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# Magnetosphere - Ionosphere Coupling Below 3000 km: Conversion of Upwelling Ions to Escaping Ions
# or
# If O+ is important in the magnetosphere, how does it get out of the ionosphere?


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with the help of
R. Arnoldy, K. Lynch, K. Frederick-Frost, E. Klatt, J-E. Wahlund, J. Moen, A. Strømme, Y. Ogawa, K. Oksavik, W. Swartz + many others

# But first
# an unashamed advertisement

- Chapman Conference on Midlatitude Ionospheric Dynamics and Disturbances
- January 3-6, 2007
- Yosemite, California
- http://www.agu.org/meetings/cc07acall.html
- Abstract deadline- September 15, 2006

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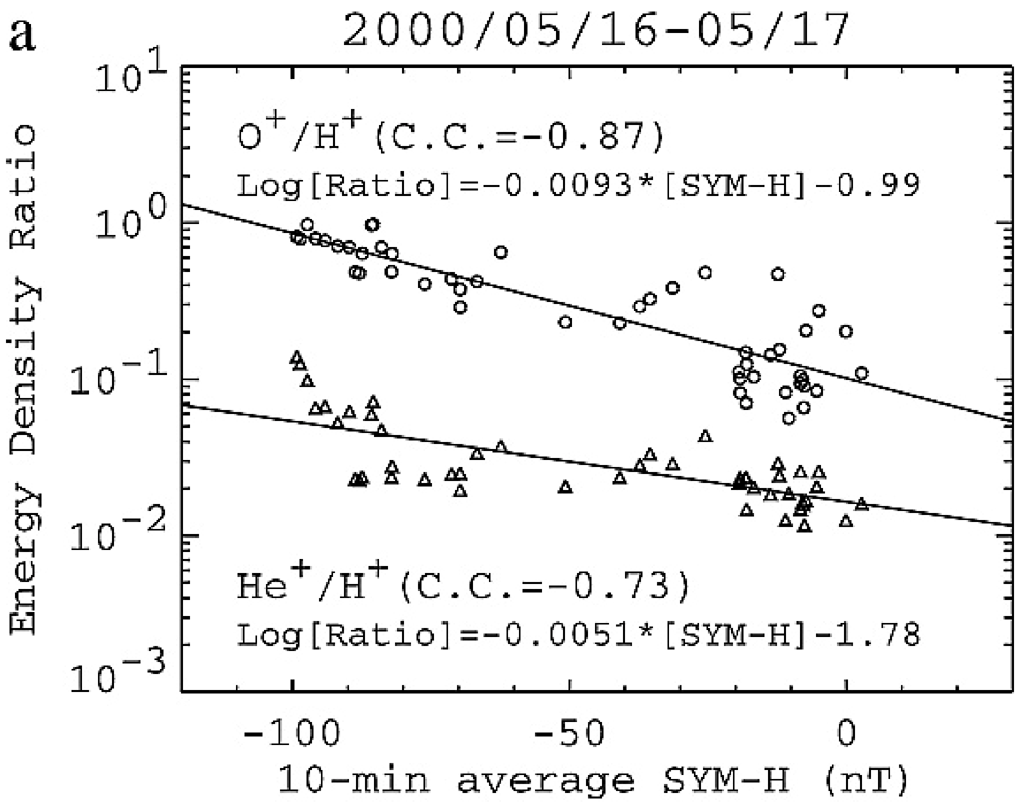
# Outline

- Motivation for investigating ionosphere-magnetosphere mass coupling
- Mechanisms of O+ escape from the ionosphere to the magnetosphere
- Radar viewpoint (up to roughly 800 km altitude)
- LEO Satellite viewpoint (near 850 km altitude)
- Sounding rocket viewpoint (up to 1400 km altitude)
- Modeling viewpoint
- The next step- SCIFER 2

# Motivation
# $O^+$ in the Plasma Sheet

Nosé, M., R. W. McEntire, and S. P. Christon (2003), Change of the plasma sheet ion composition during magnetic storm development observed by the Geotail spacecraft, *J. Geophys. Res.*, *108*(A5), 1201, doi:10.1029/2002JA009660.



# Motivation
# $O^+$ in the Ring Current

Daglis, I. A., R. M. Thorne, W. Baumjohann, and S. Orsini (1999), The terrestrial ring current: Origin, formation, and decay, *Rev. Geophys.*, *37*(4), 407–438.

**TABLE 1. Sources of Ring Current Ions, According to Composition Measurements by the AMPTE and CRRES Missions: Contribution of Main Ion Species to Total Ion Energy Density at $L \approx 5$**

| *Ion Source and Species* | *Quiet Time* | *Small–Medium Storms* | *Intense Storms* |
|---|---|---|---|
| Total energy density, keV $cm^{-3}$ | ~10 | ≥50 | ≥100 |
| Solar wind $H^+$, % | ≥60 | ~50 | ≤20 |
| Ionospheric $H^+$, % | ≥30 | ~20 | ≤10 |
| Ionospheric $O^+$, % | ≤5 | ~30 | ≥60 |
| Solar wind $He^{++}$, % | ~2 | ≤5 | ≥10 |
| Solar wind $He^+$, % | <1 | <1 | <1 |
| Ionospheric $He^+$, % | <1 | <1 | <1 |
| Solar wind, total, % | ~65 | ~50 | ~30 |
| Ionosphere, total, % | ~35 | ~50 | ~70 |

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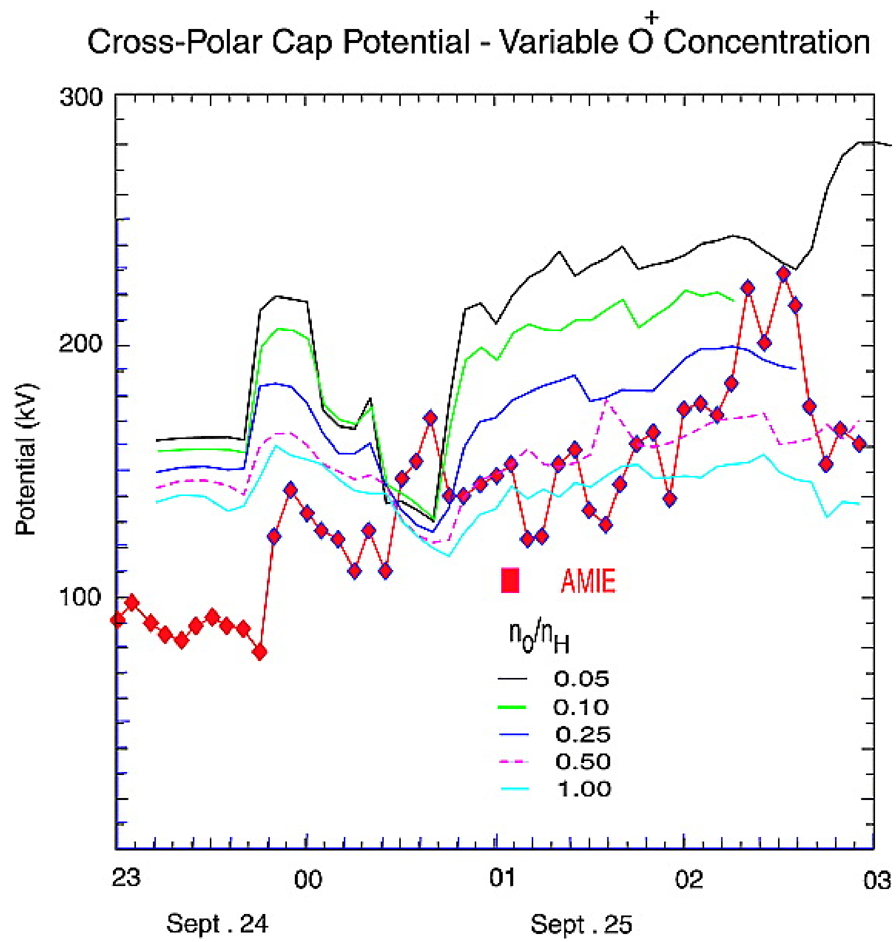
# Motivation
# O+ Effect on Polar Cap Potential

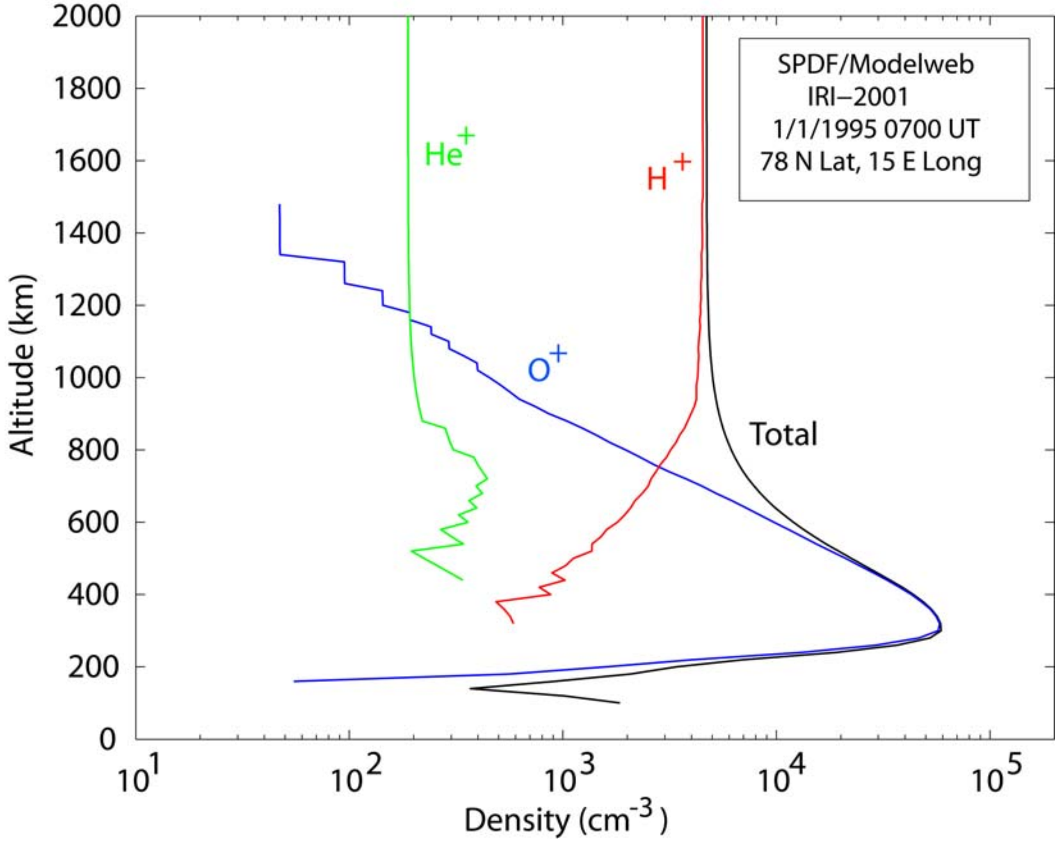
Winglee, R. M., D. Chua, M. Brittnacher, G. K. Parks, and G. Lu, Global impact of ionospheric outflows on the dynamics of the magnetosphere and cross-polar cap potential, *J. Geophys. Res.*, *107*(A9), 1237, doi:10.1029/2001JA000214, 2002



