Explorer 1 launch:
Jan. 31st 1958

The dawn of chorus in the cacophony: an update on its manifold effects, open problems, and opportunities.

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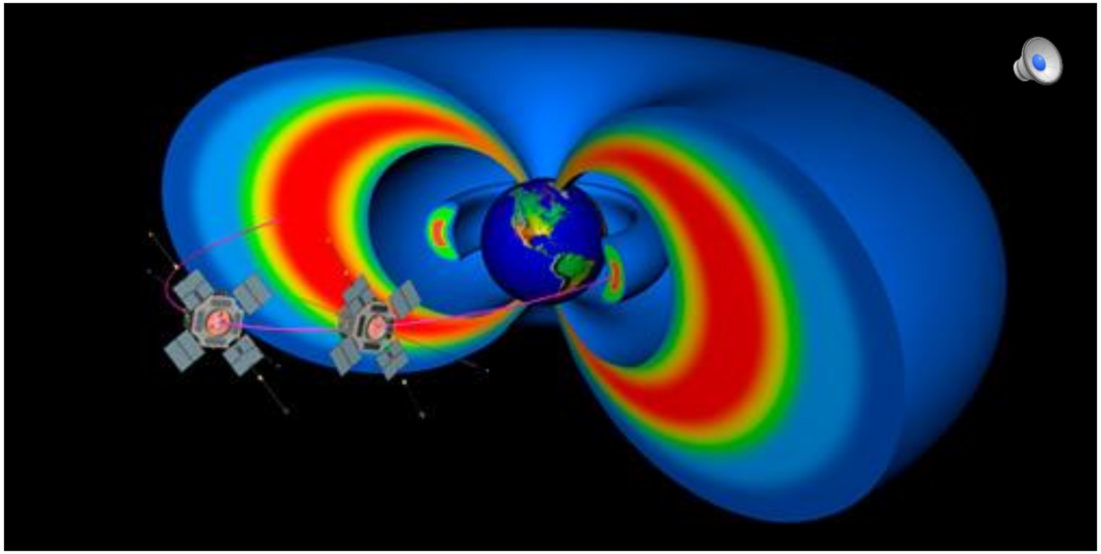
Outline



- Introduction to chorus waves and wave-particle interactions
  1. Low energy electrons (E<10 keV), e.g., diffuse aurora
  2. Medium energy electrons (10<E<100's keV), e.g., pulsating aurora
  3. High energy/relativistic electrons (~MeV), e.g., radiation belts
- *En route*: plasmaspheric hiss, real-time global chorus mapping, field line mapping, nonlinear interactions, and more!

Waves from space!

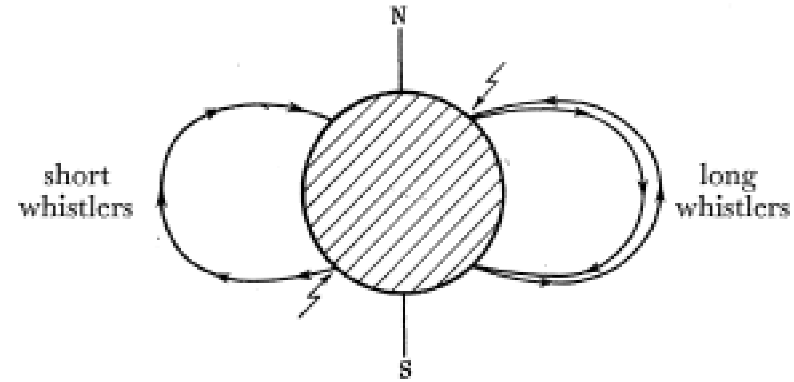
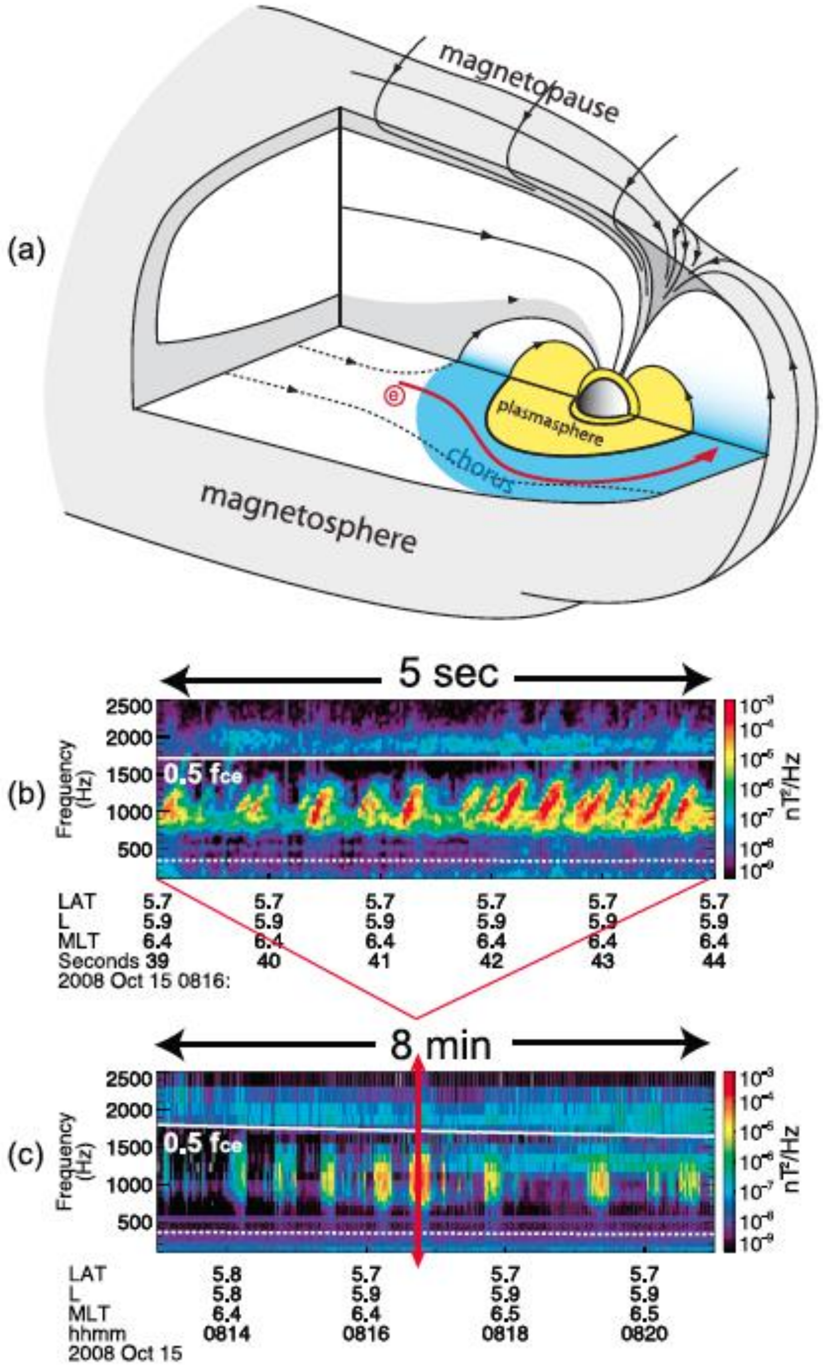


FIGURE 16. Suggested paths of the two types of whistler.

The sound of the 'dawn chorus' may be likened to that of a rookery heard from a distance. It consists of a multitude of rising whistles against a background of a warbling sound which may be mixed with varying amounts of toneless hissing. It has a pronounced daily variation of intensity with a maximum around 6 a.m., and its occurrence correlates strongly with magnetic storms; on undisturbed nights it usually does not appear at all, while on the night of a storm it may be heard continuously for five or six hours of the early morning.

From the Appendix: Other atmospherics on audio-frequencies, "An investigation of whistling atmospherics", L. R. O. Storey, Phil. Trans. Roy. Soc. London, 1953

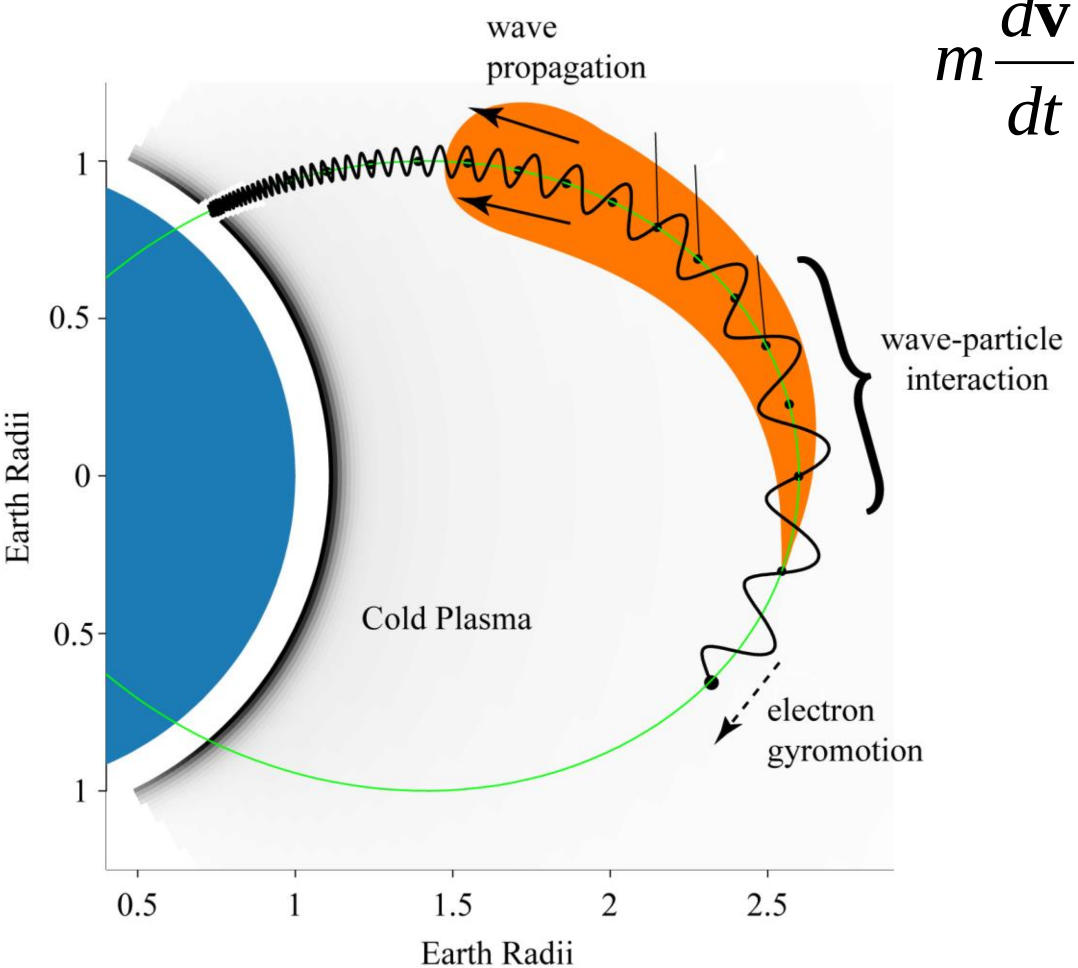
Chorus characteristics



Li et al. [2012], Fig. 1

- Found outside plasmasphere on dawn side
- Due to unstable, drifting plasmasheet electrons
- Multi-scale structure in space and time

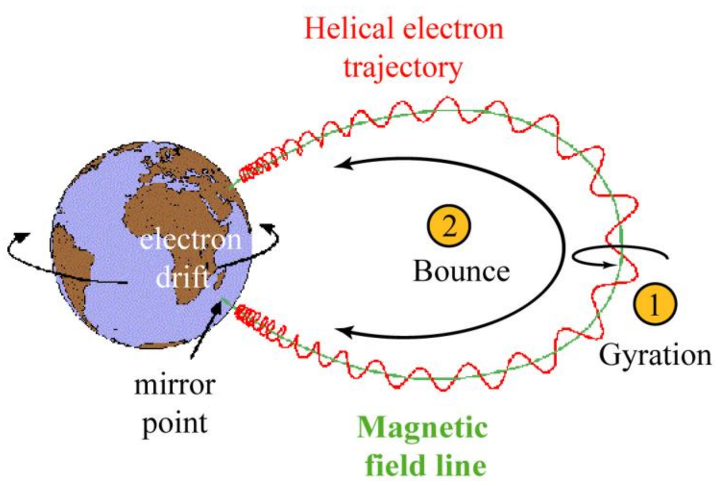
Chorus interaction with energetic electrons: geometry

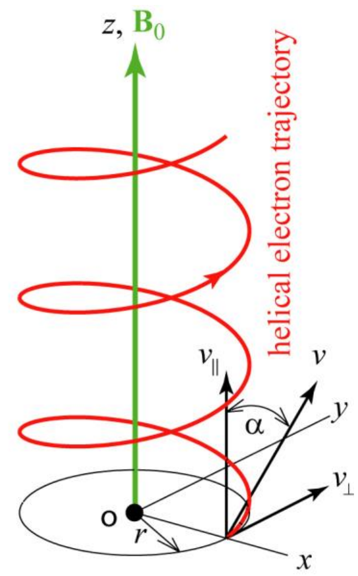


$$m\frac{d\mathbf{v}}{dt} = q\left(\mathbf{E}_\mathbf{w} + \mathbf{v}\times\left[\mathbf{B}_\mathbf{0} + \mathbf{B}_\mathbf{w}\right]\right)$$

- Wave (chorus) propagating away from equator
- Particle traveling through wave field
- Non-adiabatic changes

The unperturbed (adiabatic) motion





$$m\frac{d\mathbf{v}}{dt} = q\left(\mathbf{v}\times\mathbf{B_0}\right)$$

$$\frac{dv_\parallel}{dt} = -\frac{v_\perp^2}{2B}\frac{\partial B}{\partial z}$$

$$\frac{dv_\perp}{dt} = \frac{v_\perp v_\parallel}{2B}\frac{\partial B}{\partial z}$$

- Particle gyro-motion averaged out
- 1^{st} adiabatic invariant & energy conserved
- B-field inhomogeneity leads to bounce-motion

Perturbed motion by field aligned waves

- Non-adiabatic changes occur when η is stationary, i.e., dη/dt˜0 (resonance)

wave

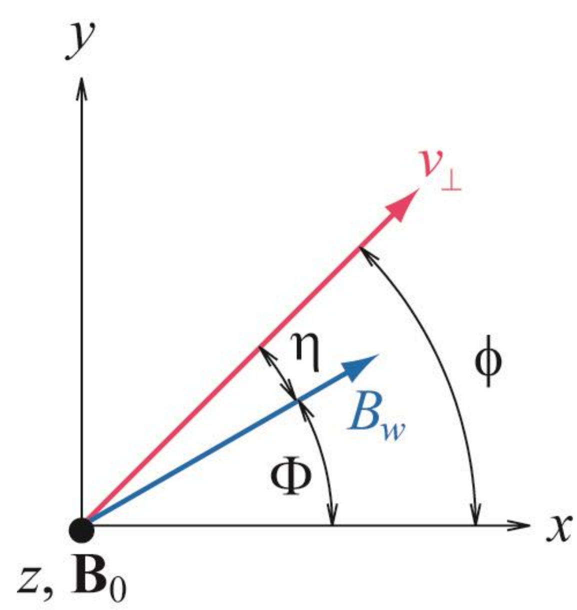
$$\frac{dv_{\|}}{dt} = \left(\frac{qB_w}{m}\right) v_{\perp} \sin\eta - \frac{v_{\perp}^2}{2B}\frac{\partial B}{\partial z}$$

adiabatic

$$\frac{dv_{\perp}}{dt} = -\left(\frac{qB_w}{m}\right)\left(v_{\|} + \frac{\omega}{k}\right) v_{\perp} \sin\eta + \frac{v_{\perp} v_{\|}}{2B}\frac{\partial B}{\partial z}$$

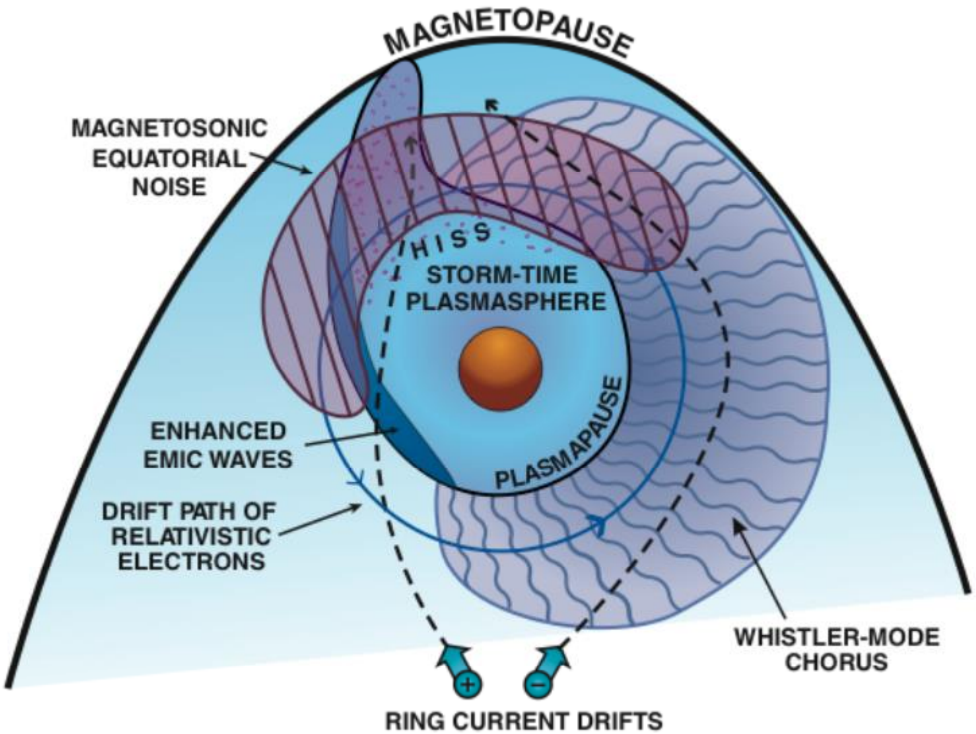
$$\frac{d\eta}{dt} = \Omega - \omega - kv_{\|}$$

phase



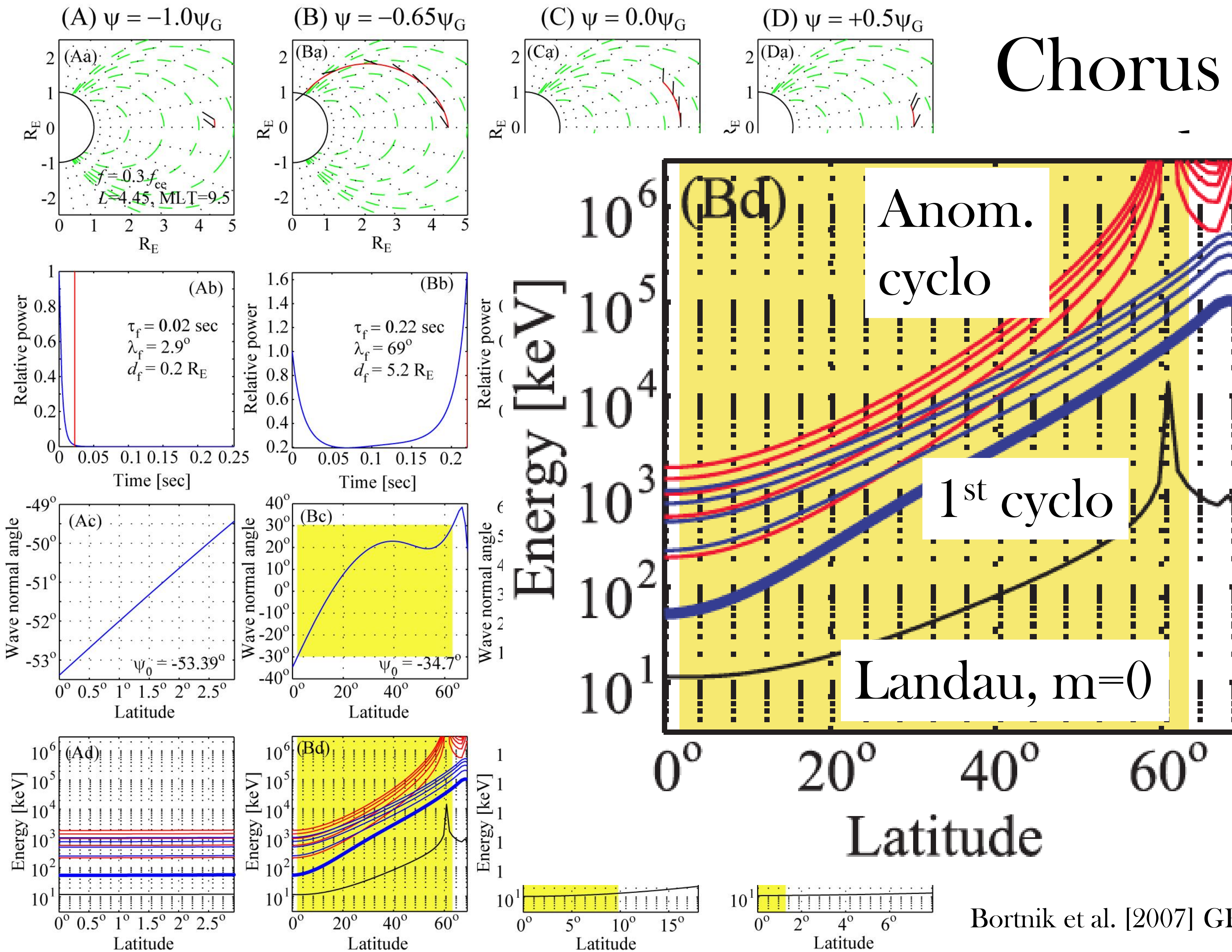
Collective wave effects

- 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 [2010] GRL
“frontiers” review

Chorus



Bortnik et al. [2007] GRL

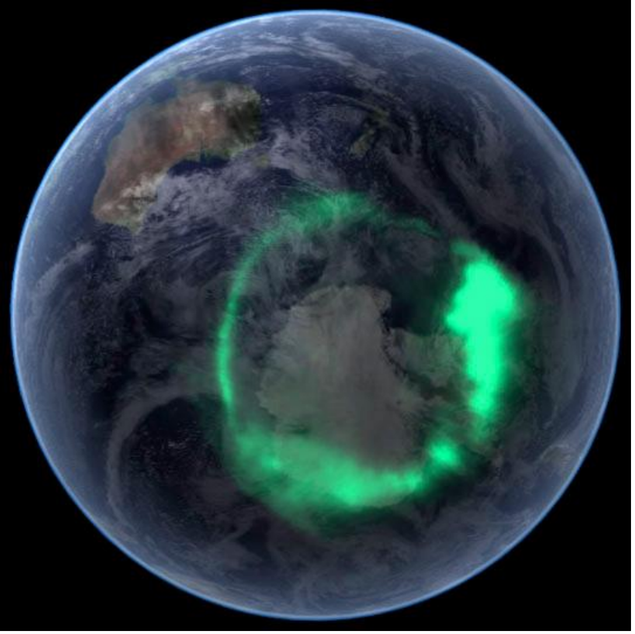
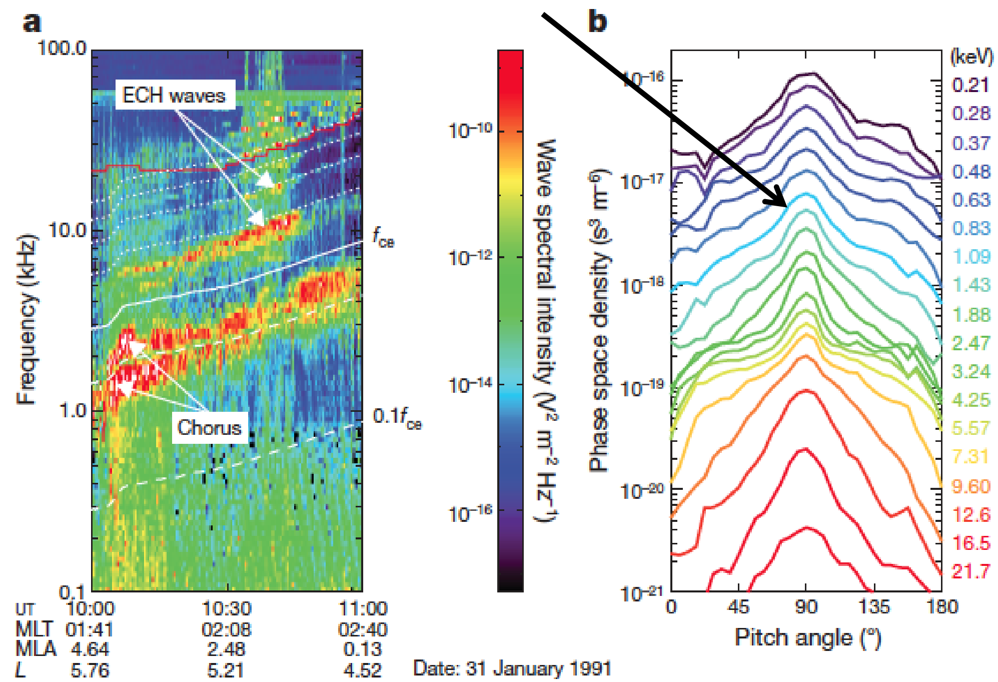


