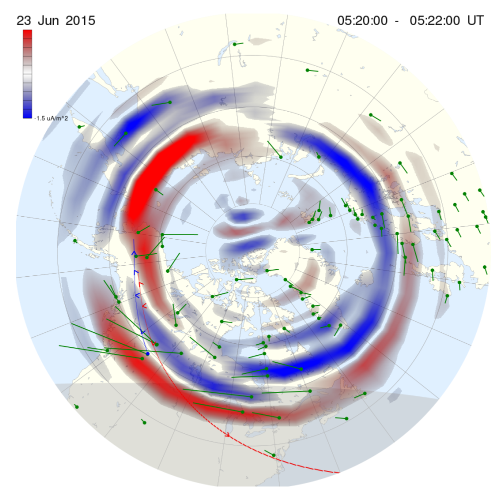
We did this in the 60s, 70s, 80s, etc…

ISEE 1 (elliptical orbit, 22.5 R_E apogee) and **Dynamic Explorer 1** (apogee at 23,300 km) missions in the past, were the first ones to explore the development of O^+ ions < keV within the inner magnetosphere.

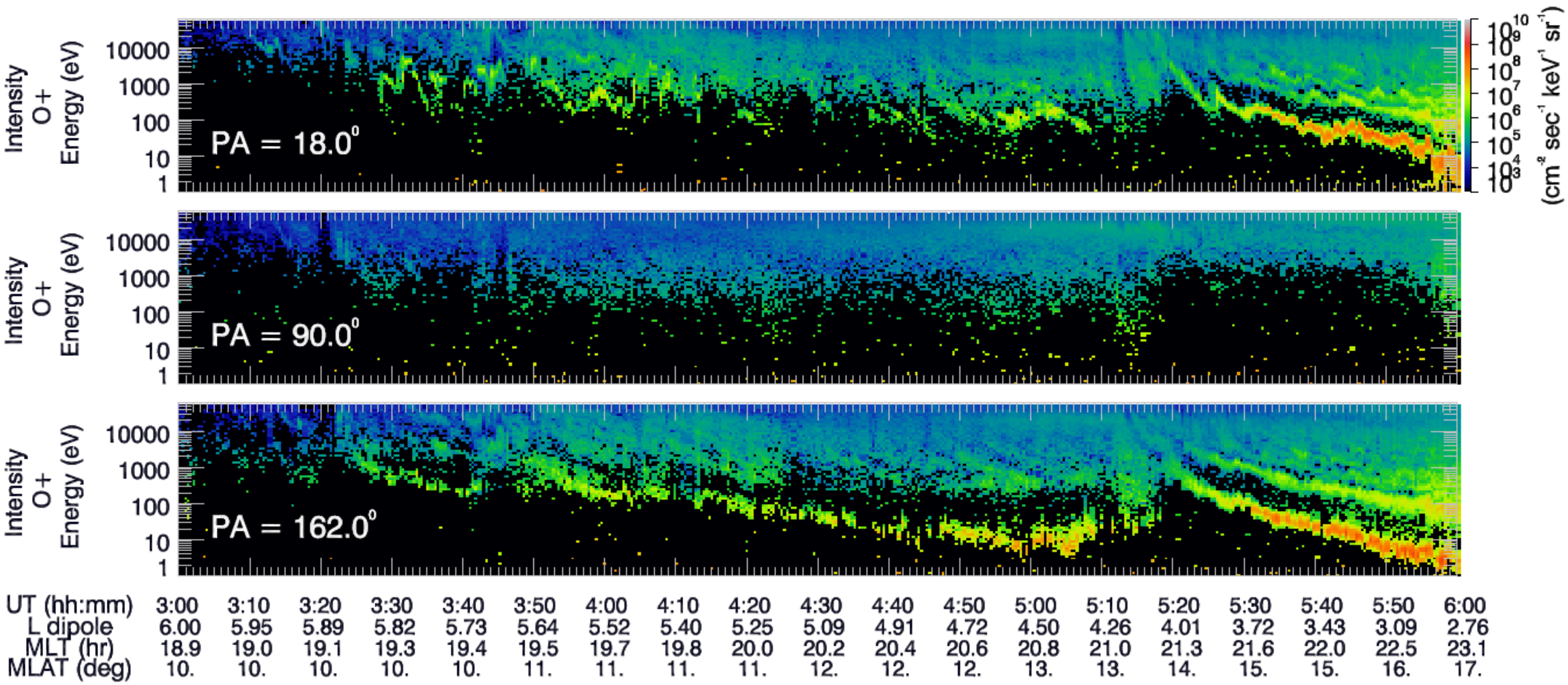
New Capabilities, New Insights

Coordinated equatorial particle and fields measurements from the Van Allen Probes and ionospheric properties measurements, such as Field Aligned Currents (FAC) from AMPERE satellites, can shed light to the inner magnetosphere - ionosphere coupling processes that could lead to O+ outflow directly into the inner magnetosphere.





How it all started…



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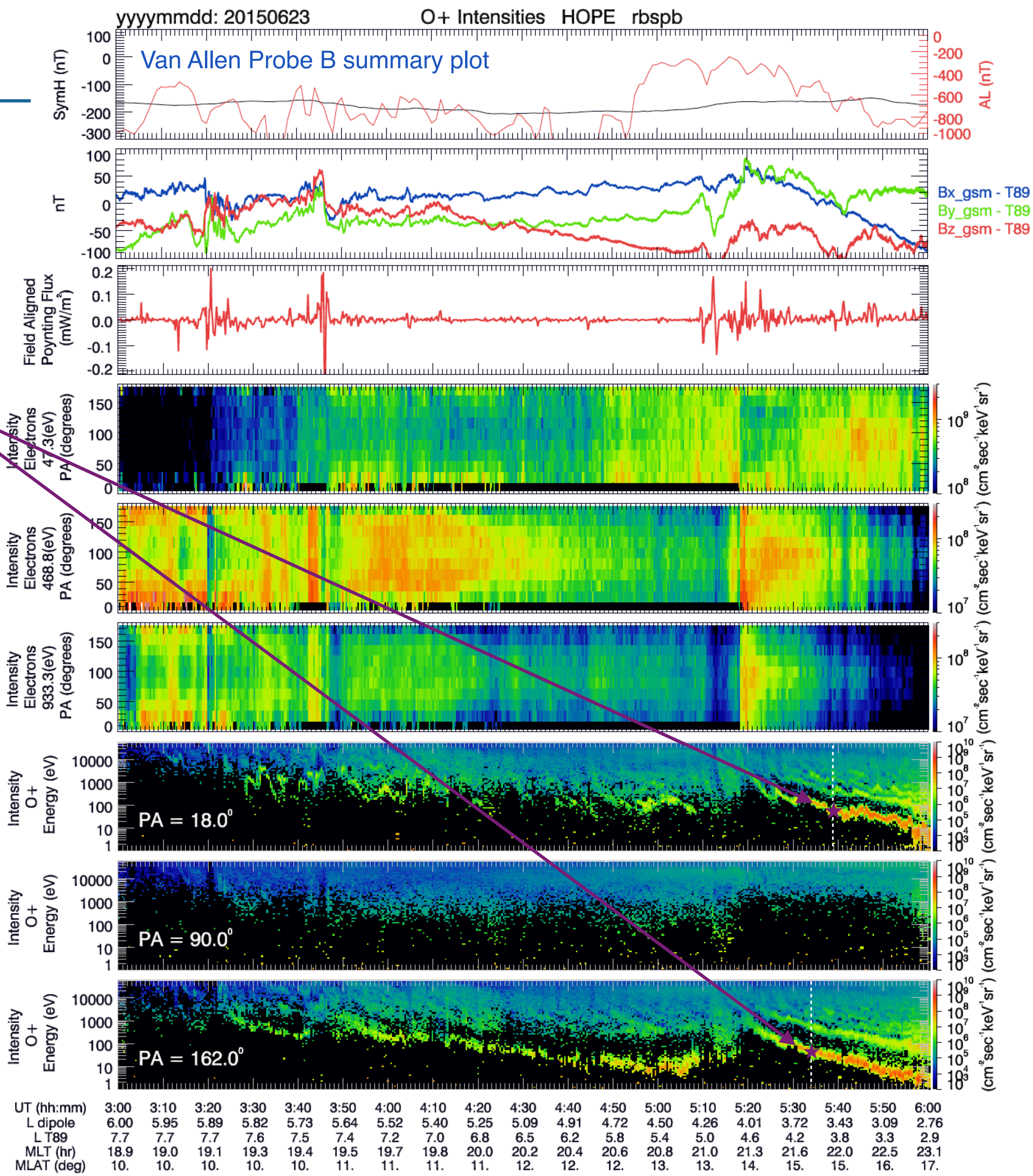
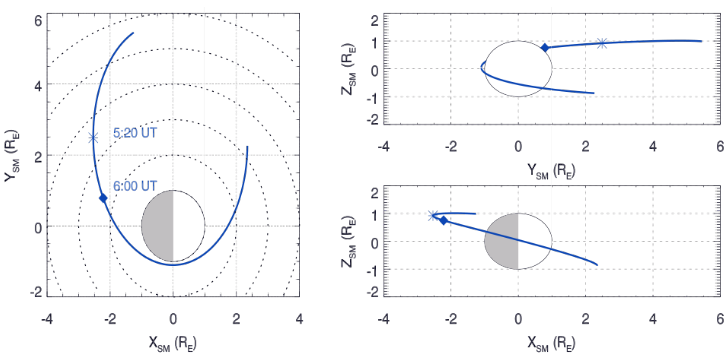
June 23 2015 storm