# Mechanisms of $O^+$ Escape

- IRI-2001 Ionosphere for pre-noon cleft in darkness over EISCAT, Svalbard at solar minimum
- $O^+$ is mostly below 1000 km
- Ti≈1500 °K
- Te≈3000 °K

MODEL



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# Mechanisms of $O^+$ Escape

## Gravitational Binding Energy

Set KE=PE

$$\frac{1}{2}mv^2 = \frac{GMm}{r}$$

$$r = (6371 + 1000)\cdot 10^5 \text{ cm}$$

$$G = 6.7\cdot 10^{-8} \text{ dyne}\cdot\text{cm}^2/\text{g}^2$$

$$M = 6\cdot 10^{27} \text{ g}$$

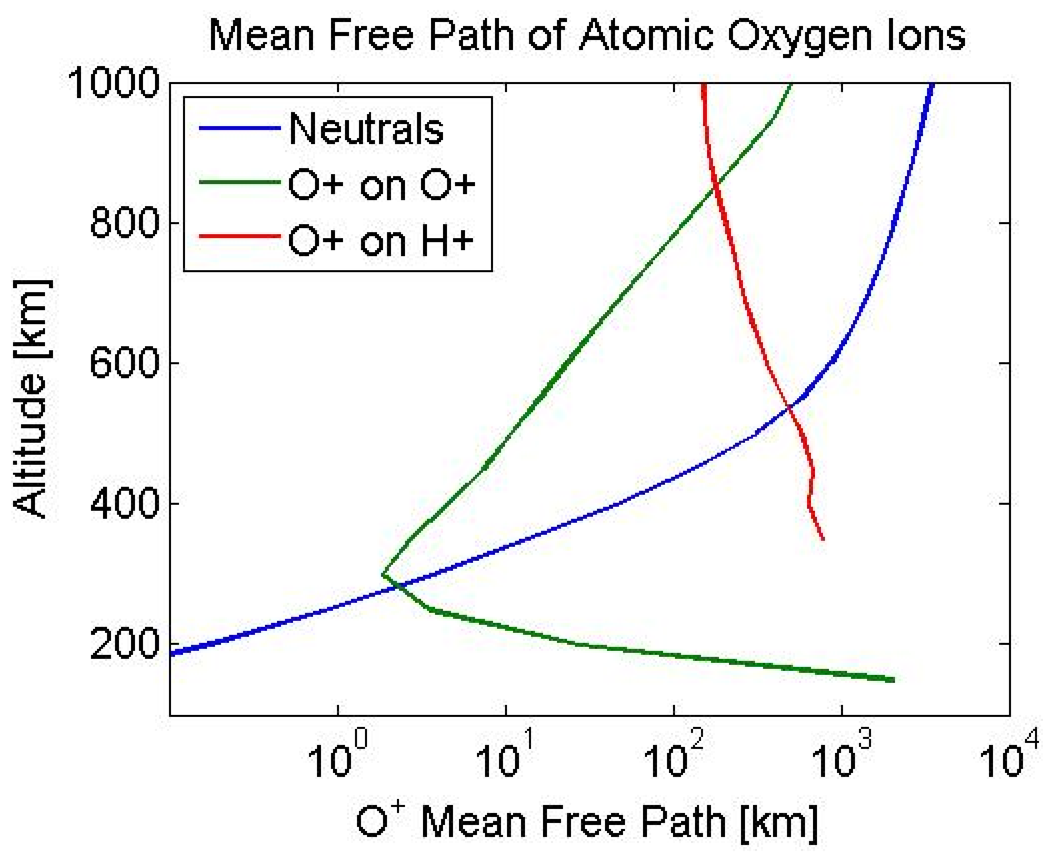
Escape Velocity $v = 10.4\cdot 10^5 \text{ cm/s}$

Energy for $O^+$

$$\frac{1}{2}mv^2 = 13.9\cdot 10^{-12} \text{ ergs} = 8.7 \text{ eV} = 101\cdot 10^3 \ {}^{\text{o}}\text{K}$$

# Mechanisms of $O^+$ Escape
# Mean Free Path

- At 500 km $O^+$ decouples from neutrals
- At 900-1000 km $O^+$ decouples from $O^+$
- $O^+$ never decouples from $H^+$ unless $H^+$ density less than IRI model



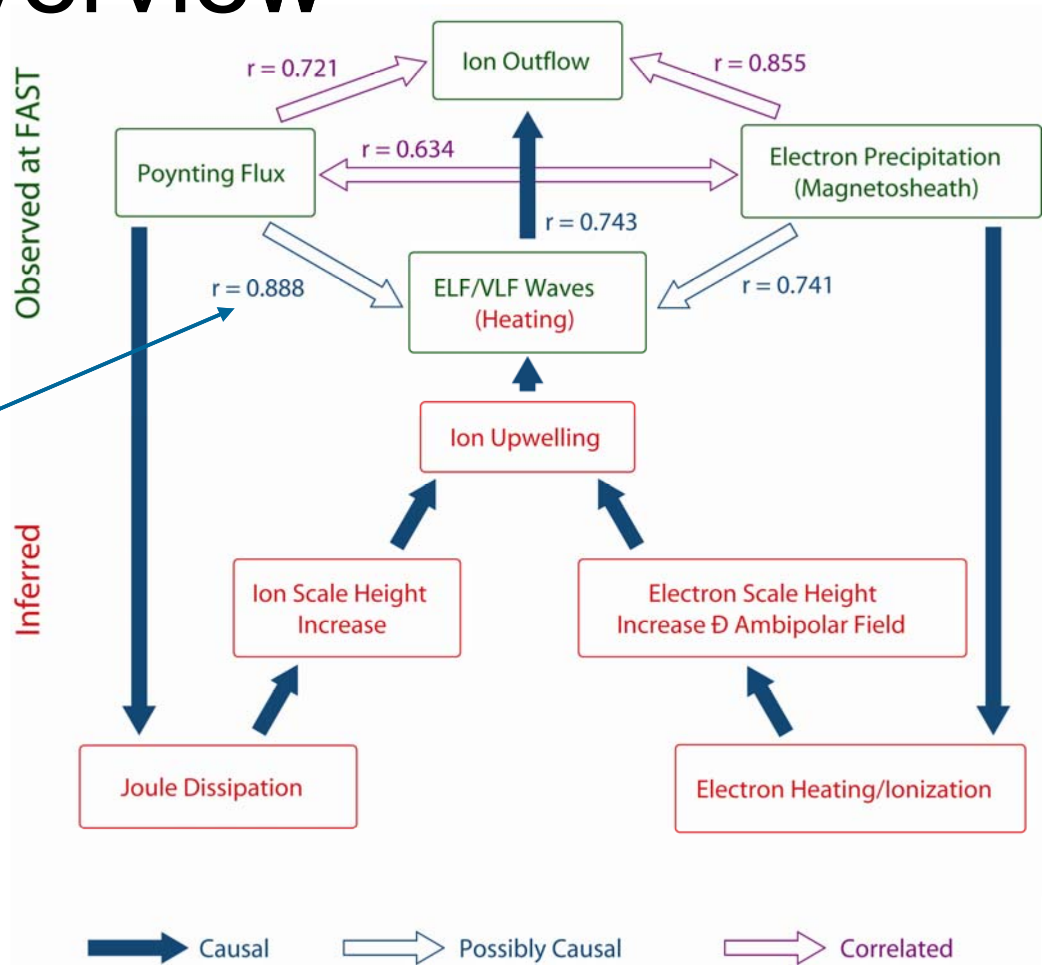
# Mechanisms of $O^+$ Escape
## Summary

- Frictional heating in strong horizontal flows producing either elevated Ti or toroidal phase space distributions ($T_\perp > T_\parallel$)
  - Called Type 1 by Wahlund et al. [1992]
- Soft precipitating electrons heat ionospheric electron gas which expands pulling ions along through ambipolar field.
  - Called Type 2 by Wahlund et al. [1992]
- Transverse ion acceleration/heating by BBELF waves
  - Waves are presumed to be a combination of electrostatic ion cyclotron waves and ion acoustic waves driven by FAC

# Mechanisms of $O^+$ Escape Overview

- Where is transition between ion upwelling and wave heating? What are their relative roles?
- How do FAC (via Poynting flux) fit into this picture?

After Strangeway et al. [2005]



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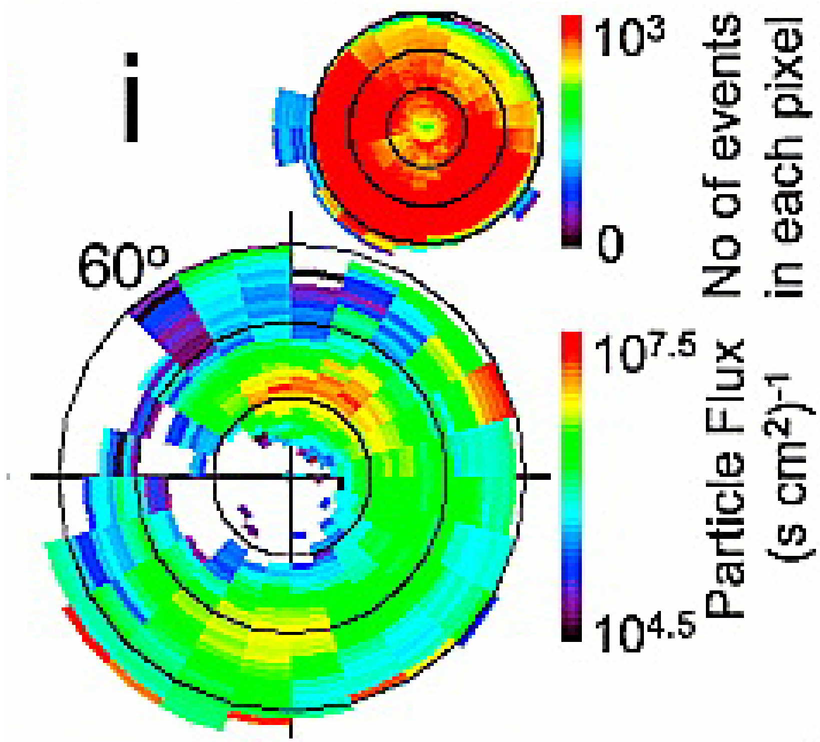
# Where Does One Go to Investigate Ion Outflows?