IMAGE satellite, 11 Sep 2005

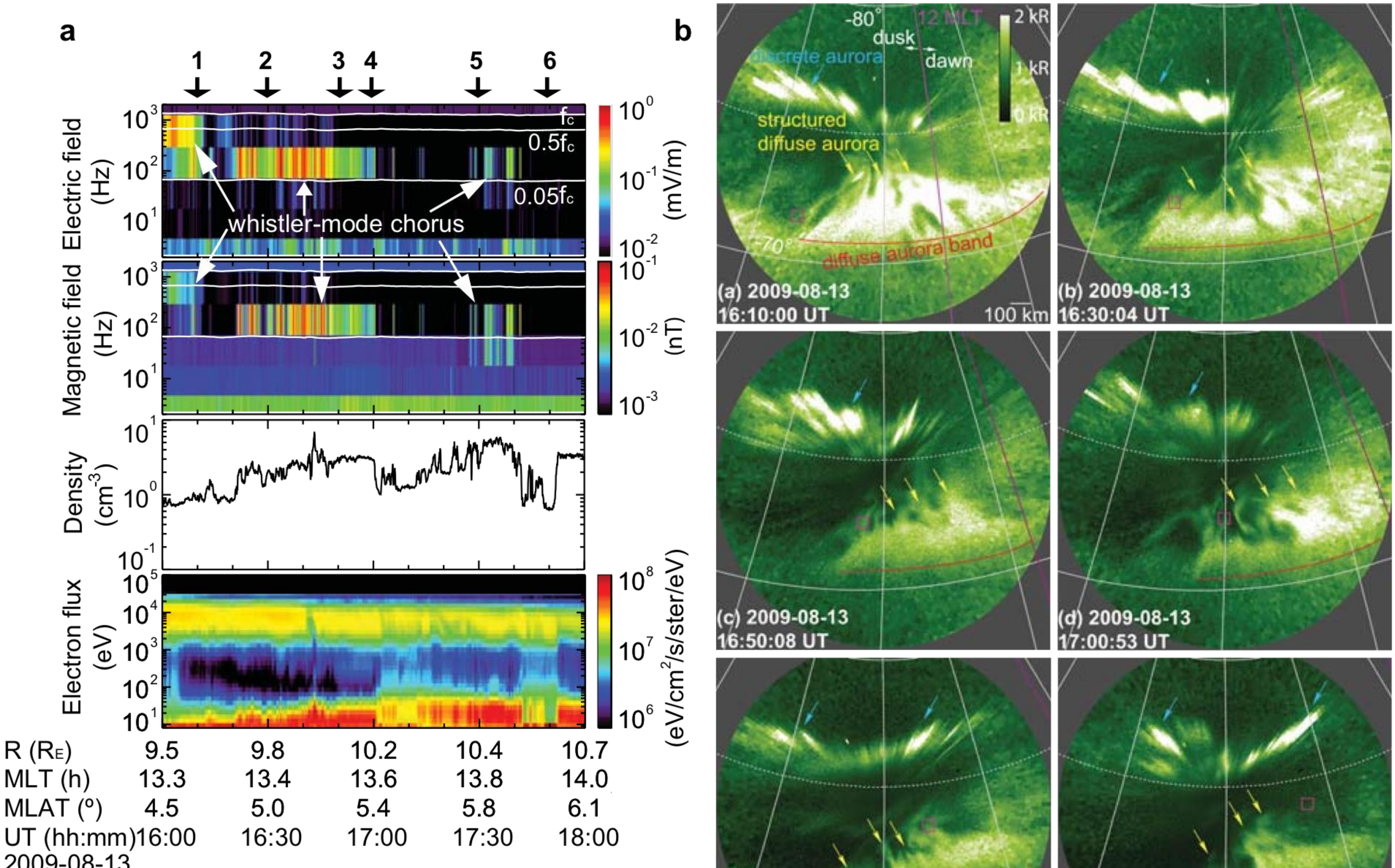
1. Diffuse aurora
(Low E<10 keV)

These “pancake” distributions provide the clue



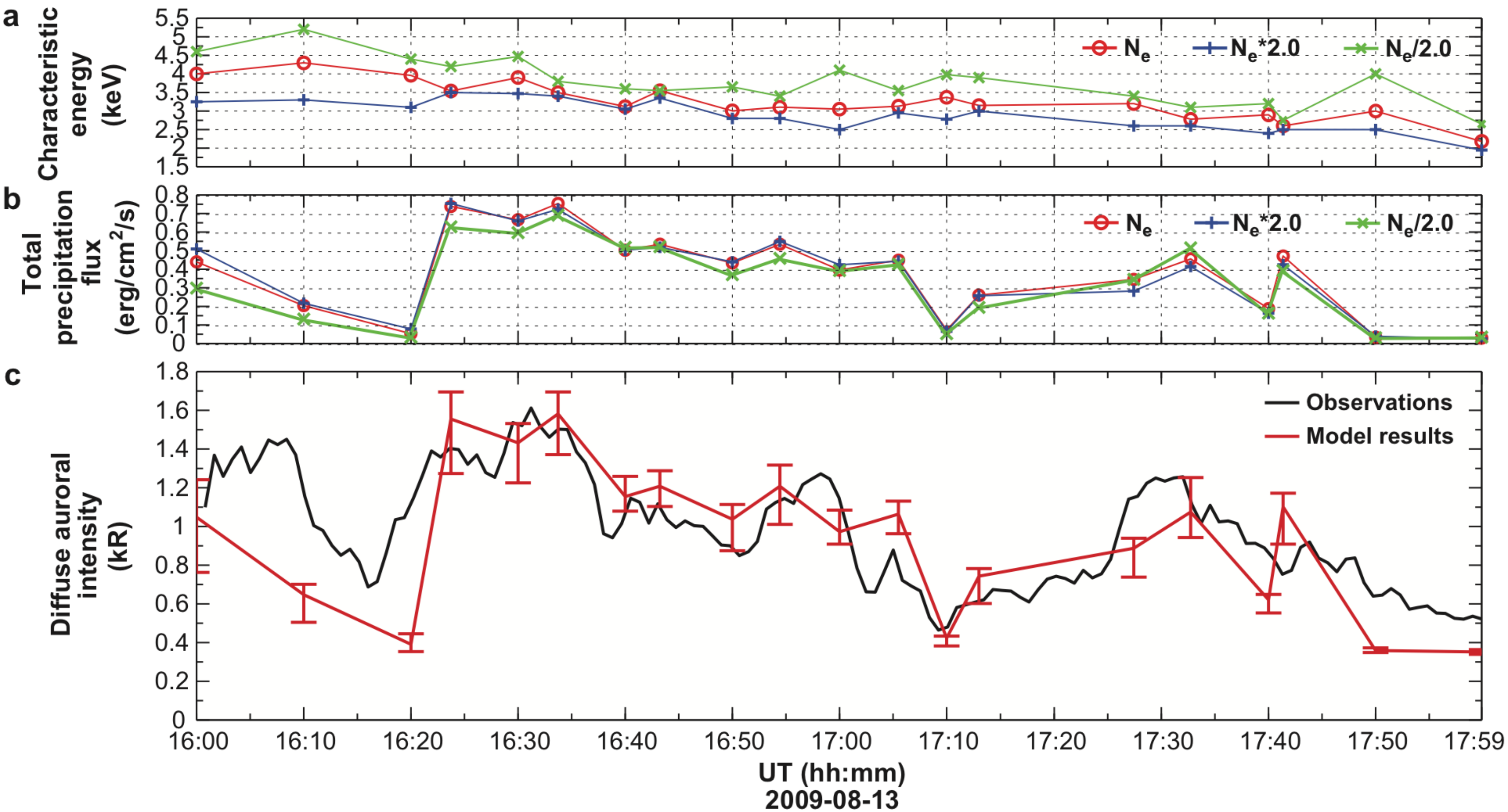
Thorne et al. [2010] *Nature*

- Only chorus can account for the resultant distributions observed in space
- Open question: what is the feedback effect of the ionospheric conductivity changes?

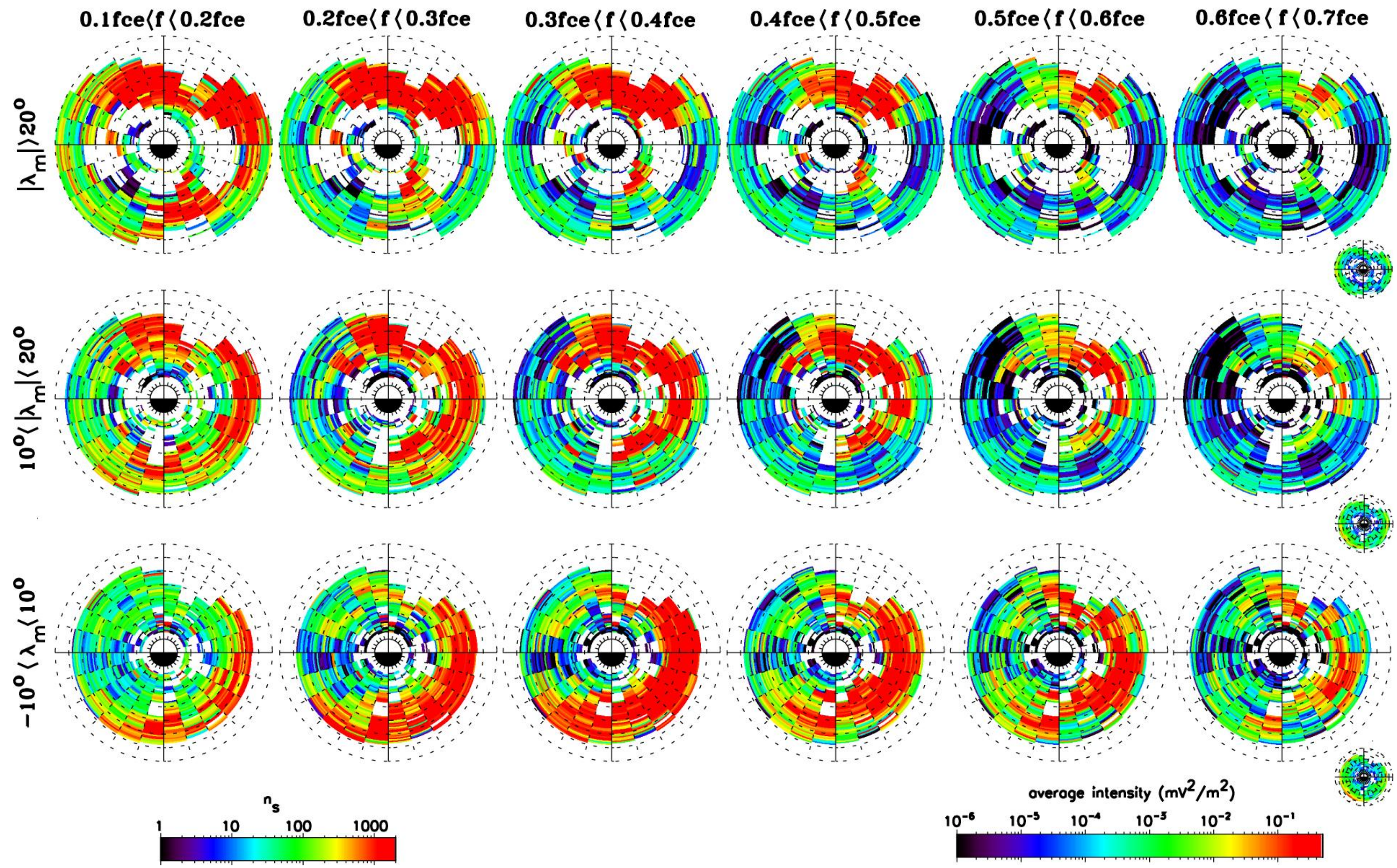


Ni et al. [2013], submitted

Chorus controls diffuse auroral emission brightness



~1 keV fluxes control chorus distribution

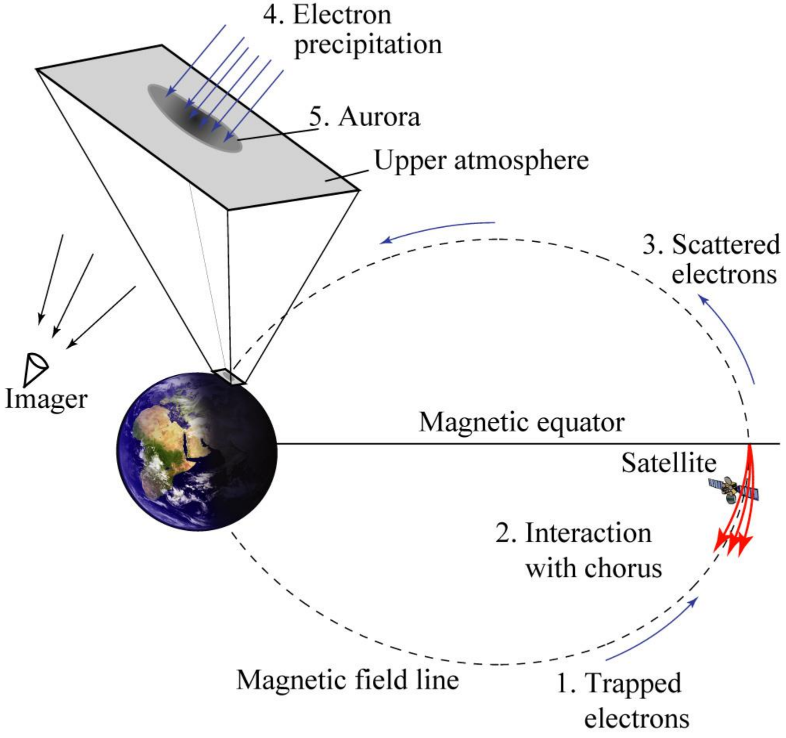


- Low *f*: high latitudes on day side
- High *f*: low latitudes on dawn

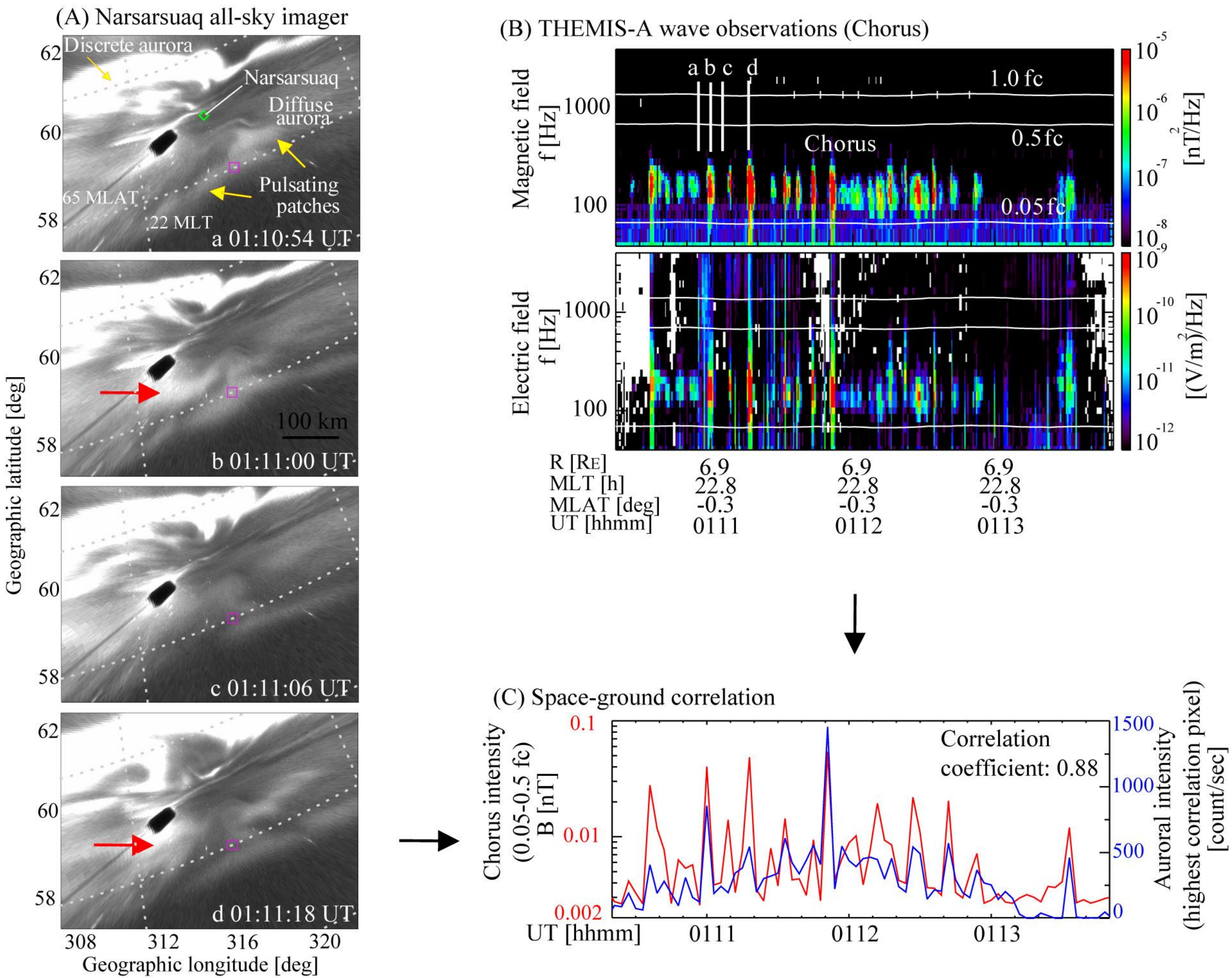
Bortnik et al. [2007]

2. Pulsating aurora (Medium 10<E<100s keV)

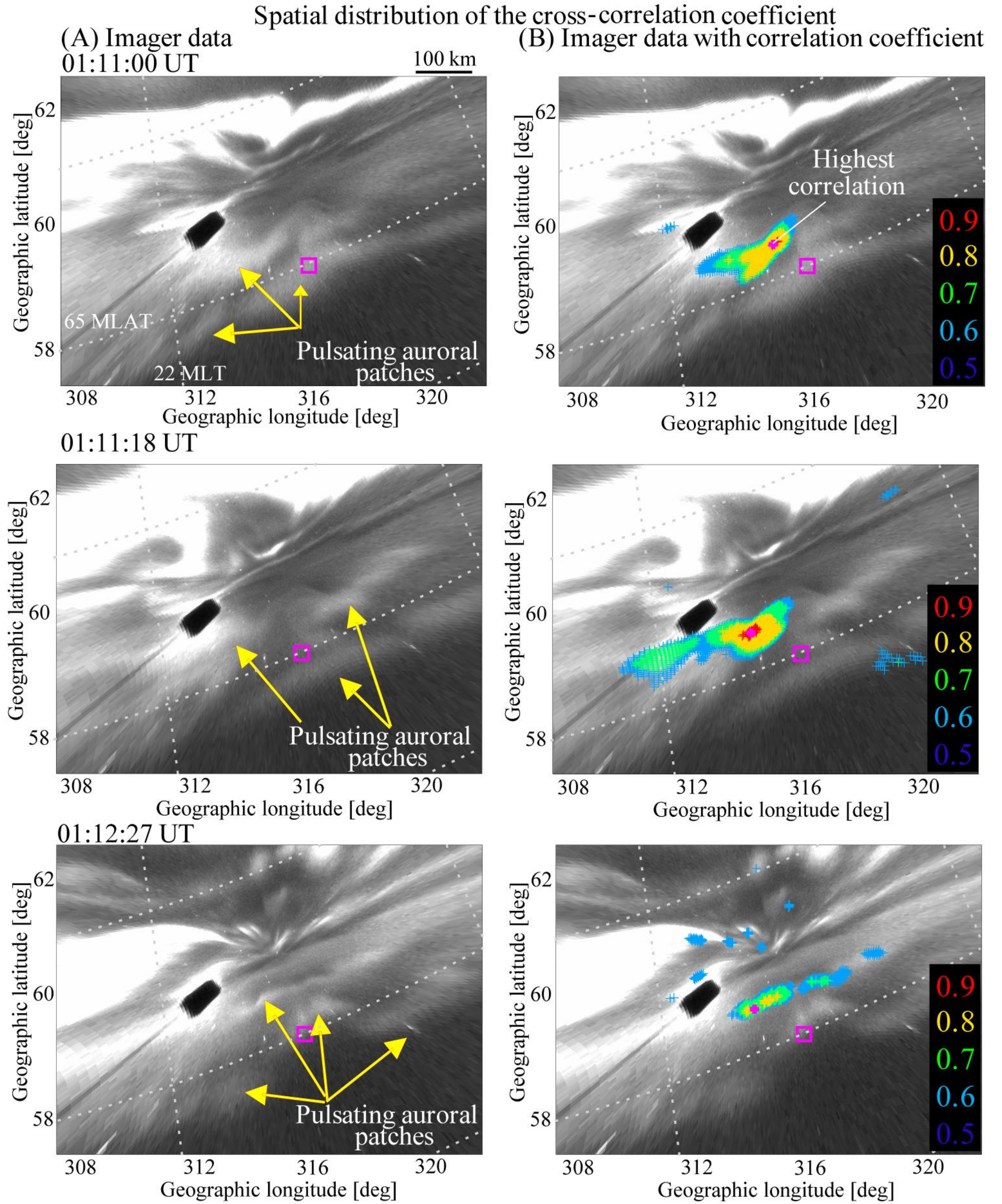
- Described in 1963 “auroral atlas”
  - Luminous patches that pulsate with a period of a few to 10’s of seconds
  - Scale, ~10-100 km
  - Precipitating electrons E>10 keV



TH-A, Nar-ASI conjunction 15 Feb 2009



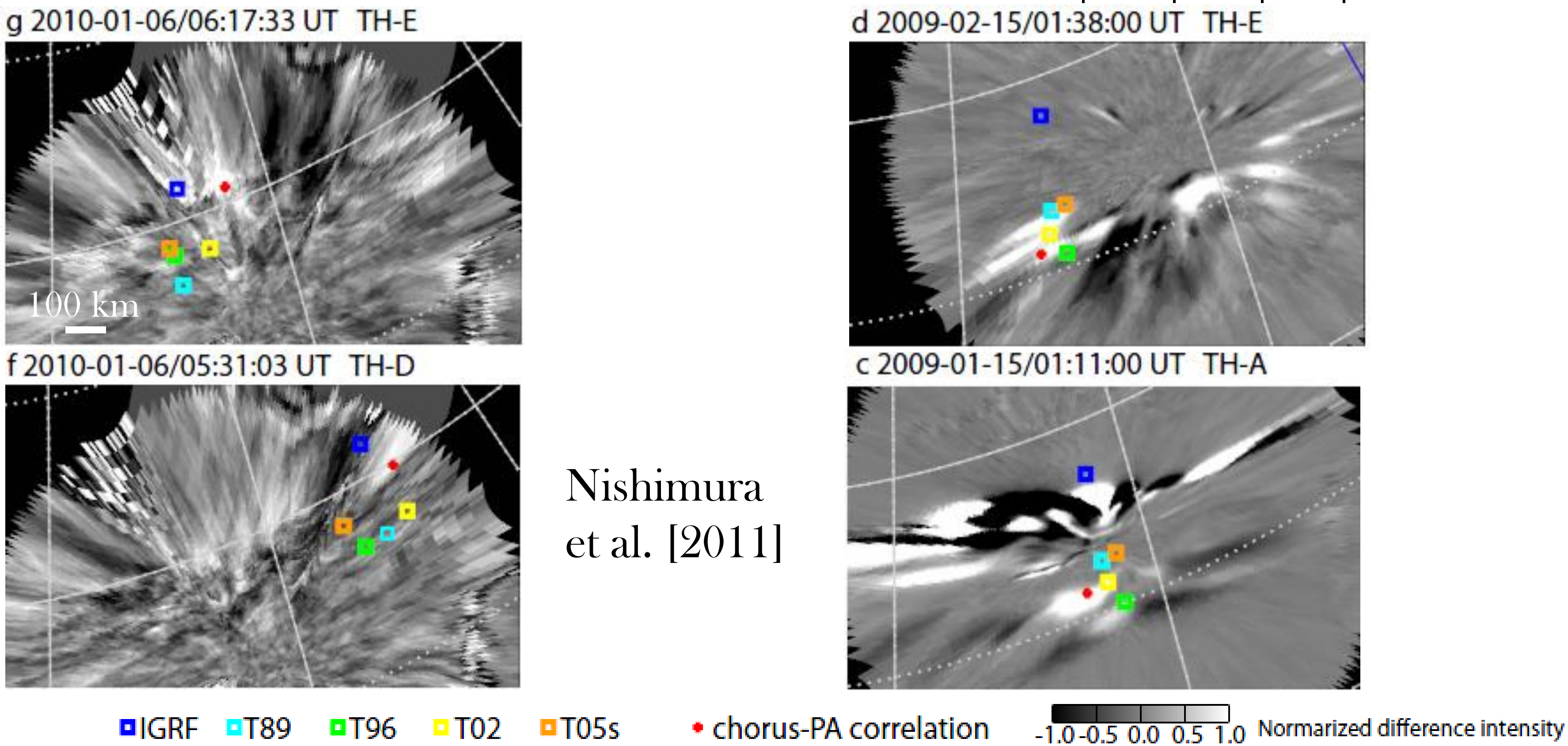
- Map of cross-correlation coefficients
- >90% correlation
- Location roughly stationary