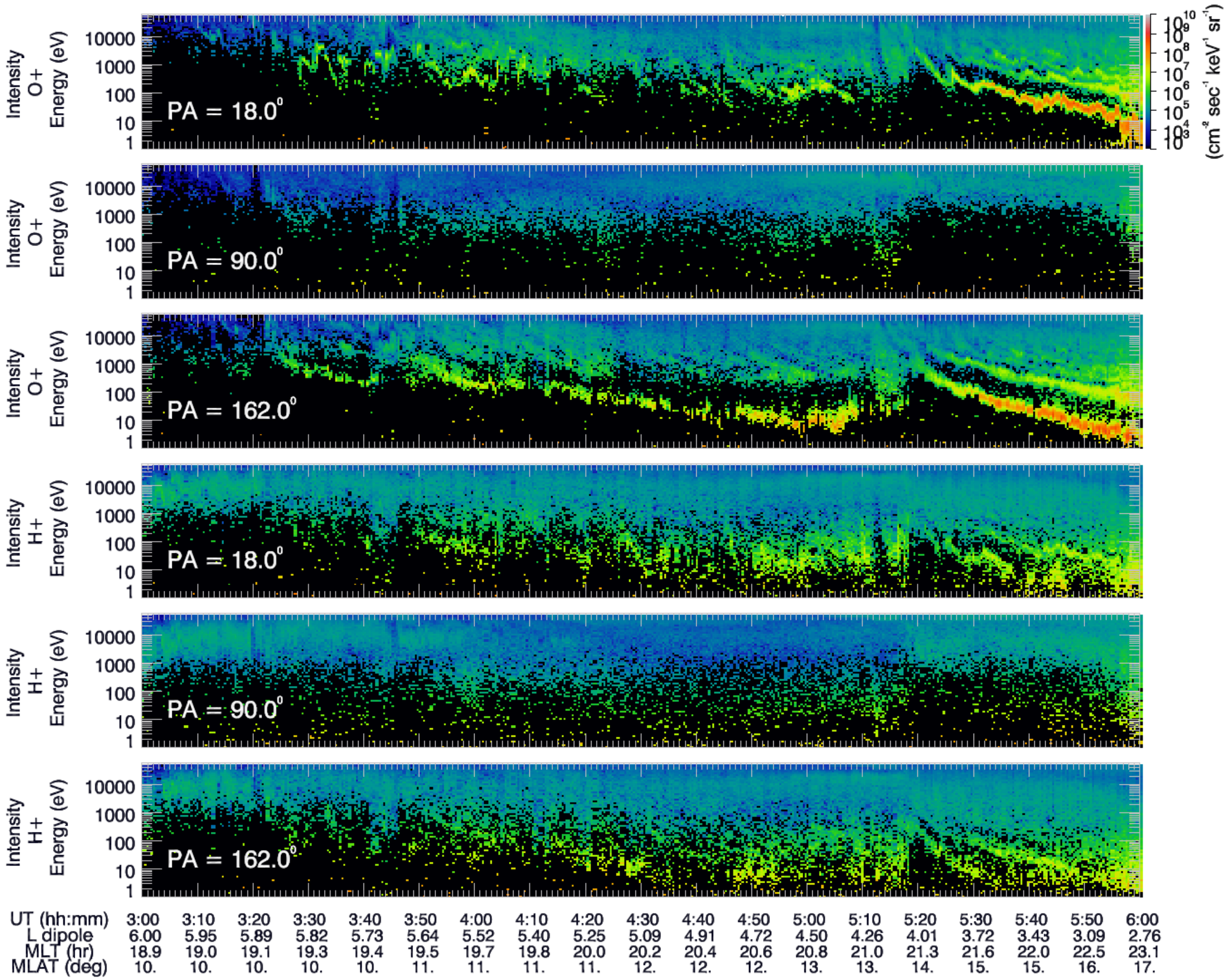
Low energy (eV - 100s eV) bi-directional O^+ outflow event observed by the HOPE instrument starting at ~ 5:20 UT:

- For the same energy, O^+ ions of 162° pitch angle arrive at the s/c few minutes faster than those of 18° pitch angle.
- There is a clear energy dispersion with higher (lower) energies seen at higher (lower) L-shells.
- There are multiple bands of high intensities both at 18° and 162° pitch angle.
- This outflow event is associated with fluctuations of the field aligned Poynting flux and field aligned heated electrons.





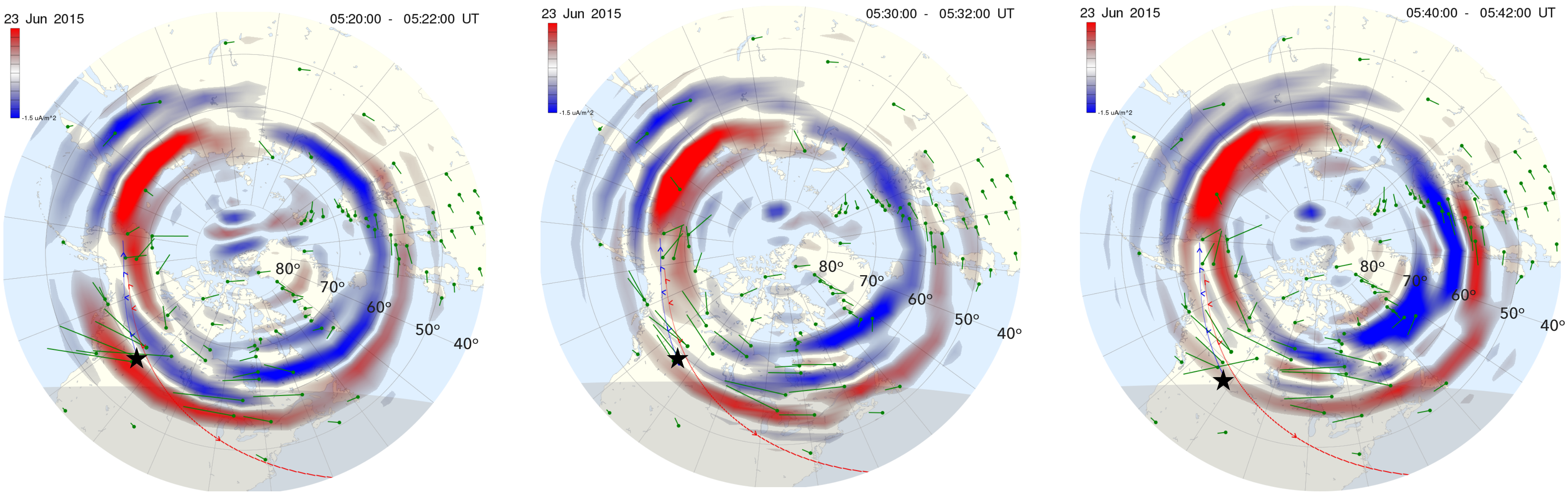
Comparison between O^+ and H^+



- Outflow is also observed for H^+ ions, however not at the same intensity.

- **Field aligned currents (AMPERE) : Downward, Upward**
- **Equivalent current from ground magnetic field perturbations (SuperMag) :**

★ Van Allen Probe B footprint



courtesy of Rob Barnes (JHU/APL)

- Throughout the O+ outflow event, Van Allen Probe B was at the vicinity of upward Field Aligned Current (FAC).
- The strongest upward FAC is observed ~5:20 UT and extends equatorward of the s/c (between 50° and 60°). For the next 20 min the s/c is moving earthward and its footprint is in the region of a weaker upward FAC.

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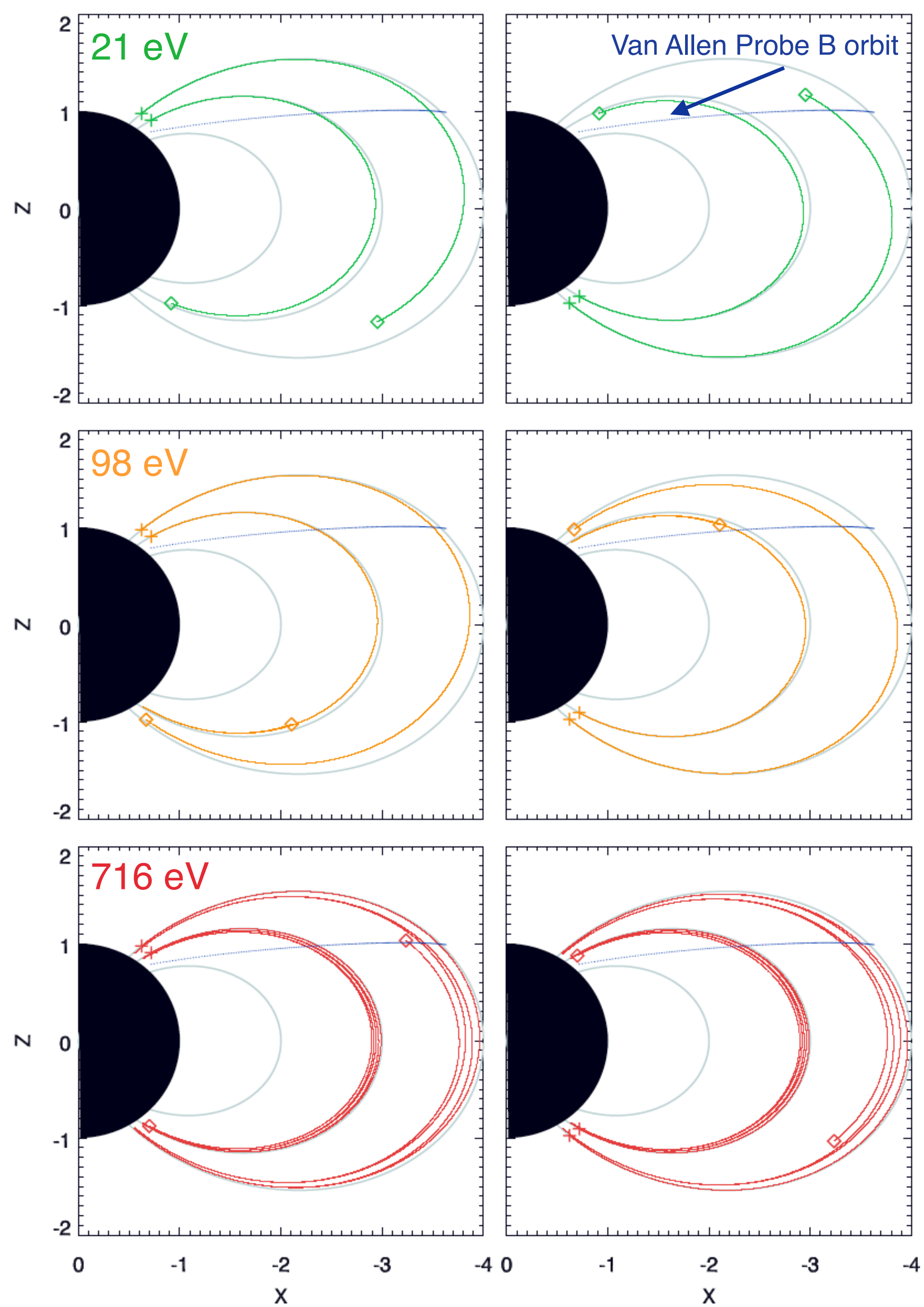
What Causes The Multiple Bands? We Employ Toy Model

- Launch O+ ions from northern and southern hemispheres at 1000 km (guiding center approximation)
- Energies: 6, 10, 21, 46, 98, 211, 453, 716, 1132, and 2834 eV
- L shells: 3-4 (every 0.1)
- B: Dipole field
- Ey: 1 mV/m
- Run time: 40 min

