Mid-Latitude Science Examples: Complex, Coupled Behaviors

Asti Bhatt, SRI International
Phil Erickson, MIT Haystack

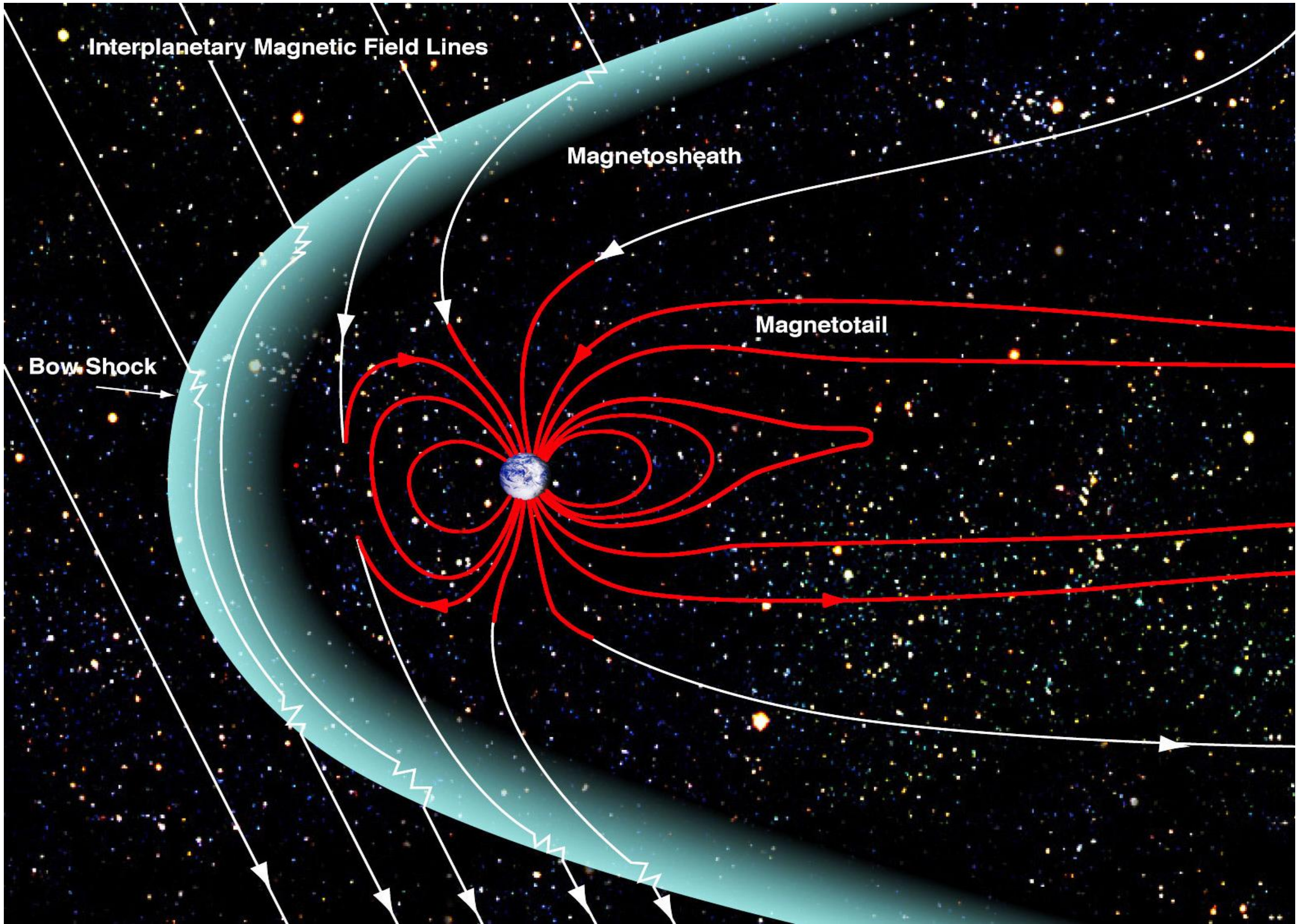
2022 IS Radar Summer School

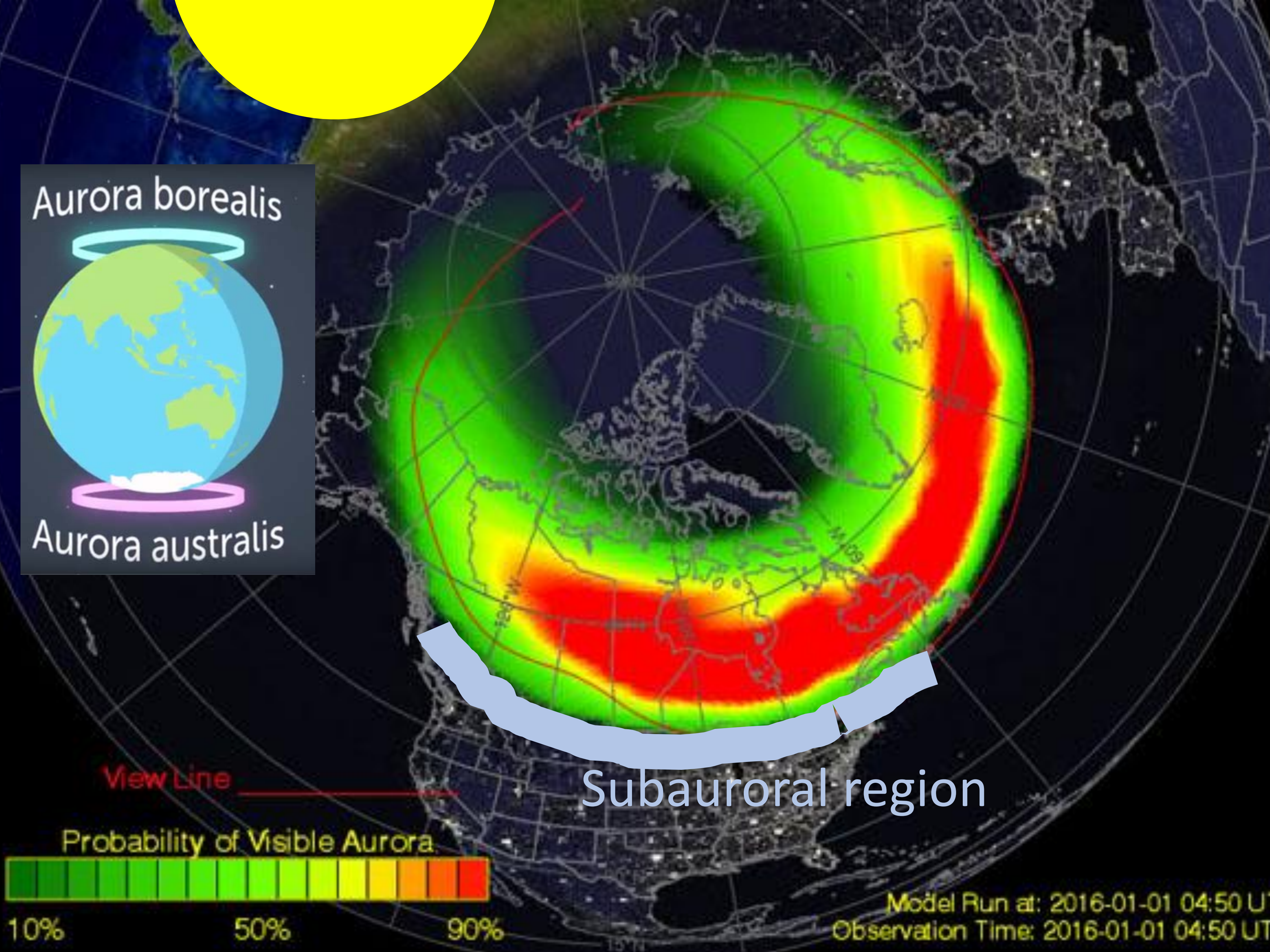
Thanks to Bea Gallardo-Lacourt, Anthea Coster, Larisa Goncharenko, Shunrong Zhang, many many others

Magnetosphere-Ionosphere coupling

- Magnetosphere-Ionosphere system is highly coupled
- Plasma sheet connected to the auroral zone
- Interesting dynamical processes occur in the transition region, where the magnetic field transitions from stretched field lines to dipolar

The subauroral region is located there!

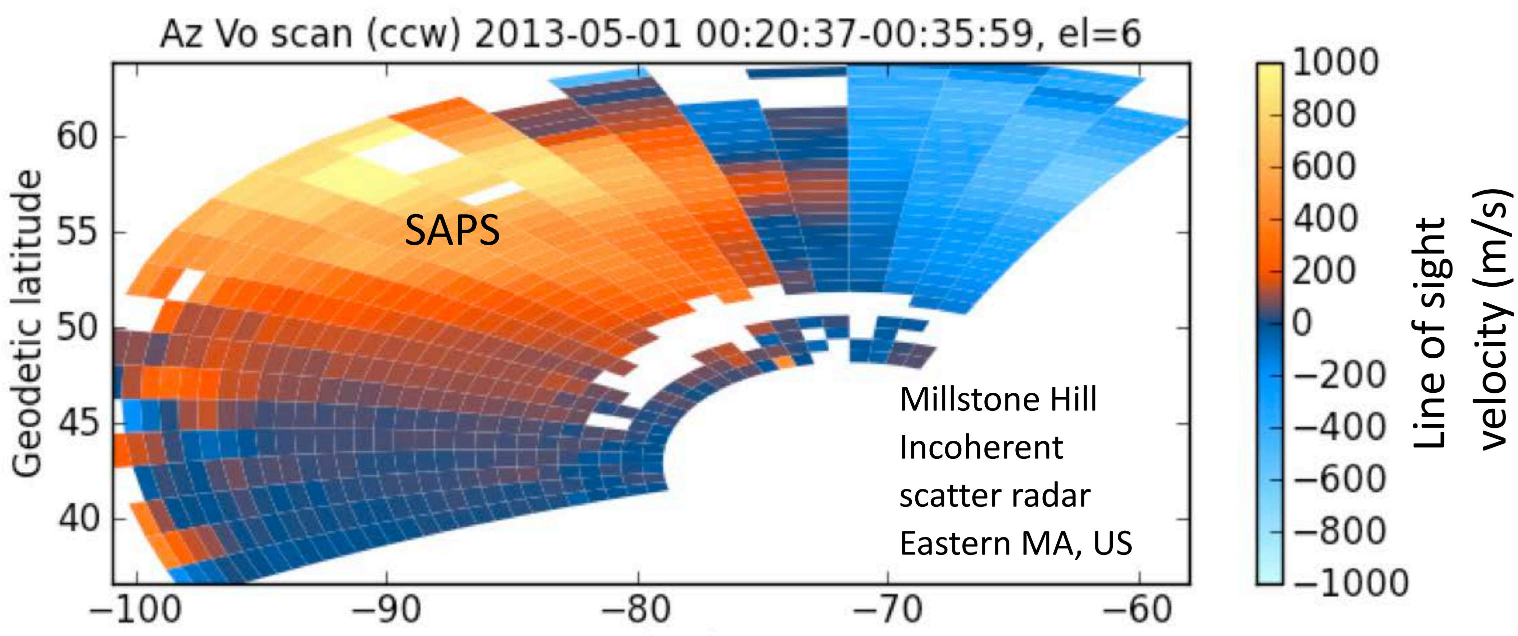



Aurora borealis
Aurora australis
Subauroral region
View Line
Probability of Visible Aurora
10%
50%
90%
Model Run at: 2016-01-01 04:50 U
Observation Time: 2016-01-01 04:50 U

What is SAPS?

