A review of wave-particle interactions in the inner magnetosphere

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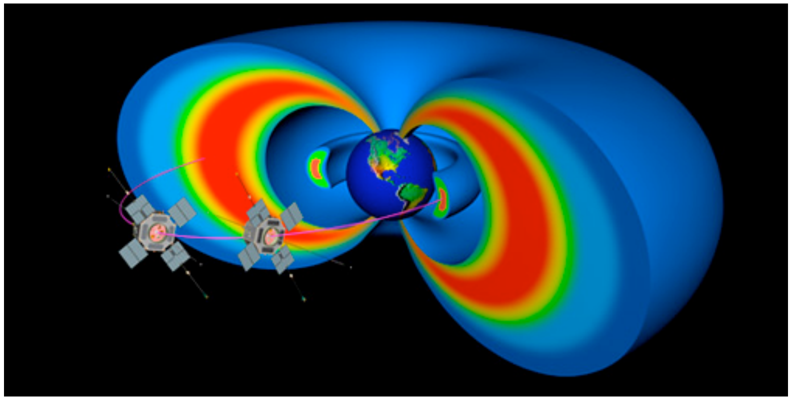
Outline: I will …

1. Focus on wave-particle interactions under the general context of radiation belt physics
    - Except when I don't (e.g., diffuse aurora, pulsating aurora, mapping)

2. Highlight the last 2 years
    - But not exclusively

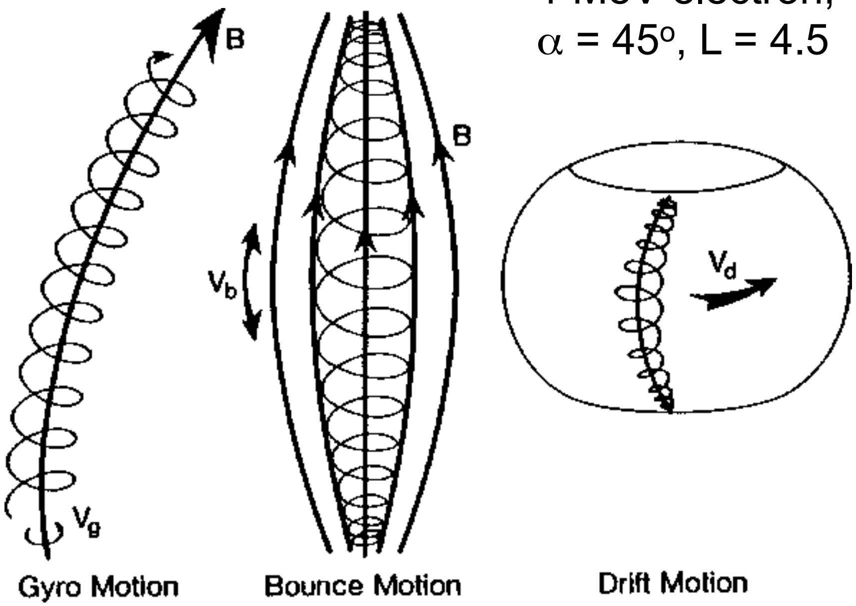
3. Not cover everything
    - Try to capture our evolving understanding in a few key areas



Stable, 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

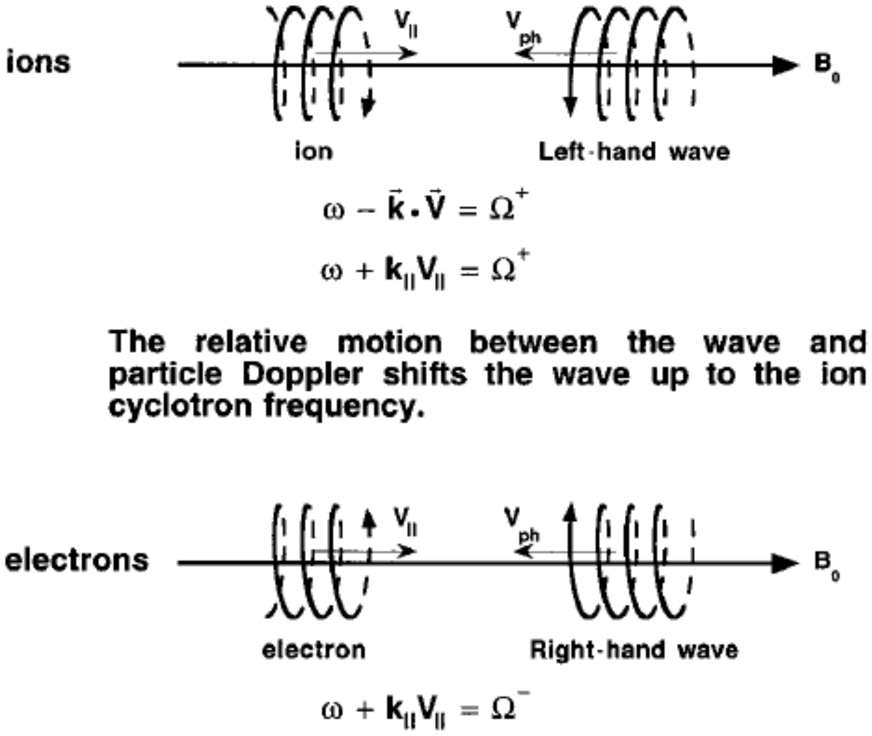


	gyro motion	bounce motion	drift motion
f	10 kHz	3 Hz	1 mHz
T	0.1 ms	0.36 s	15 min
	$\mu = \frac{p_{\perp}^{2}}{2mB}$	$J = \int_{bounce} p_{\parallel} ds$	$\Phi = \int_{drift} B dS$

Wave-particle interaction: violation of the invariant/s

1st invariant violation

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

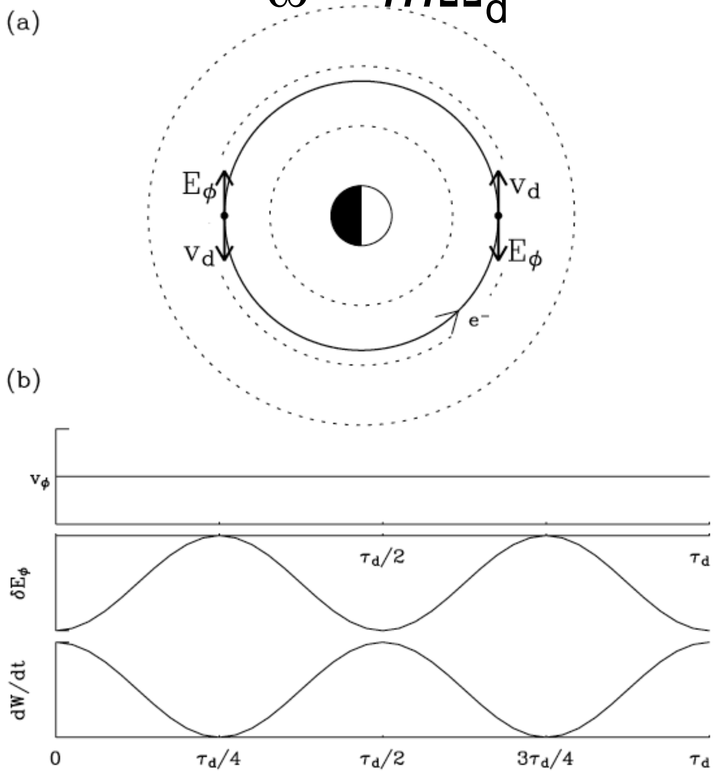


The relative motion between the wave and particle Doppler shifts the wave up to the ion cyclotron frequency.

Tsurutani & Lakhina [1997]

3rd invariant violation

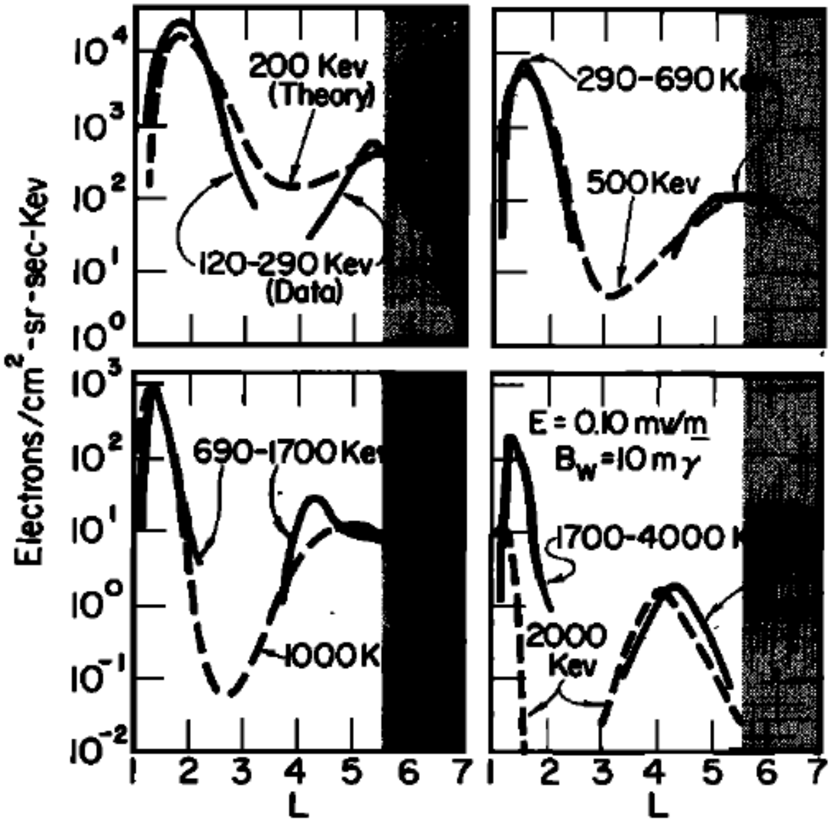
$$\omega = m\Omega_d$$



Elkington, Hudson & Chan [2003]

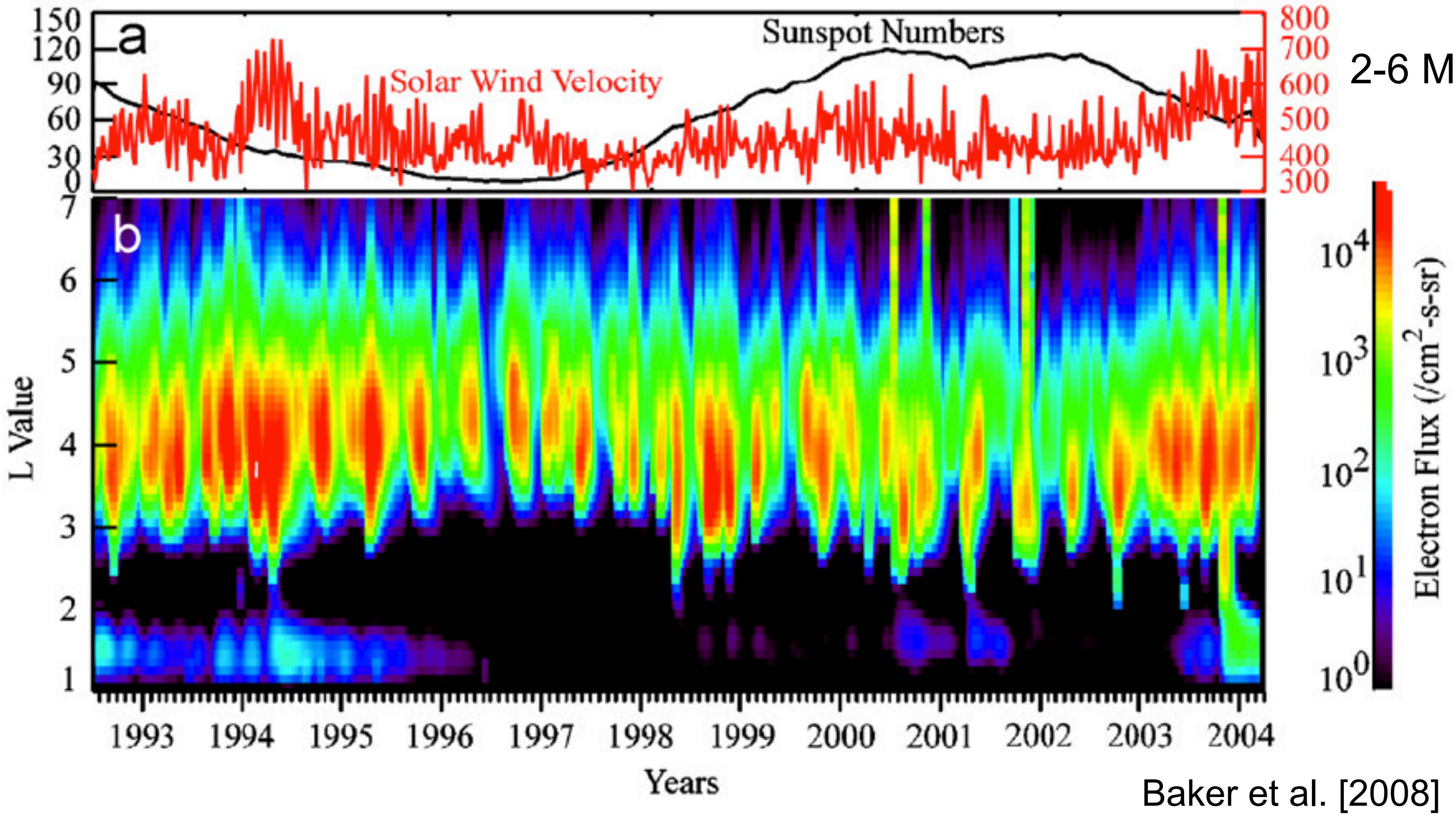
Equilibrium 2-zone structure

- 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 belt: L~ 1.2-2, relatively stable
- Outer belt: L~3-7, highly dynamic



Lyons & Thorne [1973]

Variability of the outer belt



2-6 MeV

Baker et al. [2008]

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

Predictability: solar wind

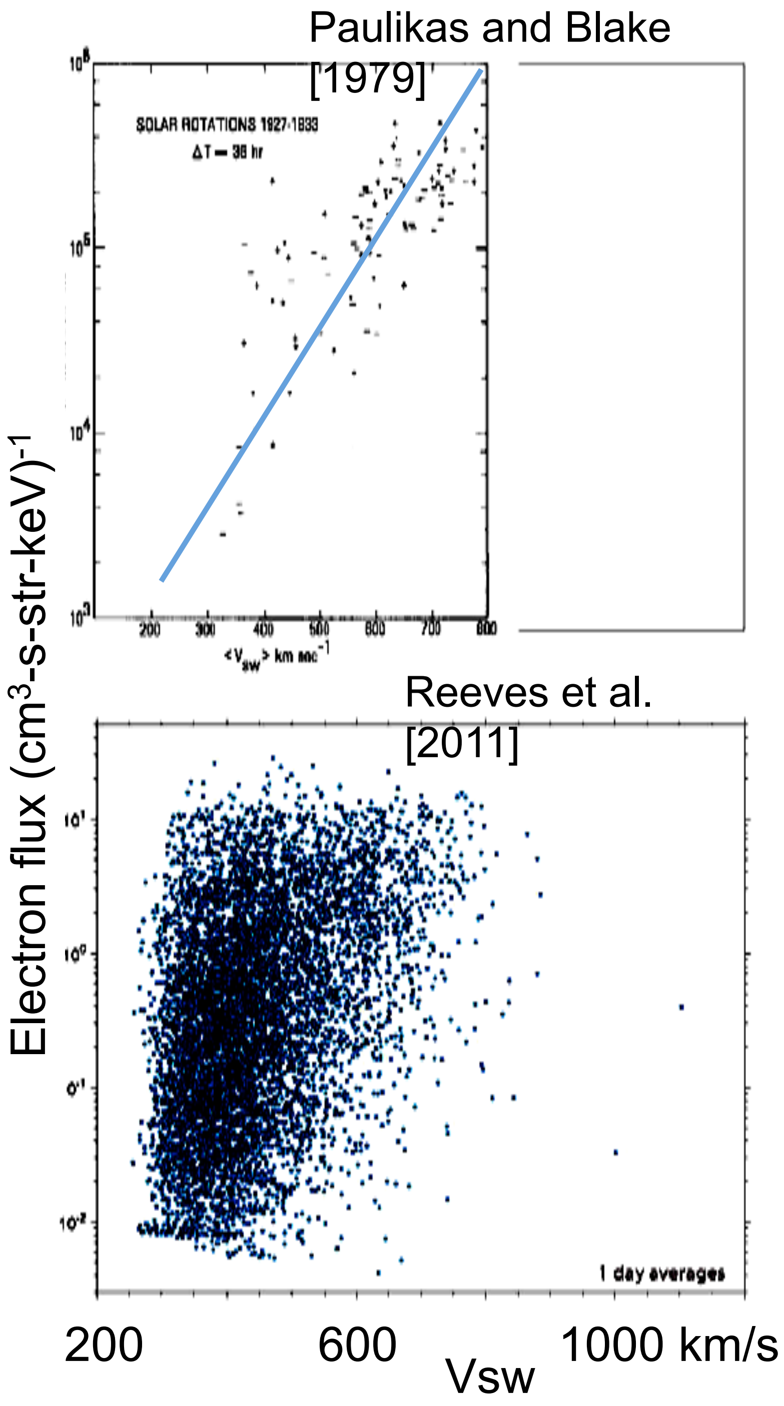
Paulikas & Blake [1979]