- FAST measurements of ion outflows
- Andersson et al, 2006
- 3200-4400 km alt.
- Ion outflow flux from all measurements



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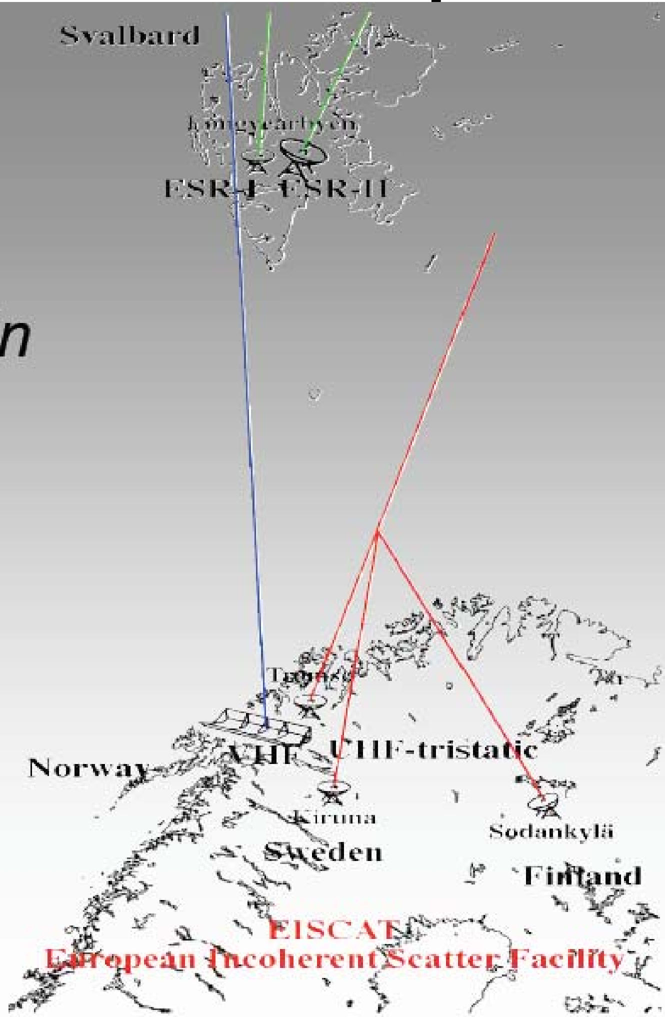
# Radar Viewpoint

- EISCAT radar and EISCAT Svalbard Radar (ESR)
- EISCAT is tristatic UHF and single VHF
- ESR has a fixed antenna along B and a steerable antenna
- Information is created by modeling echo return
  - Doppler shift yields ion drift velocity
  - Spectral shape yields Ti, Te/Ti, <Mi>, $\nu_{in}$
  - Amplitude yields density
  - Also possible to have non-thermal or enhanced echoes which are coherent scattering from plasma waves
  - Time delay yields range
  - No echoes when wavelength exceeds Debye length

# Radar Viewpoint

*Current EISCAT installations in Northern Scandinavia*




Graphic: Asta Pellinen Wannberg

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# Radar Viewpoint

Five parameters yield shape and amplitude of echo spectrum

- Electron density $N_e$
- Ion temperature $T_i$
- Electron/ion temperature ratio $T_e/T_i$
- Mean ion mass $m_i$
- Ion-neutral collision frequency $\nu_{in}$

LEGEND:

Red – F region (300 km)

$n_e = 3 \cdot 10^{11}$ $T_e$ = 2000 K
$O^+$ $T_i$ = 1000 K

Green – F region (300 km)

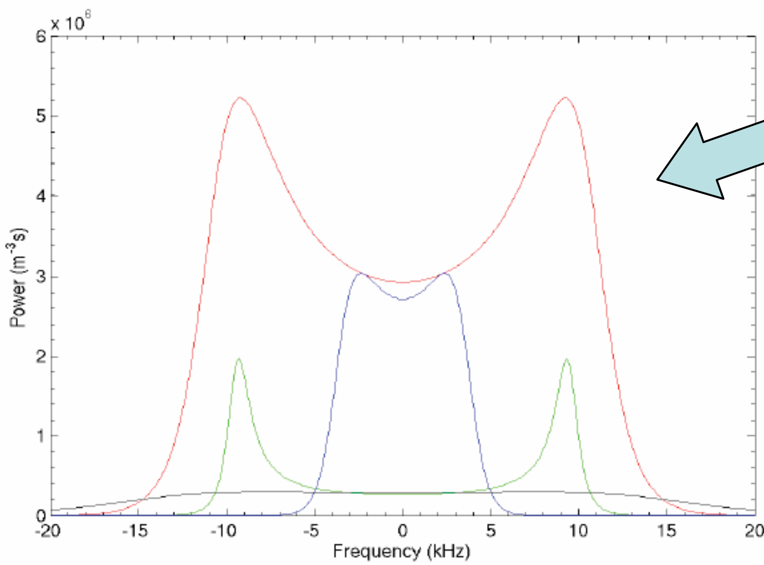
$n_e = 1 \cdot 10^{11}$ $T_e$ = 3000 K
$O^+$ $T_i$ = 500 K

Blue – E region (120 km)

$n_e = 5 \cdot 10^{10}$ $T_e$ = 300 K
$NO^+ / O_2^+$ $T_i$ = 300 K

Black – topside (1000 km)

$n_e = 5 \cdot 10^{10}$ $T_e$ = 4000 K
90% $O^+$ 10% $H^+$ $T_i$ = 3000 K




Spectra computed for the EISCAT UHF radar wavelength of 0.33 m (930 MHz).

FFT(Echo)

Additionally Doppler shift yields bulk ion drift velocity in line of sight

thanks to Gudmund Wannberg for figure

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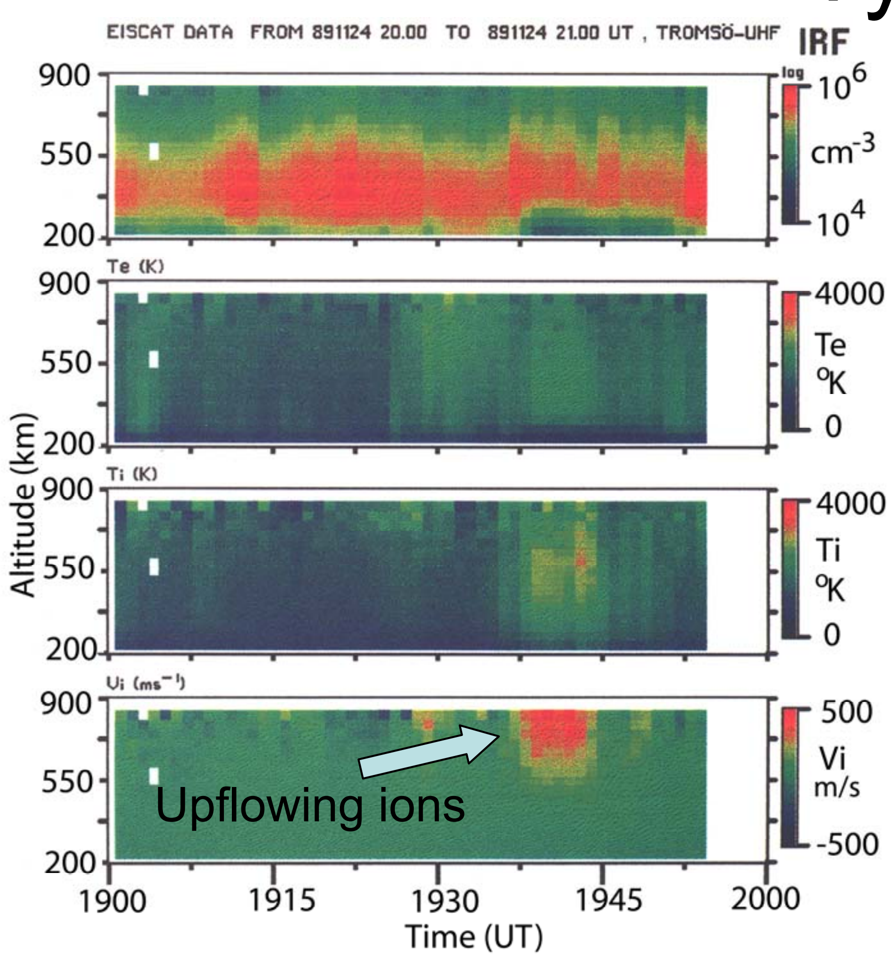
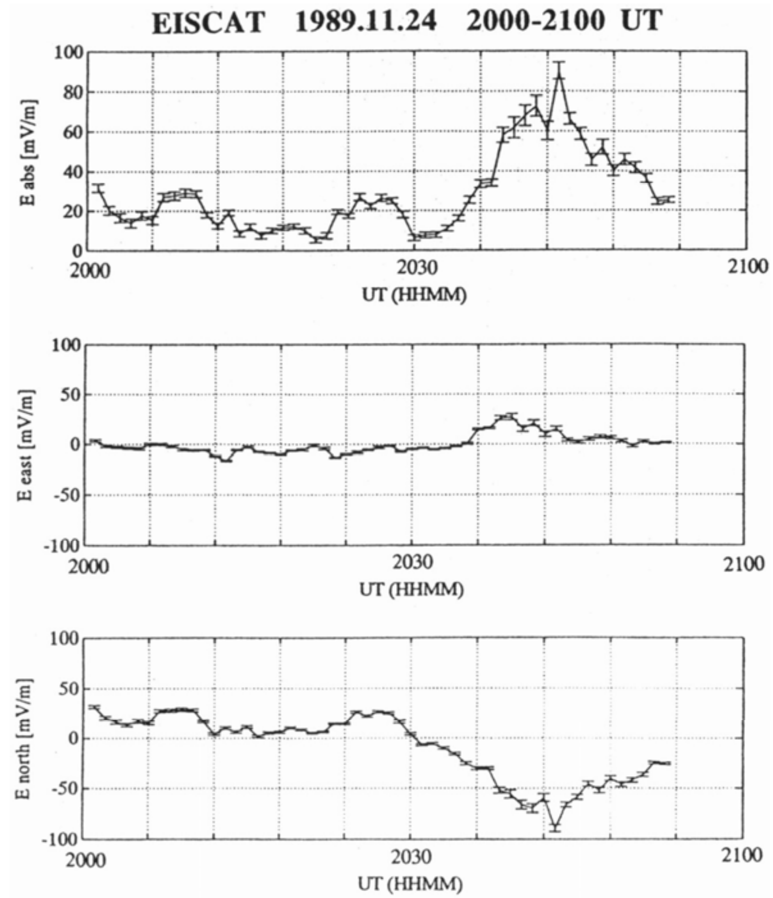
# Radar Viewpoint-UHF Tristatic
## Type 1



