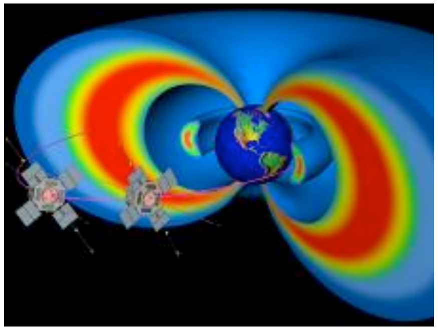


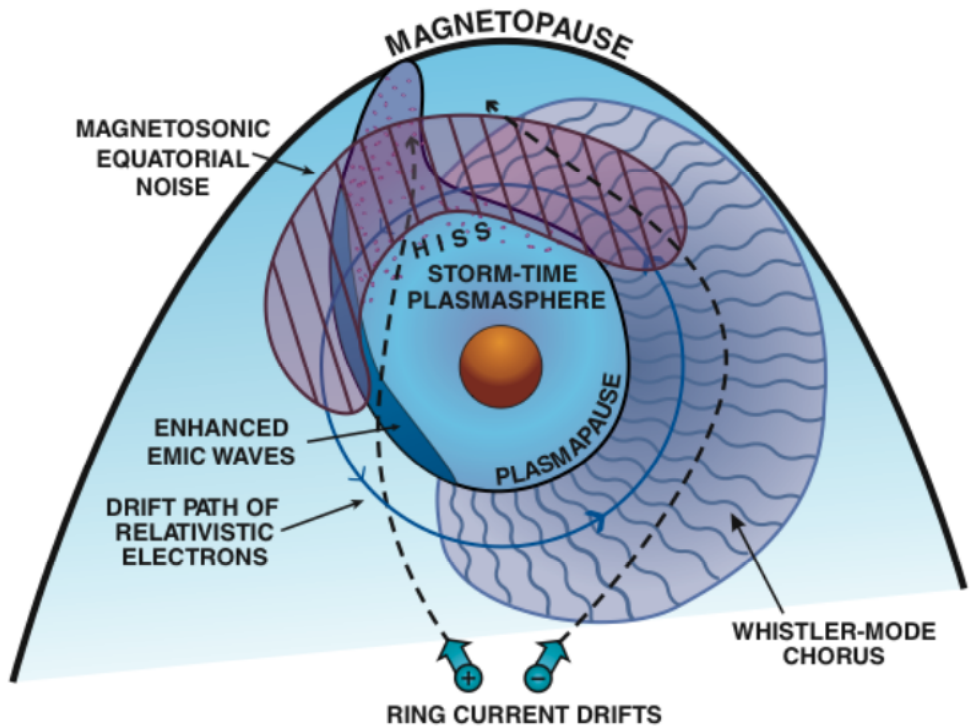
Radiation Belt Storm Probes
Science Working Group meeting
May 16-17th, 2012

Chorus, hiss, the pulsating aurora and RBSP

Jacob Bortnik
UCLA, NJIT visiting scholar

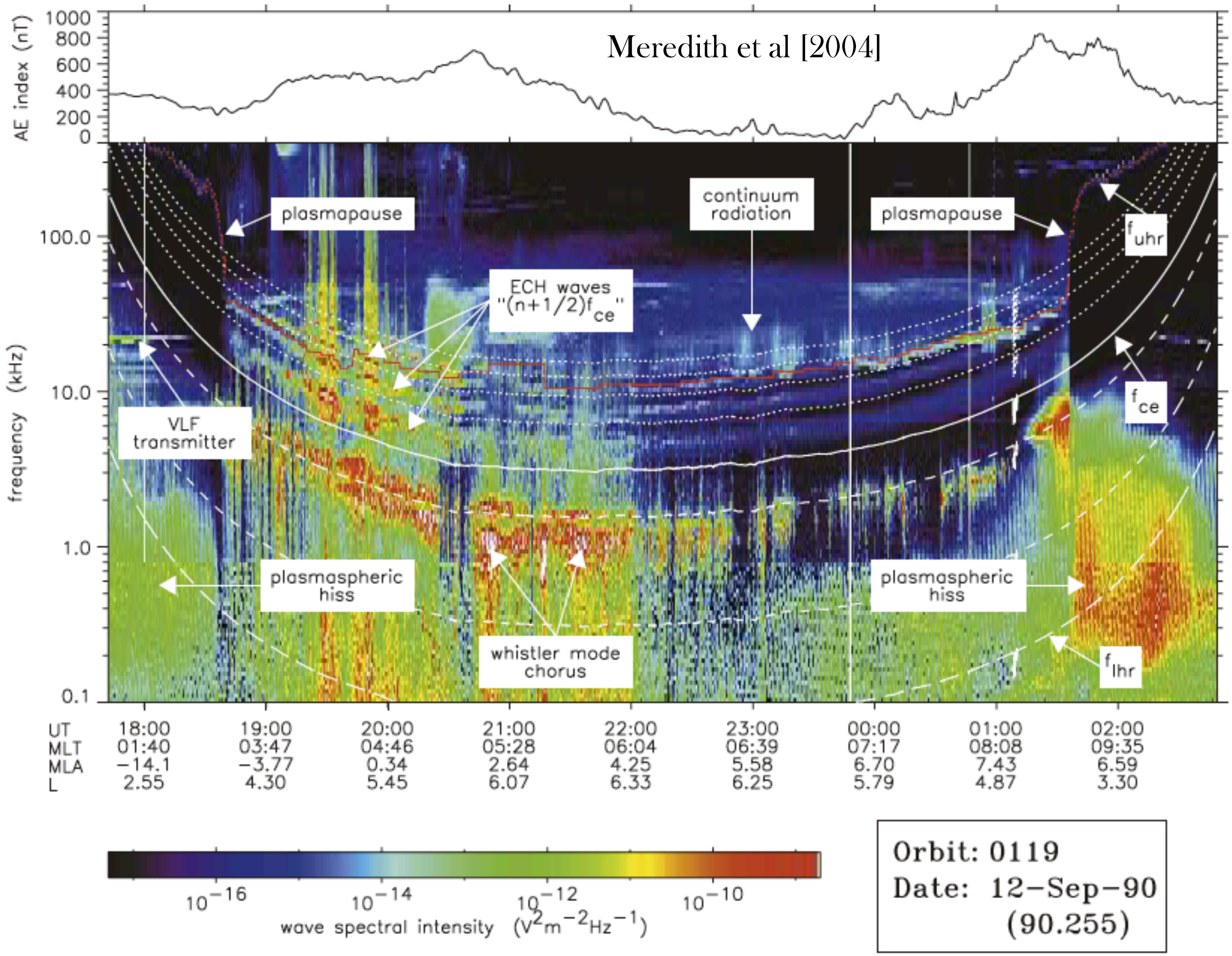
Collective wave effects

- Particles drift around the earth
- Accumulate scattering effects of:
  - ULF
  - Chorus
  - Hiss (plumes)
  - Magnetosonic
- Characteristic effects of each waves are different and time dependent



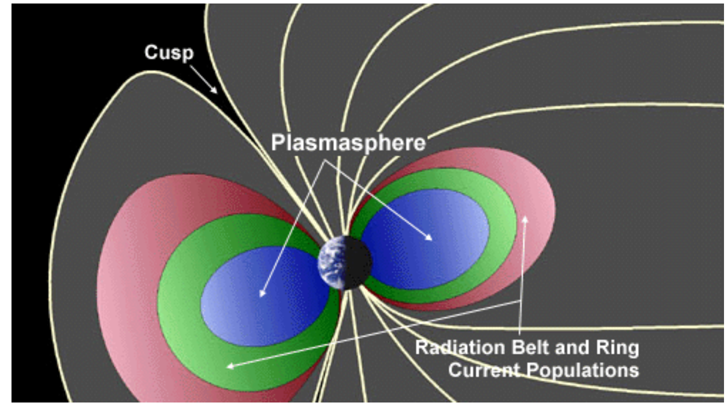
Thorne [2011] GRL "frontiers" review

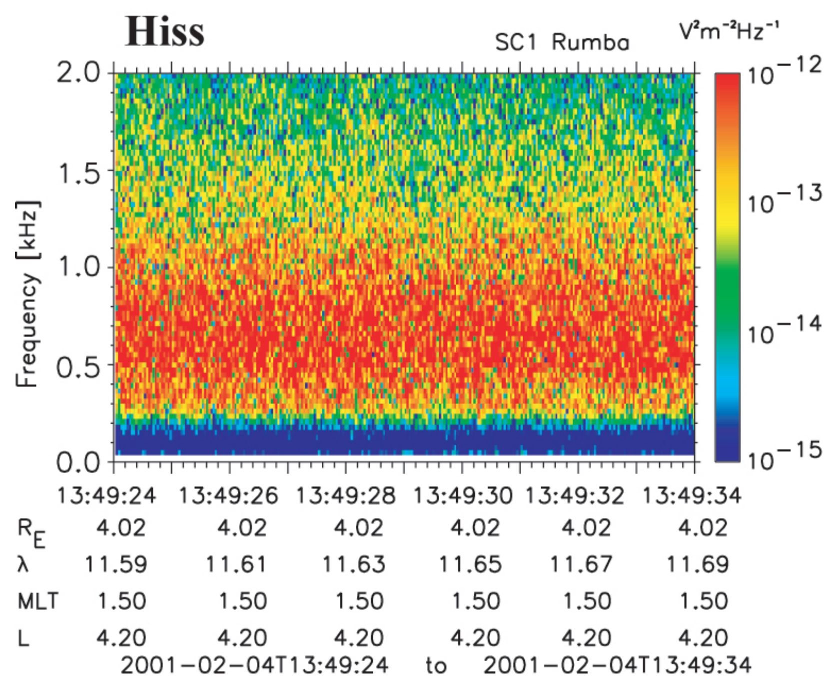
The wave environment in space



Plasmaspheric hiss

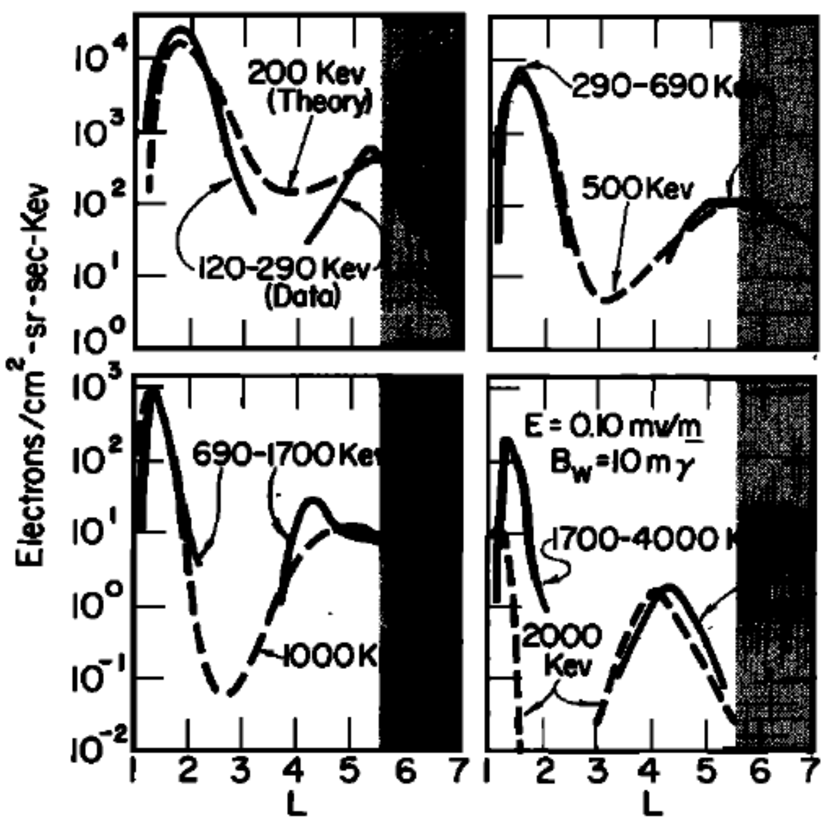
- Incoherent, electromagnetic, whistler-mode
- Wideband, f ~ 0.2 – 2 kHz
- Confined to plasmasphere, except for high latitude day side; L: ~1.6 to plasmapause
- Wave normal angles generally field-aligned, possibly some oblique
- Slot region in radiation belts





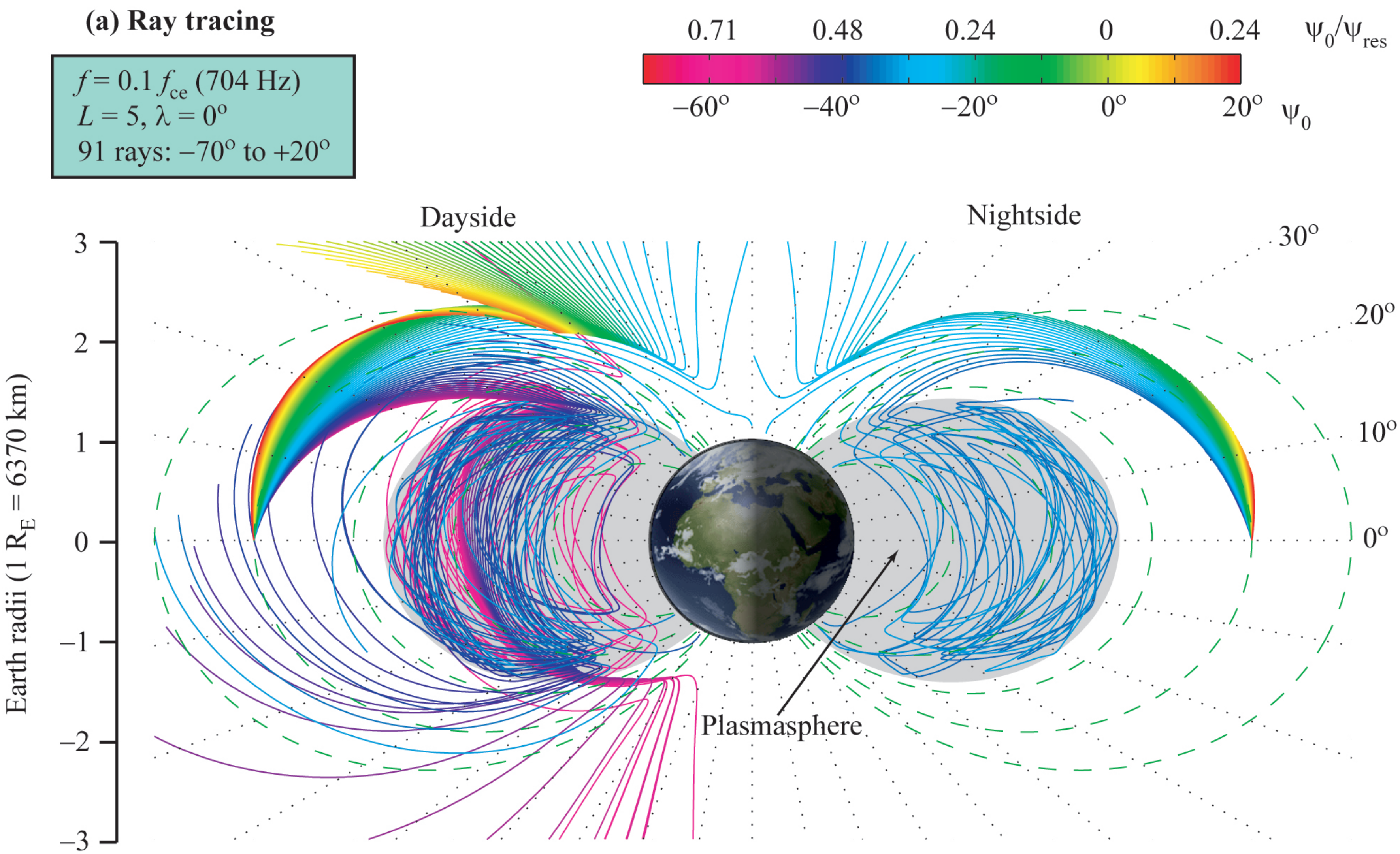
Equilibrium 2-zone structure

- The quiet-time, “equilibrium” two-zone structure of the radiation belt results from a balance between:
  - inward radiation diffusion
  - Pitch-angle scattering loss (plasmaspheric hiss)
- Inner zone: L~ 1.2-2, relatively stable
- Outer zone: L~3-7, highly dynamic



Lyons & Thorne [1973]

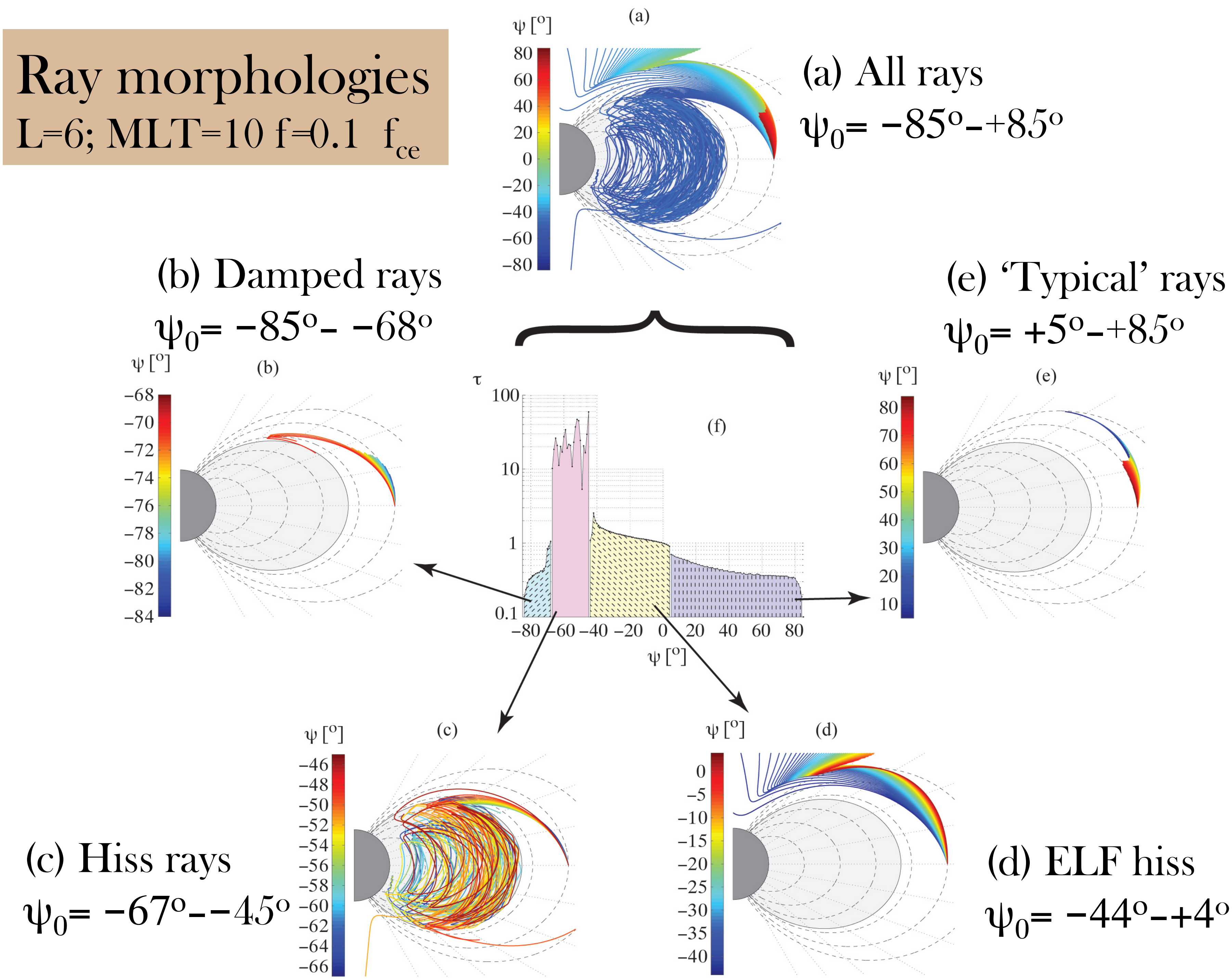
Chorus example ray bundle



Bortnik et al. [2008], *Nature*, 452(7183)

