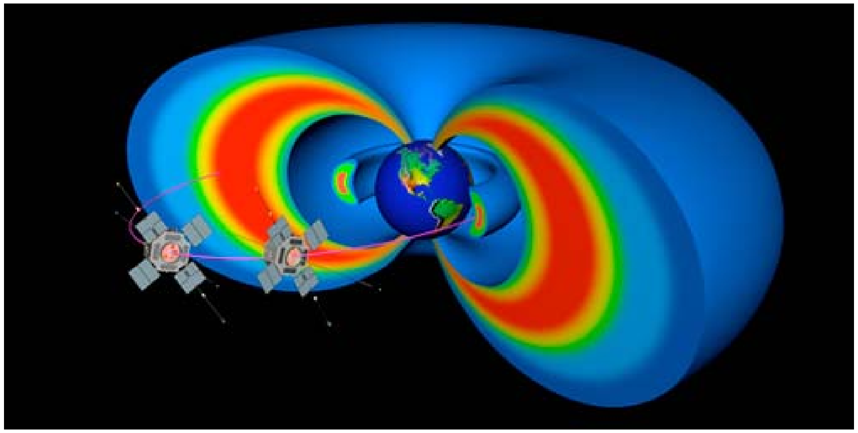
2010 Summer Workshop
June 20-25, 2010
Snowmass Conference Center - Snowmass, CO

Current challenges and opportunities in radiation belt and wave research

Jacob Bortnik, UCLA

Contents



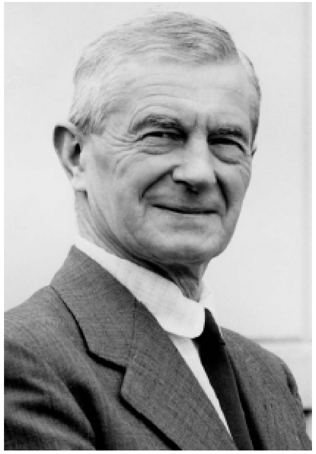
1. New GEM FG: Radiation Belt and Waves Modeling (RBWM)
2. Radiation Belt Storm Probes (RBSP) mission
3. Challenges & opportunities

We shall not cease from exploration
And the end of our exploring
Will be to arrive where we started
And know the place for the first time

T. S. Elliot, Four Quartets

April 5th, 1950: the effect of chocolate layer cake on international science

Lloyd Berkner



Sydney Chapman

Sydney Chapman en route to Caltech, stops at APL to visit Van Allen

After dinner, Chapman, Van Allen, and Berkner come up with the idea of a 3rd IPY (cake seals the deal!)

Chapman: 1957-58 is solar max

The house on Meurilee lane,
Silver Spring, Maryland

Korsmo, F. L. (2007), The genesis of the International Geophysical Year, *Physics Today*, 60, 38-44

Discovery!

Explorer 1 launch:
Jan. 31st 1958

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

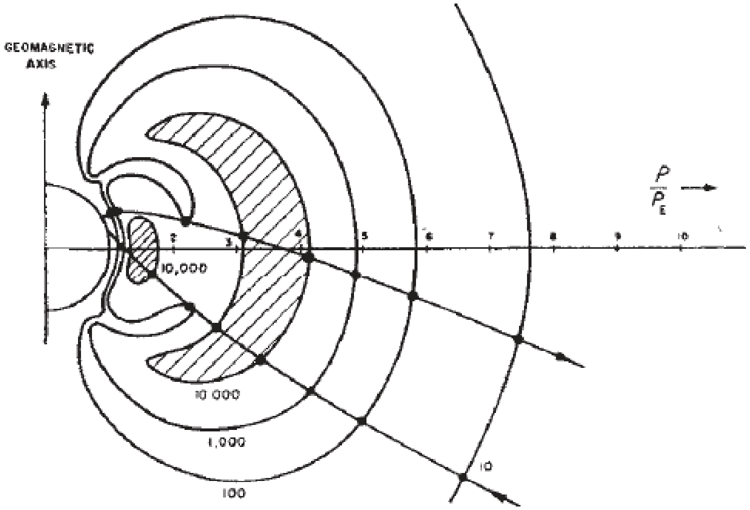
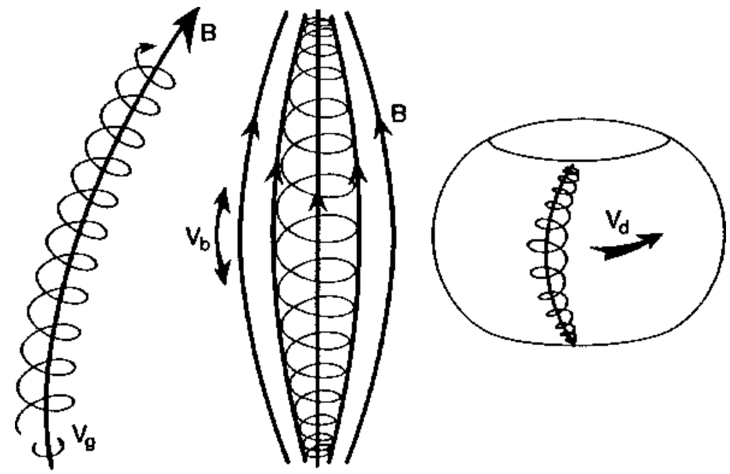


