Inter-Hemispheric Differences in Magnetosphere-Ionosphere Coupling

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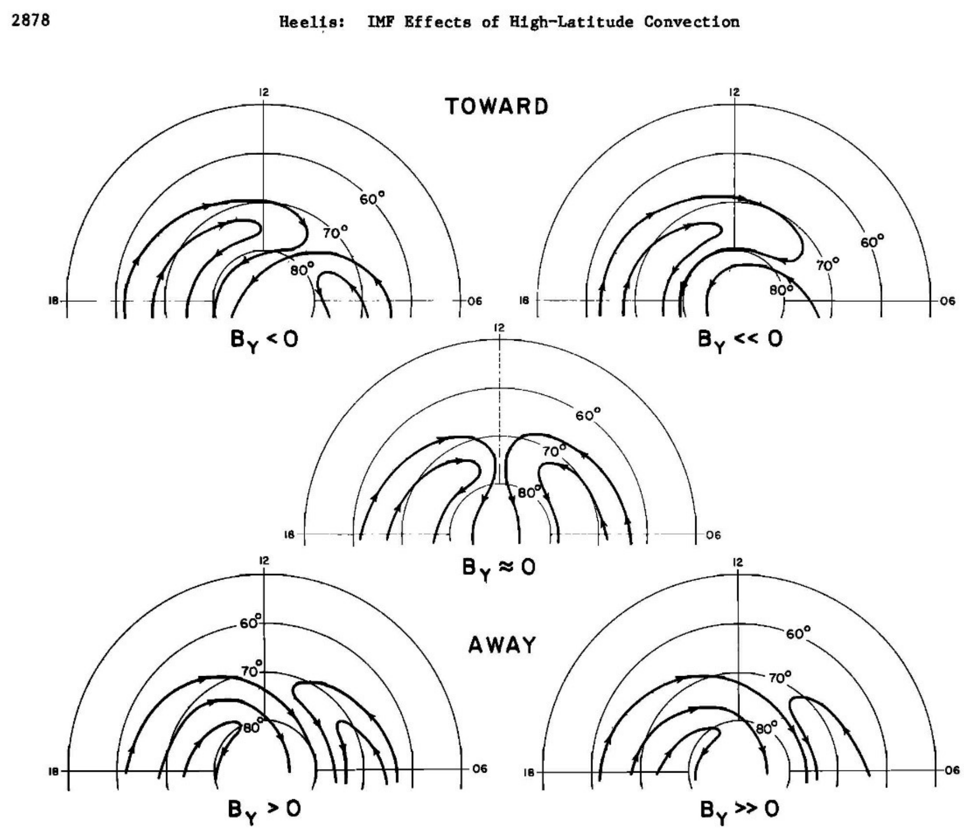
- Despite our simplified cartoons, significant difference exist between northern and southern hemispheres.
- I will focus on 3 main causes of this asymmetry:
  - IMF effects: B_y and B_x breaking of symmetry
  - Geomagnetic field effects: asymmetries in energetic particle precipitation
  - Ionospheric effects: seasonal differences, effects on M-I coupling and auroral particle acceleration

B_y effect on convection

- Observed convection pattern strongly dependent on IMF B_y (Heelis, 1984, right)
- Figure drawn for $B_z < 0$ and typical spiral IMF.
- Southern hemisphere pattern is reversed

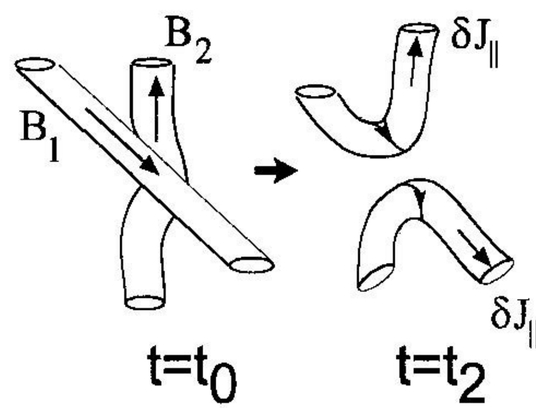


Note: $B_y << 0$ notation not very meaningful, better to say $B_y << B_x$

Asymmetric Reconnection with finite B_y

(Song, 1989, 1998; Song and Lysak, 2001)

- Reconnection does not generally happen along an extended X-line; diffusion regions are patchy.
- Approximate conservation of magnetic helicity yields twisting of reconnected flux tubes, generating field-aligned current
- Torques from **j×B** forces create vorticity to generate current
- Produces interhemispheric currents flowing from one ionosphere to the other, dependent on B_y
  - For $B_y > 0$, current flows from south to north
- Northern Hemisphere flux tube propagates toward dawn, southern hemisphere toward dush

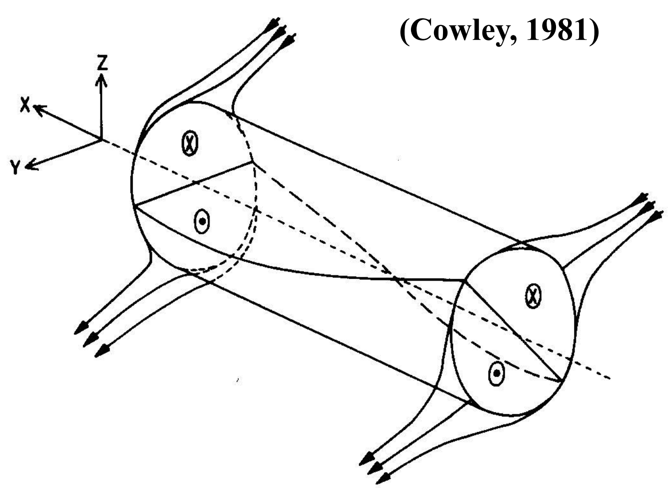


$B_z < 0$, $B_y > 0$ case, looking from Sun

“Penetration” of B_y onto closed field lines

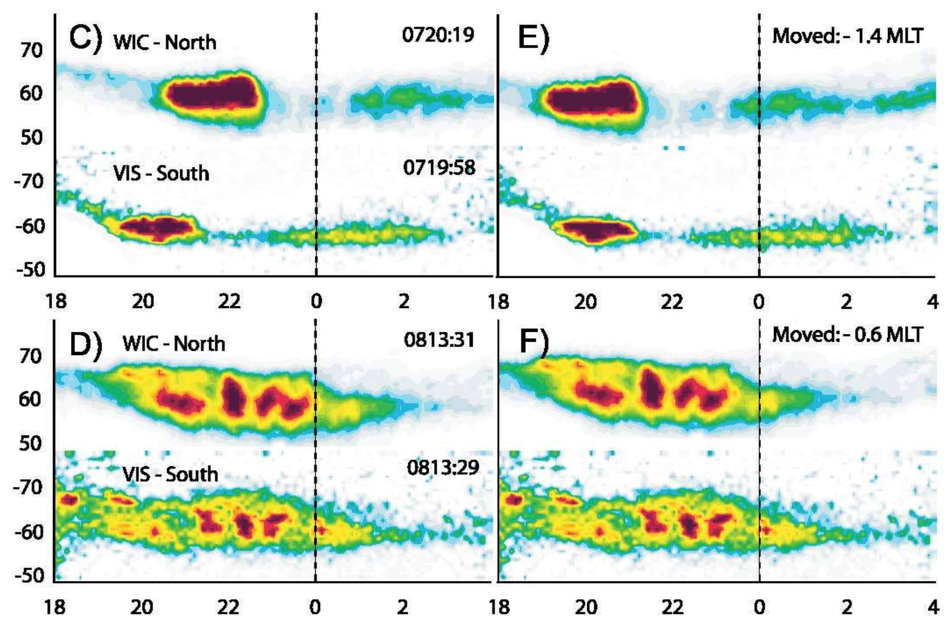
- For $B_y > 0$, asymmetry of reconnection leads to enhanced flux on northern dawn side and southern dusk (and vice versa for negative B_y)
- Often described as “penetration” of B_y, but this is not a physical process
- Tail reconnection with finite B_y would lead to enhanced B_y on closed field lines, as in Song (1989) process.
- Effects of this asymmetry can be seen ~ 10 minutes after IMF switch (Østgaard et al., 2011): too soon for tail reconnection to play a role.
  - ➢ Evidenced by MLT displacement of substorm onset locations
- Suggests enhanced asymmetric pressure can lead to fast mode front propagating onto closed field lines (Tenfjord et al., 2015), leading to finite B_y.
- B_y can also lead to twisting of tail (Cowley, 1981) with reversed sign to IMF; Tenfjord et al. (2017) note this is small effect in inner magnetosphere