Ray morphologies

L=6; MLT=10 f=0.1 f_{ce}

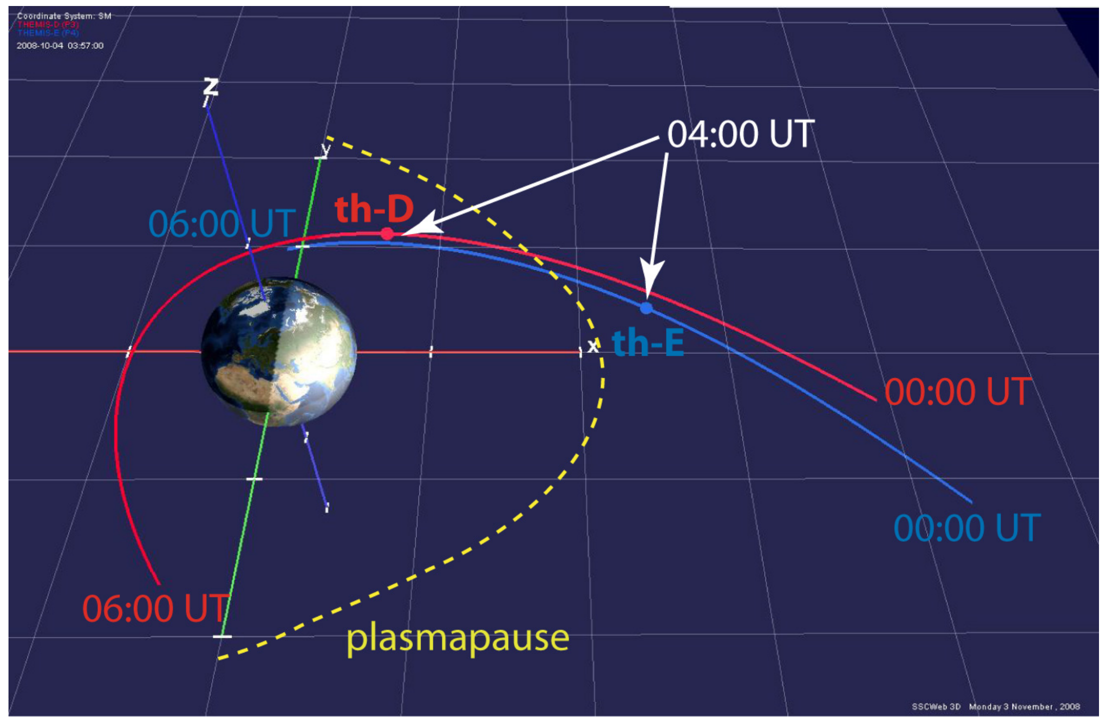


Coincident observation of chorus and hiss on THEMIS

Requirements:

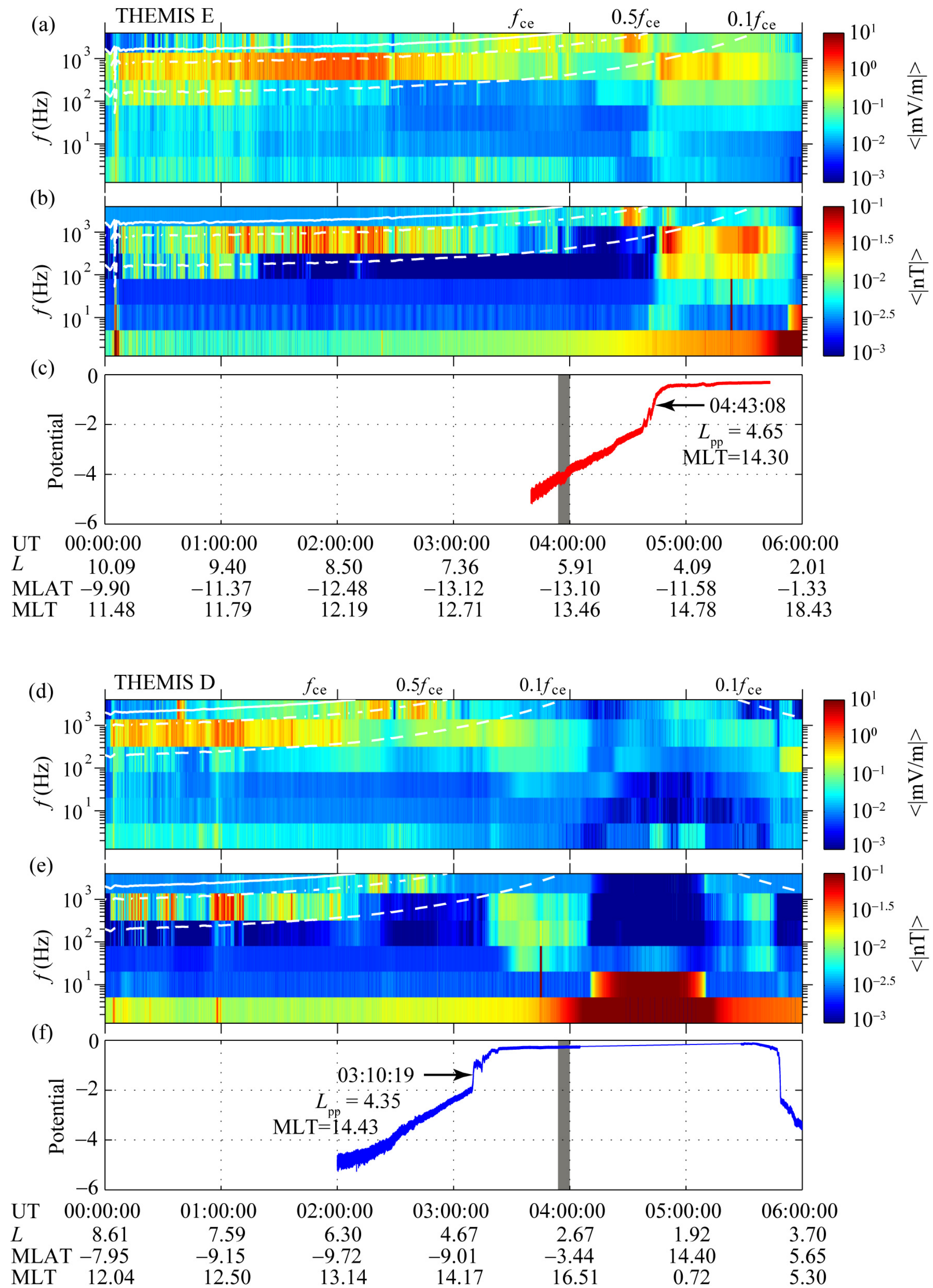
1. At least 2 satellites, 1 inside plasmasphere, 1 outside plasmasphere
2. Plasma wave instruments, recording simultaneously
3. High resolution, correct frequency range
4. Correct spatial regions, day side, ~equator
5. Geomagnetic activity

October 4th, 2008



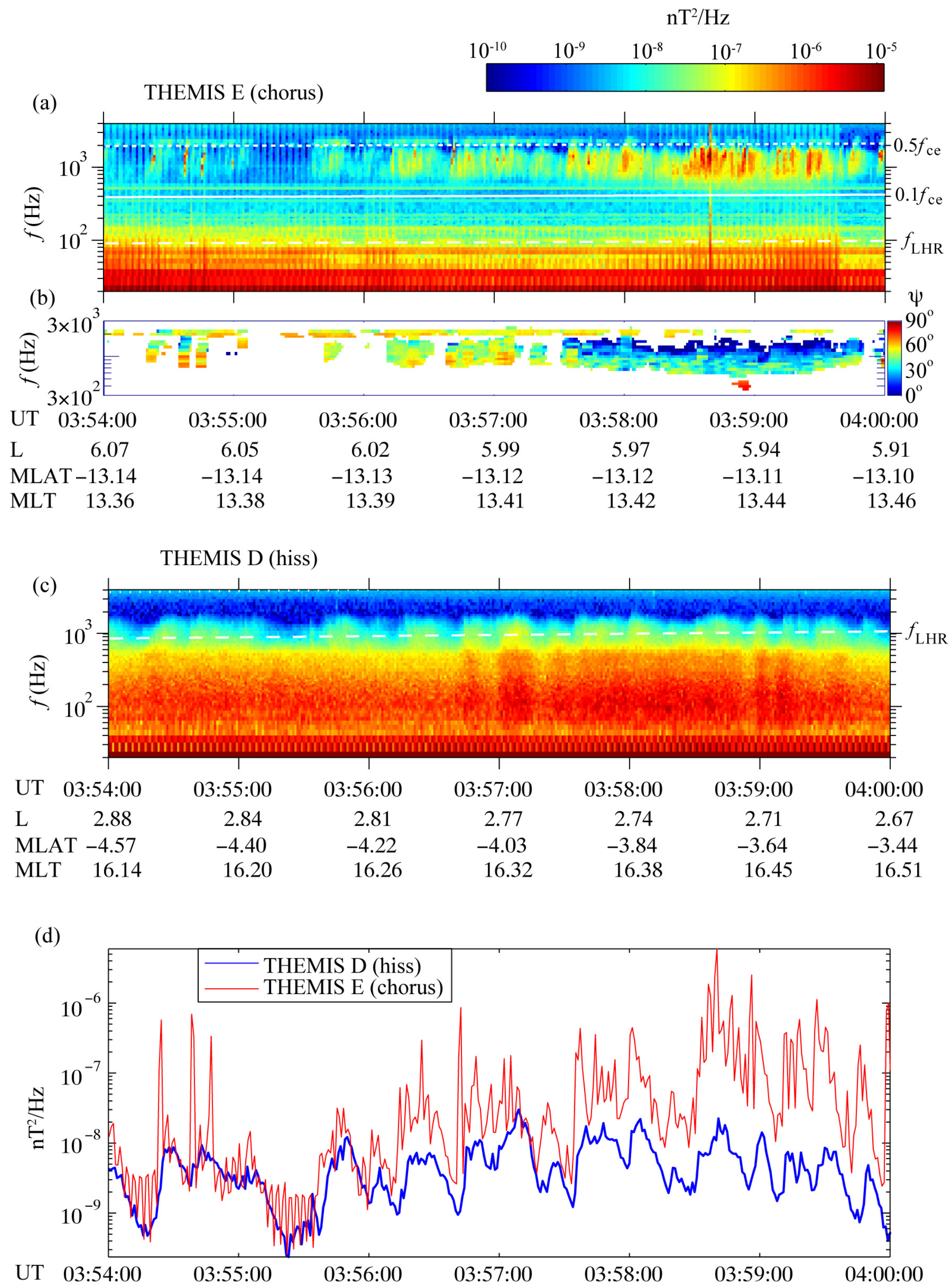
Overview plots

- 6-hour filter-bank over view plot
- THEMIS E:
  - Low density region
  - Chorus observation
- THEMIS D:
  - High density region
  - Hiss observation



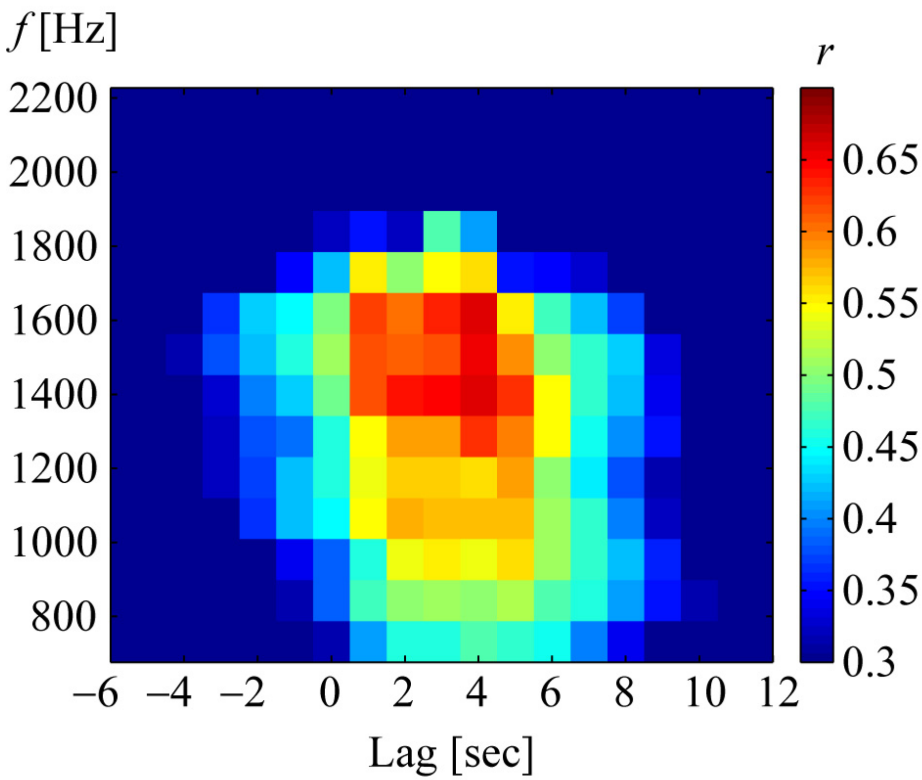
High resolution

- Wave burst mode, 64-bin FFT, 20 Hz-4 kHz, every 1s
- THM-E: discrete chorus, 600 Hz- 3 kHz, 0.2-0.5 f/f_{ce}, ψ=30-60
- THM-E: incoherent hiss, <2 kHz
- Average spectral time-series, 1.2 – 1.6 kHz, high correlation!



Bortnik et al. [2009],*Science*, 324(5928)

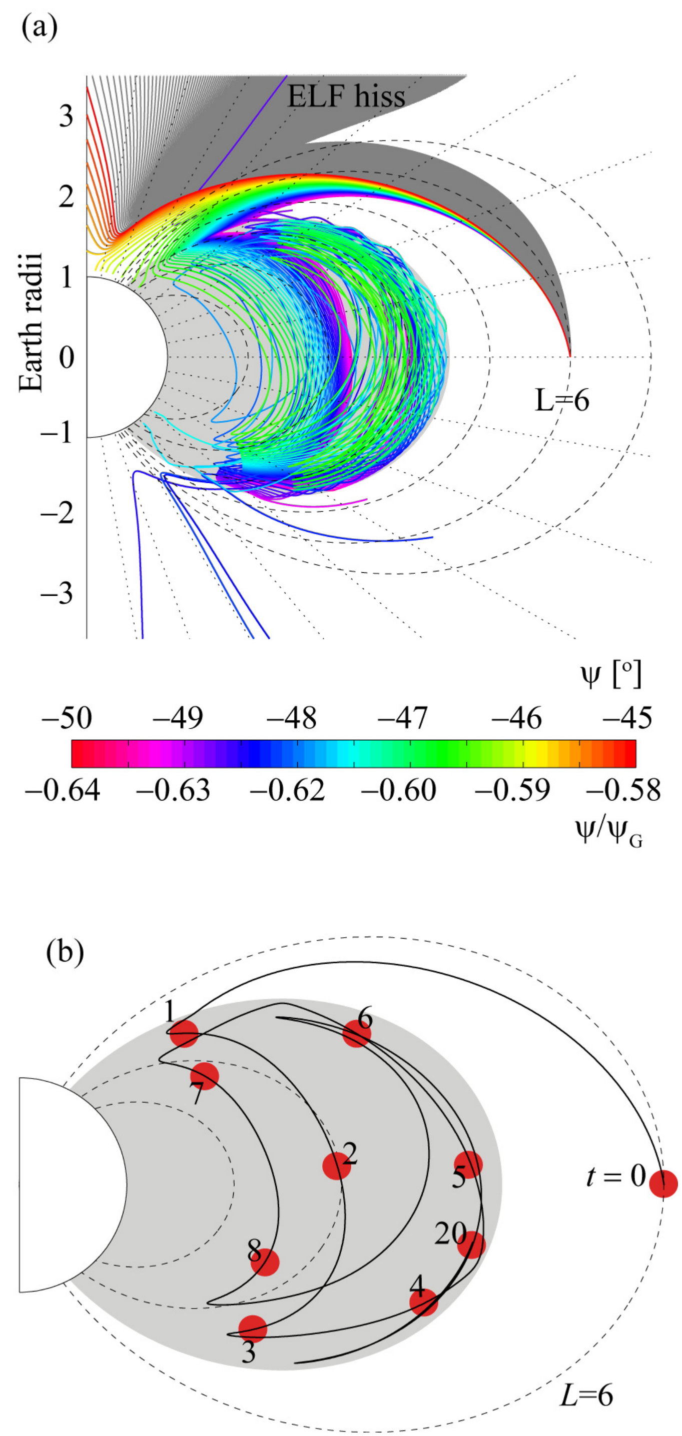
Cross covariance analysis



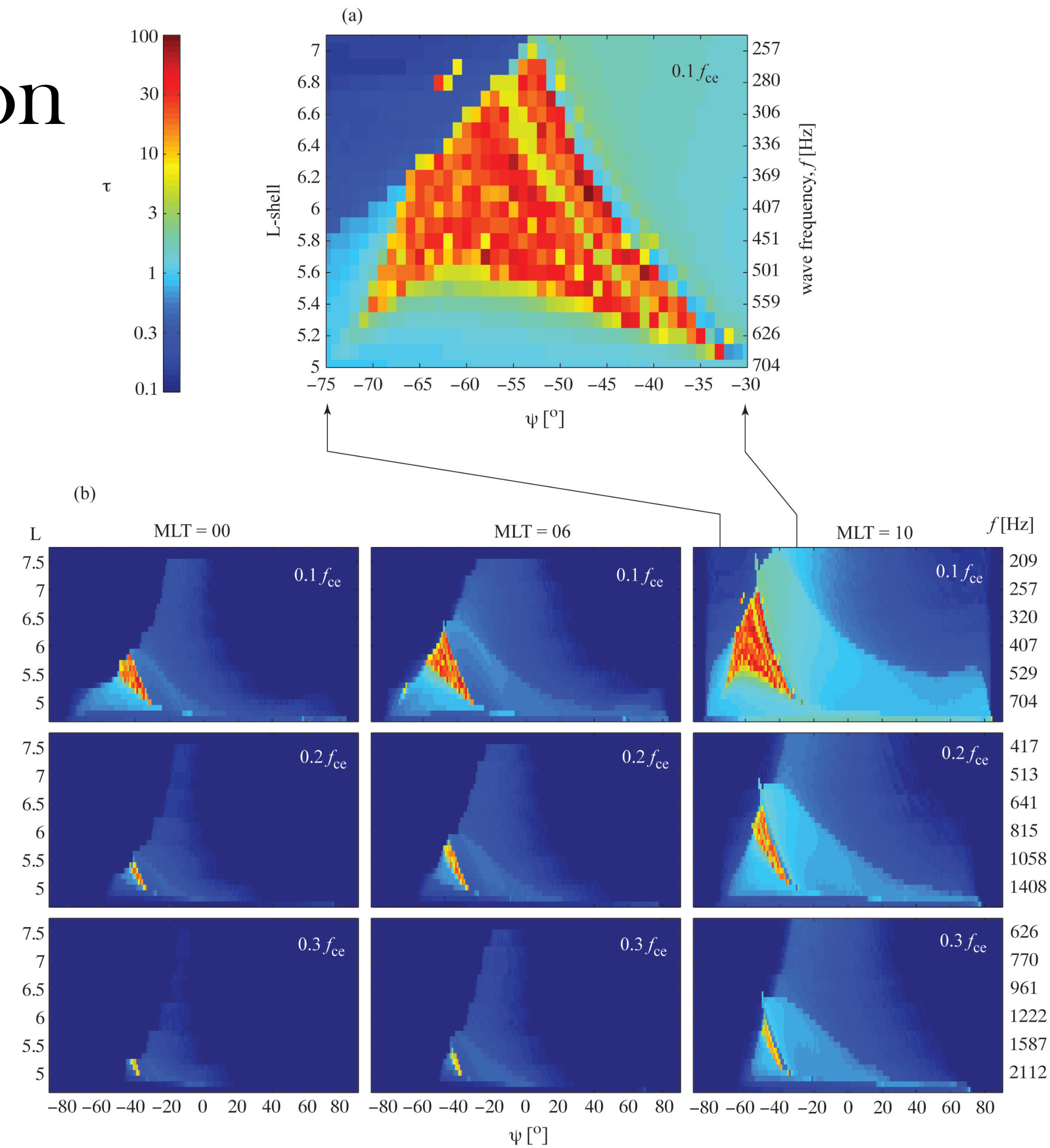
- Bin-wise cross covariance analysis
- Normalization: autocorrelation at zero-lag = 1
- Highest correlation (r=0.7), at lags ~1-7 sec, peak ~4 sec.