Sub-**A**uroral **P**olarization **S**tream

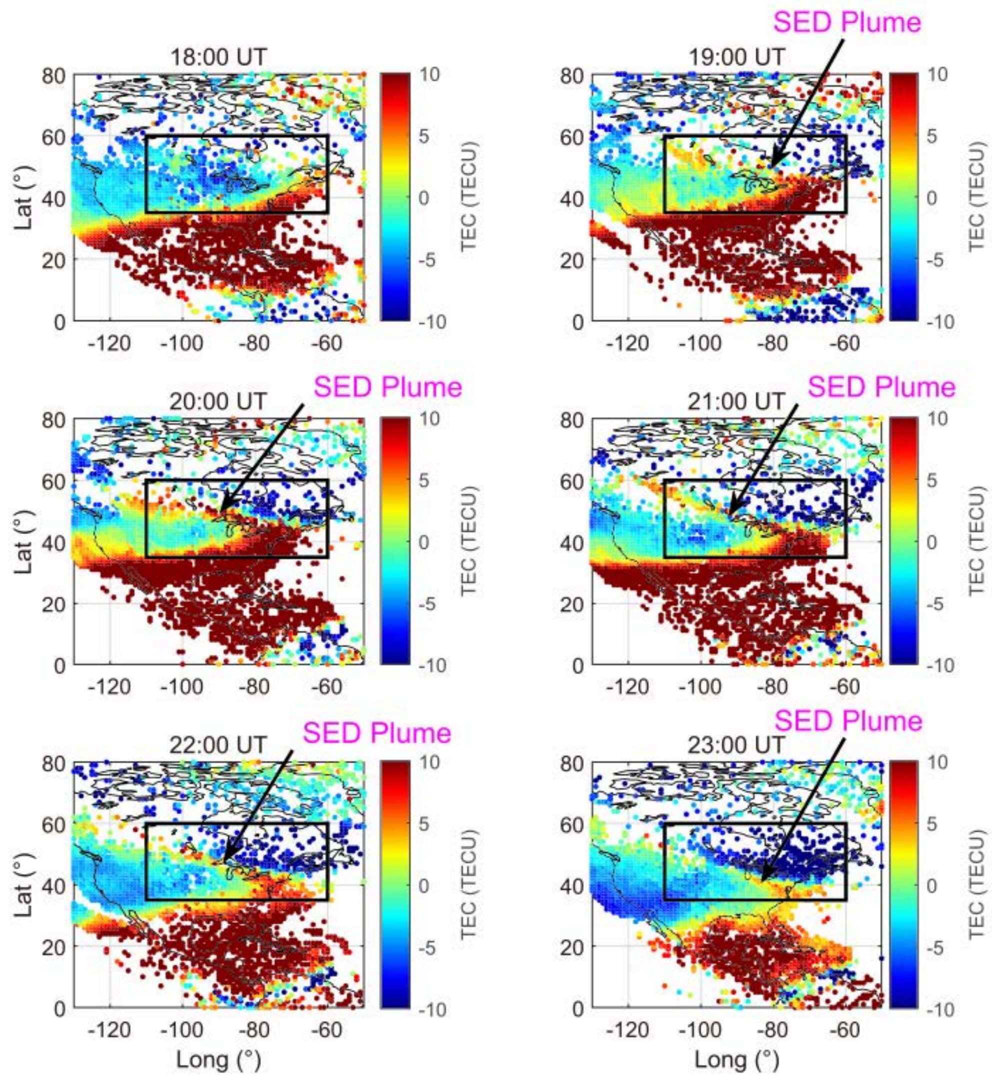
- Occurs in the subauroral region during stormtimes (moderate and up)
- Westward flow driven by ~poleward E fields
- Few deg wide in latitude
- Dusk/evening sector; lasts for hours
- Typical velocities up to 1500 m/s



What is SED?

Storm Enhanced Density

- Occurs in the subauroral region during storm times (moderate and up)
- Enhanced electron density in a narrow channel
- Severe gradients on equatorward and poleward sides
- In the Plasmasphere Boundary Layer
- Signature of a lot of cold plasma moving through mid latitudes to high latitudes
- Driven by electrodynamic coupling between the magnetosphere and ionosphere (cf. SAPS)

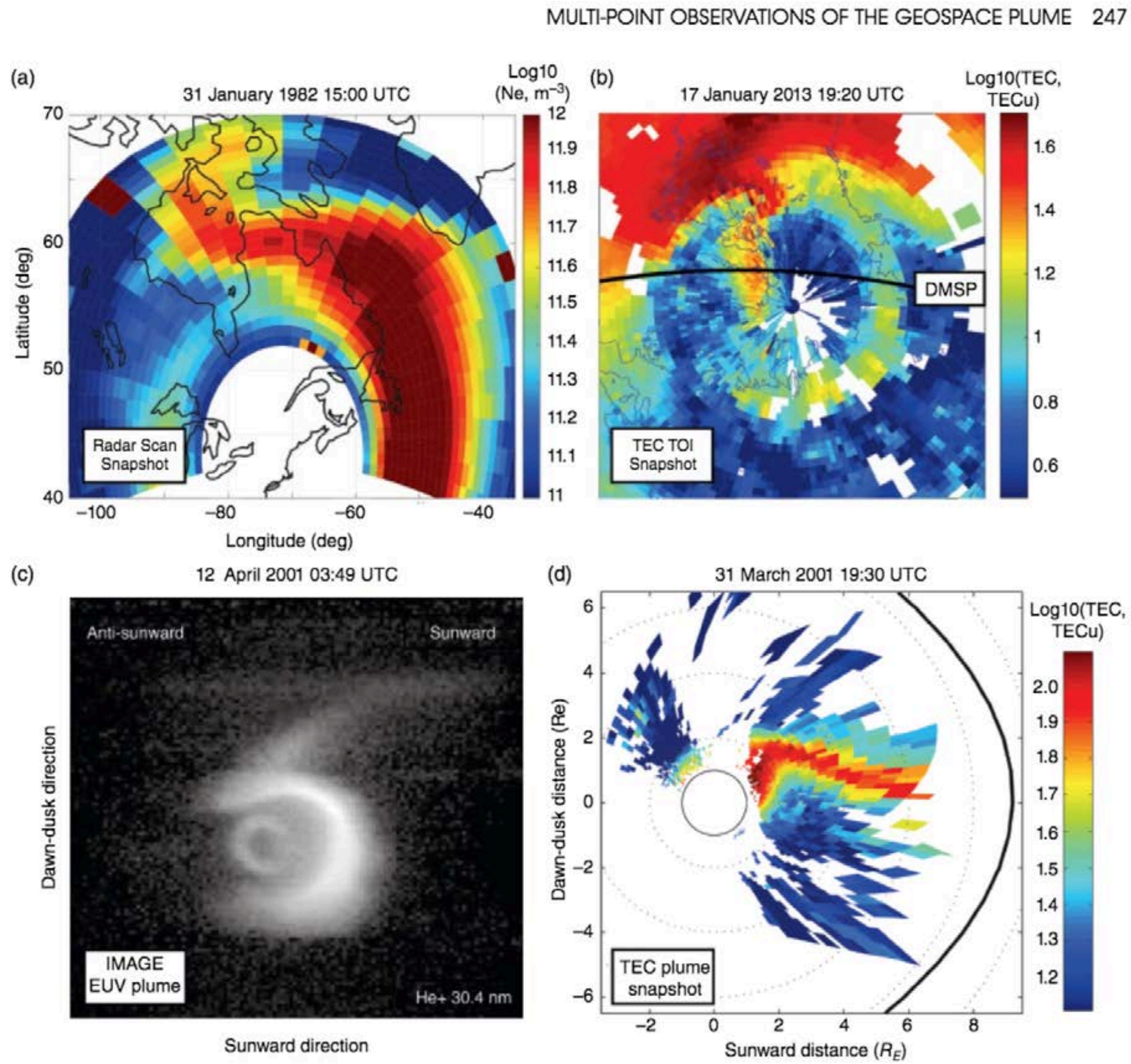


Zhai et al 2020 doi:10.1029/2020JA028257

TEC = total electron content; # of electrons in a column above a particular location

The Geospace Plume

- Stormtime: ionospheric cold plasma redistributed throughout geospace
  - Ionospheric dusk sector: storm enhanced density
  - Plasmaspheric tails / plume: magnetic connections
- Inside plasmasphere boundary layer (PBL)
- Strong subauroral ExB plasma convection
  - SubAuroral Polarization Stream (SAPS)
- Observational synthesis: the ***Geospace Plume***



(Foster et al, doi:10.1002/9781119509592.ch14 , 2020)