Magnetospheric asymmetries associated with y-component of IMF



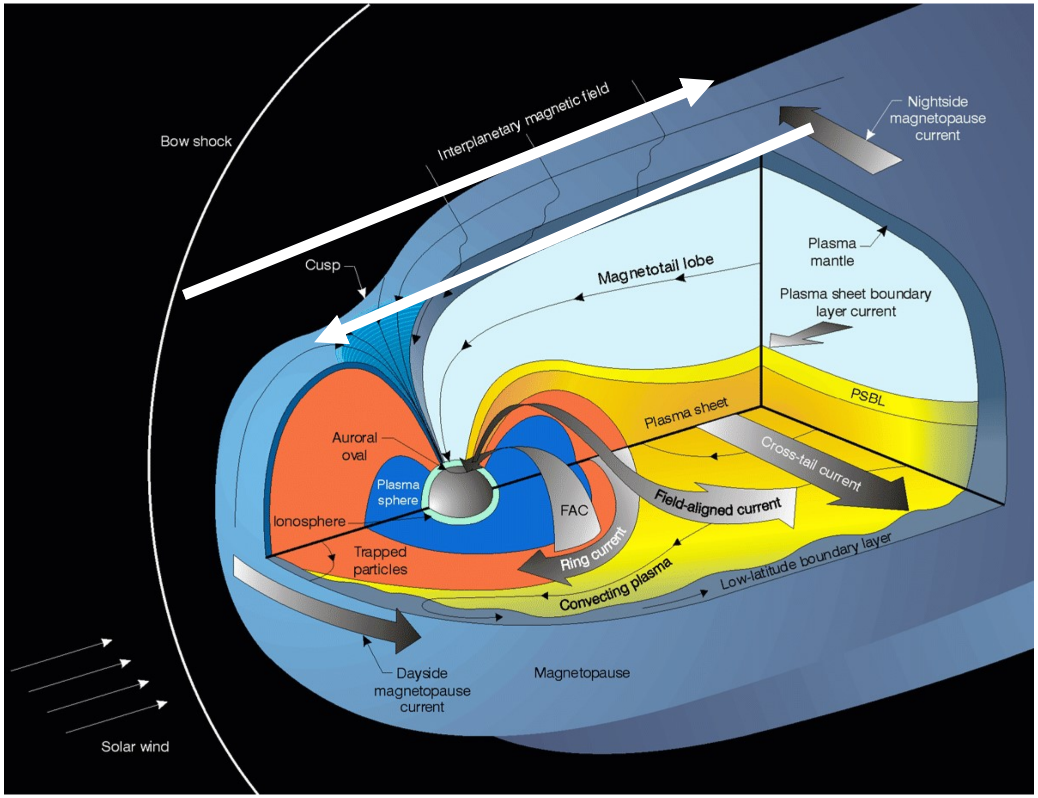
Displacement of Aurora in MLT

- Østgaard et al. (2011) showed displacement of aurora in MLT during substorm development from IMAGE-WIC instrument (north) and Polar-VIS (south)
- Panels (c) and (d) show aurora in north and south at two stages of substorm development
- Using correlation technique, panels (e) and (f) show southern aurora displaced by 1.4 and 0.6 MLT, respectively
- Suggests B_y effect causing footpoints of field lines to be displaced in MLT



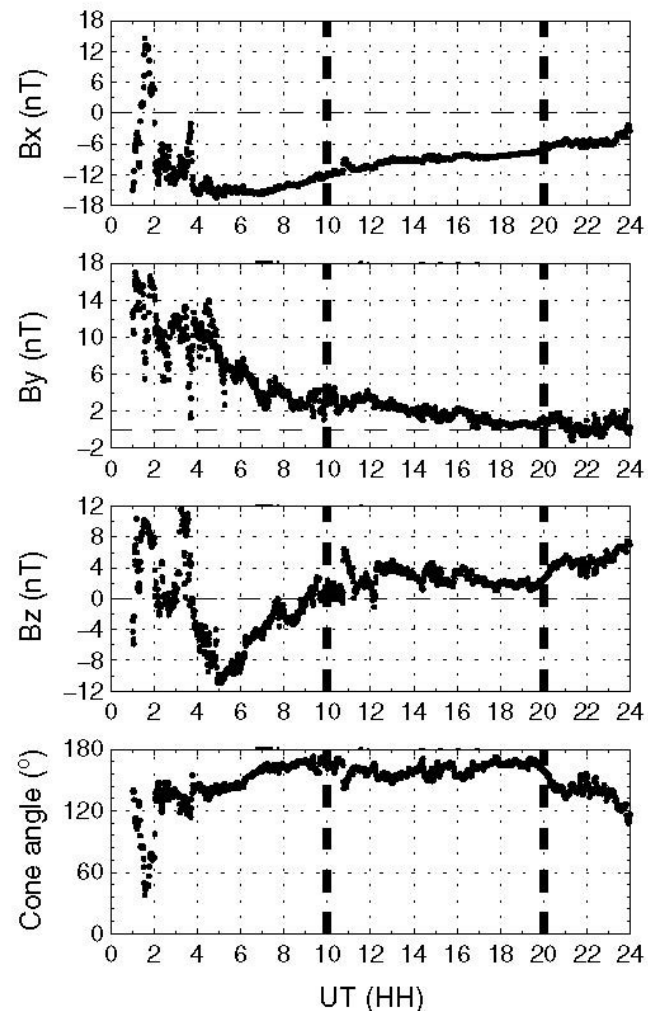
IMF B_x effect

- Radial IMF B_x can lead to interhemispheric asymmetry, especially in solstice conditions.
- For $B_x < 0$ (radial toward Earth), IMF is antiparallel with sunward directed lobe field in north, but is parallel in south, especially in northern summer when cusp tilted toward Sun
  - Opposite for $B_x > 0$
- Lobe reconnection leads to sunward flows poleward of the cusp



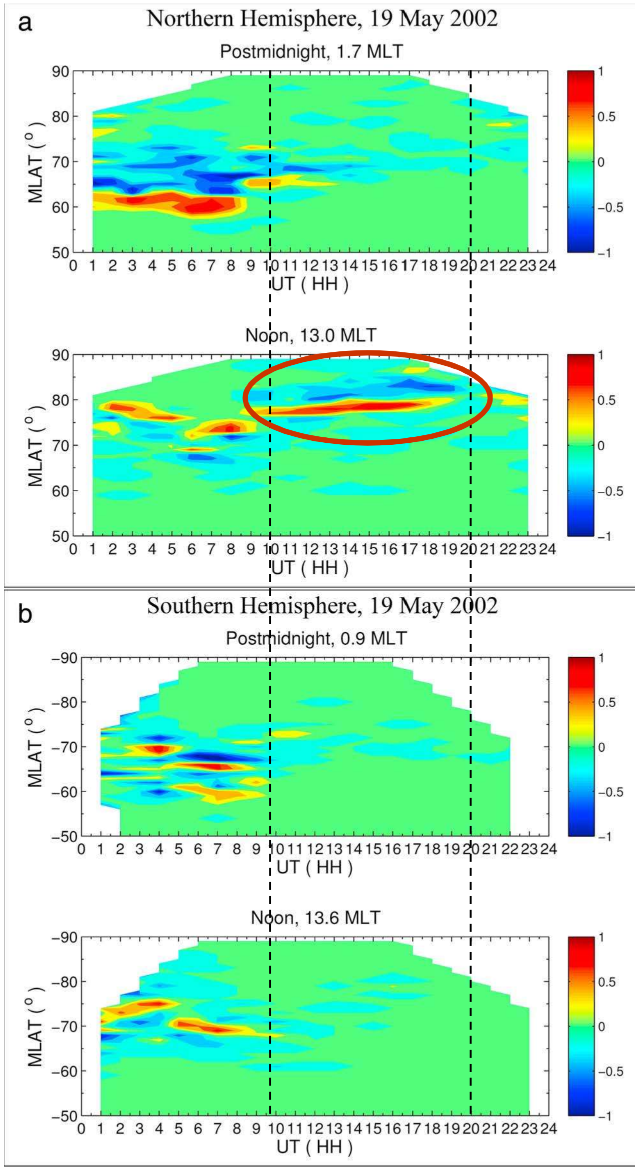
Example of B_x associated currents

- Wang et al. (2014) considered event of 19 May 2022
- IMF (from ACE) showed persistent period of strongly negative B_x, weak positive B_y and weak northward B_z
  - Cone angle nearly 180°
- Sunward flow (from DMSP, not shown) seen poleward of northern cusp, suggestive of reconnection between radial IMF and earthward lobe field
- Focus on period from 10-20 UT