Ray tracing

- Ray trace all rays in allowable angles, include L-dependent Landau damping
- Key-range (colorbar), ~ -50 to -45, L=6
- Timescale:
  - 1 s, enter plasmasphere,
  - 2 s, 1^{st} EQ crossing
  - 3.2 s, magnetospheric reflection
  - 7.7 s, second EQ crossing



Distribution of rays

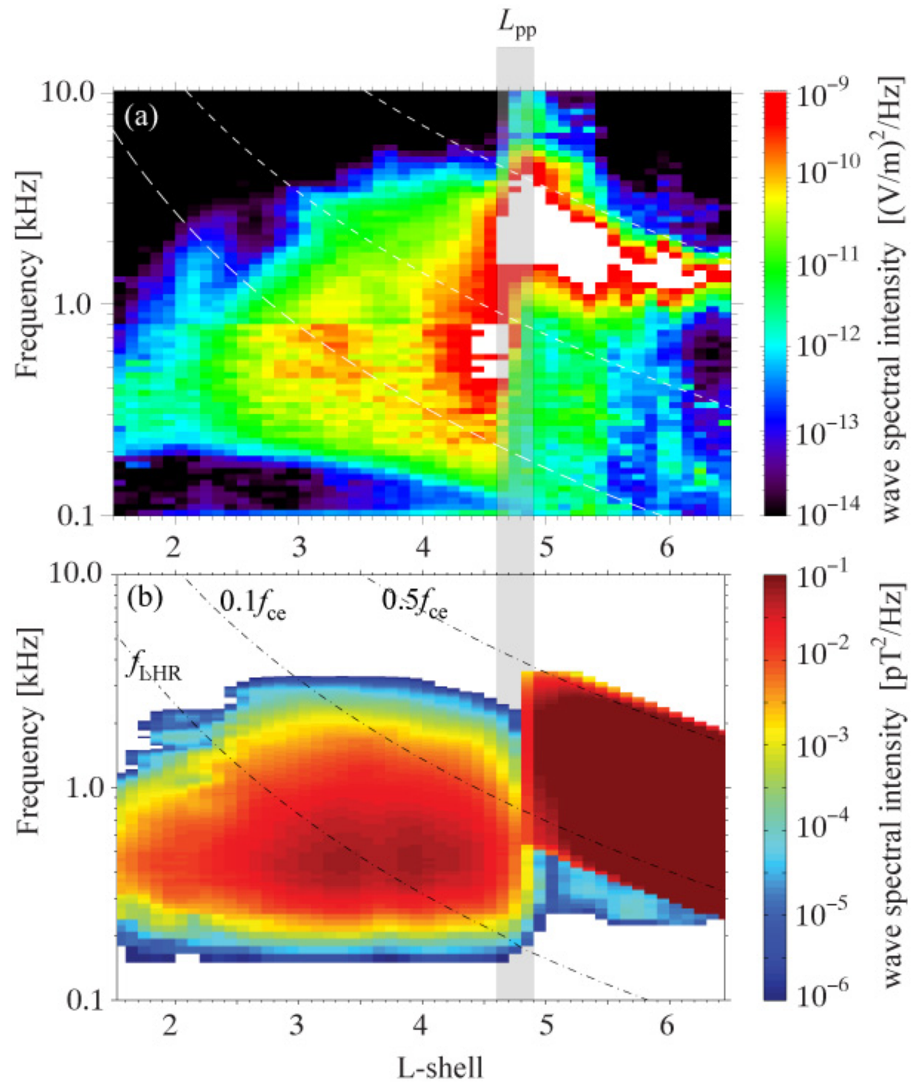


Rays show preference for:

1. Lower *f*
2. Dayside (lower damping)

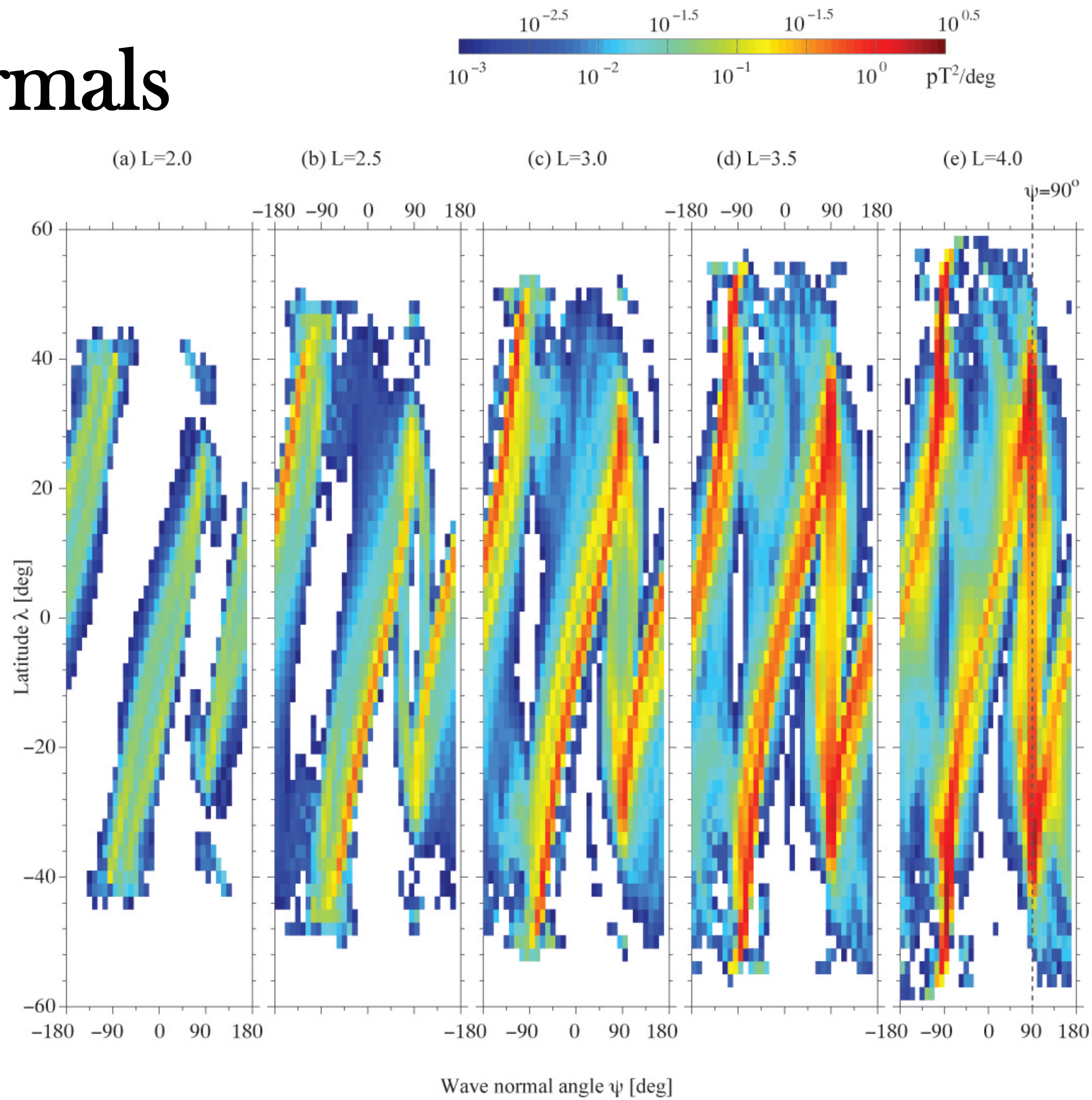
Simulated power distributions

- Ray trace thousands of rays, L=4.8-8, all angles, power-weighted.
- Agreement with observation:
  - Correct peak power
  - Bandwidth decrease at low L
  - Two zone structure
  - Correct spatial confinement
- Disagreement:
  - Power peak near Lpp
  - Too weak (factor ~3-5)
- Cause of error?

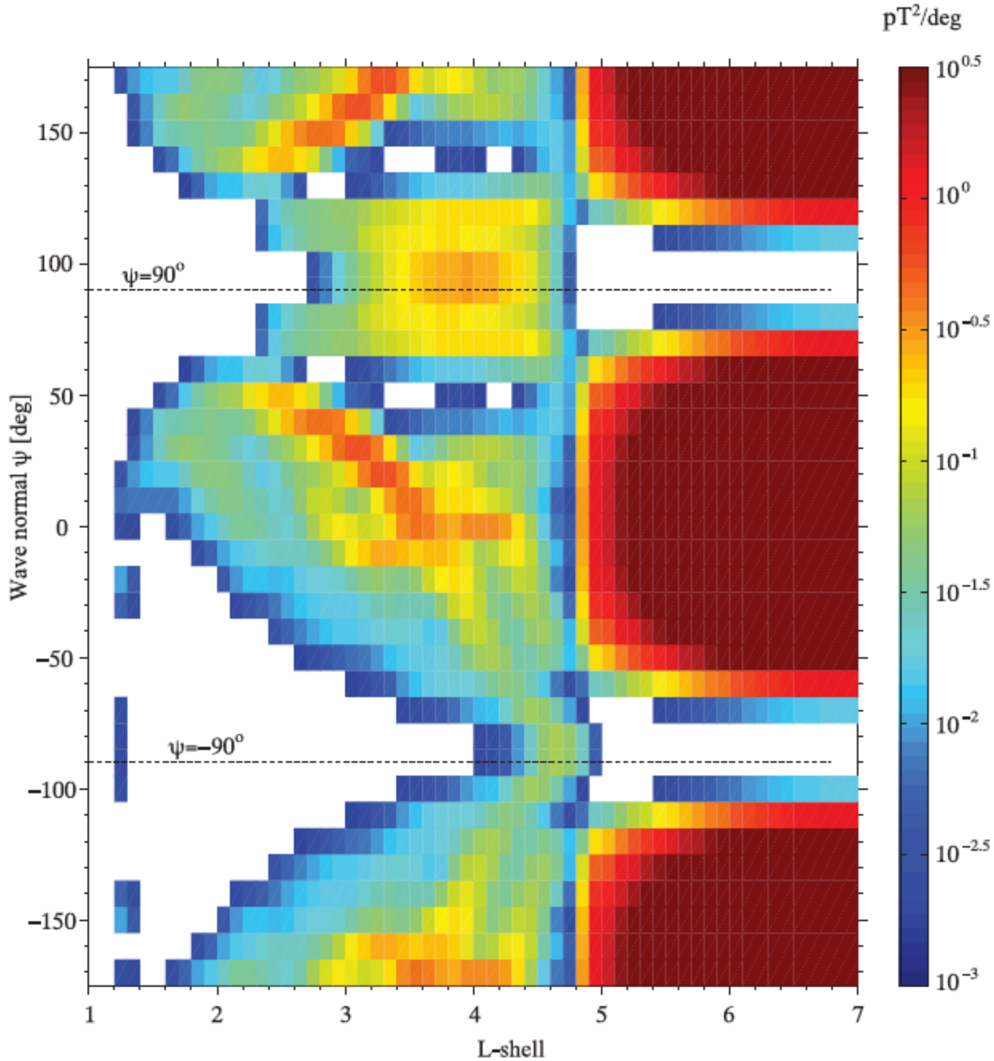


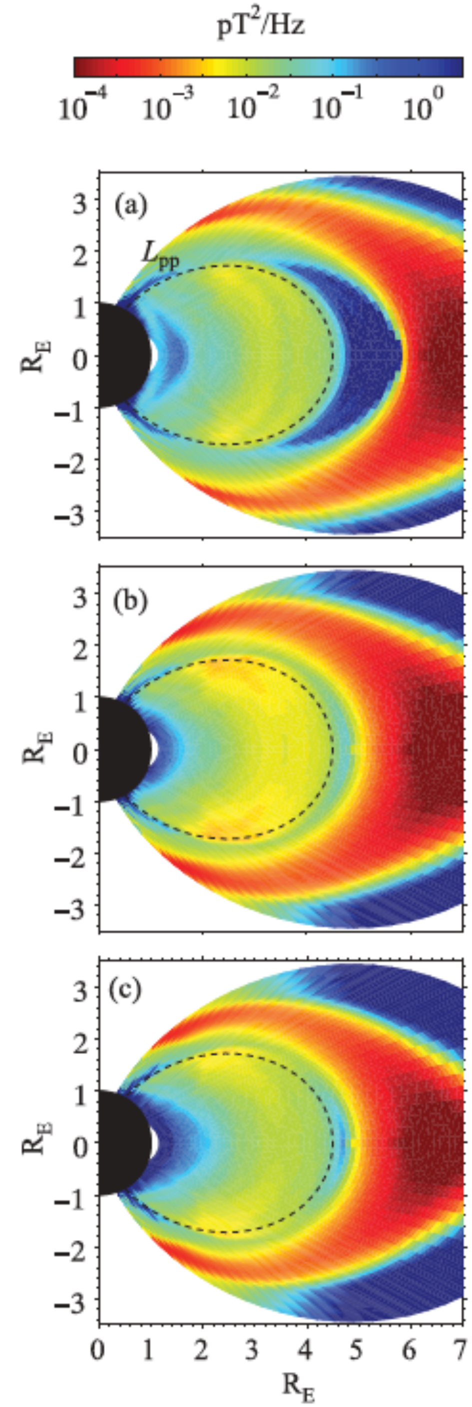
Wavenormals

- Consistent with literature!
- EQUATOR:
  - Bimodal near p'pause
  - Field-aligned deeper in
- OFF -EQ:
  - oblique

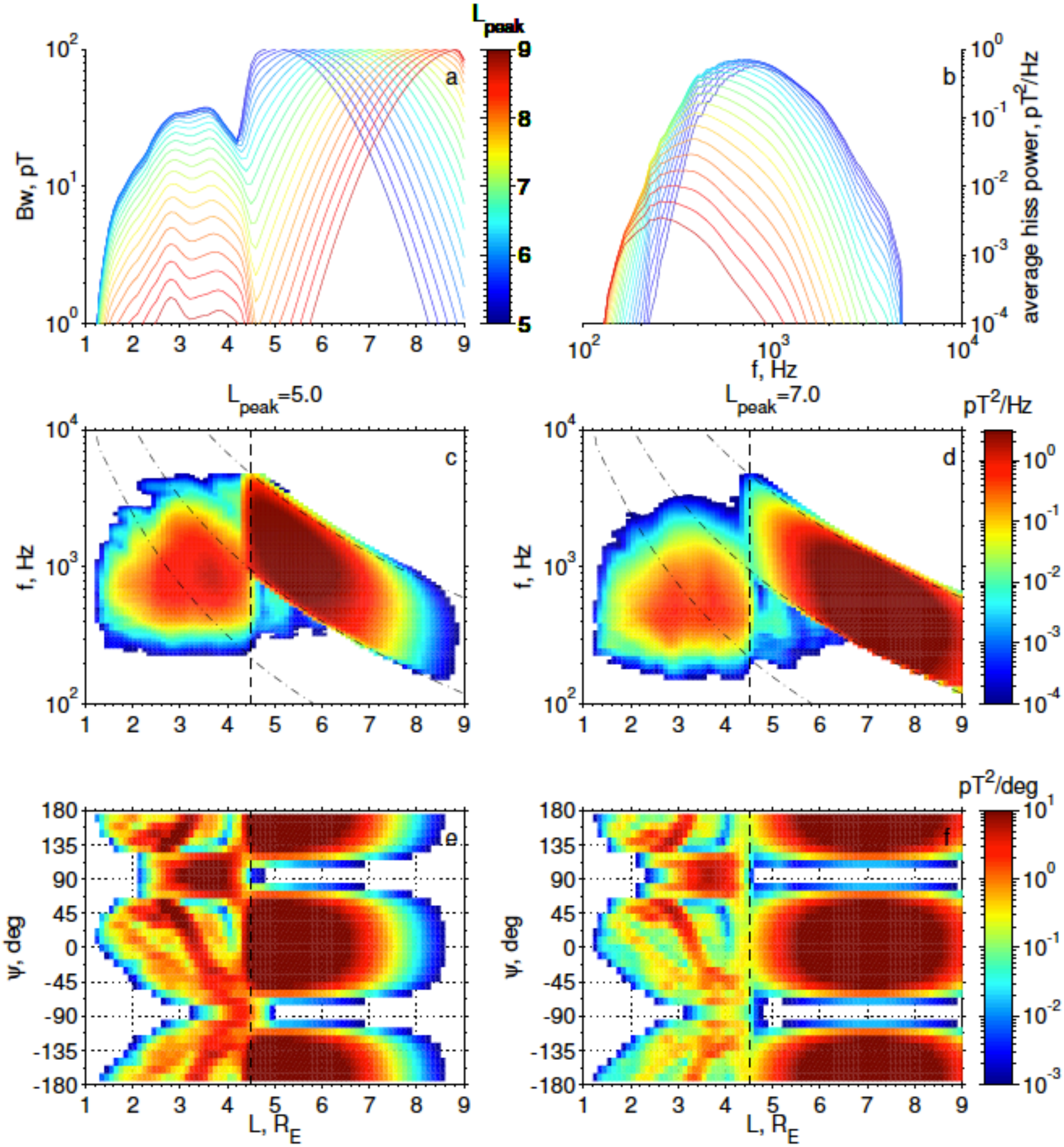


Complete distribution of all wave characteristics!