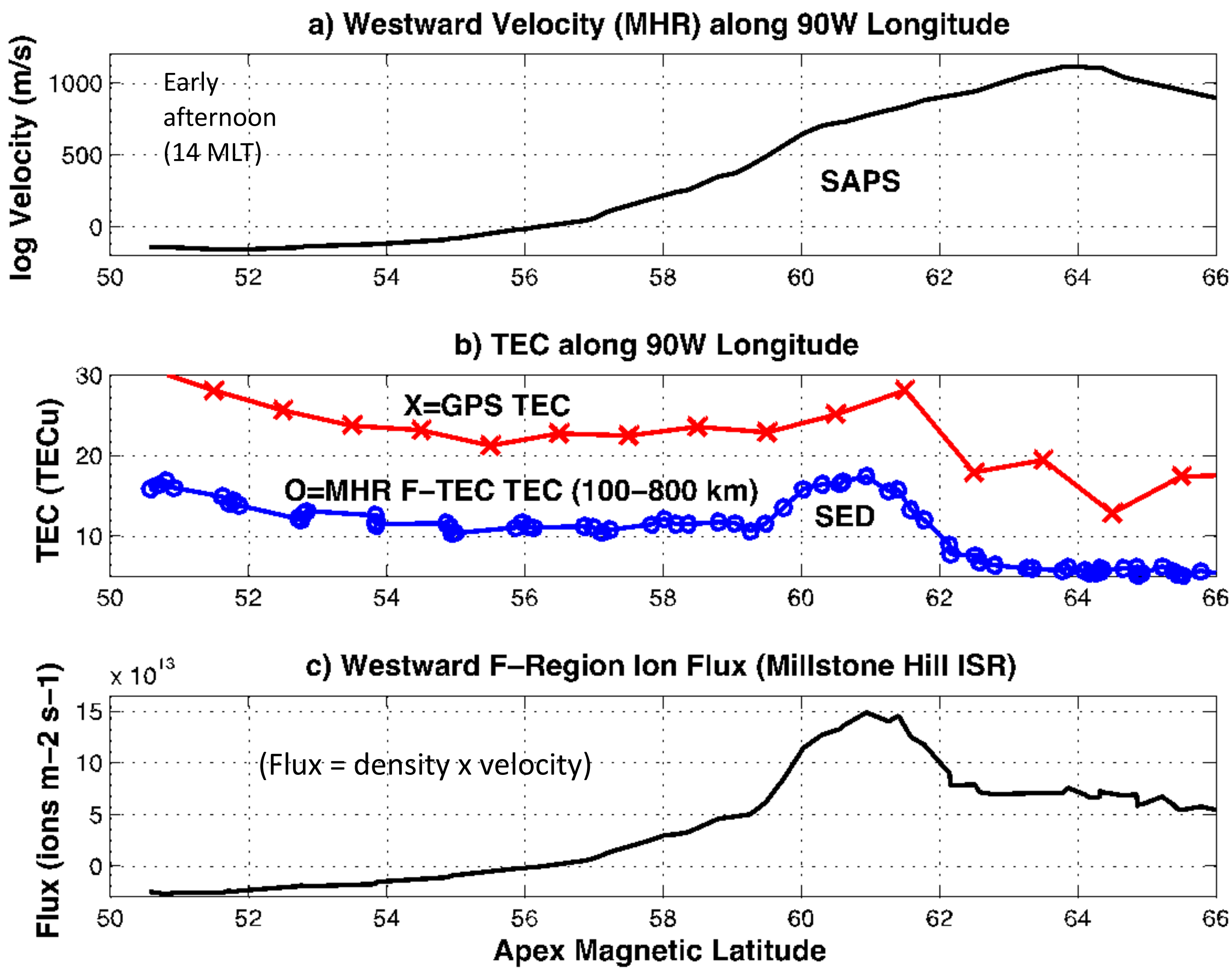
MIT HAYSTACK OBSERVATORY

More about SAPS.. and SED

SAPS overlaps the edge of the cold, dense ionosphere and plasmasphere at subauroral latitudes

Momentum, energy exchange

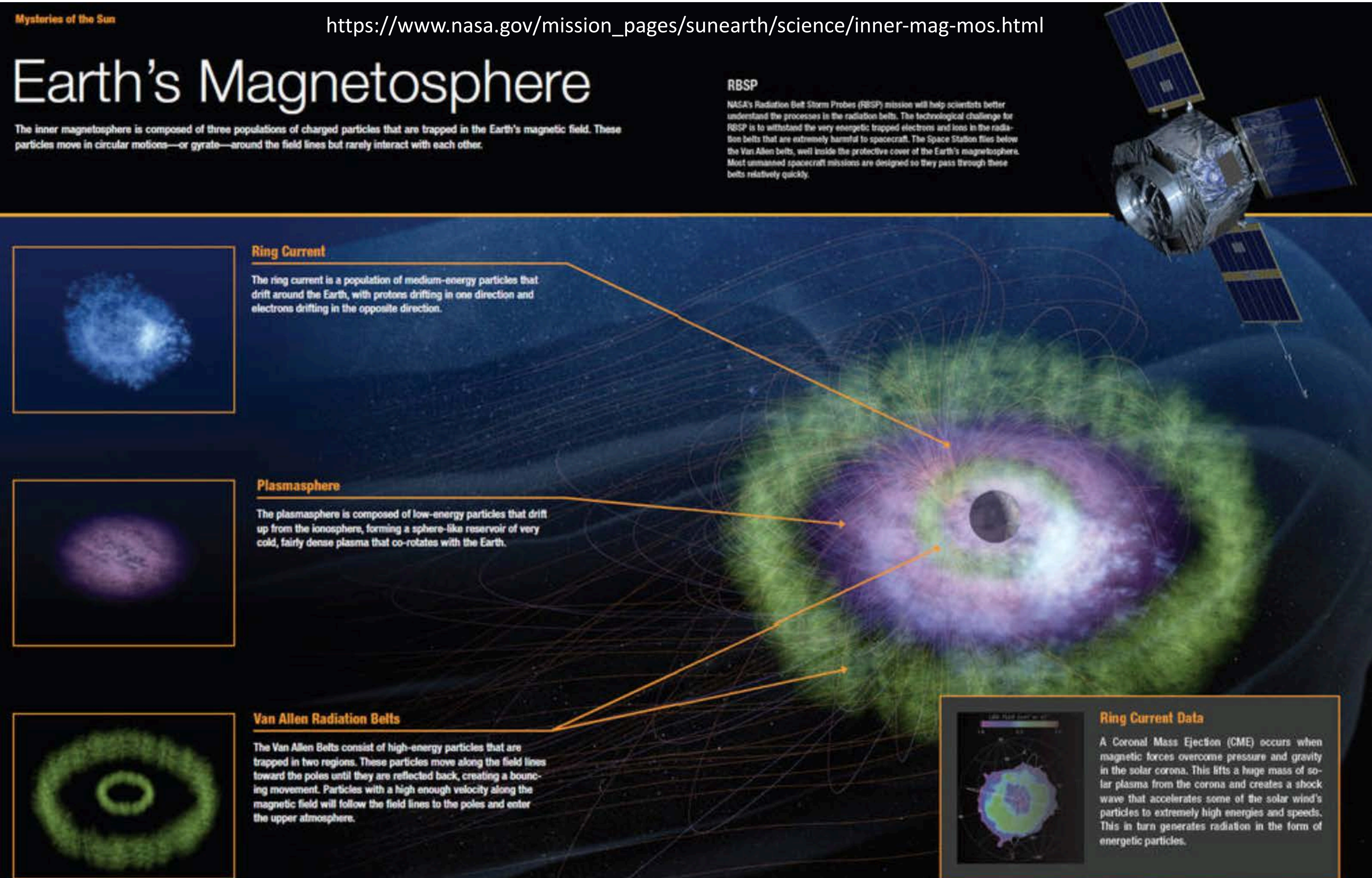
Moves a lot of heavy (O+) ionospheric material westward towards noontime



TEC = total electron content; # of electrons in a column above a particular location

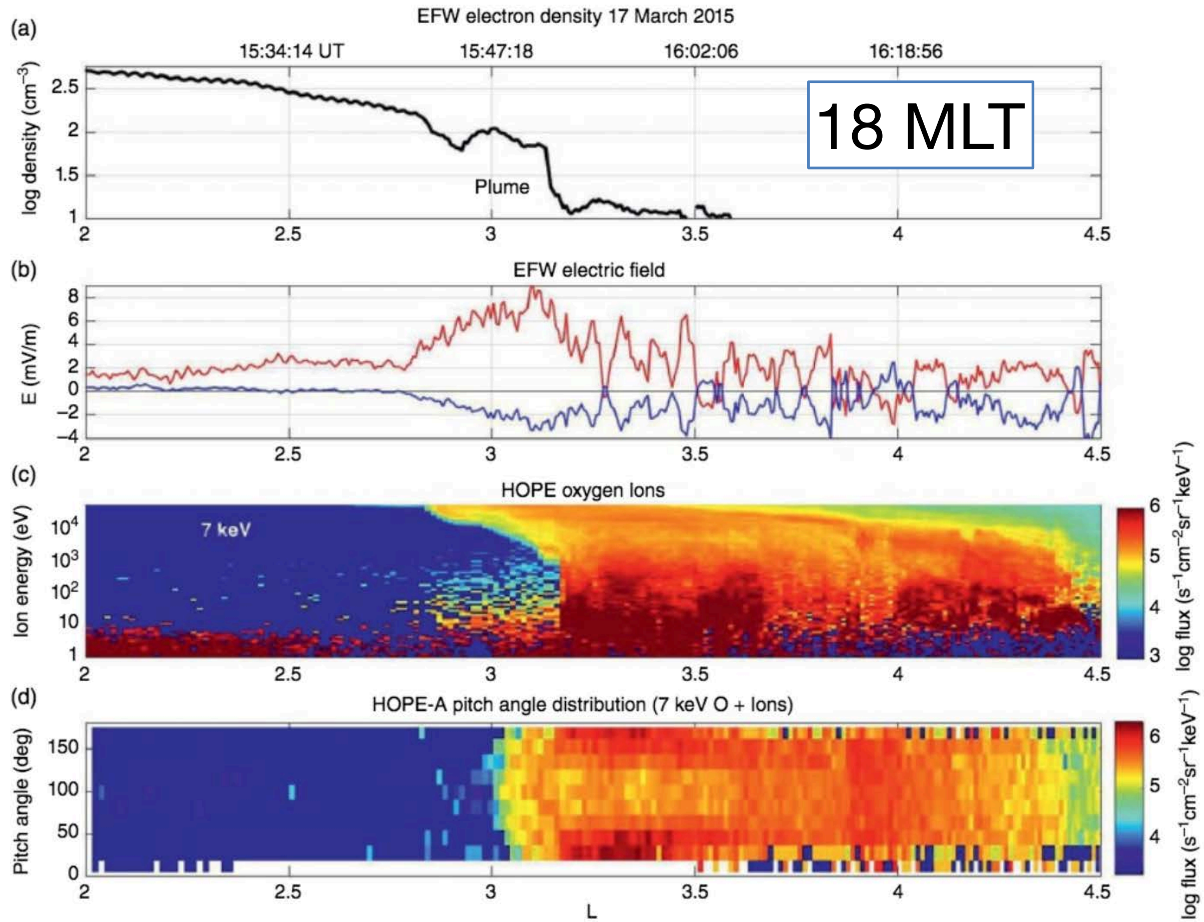
What is the Ring Current?

The ring current is a population of medium-energy particles that drift around the Earth, with protons drifting in one direction and electrons drifting in the opposite direction.

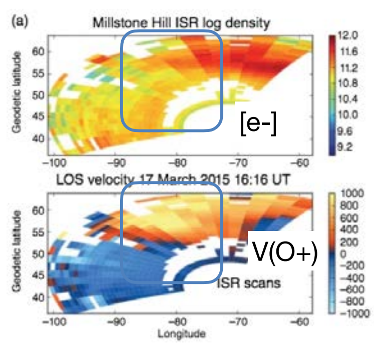


SAPS, Ring Current, and the Geospace Plume

- In-situ Van Allen Probes A identifies plume [EFW]
- Strong radial outward E fields across SAPS channel
- Advects outer plasmaspheric ions
- HOPE sees hot ring-current ions
- Bidirectional, field-aligned fluxes up to 10 keV energies adjacent to outer extent of geospace plume