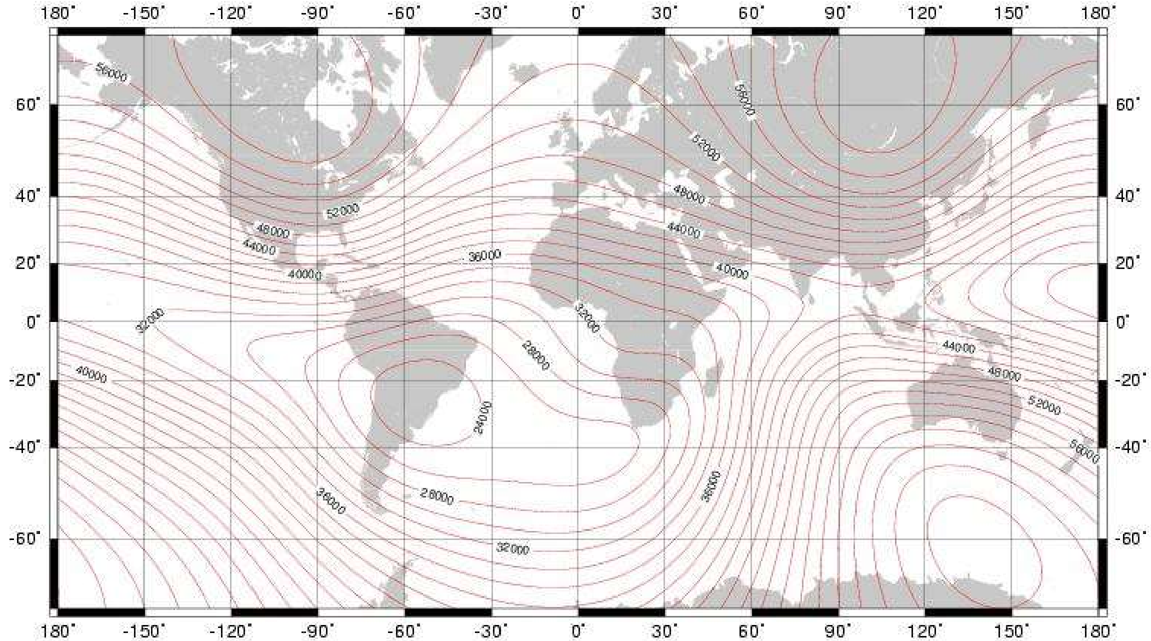
FAC from lobe reconnection

- Strong pair of FAC seen on northern dayside by CHAMP
- No corresponding currents on nightside or in southern hemisphere
- Sense of FAC is consistent with helicity conservation during lobe reconnection



Asymmetry due to Geomagnetic Field

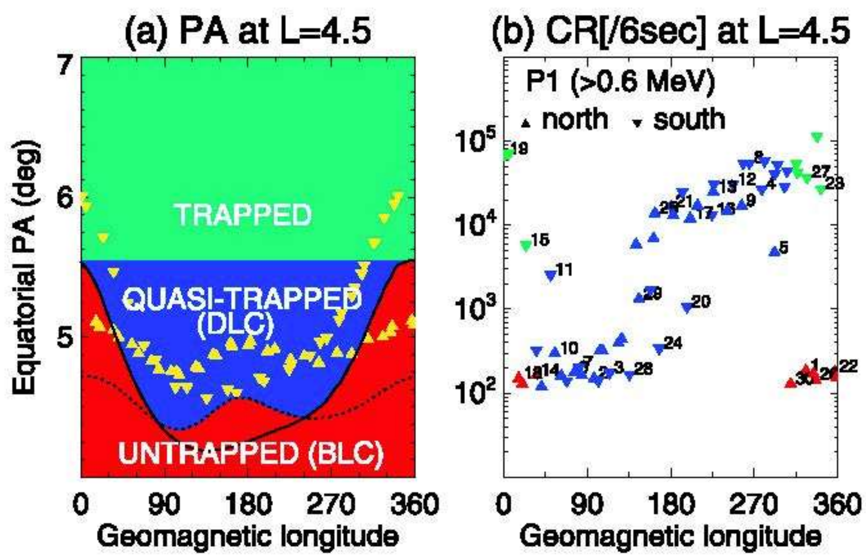
- Asymmetry of Geomagnetic field leads to differences in energetic particle precipitation
- Especially prevalent in South Atlantic Anomaly region: low magnetic field strength, favors precipitation



Total intensity (*F*) at 2005.0 from the World Magnetic Model (WMM2005). Contour interval is 2000 nT and projection is Mercator. This is an example of an isodynamic chart. Credit: British Geological Survey (Natural Environment Research Council).

Drift loss cone

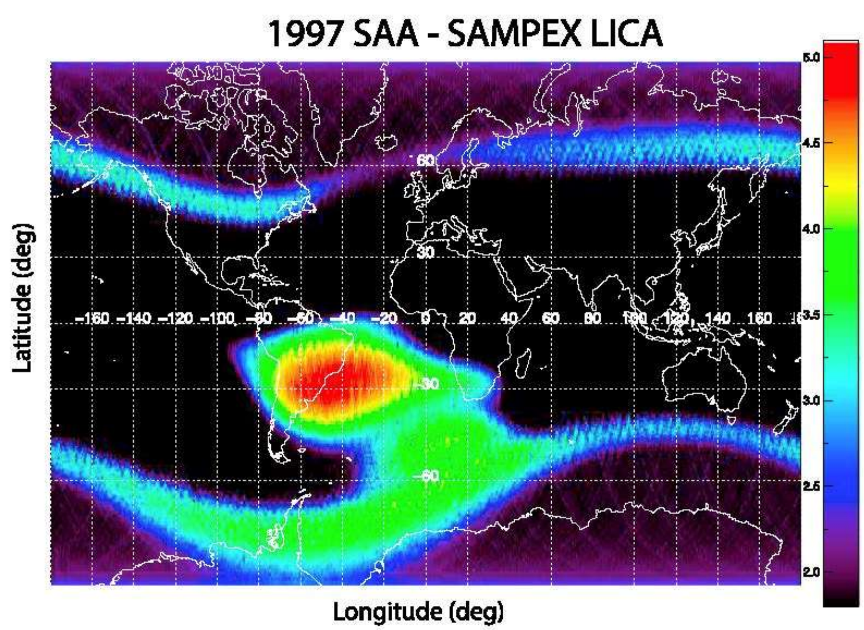
- Low magnetic field strength means mirror points reduced in altitude, more precipitation
- Energetic particles executing gradient-curvature drifts eventually find themselves in SAA region: “drift loss cone”
- Eastward drifting electrons in drift loss cone (in blue in panel b) show sudden dropout when reach SAA region



(Tu et al., 2010)

Enhanced Precipitation in SAA

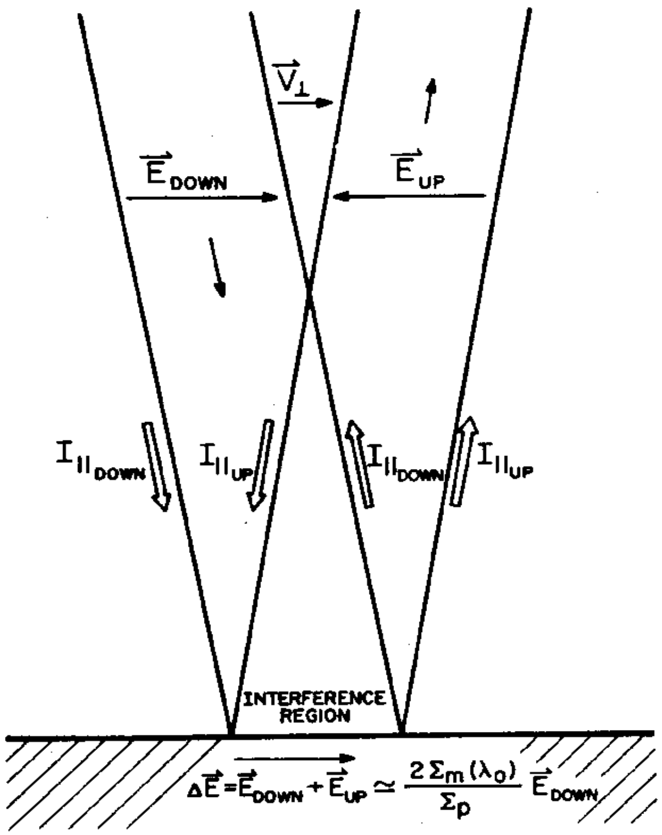
- SAMPEX measurements of energetic protons (> 0.76 MeV) and electrons (> 0.6 MeV) show clear signature of SAA (Jones et al., *Space Weather,* 2017).
- Note lack of precipitation in northern conjugate region: particles lost in SAA.