Example trajectories for particles launching at L = 3 and L = 4



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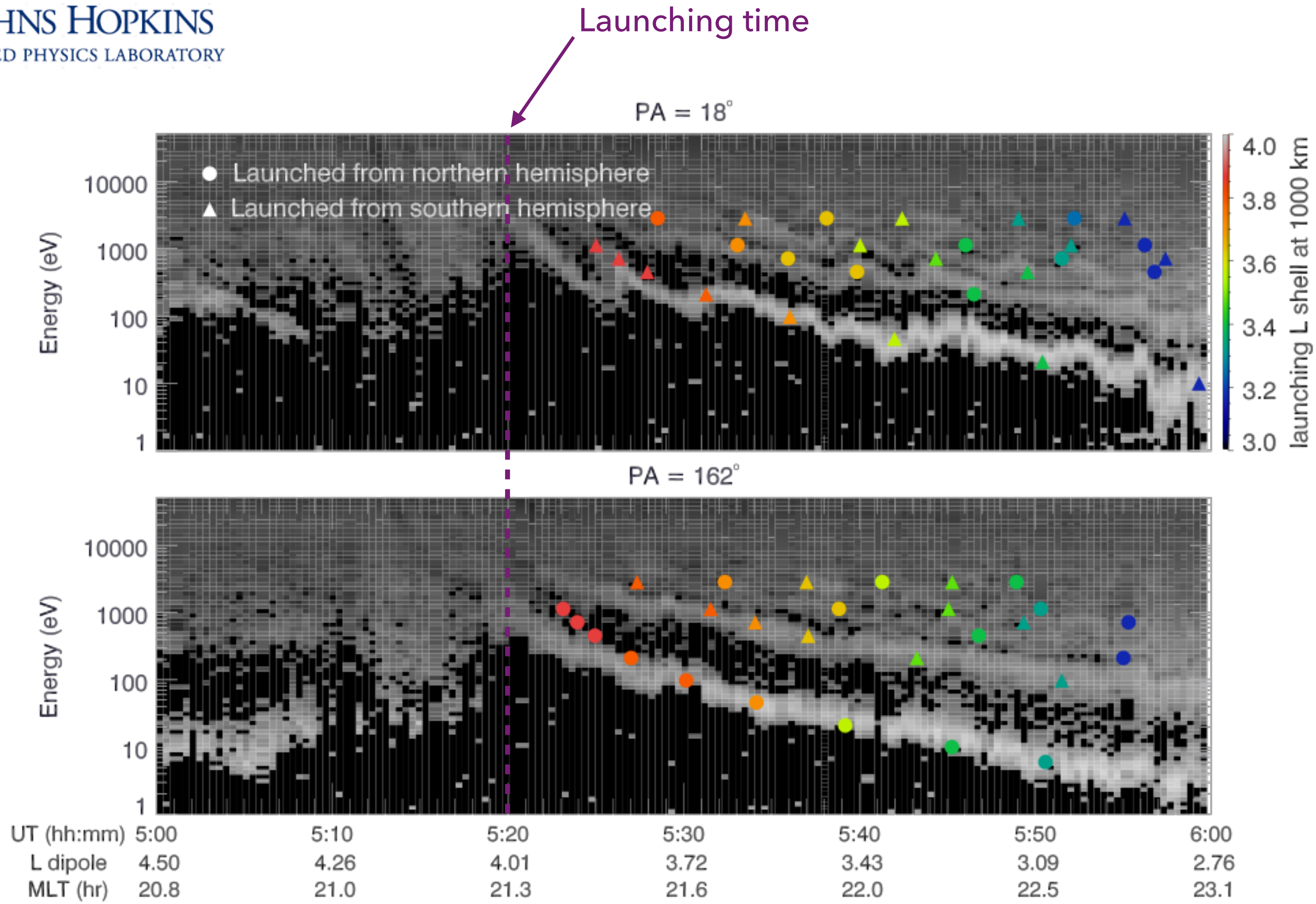
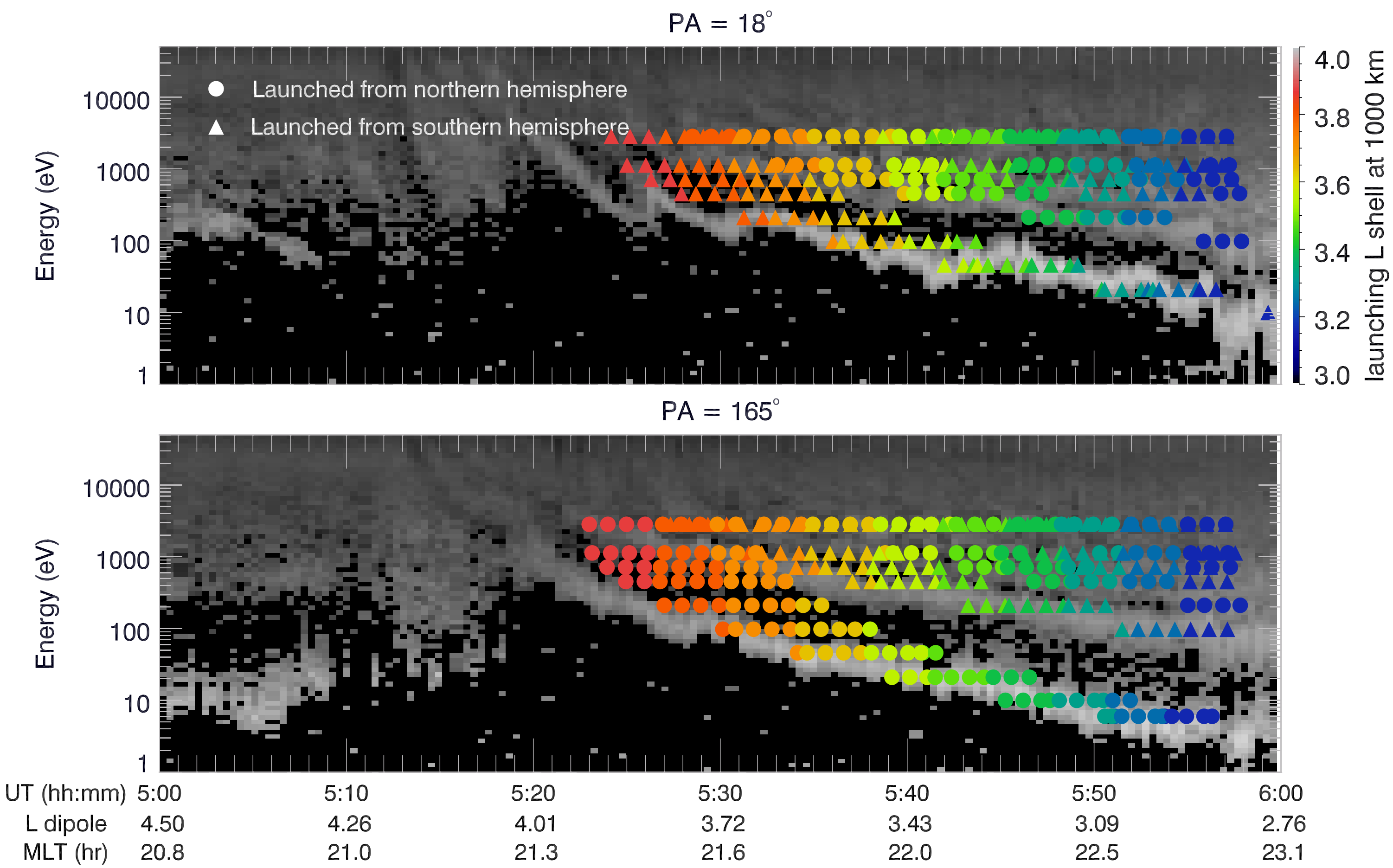
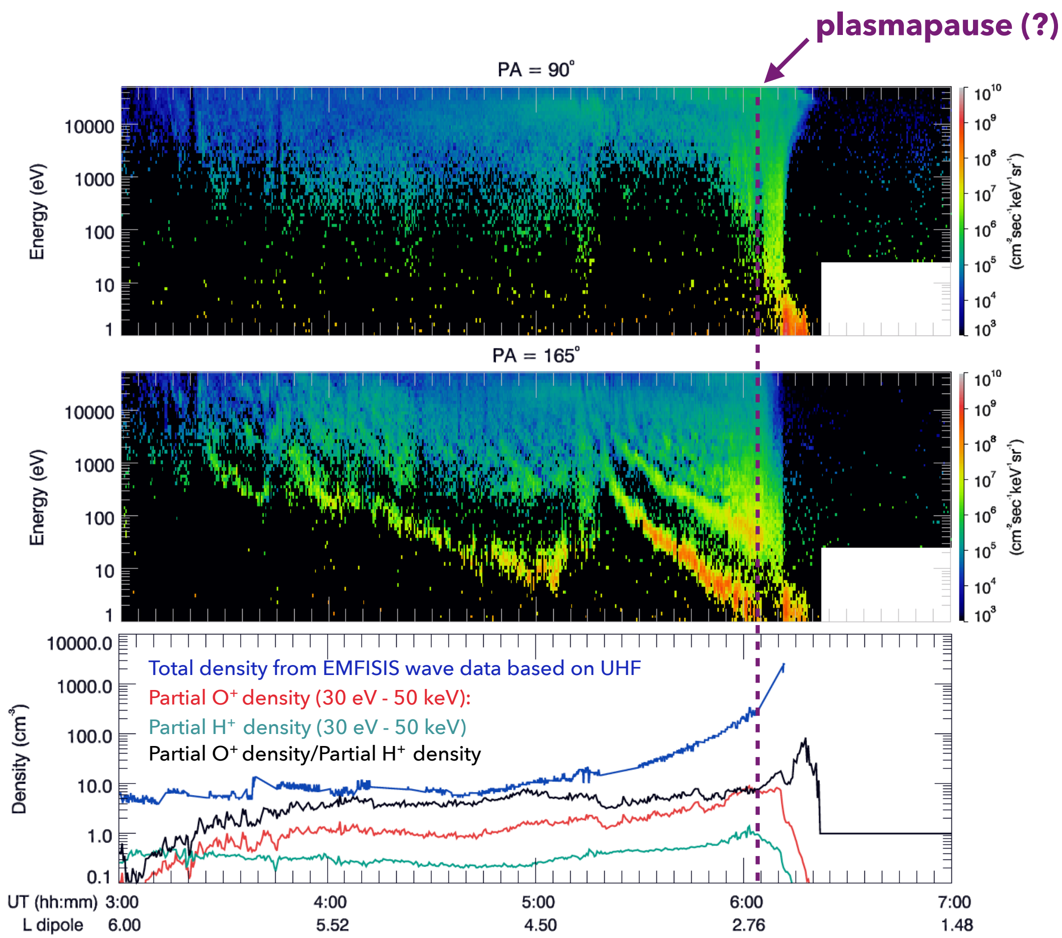


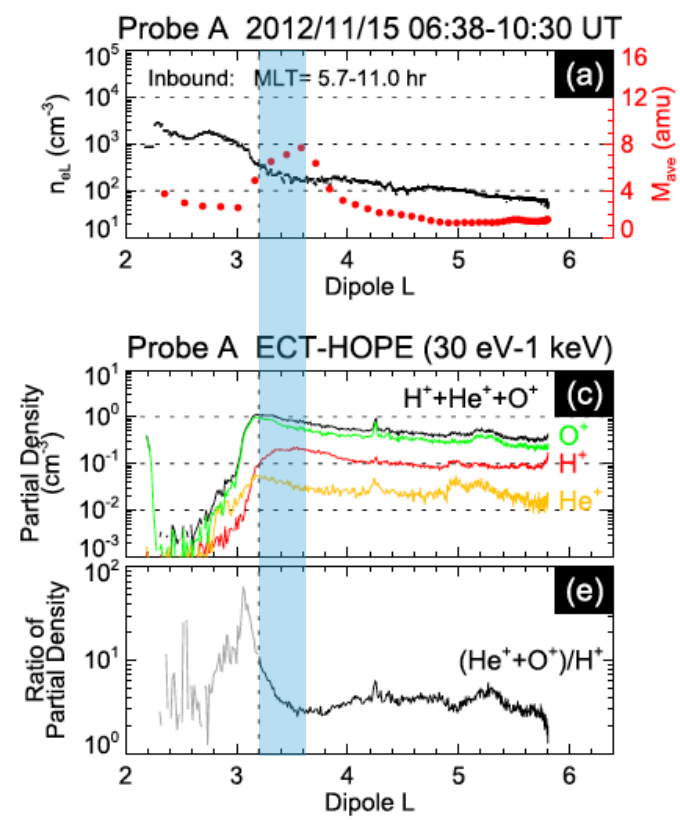
- Multiple bands are caused because O^+ ions of different energies that exit the ionosphere at different L shells, encounter the spacecraft at different times during their bouncing motion along the magnetic field lines.
- For 1mV/m electric field, outflow down to L ~ 3 is required in order to explain the observed enhanced intensities at 165° of O+ ions down to 6 eV.