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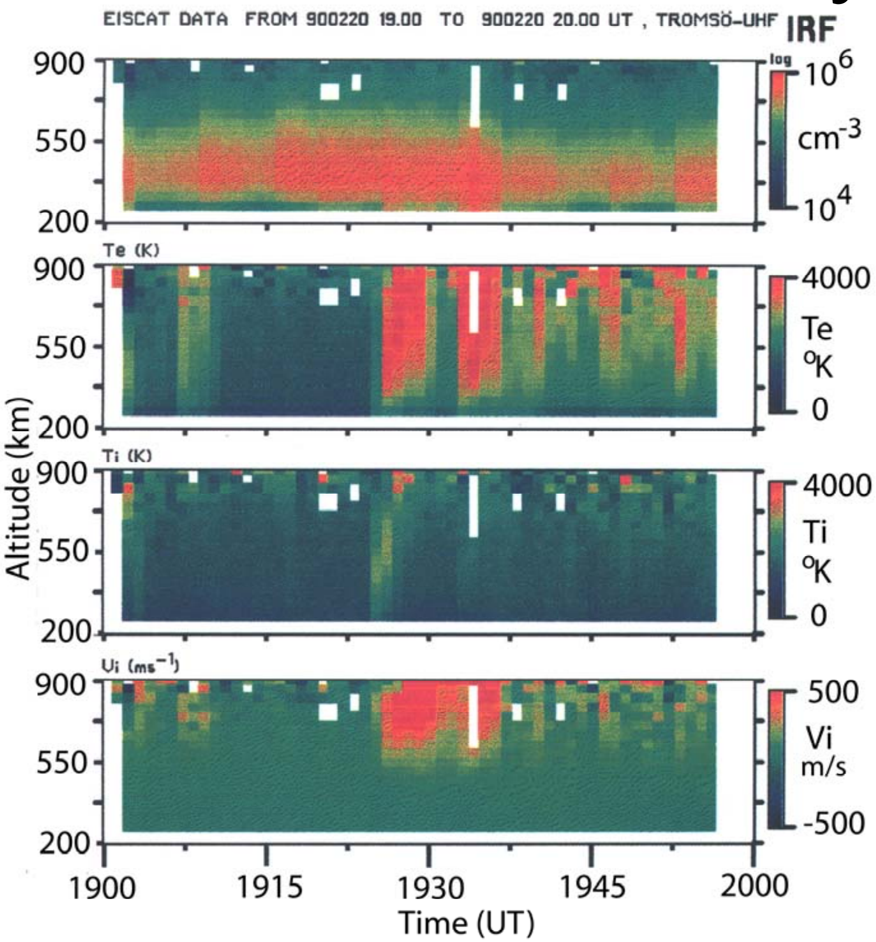
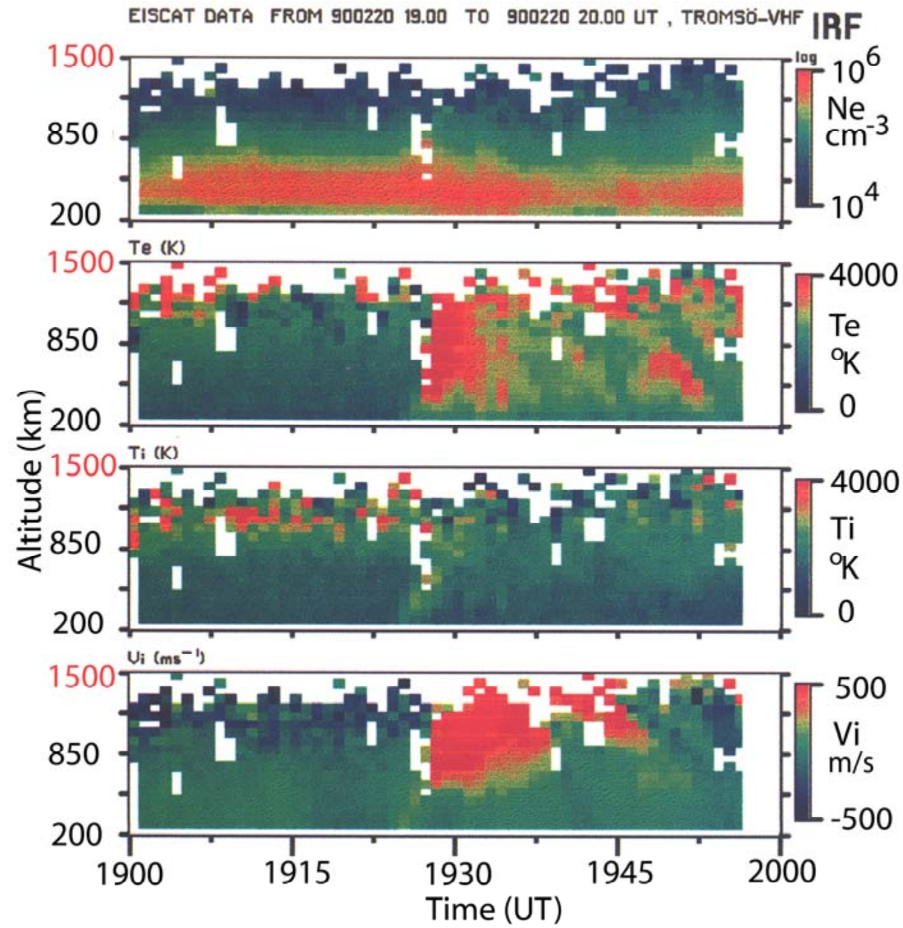
# Radar Viewpoint-UHF Tristatic & VHF Type 2

UHF




VHF (note different alt. scale)



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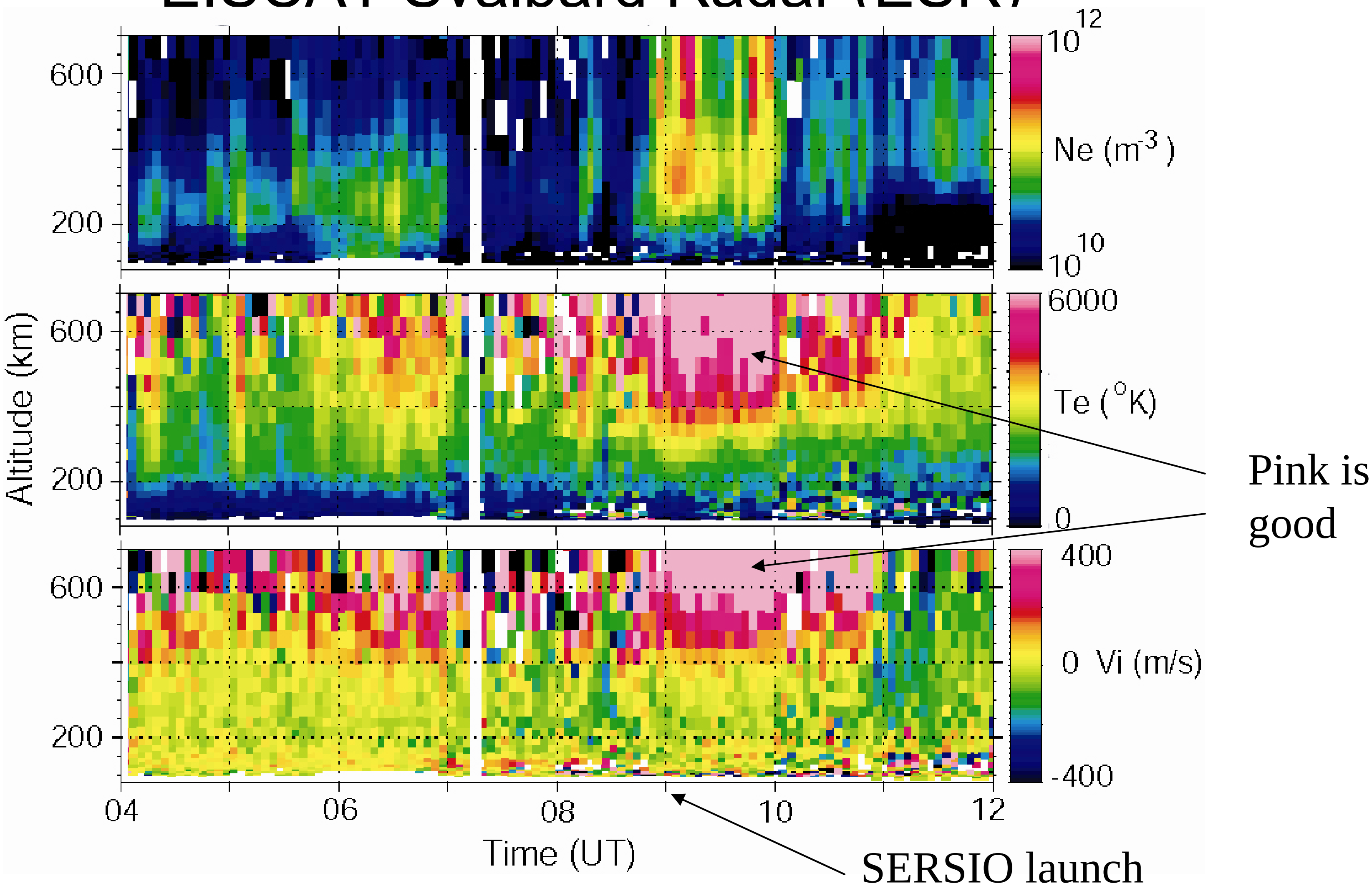
# Radar Viewpoint
# EISCAT Svalbard Radar (ESR)

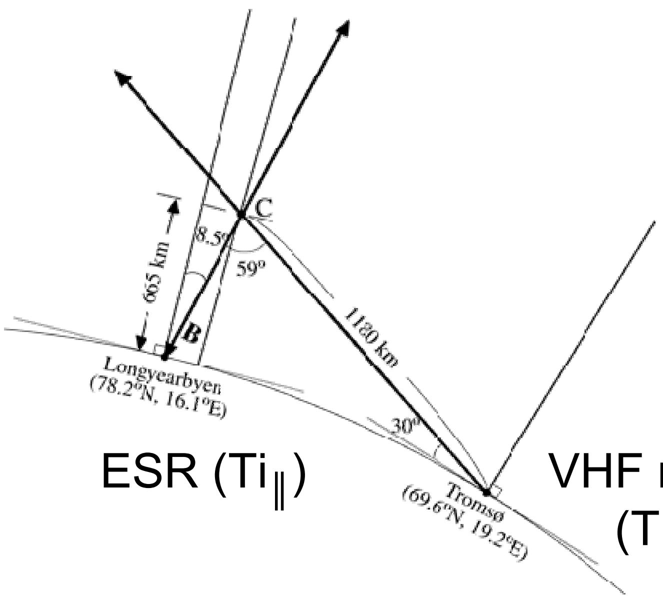


# Radar Viewpoint
# Ion Temperature Anisotropic (TIA?)

Outflow events

NEIALS

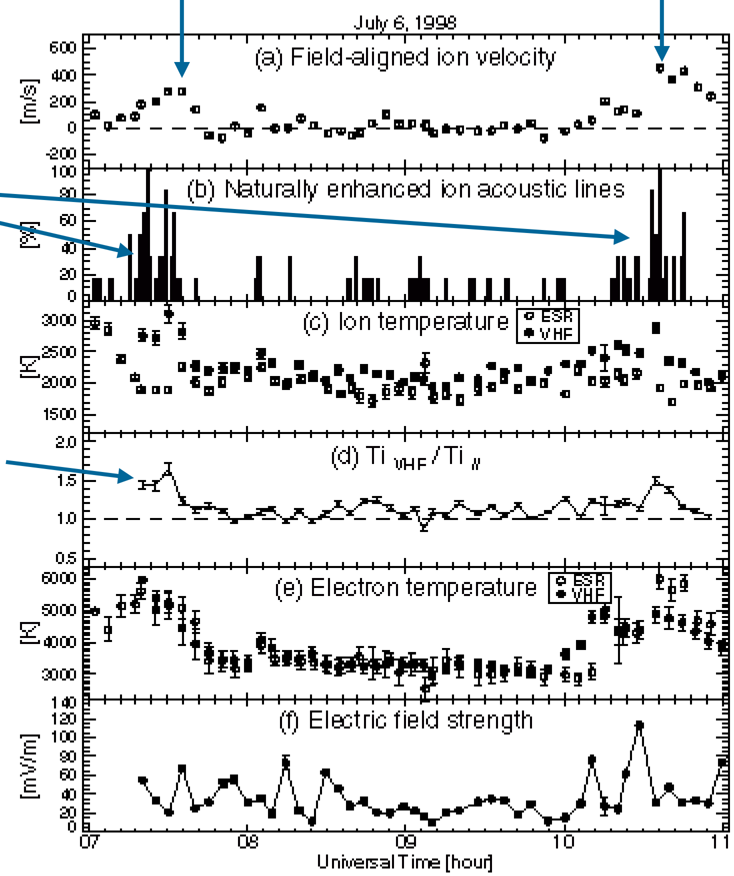
$Ti_{VHF} > Ti_{\parallel}$




ESR ($Ti_{\parallel}$)