Ionospheric Asymmetries

- Ionospheric conductivity is plays an important role in the coupling of magnetosphere and ionosphere.
- Two major sources of conductivity variation:
  - Sunlight: Produces day/night asymmetries, and during solstice, inter-hemispheric differences near terminator
  - Precipitation: Localized enhancement of conductivity, can give rise to feedback interactions.
- Interaction of ionosphere with ULF waves is key to understanding dynamics of M-I coupling

Reflection of Alfvén Waves by the Ionosphere



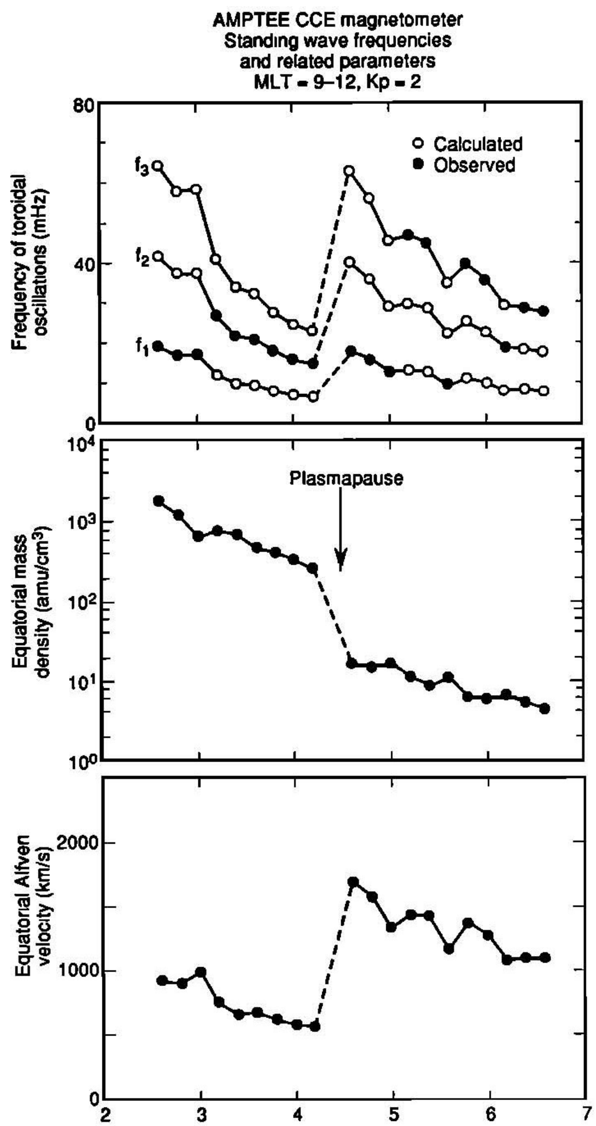
(Mallinckrodt and Carlson, 1978)

- Ionosphere acts as terminator for Alfvén transmission line, with admittance $\Sigma_A = 1/\mu_0 V_A$.
  - $\Sigma_A = 0.8$ mho/V_A (1000 km/s)
- But, impedances don't match: wave is reflected
- Usually $\Sigma_P >> \Sigma_A$, so electric field of reflected wave is reversed ("short-circuit")
- Reflection coefficient:

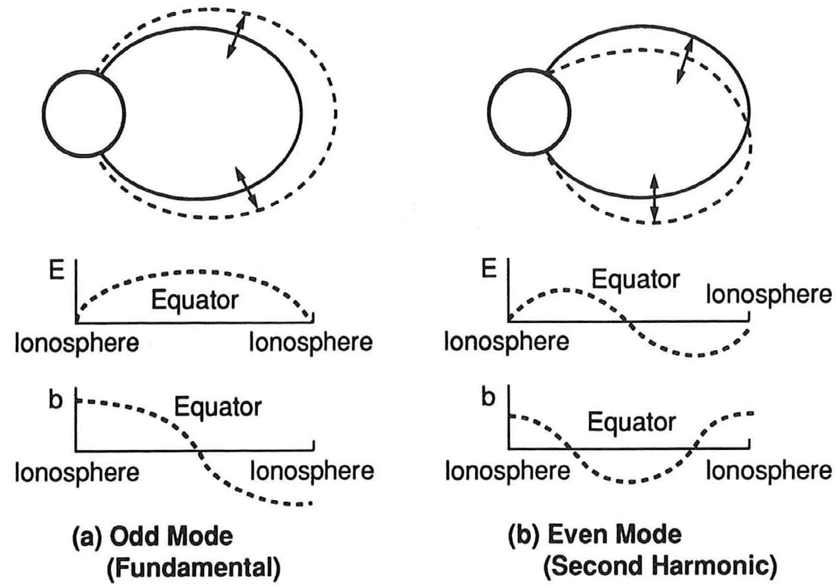
$$R = \frac{E_{up}}{E_{down}} = \frac{\Sigma_A - \Sigma_{P,eff}}{\Sigma_A + \Sigma_{P,eff}}$$

- Effective Pedersen conductivity modified by Hall conductance, parallel electric fields

Alfvén Waves are like waves on a string: Field Line Resonances



Takahashi and Anderson, 1992



Kivelson and Russell, 1995

Above: Harmonic structure of FLR. Note that highly conductive ionosphere leads to node in electric field.

Left: Observations of Field Line Resonance frequencies. Top panel gives first 3 harmonic frequencies, middle gives inferred density profile and bottom is inferred Alfvén speed: frequencies ~ 10-20 mHz (50-100 sec period)

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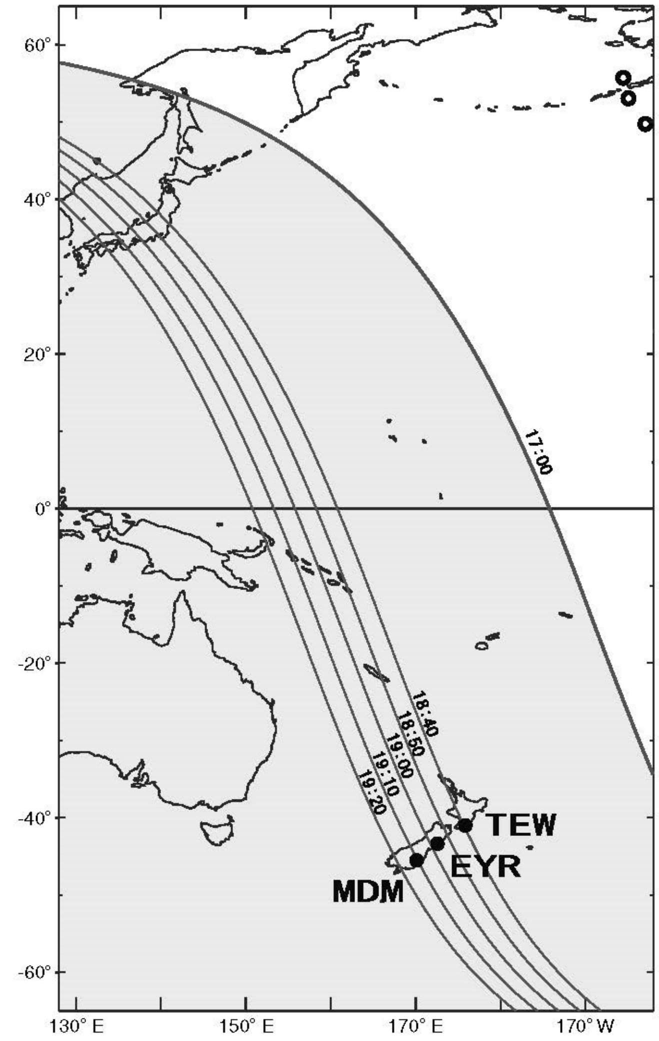
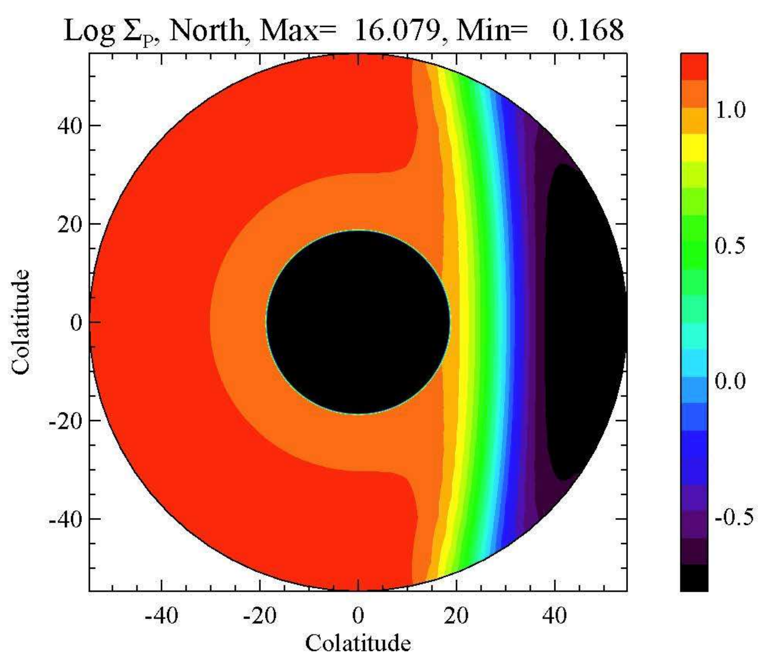
Quarter-wave modes