Continuous outflow for 10min (5:20 - 5:30 every 1 min)



Could such outflows directly into the magnetosphere be one of the sources of the O^+ torus?





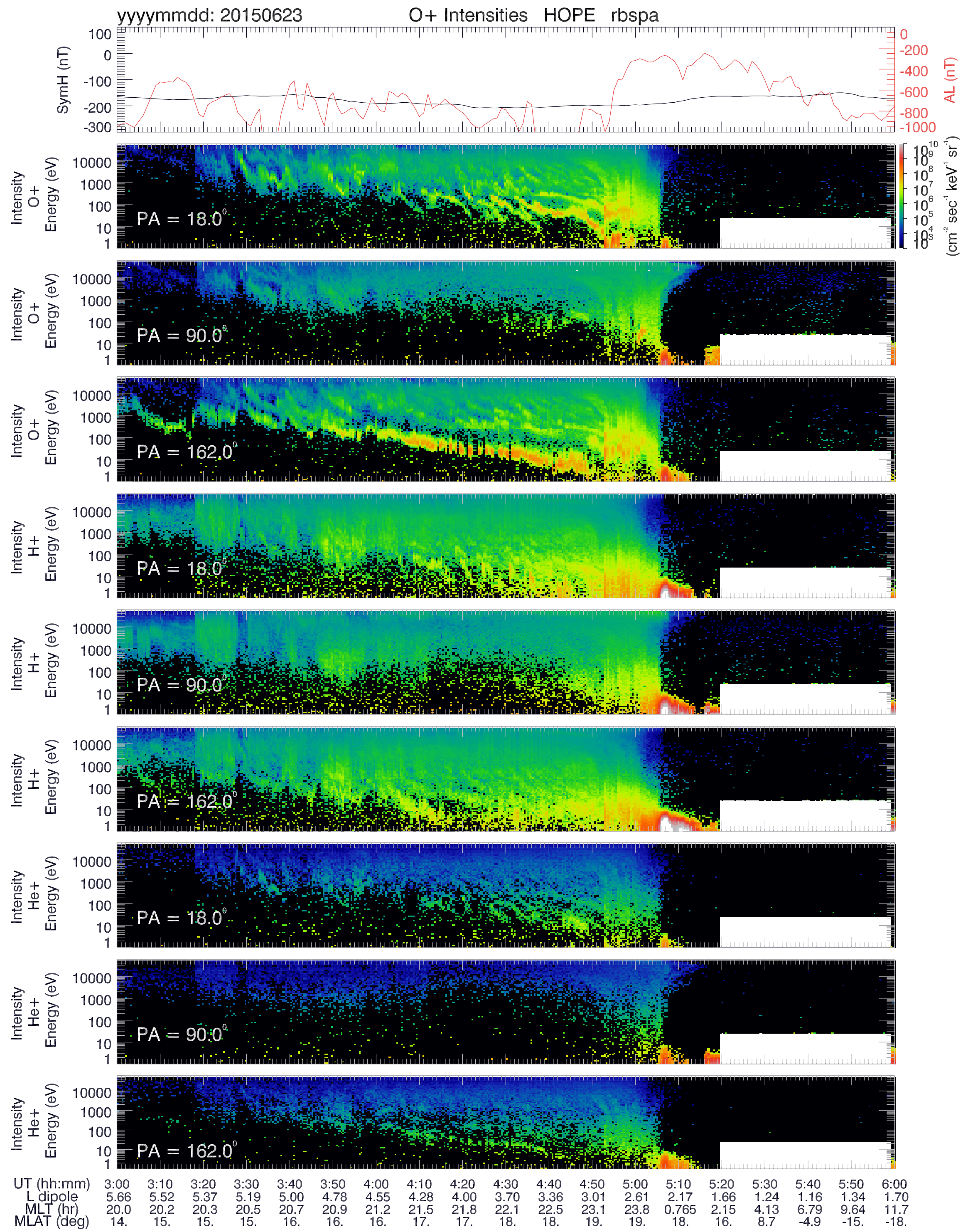
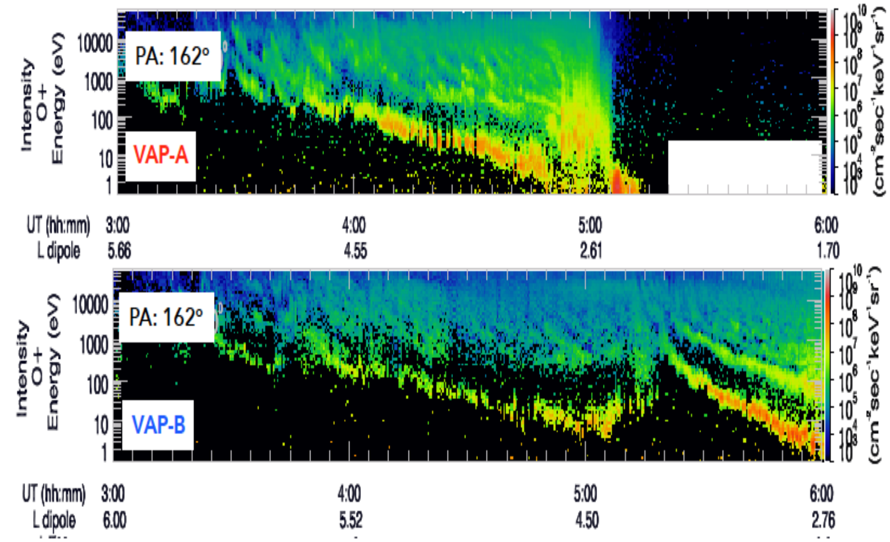
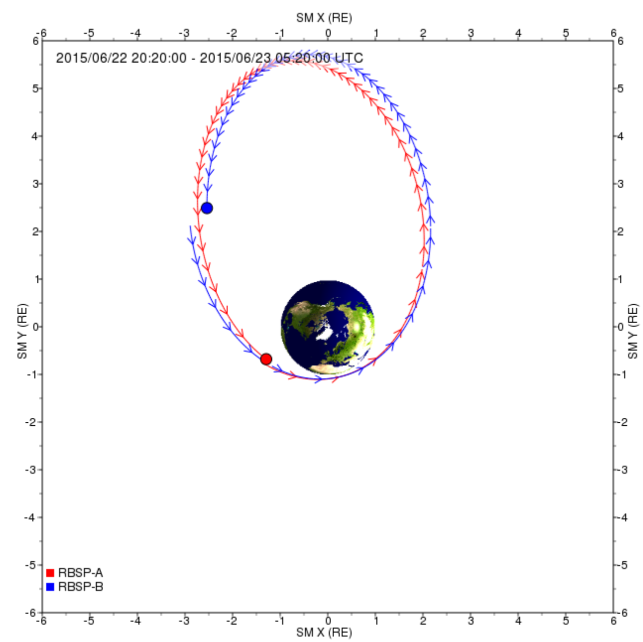
- The O^+ density prevails over the H^+ density when outflows are observed, reaching ~ 5 cm^{-3}.

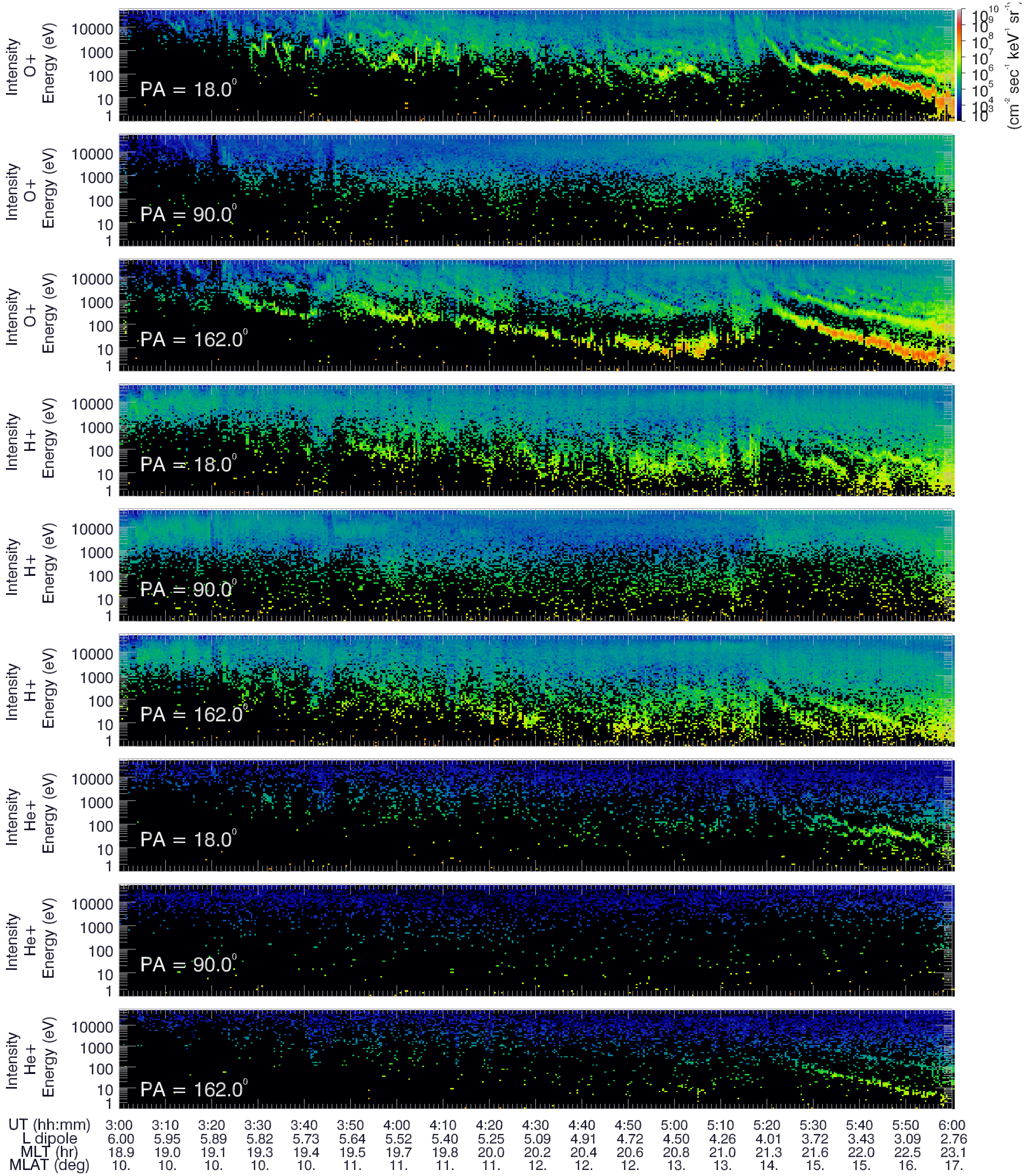
Nose et al. [2015]