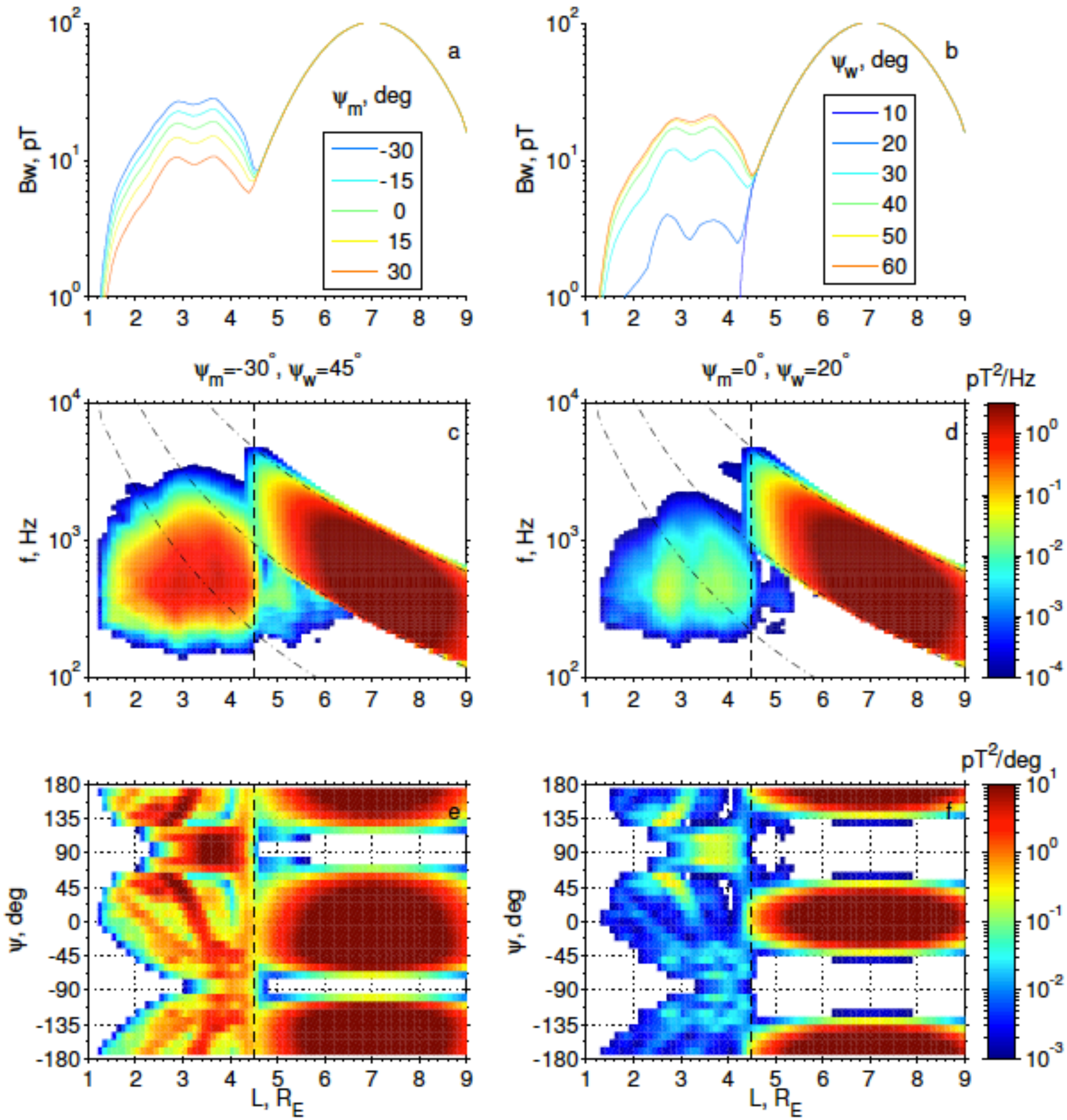




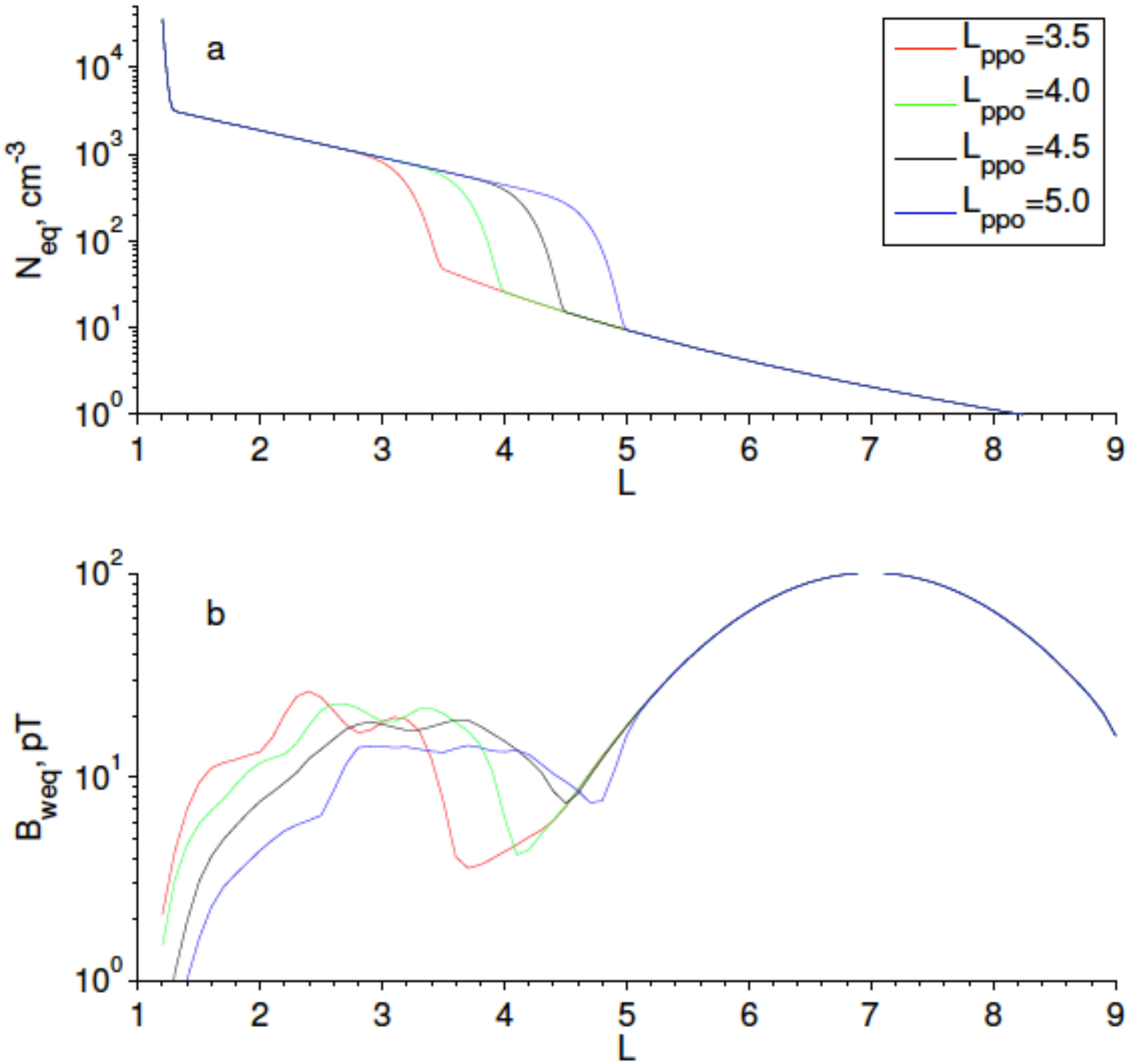
Effects of L_{peak}



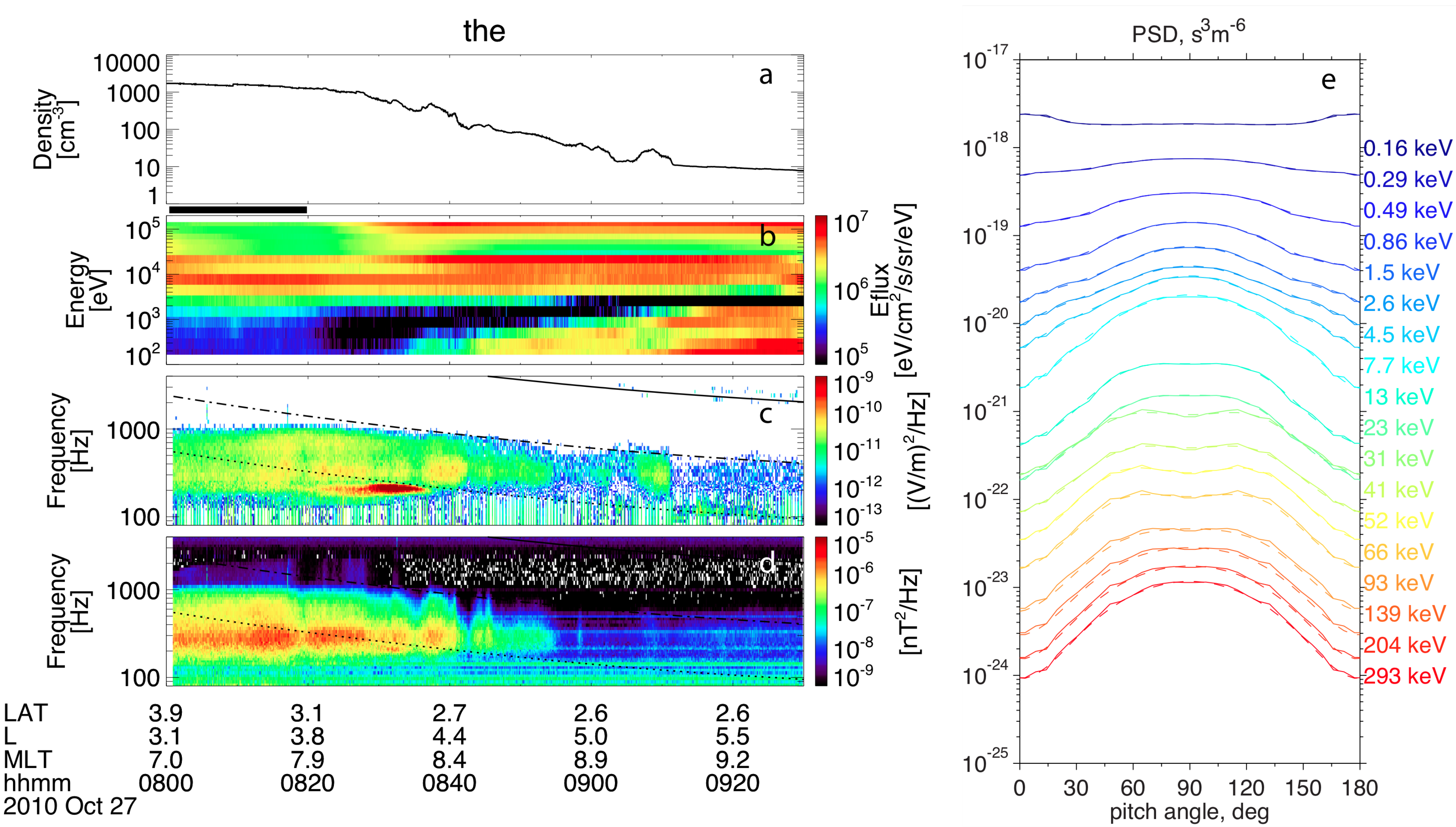
Wavenormals: Effects of ψ_m and ψ_m

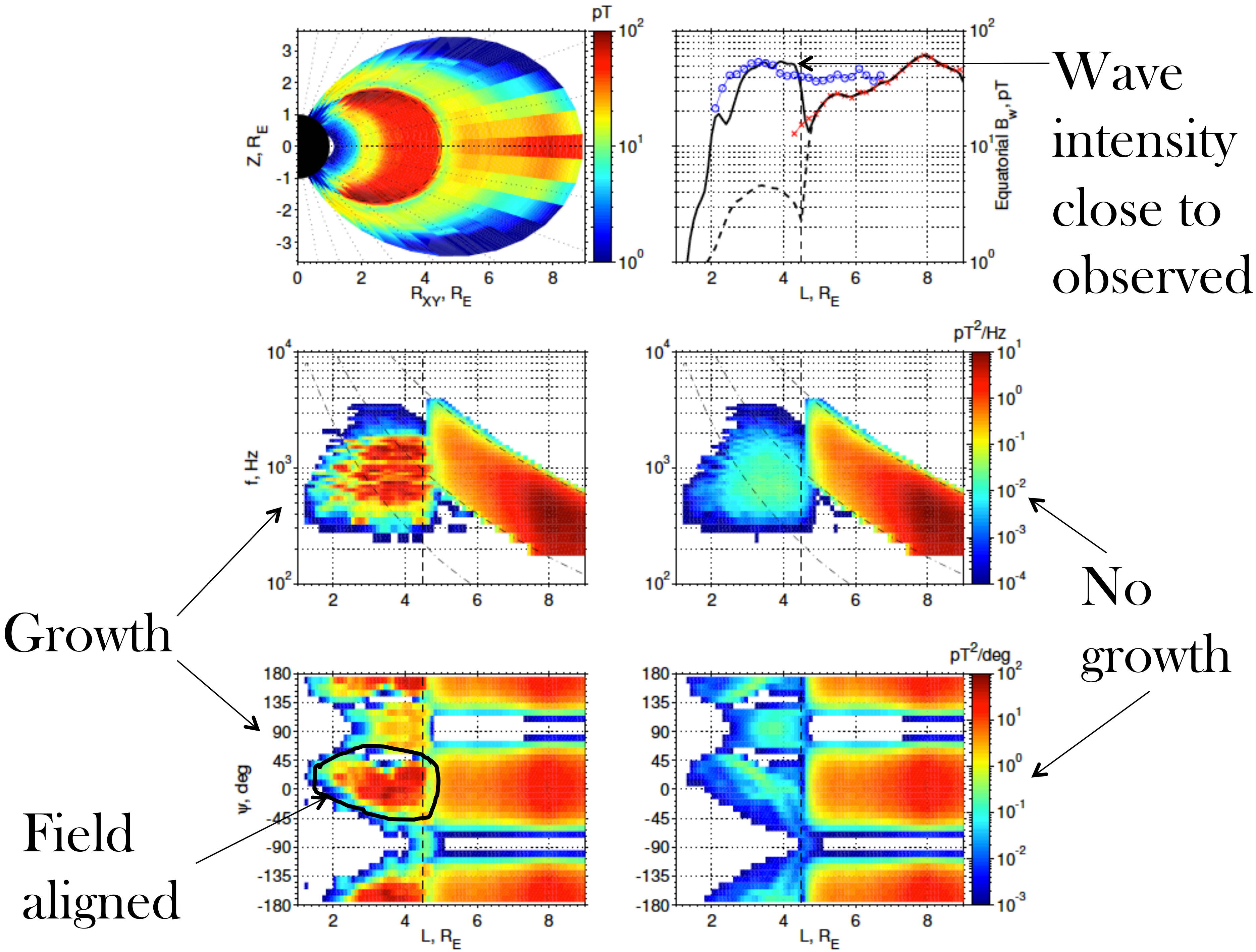


Effect of plasmapause location



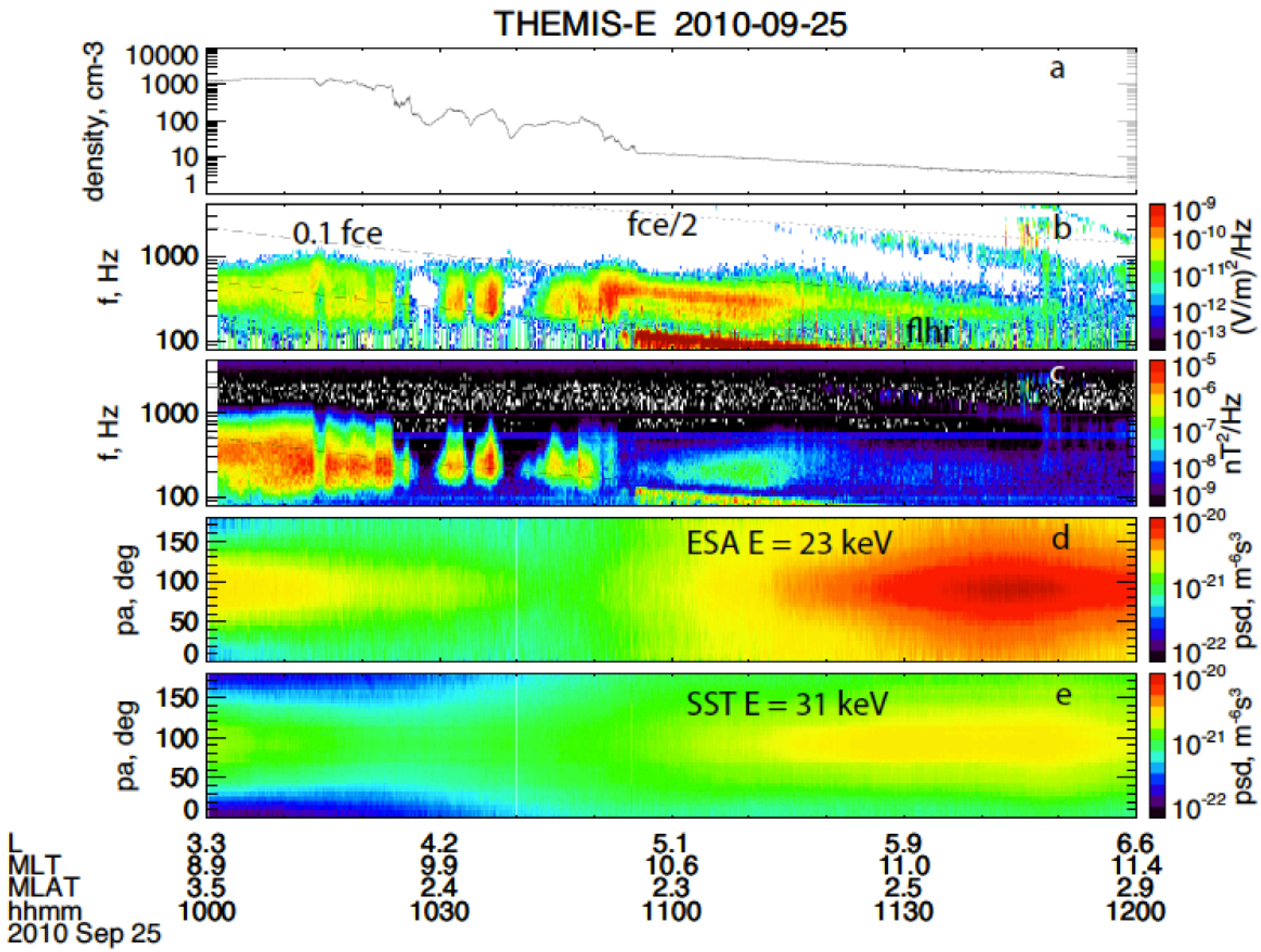
Simultaneous observation of hiss waves and particle distribution