- Linear distribution
- log(flux) proportional to V_{sw}

Reeves et al. [2011]

- Triangular distribution
- Lower bound of log(flux) proportional to V_{sw}
- upper bound independent of V_{sw}

- For a given velocity, flux can take a wide range of values

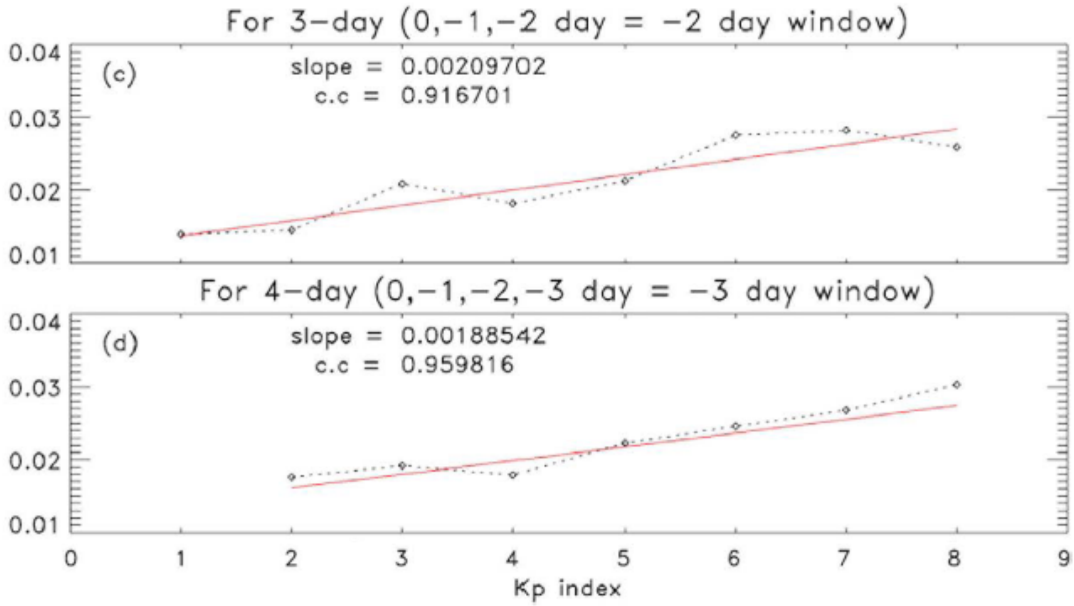


Paulikas and Blake [1979]

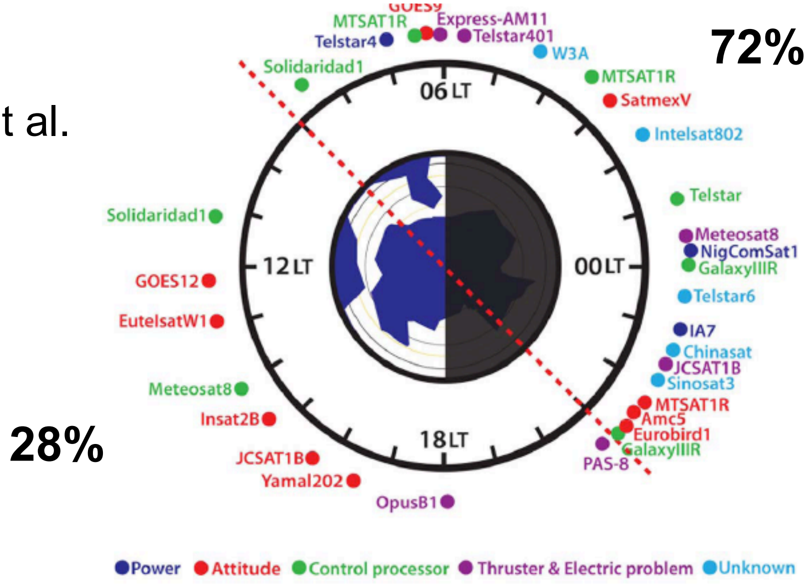
Reeves et al. [2011]

Spacecraft anomalies at GEO

- Analyzed ~100 GEO satellite anomalies from Satellite News Digest 1997-2009
- Good correlation between geomagnetic activity and anomalies (max Kp in past 3-4 days)
- Seasonal dependence (max in Spring and Fall), maybe due to Russell-McPherron effect
- Similar to lower energy electron behavior (E<100 keV)



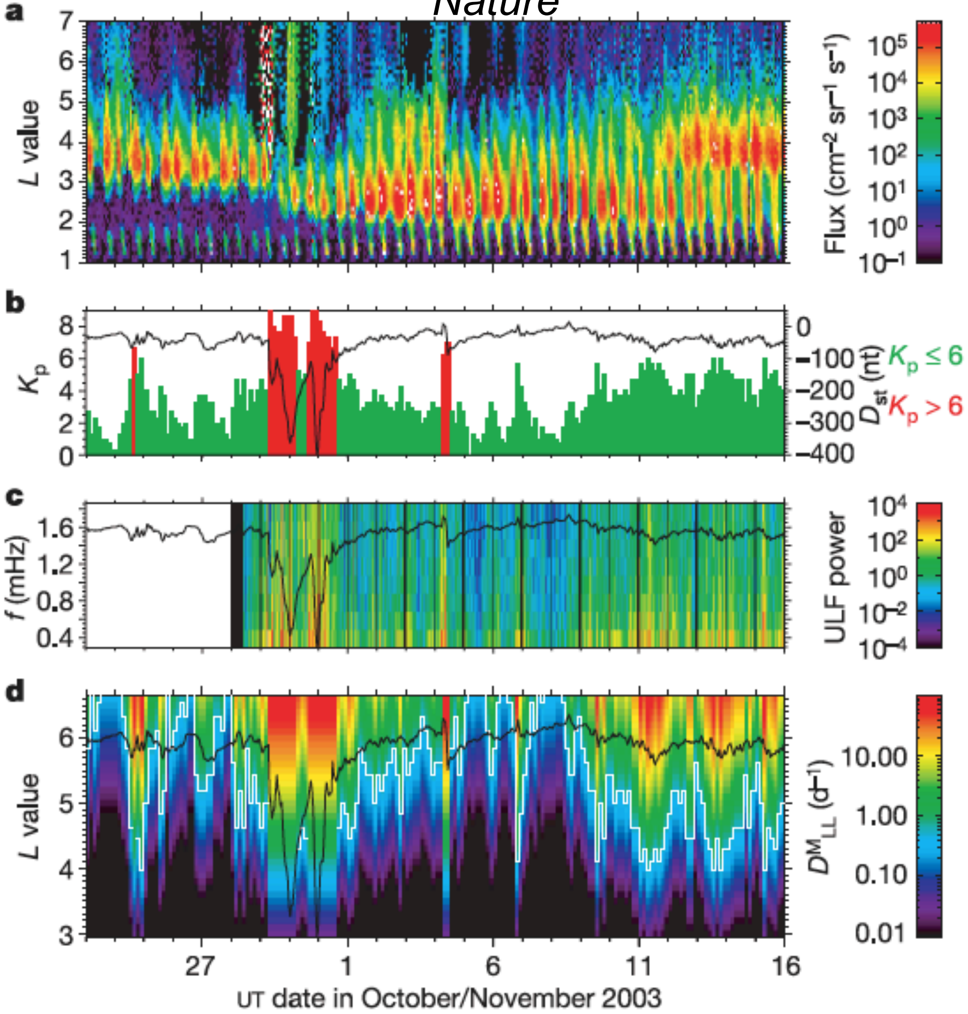
Choi et al. [2011]

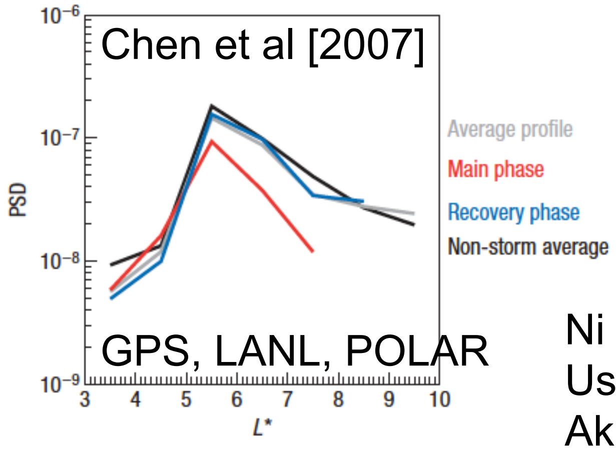


Paradigm shift

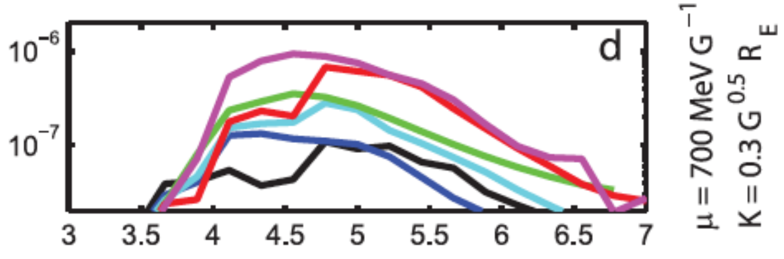
- Peaks develop at low L (~5) in PSD (e.g., Green et al. [2004]), and they are common
- ULF power occurs during dropout
- chorus during acceleration (Horne et al. [2005])

Horne et al [2005], *Nature*



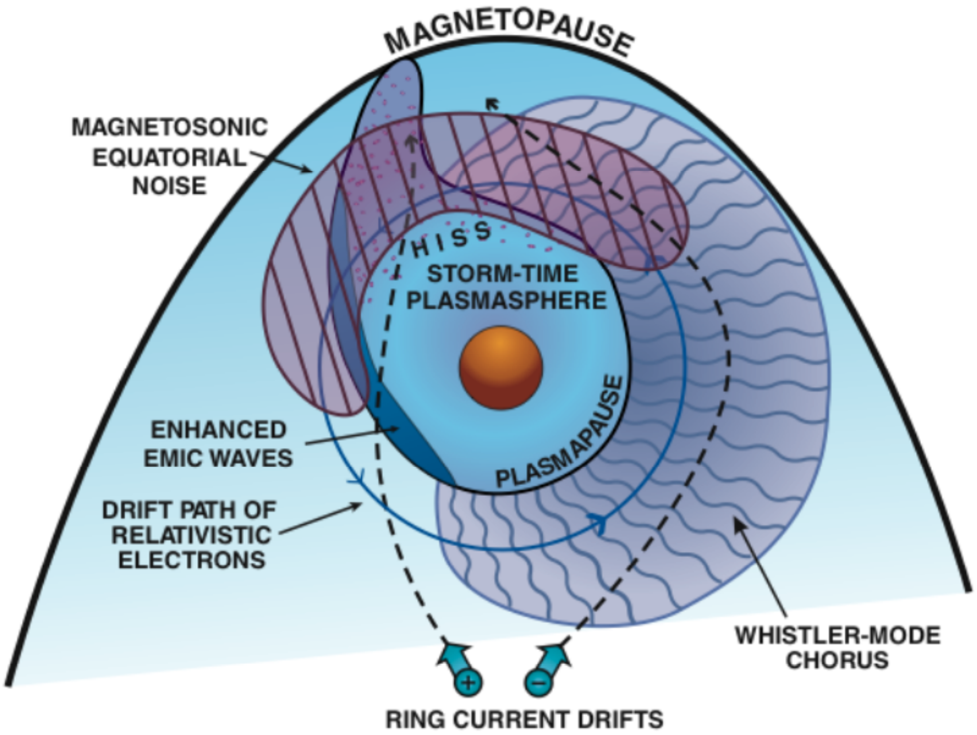


Ni et al [2009]
Using CRRES and Akebono



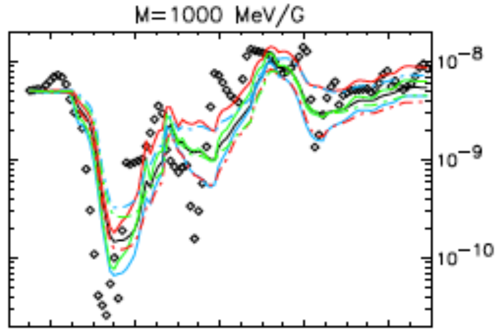
Wave effects

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



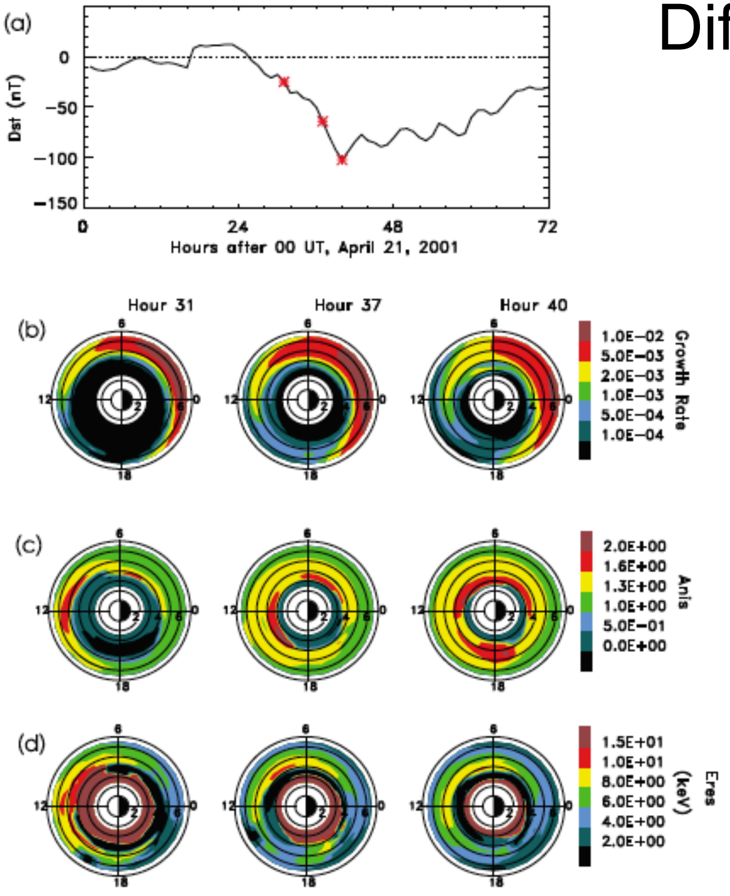
Thorne [2011] GRL “frontiers” review

Multi-dimensional diffusion

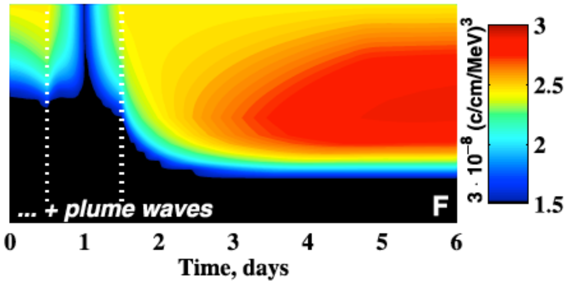


Albert et al. [2009]

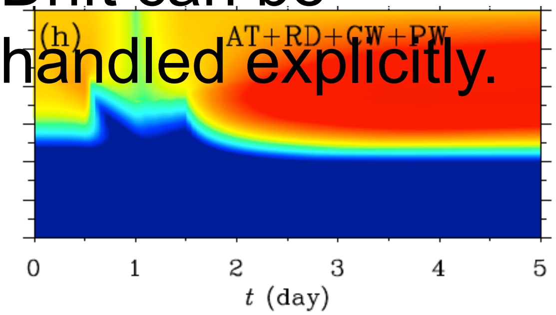
Different wave populations reflected as (time/ space dependent) diffusion coefficients. Used to solve FP-diffusion equation. Drift can be handled explicitly.