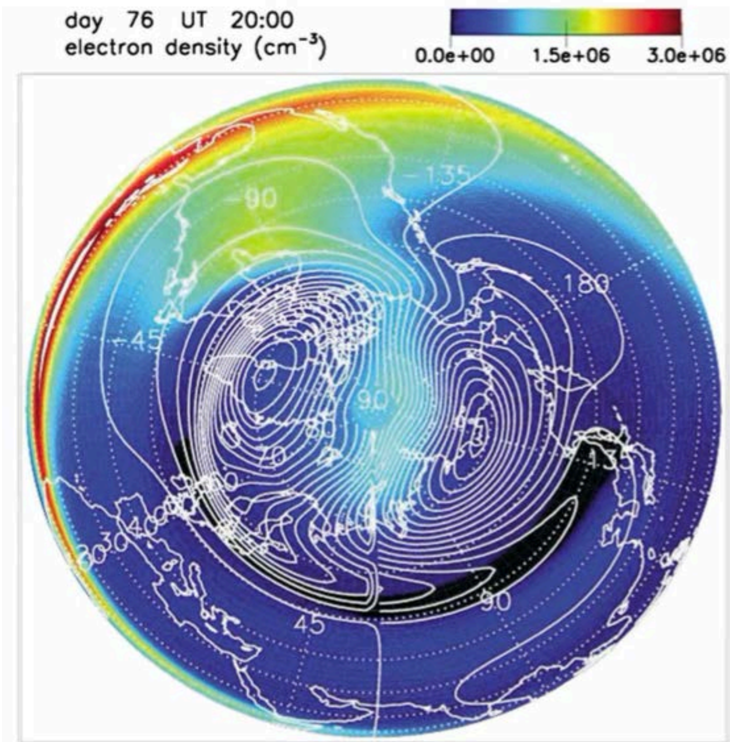


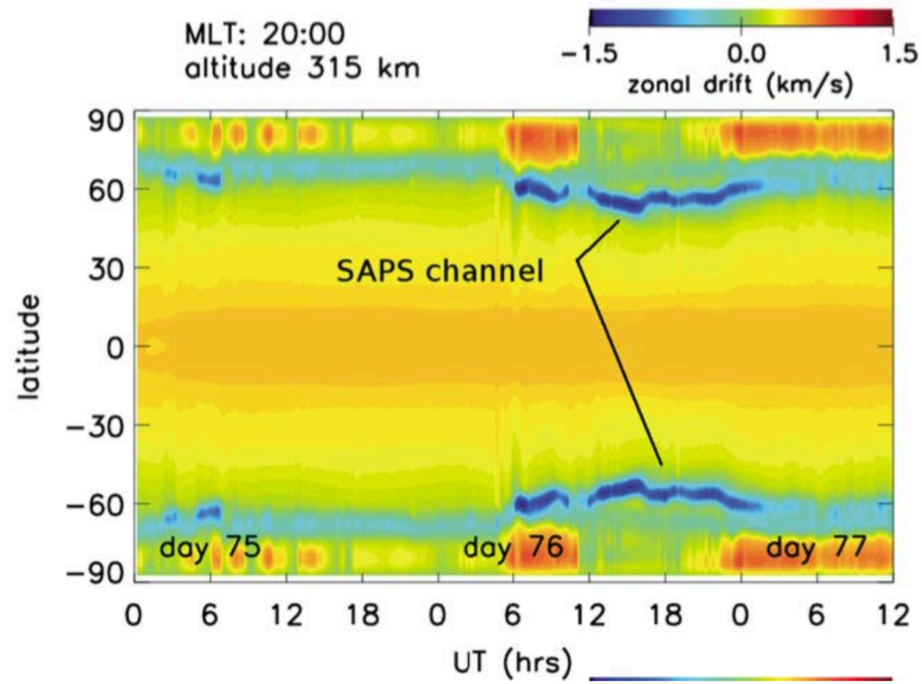
Millstone Hill O+ flux = 2E14 m^{-2} s^{-1}



MIT HAYSTACK OBSERVATORY

RCM Modeling of Subauroral Potential Drops: SAPS





Subauroral cold mass flow into cusp
(then ion upwelling/outflow)

MIT HAYSTACK OBSERVATORY

Huba, Sazykin, Coster doi:10.1002/2016JA023341, 2017

The complex, inter coupled subauroral system: Ionosphere-magnetosphere-plasmasphere coupling

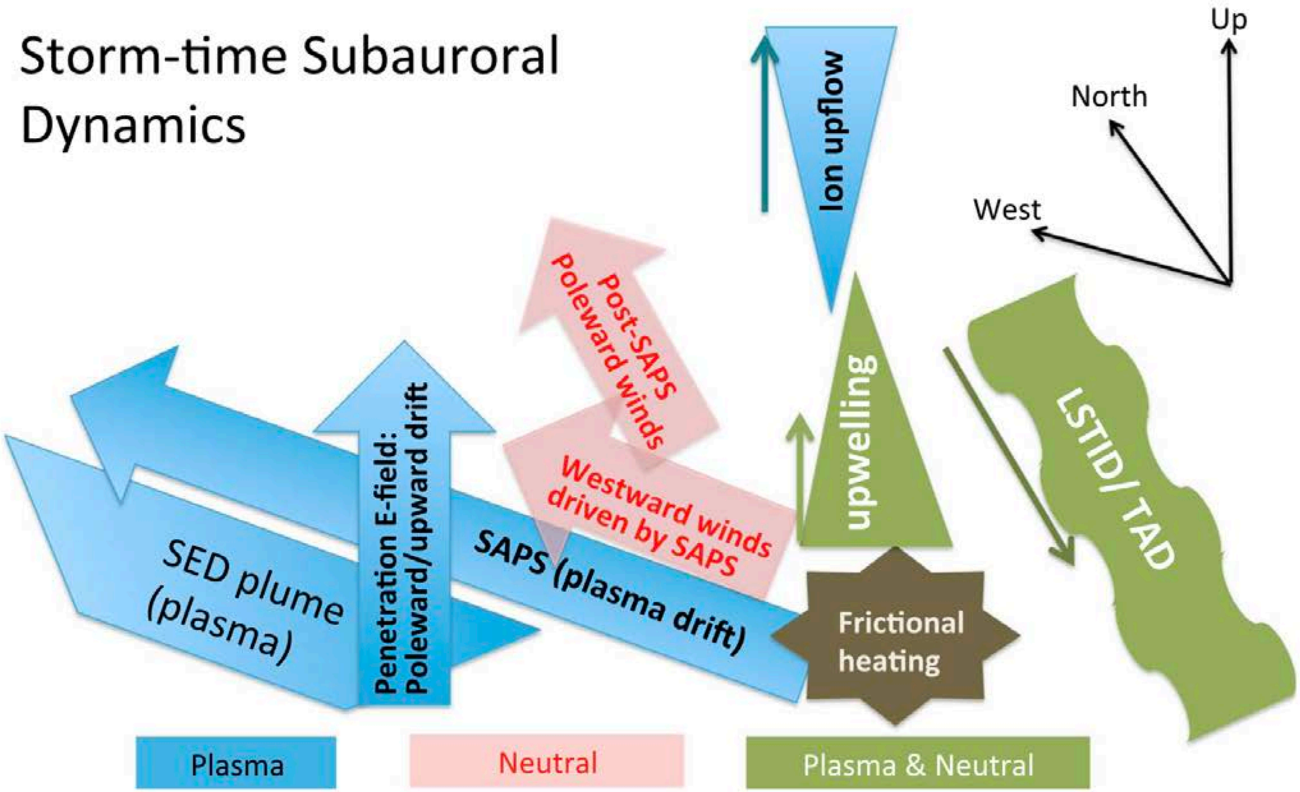
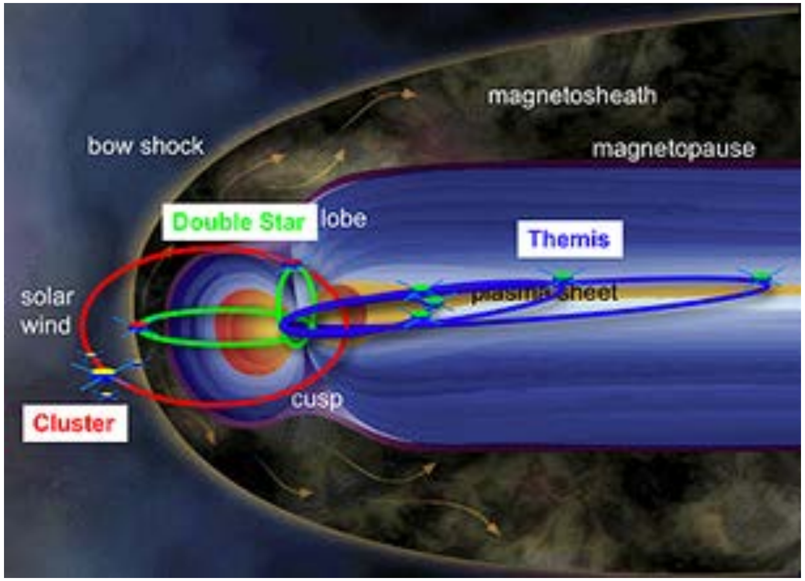


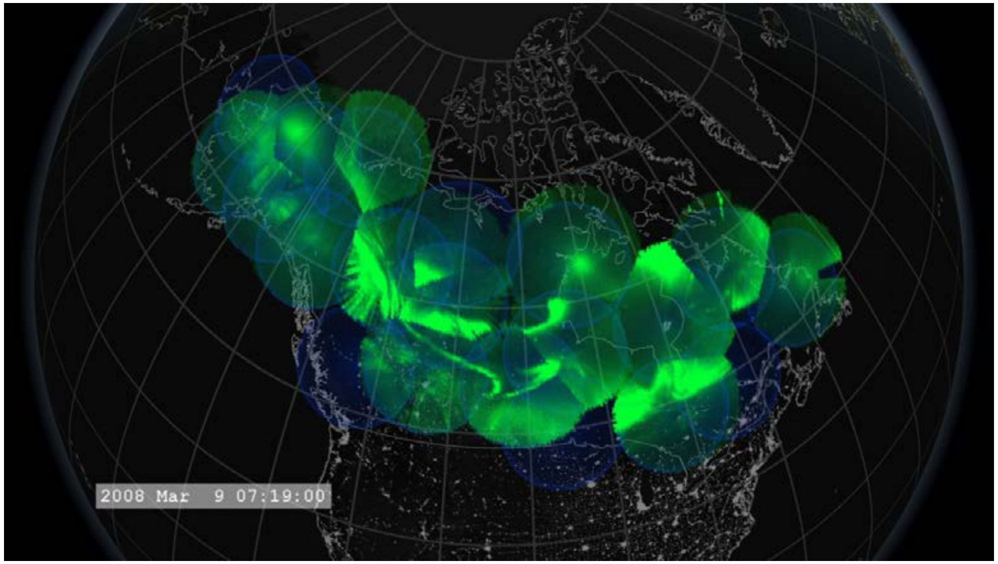
Figure 17. Schematic summary representation of primary storm time subauroral ionosphere and thermosphere dynamics observed during the 17–18 March 2015 St. Patrick's Day great geomagnetic storm.

MIT
HAYSTACK
OBSERVATORY

Zhang et al, doi:10.1002/2016JA023307, 2017

How do we experimentally study space weather?