Summary

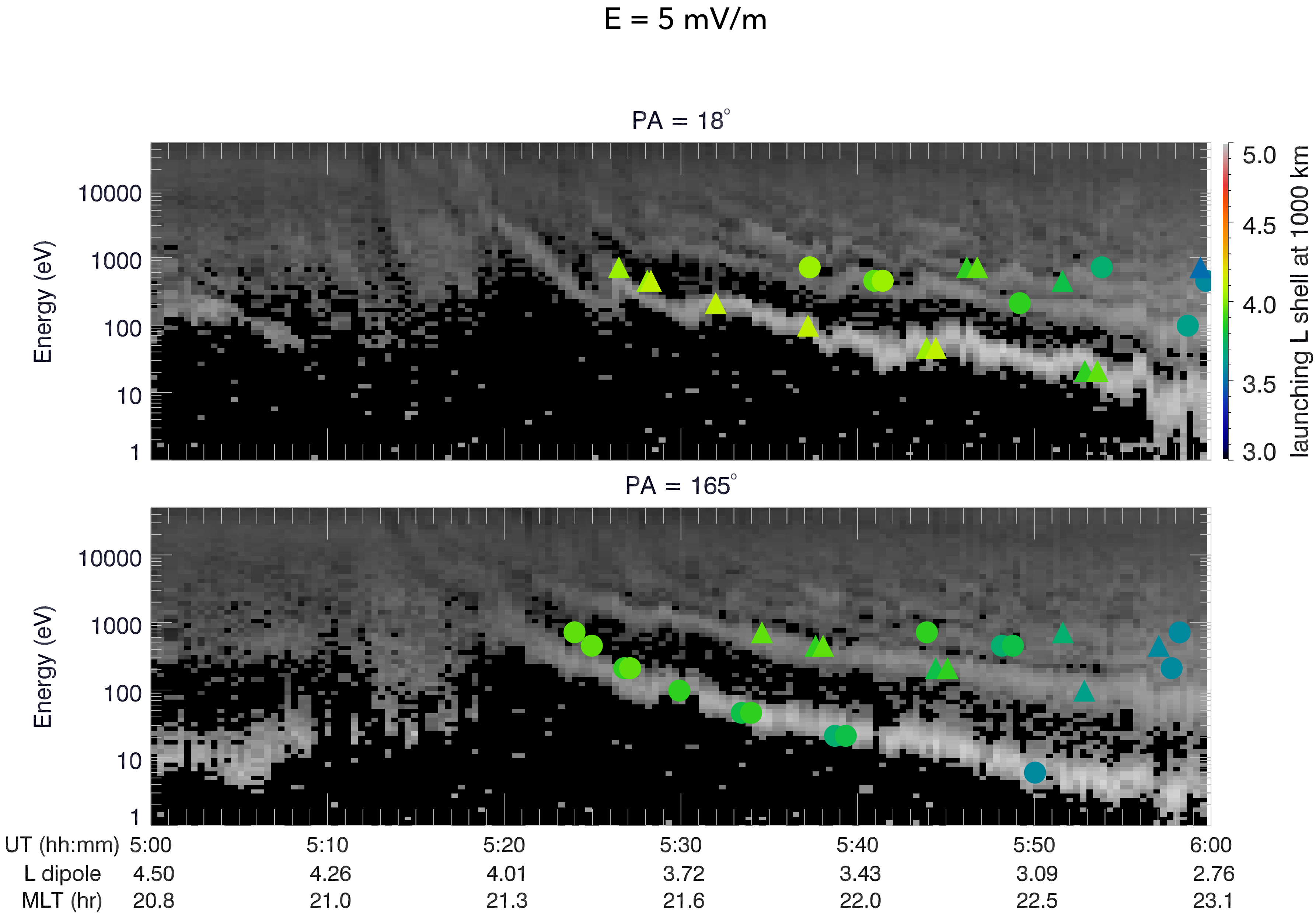
- We have investigated a low energy (few eV - 100s eV) O^+ outflow event observed by the HOPE instrument on board Van Allen Probe B, during main phase of a storm.
- Van Allen Probe B observed bi-directional field aligned density enhancements with multiple bands, which can be explained by outflowing O^+ ions of different energies, from both hemispheres and at L shells between 3 and 4, and subsequently encountering the spacecraft along their bouncing motion at different times.
- At the time of the outflow event, enhancement of the field aligned Poynting flux was also observed, calculated using electric and magnetic fields from the EFW and EMFISIS instruments respectively, indicating energy transfer from magnetosphere to ionosphere.
- The ionospheric footprint of Van Allen Probe B throughout the outflow interval was at the vicinity of a very strong upward FAC, indicating electron precipitation.
- Partial density comparisons using moments of the HOPE instrument reveal that during such outflows the O^+ density dominates over the H^+ one.
- Such outflow events are ubiquitous throughout the mission during active times.

QUESTION: Could such outflows directly into the magnetosphere be one of the sources of the O^+ torus?


yyyymmdd: 20150623
O+ Intensities HOPE rbspa
SymH (nT)
AL (nT)
Intensity O+ Energy (eV)
Intensity H+ Energy (eV)
Intensity He+ Energy (eV)
PA = 18.0°
PA = 90.0°
PA = 162.0°
(cm^-2 sec^-1 keV^-1 sr^-1)
UT (hh:mm) 3:00 3:10 3:20 3:30 3:40 3:50 4:00 4:10 4:20 4:30 4:40 4:50 5:00 5:10 5:20 5:30 5:40 5:50 6:00
L dipole 5.66 5.52 5.37 5.19 5.00 4.78 4.55 4.28 4.00 3.70 3.36 3.01 2.61 2.17 1.66 1.24 1.16 1.34 1.70
MLT (hr) 20.0 20.2 20.3 20.5 20.7 20.9 21.2 21.5 21.8 22.1 22.5 23.1 23.8 0.765 2.15 4.13 6.79 9.64 11.7
MLAT (deg) 14. 15. 15. 15. 16. 16. 16. 17. 17. 18. 18. 19. 19. 18. 16. 8.7 -4.9 -15. -18.

Intensity O+ Energy (eV)
PA: 162°
VAP-A
UT (hh:mm) 3:00 4:00 5:00 6:00
L dipole 5.66 4.55 2.61 1.70
PA: 162°
VAP-B
UT (hh:mm) 3:00 4:00 5:00 6:00
L dipole 6.00 5.52 4.50 2.76
(cm^-2 sec^-1 keV^-1 sr^-1)