Nishimura et al. [2010], *Science*, 330 (81)

Validity of multiple magnetic field models

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



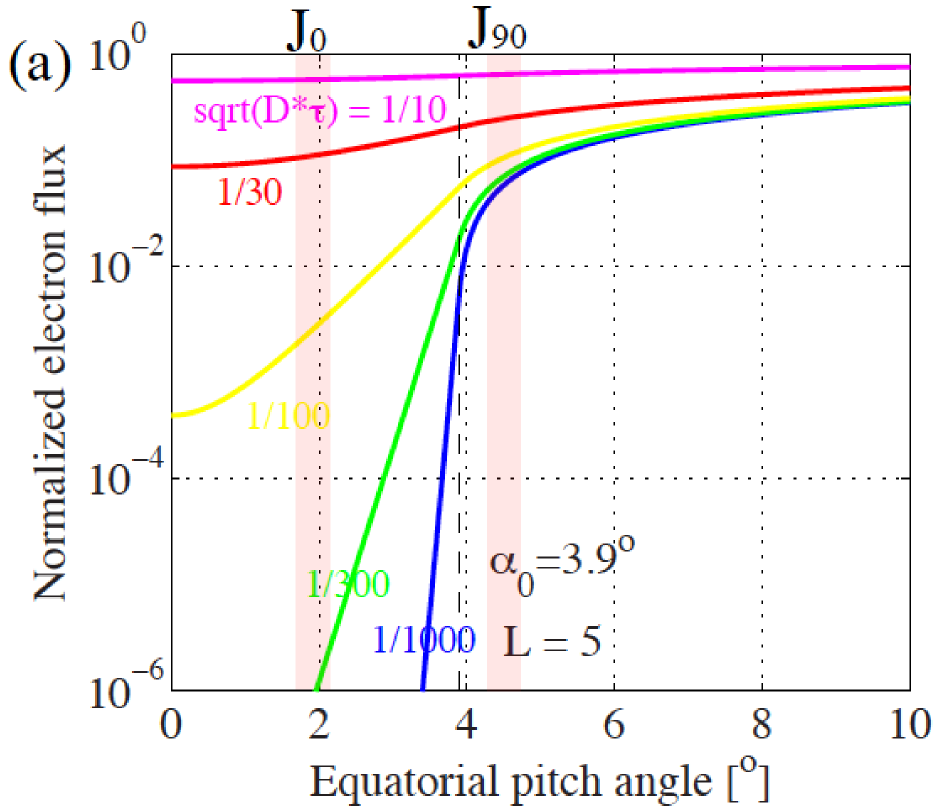
Nishimura et al. [2011]

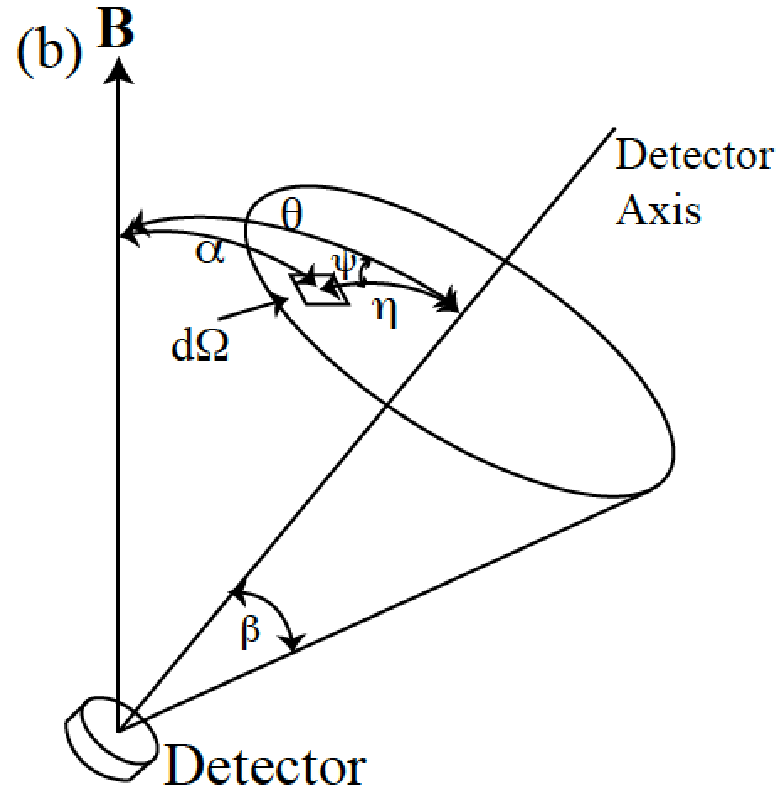
- The T02 magnetic field model (yellow) tends to be closer to the chorus-PA correlation location (error ~ 100 km in the ionosphere).

Magnetic activity dependence

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

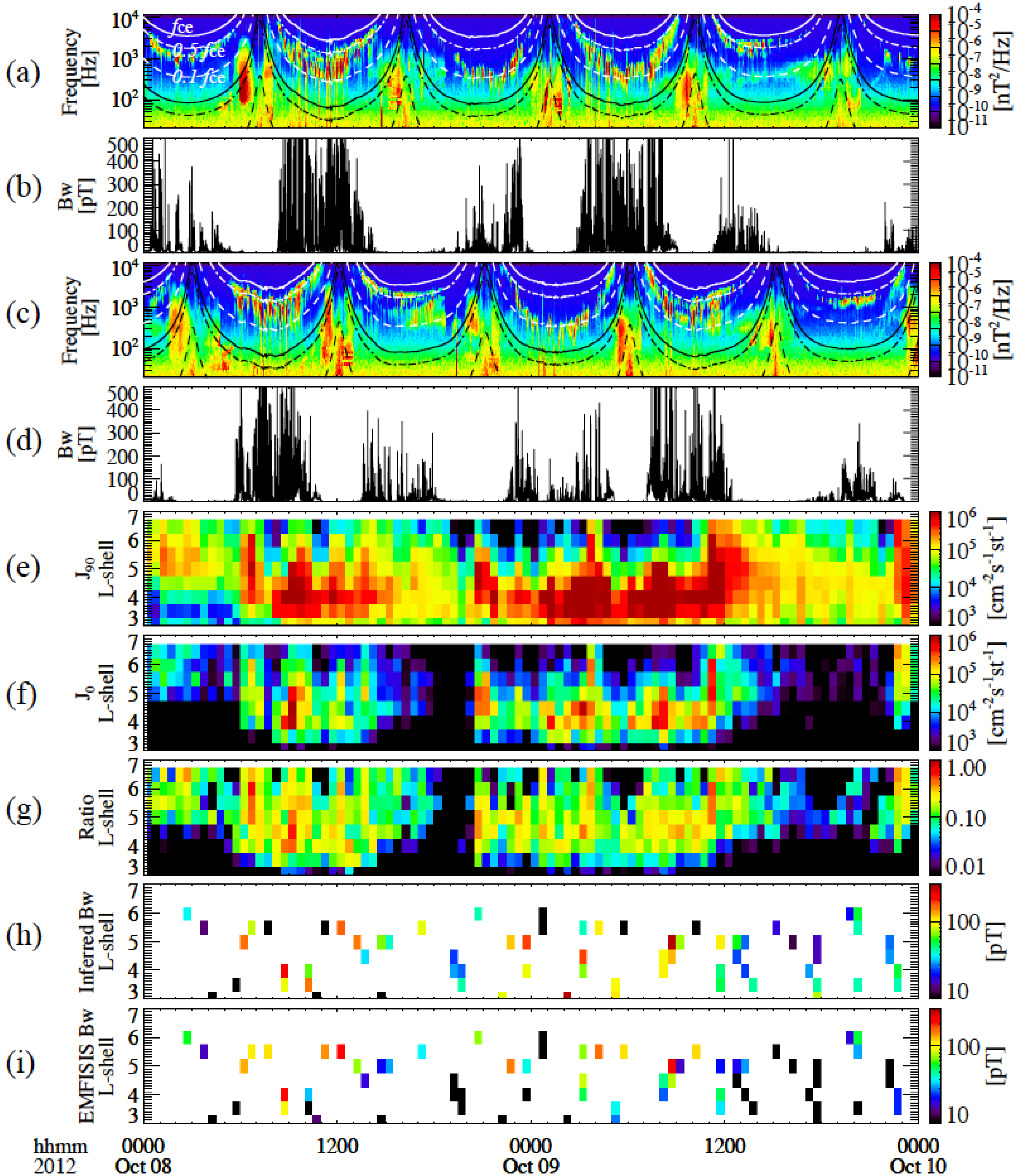
Inferring global chorus distributions



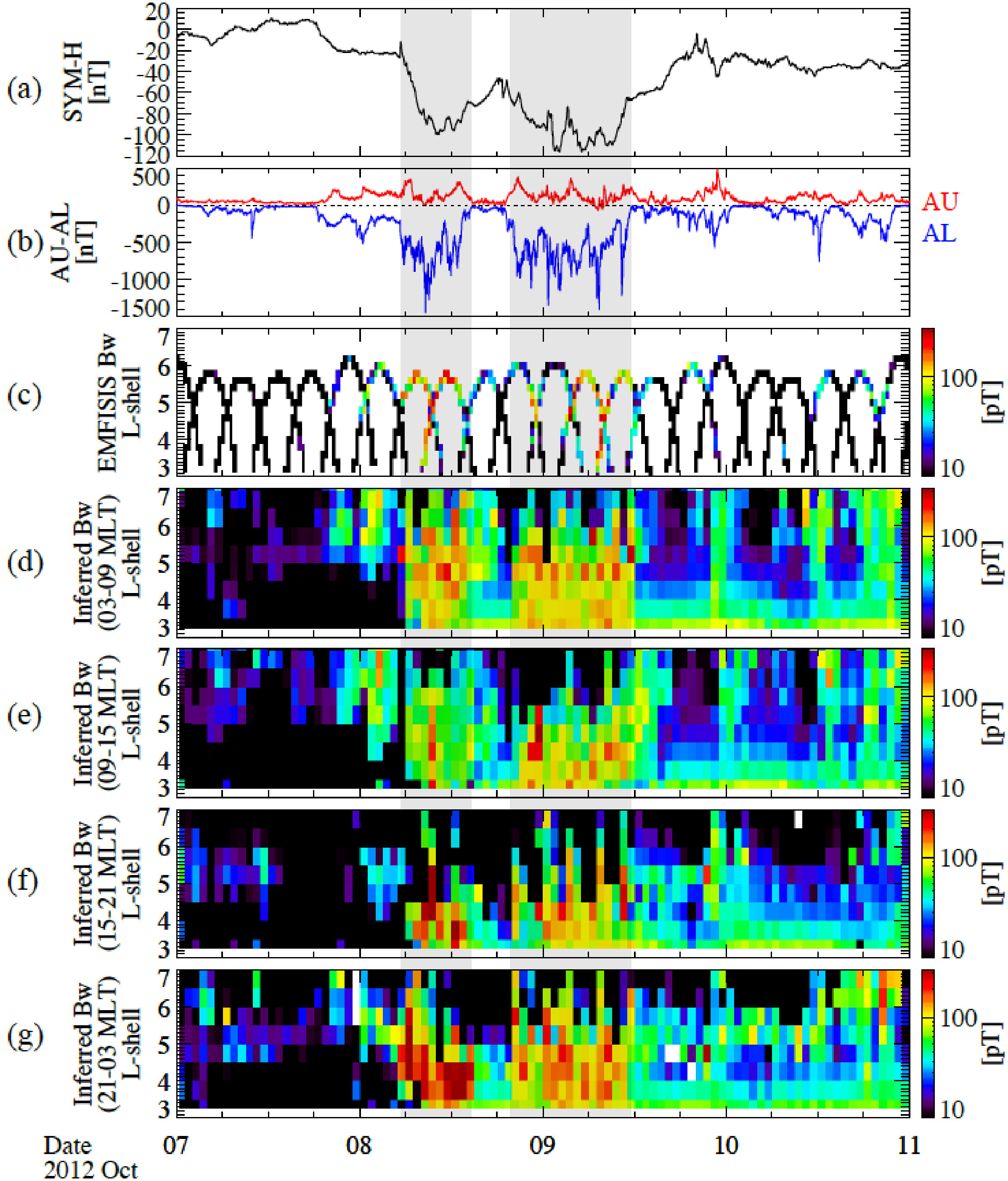


Li et al. [2013], in press

- Use POES fluxes at at 0° and 90° pitch angle
- Source population, 30-100 keV
- J_0 / J_{90} directly related to $D_{\alpha\alpha}$ near edge of loss cone -> B_w^2



Comparions to directly measured chorus wave amplitudes during rough conjunction events between POES and Van Allen Probes, where each colored bin represents a rough conjunction event.



Evolution of global chorus wave amplitudes inferred from multiple POES satellites, and observed by the two Van Allen Probes

Thorne et al. [2013], submitted

High energy/relativistic electrons (~MeV)

"There are two distinct, widely separated zones of high-intensity [trapped radiation]."

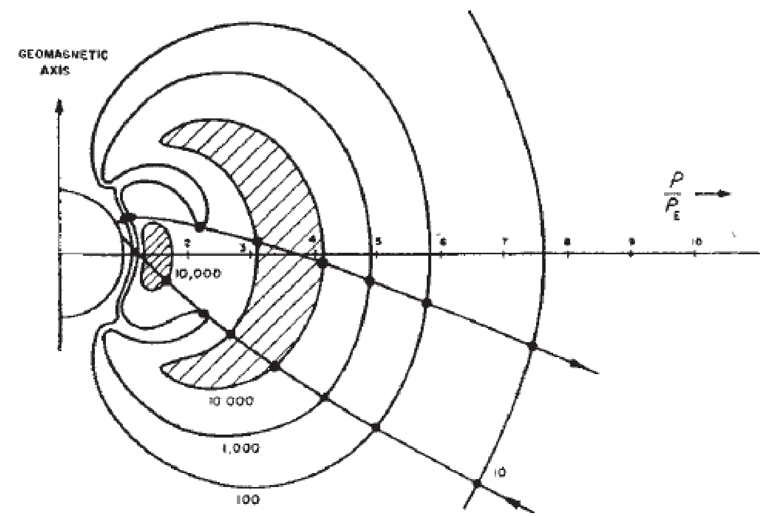
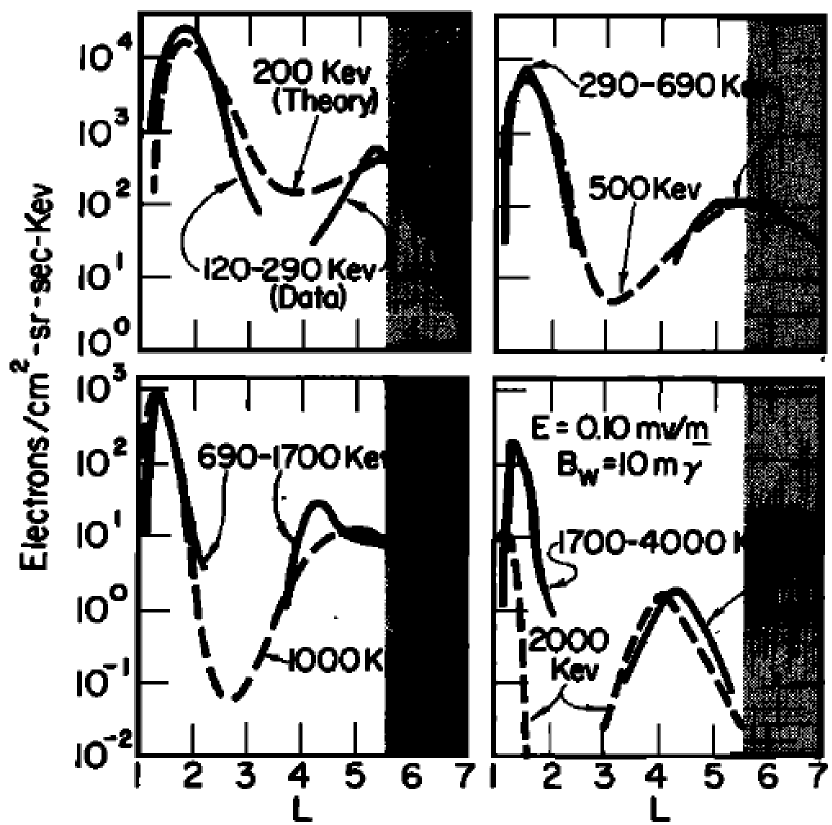


Fig. 5. A plot in a geomagnetic meridian plane of the intensity-structure of the radiation region around the Earth. The numbers associated with the several contours of constant intensity are the true counting rates *R* of the Geiger–Müller tube in *Pioneer III* or in satellite 1958ε. Within the two cross-hatched areas *R* exceeds 10,000/sec. See text for further discussion

Explorer 1 launch:
Jan. 31st 1958

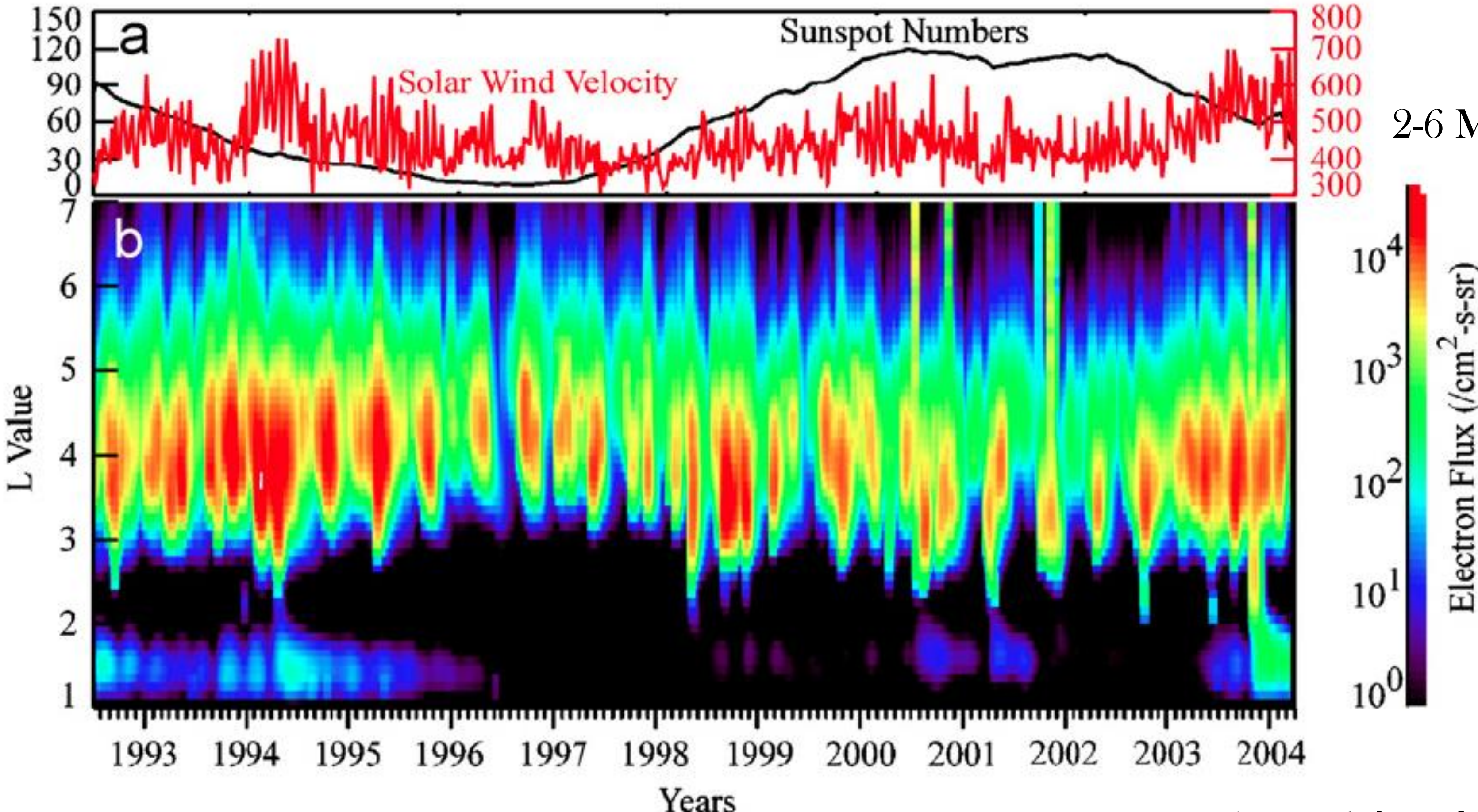
Equilibrium 2-zone structure

- 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]

Variability of Outer belt

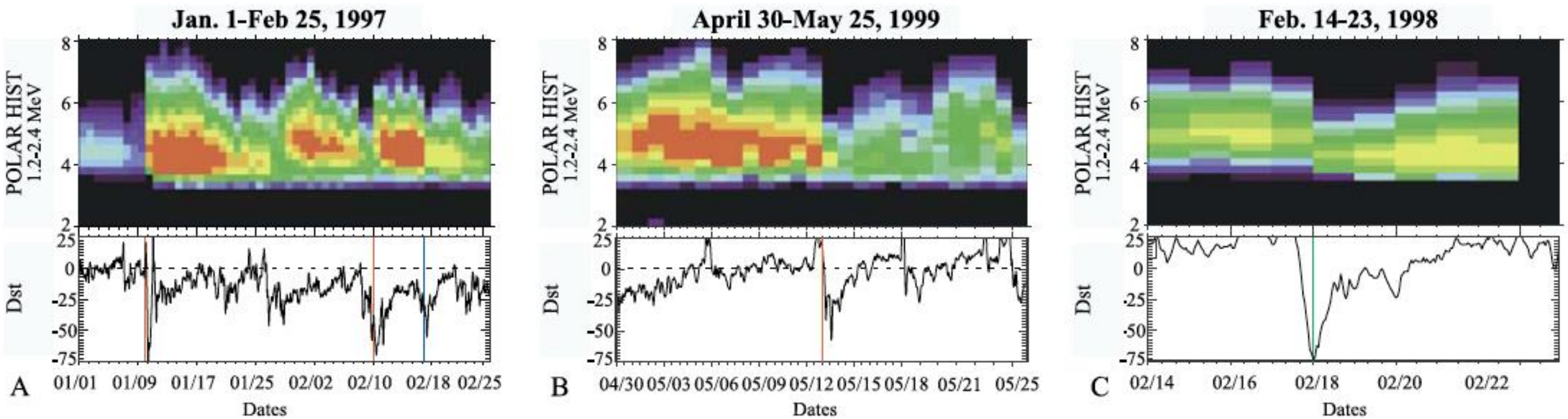


2-6 MeV

Baker et al. [2008]

Outer radiation belt exhibits variability, several orders of magnitude, timescale ~minutes.