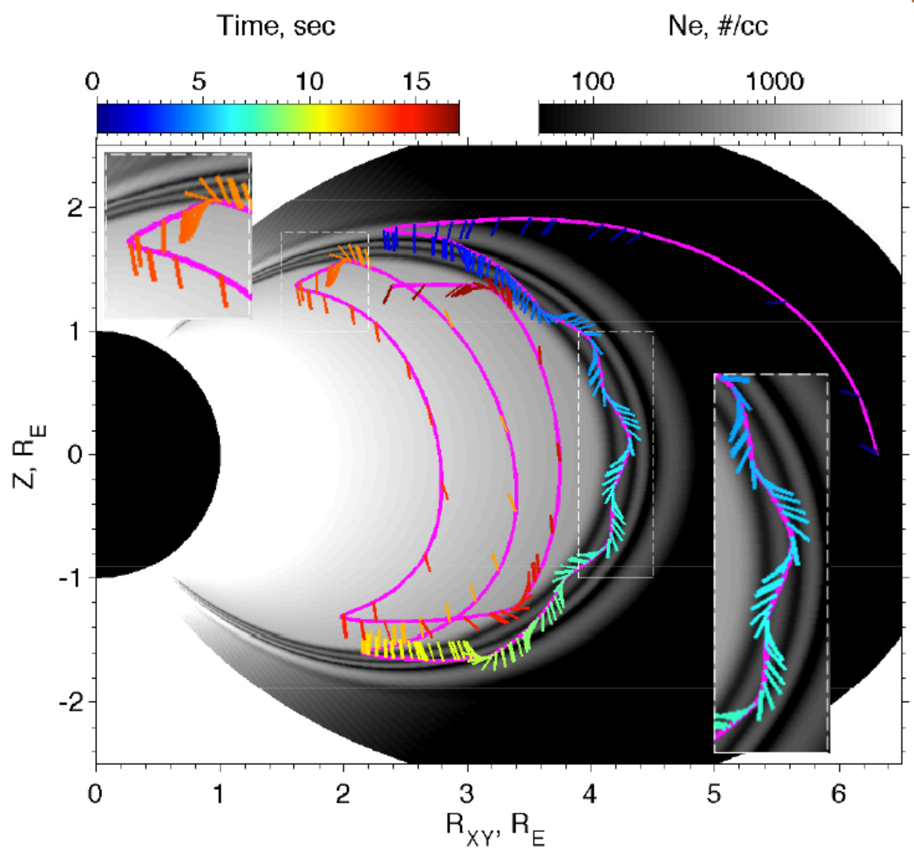
pT
Z, R_E
R_XY, R_E
L, R_E
Equatorial B_w, pT
Wave intensity close to observed
f, Hz
pT^2/Hz
Growth
No growth
ψ, deg
pT^2/deg
Field aligned
L, R_E
L, R_E

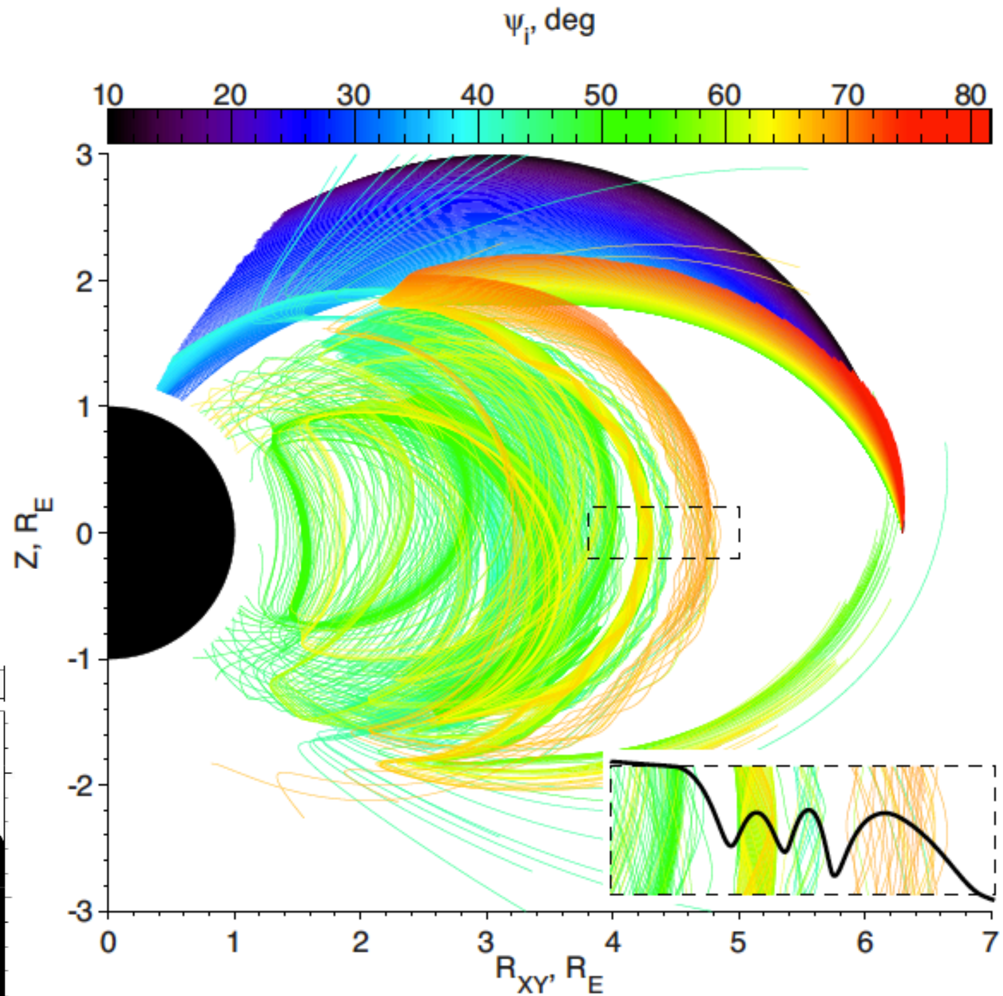
Modulation of hiss in density structures



Hiss confinement to density structures

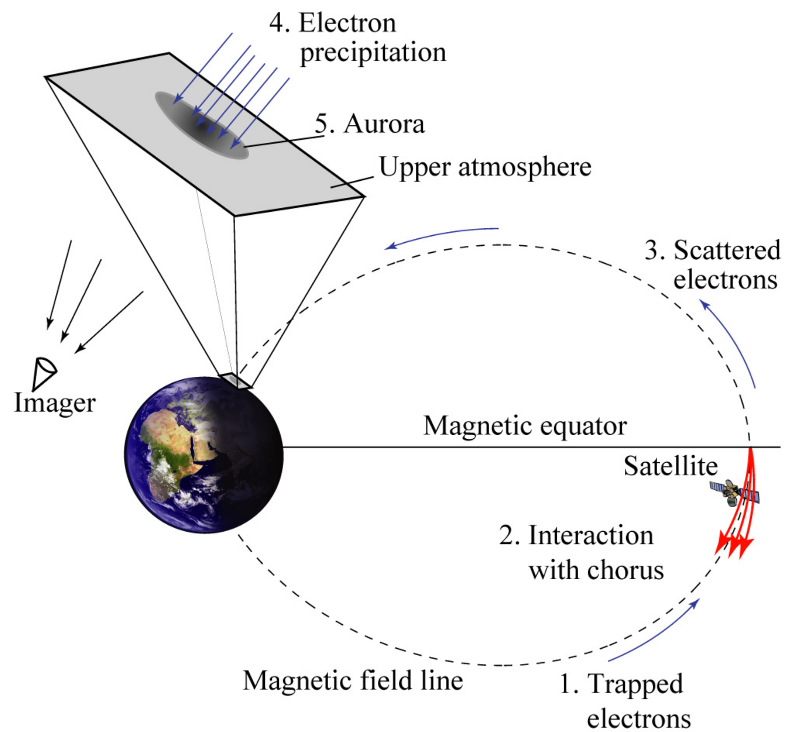
- Propagation effect
- Growth rates small & frequency too high



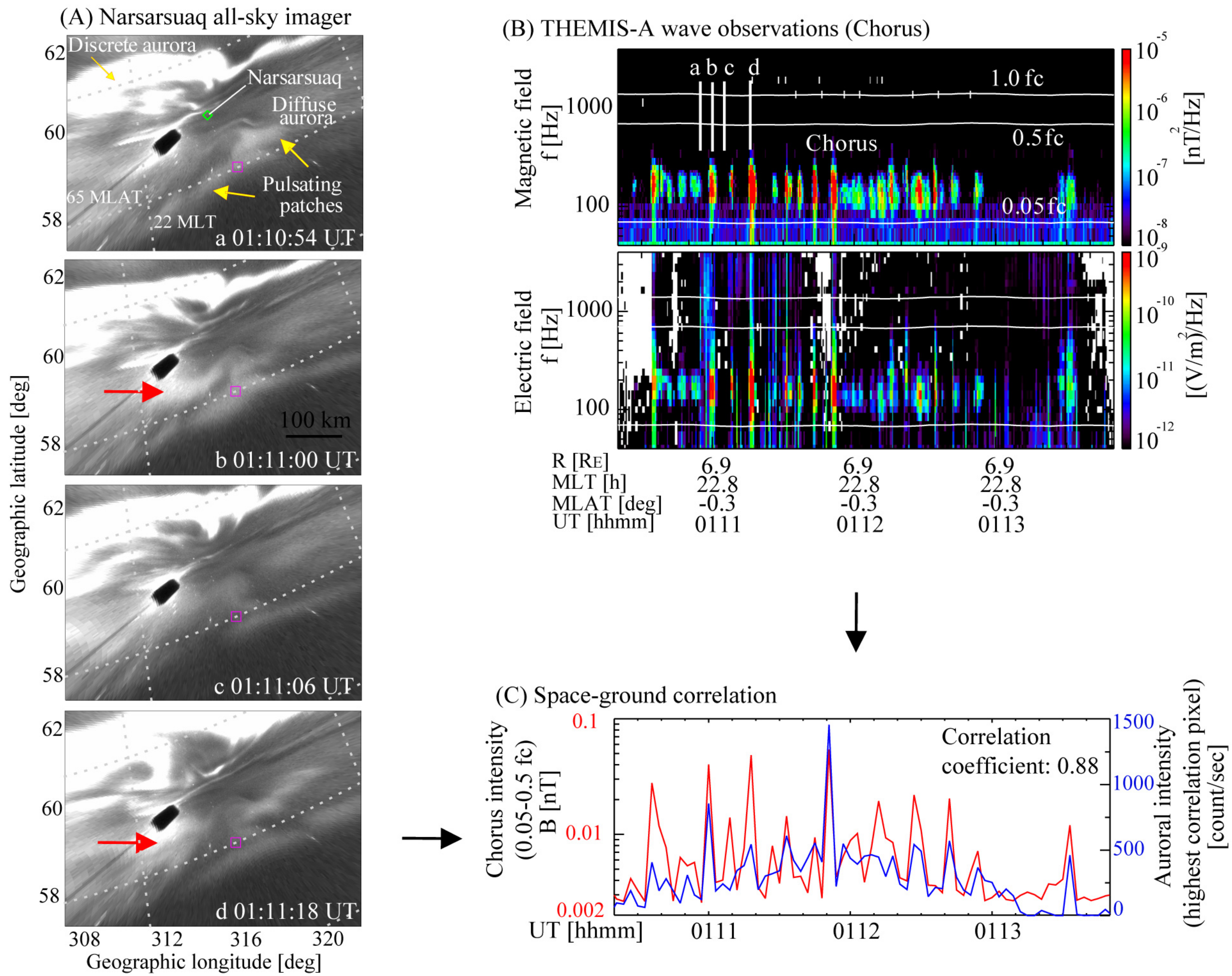


Pulsating aurora

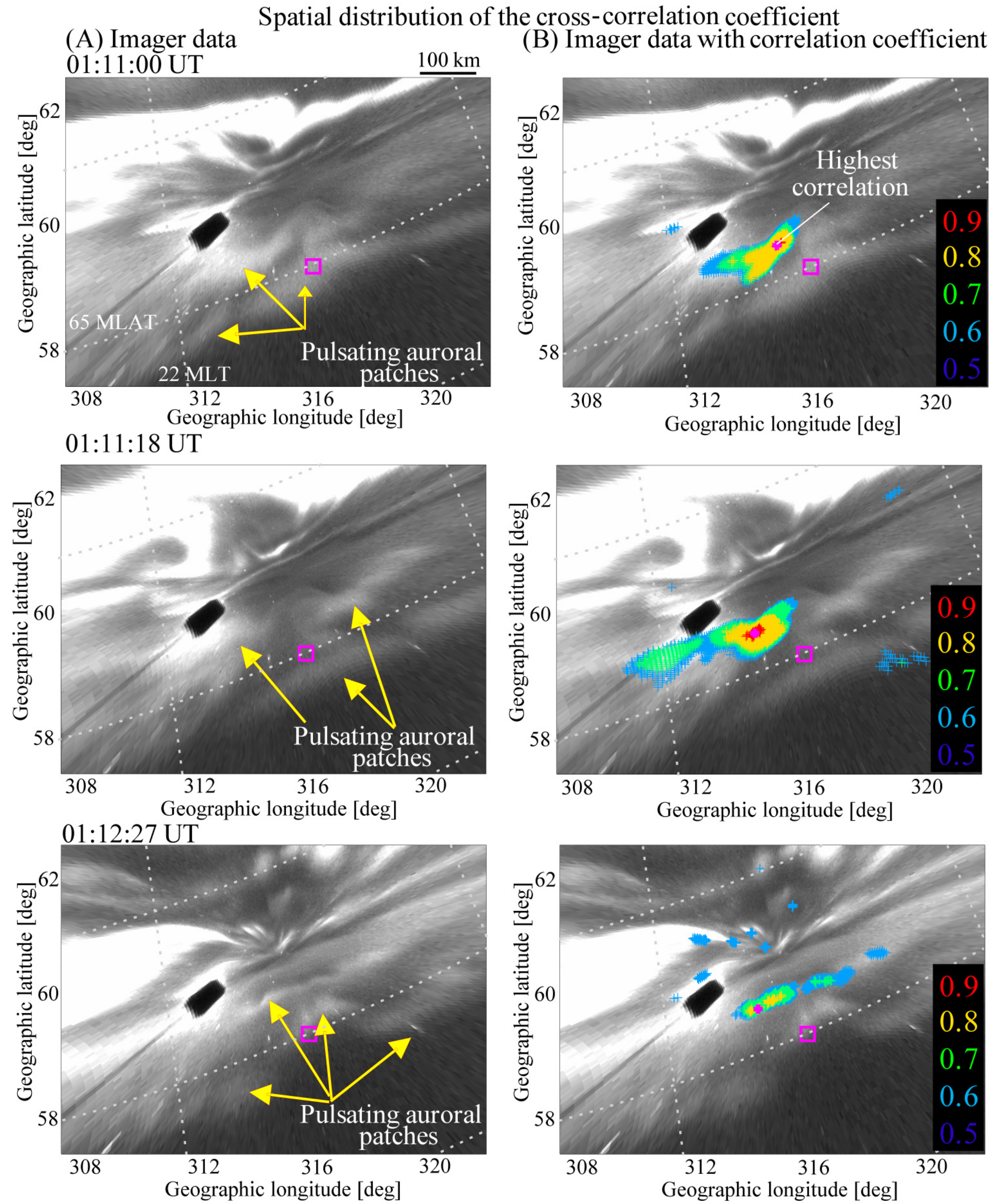
- Described in 1963 "auroral atlas"
  - Luminous patches that pulsate with a period of a few to 10's of seconds
  - Scale, ~10-100 km
  - Precipitating electrons E>10 keV



TH-A, Nar-ASI conjunction 15 Feb 2009



- Map of cross-correlation coefficients
- >90% correlation
- Location roughly stationary



Some open questions

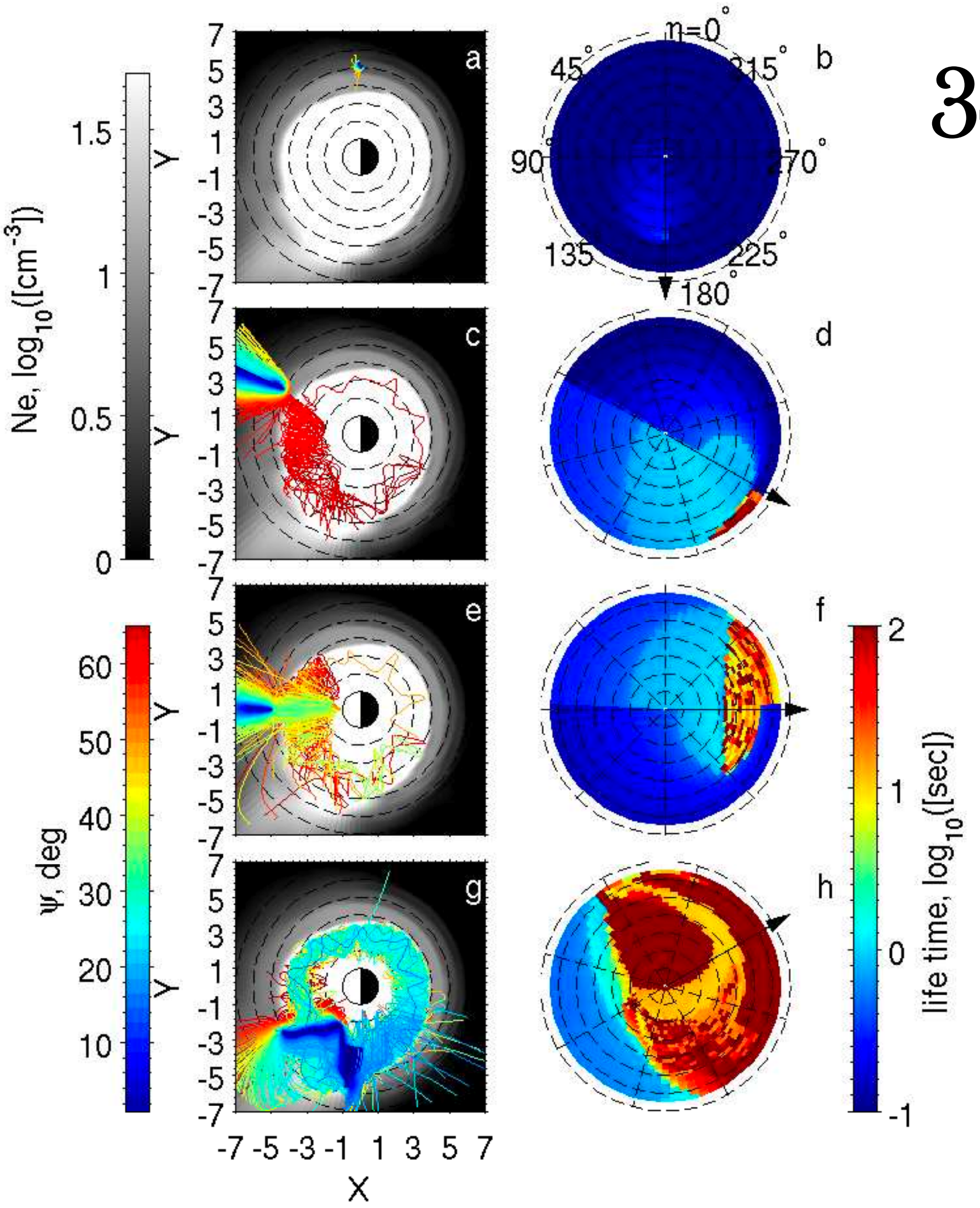
- What are the combined dynamics of chorus & hiss? E.g., evolution in time and MLT
- Origin of nightside and dusk chorus? Azimuthal propagation?
- Can ground-based imagers map the inner magnetospheric waves & particle environment? Need *VERY* good physical models