SM X (RE)
SM Y (RE)
2015/06/22 20:20:00 - 2015/06/23 05:20:00 UTC
RBSP-A
RBSP-B

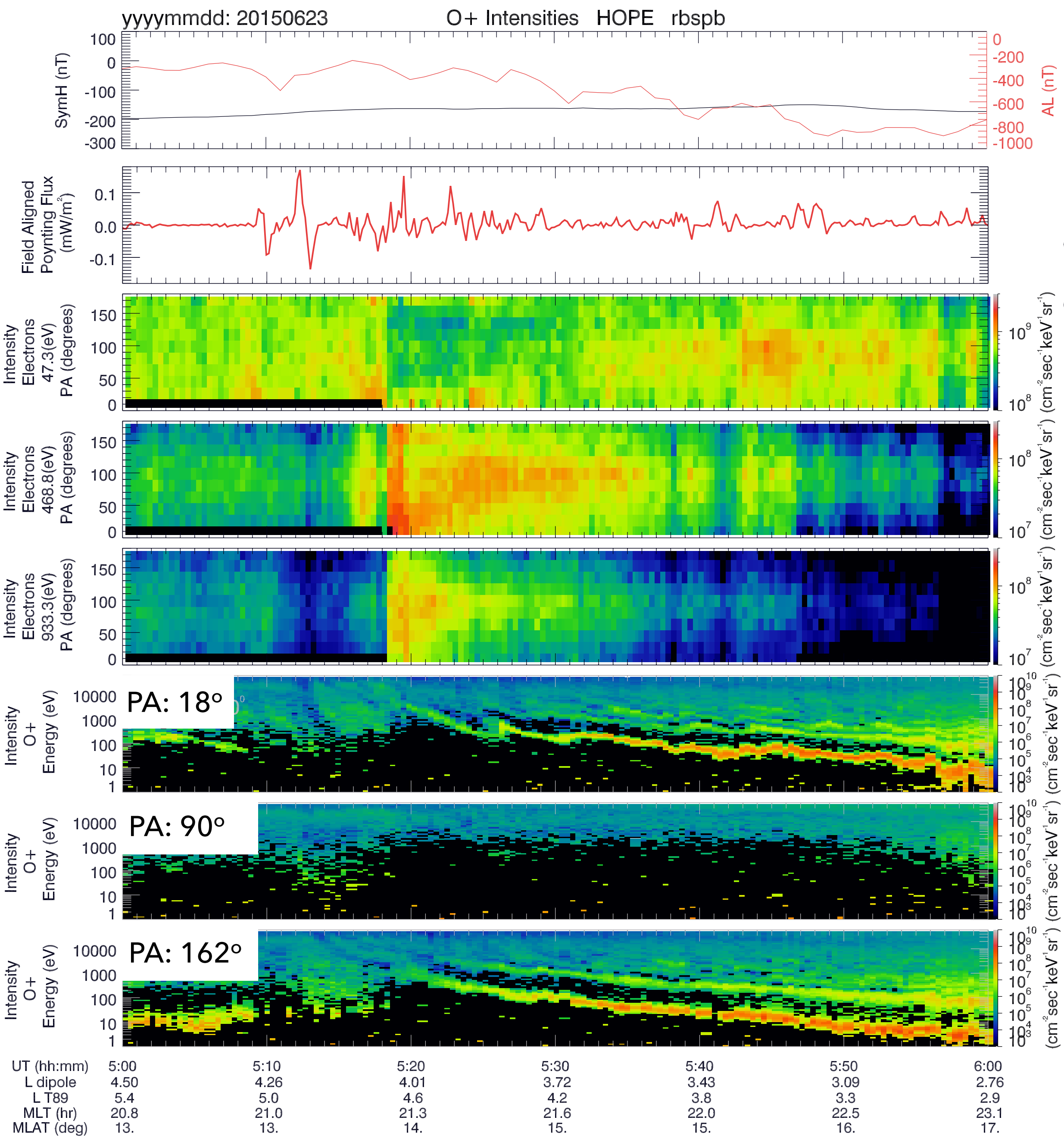


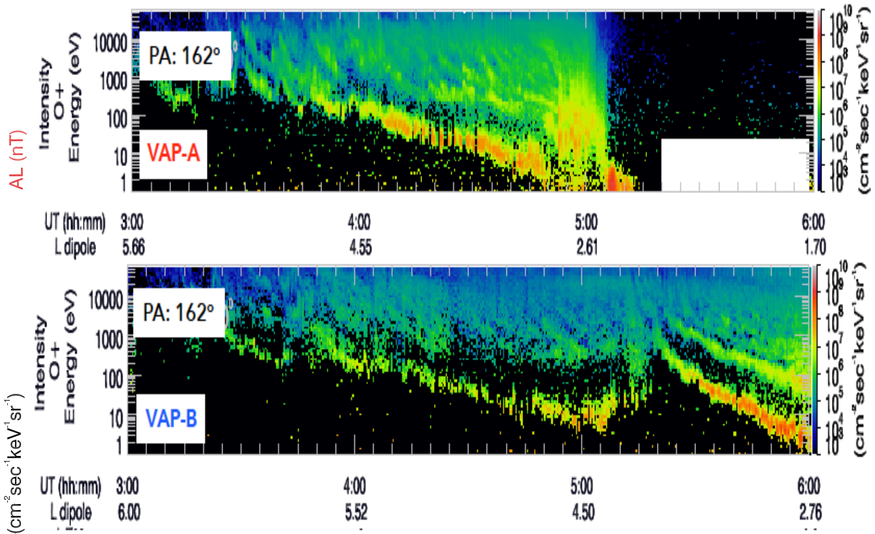
Intensity O+ Energy (eV)
PA = 18.0°
Intensity O+ Energy (eV)
PA = 90.0°
Intensity O+ Energy (eV)
PA = 162.0°
Intensity H+ Energy (eV)
PA = 18.0°
Intensity H+ Energy (eV)
PA = 90.0°
Intensity H+ Energy (eV)
PA = 162.0°
Intensity He+ Energy (eV)
PA = 18.0°
Intensity He+ Energy (eV)
PA = 90.0°
Intensity He+ Energy (eV)
PA = 162.0°
10000 1000 100 10 1
(cm⁻² sec⁻¹ keV⁻¹ sr⁻¹)
UT (hh:mm) 3:00 3:10 3:20 3:30 3:40 3:50 4:00 4:10 4:20 4:30 4:40 4:50 5:00 5:10 5:20 5:30 5:40 5:50 6:00
L dipole 6.00 5.95 5.89 5.82 5.73 5.64 5.52 5.40 5.25 5.09 4.91 4.72 4.50 4.26 4.01 3.72 3.43 3.09 2.76
MLT (hr) 18.9 19.0 19.1 19.3 19.4 19.5 19.7 19.8 20.0 20.2 20.4 20.6 20.8 21.0 21.3 21.6 22.0 22.5 23.1
MLAT (deg) 10. 10. 10. 10. 10. 11. 11. 11. 11. 12. 12. 12. 13. 13. 14. 15. 15. 16. 17.

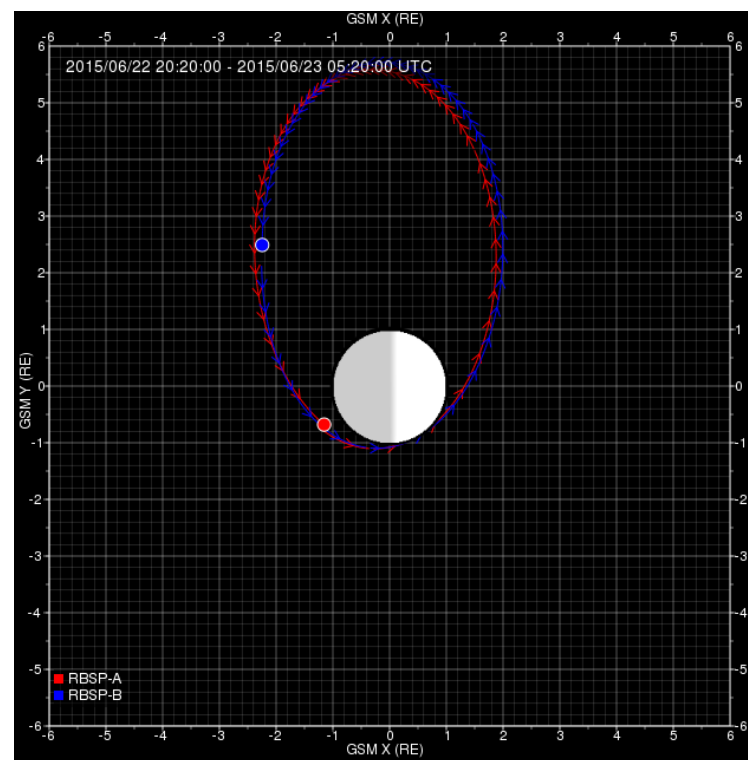


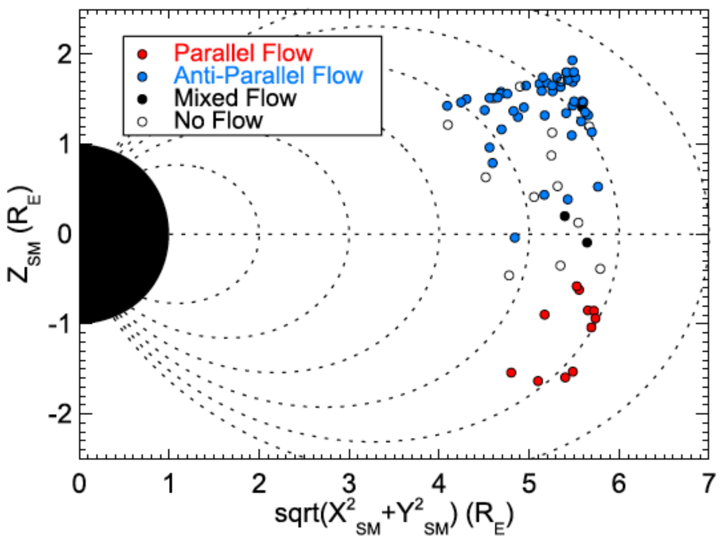
E = 5 mV/m
PA = 18°
Energy (eV)
10000
1000
100
10
1
5.0
4.5
4.0
3.5
3.0
launching L shell at 1000 km
PA = 165°
Energy (eV)
10000
1000
100
10
1
UT (hh:mm) 5:00 5:10 5:20 5:30 5:40 5:50 6:00
L dipole 4.50 4.26 4.01 3.72 3.43 3.09 2.76
MLT (hr) 20.8 21.0 21.3 21.6 22.0 22.5 23.1

June 23 2015


yyyymmdd: 20150623
O+ Intensities HOPE rbspb
SymH (nT)
AL (nT)
Field Aligned Poynting Flux (mW/m²)
Intensity Electrons 47.3(eV) PA (degrees)
Intensity Electrons 468.8(eV) PA (degrees)
Intensity Electrons 933.3(eV) PA (degrees)
Intensity O+ Energy (eV)
PA: 18°
PA: 90°
PA: 162°
UT (hh:mm) 5:00 5:10 5:20 5:30 5:40 5:50 6:00
L dipole 4.50 4.26 4.01 3.72 3.43 3.09 2.76
L T89 5.4 5.0 4.6 4.2 3.8 3.3 2.9
MLT (hr) 20.8 21.0 21.3 21.6 22.0 22.5 23.1
MLAT (deg) 13. 13. 14. 15. 15. 16. 17.

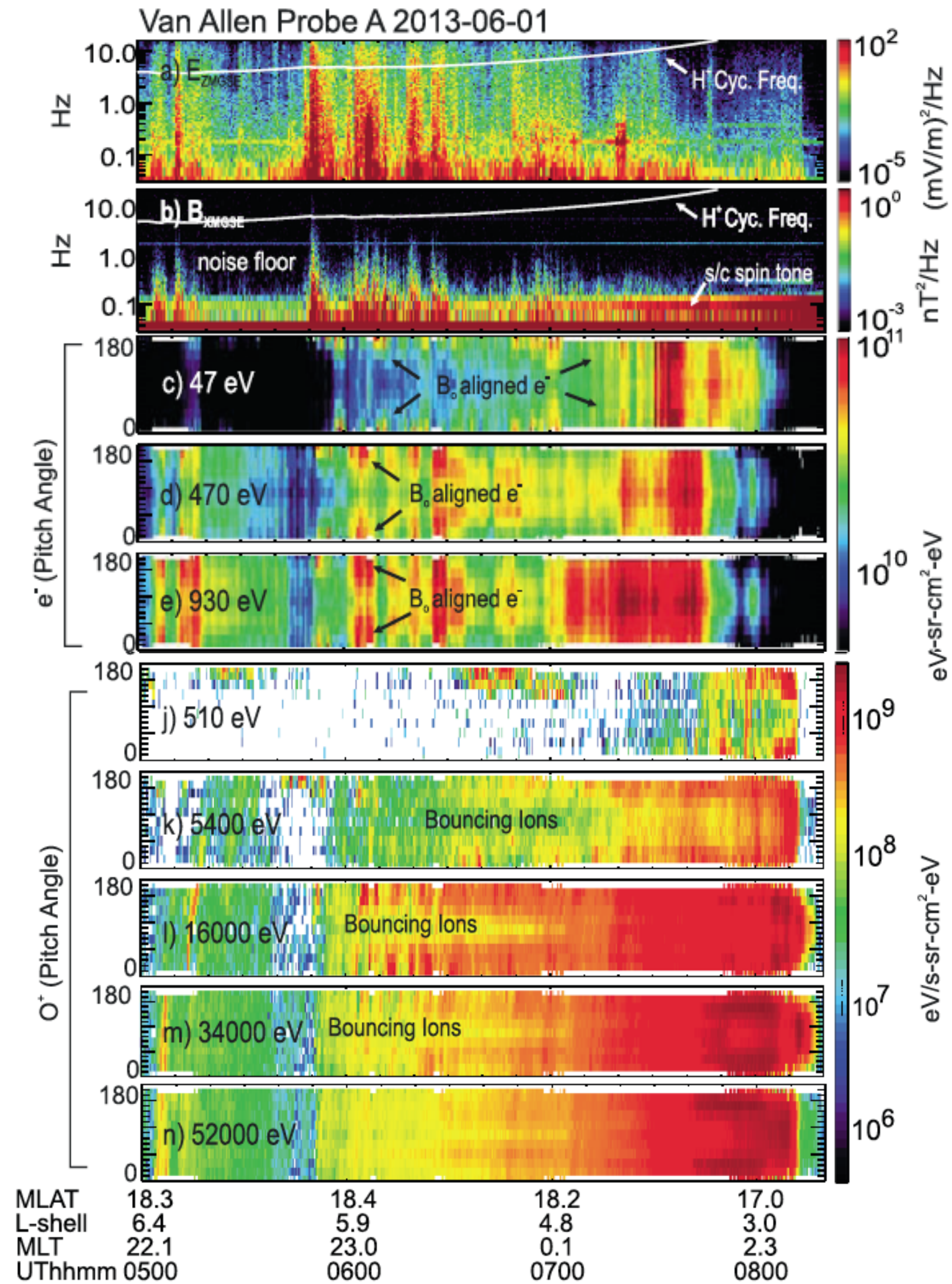

Intensity O+ Energy (eV)
PA: 162°
VAP-A
UT (hh:mm) 3:00 4:00 5:00 6:00
L dipole 5.66 4.55 2.61 1.70
PA: 162°
VAP-B
UT (hh:mm) 3:00 4:00 5:00 6:00
L dipole 6.00 5.52 4.50 2.76


GSM X (RE)
GSM Y (RE)
2015/06/22 20:20:00 - 2015/06/23 05:20:00 UTC
RBSP-A
RBSP-B

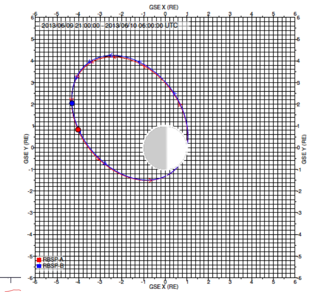


***Nose et al.*, [2016]**: Unidirectional energy-dispersed O+ flux is observed in 80% of the dipolarization events and that its direction is parallel (antiparallel) to the magnetic field when the Van Allen Probes are located below (above) the geomagnetic equator.