Fig. 5. A plot in a geomagnetic meridian plane of the intensity-structure of the radiation region around the Earth. The numbers associated with the several contours of constant intensity are the true counting rates R of the Geiger–Müller tube in *Pioneer III* or in satellite 1958ε. Within the two cross-hatched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

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

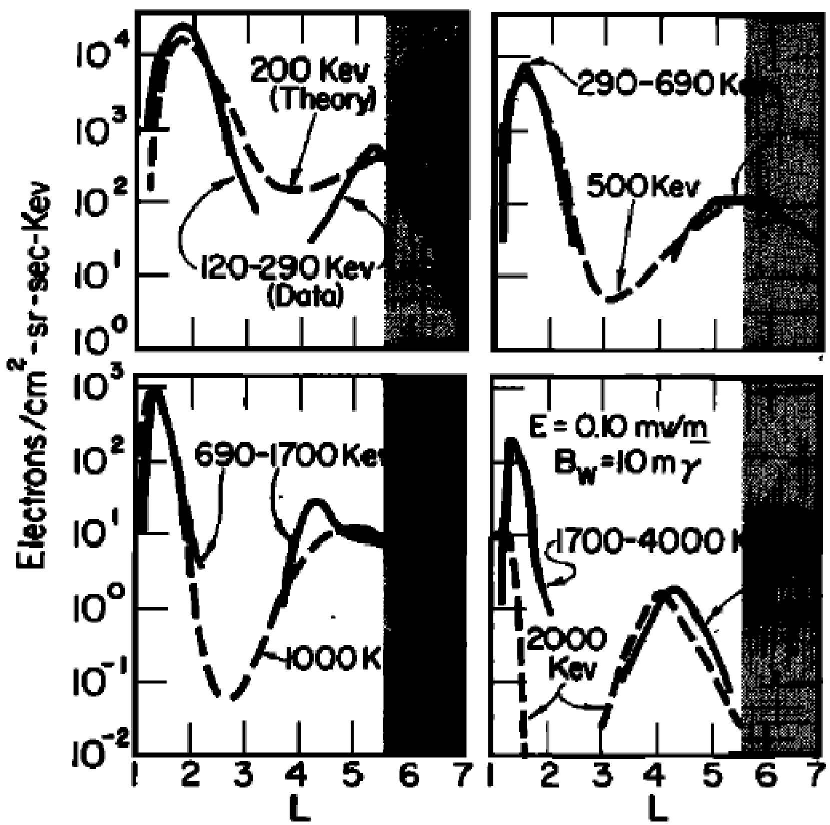
1 MeV electron, $\alpha = 45^o$, L = 4.5