Conclusions

1. Chorus is a key element of radiation belt dynamics
   - An essential acceleration & loss process
2. Chorus as the source of plasmaspheric hiss
   - Statistical characteristics reproduced, frequency band, geomagnetic control, day/night, wavenormals, exohiss
   - Case study, 4th October 2008, rare coincidental observation, intensity modulation, time lag, 3D propagation
3. Chorus as the driver of pulsating and diffuse aurorae
   - Shows the same modulation pattern
   - Only correlated with lower-band (in accordance with theory!)
   - Can we map chorus from PA?
   - Use in observational field-line mapping
   - Particle distributions consistent with chorus scattering

Backups

3-D Ray tracing



- 3-D density model:
  - Rasmussen et al. [1993] equatorial density, driven by RCM E-field for Apr. 21, 1991
  - Latitudinal extension using Denton et al. [2002]
  - Suprathermal distribution from Bortnik et al. [2007]
- HOTRAY 3D rays: L=5; MLT=6, 10, 12, 14; f~700 Hz (0.1 f_{ce}), 33 values of ψ (1–65°), 72 values of η (0-360°)

Chen et al. [2009] *GRL*

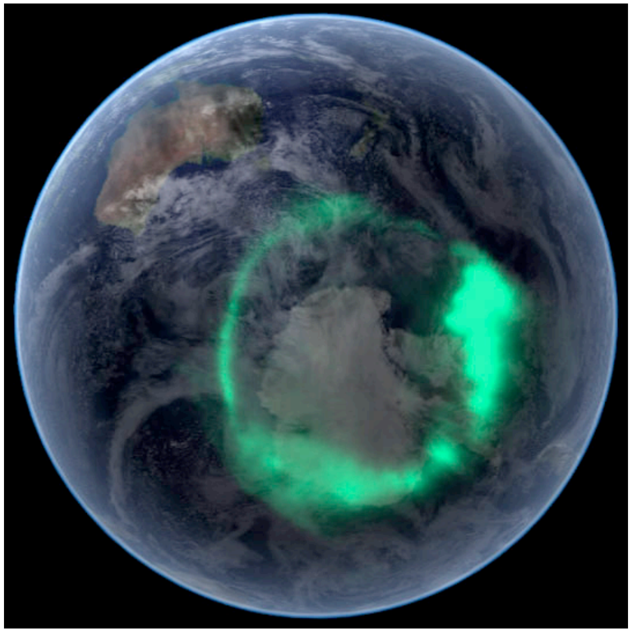
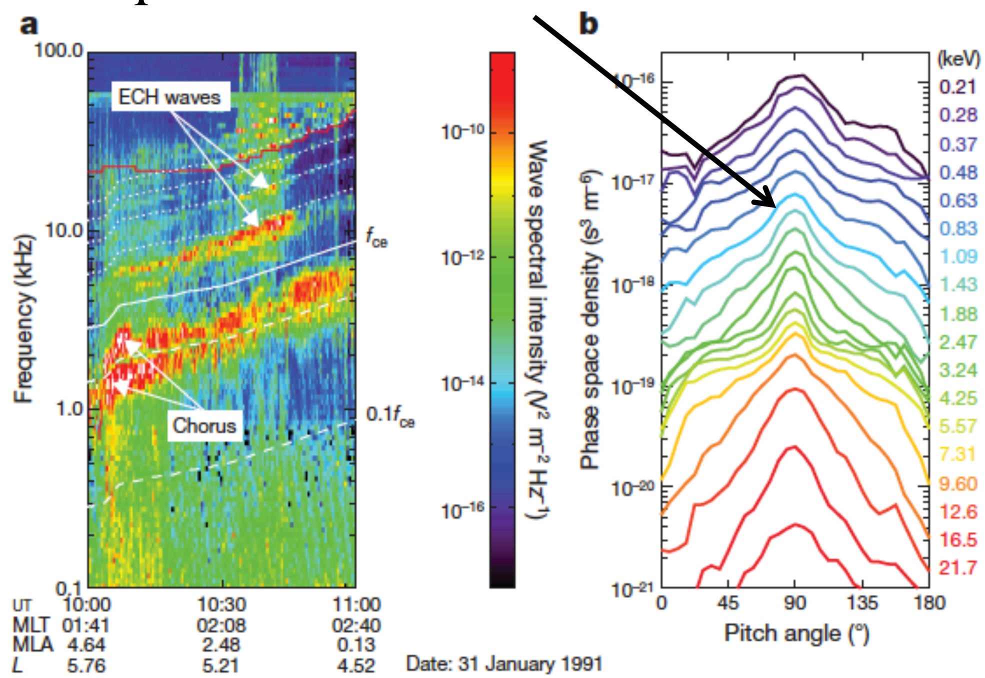


IMAGE satellite, 11 Sep 2005

3. Diffuse aurora

These “pancake” distributions provide the clue



Thorne et al. [2010] *Nature*

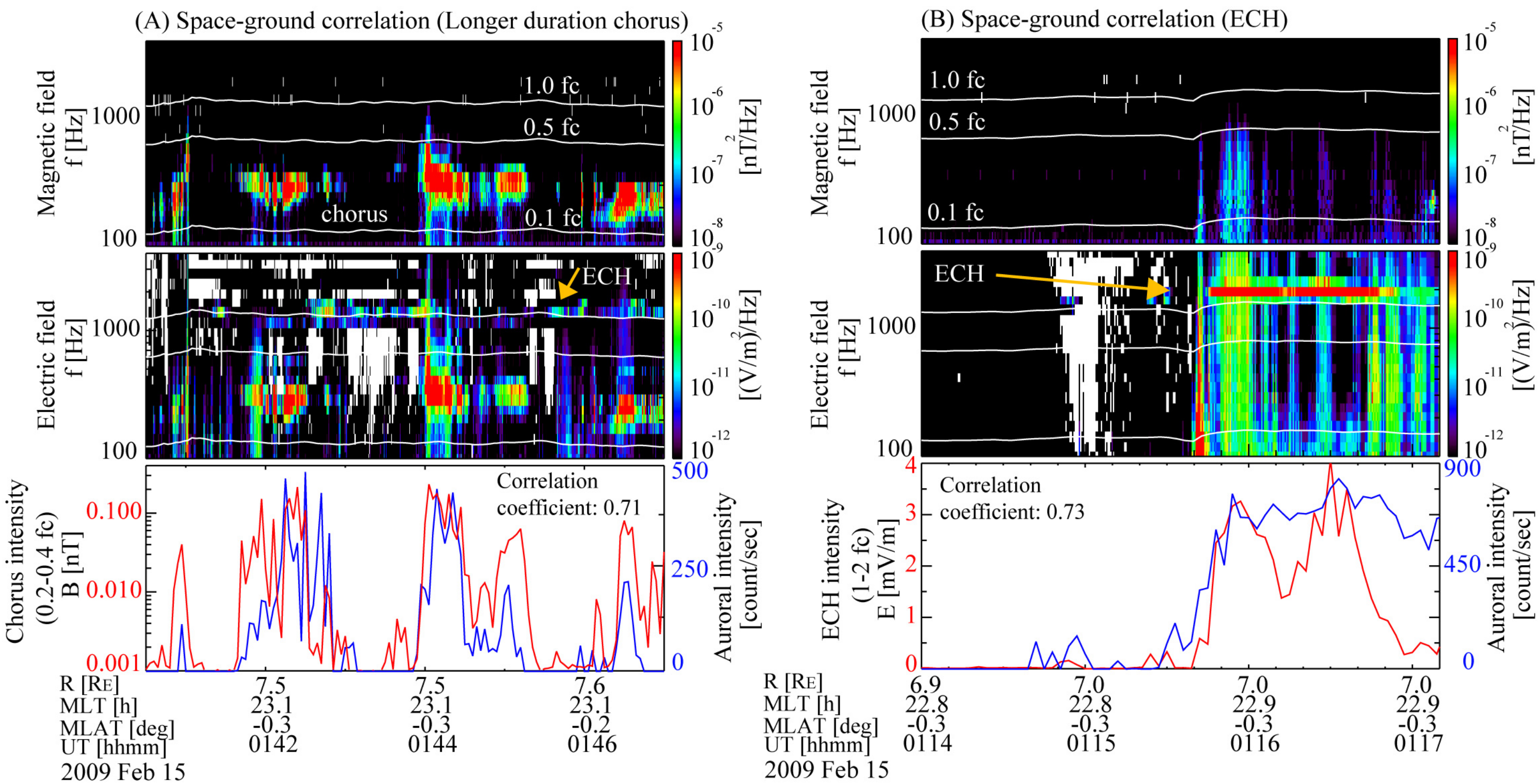
Only chorus can account for the resultant distributions observed in space

Open question: what is the feedback effect of the ionospheric conductivity changes?

Origin of plasmaspheric hiss: possible mechanism

- Anthropogenic source: power line harmonic radiation
- **Cyclotron instability with energetic electrons** (gain problem!!!)
- Cyclotron instability with energetic protons (ring current)
- Generation in ionosphere
- 'non-linear' interaction mechanism (oblique wave generation)
- Lightning generated – ducted mechanism
- **Lightning generated – nonducted evolution (MR whistlers)**
- Other mechanisms? (1 sentence suggestions)
  - Leakage of auroral hiss into plasmasphere
  - Leakage of chorus into plasmasphere ...

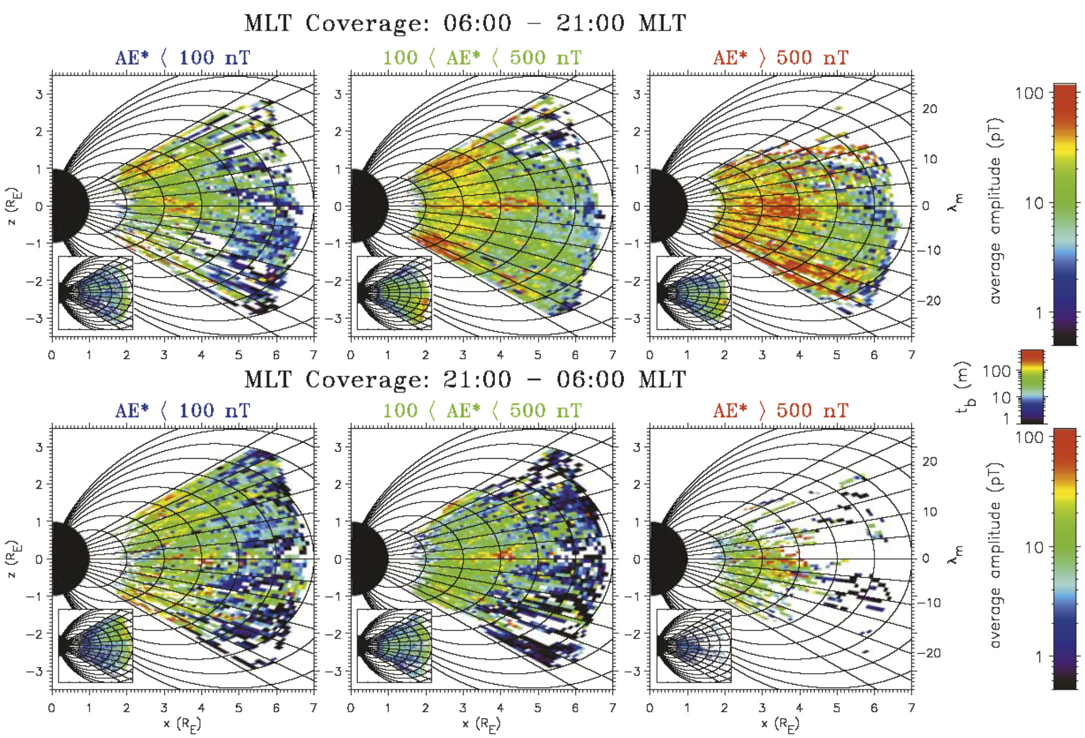
Chorus vs ECH correlations



- Modulation of PA controlled by lower-band chorus modulation
- Not correlated to ECH or upper-band chorus

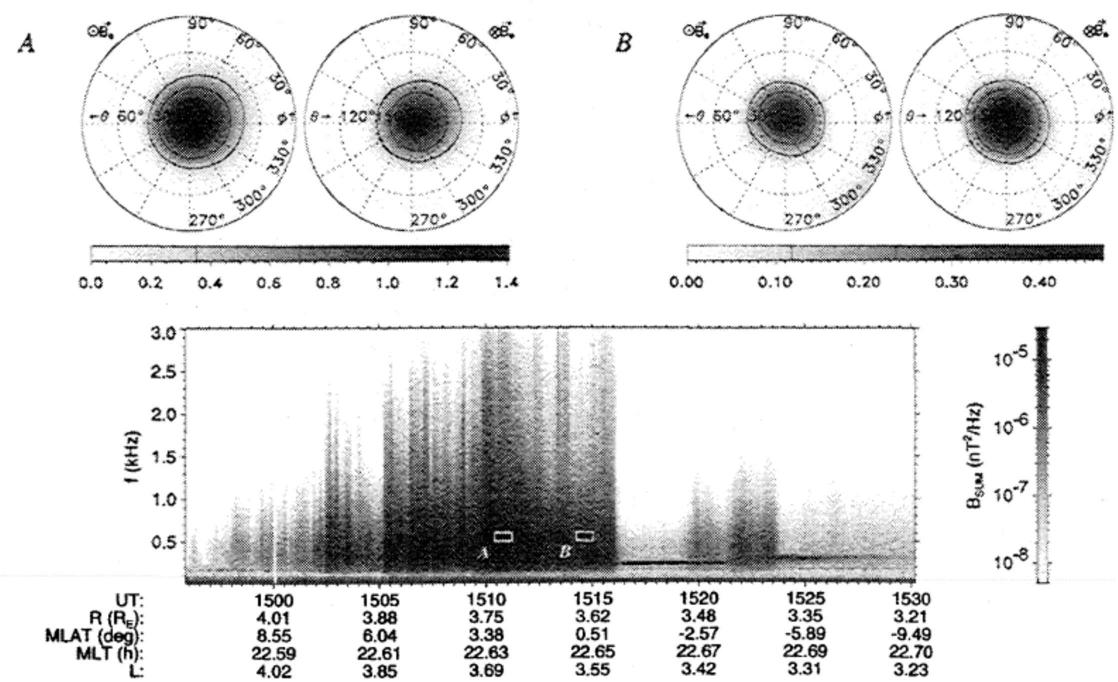
Recent Observations

Magnetospherically reflected chorus [Parrot et al., 2003; 2004], possible connection with plasmaspheric hiss?



Meredith et al. [2004]

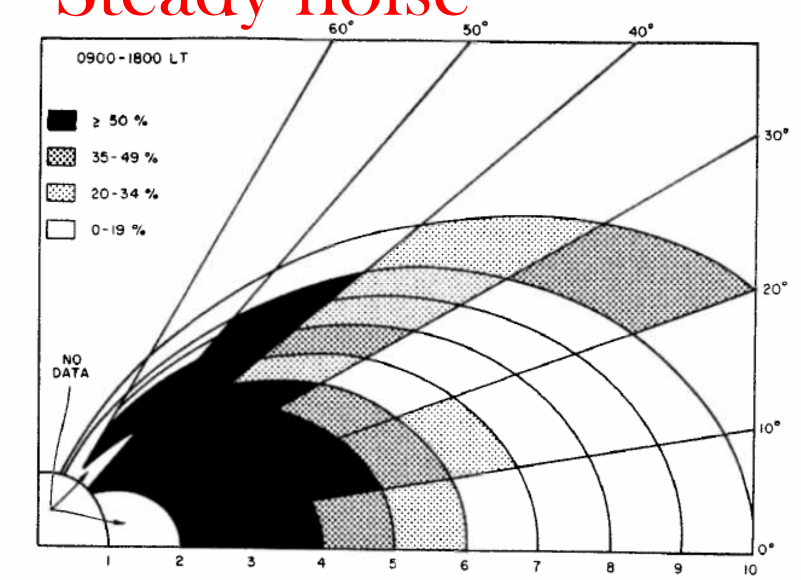
Santolik et al. [2001]



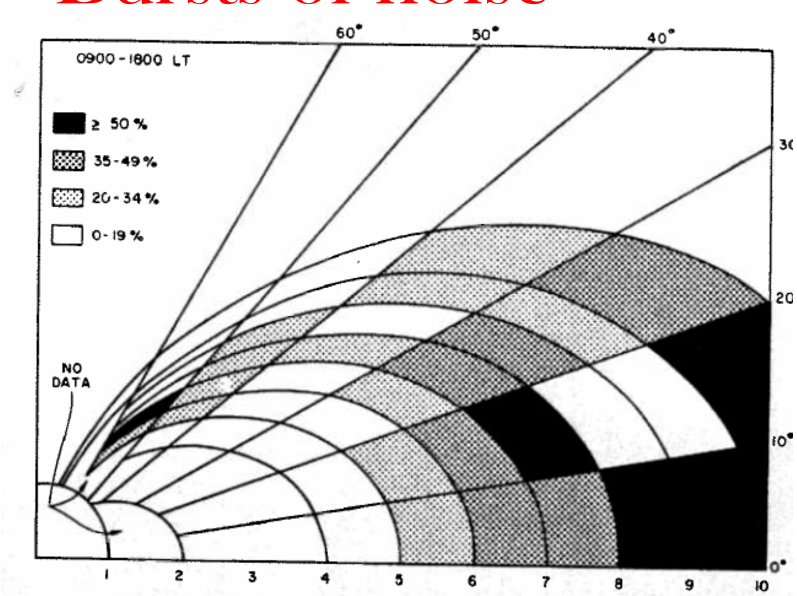
Ray tracing of chorus, observation of “structured hiss”, connection with ELF hiss? [Chum & Santolik, 2005; Santolik et al., 2006;]

Original VLF work

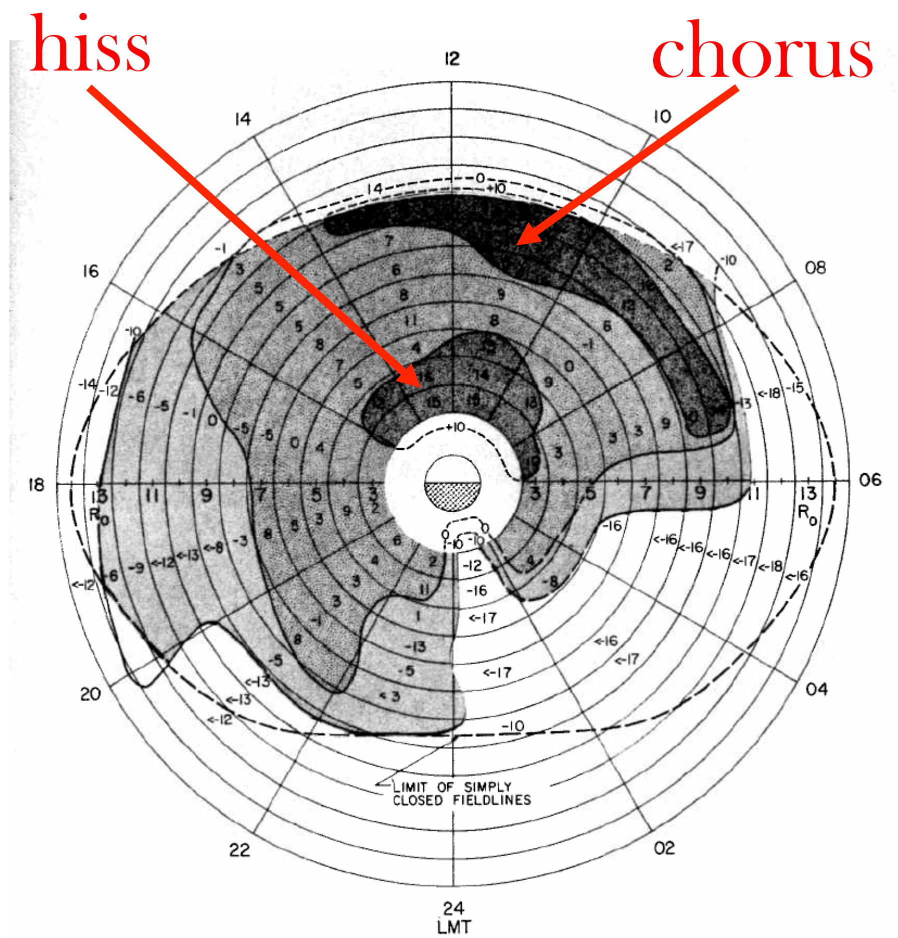
“Steady noise”