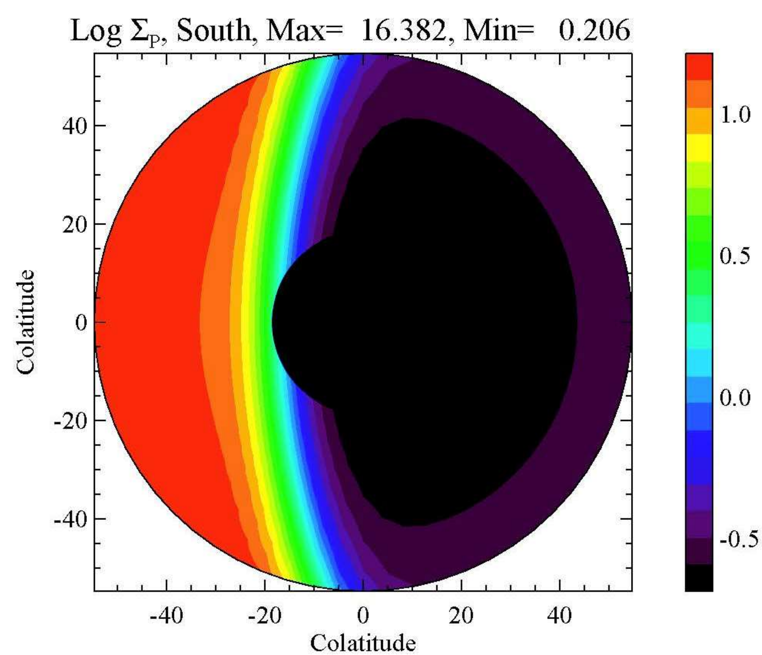
- Normally, FLR has nodes in electric field at conducting ionosphere, with field line being half the total wavelength of the wave
- However, if one hemisphere in darkness while the other is sunlit, electric field has node in lit hemisphere and antinode in darkness: Quarter waves
- Quarter waves have lower frequency, broader resonance width than usual FLR (Obana et al., 2015)
- Quarter waves observed on 22 July 2012 from New Zealand



Modeling Seasonal Conductivity Differences

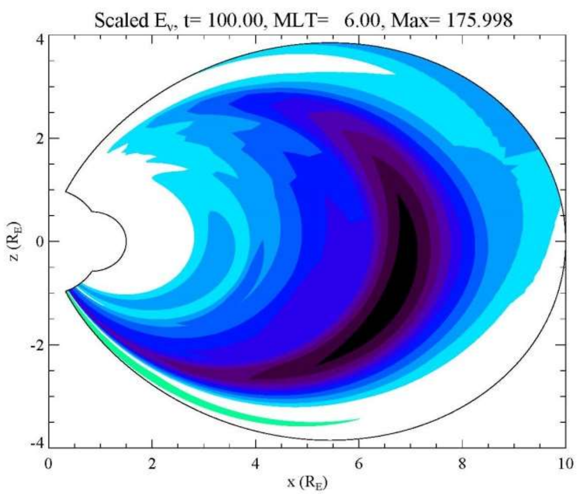
- Quarter-wave modes explored in 3D ULF wave model in dipole geometry
- Sun is placed at 23° North: solstice conditions
- Ionosphere varies from daytime profile to nighttime profile based on solar zenith angle:



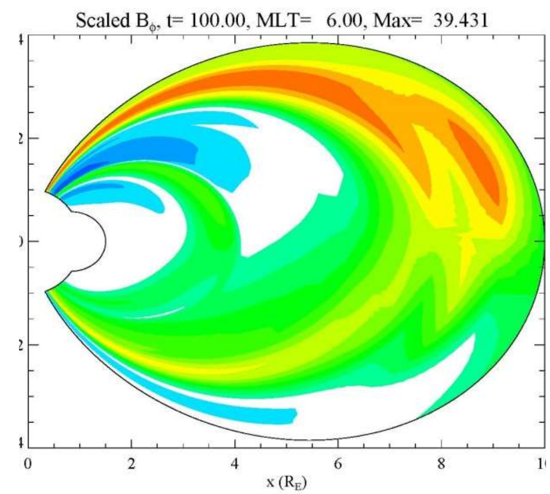


Northern Summer: Search for ¼ waves

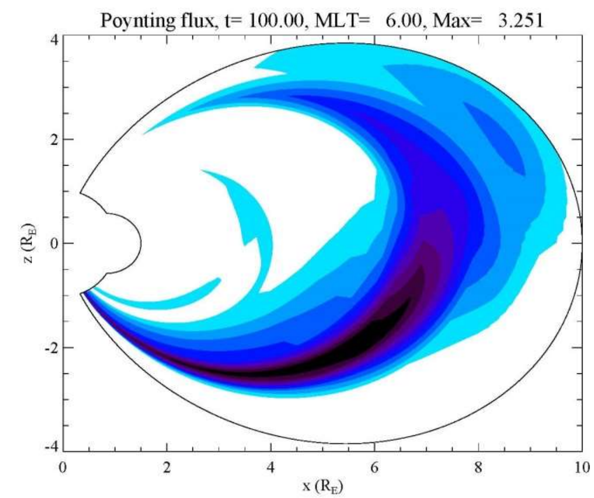
- System driven at 100 second period on dayside
- Fields shown at dawn terminator (MLT = 6)
- Electric fields stronger in winter hemisphere, magnetic field in summer
- Poynting flux directed toward winter hemisphere (agrees with statistical results of Junginger et al., 1985)
- In contrast to symmetric case, field-aligned current flows from one hemisphere to the other (contours of B_φ approximate current flow lines)