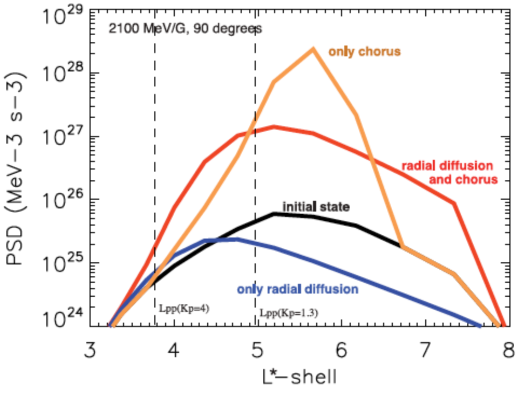
Jordanova et al. [2010] RAM, RCM, HTORAY 4D code



Shprits et al. [2009] VERB



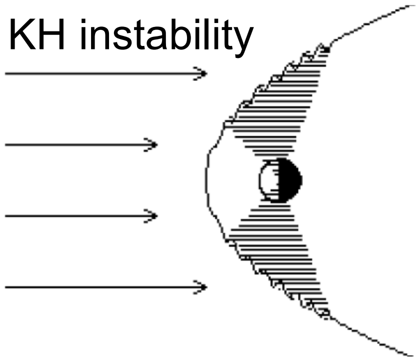
Su et al. [2010,2011] STEERB



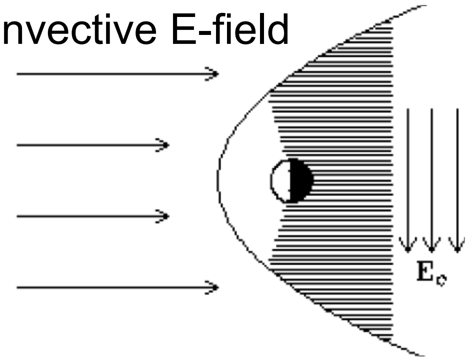
Varotsou et al. [2008] Salammbo

ULF Waves

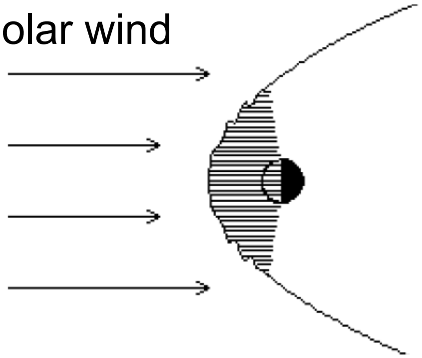
Shear waves due to KH instability



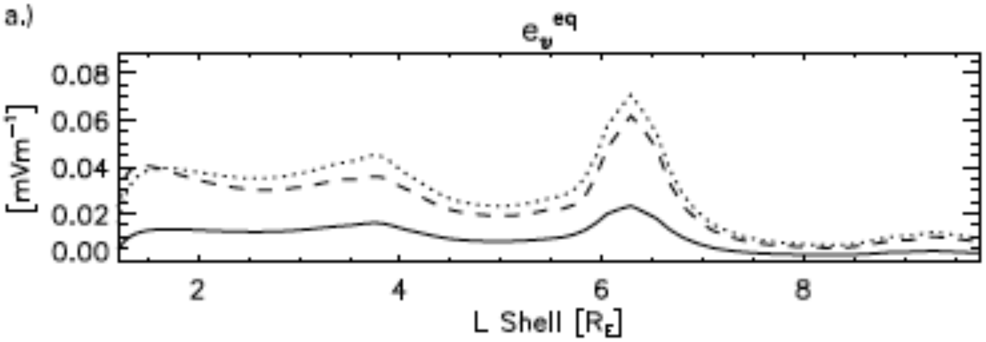
Variations in convective E-field



Impulsive variations in solar wind



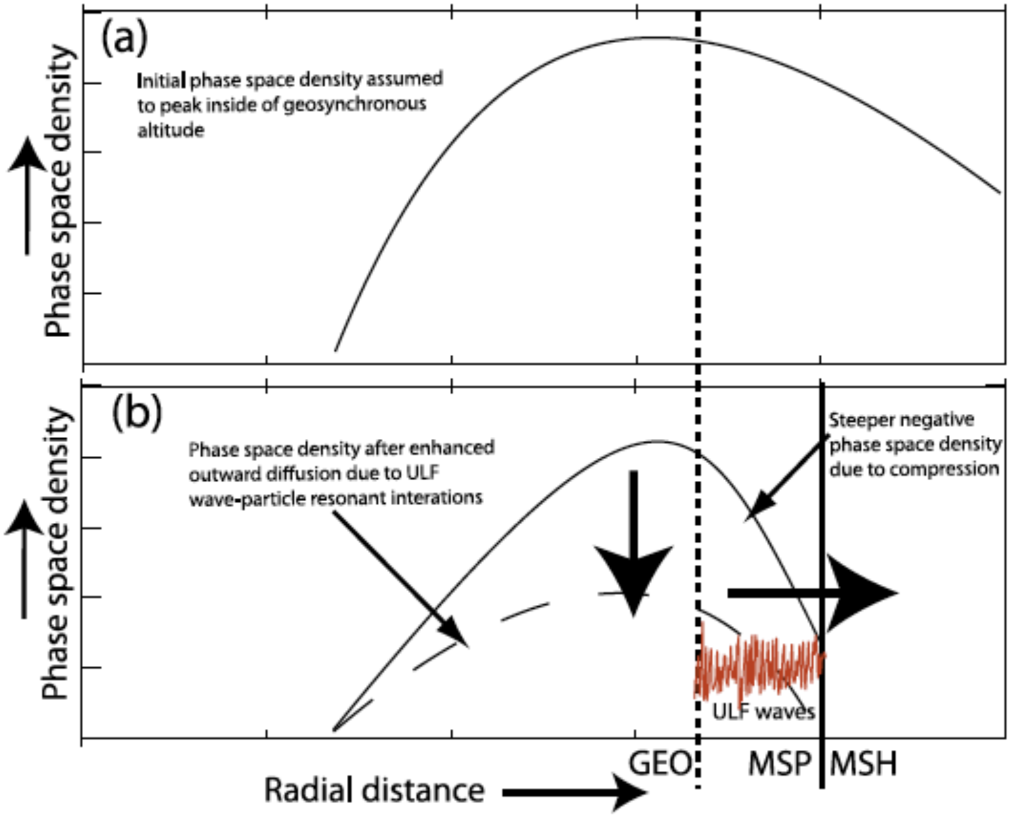
- The evolving role of ULF waves:
  - Inward radial transport as source of radiation belts
  - Redistribution of PSD peaks; impulsive transport and acceleration of particles
  - Outward radial diffusion, possibly leading to RB



Sciffer and Waters [2011], following Ozeke et al. [2009]

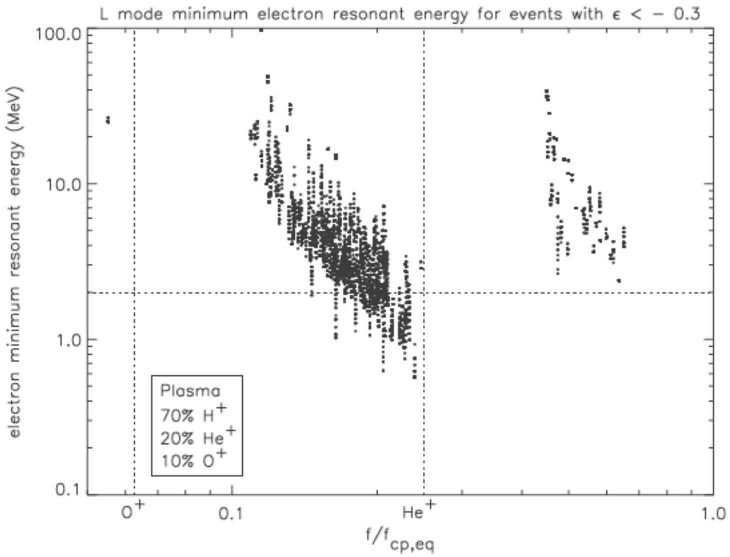
Dropouts: magnetopause shadowing and radial diffusion

- A dropout event on 25 June 2008
  - Magnetopause, L~8
  - Loss time ~4 hrs
- ULF waves measured on ground magnetometers
  - Radial diffusion rates estimated
  - Lifetimes ~2.5 hrs
- **Key question: magnetopause at low L + large D_{LL}, always true for dropouts?**

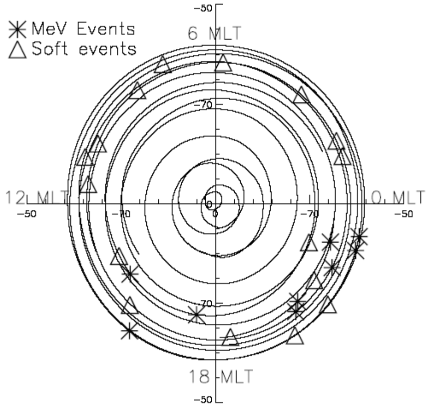


Loto'aniu et al. [2010]

EMIC wave scattering: then



Meredith et al. [2003]: e^- resonant energies below 1 MeV



Millan et al. [2002]: Hard X-ray (MeV) events on duskside EMIC dominant Loss mechanism in dropouts

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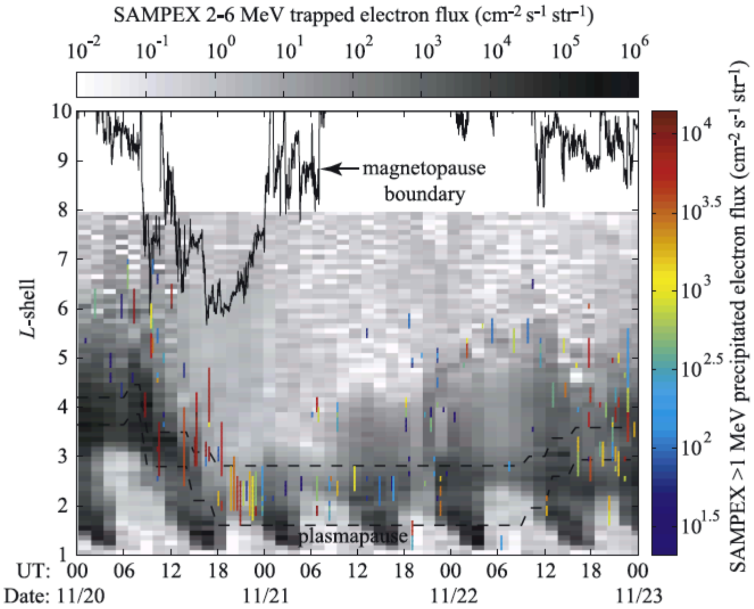
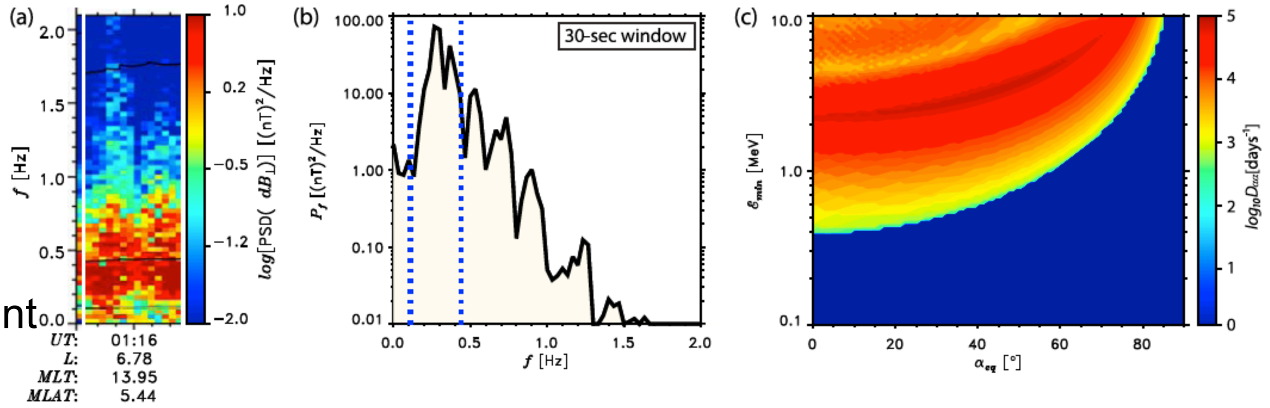


Bortnik et al. [2006]: e^- precipitation bands during dropouts. Evidence suggests EMIC.

Borovski & Denton [2009]: Need
Plume & hot ions for dropouts

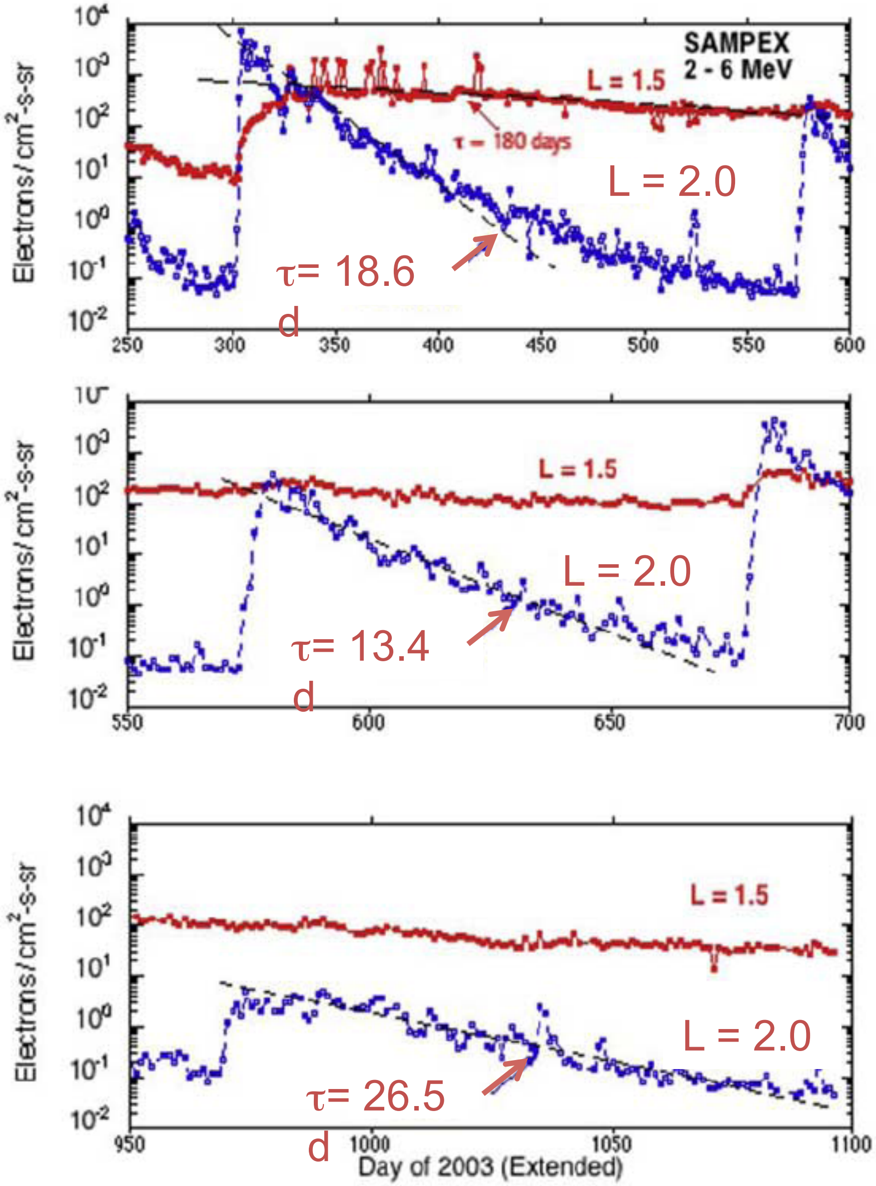
Ukhorskiy et al. [2010]: e^- resonant energies below to 400 keV