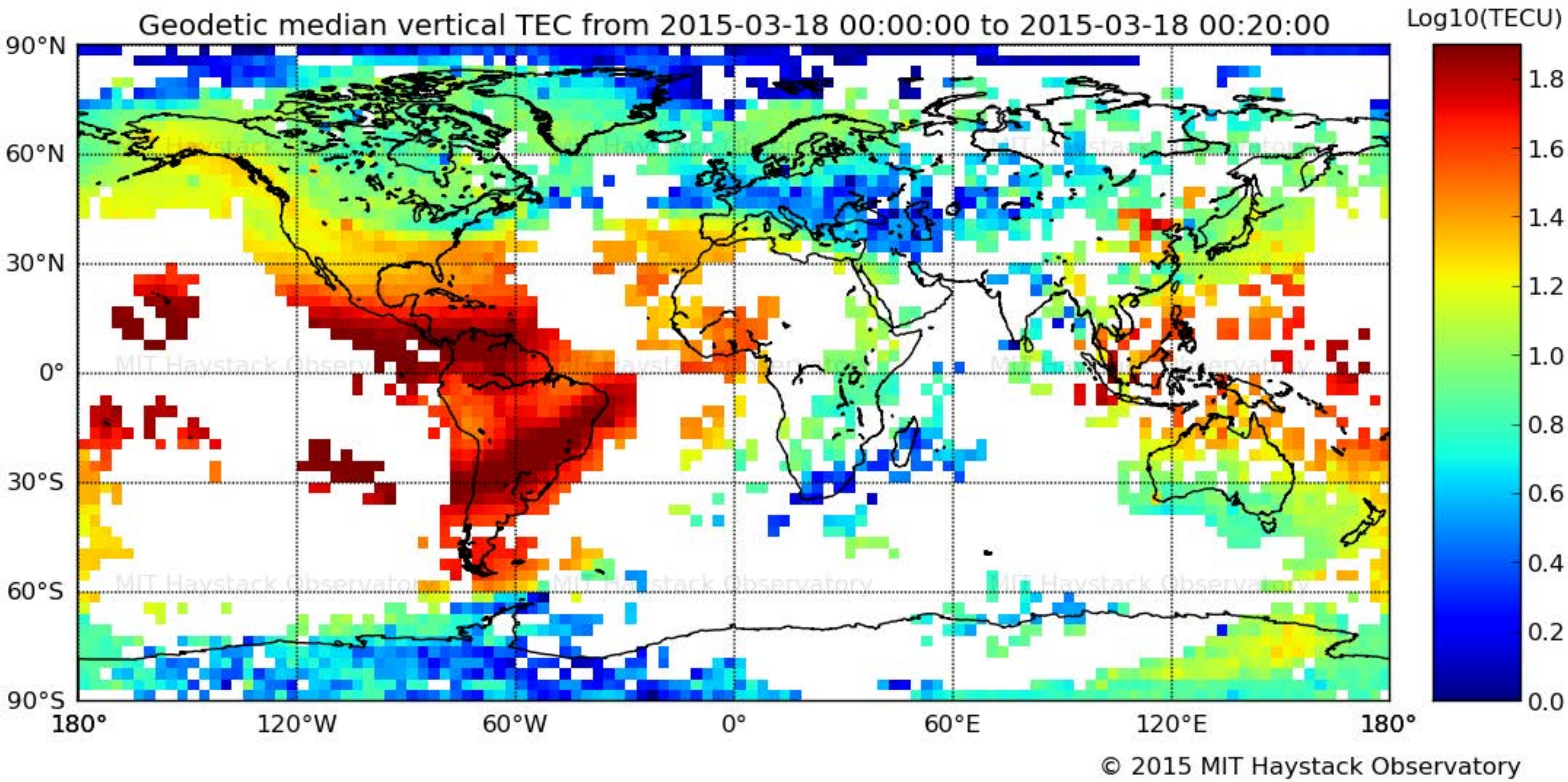




- Different satellites' orbits allow us to explore different regions of Earth's magnetosphere
- For example, some satellites measure the solar wind, other mainly the plasma sheet and others the radiation belts

- All-sky cameras, FPIs with different wavelengths reveal important magnetospheric dynamics
- Magnetometers show us variations of magnetic field
- Radar data reveals plasma motion
- Ionosondes to study variations of Earth's ionosphere
- …

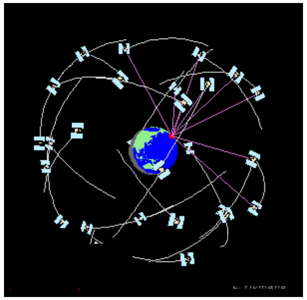
GNSS TEC: Global Ionospheric Space Weather



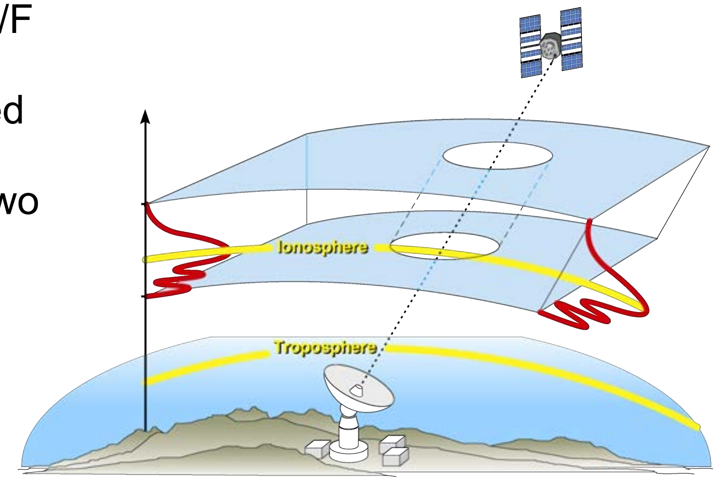
- 6000+ GNSS receivers from many sources (e.g. UNAVCO, SOPAC, IGS)
- Processed by MIT Haystack to extract ionospheric delay information
- Data provides large scale picture of global ionospheric space weather variations
- Available to space science community through Madrigal distributed database
- Currently GPS and GLONASS TEC, other GNSS systems will be included in the future

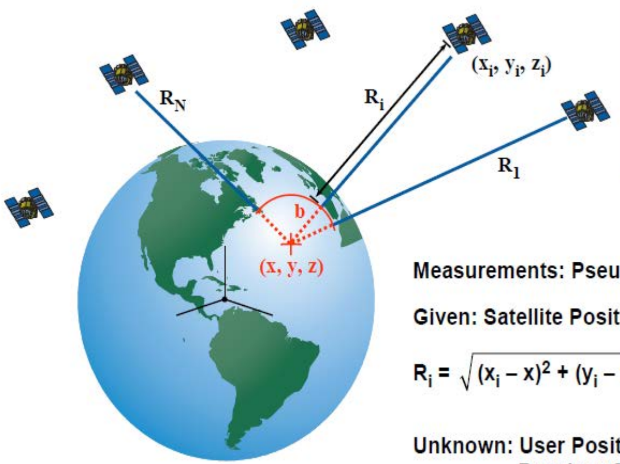
MIT
HAYSTACK
OBSERVATORY

GNSS: Sensor for positioning, timing, and ionospheric TEC



TEC = Total Electron Content (10^{16} x el/m^2)
Integrated Content to ~20,000 km
Dominated by ionosphere (E/F region)
Both line-of-sight and mapped vertical TEC used
Differential Doppler based (two frequency transmission)



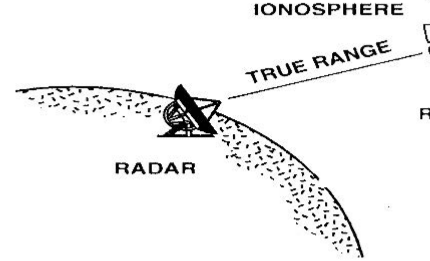


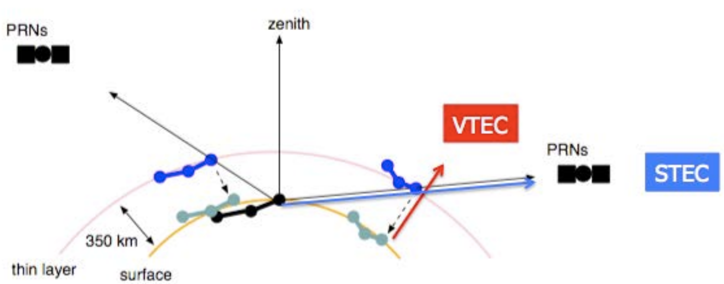
Measurements: Pseudoranges $\{R_i\}$

Given: Satellite Positions $\{(x_i, y_i, z_i)\}$

$$R_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} - b, \quad i = 1, 2, \ldots, N$$

Unknown: User Position (x, y, z)
Receiver Clock Bias b





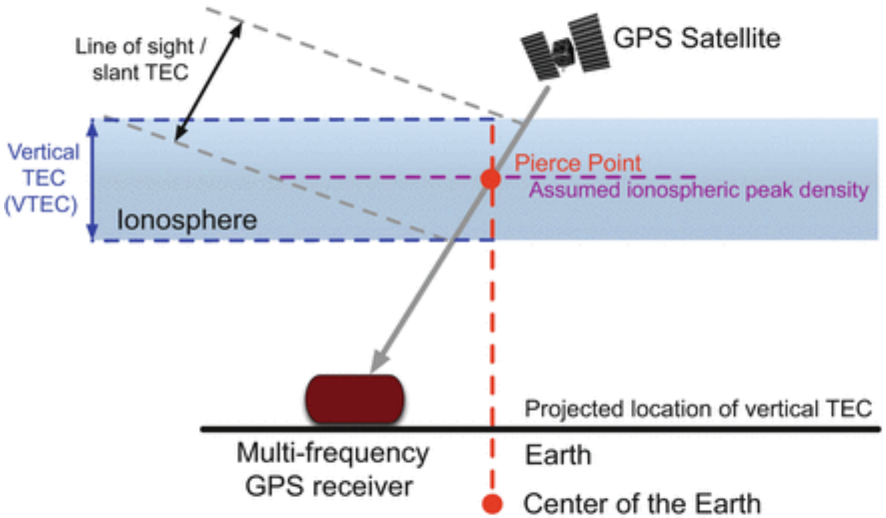
Slant TEC projected into Earth's surface

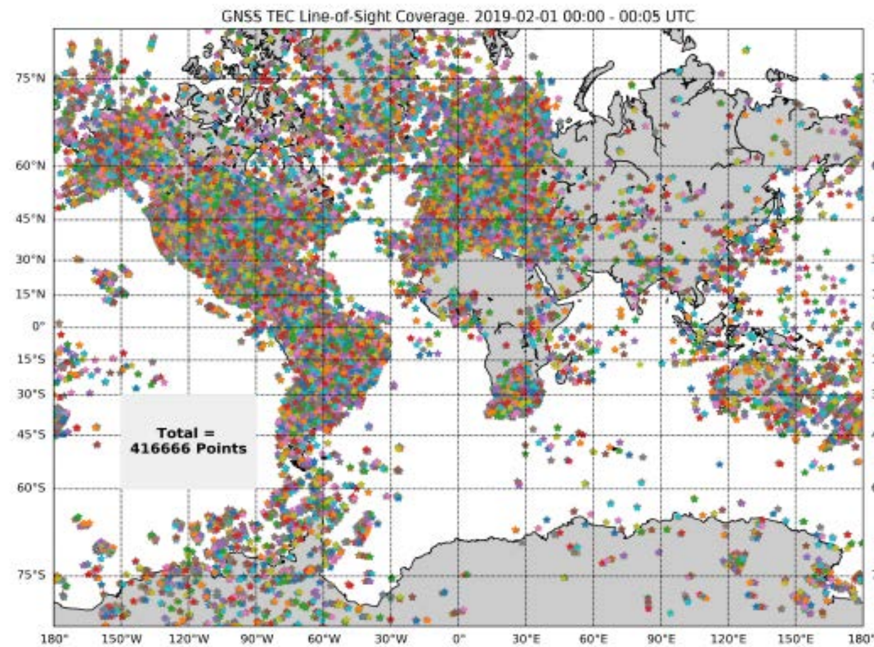
Geometric mapping of Line-of-sight to vertical TEC

$$z = \frac{1}{\sqrt{(1.0 - (F\cos(\mathrm{el}))^2)}}$$

(Tropospheric water vapor delay not shown)