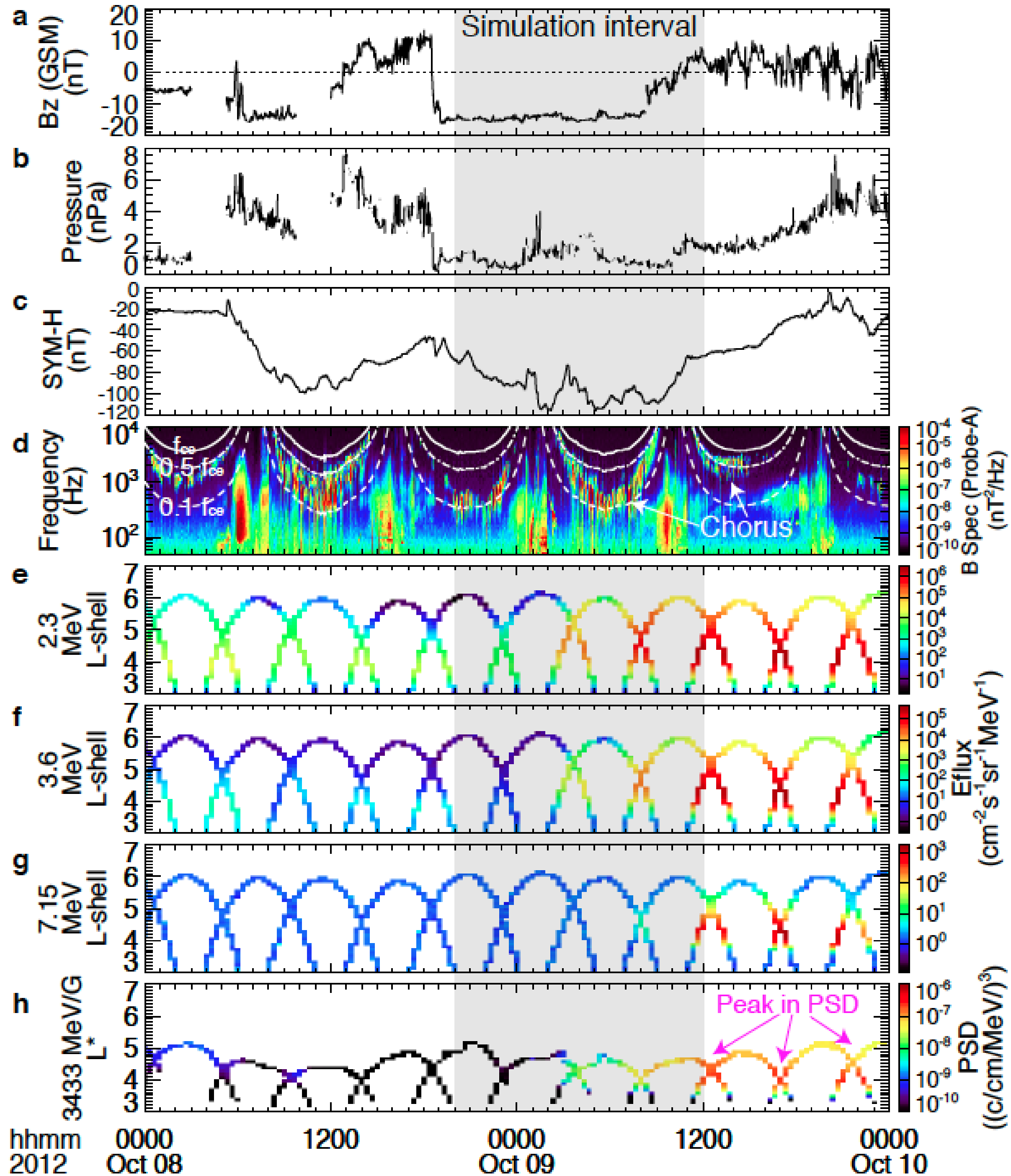
Predictability of outer belt fluxes



Reeves et al. [2003]

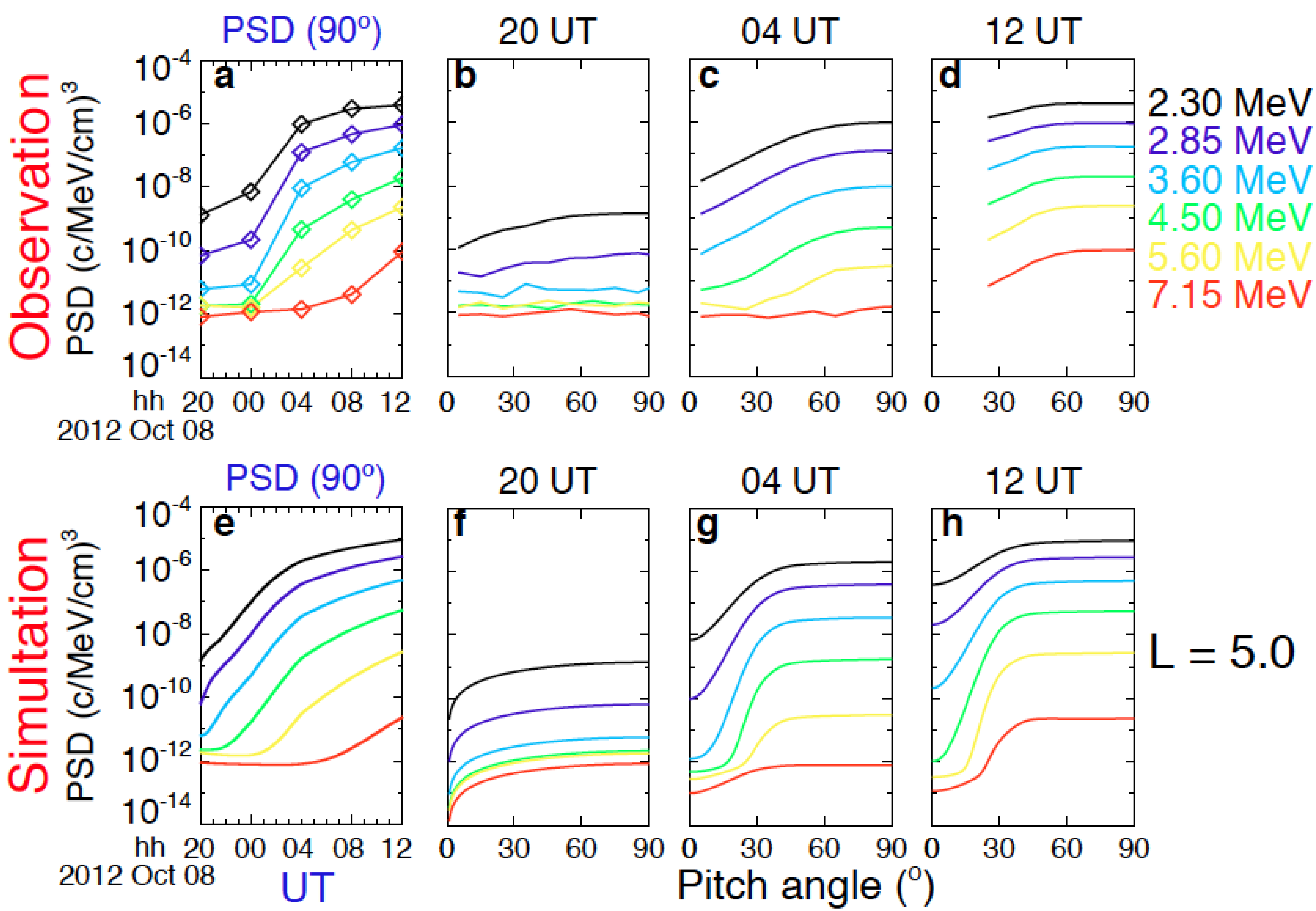
- Similar sized storms can produce net increase (53%), decrease (19%), or no change (28%). "*Equally intense post-storm fluxes can be produced out of nearly any pre-existing population*"
- Delicate balance between acceleration and loss, both enhanced during storm-time, "*like subtraction of two large numbers*".

Electrons accelerated to ultra-relativistic energies during Oct 8-9 2012 storm

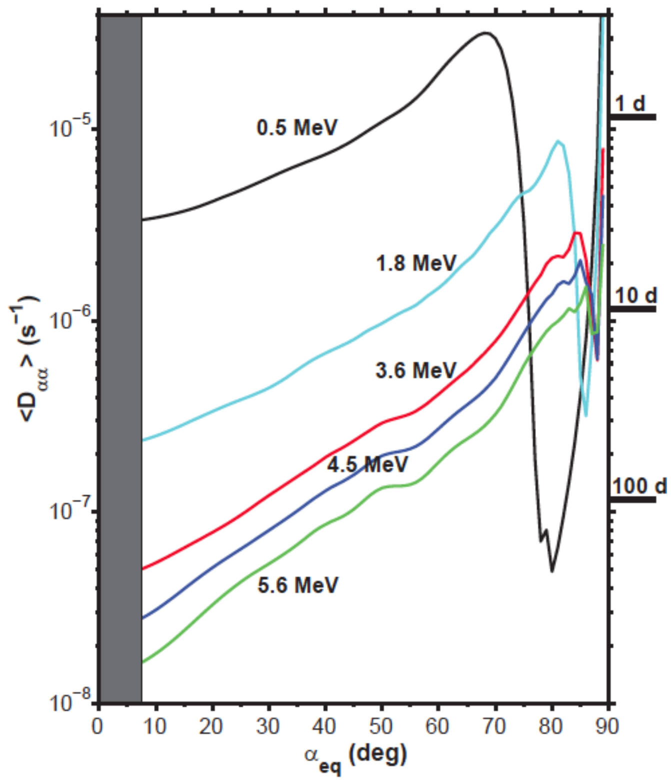


Thorne et al. [2013], submitted

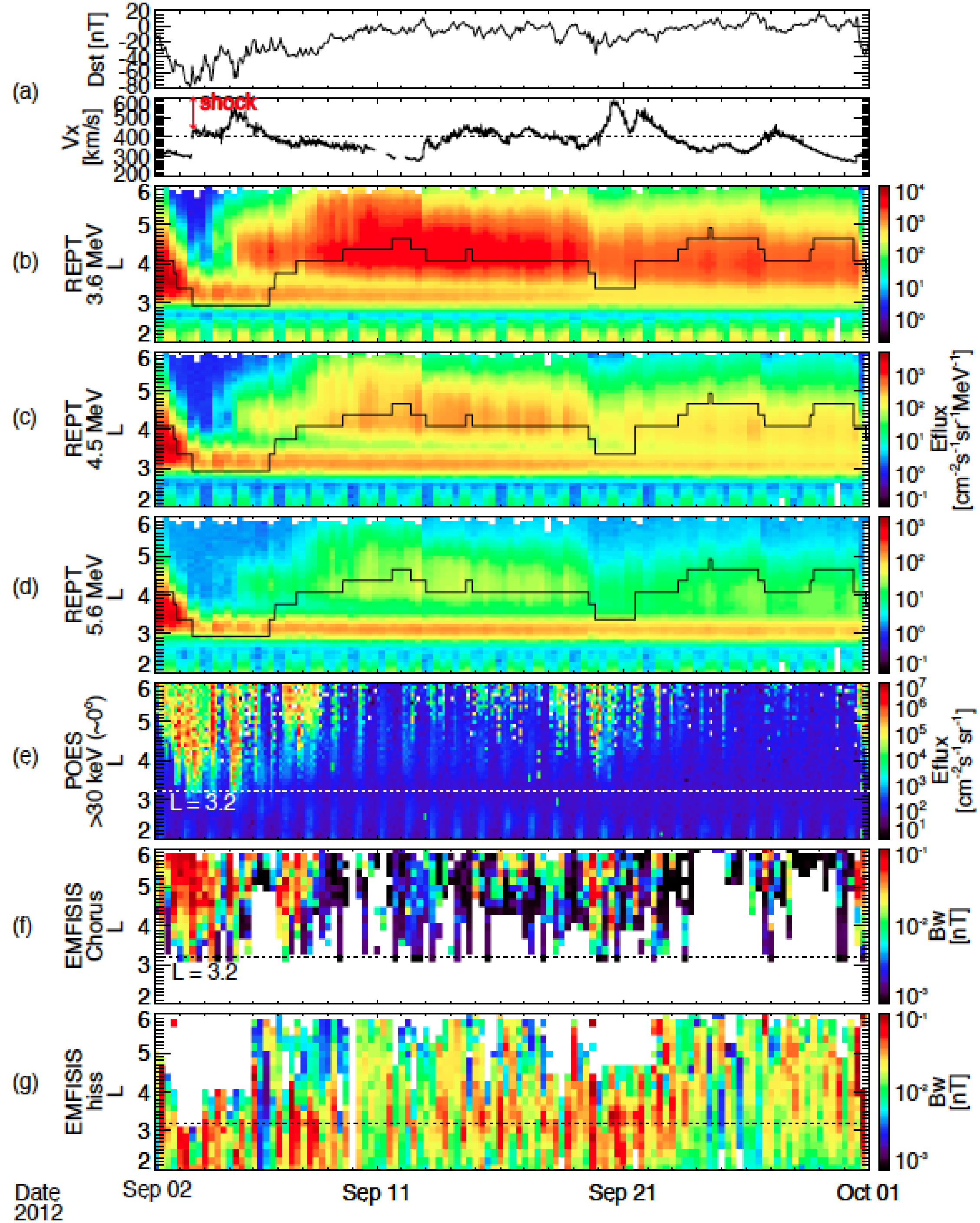
Chorus-driven acceleration of electrons, Oct 8-9 2012



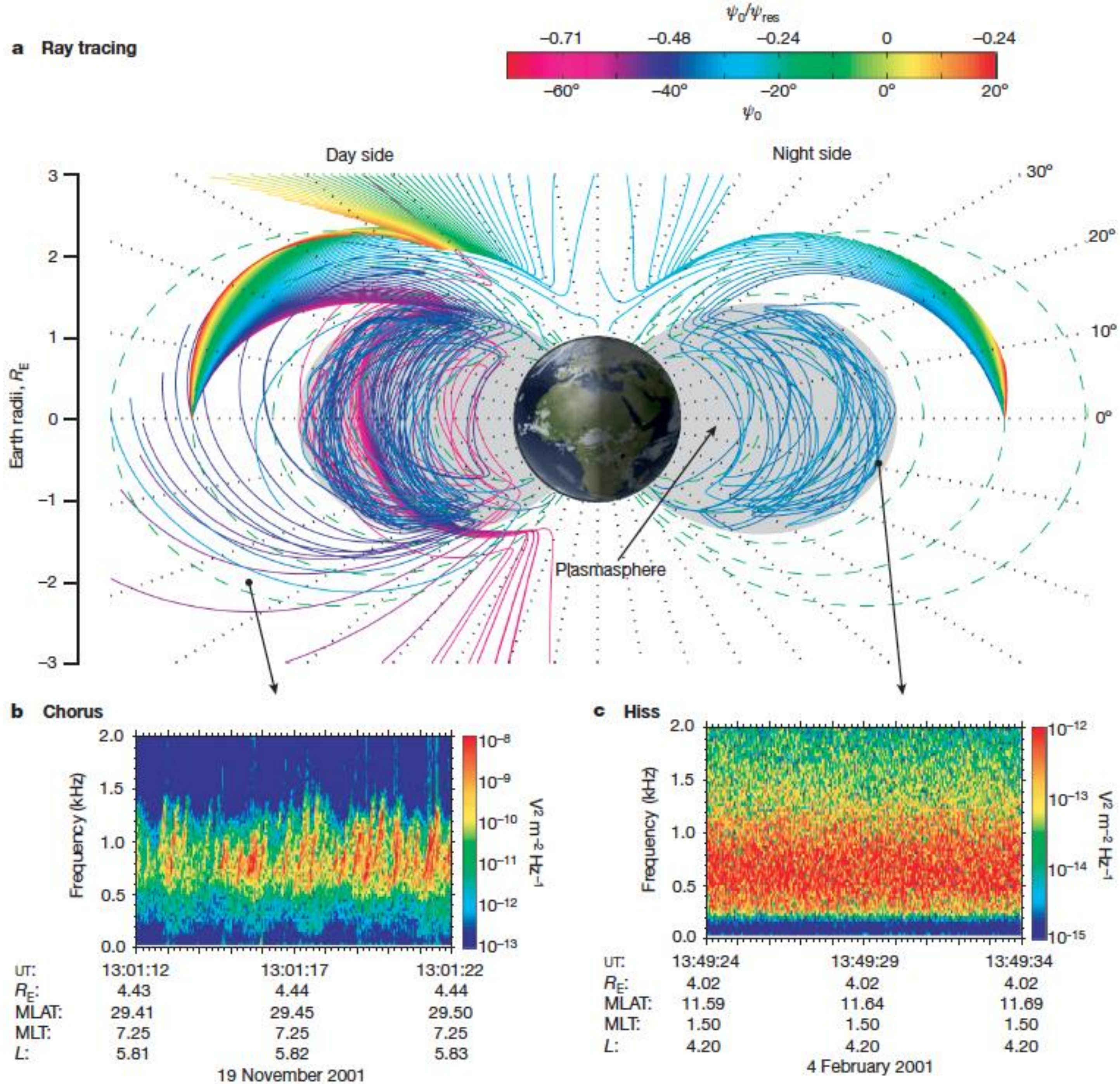
Decay of the ultra-relativistic 'storage ring' of electrons, Sept 2012



Thorne et al. [2013], GRL



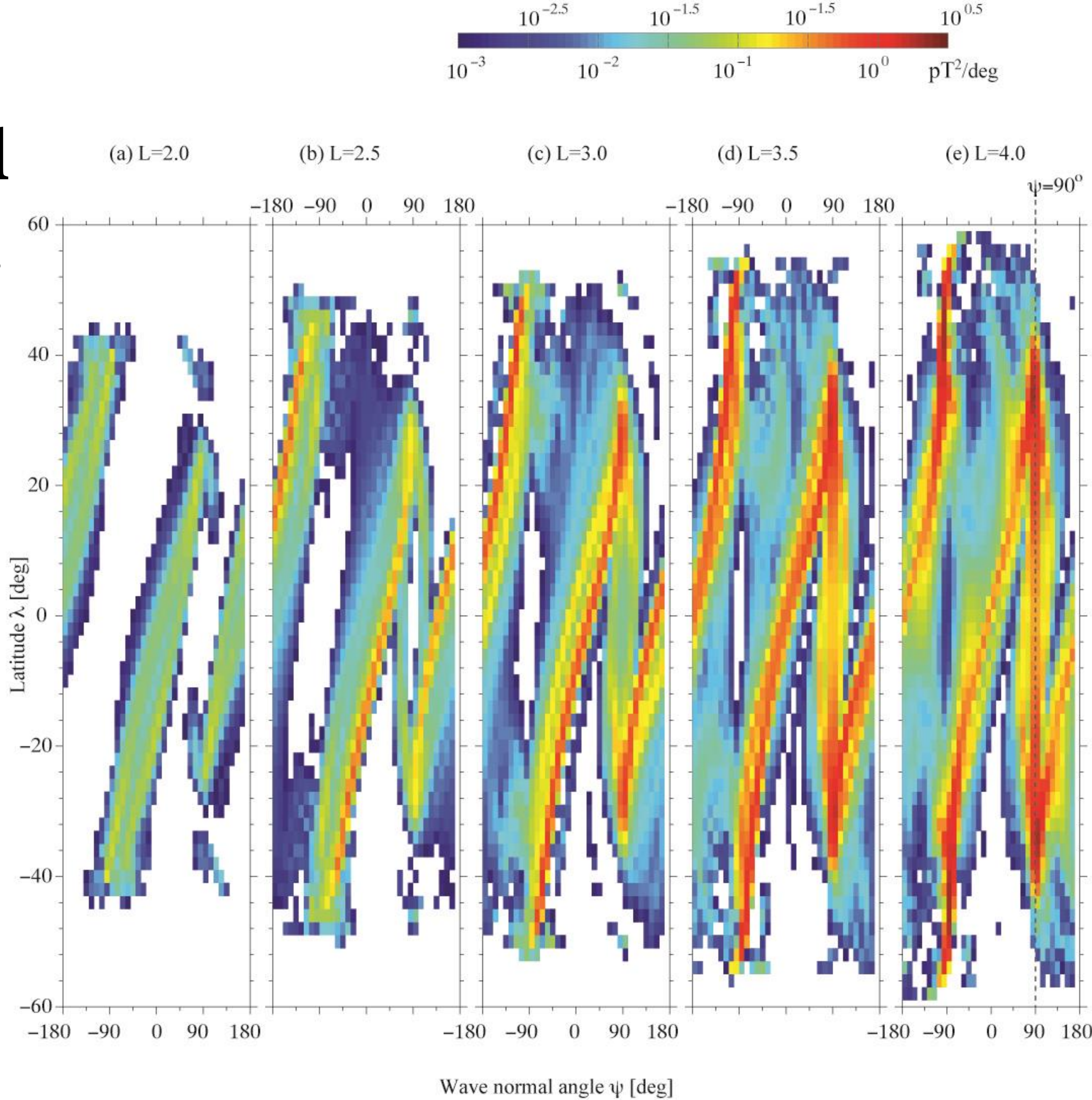
Chorus as the origin of plasma-spheric hiss



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

Unique wavenormal distribution

- Can resonate with ultra-relativistic electrons
- EQUATOR:
  - Bimodal near p'pause
  - Field-aligned deeper in
- OFF –EQ:
  - oblique



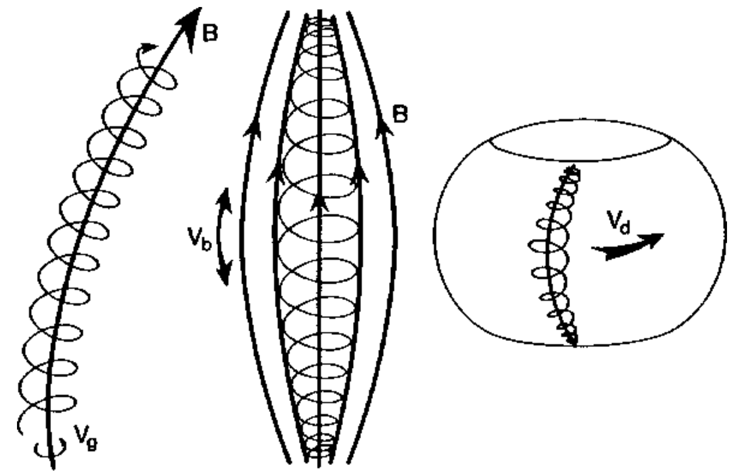
Summary

- Chorus is excited by ~10-100 keV plasmasheet electrons
  - Precipitation: pulsating aurora
  - field line mapping
  - chorus mapping from ground or LEO (POES)
  - Propagation: plasmaspheric hiss
- Landau damping due to ~1 keV electrons
  - Diffuse aurora: ionospheric conductivity modifications
- 'Parasitic' interactions with 100's keV to MeV electrons leads to radiation belt acceleration

Background: periodic motion

- Energetic particles undergo three types of periodic motion:
  - They gyrate around the magnetic field
  - They bounce between the mirror points
  - They drift around the Earth
- Associated adiabatic invariant

1 MeV electron, $\alpha = 45^o$, L = 4.5



	gyro motion	bounce motion	drift motion
f	10 kHz	3 Hz	1 mHz
T	0.1 ms	0.36 s	15 min
	$\mu = \frac{p_\perp^2}{2mB}$	$J = \int_{bounce} p_\parallel ds$	$\Phi = \int_{drift} BdS$