VHF radar ($Ti_{VHF}$)

Ogawa et al., 2000



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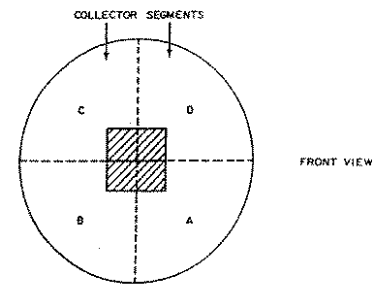
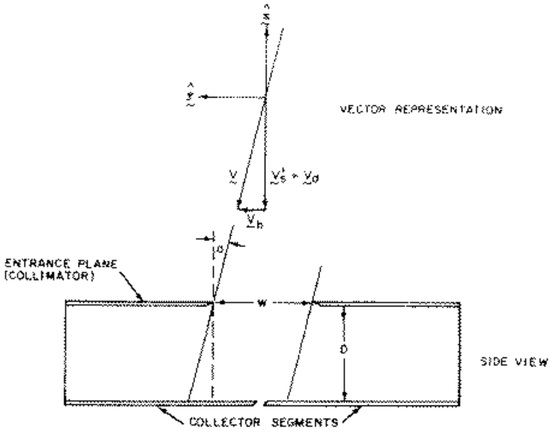
# LEO Satellite Viewpoint

- Plasma properties measured with plasma drift meter or segmented retarding potential analyzer
- Yields mean or bulk cross track drift in horizontal and vertical directions
- Drifts need to be fraction of orbital velocity (7 km/s)

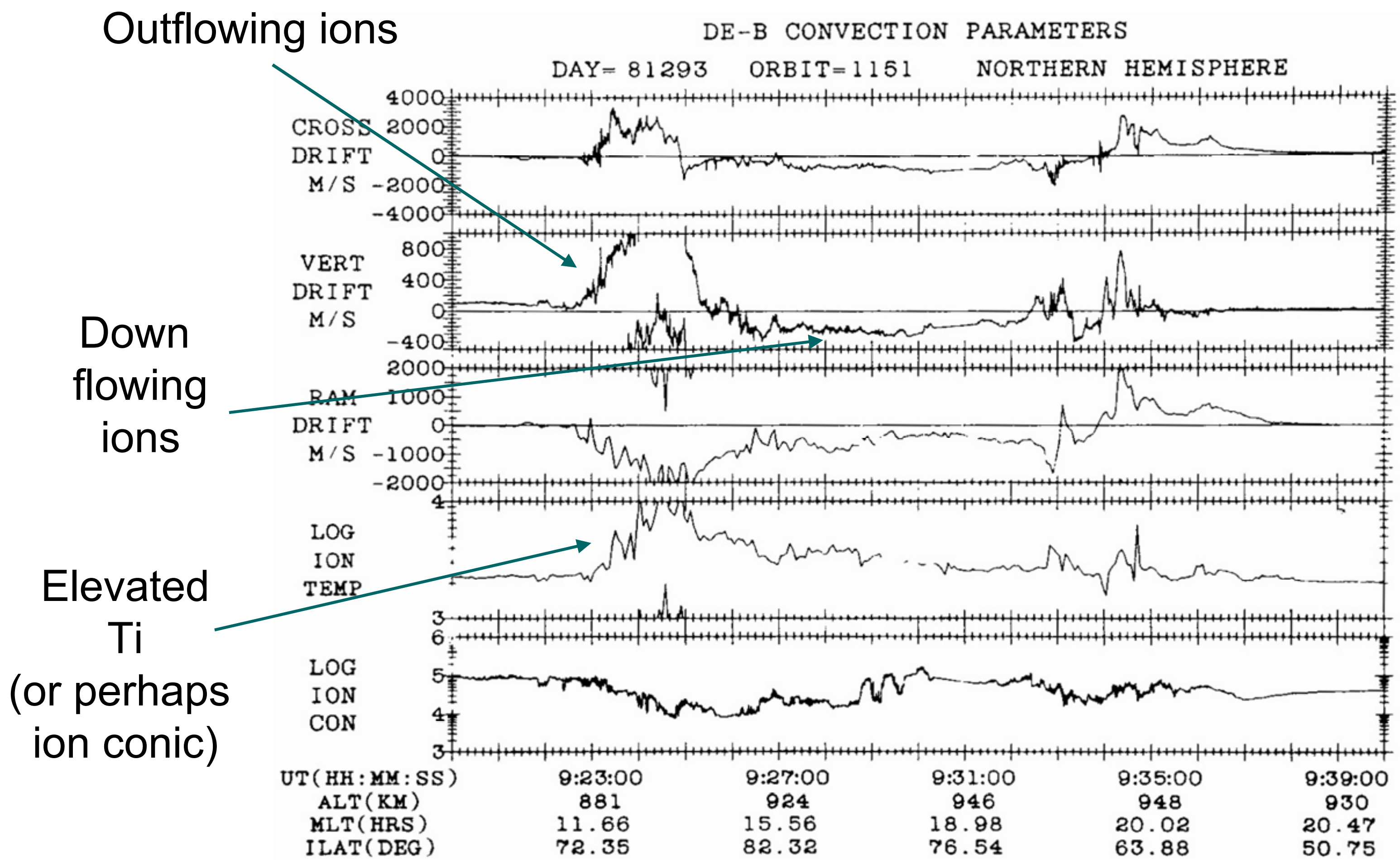



IDM COLLECTOR / APERTURE CONFIGURATION



# LEO Satellite Viewpoint

## Loranc et al. 1981



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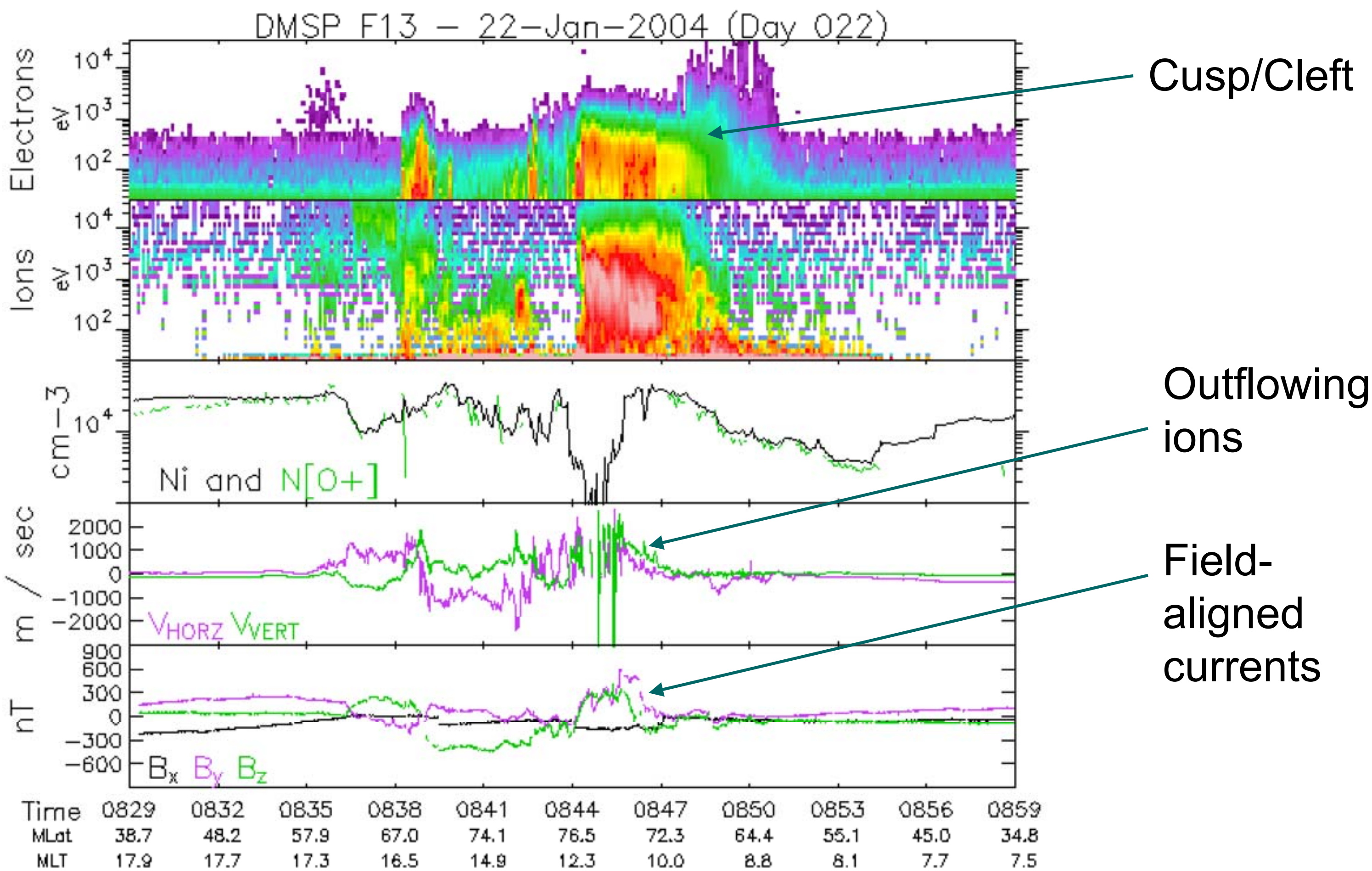
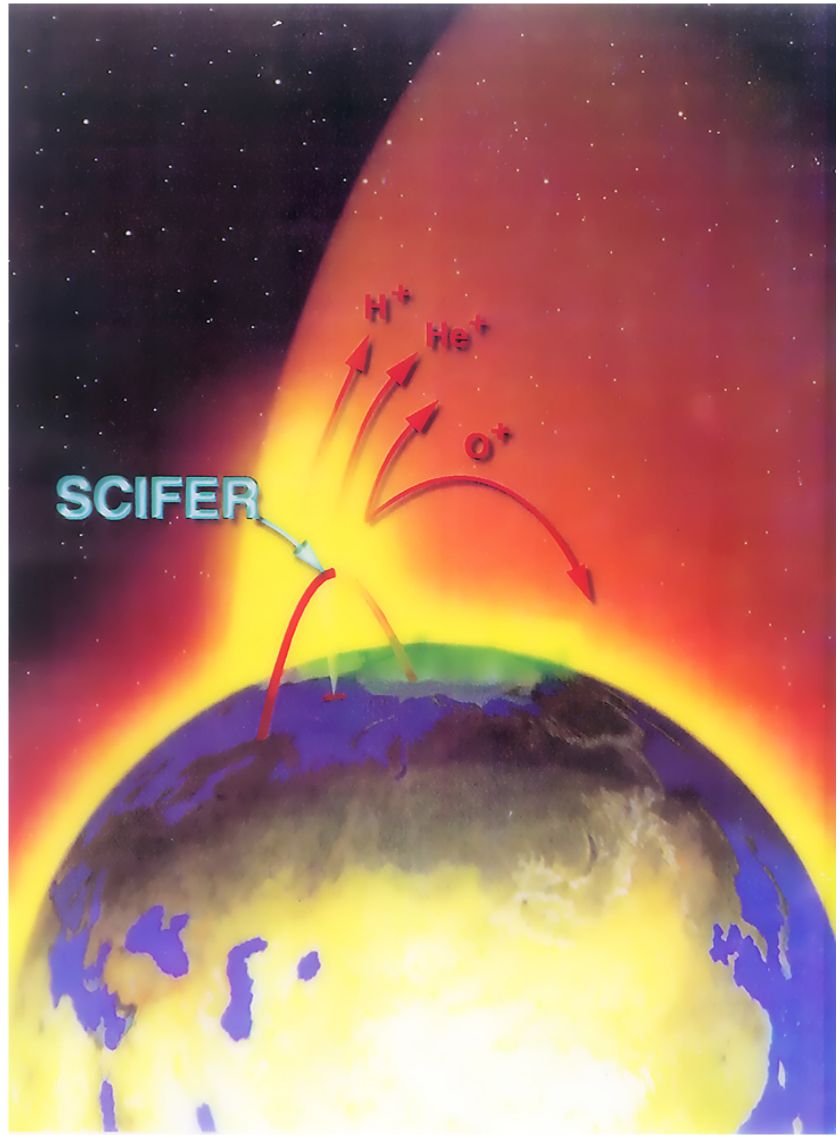
# LEO Satellite Viewpoint