EMIC wave scattering: now

- Millan et al. [2010]: X-ray balloon observations, wrong place! Precipitation was not the direct cause of flux dropouts at GEO
- Meredith et al. [2010]: During HSS's, no evidence for MeV electron precipitation during the dropout event
- Morely et al. [2011]: Dropouts down to ~200 eV, well below minimum resonant energy of EMIC. Loss timescales too fast.
- Silin et al. [2011]; Chen et al. [2011]: Including warm plasma effects: EMIC can be excited in the stop bands, and precipitation >2 MeV
- Borovski and Cayton [2011]: The radiation belt and tail energetic electrons are the SAME population. Inward or outward transport?
- Turner et al. [GEM talk]: no precipitation accompanying dropout

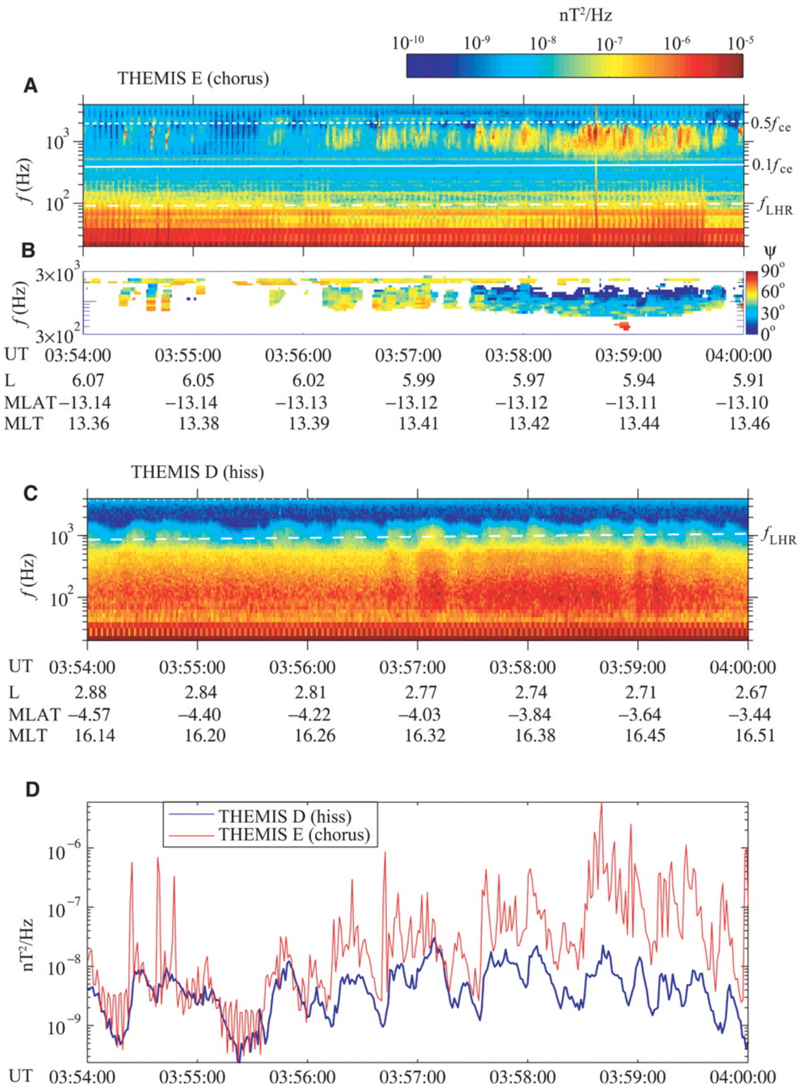
Plasmaspheric hiss



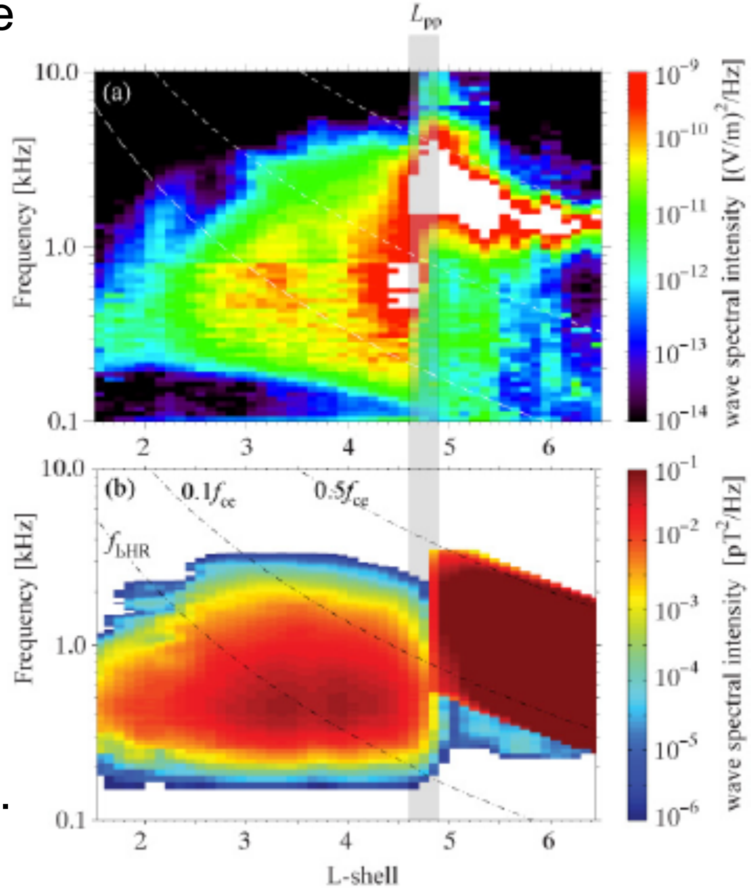
- Plasmaspheric hiss:
    - Incoherent EM wave
    - confined to the plasmasphere
    - *f* ~ 0.2-2kHz, strong on dayside
    - Intensity is dependent on AE
    - Responsible for electron scattering in the slot region
- Baker et al., [GRL, 2007] decay rates for 2-6 MeV electrons from SAMPEX ~20 days at L = 2.0
- Meredith et al. [2007] hiss scattering must be from nearly parallel waves (otherwise lifetime is too long)
- Bortnik et al. [2008] Origin of hiss suggested from chorus

Plasmaspheric hiss observations and distribution modeling

Chorus as the origin of plasmaspheric hiss: Reproduced observed spatial and spectral distributions: wavenormals oblique off-equator, Quasi-parallel at low L, bimodal near plasmapause



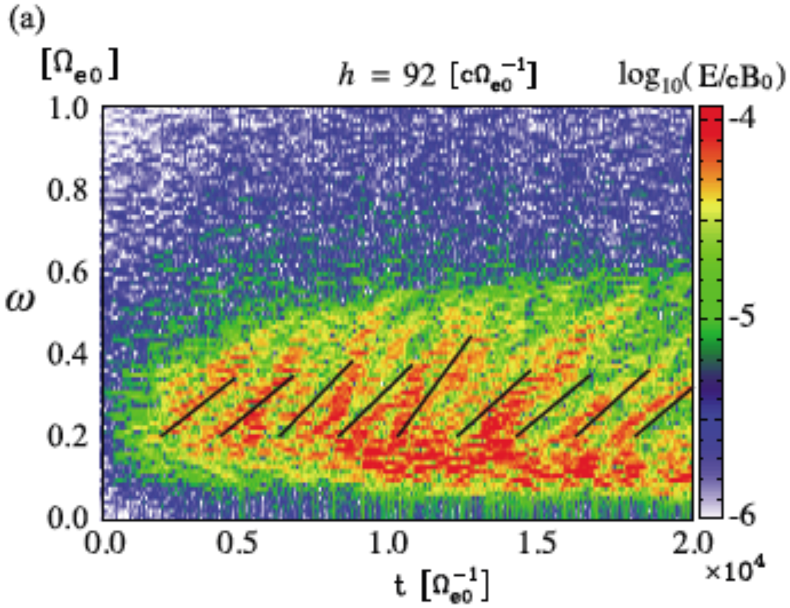
Bortnik et al. [2009]



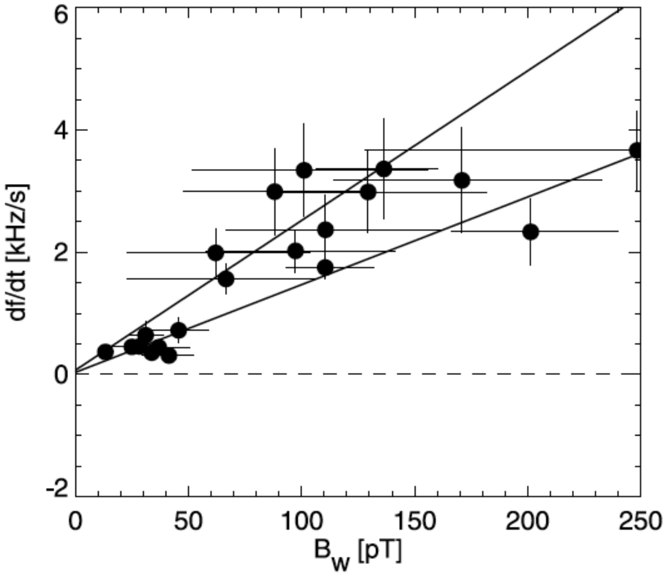
Bortnik et al. [GEM 2011]

Chorus growth

Recent (2 years) proliferation of research into chorus excitation, e.g., Omura et al. [2009], Nunn et al. [2009], Schriver et al. [2010], Santolik et al. [2010], Bespalov et al. [2010], Lampe et al. [2010], Hikishima et al. [2010], Katoh and Omura [2011], Omura and Nunn [2011], Demekhov [2011], etc.



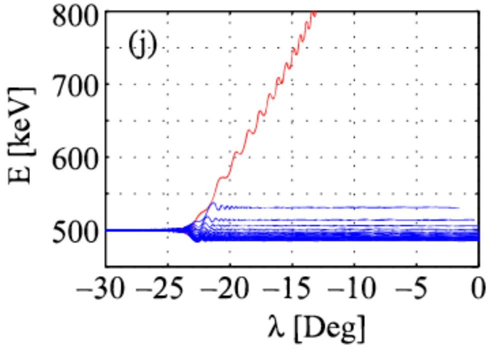
Katoh and Omura [2011], electron hybrid code simulations: frequency sweep is established very near the equator, but wave amplitudes grow as wave propagates away.



Cully et al. [2011], THEMIS data used to test theory with NO INDEPENDENT PARAMETERS, showing good consistency.

Q: Based on distribution function, can we analytically predict wave characteristics? E.g., saturation amplitude, upper and lower f cutoffs, df/dt, wave normal, etc.

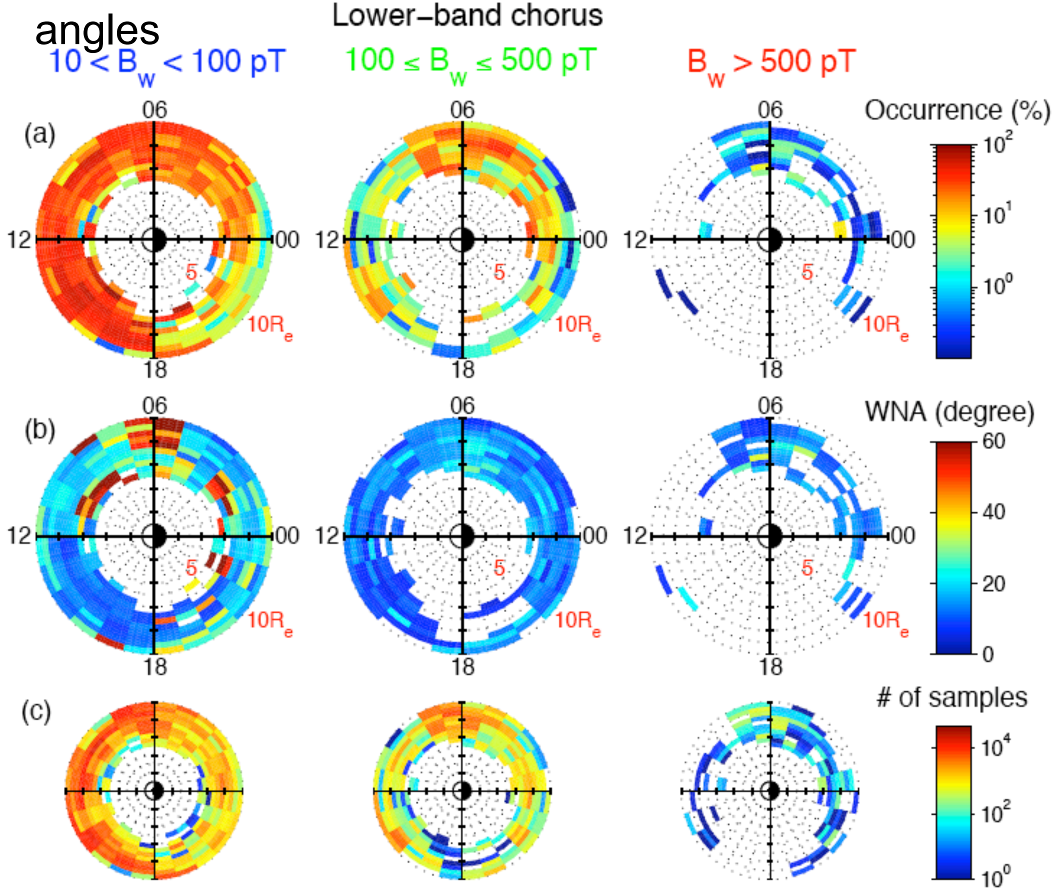
Large amplitude chorus

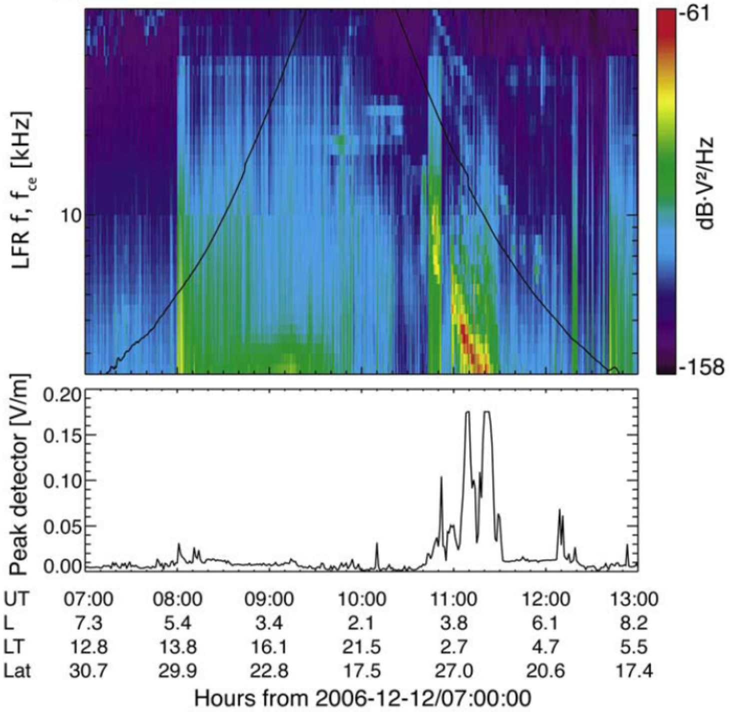


Bortnik et al. [2008]

pronounced nonlinear effects, including rapid acceleration of a small percentage of particles.