Line-of-sight TEC for data assimilation: 150M measurements per day

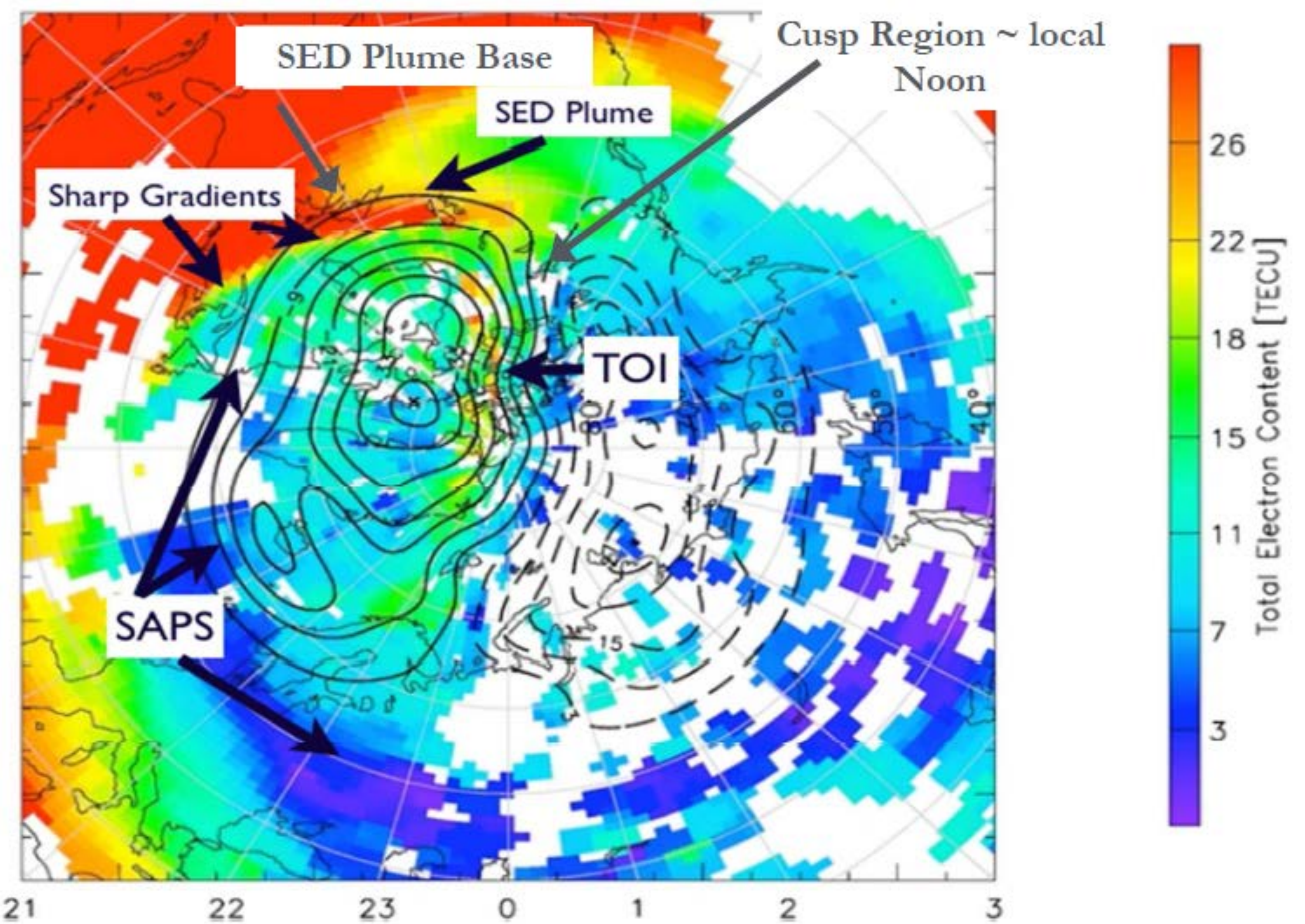




GNSS line of sight total electron content spatial coverage for a 5 minute interval on February 1, 2019, from data in the MIT Haystack Madrigal data system. Each of 416,666 colored asterisks represents the ionospheric pierce point of the line of sight between a single ground receiver and one of the GNSS global navigation satellites.

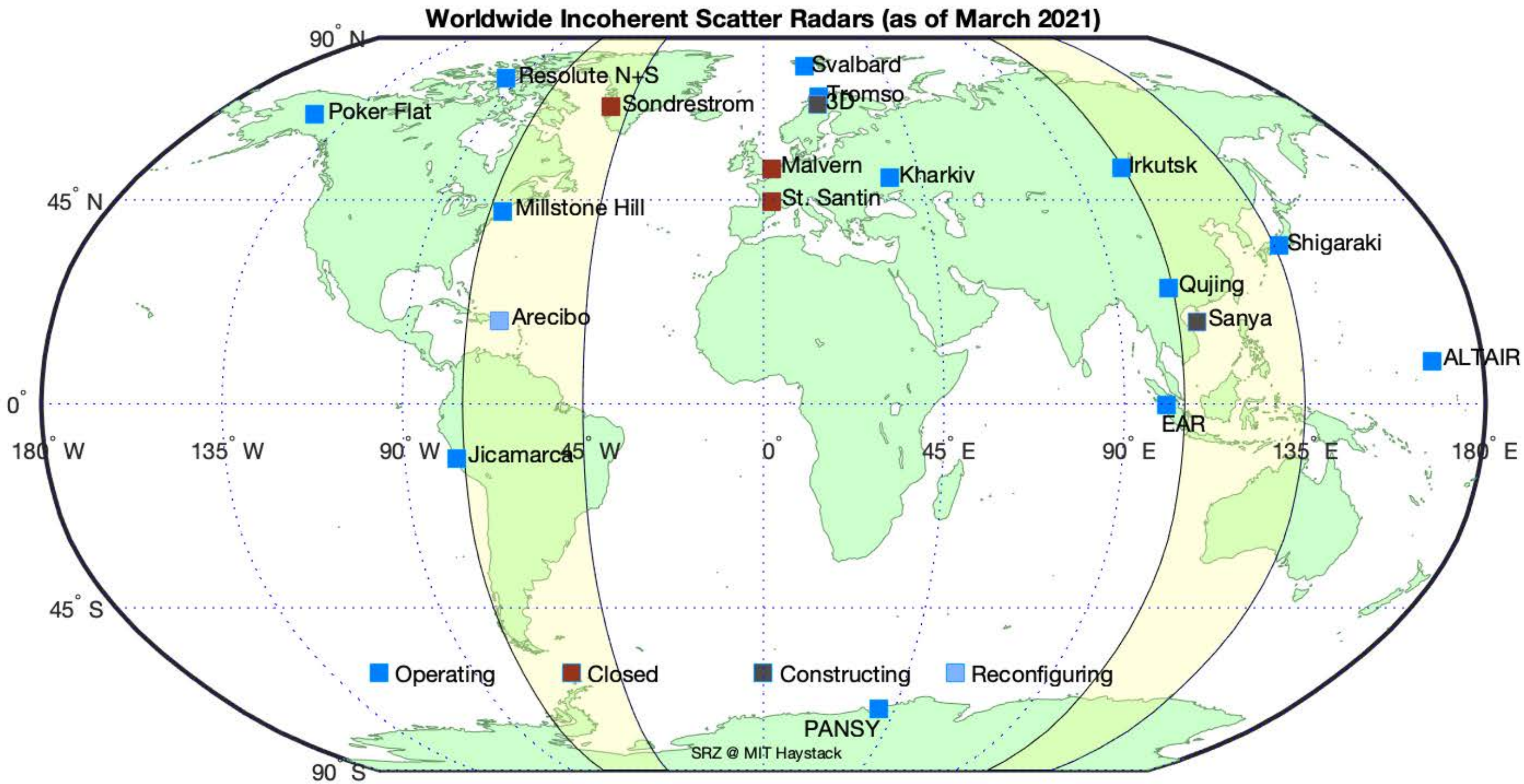
MIT HAYSTACK OBSERVATORY

Common large-scale features observed in TEC during geomagnetically disturbed conditions



MIT HAYSTACK OBSERVATORY

Incoherent Scatter Radars



Global Network of High Power Radars

- ➢ Measure Physical Properties of the Space Environment as a function of altitude: Electron density, electron temperature, ion temperature, plasma velocity, and more...
- ➢ Infer: Electric field, conductivity, current, neutral air temperature, wind

MIT HAYSTACK OBSERVATORY

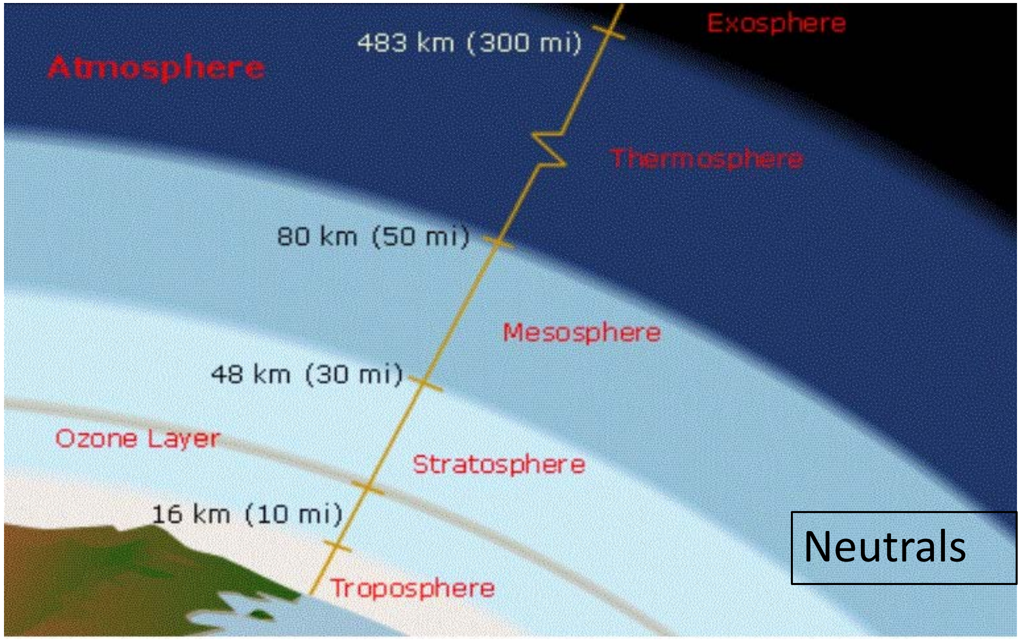
STEVE

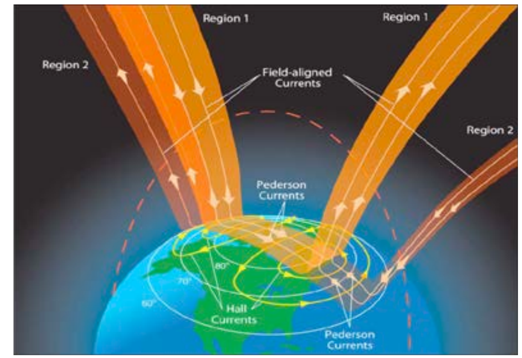
- Discovered in the modern era by citizen scientists in Alberta, Canada (earlier reports in literature)
- A well-known phenomenon among amateur auroral photographers (Alberta Aurora Chasers) …
  but a completely new phenomenon for the scientific community
- Appears as a purple structure, located in a ***sub-auroral*** region lower in latitude from the place where auroras are observed (different B-field topology)
- Different from other subauroral emissions (like SAR arcs)
- Emissions in green (“picket fence”) and also in near-white can occur
- The name Steve was selected by the photographers: acronym without physical meaning (taken from the movie *Over the Hedge*)