# Sounding Rocket Viewpoint

Sounding of the Cleft Ion Fountain Energization Region (SCIFER)

Launched 1995 before ESR was built
Apogee 1452 km over Svalbard



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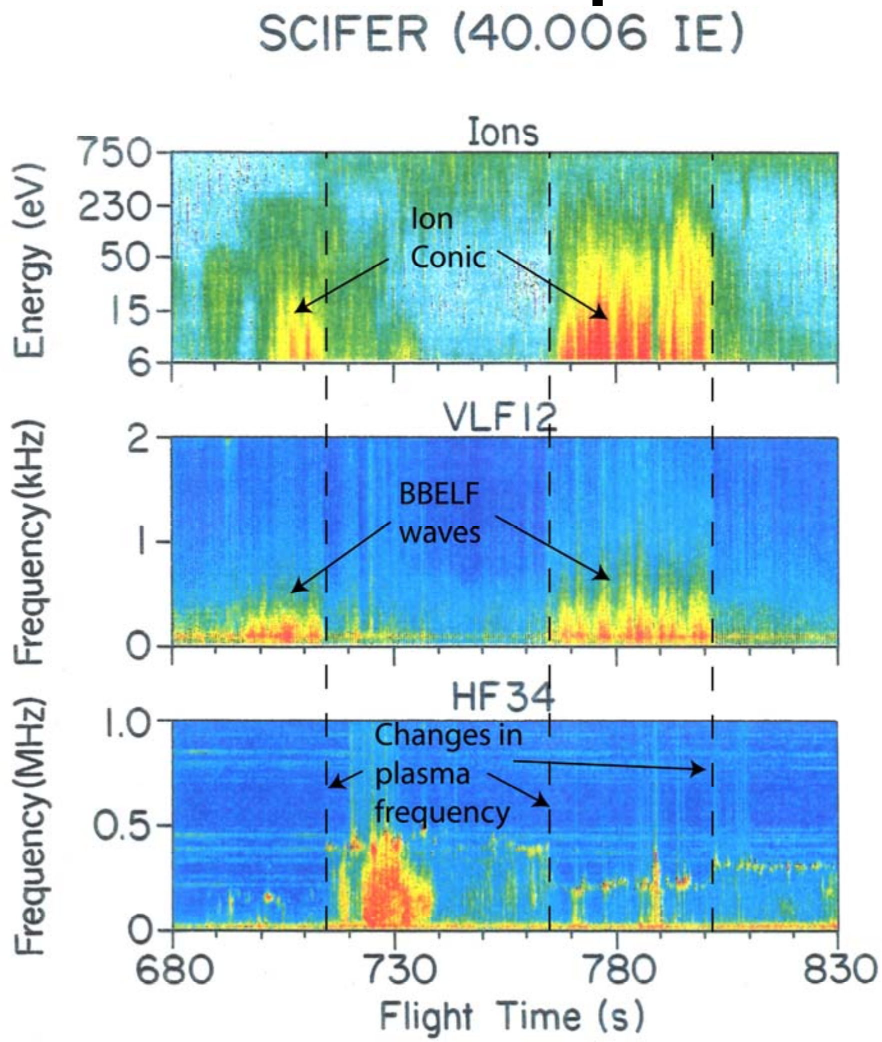
# Sounding Rocket Viewpoint

- Apogee at 700 s
- Ne tracked by plasma frequency emissions
- Strong correlation between low densities, BBELF waves, and ion conics (TIA)
- Examine boundary at 765 s next



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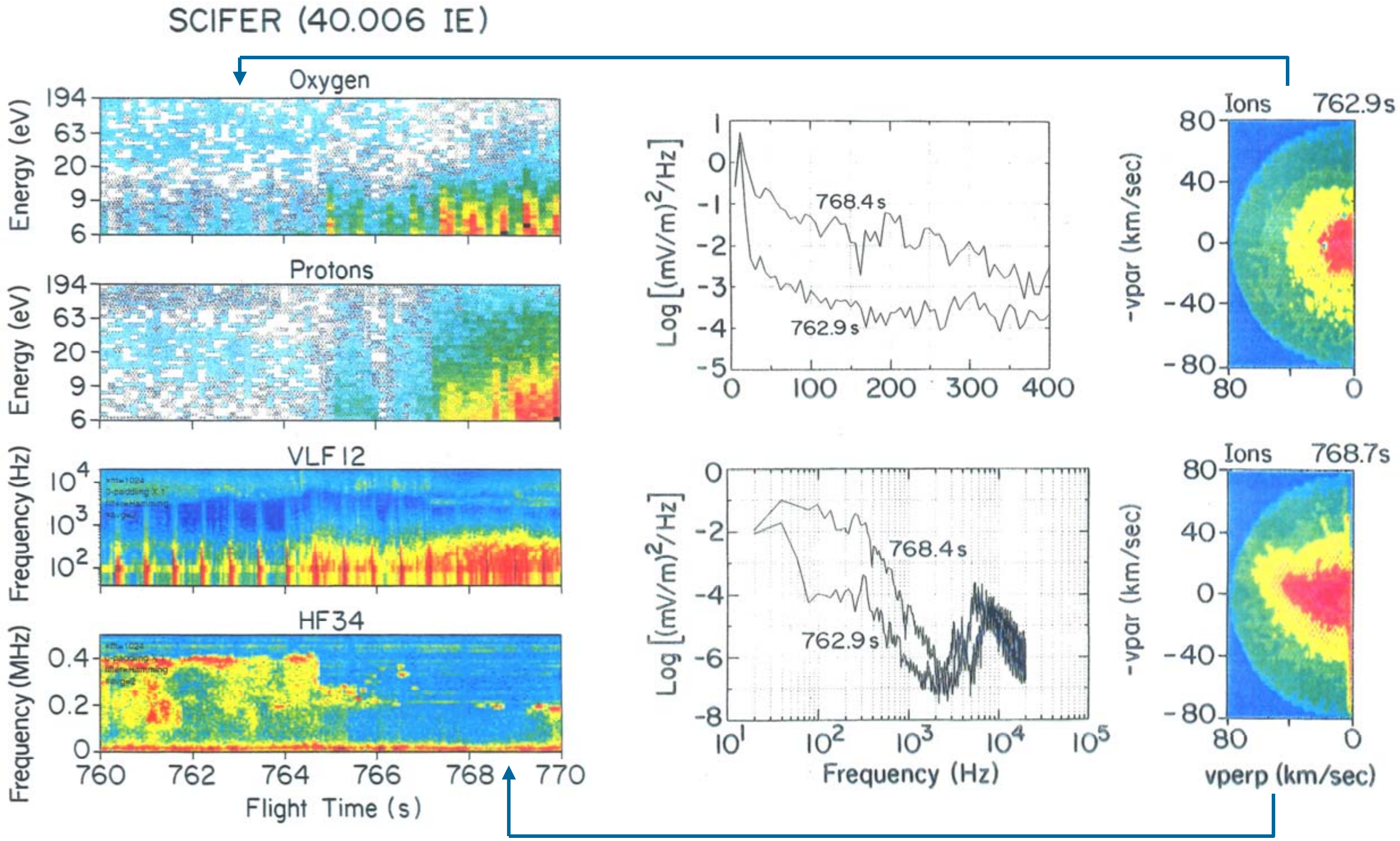
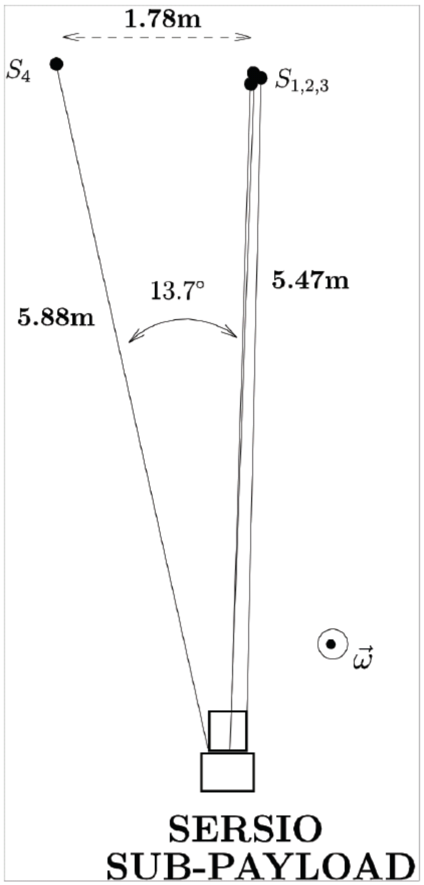
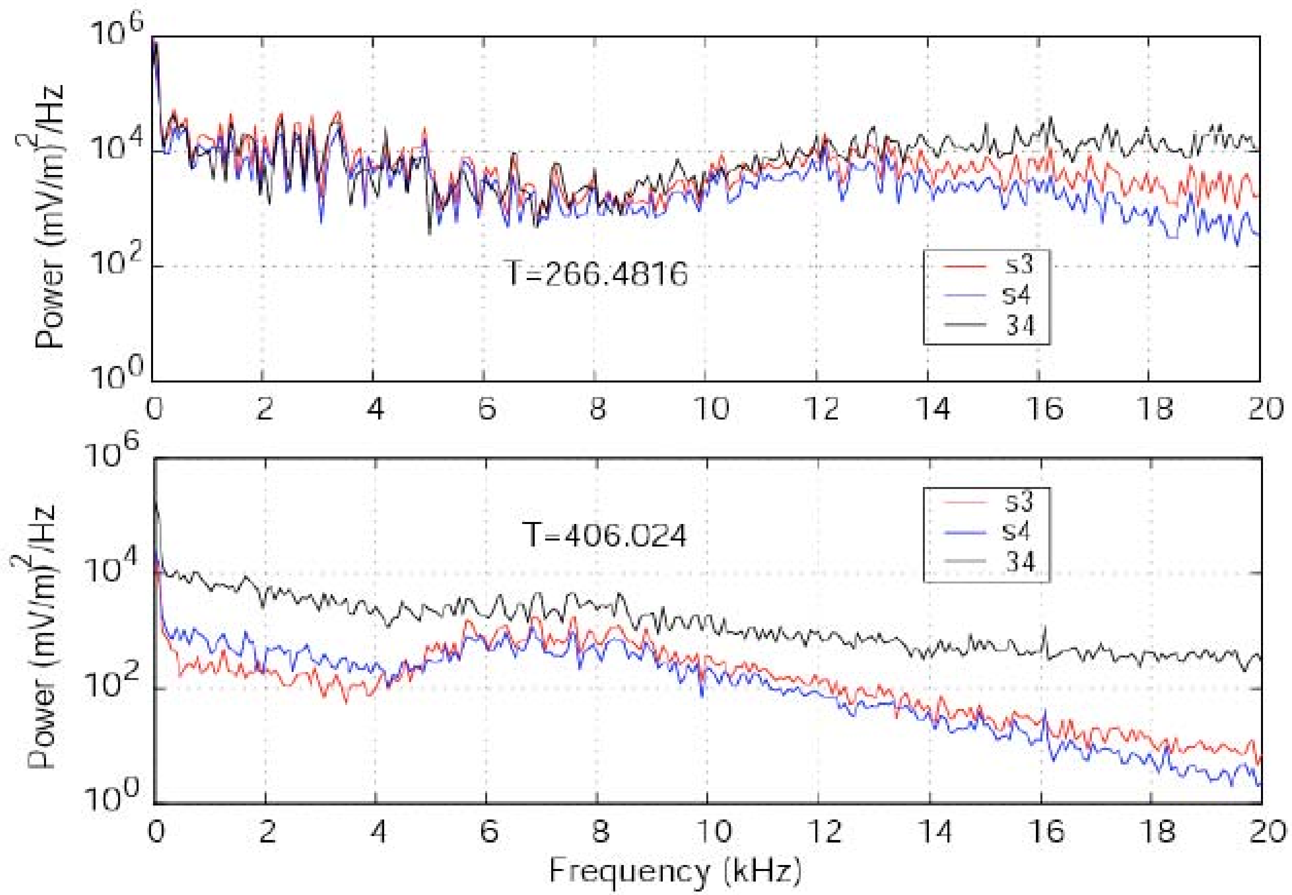
# Sounding Rocket Viewpoint