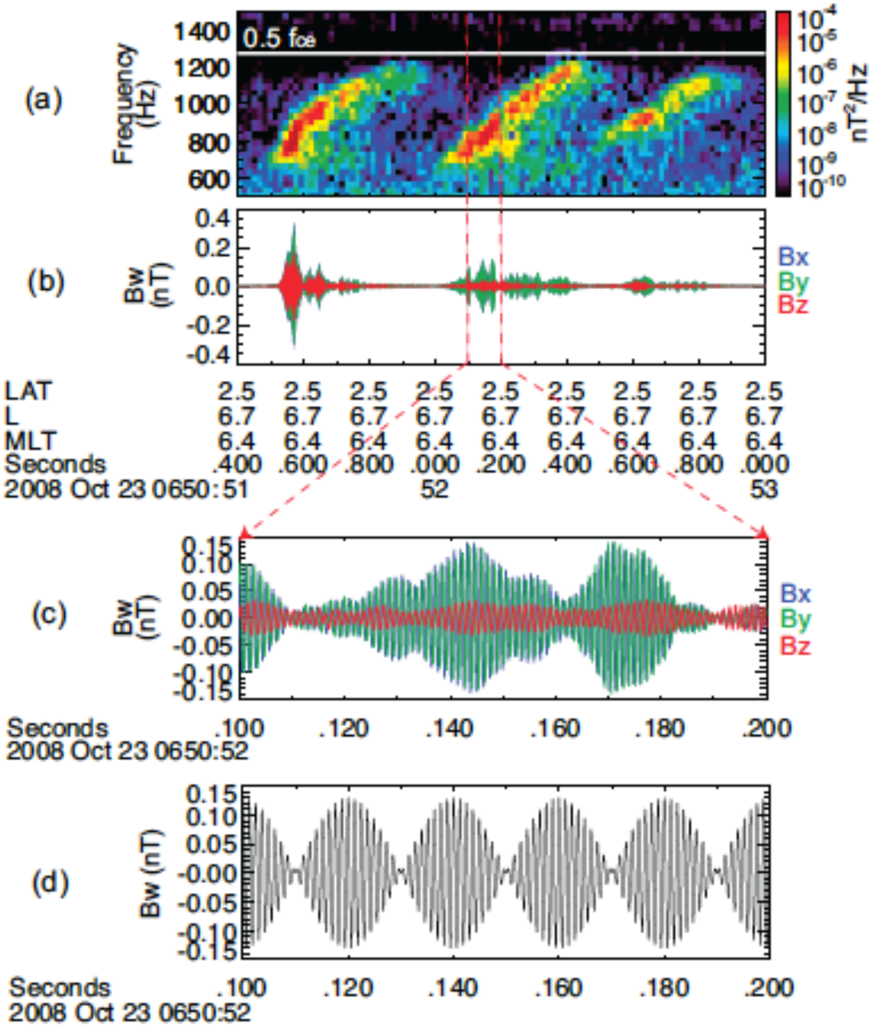
Li et al. [2011], Burst mode observations from THEMIS: Large amplitude chorus is ubiquitous, midnight-dawn, predominantly small wave normal angles



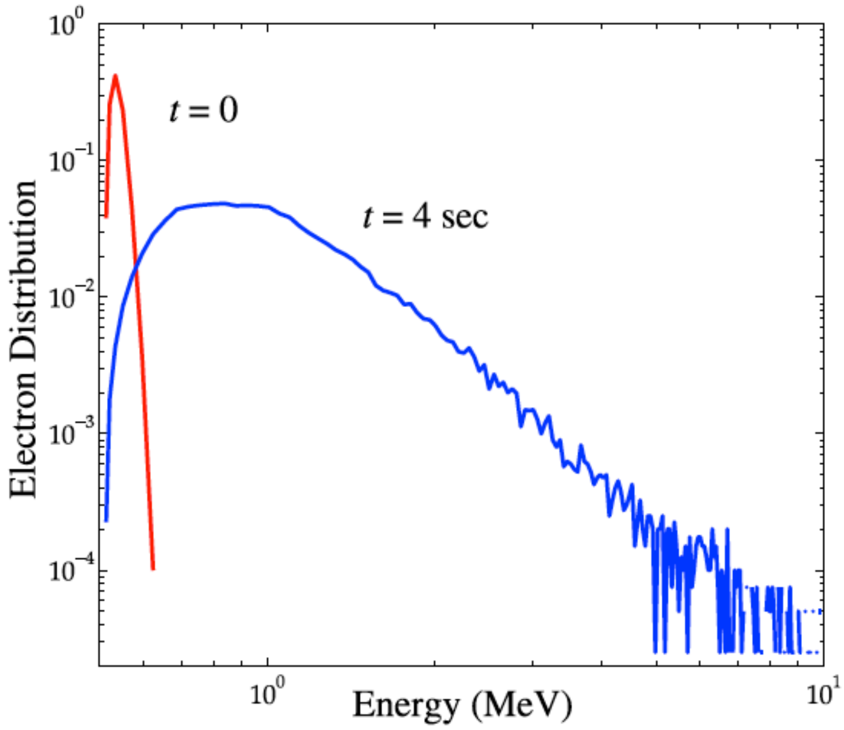


Cattell et al. [2008], First reports of large amplitude chorus, STEREO B

Scattering by large amplitude chorus



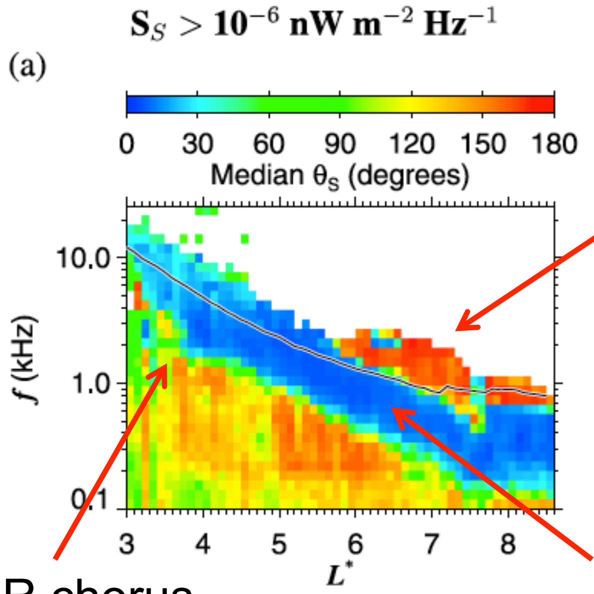
Yoon [2011] GRL: Solves fully nonlinear cold electron fluid equations for obliquely propagating large amplitude chorus: acceleration in seconds.



Tao et al. [under review] Inclusion of subpacket structure modifies the single-wave scattering picture

Chorus wave normals and Poynting vectors

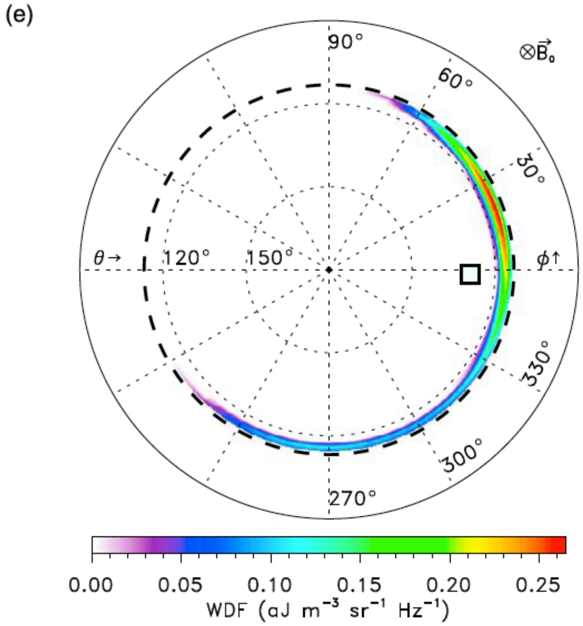
Santolik et al., [2010], POLAR PWI: survey of Poynting fluxes



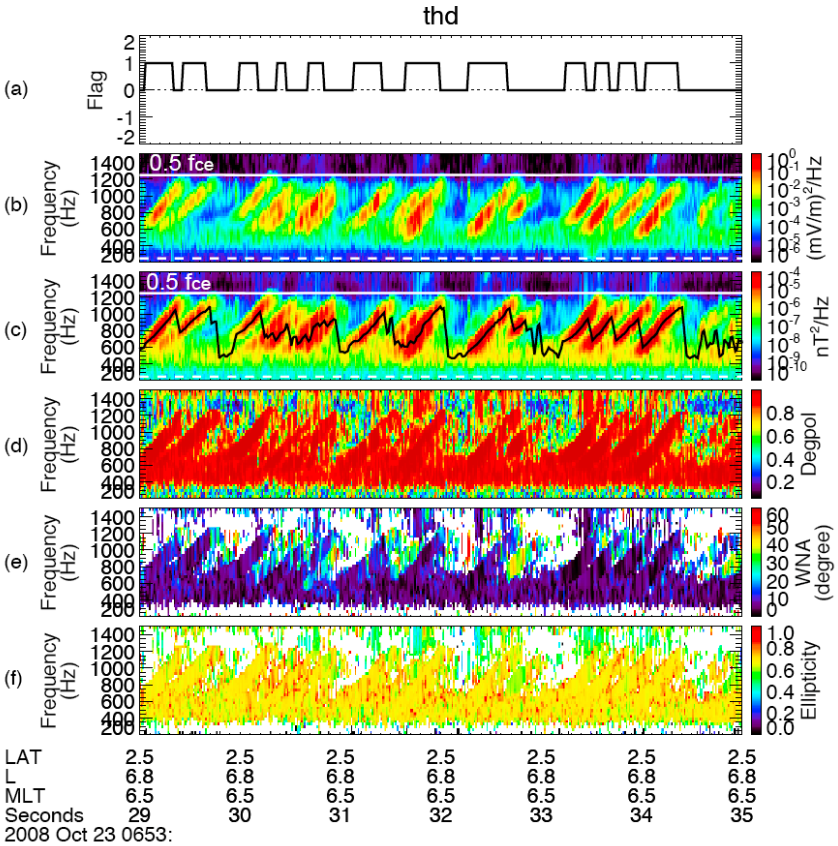
DOZ chorus [Tsurutani and Smith 1977; Tsurutani et al., 2009]

chorus

MR chorus

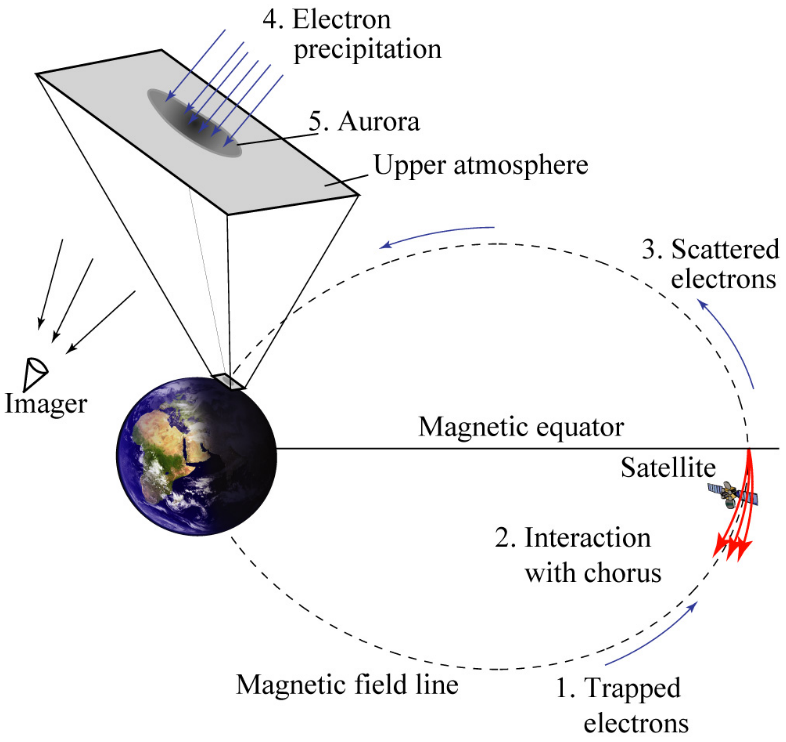


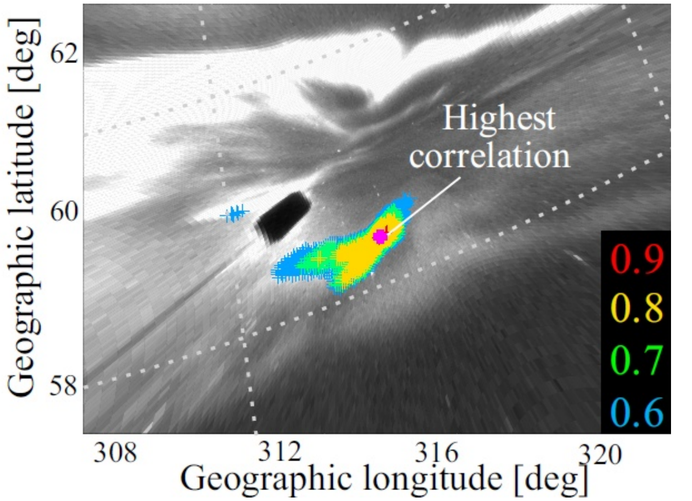
Santolik et al., [2009]



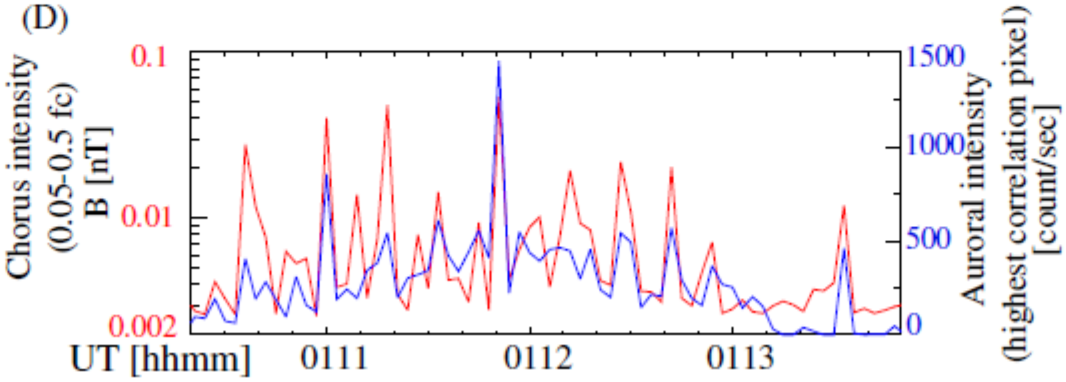
Systematic differences THEMIS analysis of rising tone vs. falling tone, and upper-band vs. lower band chorus [Li et al., under review]

Pulsating aurora: origin



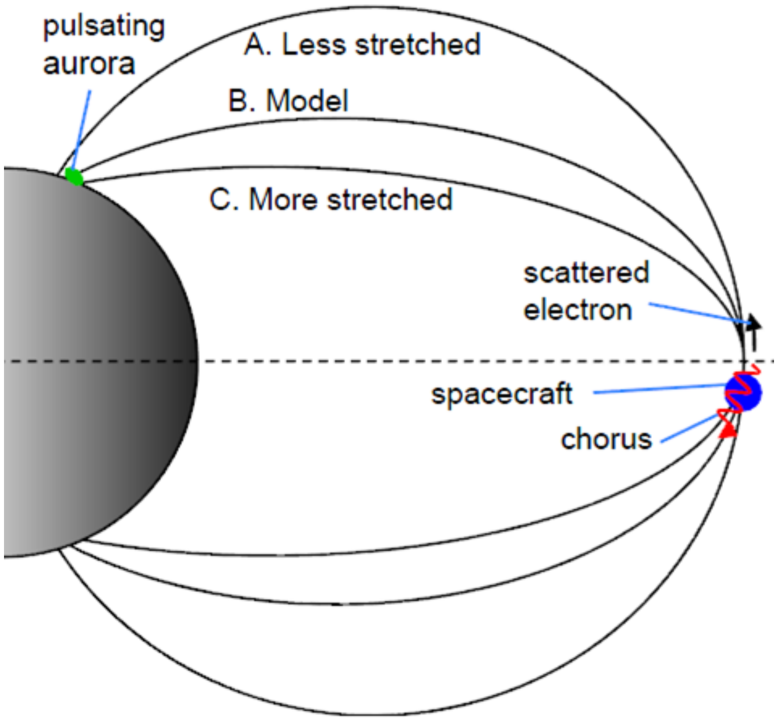


- Described in 1963 “auroral atlas”
- Origin is lower band chorus
- Allows visualization of chorus source region