Electric field E_ν



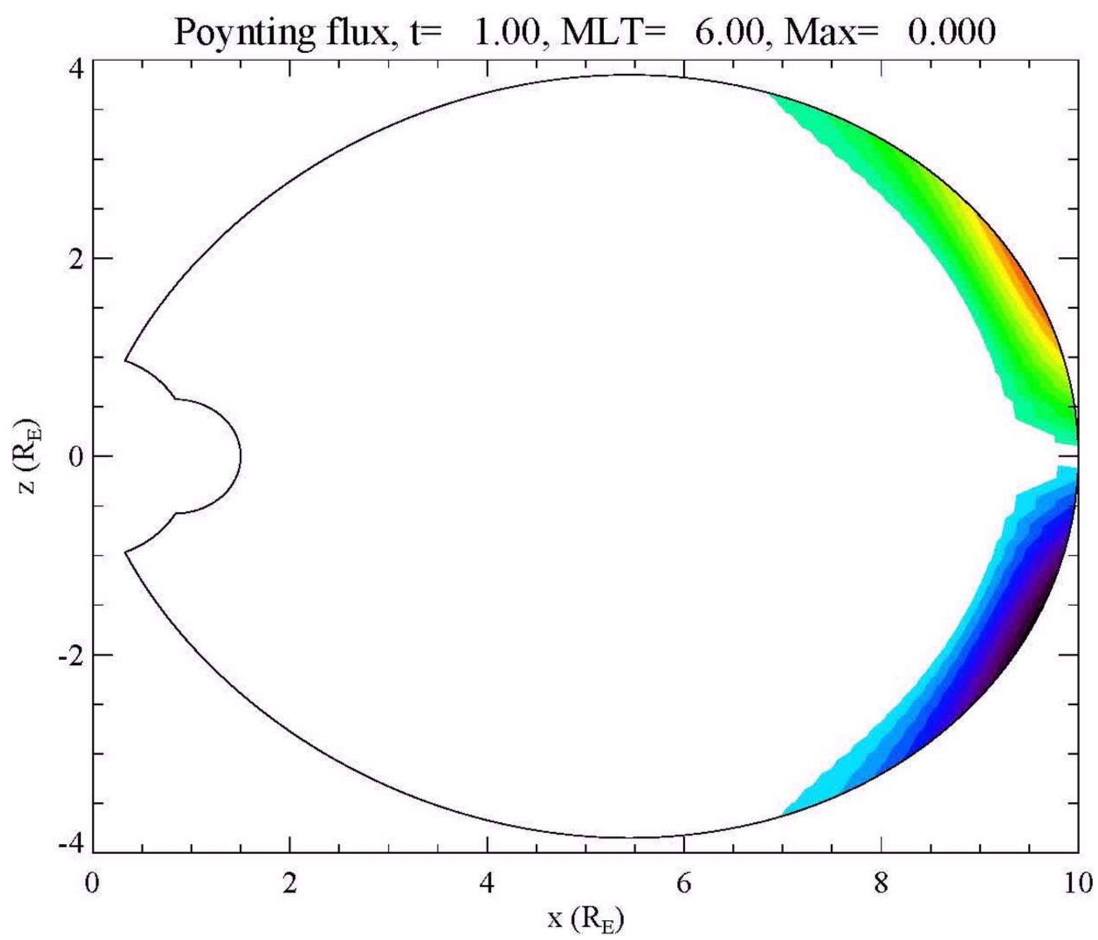
Magnetic field B_φ



Field-aligned Poynting flux (blue southward)

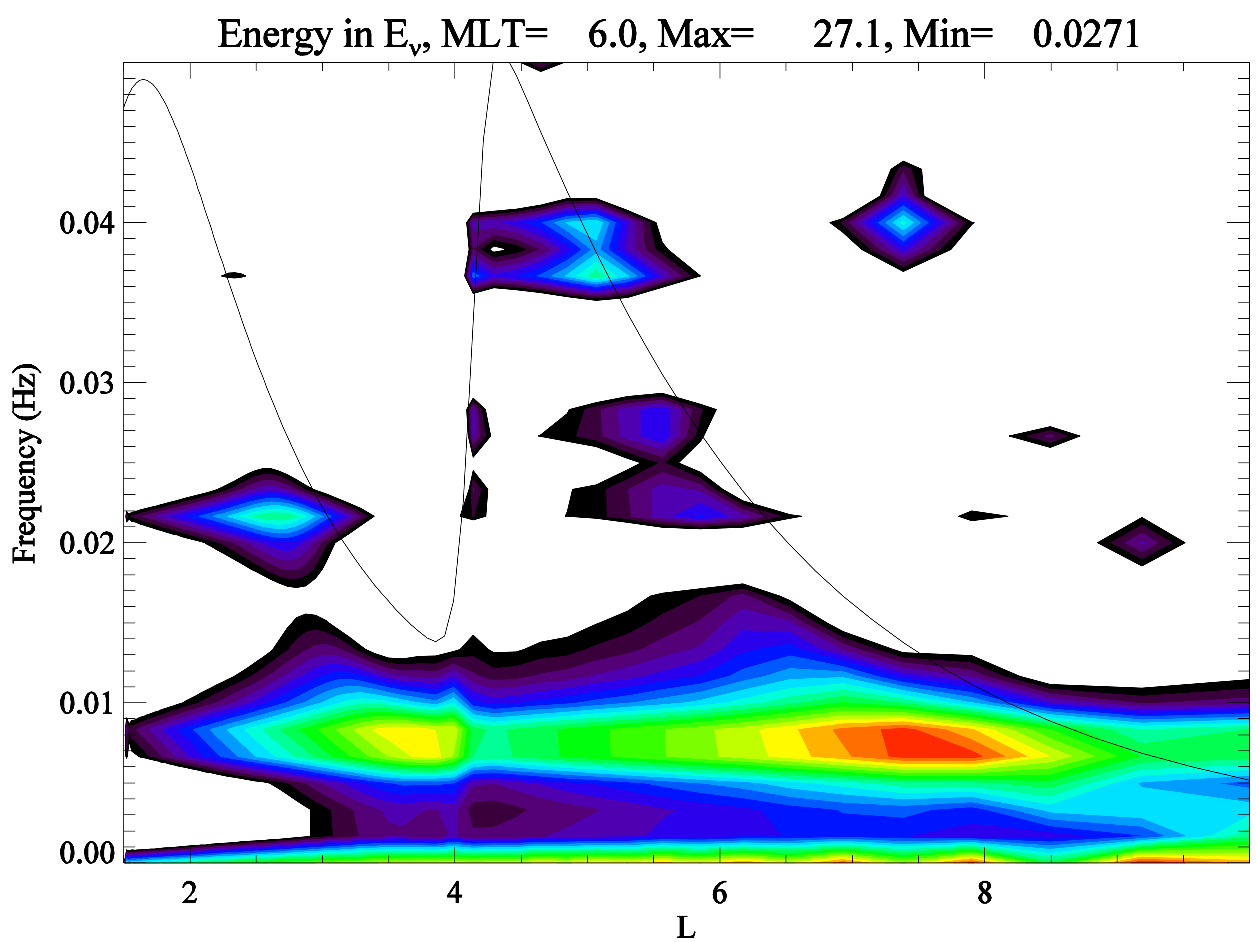
Poynting Flux at 6 MLT

- Northern summer conditions at dawn terminator
- Red/green toward north, purple/blue toward south



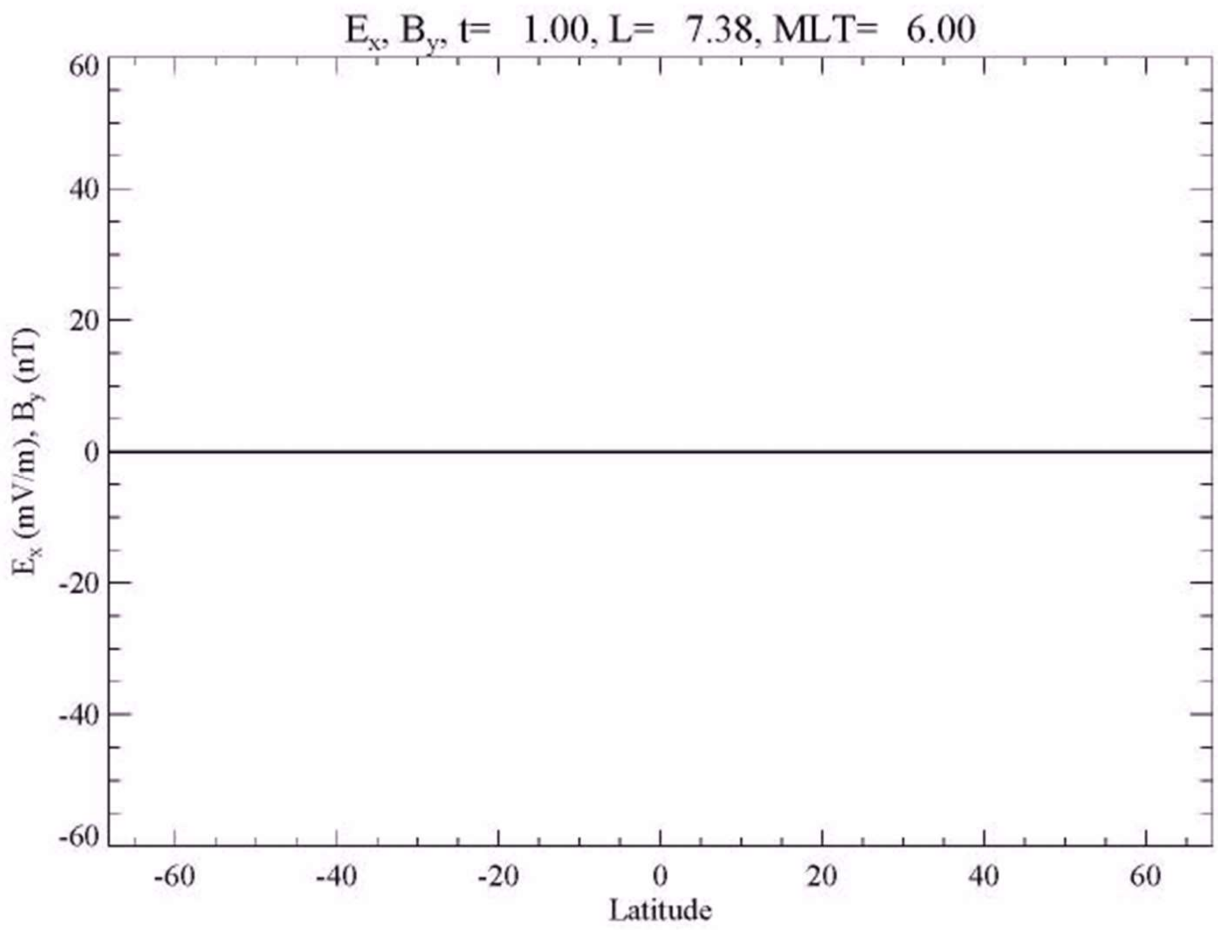
Energy Density in Toroidal Field 6 MLT

- Energy density plotted as function of L shell and frequency
- Black line indicates fundamental FLR period