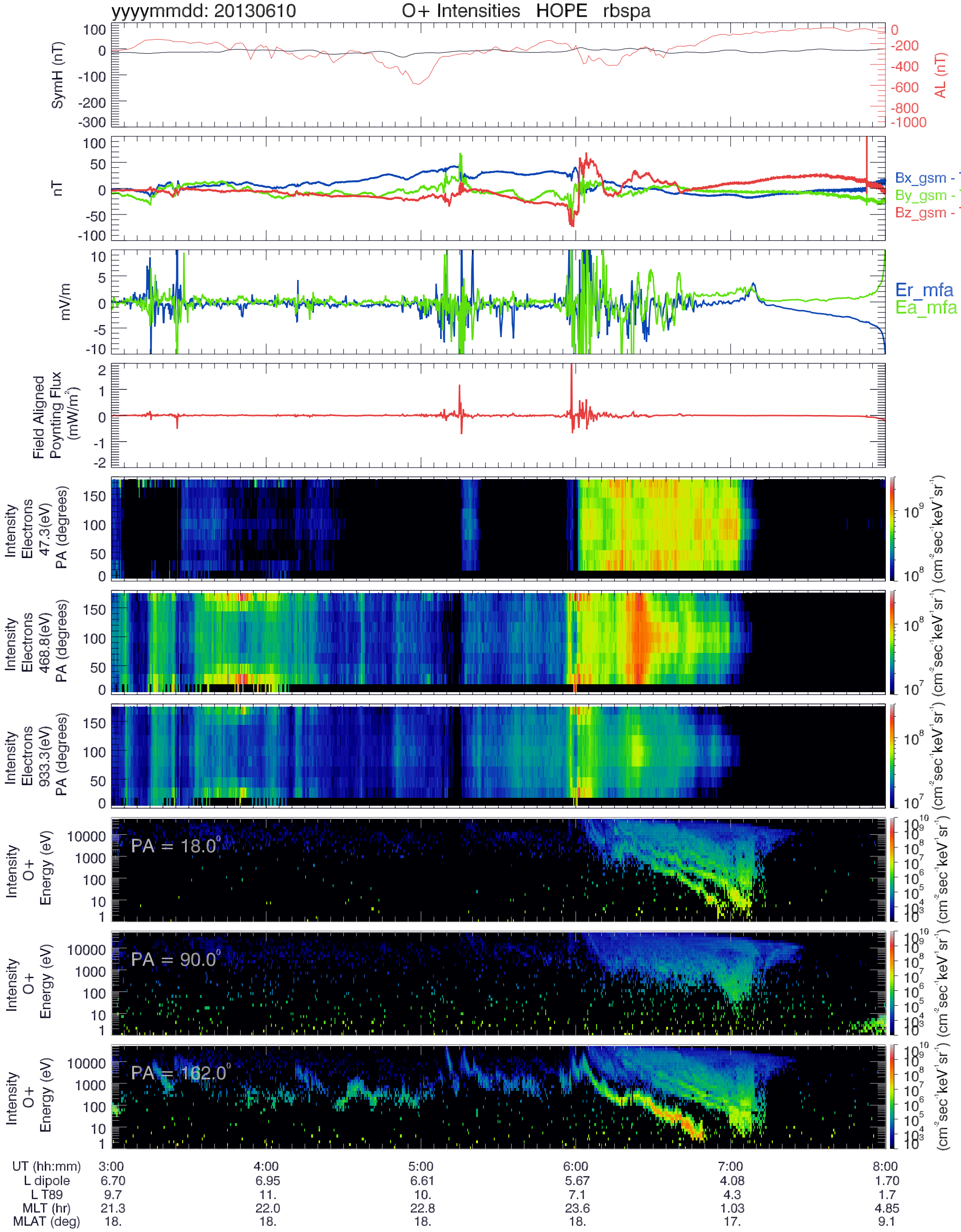
Chaston et al., [2015]: Geomagnetic storm time measurements of large-amplitude broadband low-frequency electromagnetic waves that coincide with field-aligned heated electron distributions and energetic outflowing/bouncing or trapped ionospheric ions.



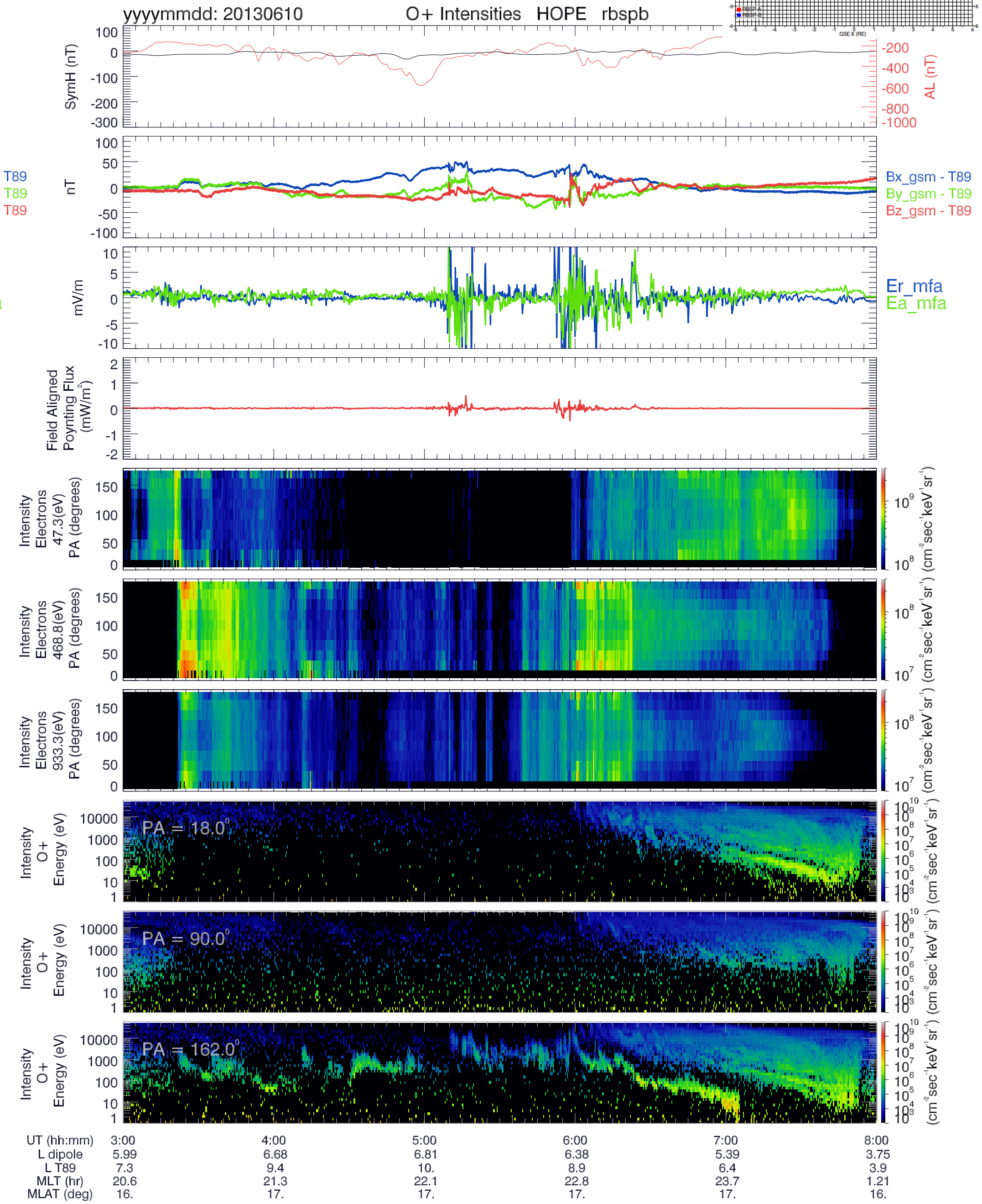
Non- Storm Event: June 10 2013



VAP - A



VAP - B



Supporters Of The Ionospheric Source: Motion Along Field Line + Convective Transport

Hirahara et al., [1997]: Akebono

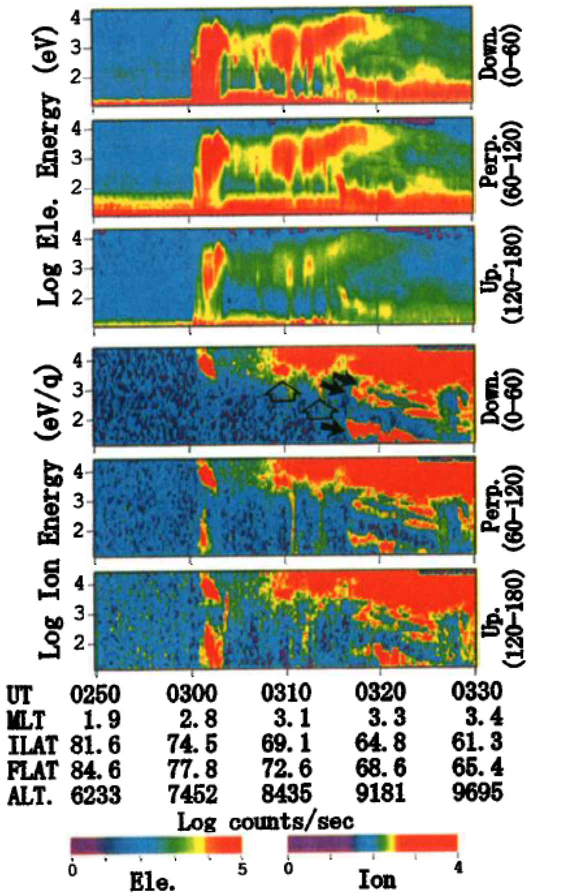


Plate 1. Energy-time (E-t) diagrams of electrons and ions observed by Akebono during event 1 on December 21, 1989. The top three panels are spectra for electrons; the bottom three panels are spectra for ions. The pitch angle distributions are divided into three ranges (0°-60°, downward; 60°-120°, perpendicular; 120°-180°, upward). The observation time (UT, in hours and minutes) and orbital information: magnetic local time (MLT, in hours), invariant latitude (ILAT, in degrees), foot point latitude (FLAT, in degrees), and altitude (ALT, in kilometers), are shown at the bottom. The ordinates are electron and ion energies (eV) on a logarithmic scale. The multiple energy-dispersed ion signatures are indicated by three solid arrows in the E-t diagram for the downward ion flux. Two open arrows indicate faint downward components consisting of H^+.