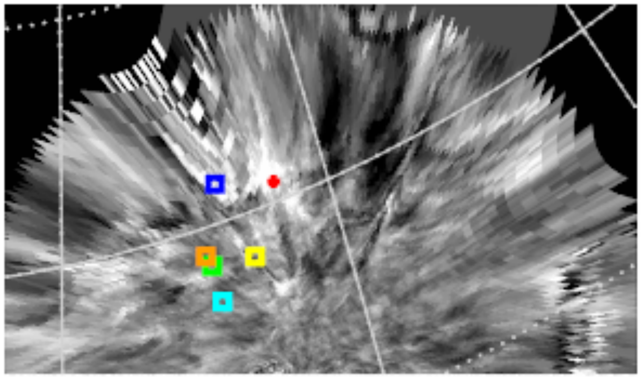
Nishimura et al. [2010] *Science*

Pulsating aurora: mapping



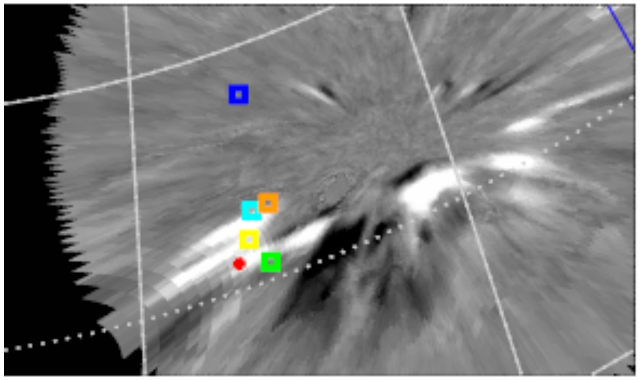
Quiet time
(ΔH and ΔZ~0)

g 2010-01-06/06:17:33 UT TH-E



Disturbed time
(|ΔH| or |ΔZ|
>~50 nT)

d 2009-02-15/01:38:00 UT TH-E



Nishimura et al.
[2011] in press

Magnetic activity dependence

- Quiet time footprint: Closer to IGRF than Tsyganenko
- Disturbed time footprint: Closest to T02

Diffuse aurora

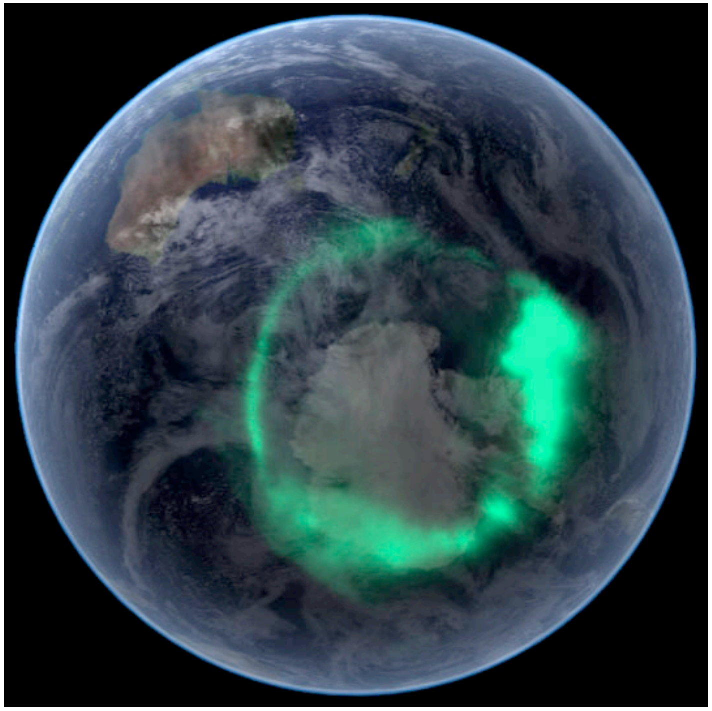
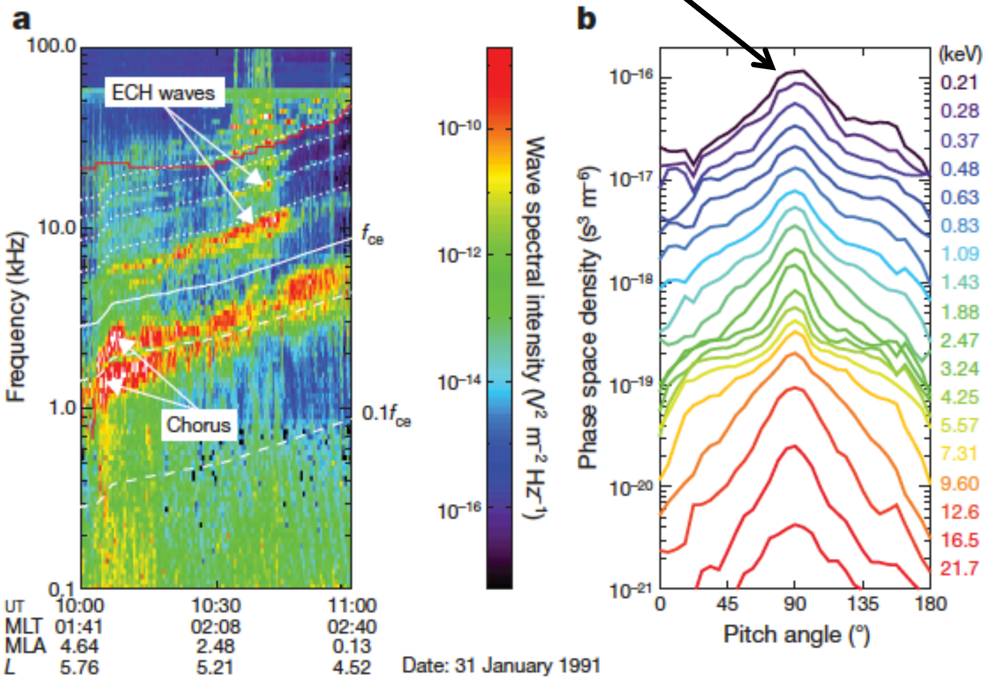


IMAGE satellite, 11 Sep 2005

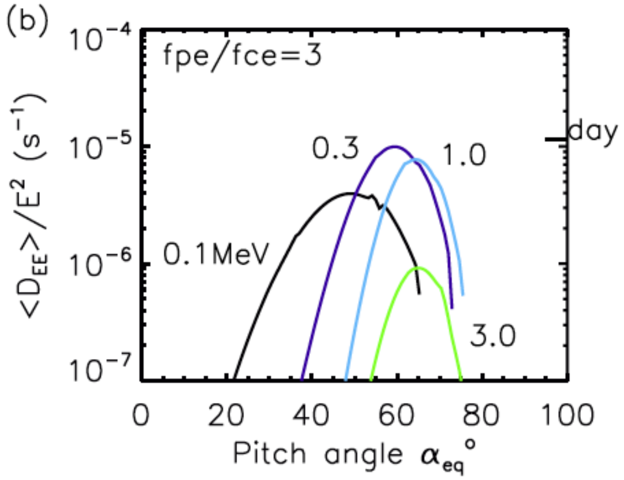
Only chorus can
account for the
resultant
distributions
observed in space

These “pancake”
distributions provide
the clue

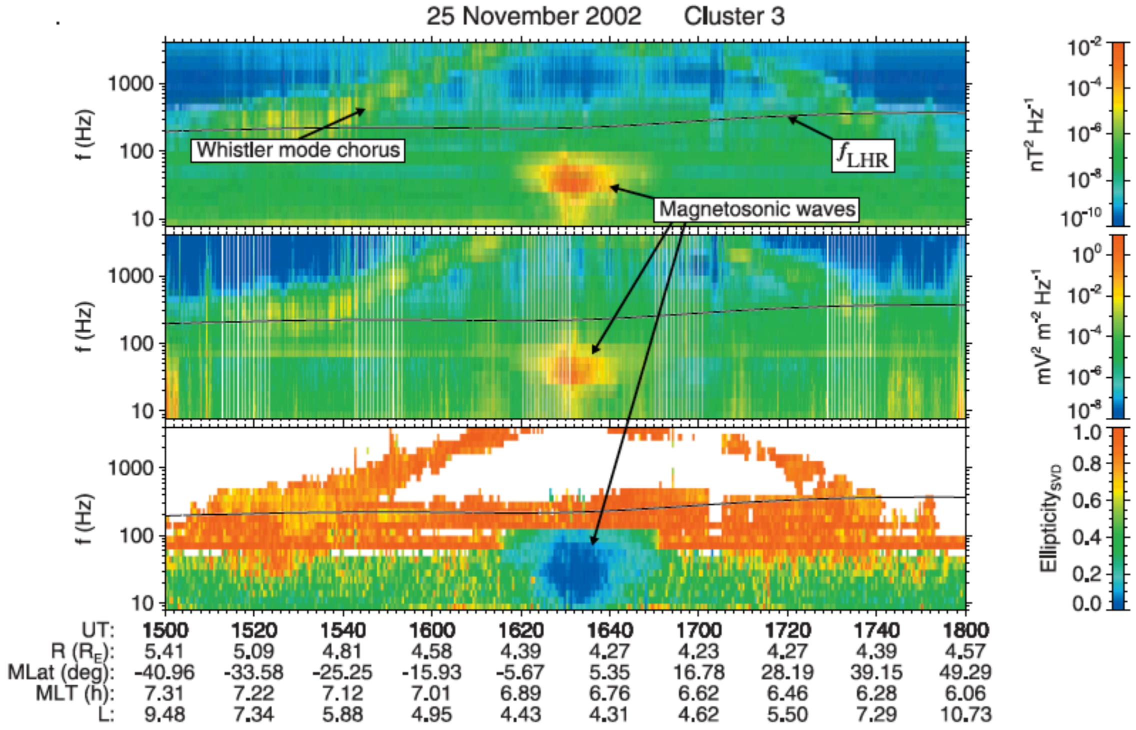


Thorne et al. [2010] *Nature*

Magnetosonic waves



Horne et al. [2007]

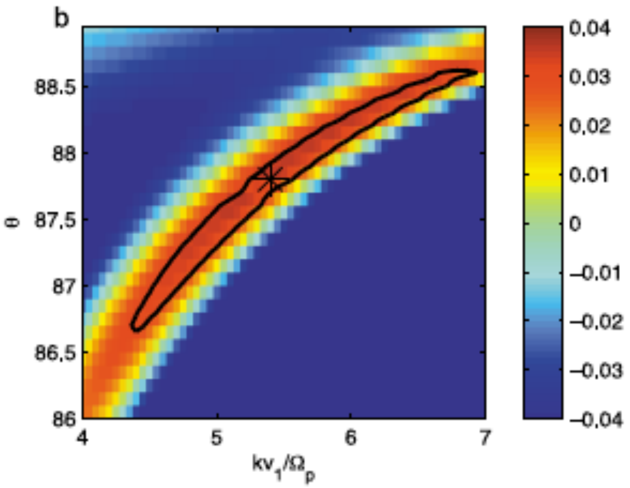


Acceleration due to magnetosonic waves could be as fast as ~1 day, based on ~200 nT CLUSTER observation

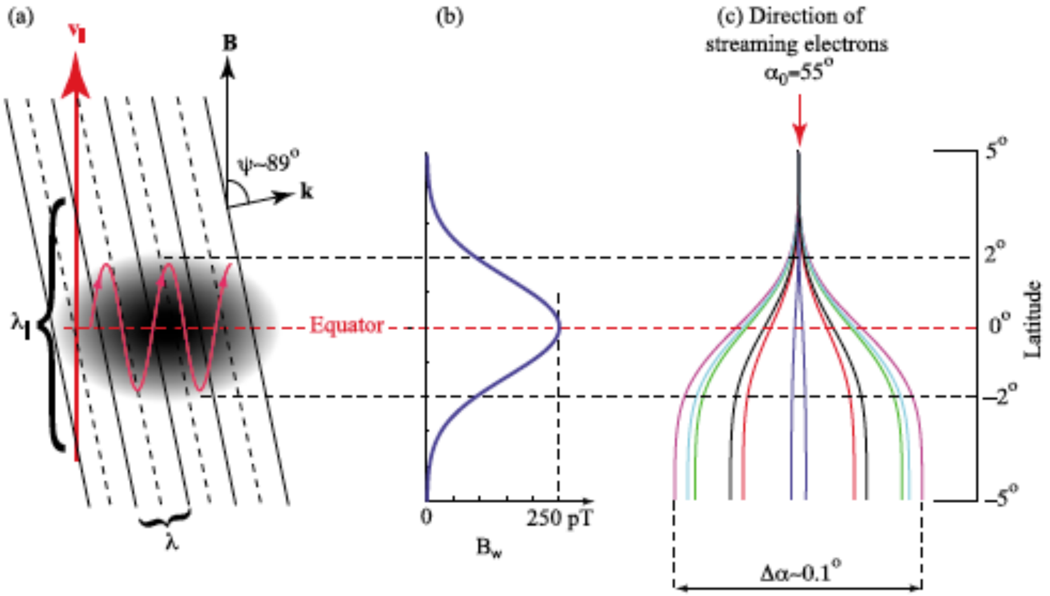
Open question: how often do large amplitude MS waves occur?

Magnetosonic waves

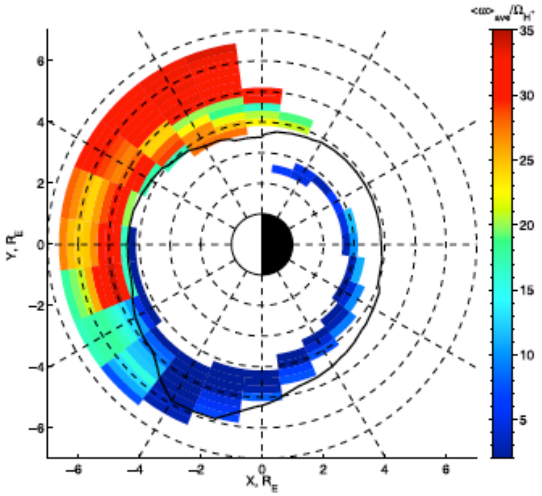
- Progress in understanding excitation, relation to the ion-Bernstein mode, and to ring distributions
- Transit-time scattering broadens the energy range of particles that can be affected



Gary et al. [2010]; Liu et al. [2010] Linear/PIC theory, transition to ion Bernstein instability

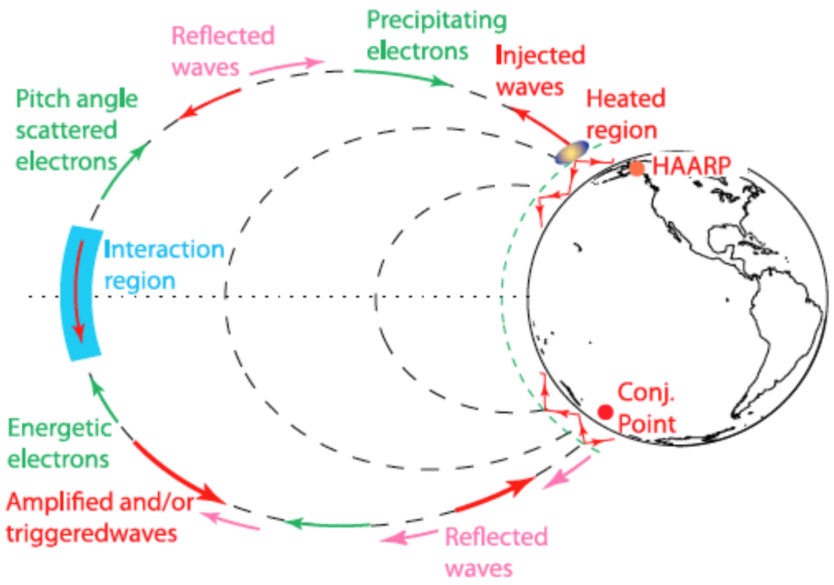


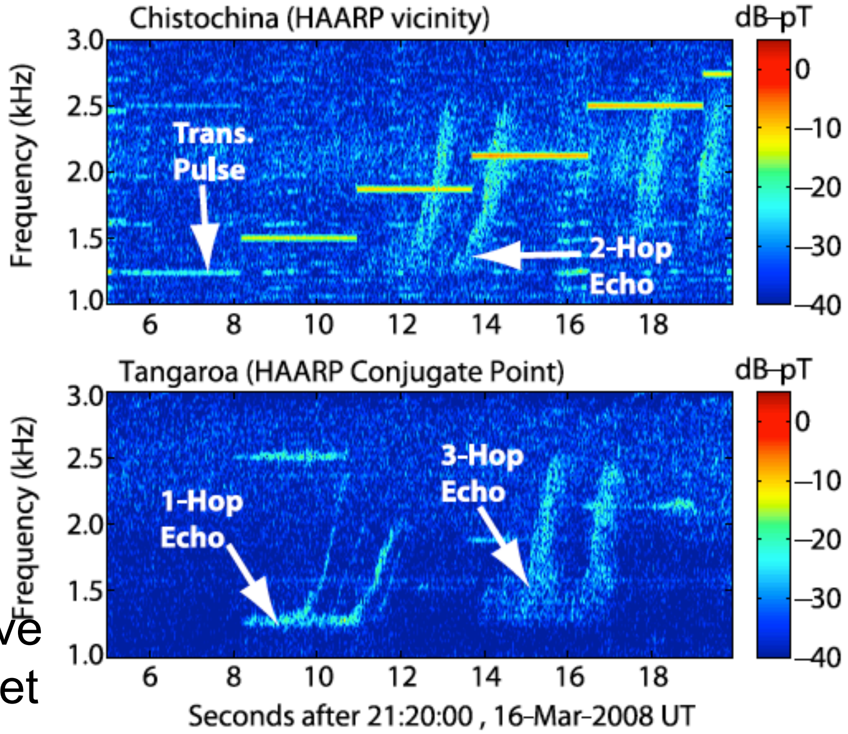
Bortnik et al. [2010]: transit-time scattering