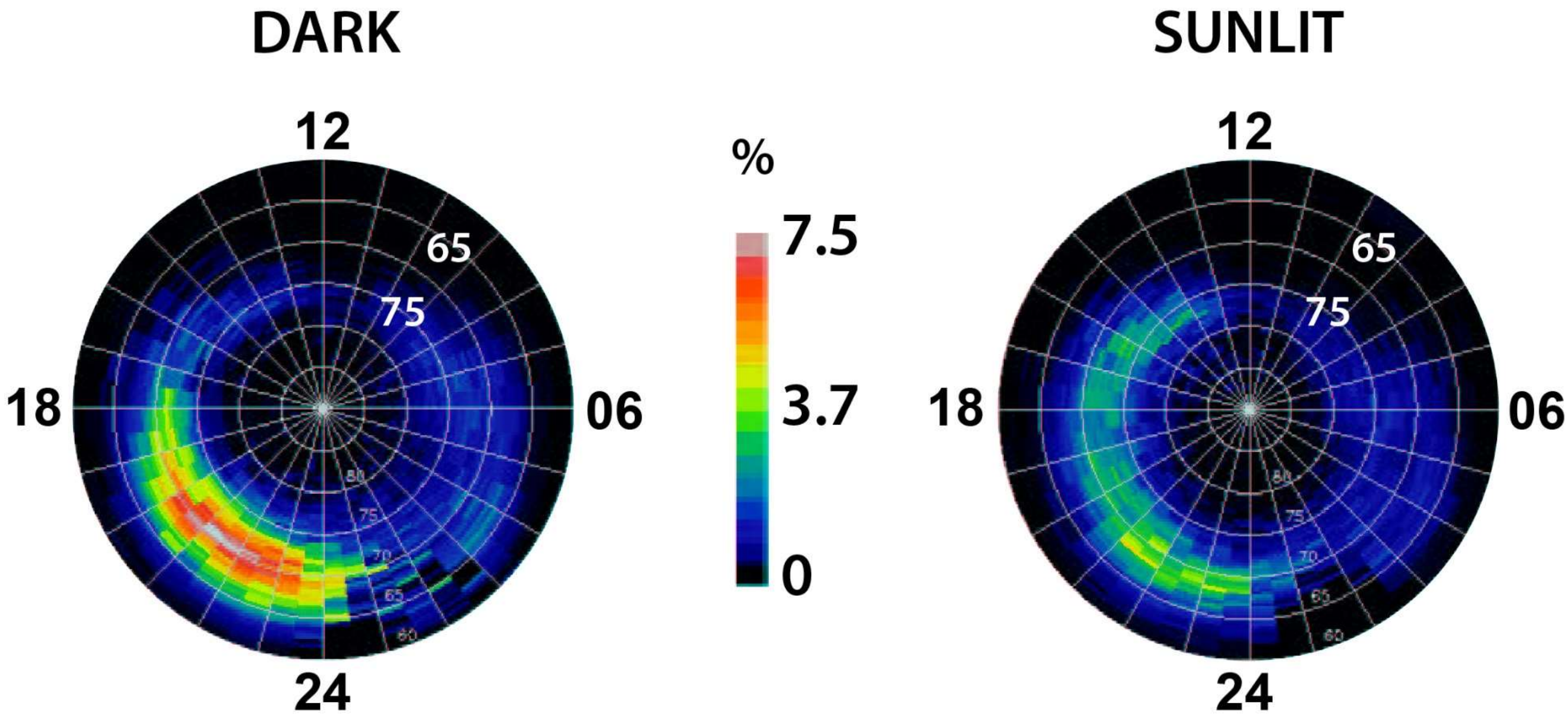
Fields Along L=7.5, MLT=6 Field line

- Toroidal electric field (solid line) and magnetic field (dashed) along field line
- Electric field has antinode in southern (winter) hemisphere, node in north (summer)



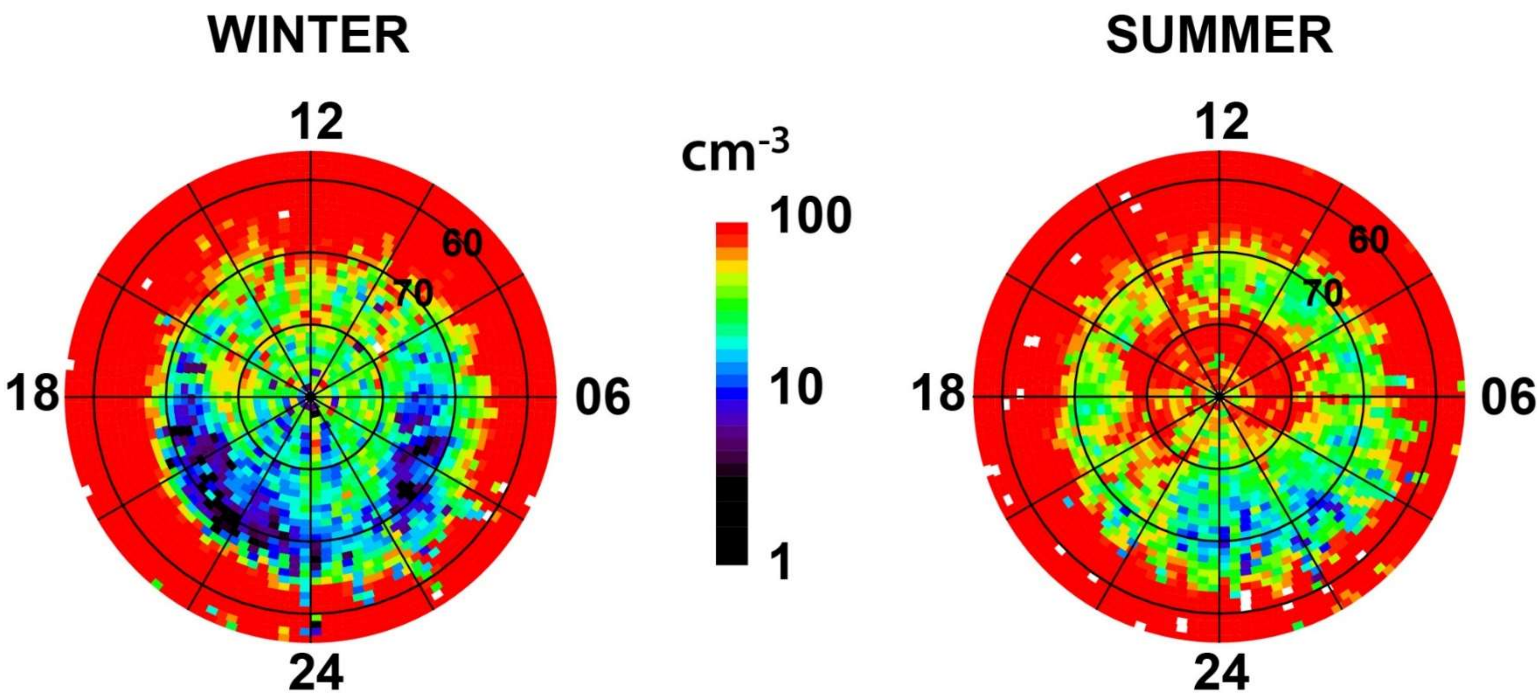
Asymmetries in the Aurora

- Newell et al. (1996) compared auroral energy flux in darkness vs. in daylight
- DMSP observations of probability of precipitating energy flux > 5 mW/m^2



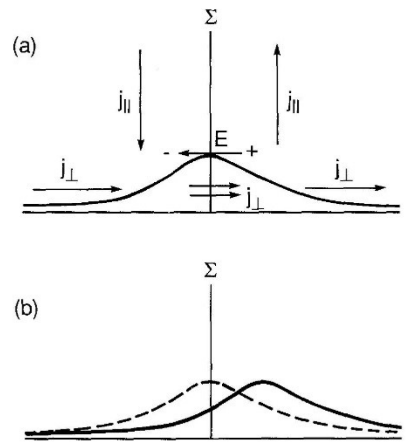
One possibility: density in auroral acceleration region