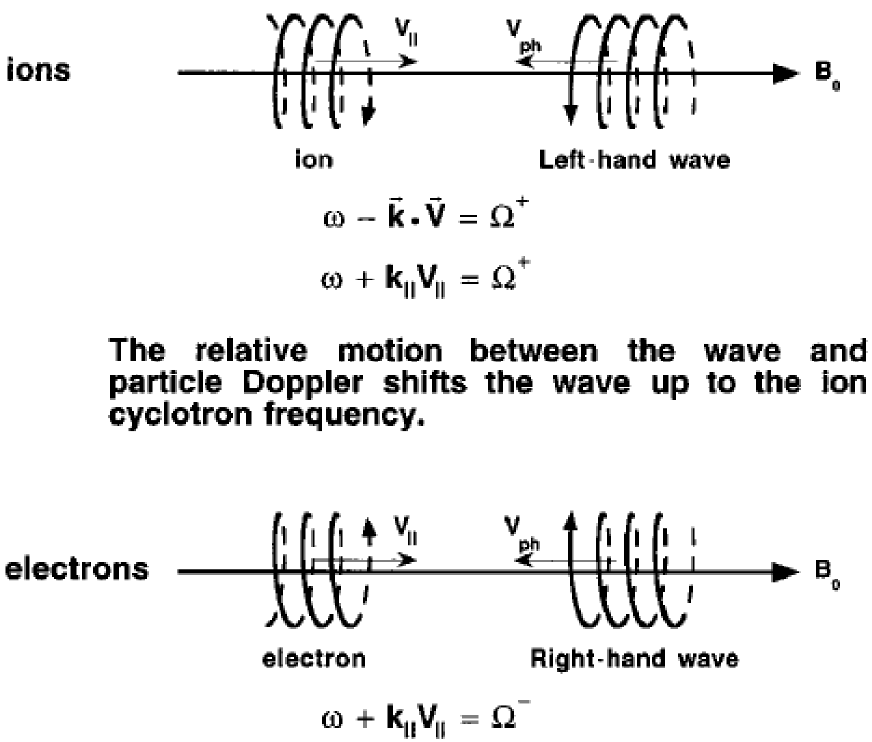
Wave-particle interaction: violation of the invariant/s

1st invariant violation

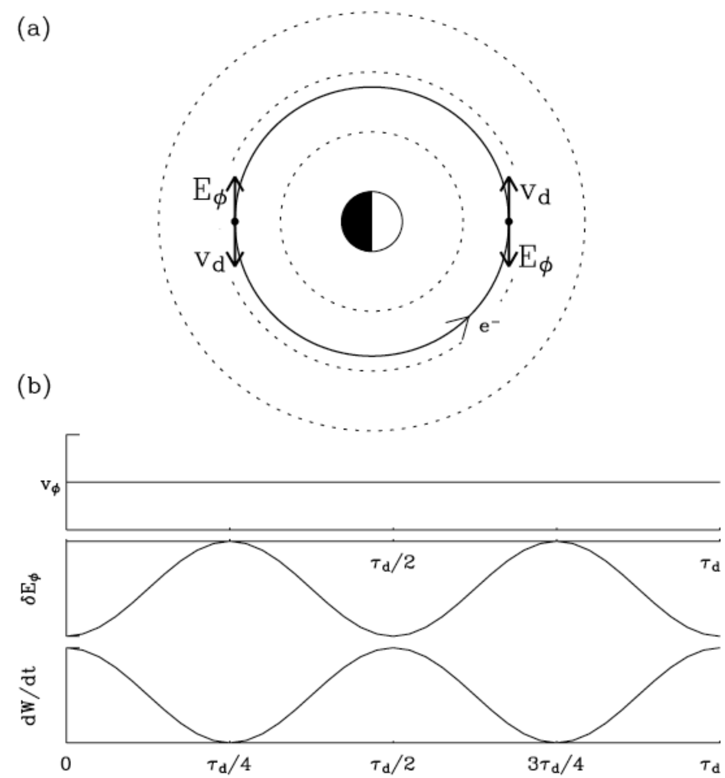
$$\omega - k_{\parallel} v_{\parallel} = n\Omega_e/\gamma$$

3rd invariant violation

$$\omega = m\Omega_d$$

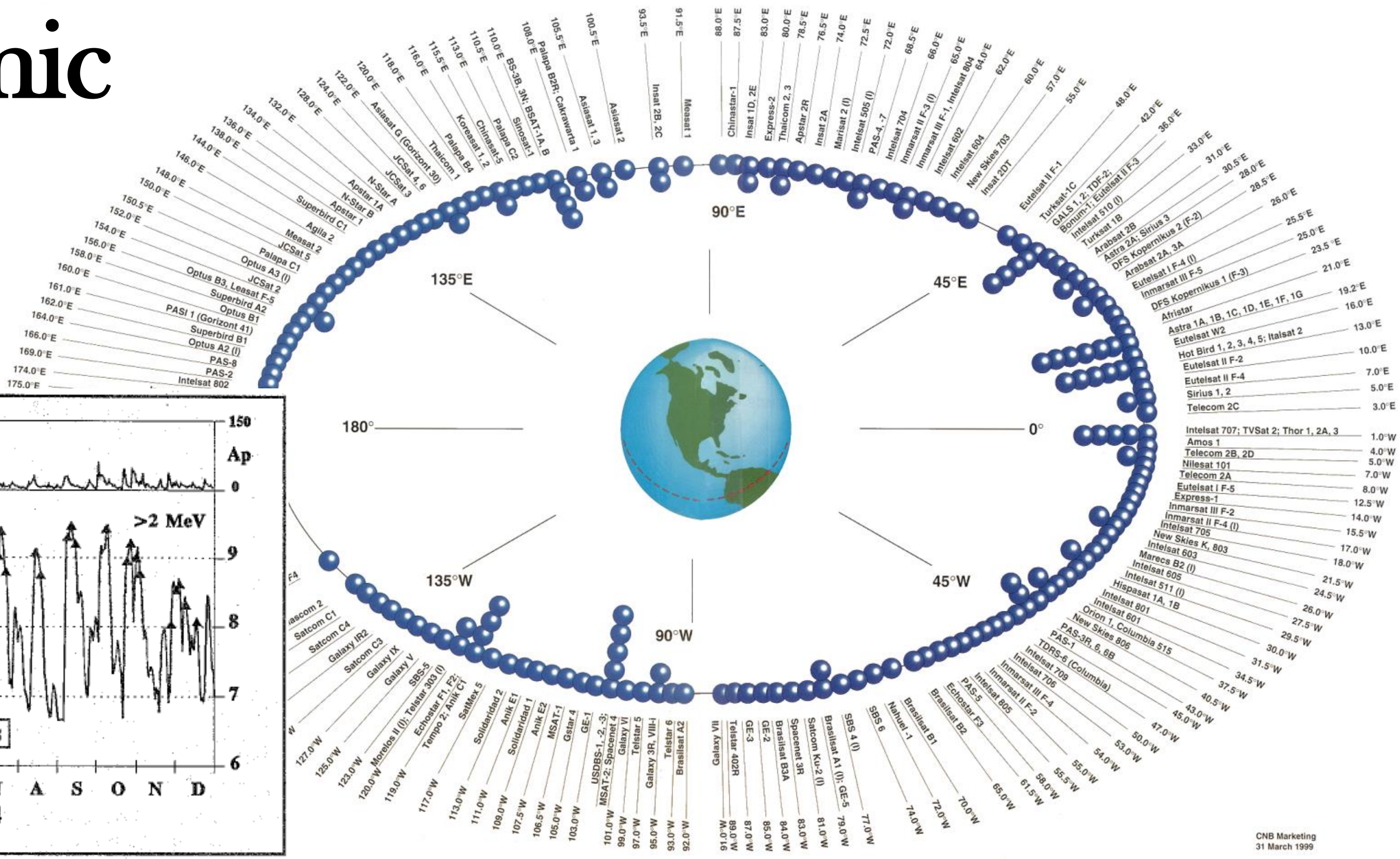


Tsurutani & Lakhina [1997]

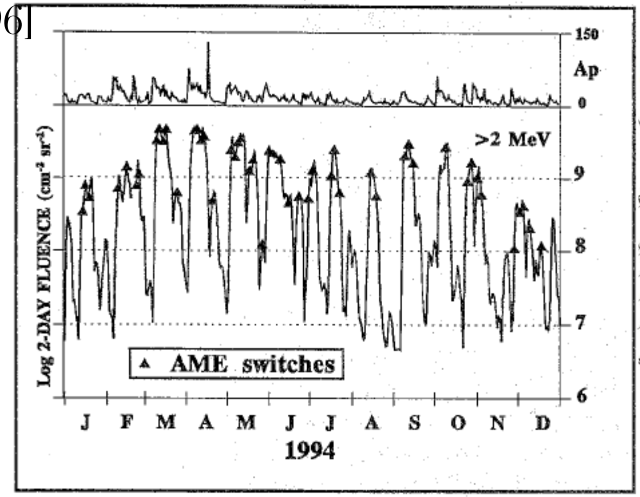


Elkington, Hudson & Chan [2003]

Economic Impact

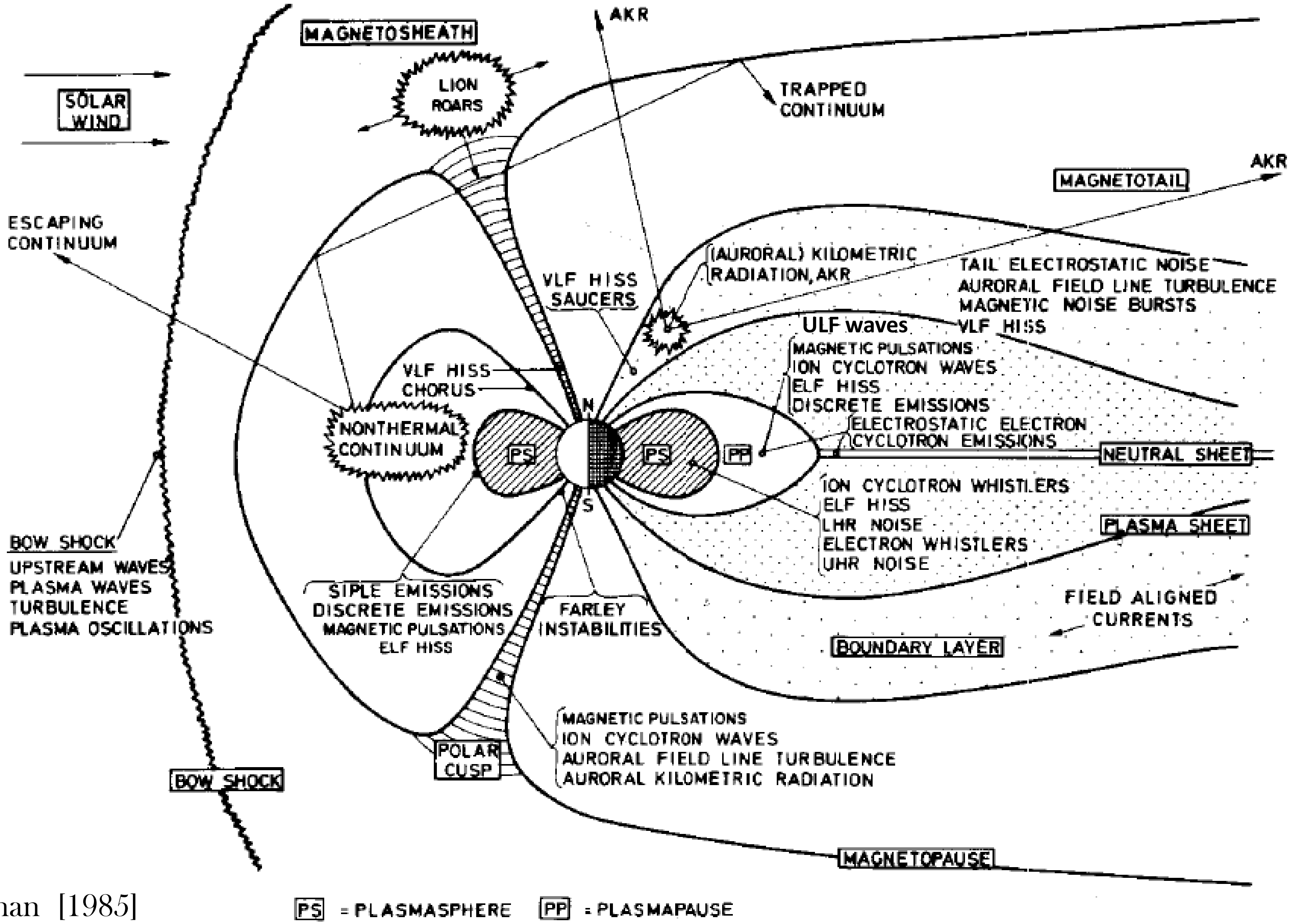


Wrenn & Smith [1996]



- MeV el: internal charging; 0.1-100keV: surface charging; MeV ions: SEU
- ¾ satellite designers said that internal charging is now their most serious problem, 2001 ESA study [Horne, 2001]
- Examples: Intelsat K, Anik E1 & E2, Telstar 401, Galaxy IV
- Costs: ~$200M build, ~$100M launch to GEO, 3%-5%/yr to insure; e.g., in 1998 $1.6B in claims, but $850M in premiums.

“The menagerie of geospace plasma waves”



Shawhan [1985]

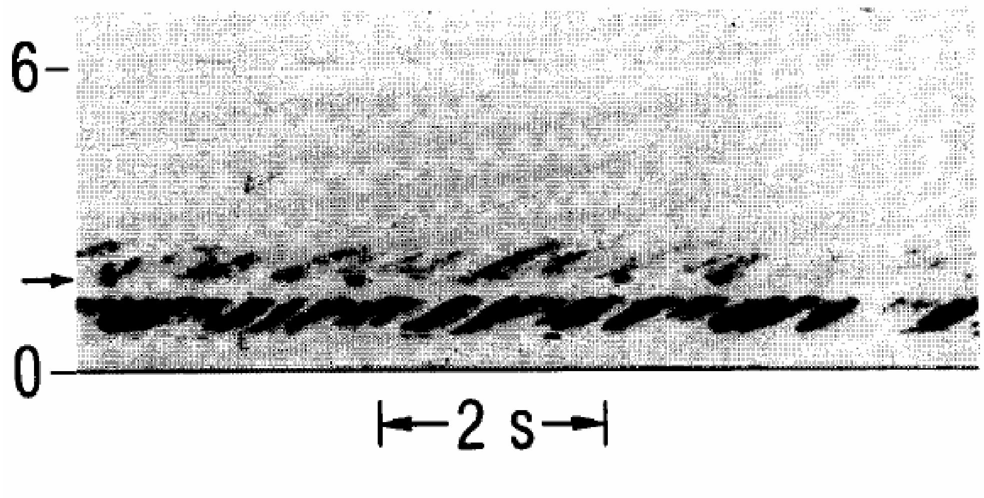
A quick recap...

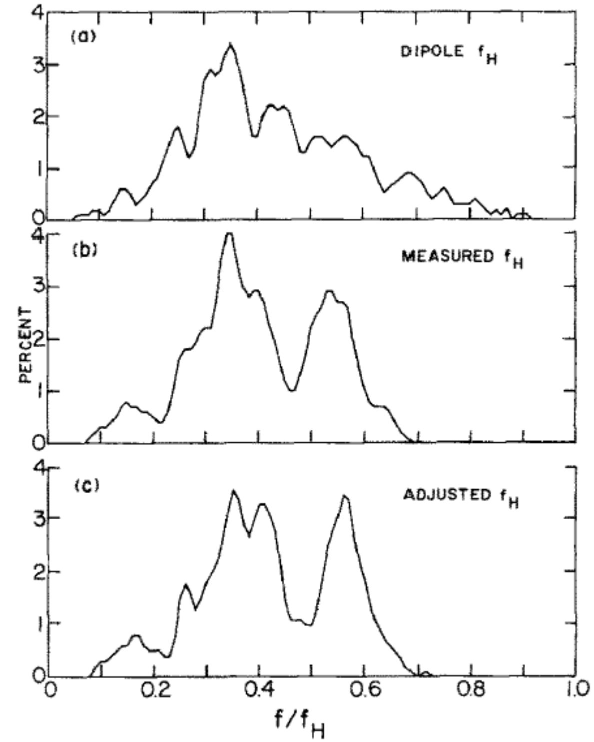
1. Radiation belts consist of trapped electrons that gyrate around field lines (kHz), bounce between hemispheres (Hz), and drift around the Earth (mHz, ~15 mins)

2. Radiation belt structure:
   - Outer belt (L=3-7): very dynamic, unpredictable, dangerous to satellites
   - Slot region (L=2-3): result of scattering by plasmaspheric hiss
   - Inner belt (L=1.2-2): stable

3. Waves play a major role in controlling radiation belt dynamics, by violating adiabatic invariants

Chorus general characteristics



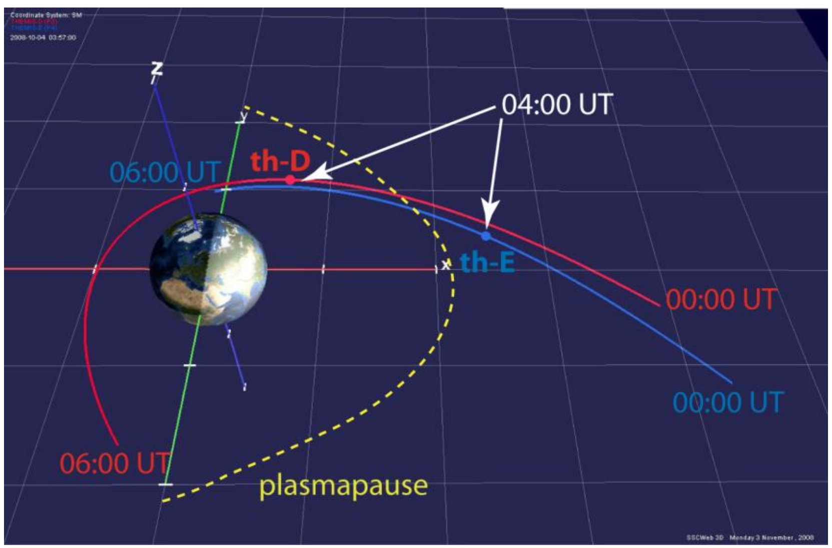


- Sequence of narrowband tones, df/dt ~ 0.2-2 kHz/sec
- Rising (P~77%), falling (P~16%), hooks etc. (P~18%)
- Bimodal distribution, ~$0.34f_{ce}$ (lower) ~$53f_{ce}$ (upper)
- Persistent gap at ~$0.5f_{ce}$

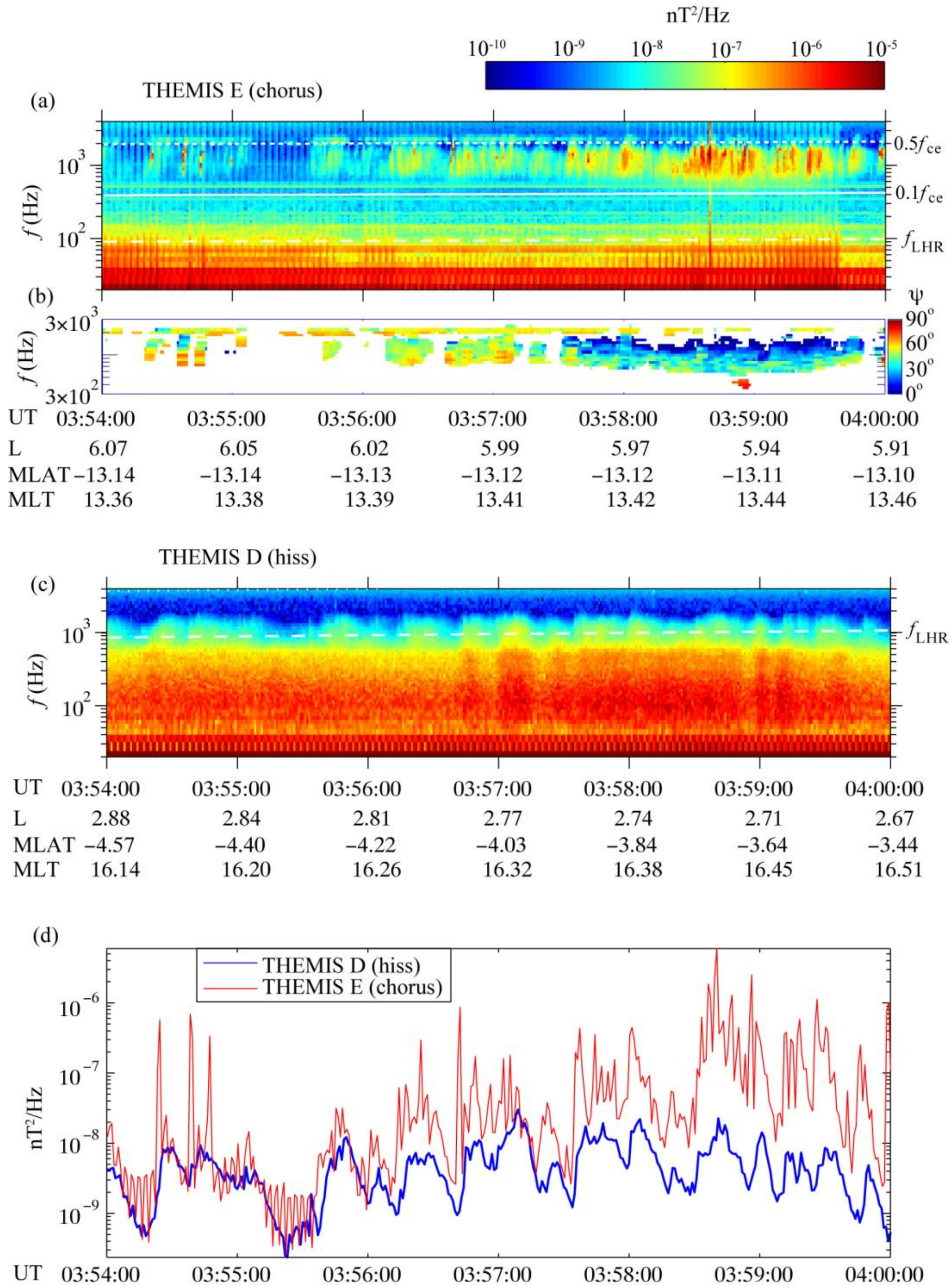
Tsurutani and Smith [1974, 1977]; Burton and Holzer [1974]; Burtis and Helliwell [1969, 1976]; Koons and Roederer [1990]

2. The origin of plasmaspheric hiss

October 4th, 2008



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



When are nonlinear effects important?