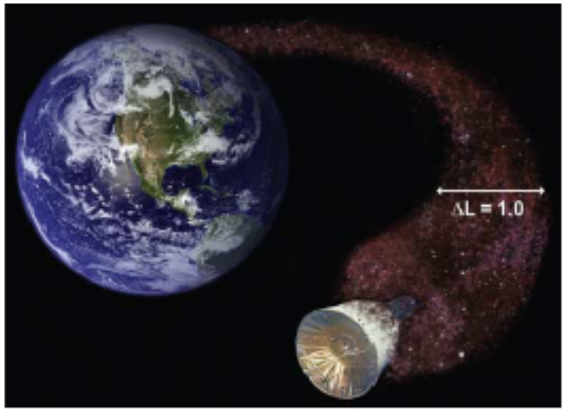
Chen et al. [2010; 2011] MS wave growth rate and spectral characteristics

Remediation and triggered emissions





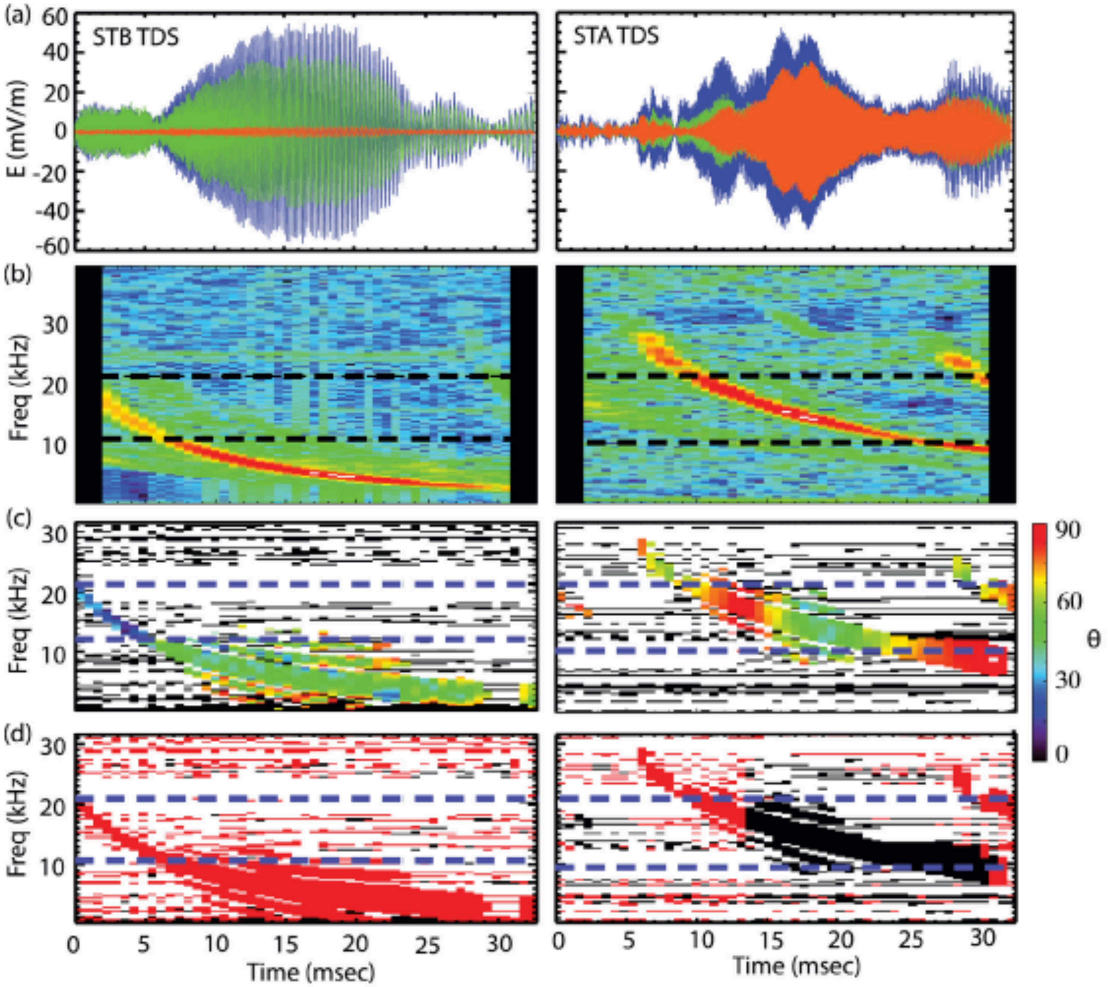
- Golkowski et al. [2011], manmade VLF wave injection: modulation of the auroral electrojet by the HAARP transmitter.
- Papadopoulos et al. [2011] Self-generated currents.
- Inan et al. [2003]; Kulkarni et al. [2008]; Graf et al. [2009] Ground-based and space-based VLF wave injection
- Shao et al. [2009]; Ganguli et al. [2007] Space-based or ground based injection of EMIC waves for remediation of relativistic electrons and protons



The role of large-amplitude lightning and VLF transmitters

Breneman et al. [2011]

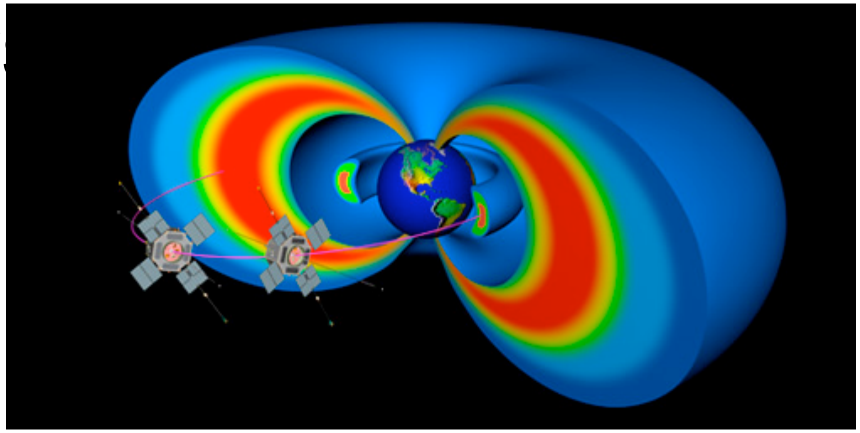
- STEREO observations of large amplitude lightning whistlers and VLF transmitters in inner plasmasphere (L<2)
- 2-3 orders of magnitude larger (30-110 mV/m)
- Polarization reversals!?



NASA: 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.

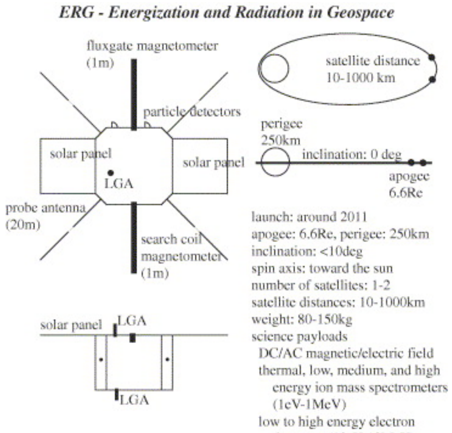
- NASA Living With a Star (LW
- Launch >Aug 2012
- 2 probes, <1500 kg for both
- ~10° inclination, 9 hr orbits
- ~500 km x 30,600 km



Coordination with other missions

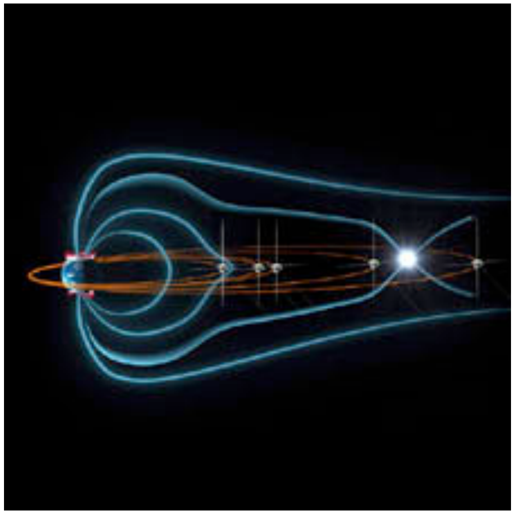
BARREL (NASA)
Launch ~2012
2 campaigns, 5-8 balloons each

RESONANCE (Russia)
Launch ~2012-14, 4-spacecraft Orbit:
1800x30,000km, ~63° incl.

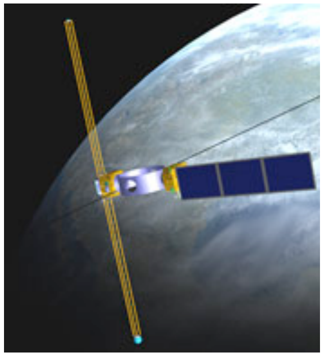


launch: around 2011
apogee: 6.6Re, perigee: 250km
inclination: <10deg
spin axis: toward the sun
number of satellites: 1-2
satellite distances: 10-1000km
weight: 80-150kg
science payloads
DC/AC magnetic/electric field
thermal, low, medium, and high energy ion mass spectrometers (1eV-1MeV)
low to high energy electron detectors (10eV-10MeV)

ERG (Japan)
Launch ~2013,
GTO



THEMIS (NASA)
Launch Feb 17, 2007
5 ide
(3)



DSX (AFRL)
Launch ~2012
MEO, wave/particle

ORBITALS (CSA)
Launch 2012-(?)
Orbit ~L=2 to L=6

A brief summary

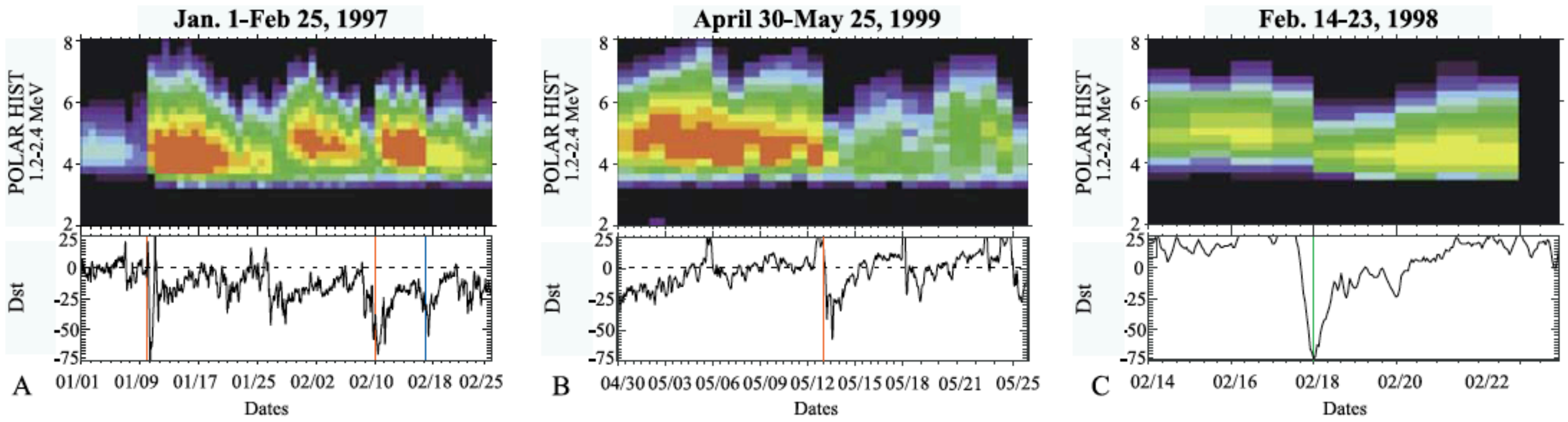
- Radiation belts as a backdrop for inner magnetospheric wave-particle interactions
  - Discovered in 1958, revisited in 2012
  - Exhibits dynamics variability that is hard to predict
- Waves responsible for particle dynamics
  - ULF, EMIC, magnetosonic, hiss, chorus, ECH, VLF transmitters, lightning
  - Wave distributions need to be accurately quantified
  - Modes of interaction need to be understood
- Wave-particle interactions are critical in a host of applications
  - Diffuse aurora, pulsating aurora, magnetic field mapping, triggering
- Several dedicated missions to be launched 2012-2013
  - RBSP, ORBITALS, DSX, ERG, RESONANCE, BARREL
  - This is an exciting period of discovery!

Some outstanding questions (pun intended)

- What are the distributions of the leading wave types?
  - as a function of physical space, k-space, and time?
- What are the modes of interaction of various wave and particles?
  - Linear/nonlinear/non-resonant
  - Depends on particle energy and wave characteristics
- What are the relative contributions of the various waves?
- What is the role of ULF waves?
  - Inward/outward diffusion/transport, or both/all
- What are the tools we need to address these questions?
  - This is not a trivial question

THANK YOU!