2017-09-19 British Columbia, Canada

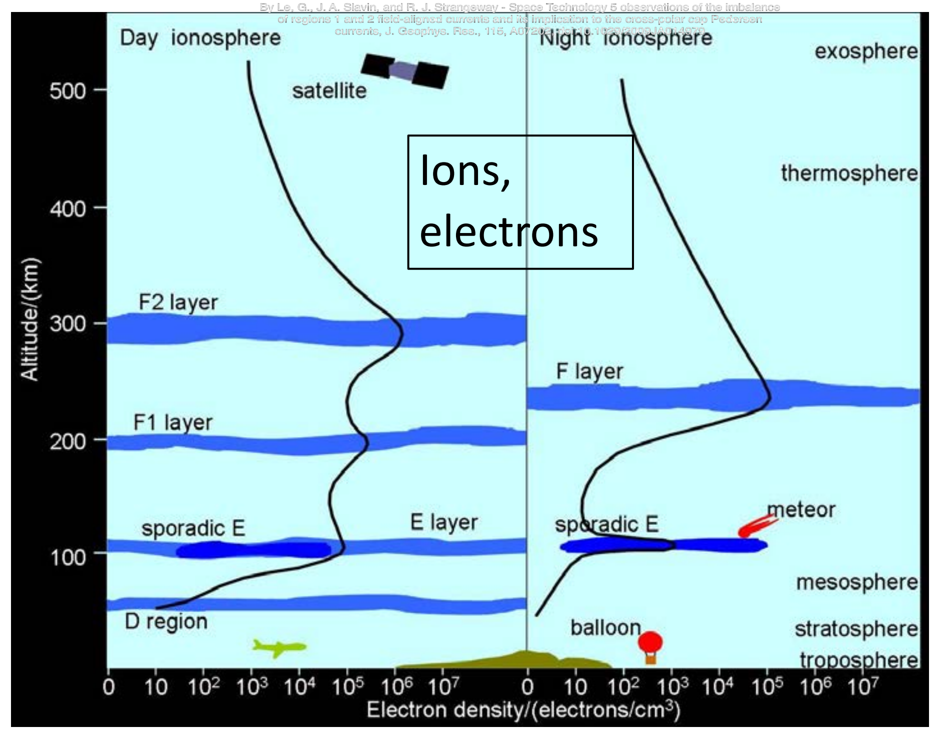
Courtesy of Robert Downie https://www.robertdowniephotography.com/

STEVE relationship to altitude structure: Atmosphere and Ionosphere





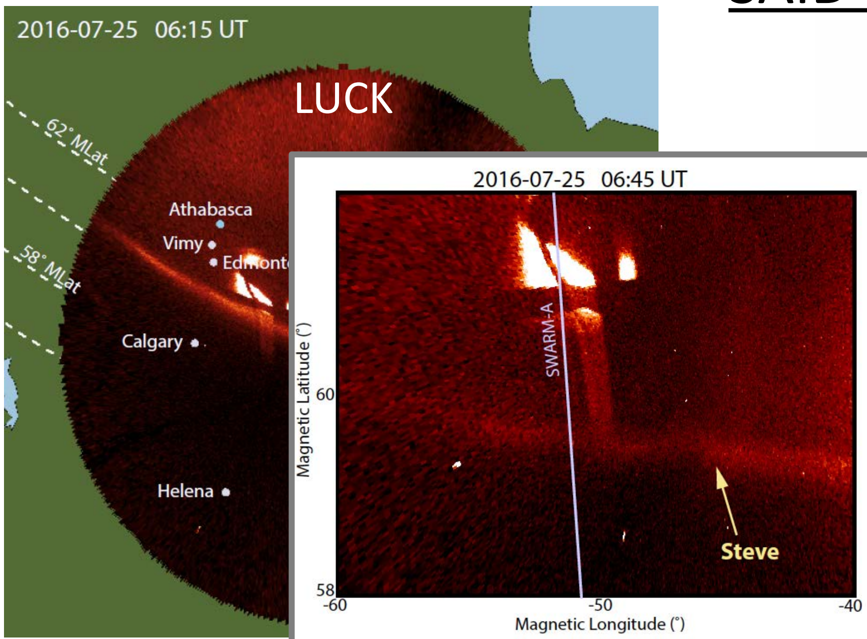
By Le, G., J. A. Slavin, and R. J. Strangeway - Space Technology 5 observations of the imbalance of regions 1 and 2 field-aligned currents and its implication to the cross-polar cap Pedersen currents, J. Geophys. Res., 115, A07202, doi:10.1029/2009JA014979.

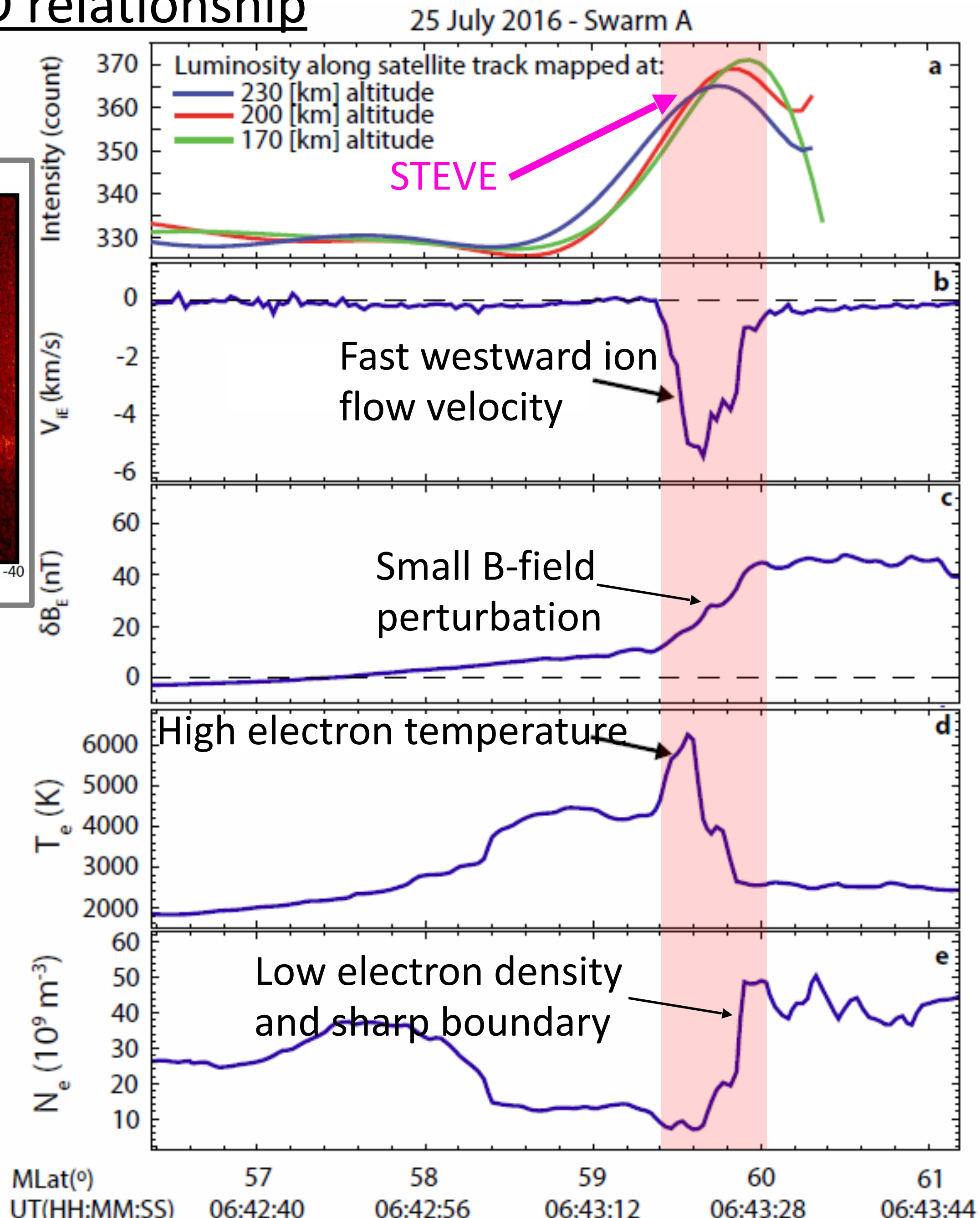


- STEVE is occurring in the lower thermosphere
- STEVE continuous emission overlaps **lower F region**, where electrons and ions move together across B
- Picket fence overlaps a **special region (E region)** where electrons are highly magnetized and 'stuck' to field lines, but ions collide with neutrals and can move across field lines = horizontal currents
- Remember though that E region ionosphere ***disappears*** shortly after sunset (recombination) = low conductivity

Strong Thermal Emission Velocity Enhancement(STEVE) : SAID relationship

[MacDonald et al., 2018]





- STEVE is in the subauroral ionosphere
- Narrow in latitude (10s km/<1º) and wide in longitude (1000s km, several hours MLT)
- Associated with narrow and fast-moving ions (~5 km/s, about 2 times stronger than regular SAID [Archer et al., 2017])
- Steve is in a region of extremely hot electrons (more than 6000K)
- **Not produced** by particle precipitation, **not an aurora** [e.g., Gallardo-Lacourt et al., 2018, Nishimura et al., 2019]