“Bursts of noise”

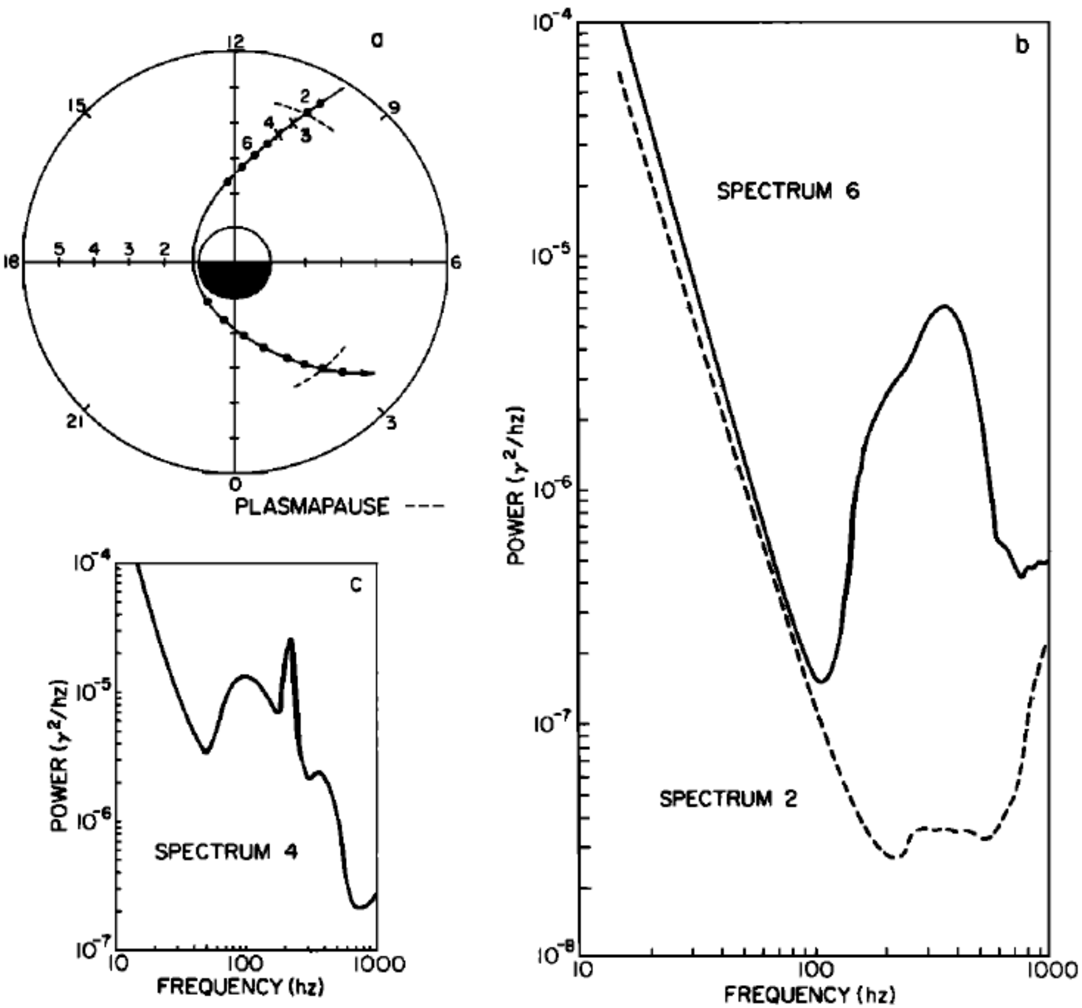


Russell et al. [1969]



OGO 1 satellite, ~0.3 – 0.5 kHz emissions
Dunckel & Helliwell [1969]

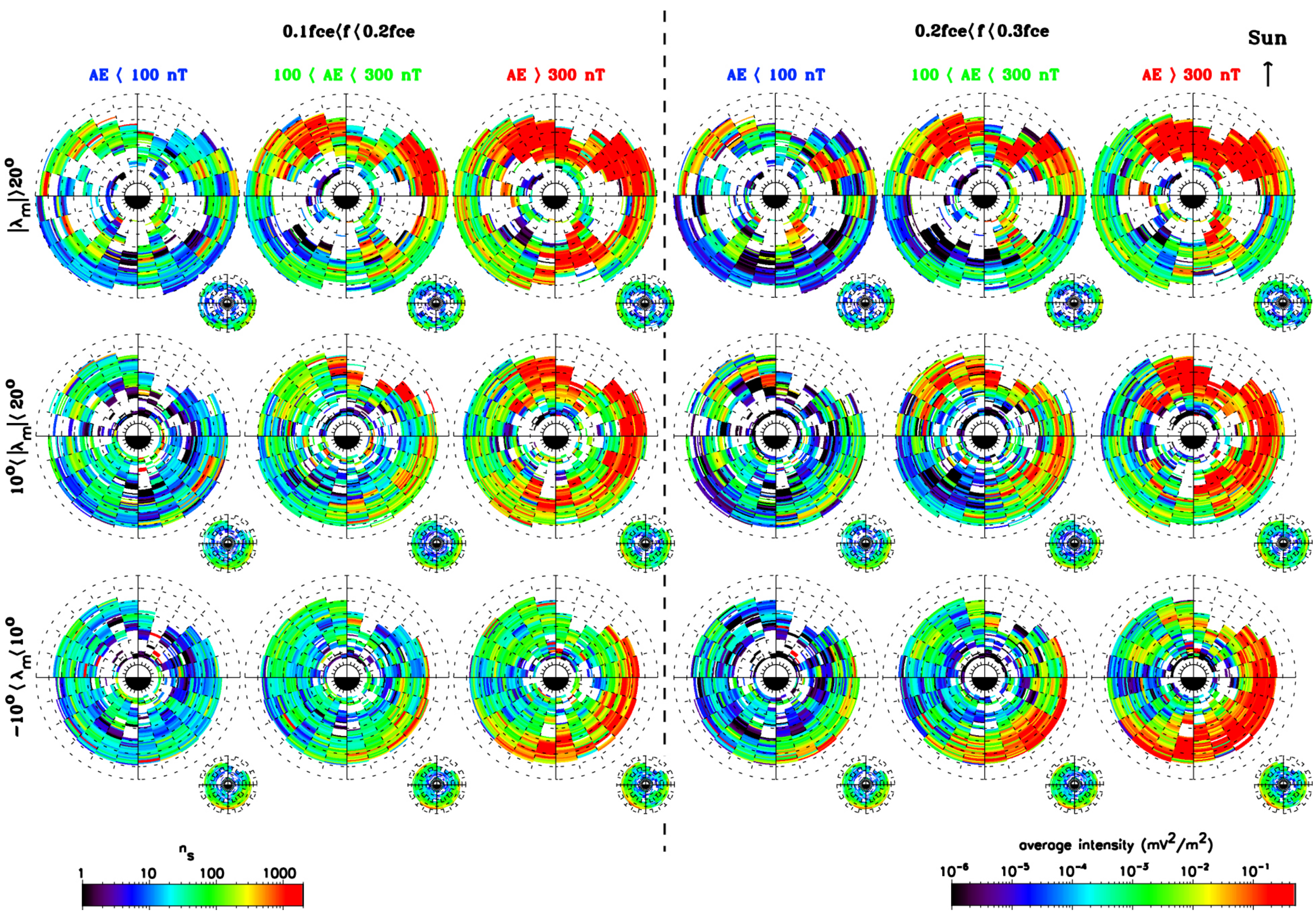
Early Space-based studies



OGO 5 pass, April 4^{th} 1968 [Thorne et al., 1973].

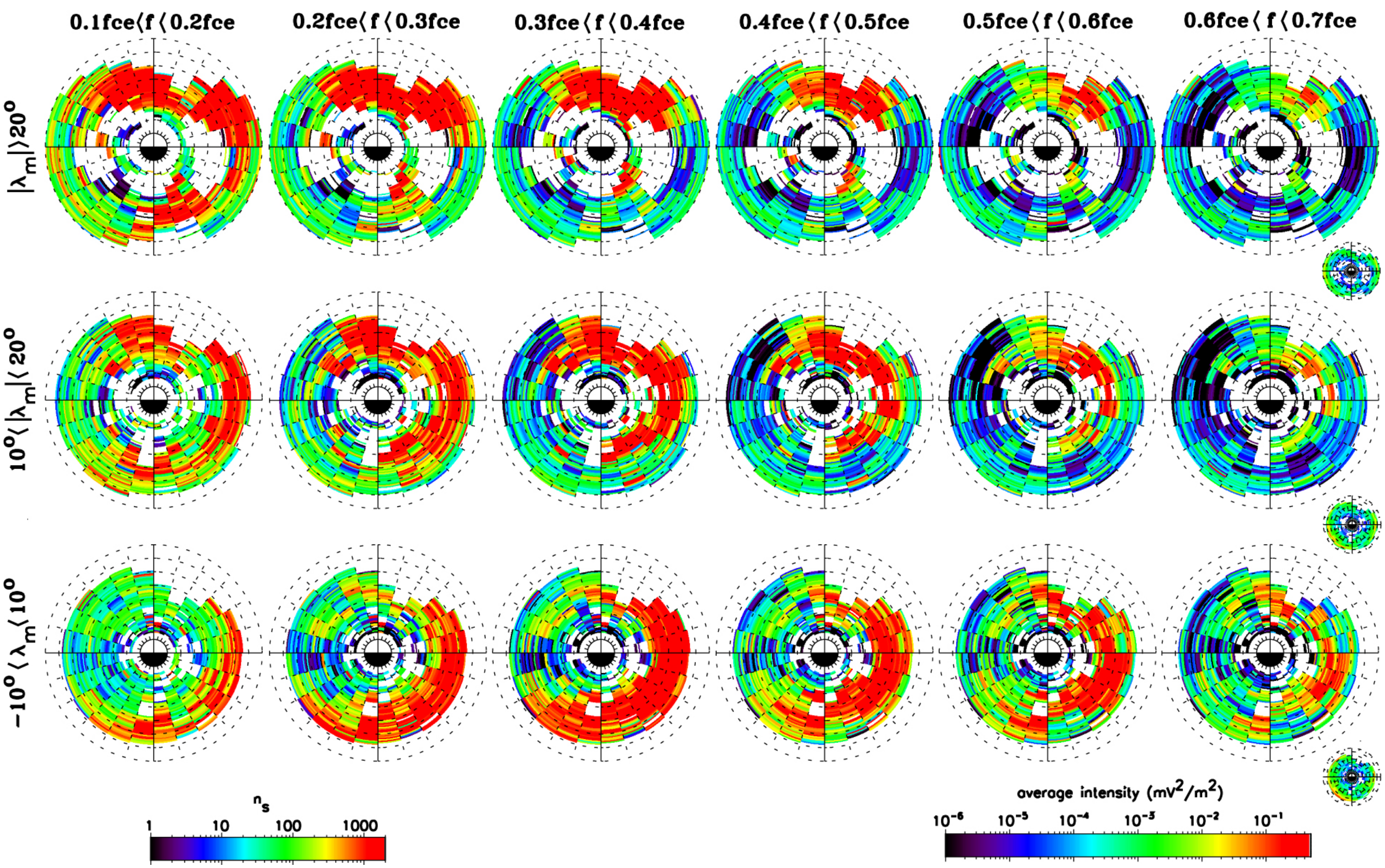
- Emission terminate abruptly at p-pause ➔ plasmaspheric hiss (except high lat day side)
- Amplitude ~5-50 pT
- Sharp lower cutoff, diffuse upper cutoff
- Max ~500-600 Hz
- Constant throughout plasmasphere (?)
- Probably generated by cyclotron instability just within p'pause (?)

Chorus intensity: geomagnetic control



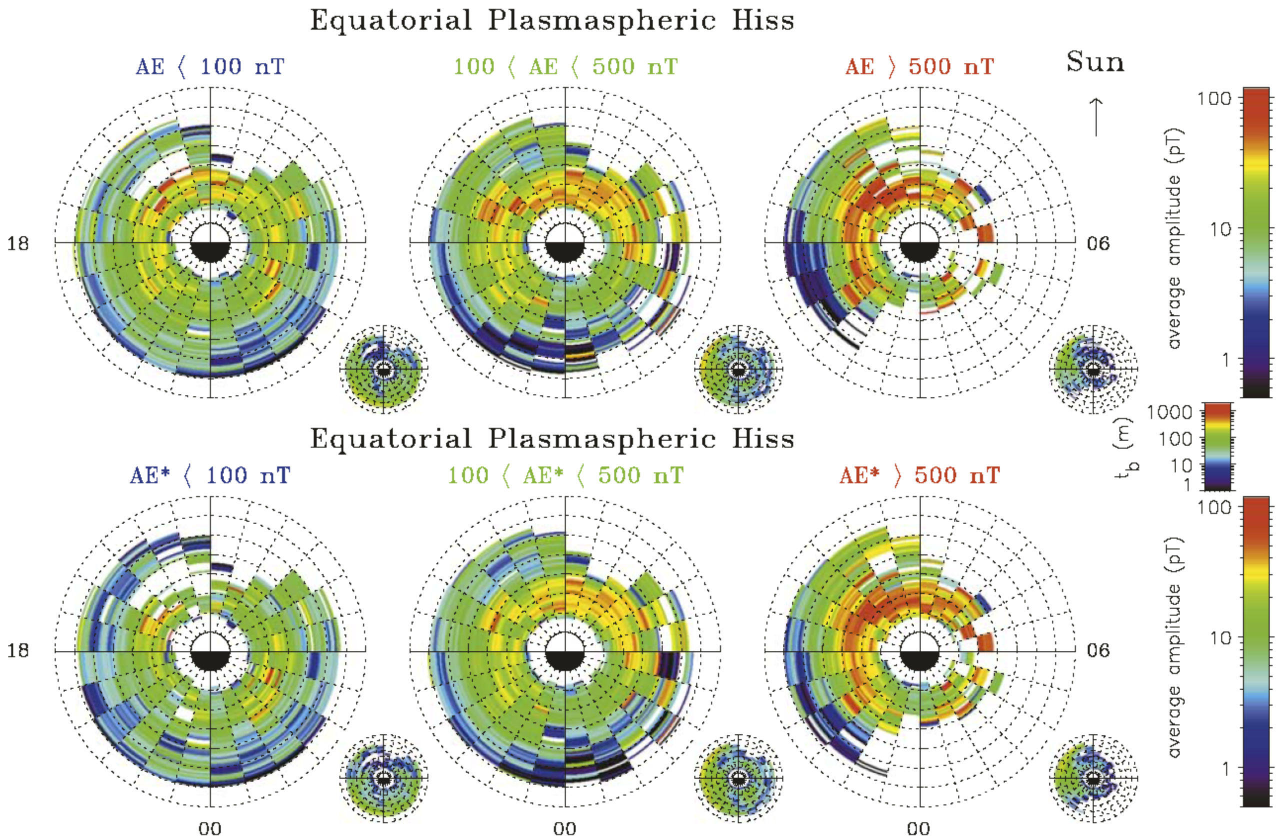
- Increasing asymmetry with AE

Chorus distribution



- Low f: high latitudes on day side
- High f: low latitudes on dawn

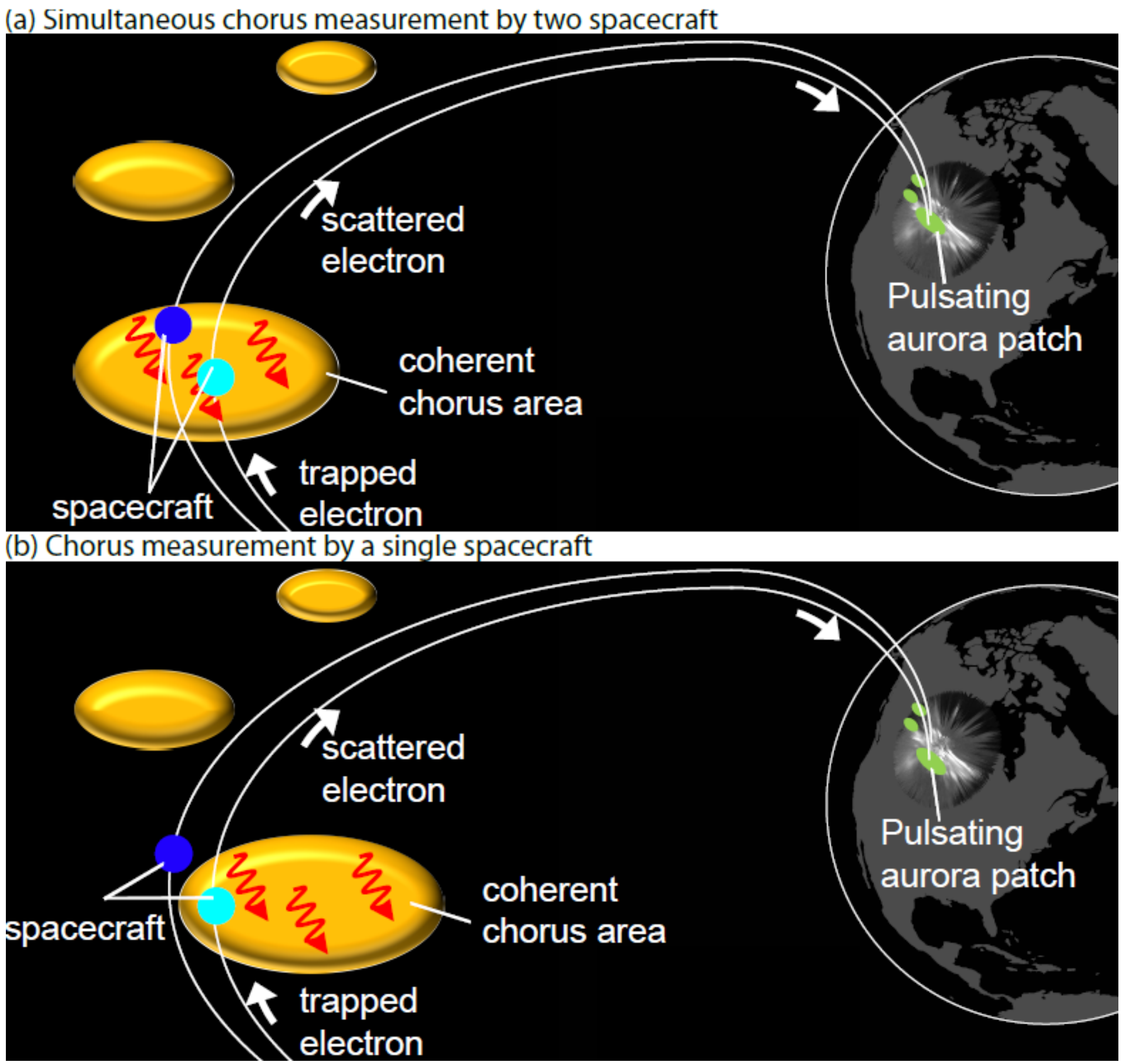
Plasmaspheric hiss statistical distribution