Predictability: D_{st}

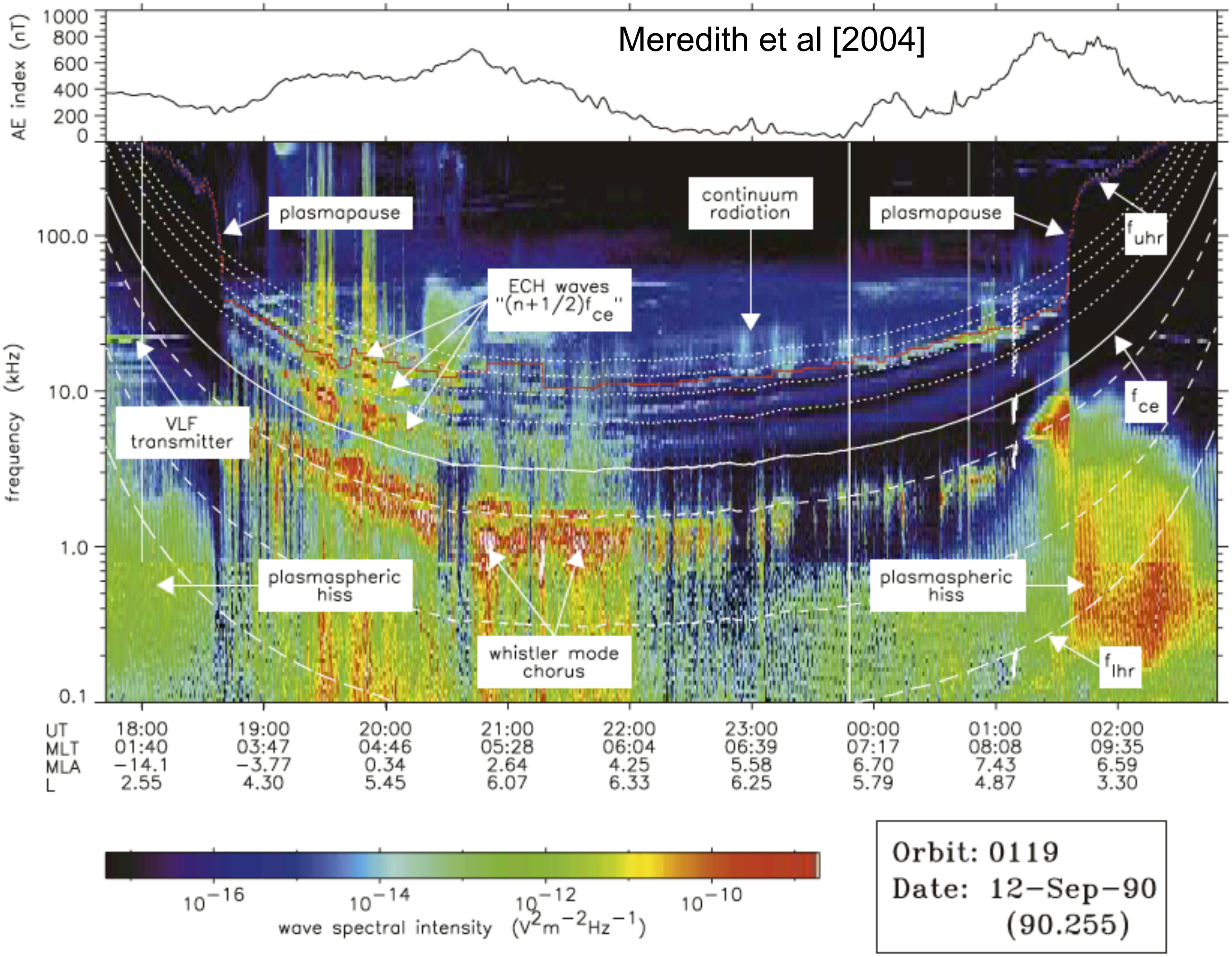


Reeves et al. [2003]

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*”

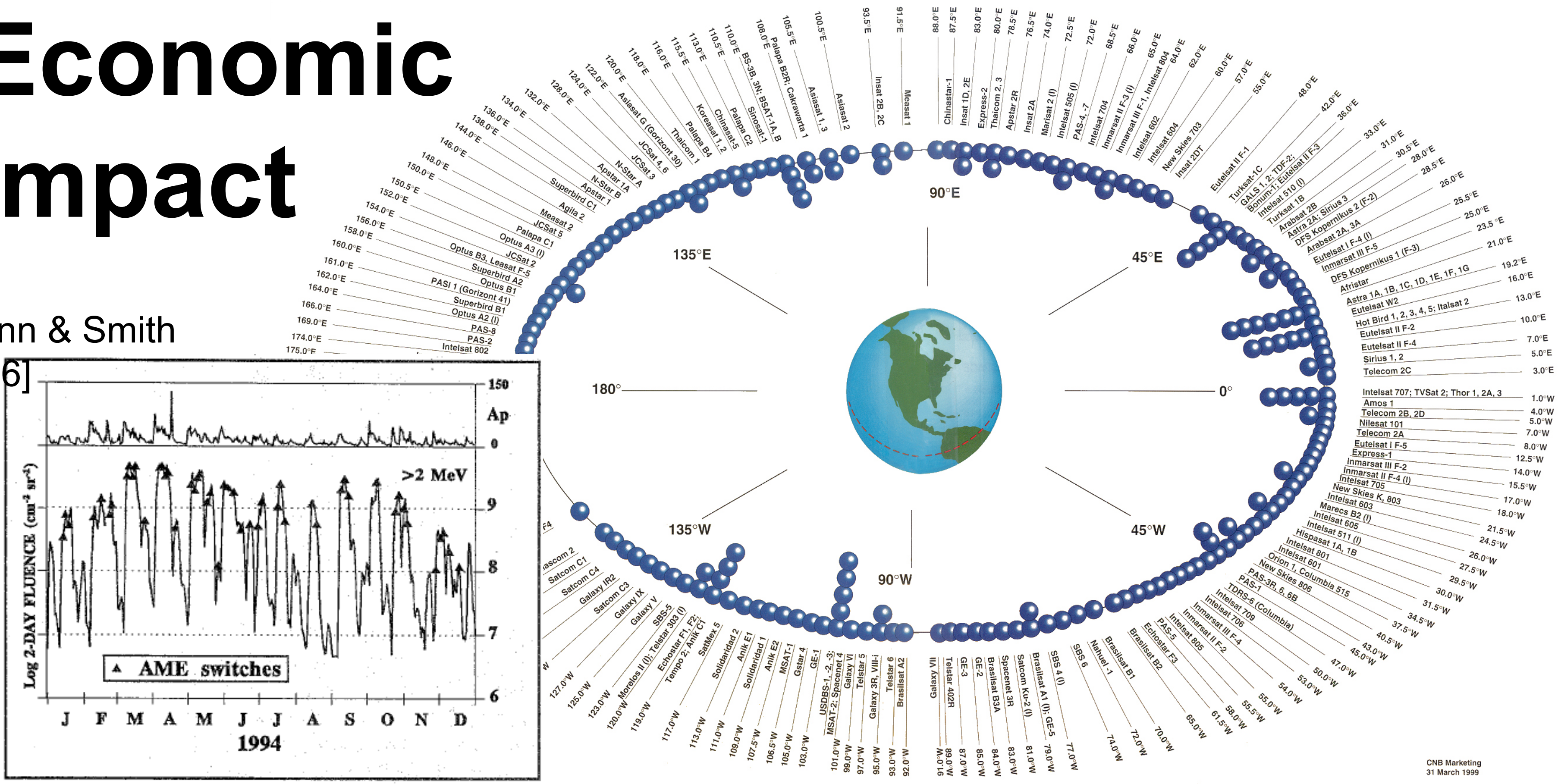
Delicate balance between acceleration and loss, both enhanced during storm-time, “*like subtraction of two large numbers*”.

The wave environment in space



Meredith et al [2004]

Economic Impact



Wrenn & Smith [1996]

- MeV el: internal charging; 0.1-100 keV: surface charging; MeV ions: SEU
- ¾ satellite designers said that internal charging is now their most serious problem, 2001 ESA study [Horne, 2001], e.g., Intelsat K, Anik E1 & E2, Telstar 401, Galaxy IV,
- Most recently Galaxy 15 (AE>2000 nT, 28 mins before anomaly), “wrong place, wrong time” [Allan, 2010]
- Costs: ~$200M build, ~$100M launch to GEO, 3%-5%/yr to insure; e.g., in 1998 $1.6B in claims, but $850M in premiums.

Radiation belts

Explorer 1 launch:
Jan. 31st 1958

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

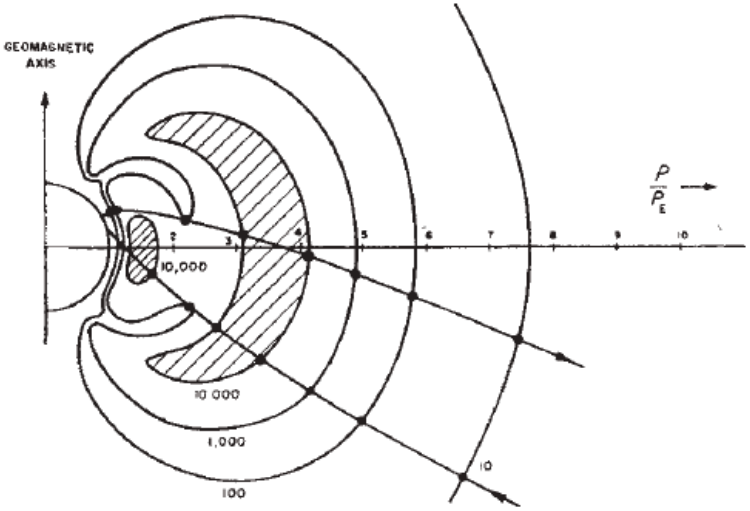
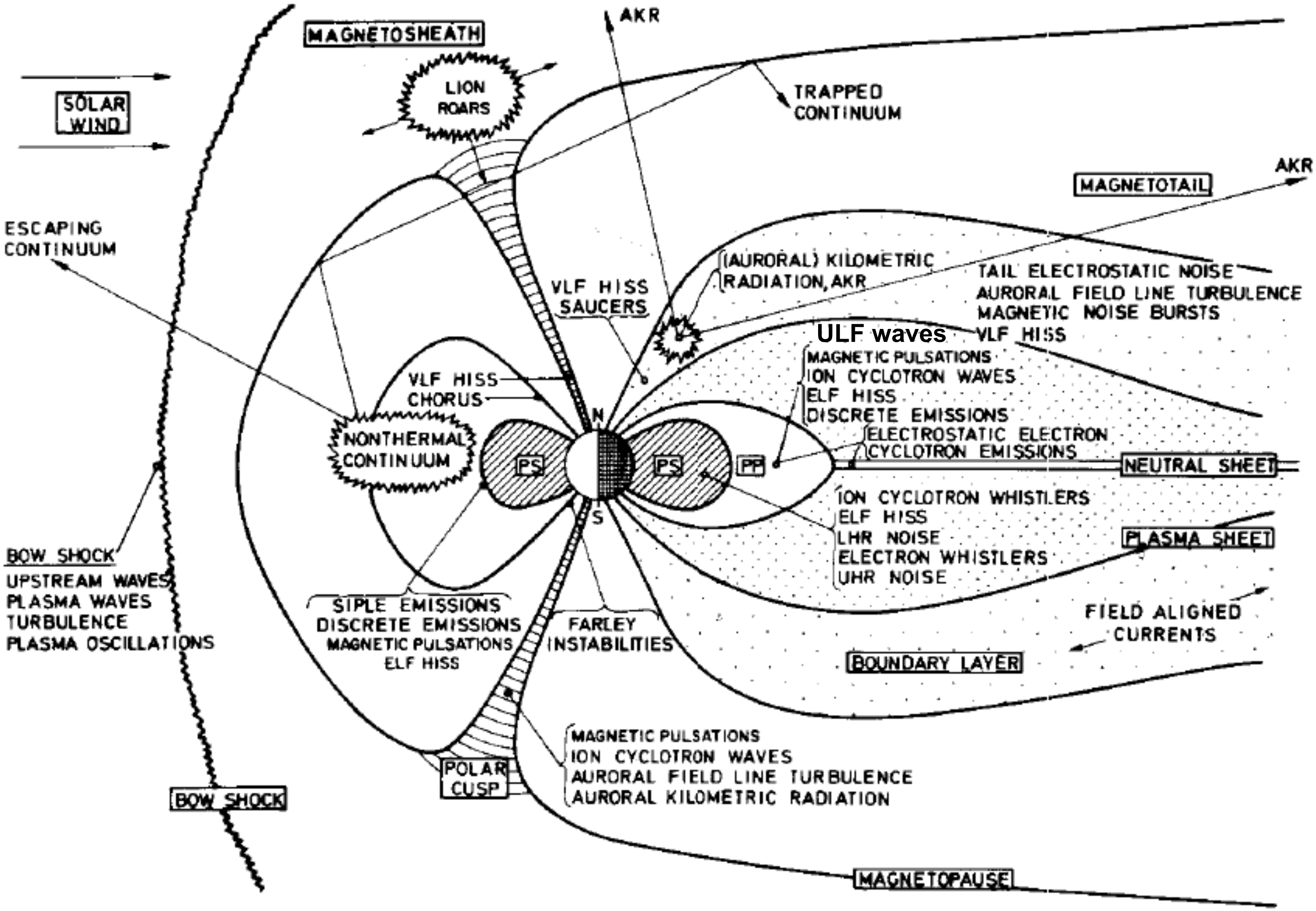


Fig. 5. A plot in a geomagnetic meridian plane of the intensity-structure of the radiation region around the Earth. The numbers associated with the several contours of constant intensity are the true counting rates *R* of the Geiger–Müller tube in *Pioneer III* or in satellite 1958ε. Within the two cross-hatched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

“The menagerie of geospace plasma waves”

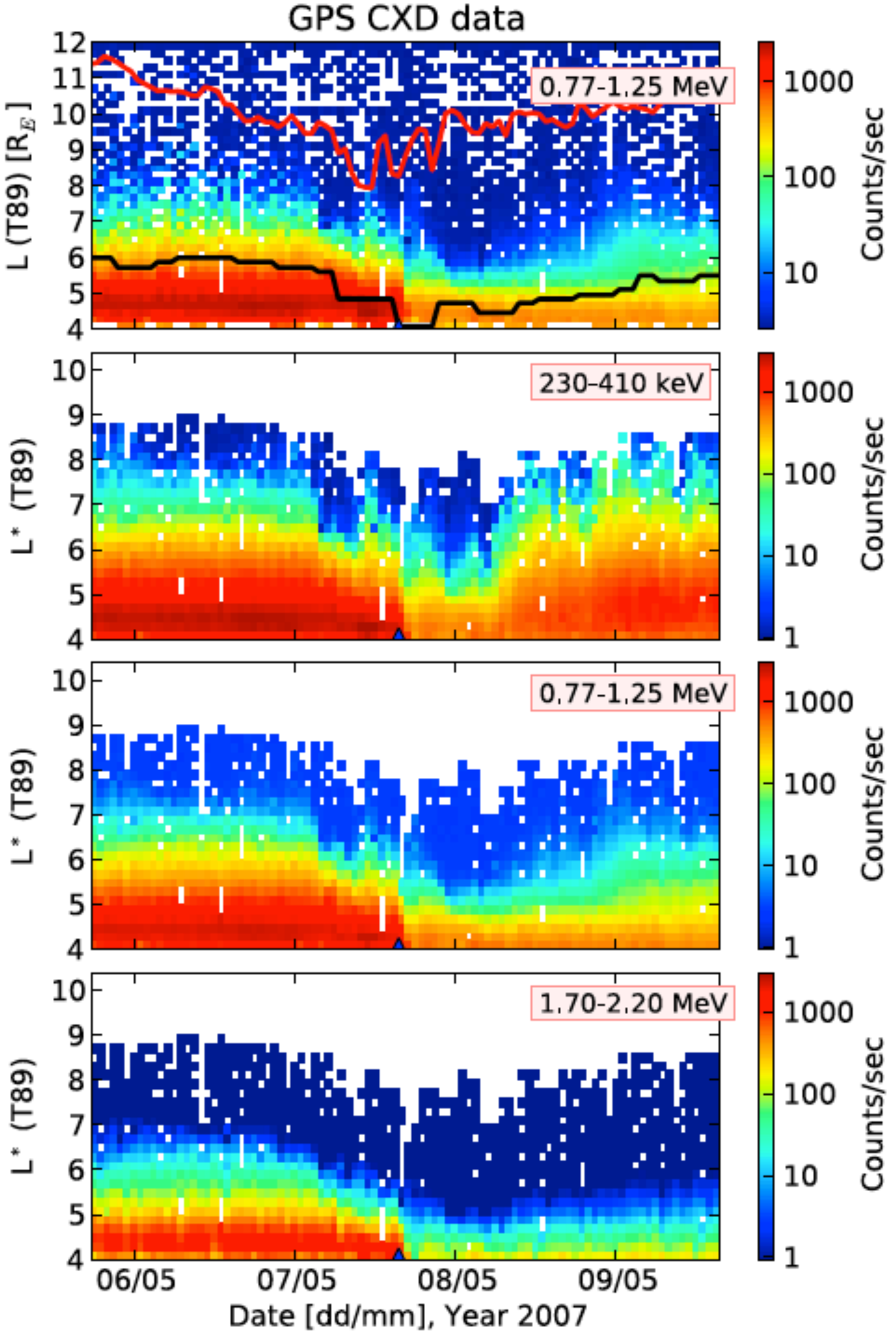


Shawhan [1985]

PS = PLASMASPHERE PP = PLASMAPAUSE

Dropouts: GPS

- Morley et al. [2011] observed dropout with GPS X-ray dosimeters, unprecedented spatial (0.2 L) and temporal (~1 hr) resolution
- Dropouts: energy down to 230 keV at least (too low for EMIC waves)
- Timescale ~2 hrs, too fast for hiss/chorus
- Magnetopause L~8, requires unrealistic diffusion rates?
- **Key question: magnetopause at low L + large D_{LL}, always true for dropouts?**



Morley et al. [2011]