"restoring" force

"driving" force

$$\frac{d^2\eta}{dt^2} + k\left(\frac{qB_w}{m}\right)v_\perp \sin\eta = \left[\frac{3}{2} + \frac{\Omega-\omega}{2\Omega}\tan^2\alpha\right]v_\parallel \frac{\partial\Omega}{\partial z}$$

$$\frac{d^2\eta}{dt^2} = \omega_t^2(\sin\eta + S) \approx 0$$

$$\rho \approx \left(\frac{B^w}{dB_0/dz}\right)\left(\frac{2\Omega}{v}\right)\Gamma$$

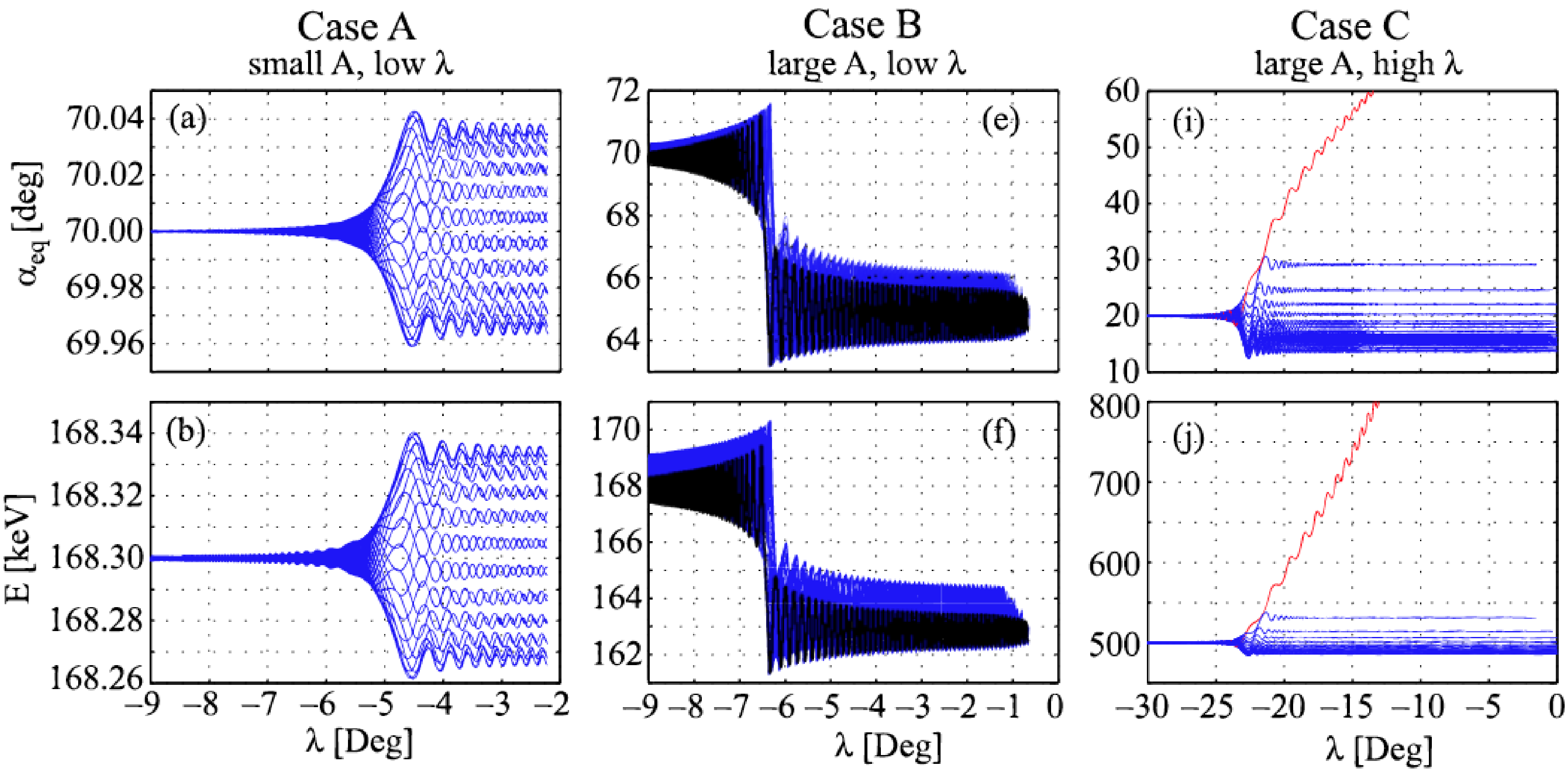
$$\Gamma = \begin{cases} \left(1 - \frac{\omega}{\Omega}\right)\frac{\sin\alpha}{3\cos^2\alpha}, & \alpha < 60^\circ \\ \frac{1}{\sin\alpha}, & \alpha > 60^\circ \end{cases}$$

Conditions for NL:

- Waves are "large" amplitude
- Inhomogeneity is "low", i.e., near the equator
- Pitch angles are medium-high

Bortnik et al. [2010]

Three representative cases



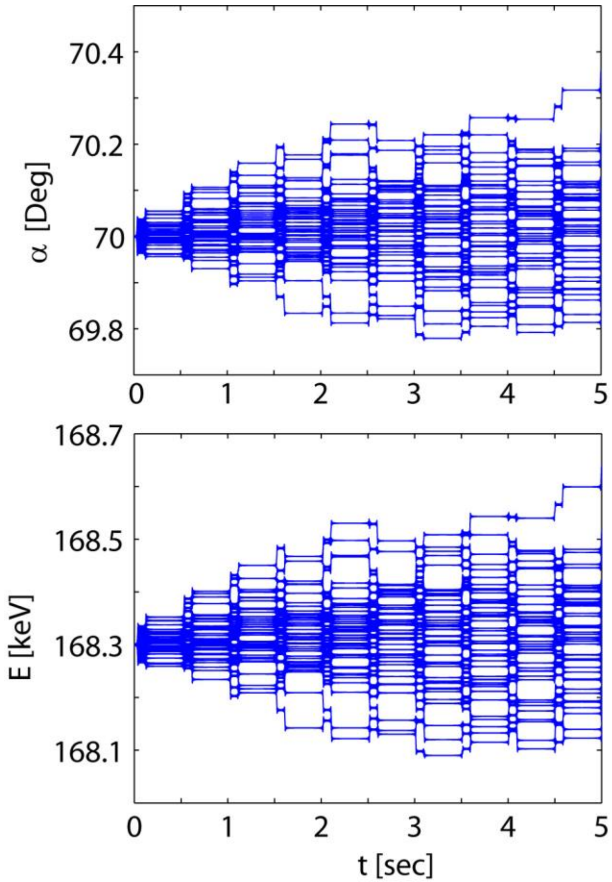
Bortnik et al. [2008]

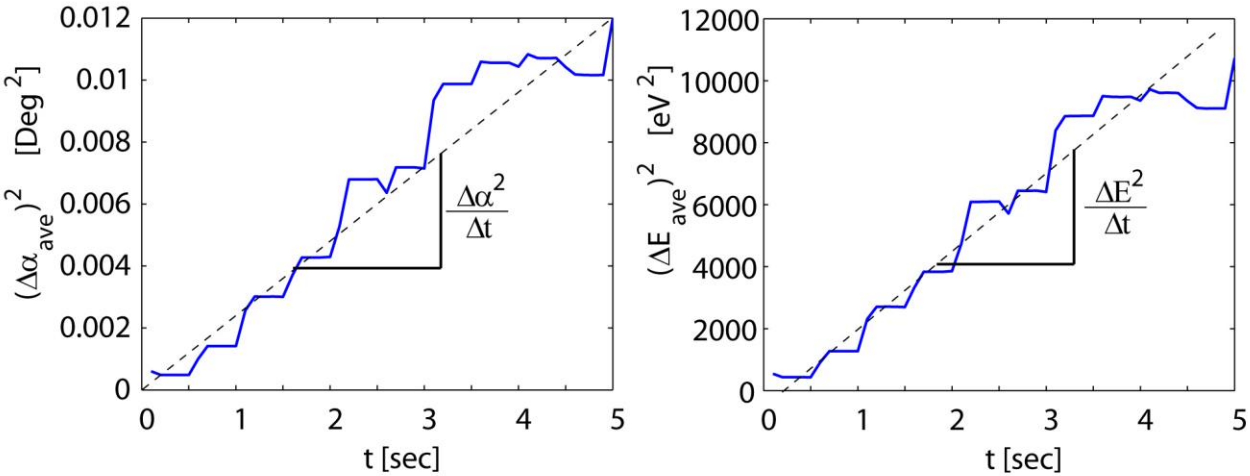
Towards diffusion: small A, low λ (5 sec)

- Diffusion coefficients:

$$D_{\alpha\alpha} = \langle \Delta\alpha^2 \rangle / 2\Delta t$$

$$D_{EE} = \langle \Delta E^2 \rangle / 2\Delta t$$





48 electrons , 5 sec,
10 bounce periods,
20 res. interactions

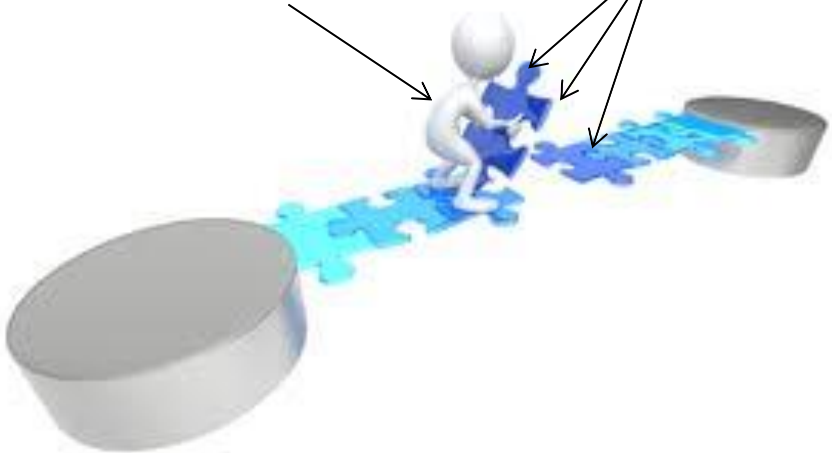
Diffusive spreading in α, E

Inan [1987]; Albert [2010]

Objective

Reality, somewhere in this region …

US



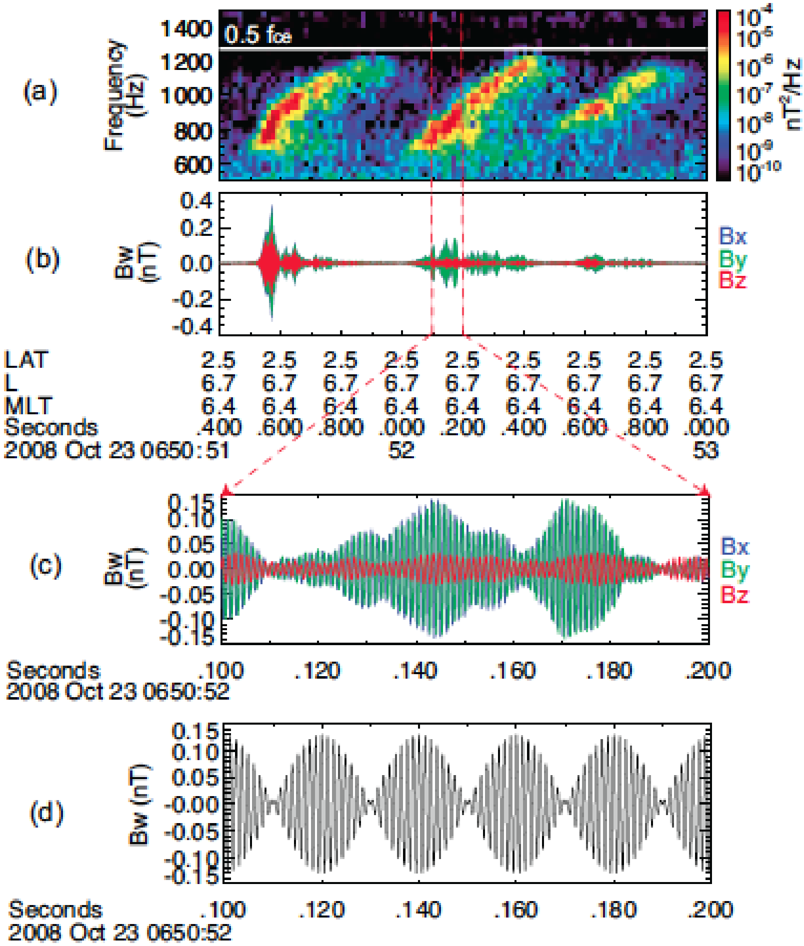
1. Single-wave/test-particle

- Waves can be strong
- Narrowband & coherent
- Interactions all correlated
- Microphysics

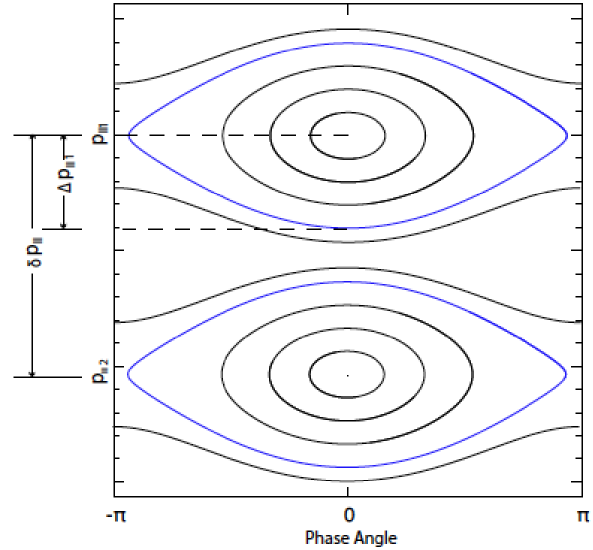
2. Quasilinear theory

- Waves are all weak
- Wideband & incoherent
- Interactions uncorrelated
- Global modeling

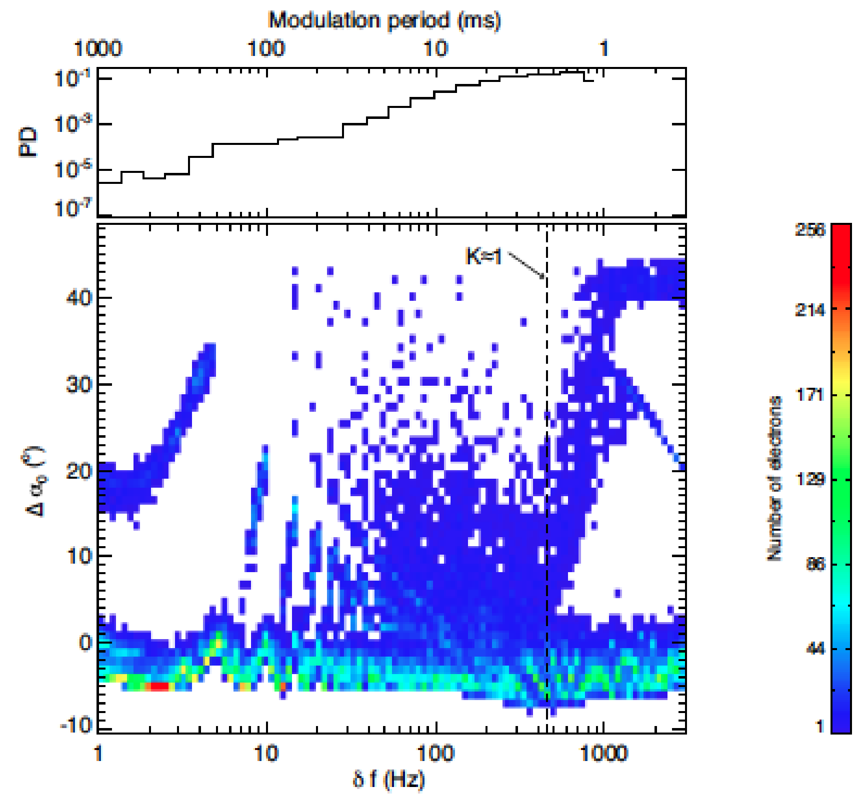
Subpacket structure: a Two-wave model



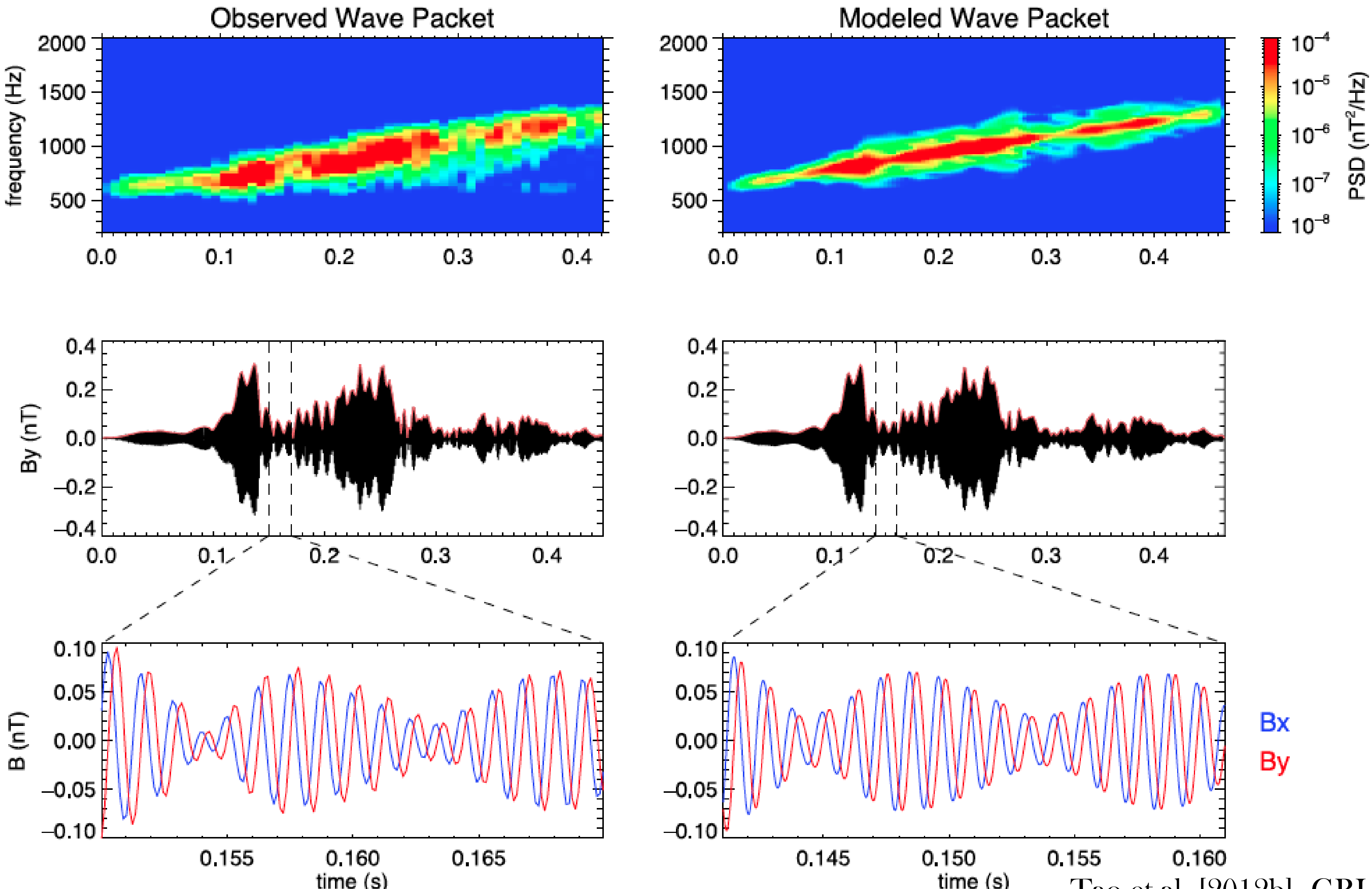
Tao et al. [2012a] subpacket structure modifies the single-wave scattering picture



Two-wave model

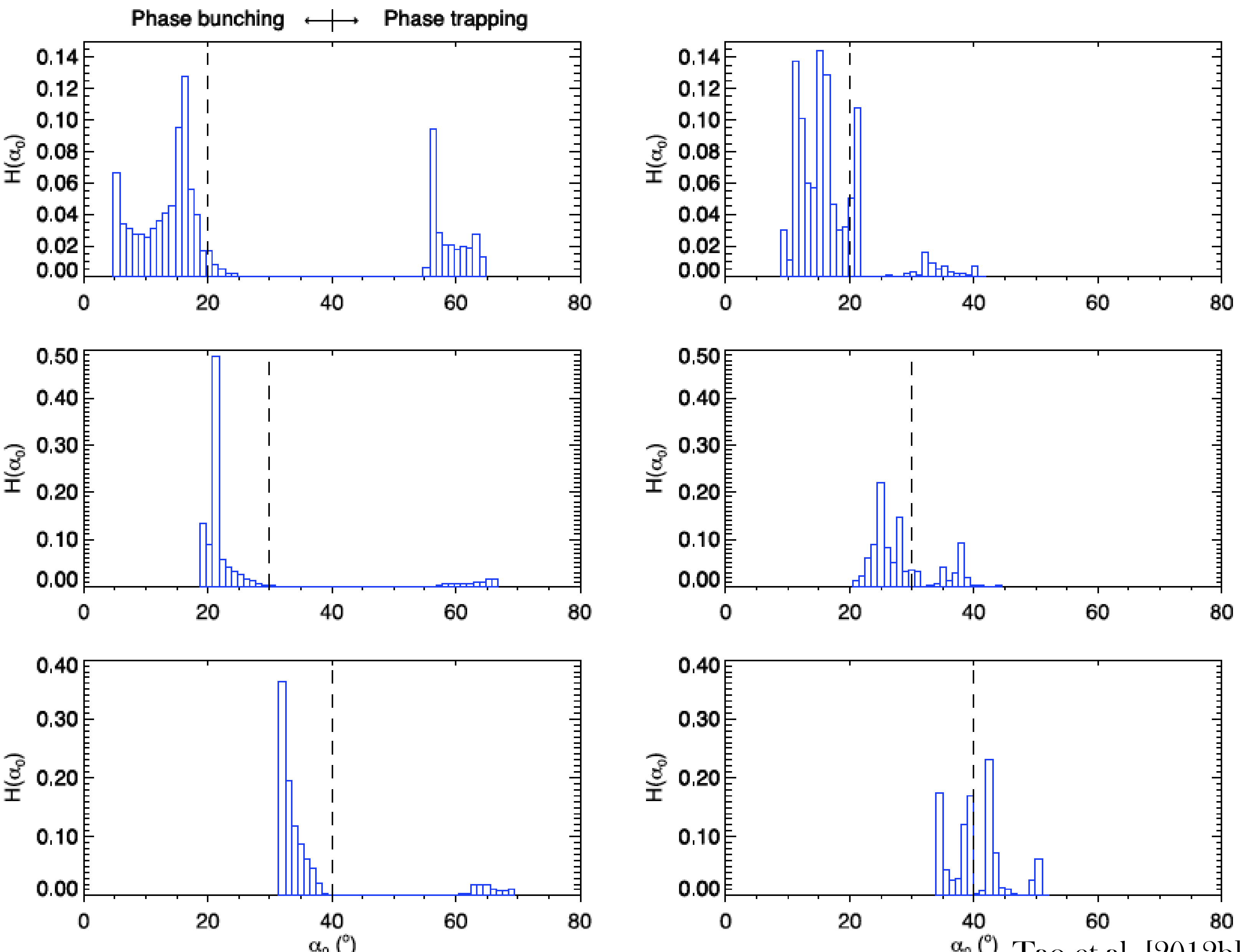


Subpacket structure: full spectrum model



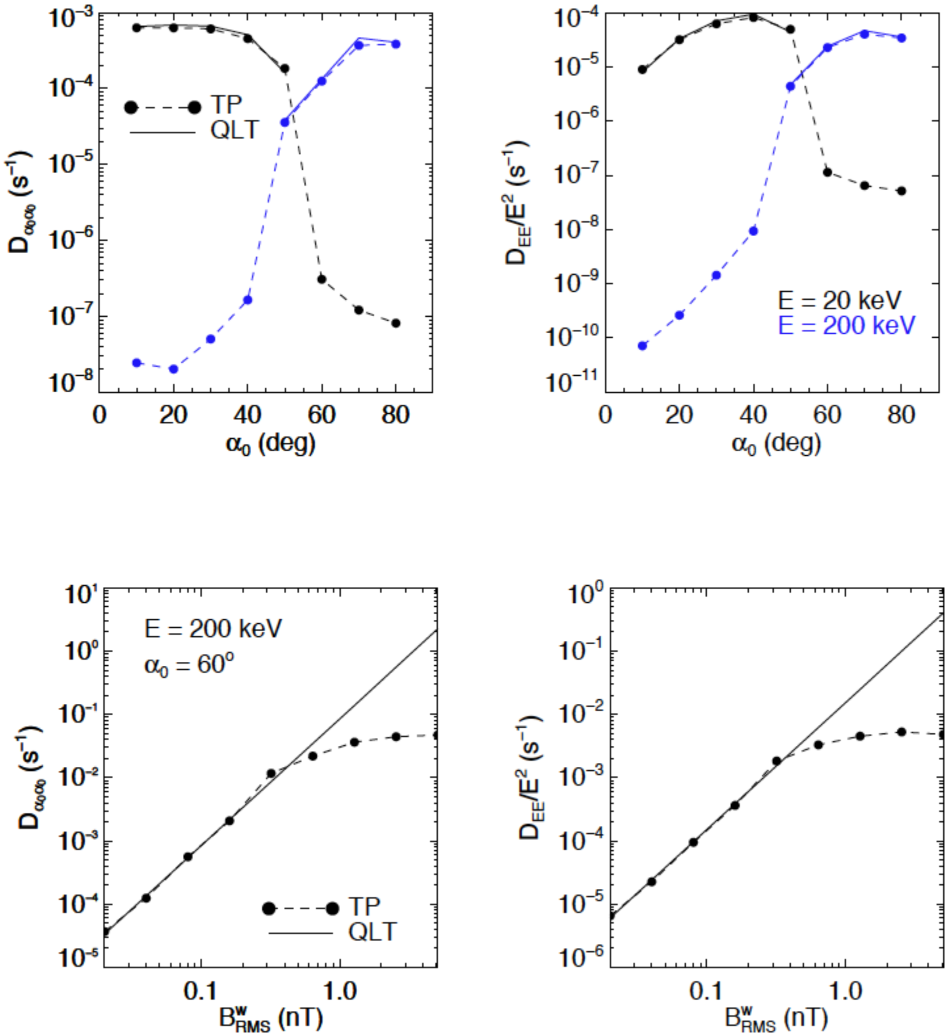
Tao et al. [2012b], GRL

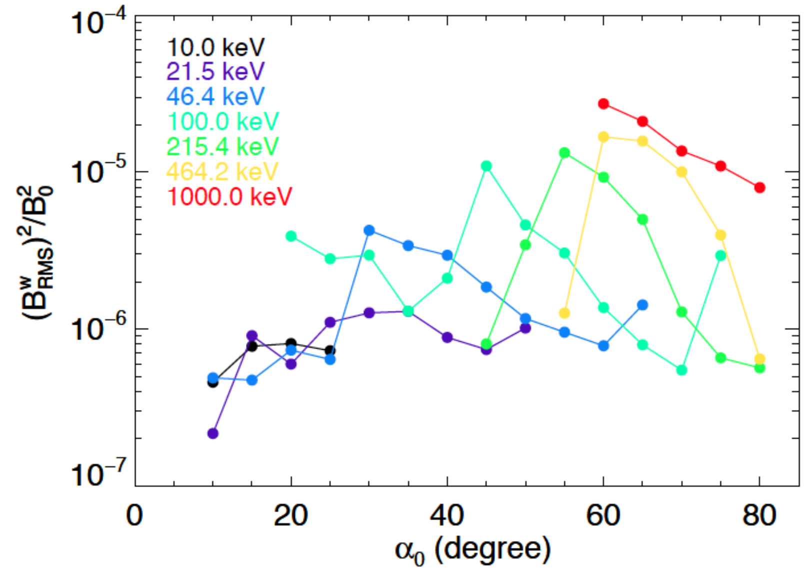
Subpacket structure: full spectrum model



Tao et al. [2012b], GRL

Amplitude threshold of QLT





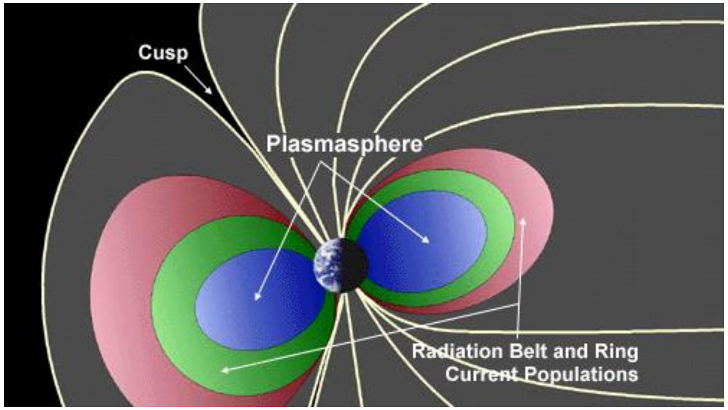
Tao et al. [2012c] (in press)
Quasilinear diffusion coefficients deviate from test-particle results in a systematic way.