Meredith et al. [2004]

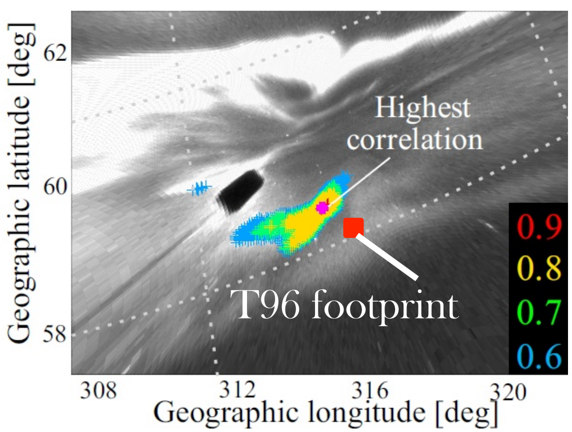
- Geomagnetic control and local time asymmetry
  - Weak: night, Intense: day
- 2-zone distribution; bandwidth distribution vs. L, exo-spheric/ELF hiss

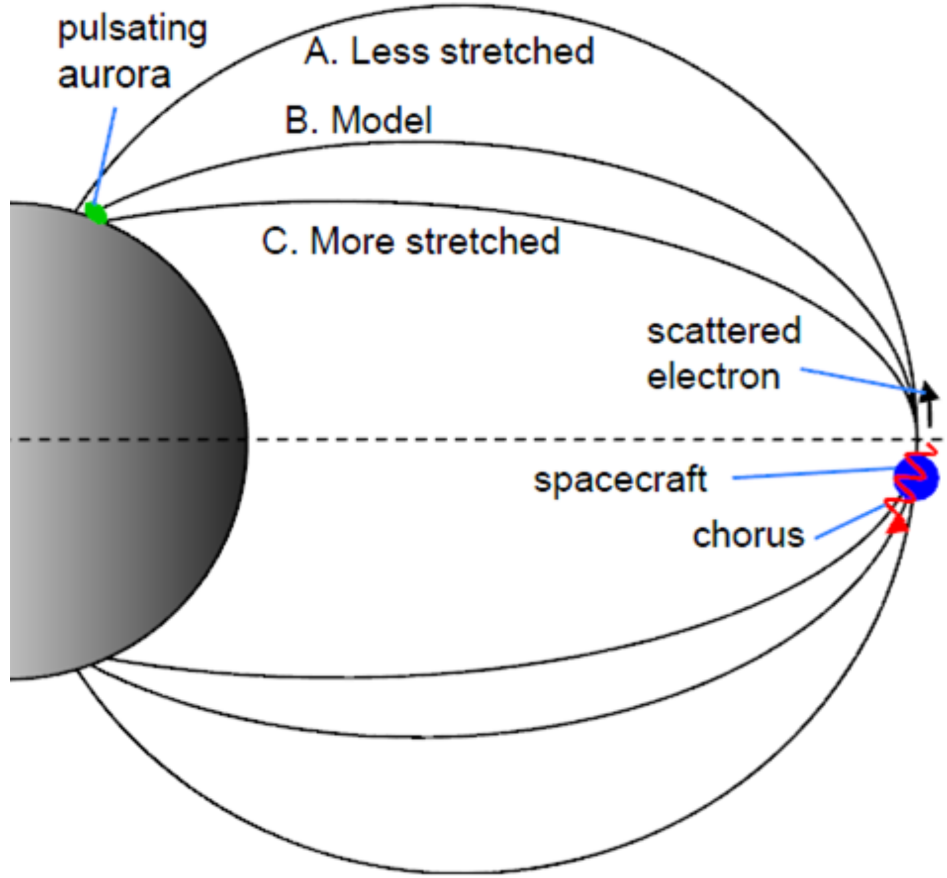
Source region bounding



Magnetic mapping

- Unique 1 to 1 correlation allows estimation of magnetic field models

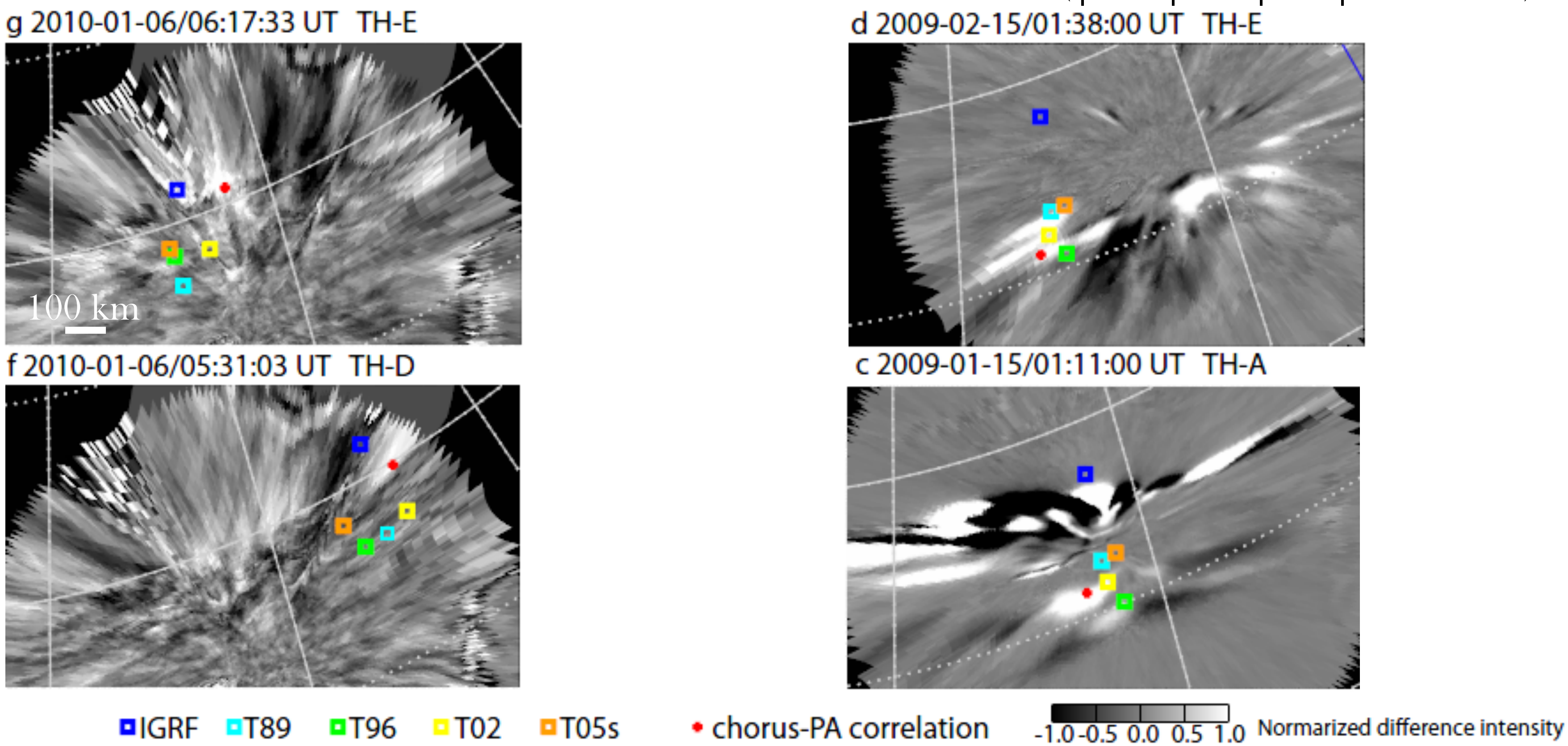




What is the typical error of the Tsyganenko magnetic field models?

Footprint location compared to multiple models

Quiet time (ΔH and ΔZ ~ 0) | Disturbed time (|ΔH| or |ΔZ| > ~ 50 nT)



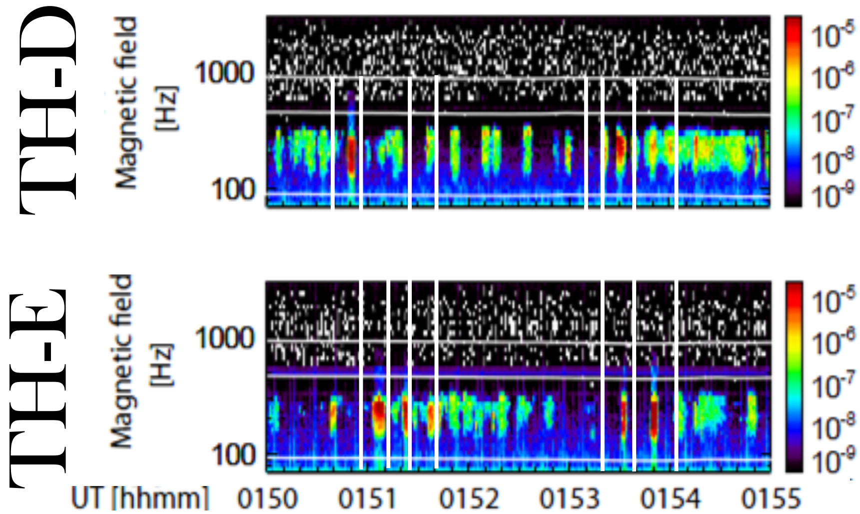
- The T02 magnetic field model (yellow) tends to be closer to the chorus-PA correlation location (error ~ 100 km in the ionosphere).

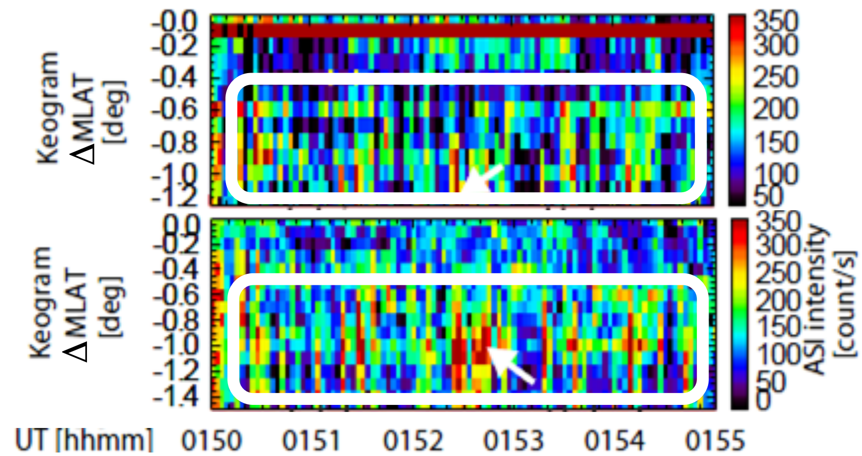
Magnetic activity dependence

- Quiet time footprint: Closer to IGRF than Tsyganenko
- Disturbed time footprint: Closer to or slightly equatorward of Tsyganenko

Simultaneous observation by two spacecraft

Spacecraft separation: ~1500 km



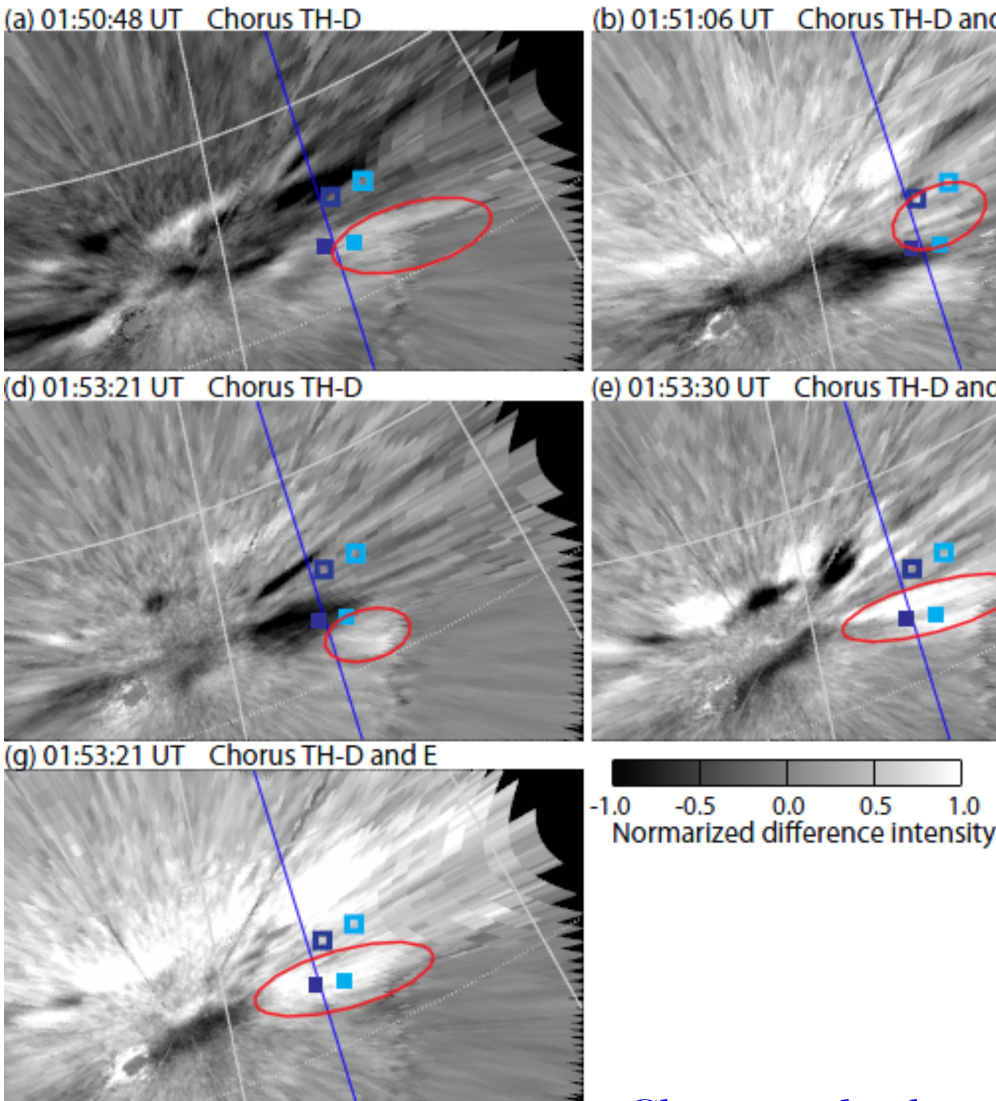


Chorus occasionally occur simultaneously at two spacecraft locations, but many chorus bursts are measure only by one of the spacecraft.

PA at the footprints are also not highly correlated.

This partial correlation using simultaneous aurora observations can be used to estimate the coherent chorus size near the equator.

Correlation with pulsating aurora for 7 most intense chorus bursts



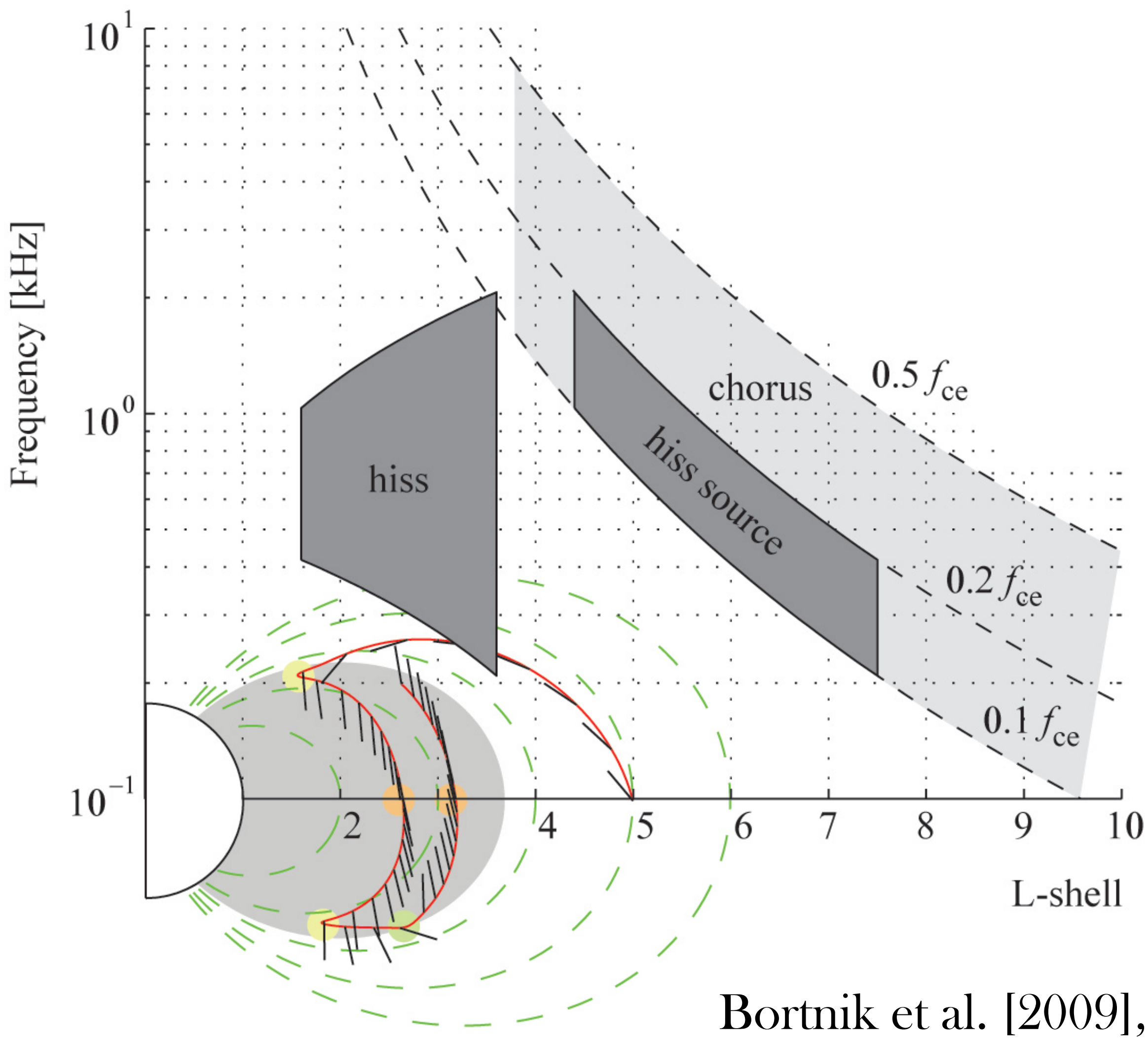
Chorus	Pulsating aurora
D only: a, d	D only: a, d
E only: c	E only: c
D and E: b, e, f, g	D and E: b, e, f, g

Chorus at both spacecraft = PA at both footprints

Chorus at single spacecraft = PA at single footprint

The PA patch shape would reflect the w-p interaction size.

Evolution of discrete chorus emissions into the plasmaspheric hiss continuum



Chorus ➔ hiss:

- Avoids Landau damping
- Propagates into plasmasphere at high latitudes
- Low frequencies
- Range of L-shells
- Range of wave normals

Statistical characteristics reproduced

Bortnik et al. [2009], *JASTP*