# Sounding Rocket Viewpoint BBELF Wavelength



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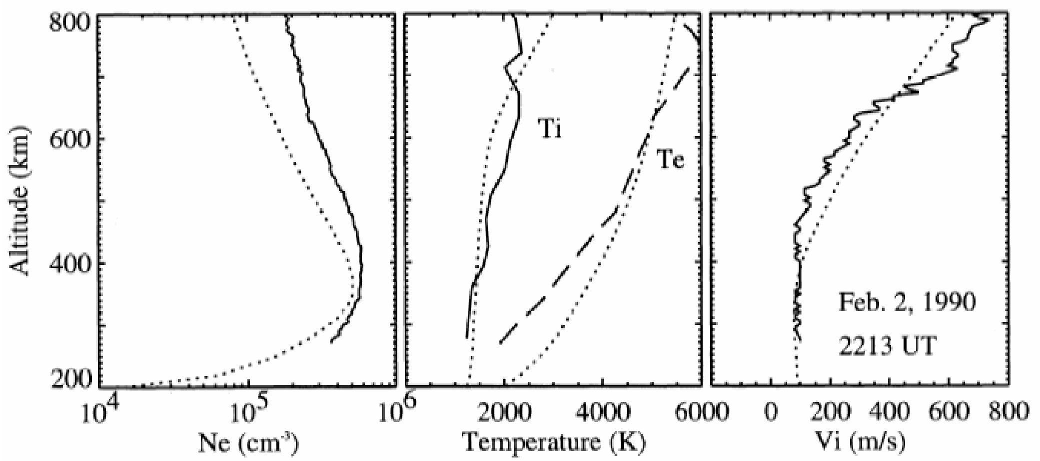
# Model Viewpoint

- Electron precipitation 1.75 ergs/cm$^2$ at <E>=300 eV
- Convection 50mV/m
- Downward heat flux $9 \times 10^9$ eV/cm$^2$-s
- Fluid model




Seo, Y., J. L. Horwitz, and R. Caton (1997), Statistical relationships between high-latitude ionospheric *F* region/topside upflows and their drivers: DE 2 observations, *J. Geophys. Res.*, *102*(A4), 7493–7500.

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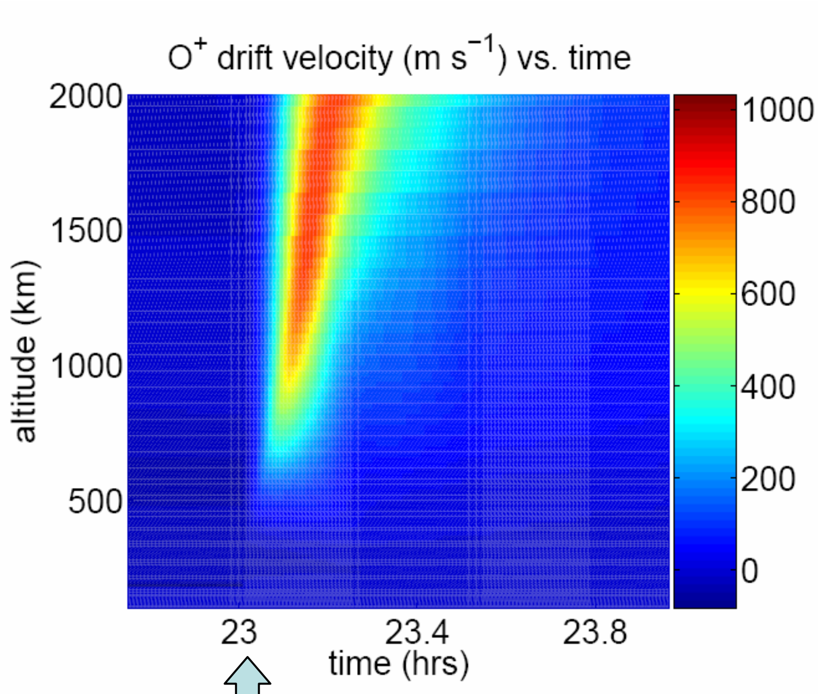
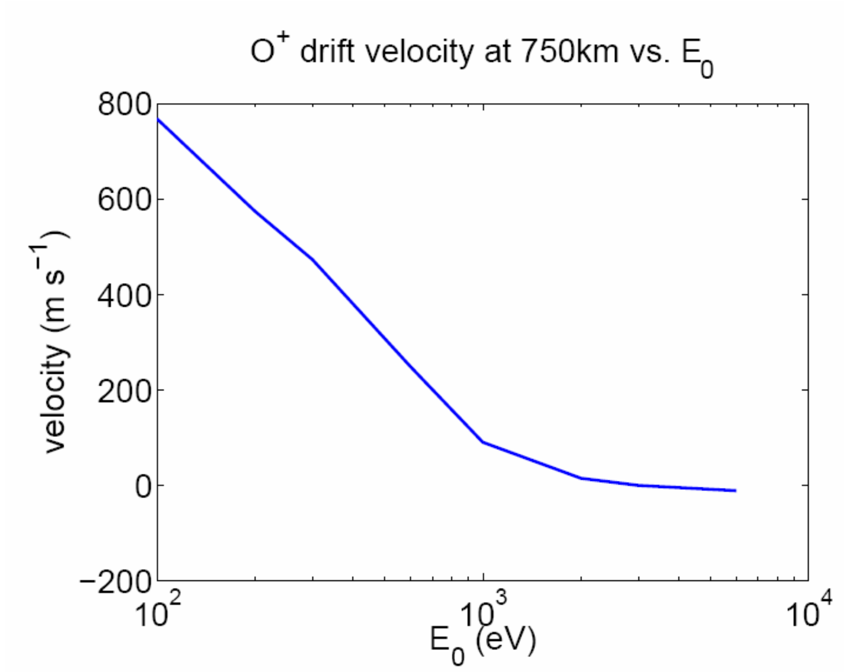
# Modeling Viewpoint

- Zettergren and Semeter at CEDAR
- Model ionospheric response to soft electron precipitation
- Result is increased Te, ambipolar E, and O+ outflow

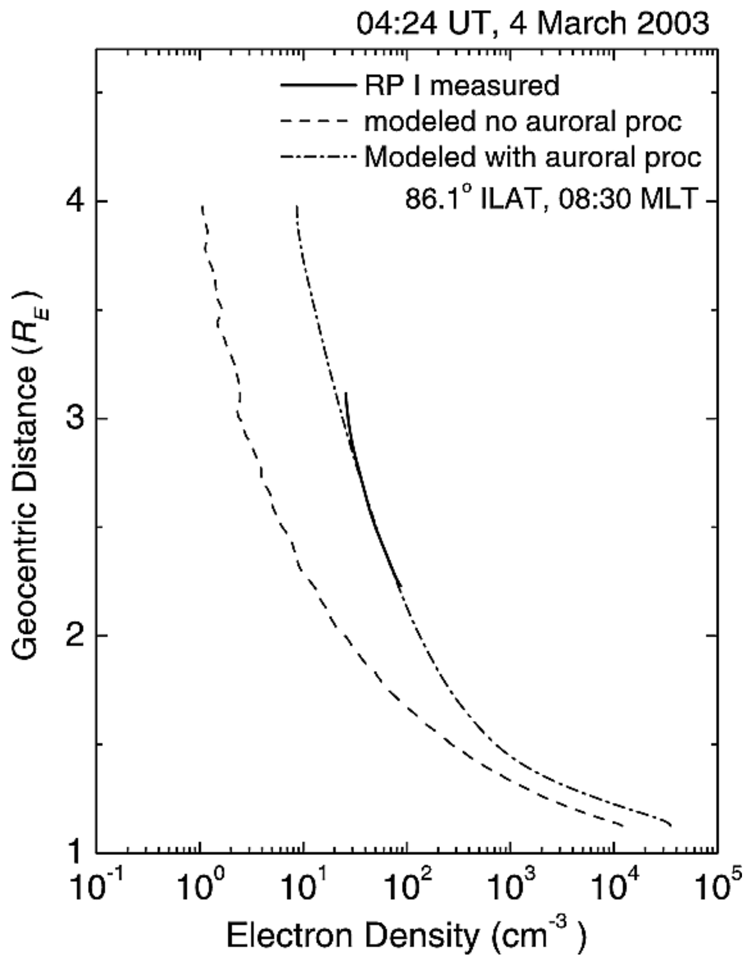



Turn on soft electron precipitation

# Model Viewpoint

- "…combined effects of the soft electron precipitation at *F*-region/topside ionosphere and wave heating at higher altitudes considerably enhanced the O+ outflow at higher altitudes."
- Tu et al. [2004]