Mid-Latitude Traveling Ionospheric Disturbances

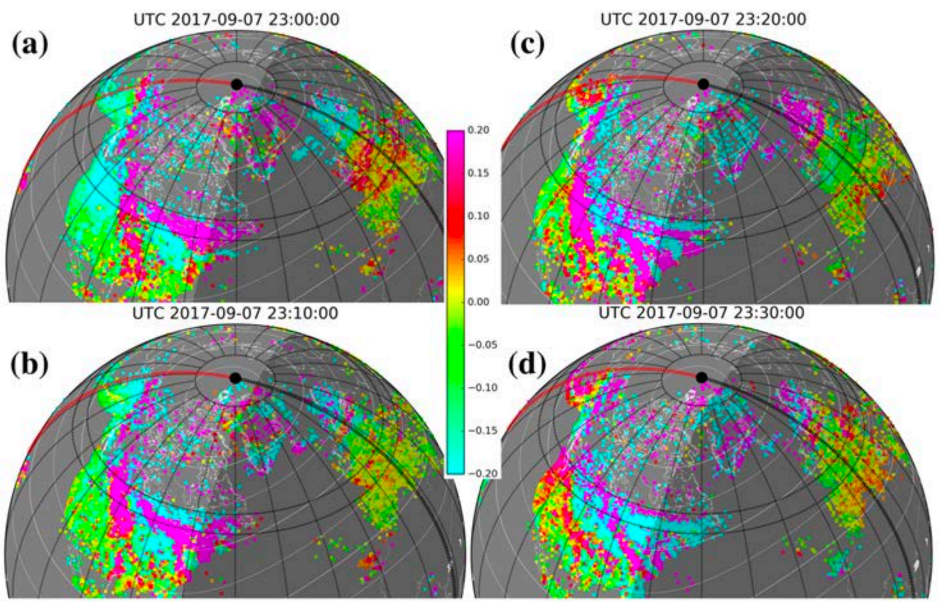
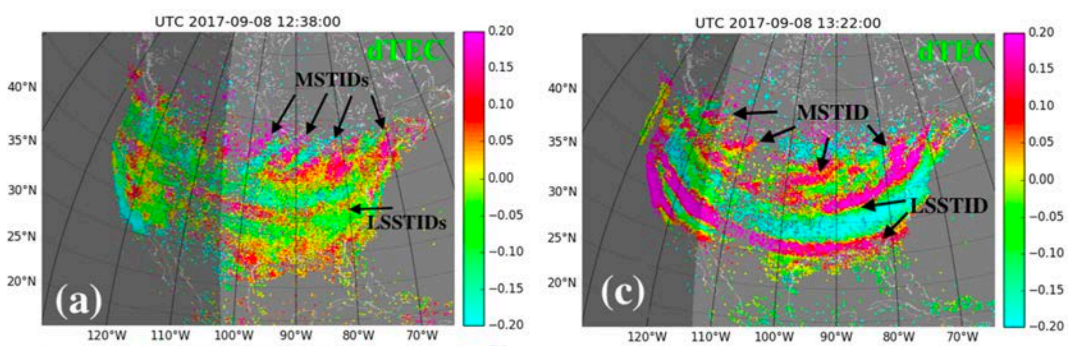


Figure 4. A sequence of TID maps between 2300 and 2330 UT on 7 September demonstrates dynamic evolution of concurrent large- and medium-scale TIDs near the dusk sector as a bright SAPS feature occurred. White thin lines mark the iso-apex latitude at a 10° interval. The double black circles mark the 45–50°N latitude range which is the cross section used for the keogram in Figure 5.

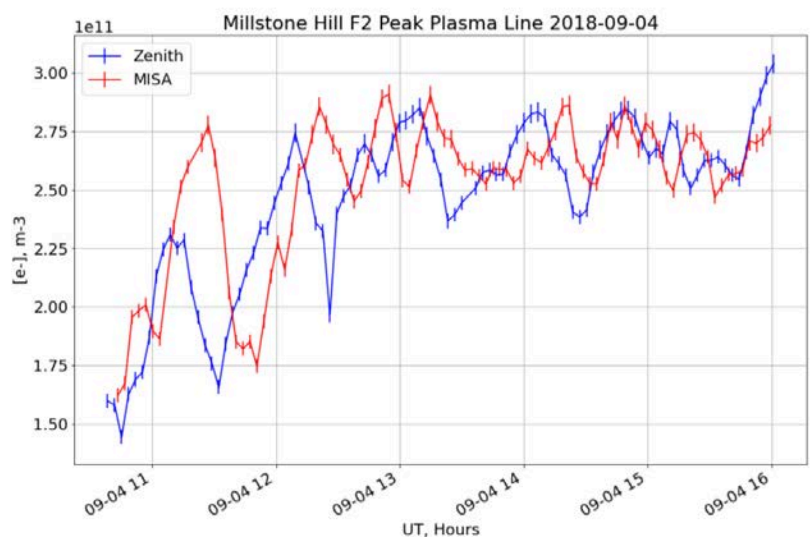


Large scale (LSTIDs): wavelengths > 1000 km, speeds 400 - 1000 m/s, periods 30 - 180 min
Mid scale (MSTIDs): wavelengths = 100s km, speeds = 100s m/s, periods 15-60 min

Zhang et al 2019 — Sep 2017 storm:

"LSTIDs and MSTIDs represent different modes of ionospheric waves and are excited through different physical processes. They are often observed and studied separately. [But there is] clear evidence of concurrent MSTIDs and LSSTIDs at midlatitudes for both dusk and dawn sectors."

Strong correlation between SAPS forcing and TIDs



Ion-Neutral Coupling: Traveling Atmospheric Disturbances (TADs)

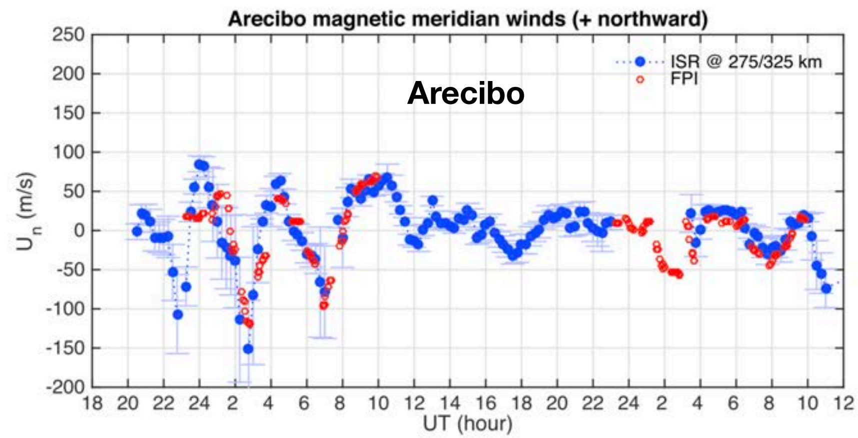


Figure 9. Same as Figure 7 but for the Arecibo site. The wind calculation here used a 1.3 Burnside factor for the O^+–O collision frequency correction.

Mar 2015 storm
Zhang et al 2017

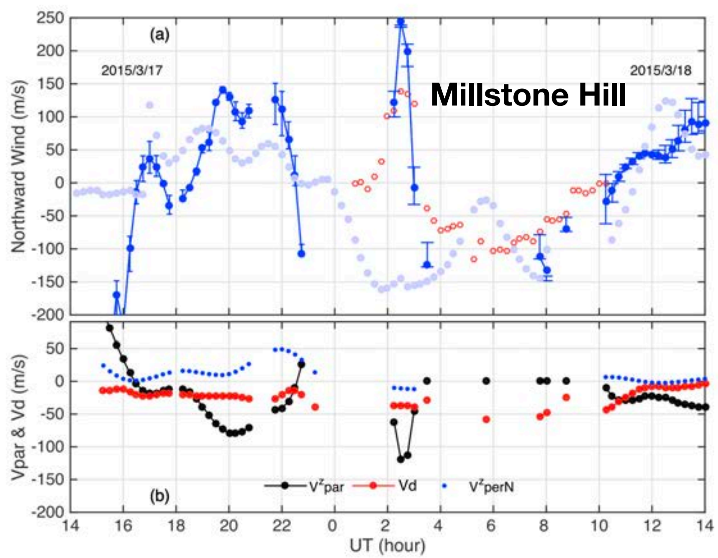


Figure 8. (a) Geomagnetic meridional winds at Millstone Hill, measured near the F_2 peak height by the ISR (blue) and by the on-site FPI (red). The blue error bars indicate the range of the wind magnitude within 20 km around the peak value. The light blue curve plots the same winds but for 20–21 March with quiet magnetic activity. (b) The diffusion velocity V_d, the field-aligned ion velocity V_{par} projected vertically V^z_{par}, and perpendicular northward velocity V_{perN} projected vertically V^z_{perN} are also shown as averages within 250–300.

During storms, neutrals get spun up by ions (and then affect ions through collisions)

TAD response can be different as a function of latitude
(Quasi periodic 2-3 hr oscillations)

Coupling between neutral atmosphere (TAD) and ionosphere (TID):
- Spatial scales?
- Temporal scales?

Ion-Neutral Coupling: Tidal Motions

Neutral atmosphere has tides
- Diurnal (24 hour)
- Semidiurnal (12 hour)
- Others (e.g. 8 hour)

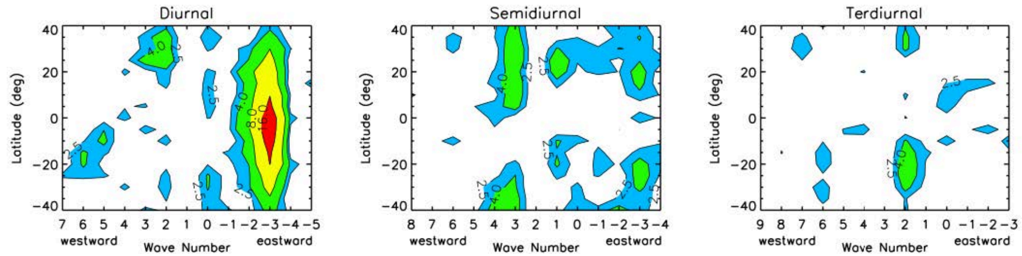
Longer period oscillations also happen: planetary waves
- 1, 2, 3, 5, more days..

Neutrals are coupled to the ions through e.g. collisions at E region altitudes, and vice versa

These tidal signatures appear in ionospheric data!
- Velocities
- Ion temperature
- More..

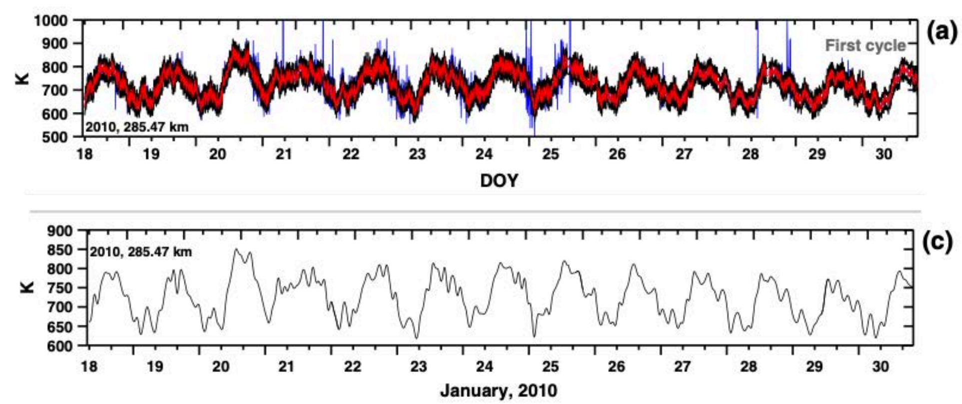
They can get perturbed:
<u>Sudden Stratospheric Warming</u>
[Goncharenko and colleagues]

Neutral atmosphere:
Thermospheric Tidal Modes (SABER on TIMED)



Forbes et al 2006 doi:10.1029/2005JA011492

Millstone Hill ion temperature over multiple days



Goncharenko et al 2013 doi:10.1029/2012JA018251