Summary

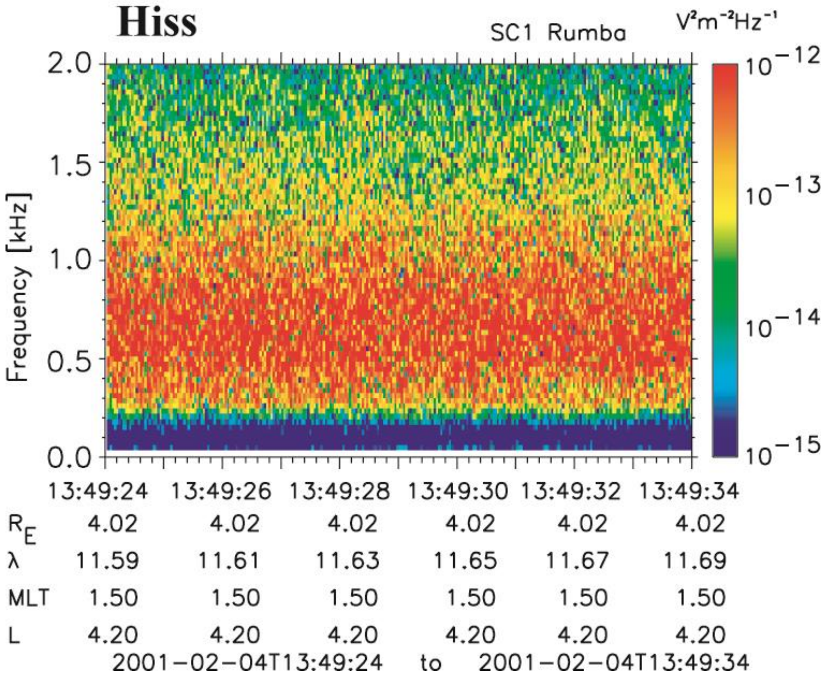
1. Radiation belts are of great current interest
    - Highly dynamic and dangerous to spacecraft
    - Physics are complex and poorly understood
2. Chorus: a critical component of the space environment
    - Origin of plasmaspheric hiss
    - Origin of pulsating aurora
    - Origin of diffuse
    - A key acceleration and loss process for radiation belts
3. Large amplitude chorus raises new questions
    - Is quasilinear theory adequate to model RB dynamics?
    - Are we missing critical effects? (i.e., dropouts, rapid accel.)
    - What is the role of amplitude vs. subpacket structure?
4. Radiation Belt Storm Probes (RBSP): mission to the radiation belts

Backups

1. 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

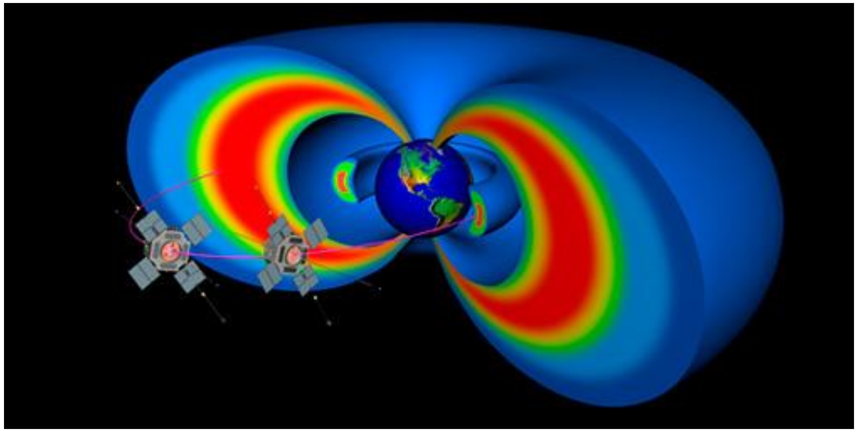


Russell et al. [1969]; Dunckel & Helliwell [1969] Thorne et al. [1973]; Hayakawa & Sazhin [1992]; Santolik et al. [2001]; Meredith et al. [2004; 2006]; Green et al. [2005], etc.

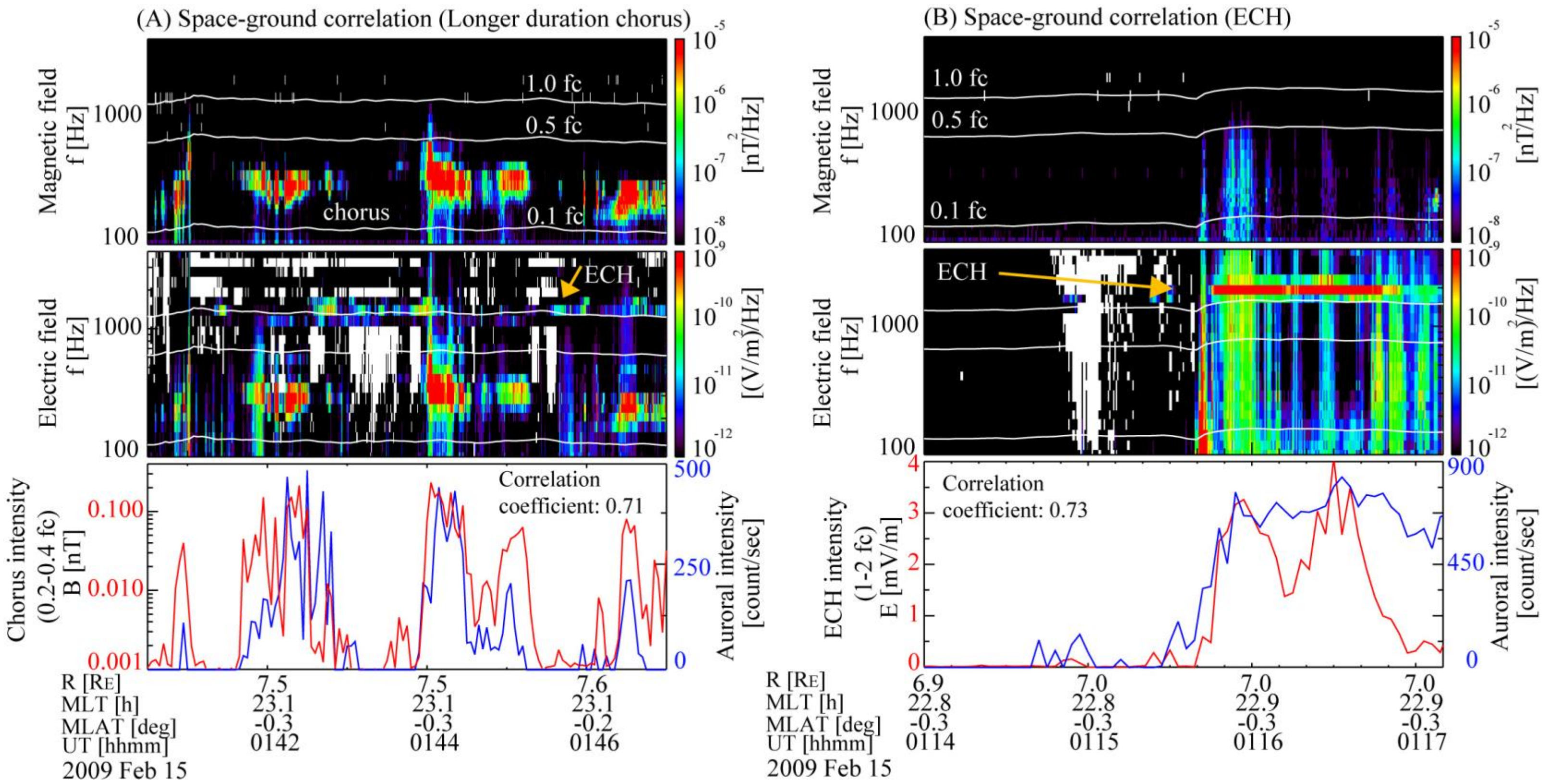
Radiation Belt Storm Probes

1. Discover which processes, singly or in combination, accelerate and transport radiation belt electrons and ions and under what conditions.
2. Understand and quantify the loss of radiation belt electrons and determine the balance between competing acceleration and loss processes.
3. Understand how the radiation belts change in the context of geomagnetic storms.

- NASA Living With a Star
- Launch Aug 15, 2012
- 2 probes, <1500 kg for both
- ~10° inclination, 9 hr orbits
- ~500 km x 30,600 km



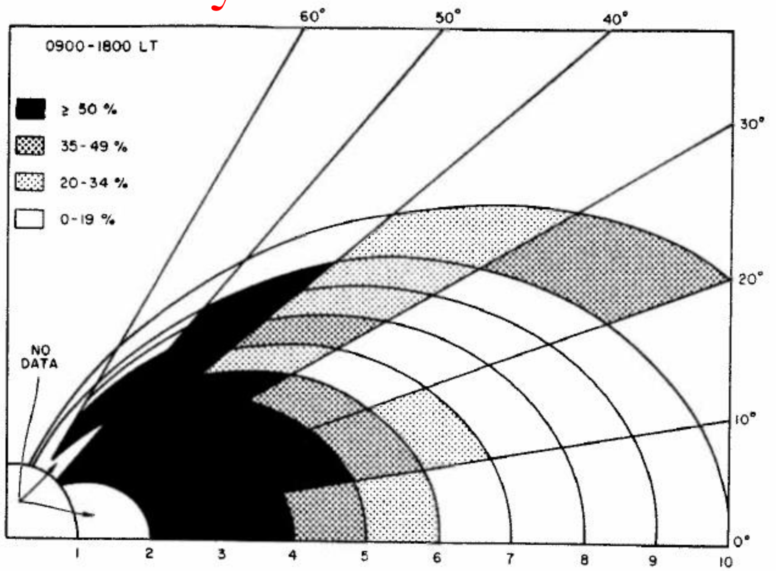
Chorus vs ECH correlations



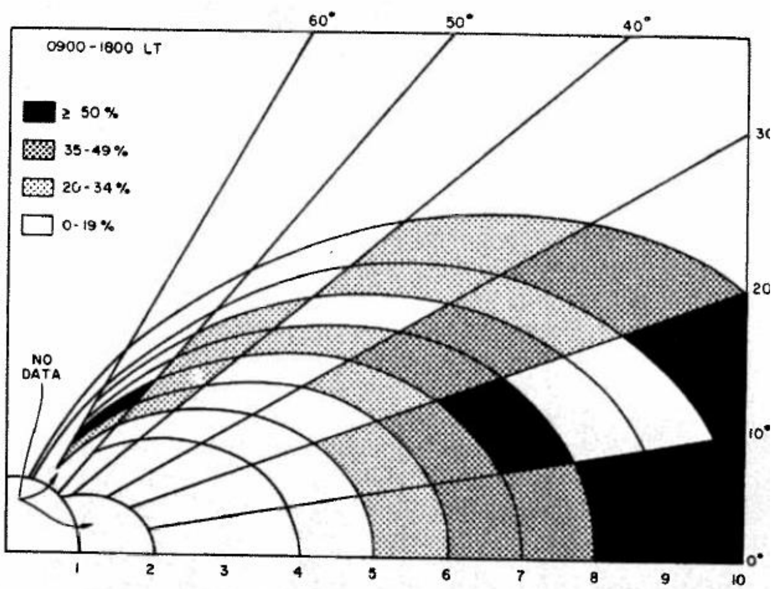
- Modulation of PA controlled by lower-band chorus modulation
- Not correlated to ECH or upper-band chorus

Original VLF work

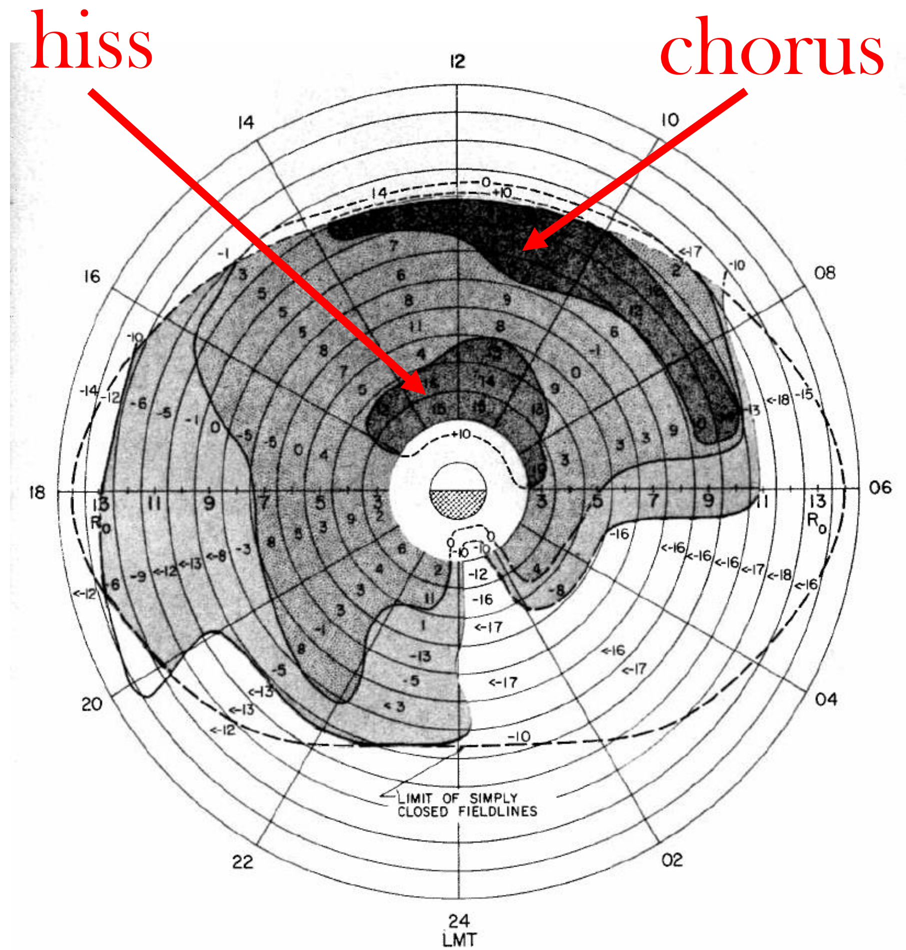
“Steady noise”



“Bursts of noise”



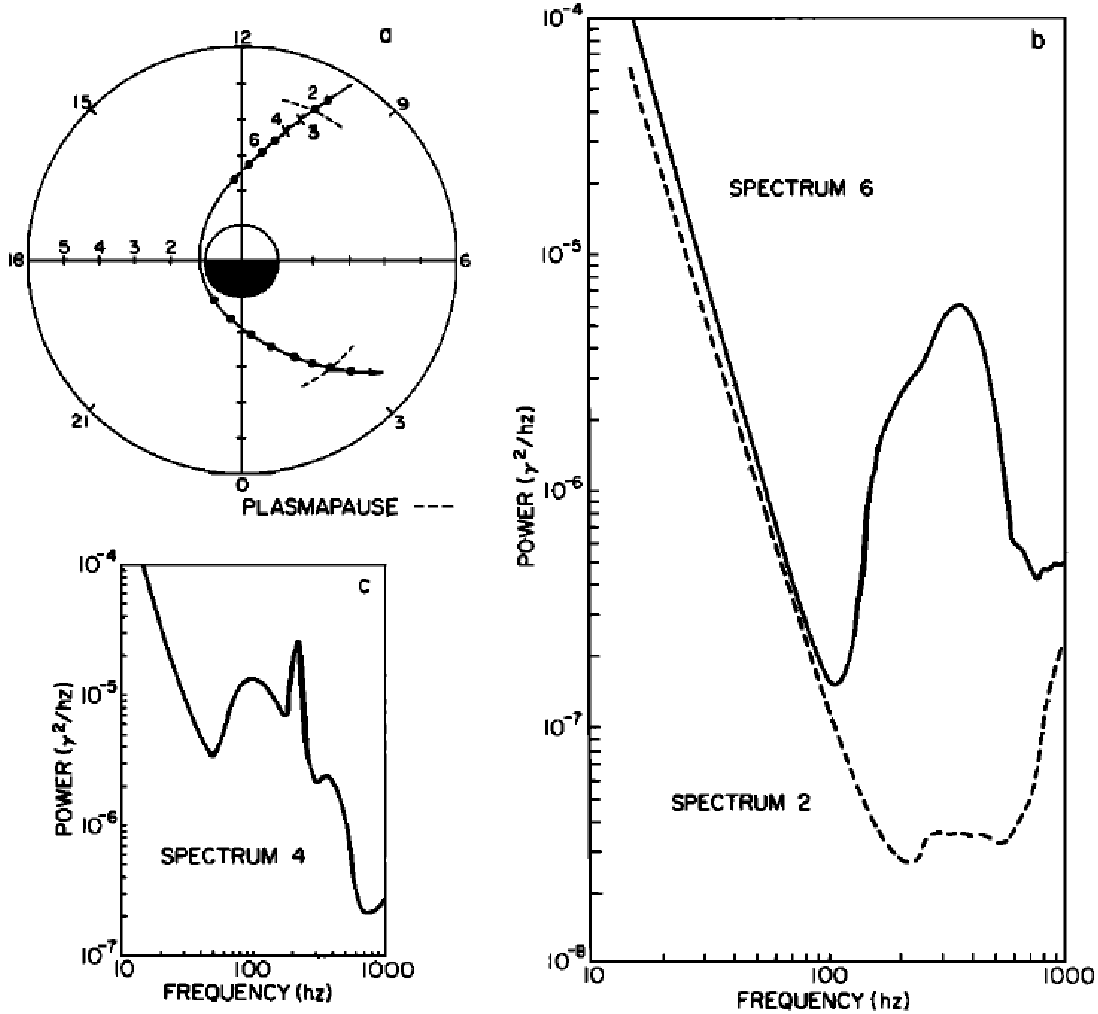
Russell et al. [1969]



OGO 1 satellite, ~0.3 – 0.5 kHz emissions

Dunckel & Helliwell [1969]

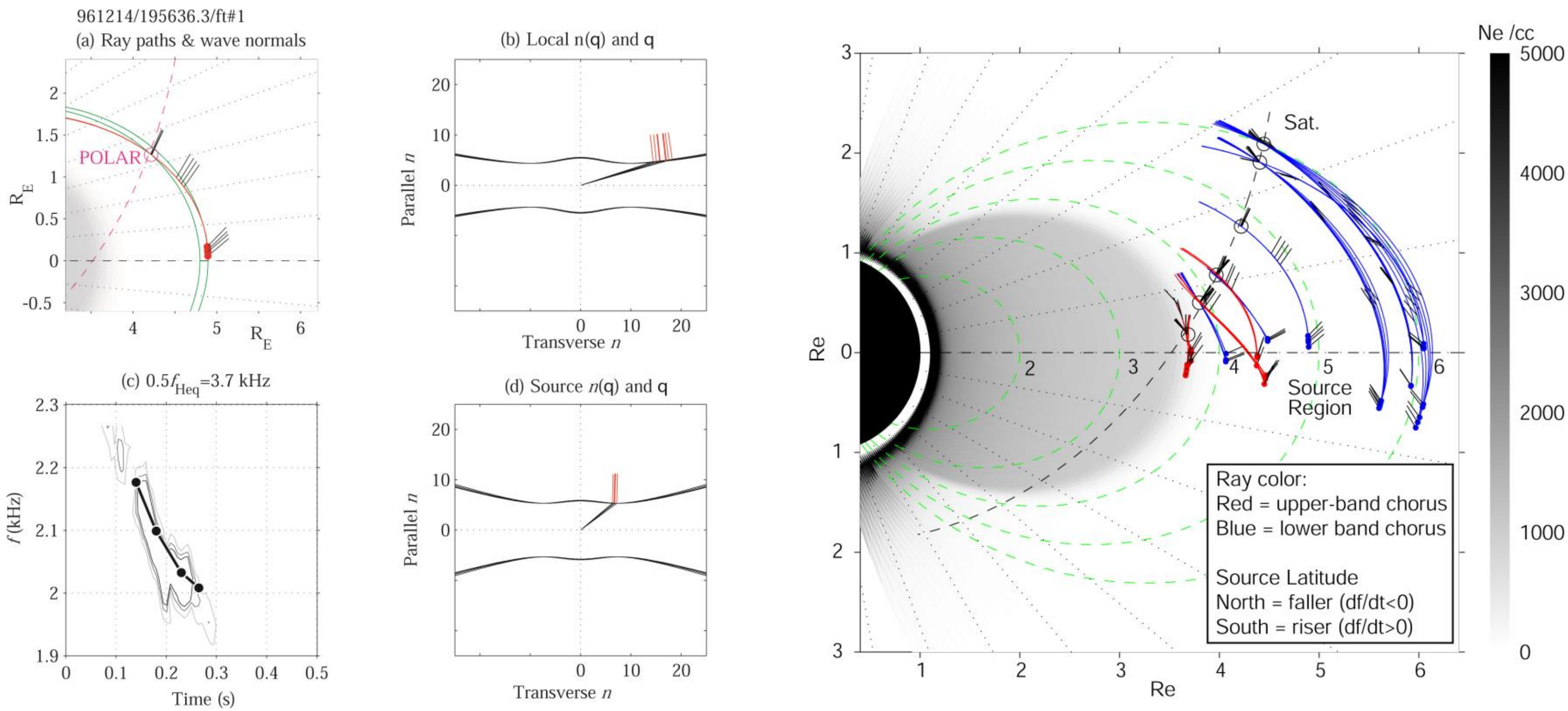
Early Space-based studies



OGO 5 pass, April 4th 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 (?)