- Using Polar data, Johnson et al. (2001) showed that plasma density at 1 R_E altitude is lower in winter than in summer
- Lower density requires potential drop to carry field-aligned current, leading to auroral particle acceleration

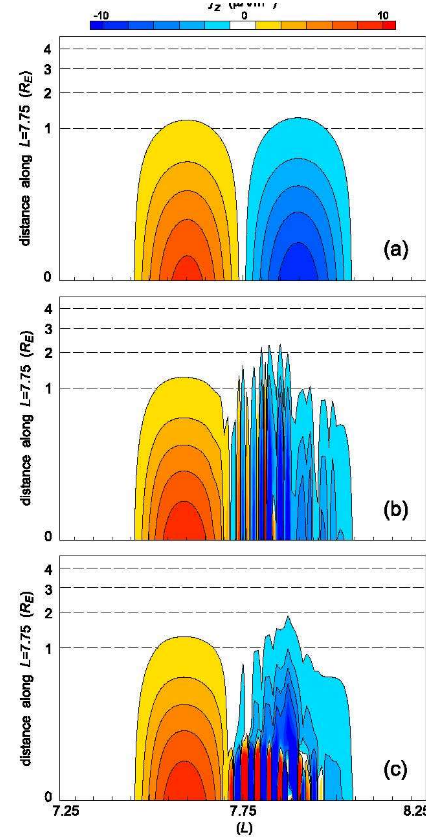


Ionospheric Feedback

- In presence of background convection, fluctuations in conductivity can give rise to a feedback interaction
  - Conductivity enhancement requires either polarization electric field or closure of enhanced currents by field-aligned currents
  - Upward field-aligned current (downward electrons) can enhance conductivity
  - Reflections in IAR or from conjugate ionosphere can lead to instability
- Small-scale structures can form in large-scale downward current regions (blue and violet in lower figure)
- Scale size limited by parallel resistivity, < 1 km
- However:
  - Theory has only been developed with height-integrated conductivity (but see Sydorenko and Rankin, 2017)
  - Convincing observations of this process have been rare (e.g., Cohen et al., *JGR*, 2013)



(Lysak, 1990)

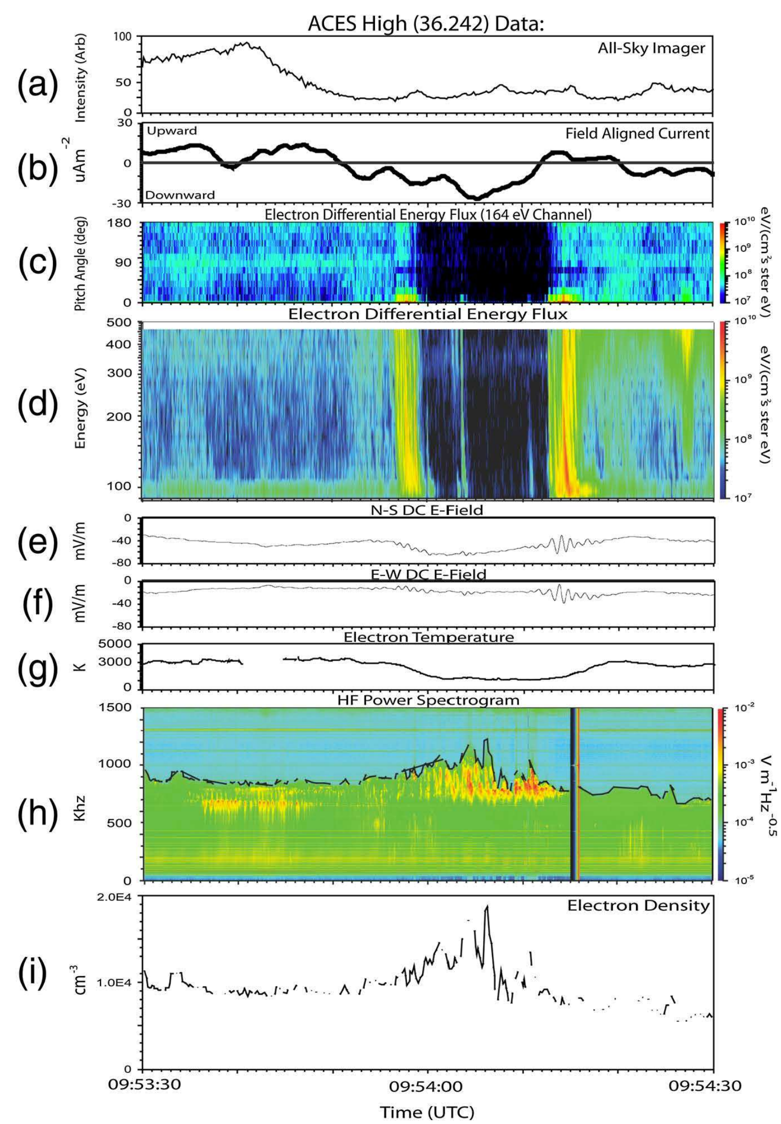


(Streltsov and Lotko, 2008)

Feedback Observation?

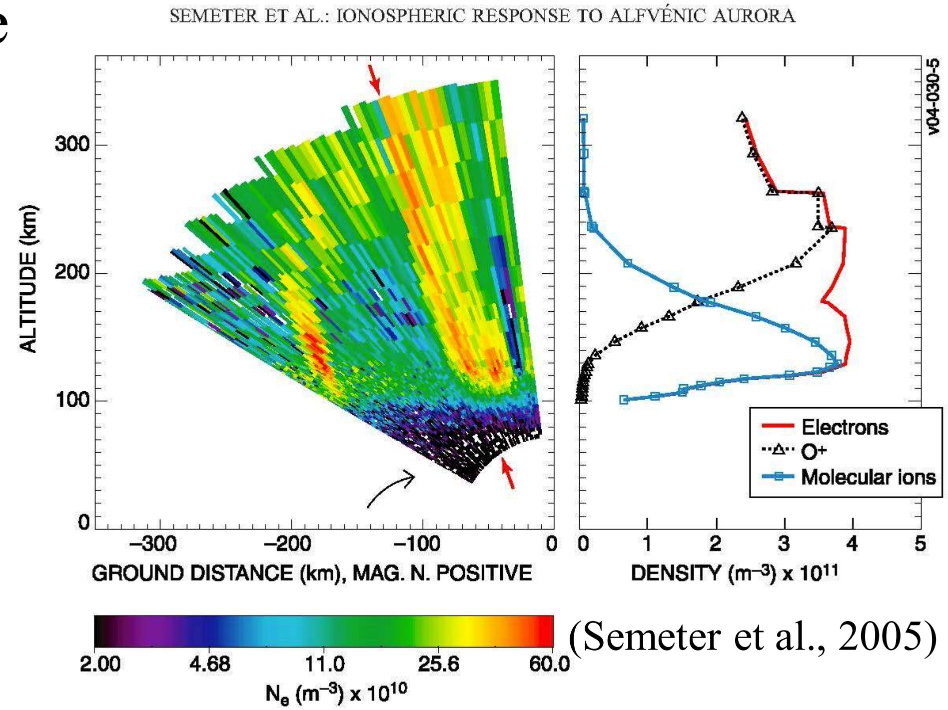
- Cohen et al. (2013) show observations consistent with ionospheric feedback instability.
- Strong regions of Alfvénic (broadband) electron precipitation at edges of downward current regions.
- Density fluctuations and a lack of energetic particles indicate possible feedback interactions.

COHEN ET AL.: ACES OBSERVATIONS OF IFI



Horizontal Gradients

- Ionosphere is not only vertically stratified (as assumed in most M-I coupling models), but can have perpendicular gradients
  - Especially true in auroral ionosphere where localized electron precipitation can give columns of ionization
- Gradients in Alfvén speed can give rise to phase mixing, producing smaller-scale, intense field-aligned currents
- In presence of background convection, conductivity gradients can also lead to strong currents



(Semeter et al., 2005)

Summary: Interhemispheric asymmetries in solar wind-magnetosphere-ionosphere interactions

- IMF B_y leads to hemisphere-dependent skewing of magnetospheric convection, currents, and aurora
- IMF B_x is parallel to lobe field in one hemisphere and antiparallel in the other, leading to asymmetric coupling
  - Effect enhanced due to dipole tilt
- Geomagnetic field asymmetry affects energetic particle precipitation, particularly in South Atlantic Anomaly
  - Leads to differences in ionospheric conductance
- ULF wave energy preferentially absorbed in low conductivity ionosphere, leading to quarter-wave resonances
- Auroral precipitation seems to favor dark ionosphere
  - Low density in acceleration region favors parallel electric fields
  - Ionospheric feedback structures currents, especially in dark ionosphere