Frahm et al., [1986]: DE-1

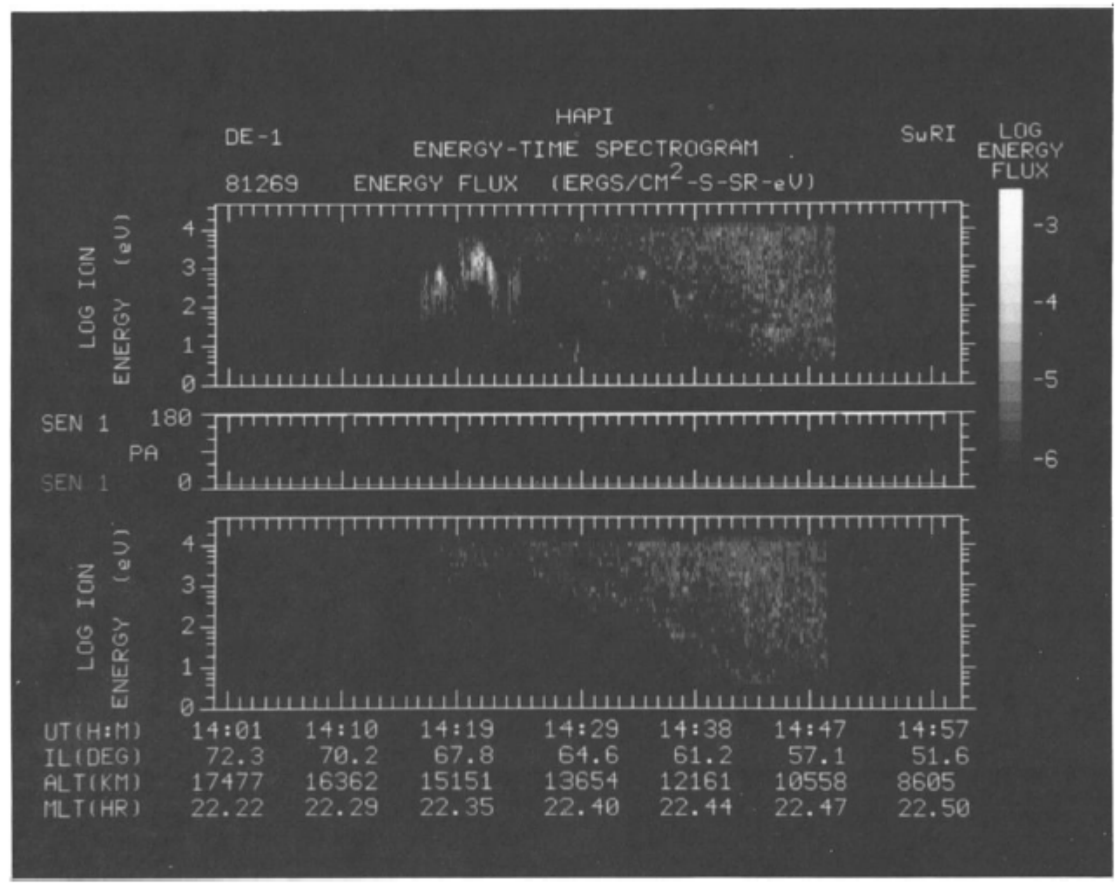


Fig. 1. HAPI banded ion spectrogram. Universal time (UT) is plotted on the horizontal axis. On the vertical axis of the upper and lower panel is plotted the log of the particle energy (in eV). Energy flux (ergs/cm²-s-sr-eV) is shaded using the scale at the upper right. Plotted on the center panel is the pitch angle (PA). This HAPI plot is a collection of energy sweeps near 180° PA for the ions from sensor 1 on the upper panel and sweeps near 0° for the ions from sensor 1 on the lower panel. After each time interval, the time (UT), invariant latitude (IL), altitude (ALT), and magnetic local time (MLT) are given. A distinct band can be seen in the ions of 0° PA beginning at 14:29 UT (≈1000 eV) to 14:41 UT (≈8 eV). This is an example of a main storm phase, night side, northern hemisphere, HAPI band. Under the convective dispersion hypothesis, the up-going ions (180° PA) from 14:16 UT to 14:24 UT would be possible sources for bands that would form in the opposite (southern) hemisphere. This pass occurred on day 81269.

Supporters Of Equatorial Acceleration

Quinn and Southwood, [1982]: ATS 6

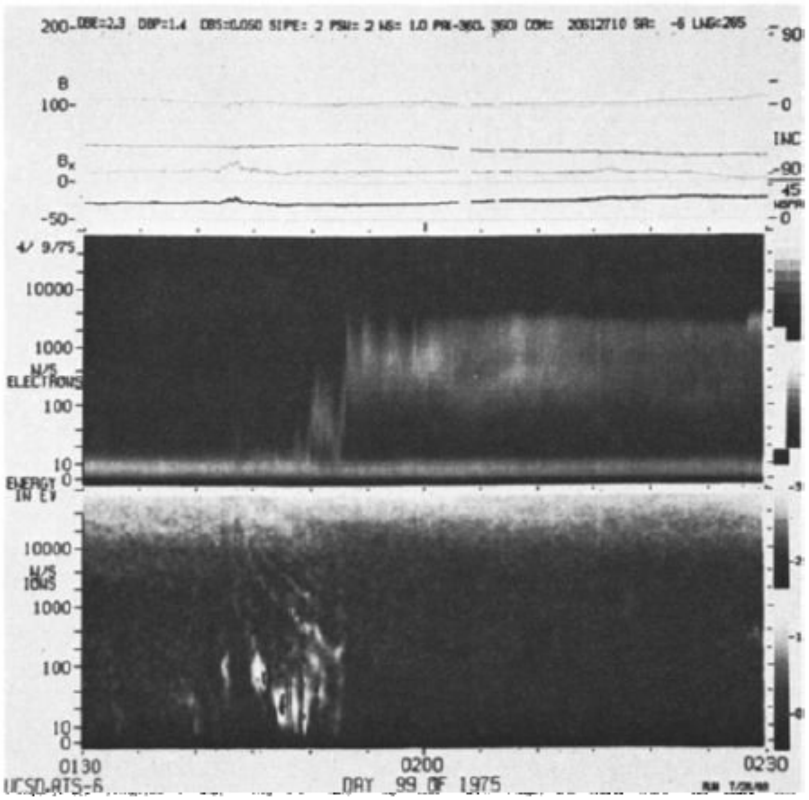


Fig. 1. Spectrogram showing 1 hour of data from the UCSD Auroral Particles Experiment on ATS 6. Ions from the dispersing cluster are visible as striations in the ion portion of the spectrogram from 1:44 to 1:53. The velocity dispersion is evident in each striation as the higher-energy ions (20 keV) arrive at the spacecraft first, followed by lower energies at later times.

Boehm et al., [1999]: FAST, Akebono, DMSP

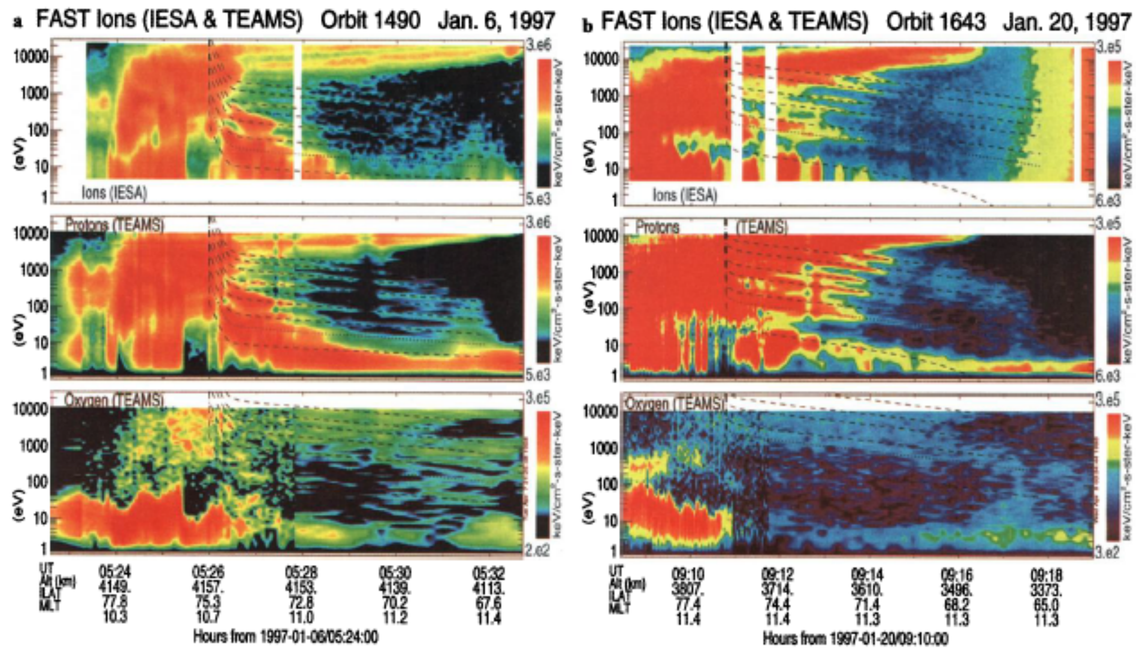


Plate 2. Two FAST multienergy ion events; (top) IESA-measured ion differential energy flux averaged over the spin plane (equal weighting over a plane containing all pitch angles). The superimposed dashed lines show the expected proton "dispersion", largely due to field line length variations, assuming simultaneous acceleration near the equator for all invariant latitudes at 0527:30 and 0846:30 UT for (a) orbit 1490 and (b) orbit 1643, respectively. The next two panels show the TEAMS spectrograms (all angles, equally weighted over the full sphere) for H^+ and O^+. A small oxygen flux is marginally visible at energies roughly equal to 16 times the proton energies. The time resolution of TEAMS is 20 s after 0528 UT in Plate 2a and 10 s after 0912 UT in Plate 2b. The data have been smoothed; counting statistics produce most of the small-scale variations in the oxygen.