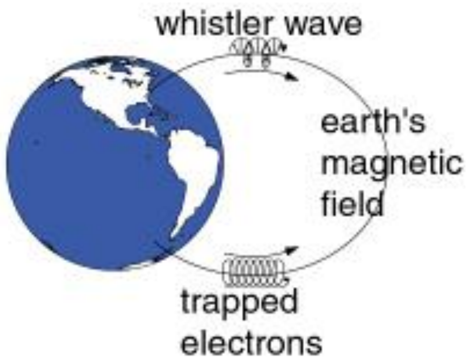
Chorus propagation



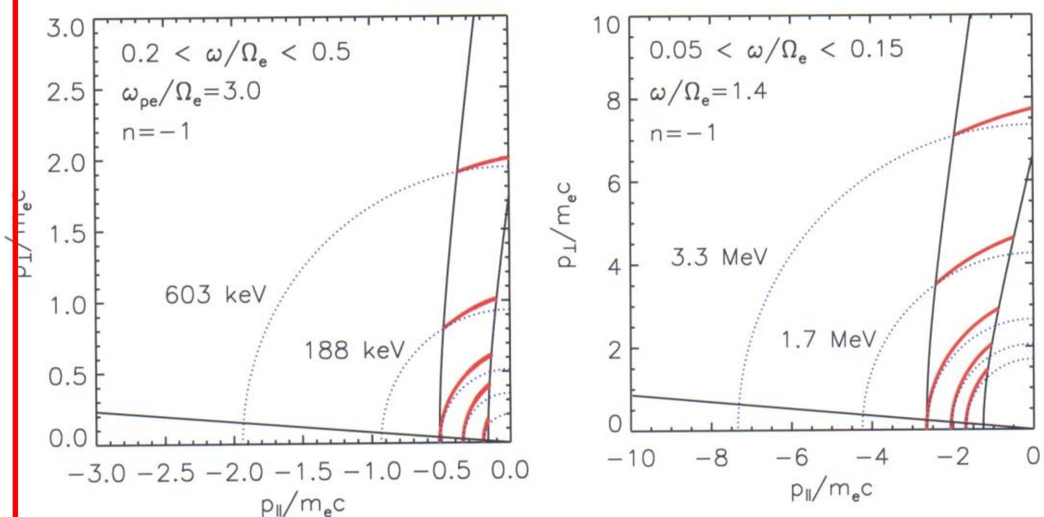
- Chorus propagates away from equatorial source region
- Generation at 0 to oblique wave normal angles

LeDocq et al. [1998]; Lauben et al. [2002]; Parrot et al. [2002];

Wave-particle interactions



- $\omega + k_{\|} v_{\|} = m\omega_H/\gamma$
- Landau resonance; m=0
- Cyclotron resonance; m=±1, ±2, ± 3 etc.
- Cause particle to change pitch angle and energy



- **Low latitude ~ 0°**
- 10-100 keV electrons lose energy → wave growth
- Resonant wave absorption → local acceleration of trapped MeV electrons

High latitude ~25°

- Microburst precipitation ~1 MeV electrons
- Effective acceleration to higher energies

Horne and Thorne [2003]

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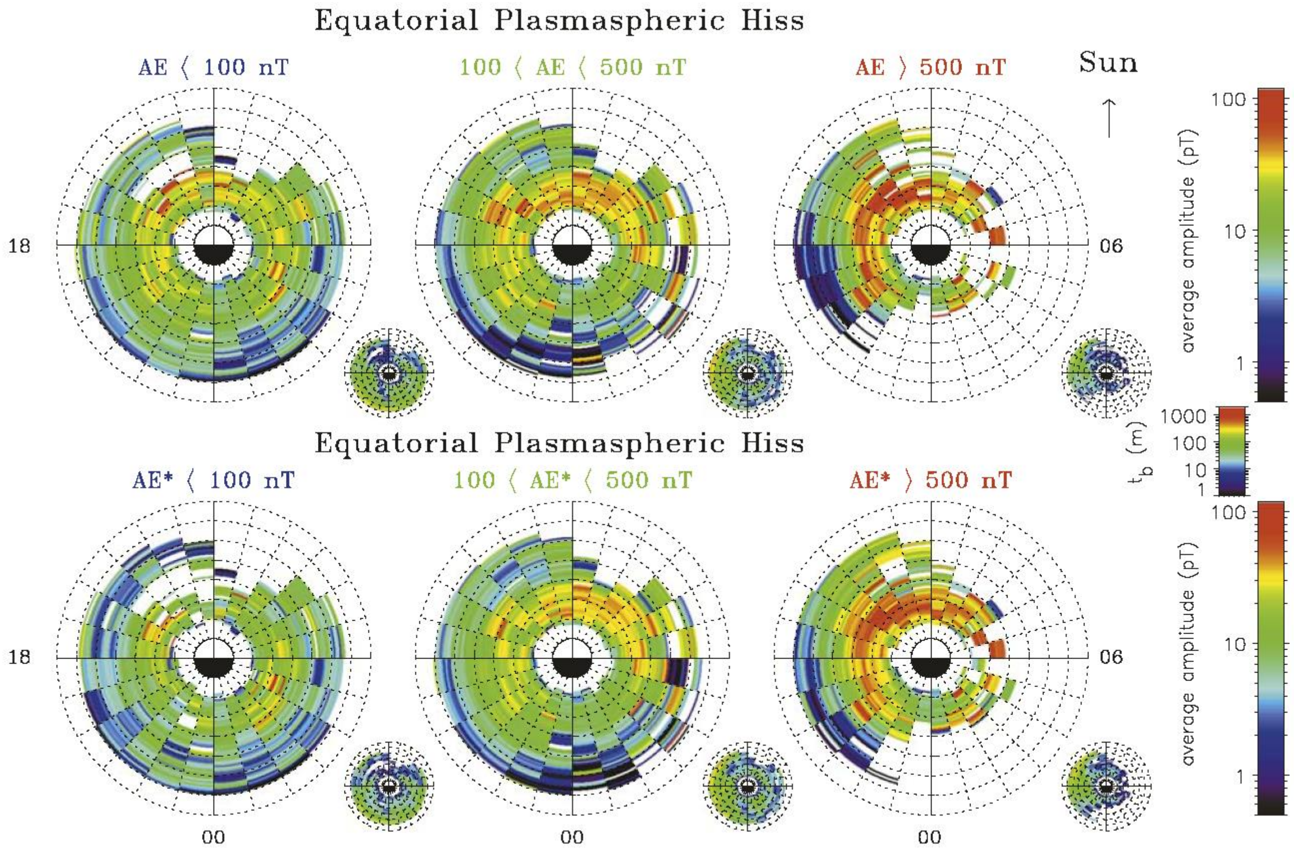
e.g., Kennel and Petschek [1966]; Roberts [1966], and many more!

Plasmaspheric hiss statistical distribution

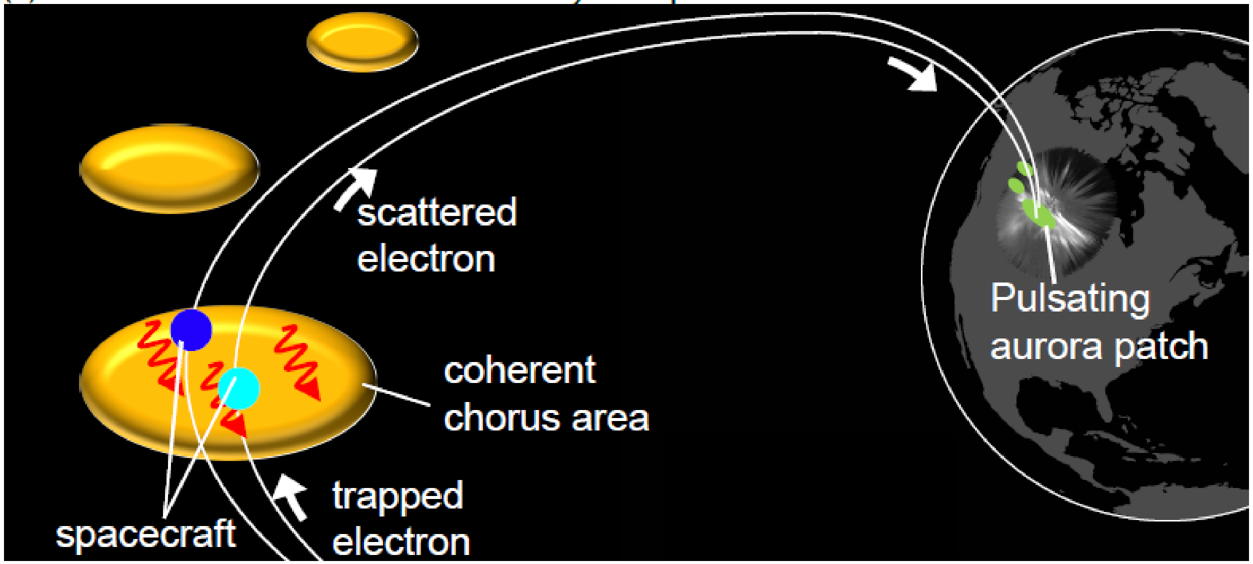


Meredith et al. [2004]

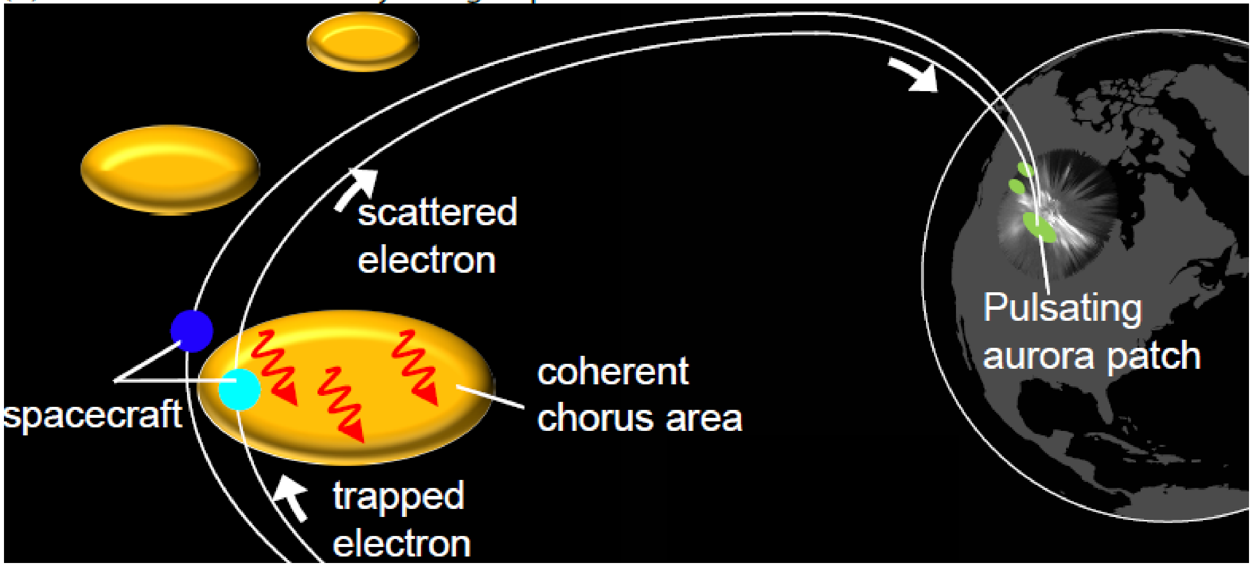
- Geomagnetic control and local time asymmetry
  - Weak: night, Intense: day
- 2-zone distribution; bandwidth distribution vs. L, exo-spheric/ELF hiss

Source region bounding

(a) Simultaneous chorus measurement by two spacecraft

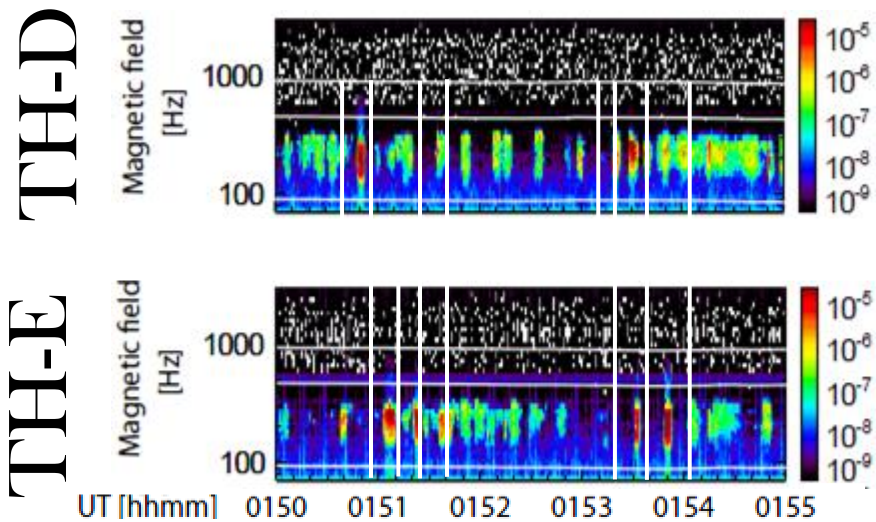


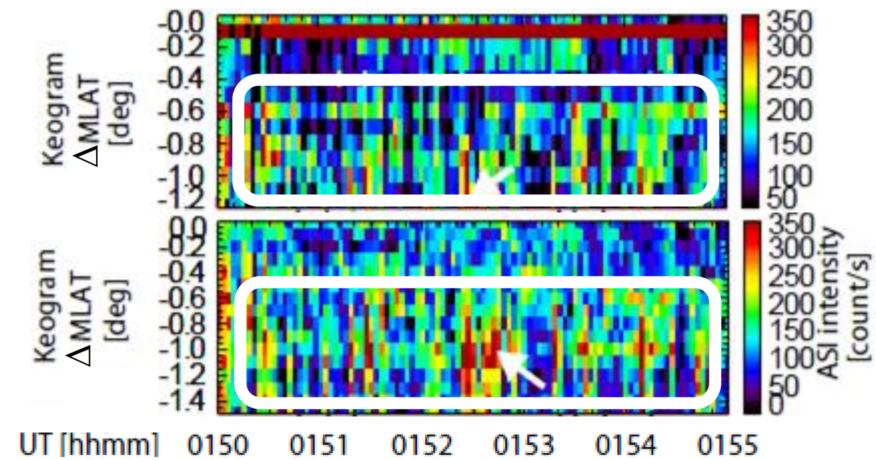
(b) Chorus measurement by a single spacecraft



Simultaneous observation by two spacecraft

Spacecraft separation: ~1500 km



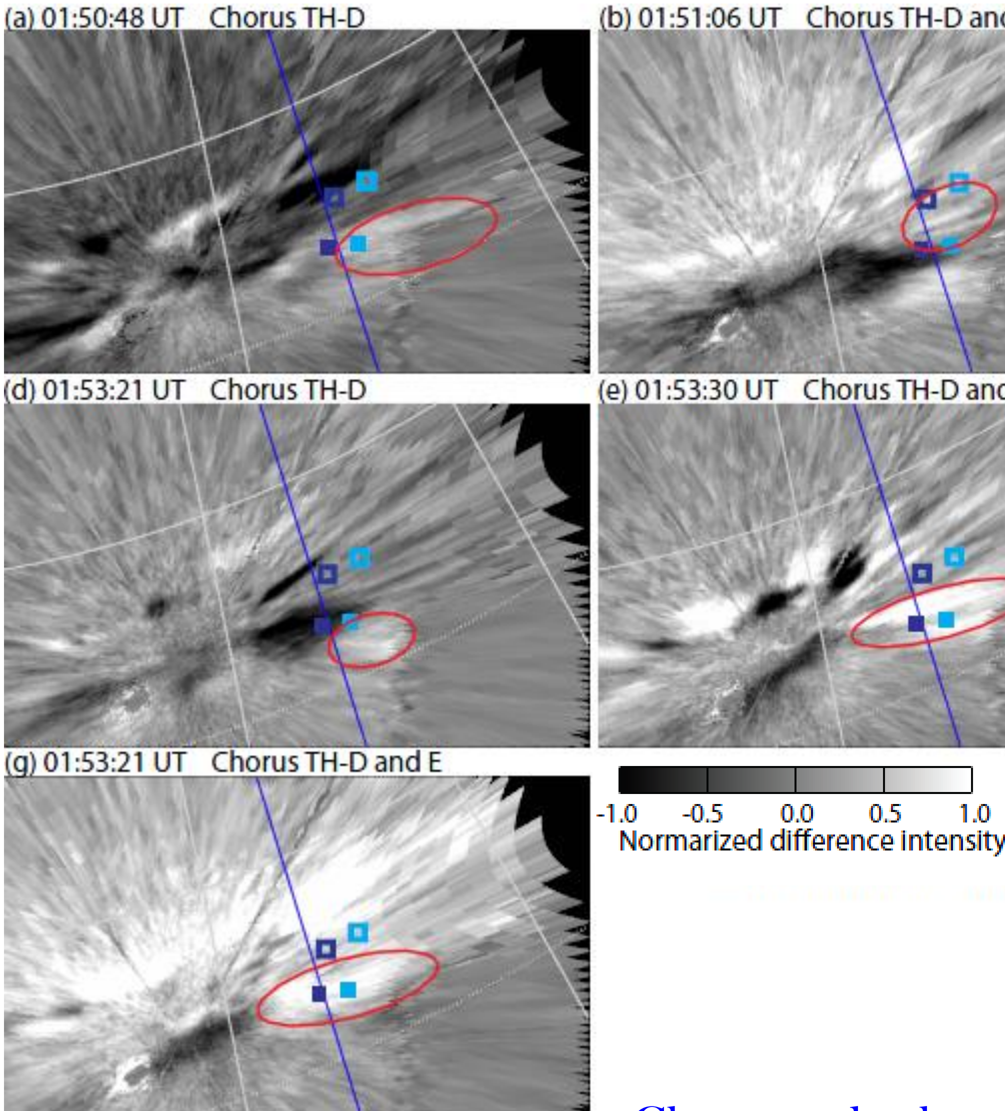


Chorus occasionally occur simultaneously at two spacecraft locations, but many chorus bursts are measure only by one of the spacecraft.

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

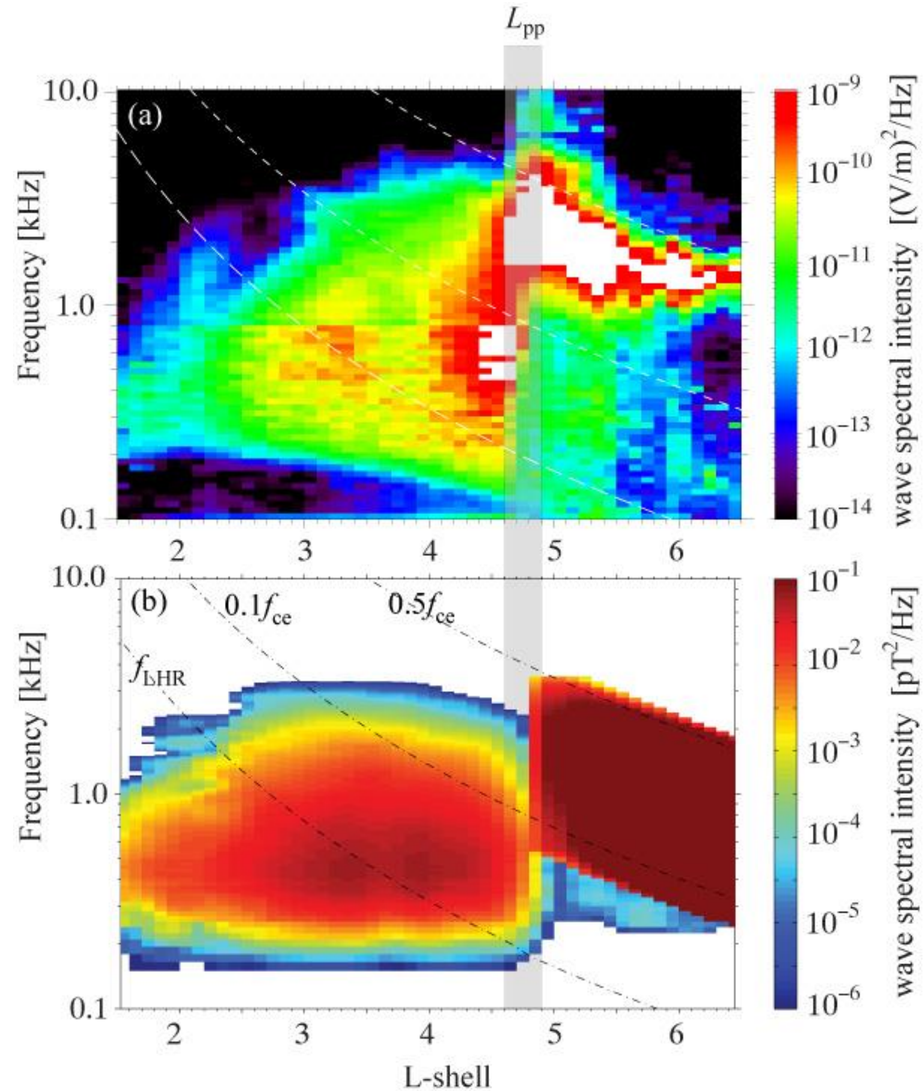
Chorus at both spacecraft = PA at both footprints

Chorus at single spacecraft = PA at single footprint

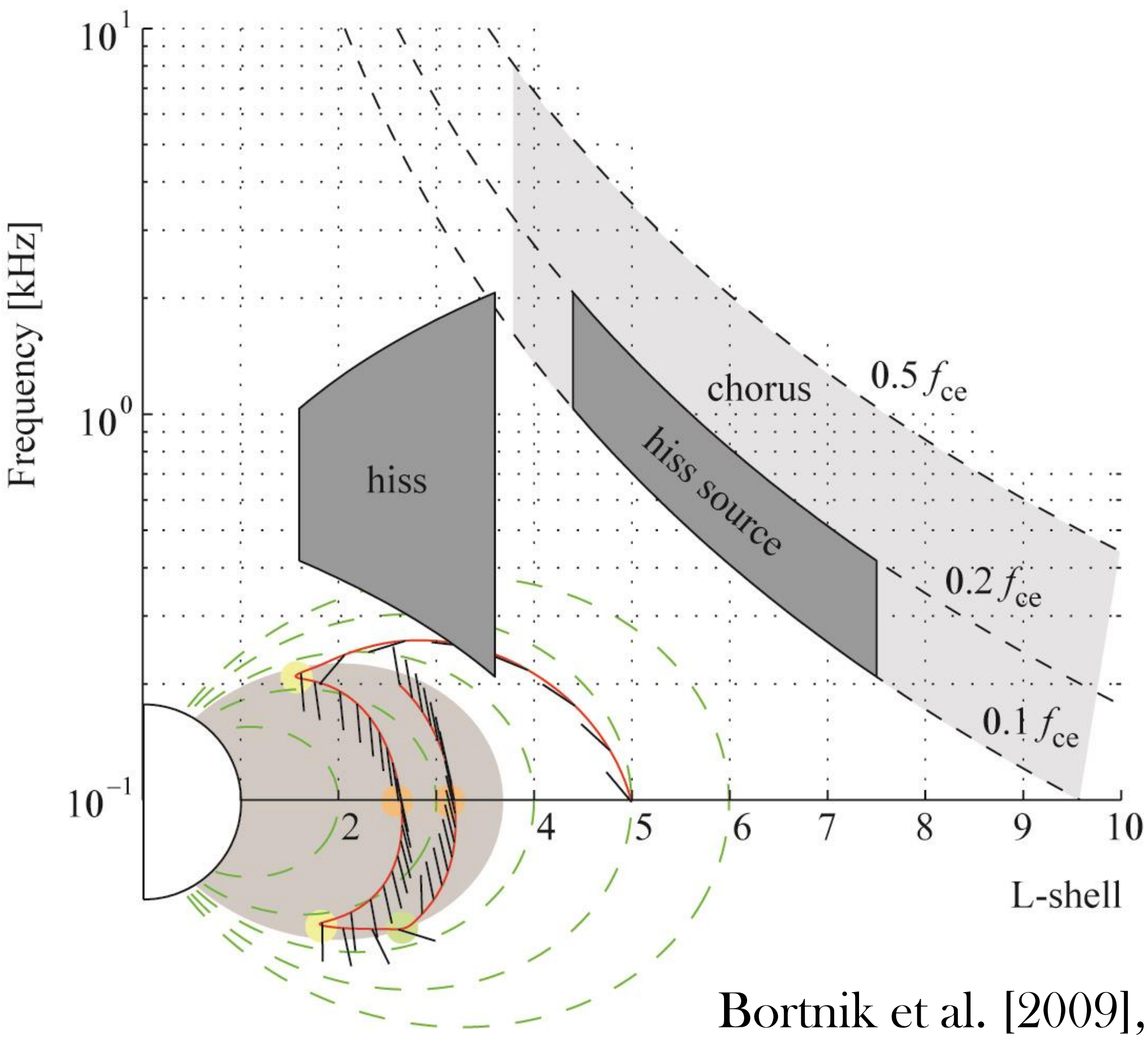
The PA patch shape would reflect the w-p interaction size.

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?



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*