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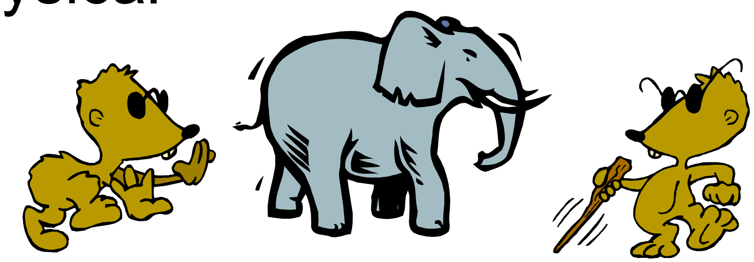
# Summary- Cautions

- The ions lie (reflect history not instant in time)
  - 1000 m/s upflowing ion takes 10 minutes to climb 600 km during which the environment can change dramatically
- Bulk measurements (ESR, plasma drift meters) average over entire distribution function and may disguise non-thermal distributions and wave-particle interactions
- Rockets get snapshot of a biased event and do not make bulk measurements although they are getting better
- Correlations do not imply causality
- Interpretations depend on the physical

observables obtained from

a specific technique



# Where do viewpoints agree?

- Upward ion velocities
  - Radar: 200-600 m/s (higher velocities at higher altitudes)
  - LEO Sat: 500-1000 m/s
  - Supported by Zettergren and Semeter model
- Ion fluxes
  - Radar: $5x10^9$ $cm^{-2}s^{-1}$
  - LEO Sat: $1\text{-}10x10^9$ $cm^{-2}s^{-1}$
  - Rocket: $8x10^8$ $cm^{-2}s^{-1}$ (all above 6 eV as ion conic)
  - Agrees with Z and S model
- Electron temperature increases
  - Radar: Te≈ 6000°
  - Rocket : Te≈ 6000°
  - Agrees with Z and S model
- Ion temperature increases
  - Radar: Ti≈ 4000°
  - Rocket : Ti≈ 4000° *but* also TIA and ion conics
  - Z and S model predicts 6000° but this may be because of long period of energy input

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# Where do viewpoints disagree?

- Ionospheric density
  - Radar and Z and S model say density increases: $10^5$ $cm^{-3}$
  - LEO satellites and rocket say density decreases: $<10^3$ $cm^{-3}$
- Large electric fields/drifts
  - Radar: Type 1 events
  - LEO sat: Not clear
  - Rocket: Large drifts in neighborhood but not coincident
- Precipitating soft electrons
  - Radar: Implied by increased electron density and temperature
  - LEO sat: Cusp precipitation
  - Rocket: Precipitating soft electrons in neighborhood but not coincident

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# So what is needed to resolve these apparent contradictions?

- An experiment that measures thermal populations, suprathermal populations, fields, waves, and FAC (SCIFER-2 sounding rocket)
- Continued modeling from the Zetergren and Semeter viewpoint
- Understanding and modeling of how BBELF waves are created and transversely accelerate ions
- Understanding the time dependence and evolution
  - Does Type 1 or 2 prime the pump for TIA?
  - Does TIA eat into the ionosphere expelling ions regardless of Type 1 or 2 contribution to outflows
  - Can Type 1 or 2 supply plasma with no TIA

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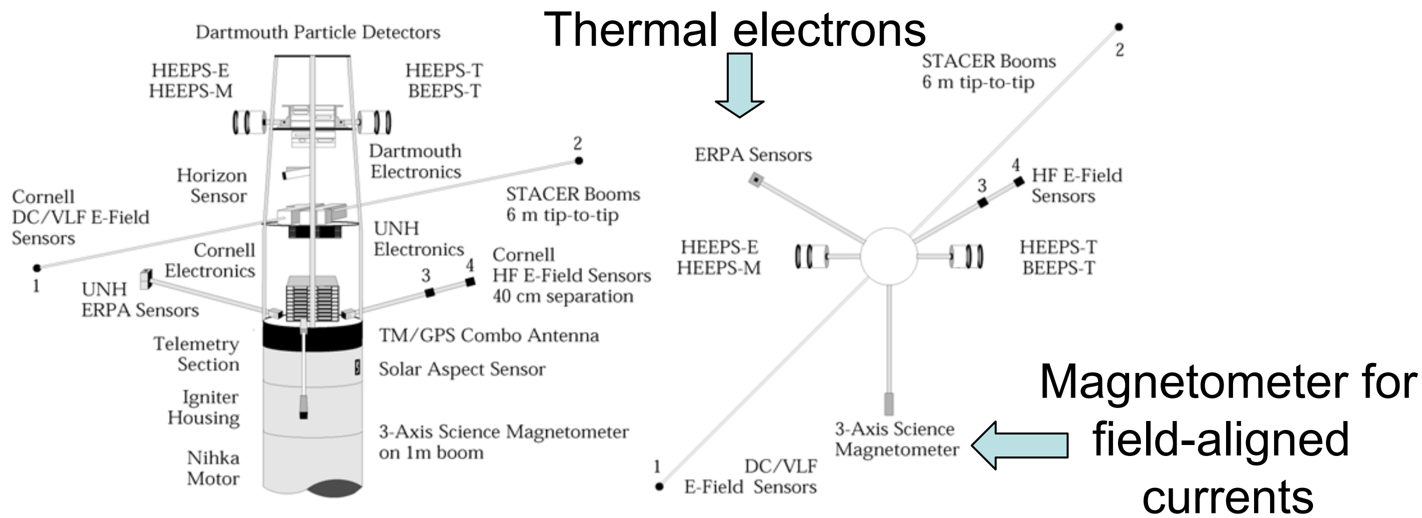
# Next Step SCIFER-2




| Instrument Parameter | Heeps-e Energetic Electrons | Heeps-M Ions Mid-Energy | Heeps-T Ions Thermal | Beeps-T Thermal Ion Mass |
|---|---|---|---|---|
| energy [eV] | 5-16000 | 7-800 | 0.1-20 | 0.1-20 |
| Number pitch angle bins | 30 | 64 | 64 | 16 |
| bin width deg | 6 or 18 | 5 | 5 | 20 |
| delta E/E [%] | 15 | 20 | 10 | 10 |
| G [cm$^2$-ster-keV/keV/bin] | 2e-4 | 1e-3 | 5e-5 | 2e-4 |

# Extra Slides

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# Summary- Observations

| Observation | ESR/EISCAT | LEO Sat | Rocket |
| --- | --- | --- | --- |
| Upflow velo. | ≈ 1000 m/s | ≈ 1000 m/s | ?? nightside* |
| Large ⊥ drifts | Yes | Yes | No (nearby) |
| Te Increase | Yes | Yes | Yes |
| Ti Increase | Yes but contaminated | Yes | NA* |
| Ne | Increases | Decreases | Decreases |
| TIA (conics) | Maybe | NA | Yes |
| BBELF | ?? (NEIALS) | NA | Yes |
| FAC | NA | Yes | NA* |
| <1keV electrons | NA | Yes | No (nearby) |
| Fluxes | $5x10^9$ $cm^{-2}s^{-1}$ | $1\text{-}10x10^9$ $cm^{-2}s^{-1}$ | $8x10^8$ $cm^{-2}s^{-1}$ |

# Increased scale ht. vs. TIA and wave particle interactions?

- Evidence for waves
  - Direct rocket observations of BBELF
  - Radar Naturally Enhanced Ion Acoustic Waves (NIEALS) which my be related to BBELF
  - LEO Satellite measurement of field-aligned currents required to create BBELF
- Evidence for TIA (ion conics)
  - Direct rocket observations
  - VHF radar showing that $T_{\perp} > T_{\parallel}$

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# Extra slides

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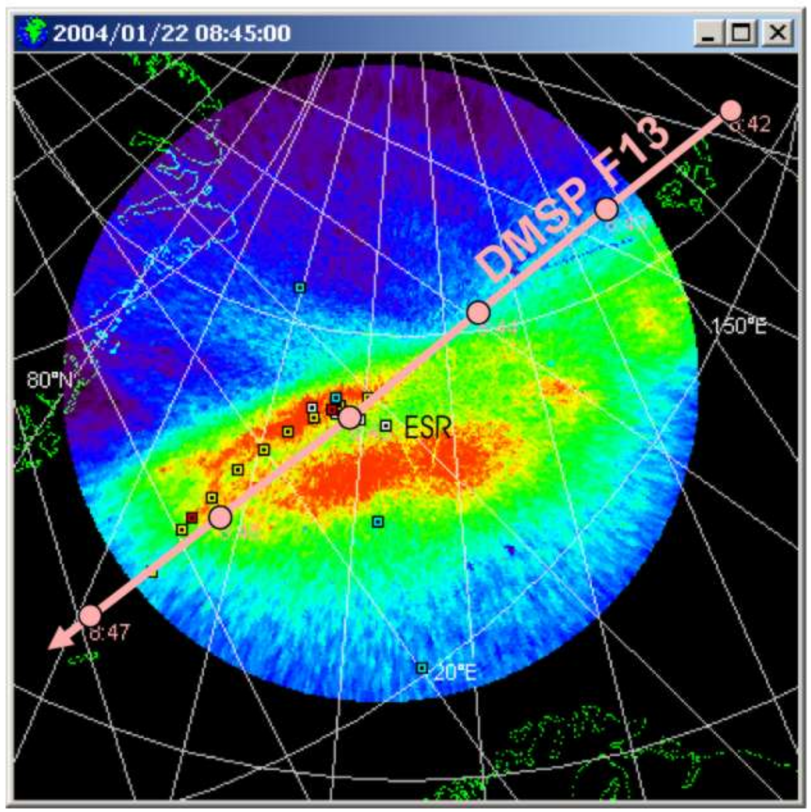
# SERSIO Aurora

**DMSP-F13**

08:42-08:47 UT



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# SCIFER 2