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

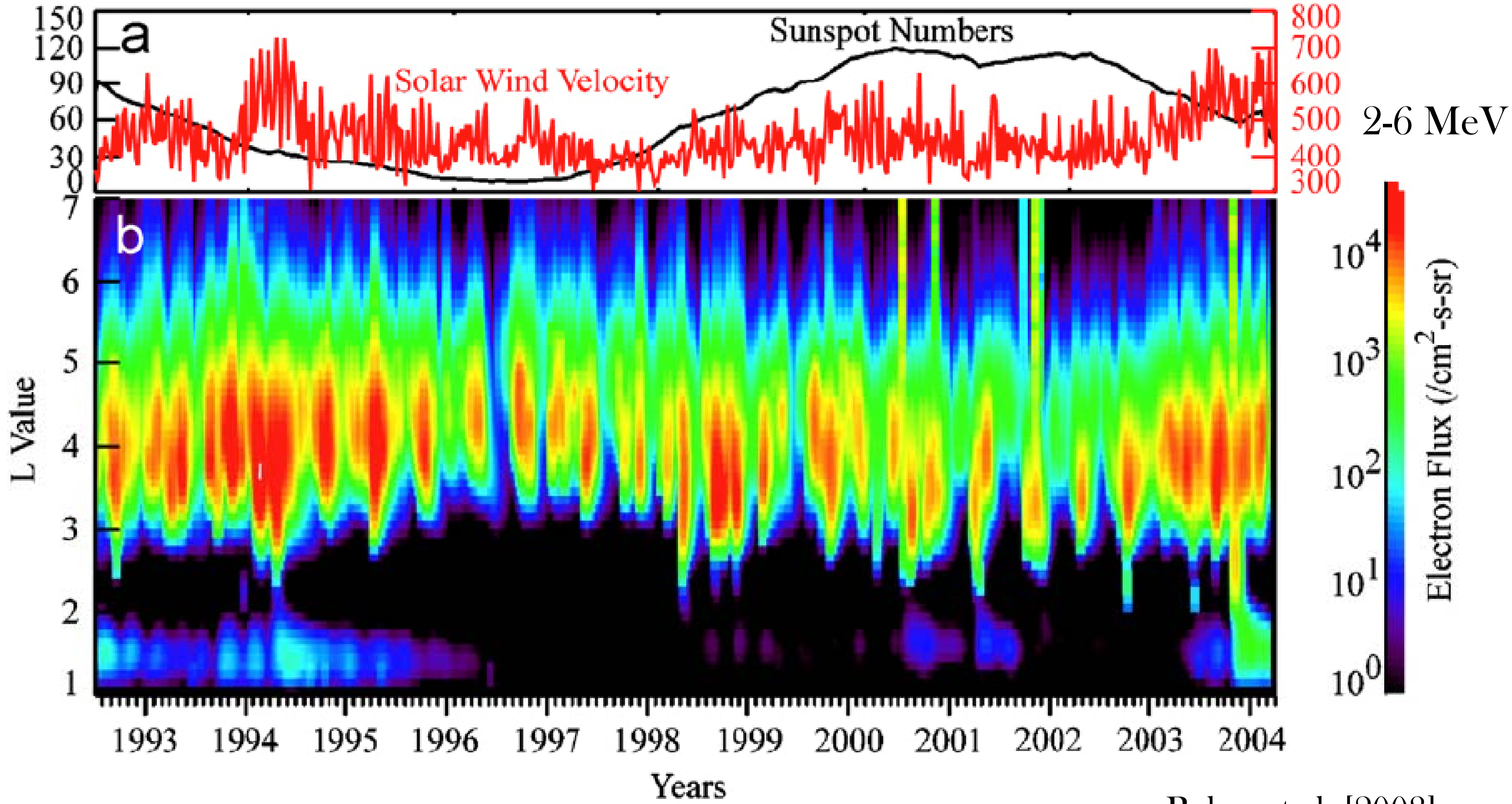
Equilibrium 2-zone structure

- 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]

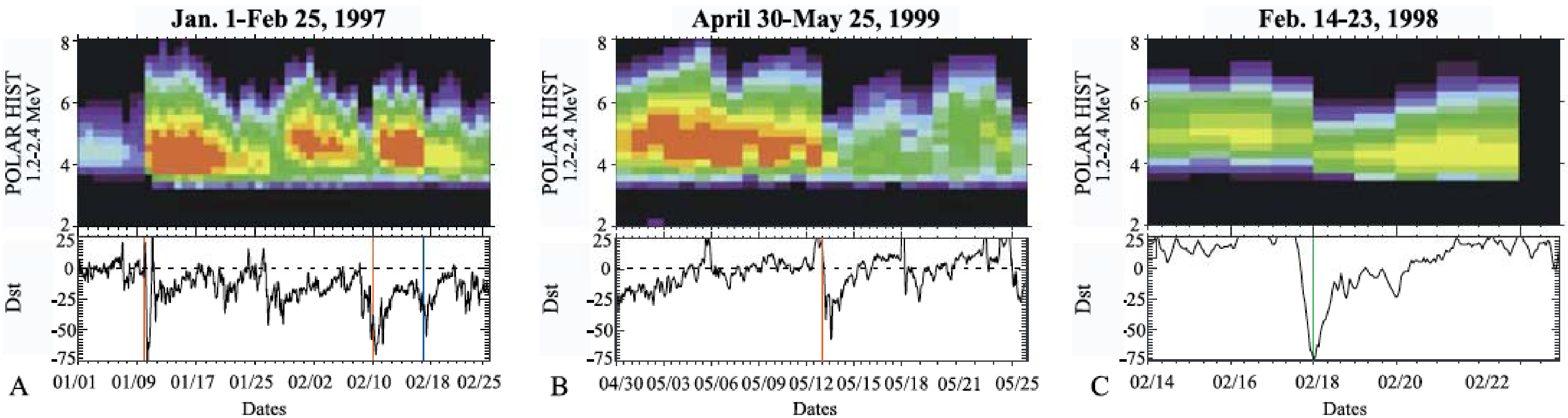
Variability of Outer belt



Baker et al. [2008]

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

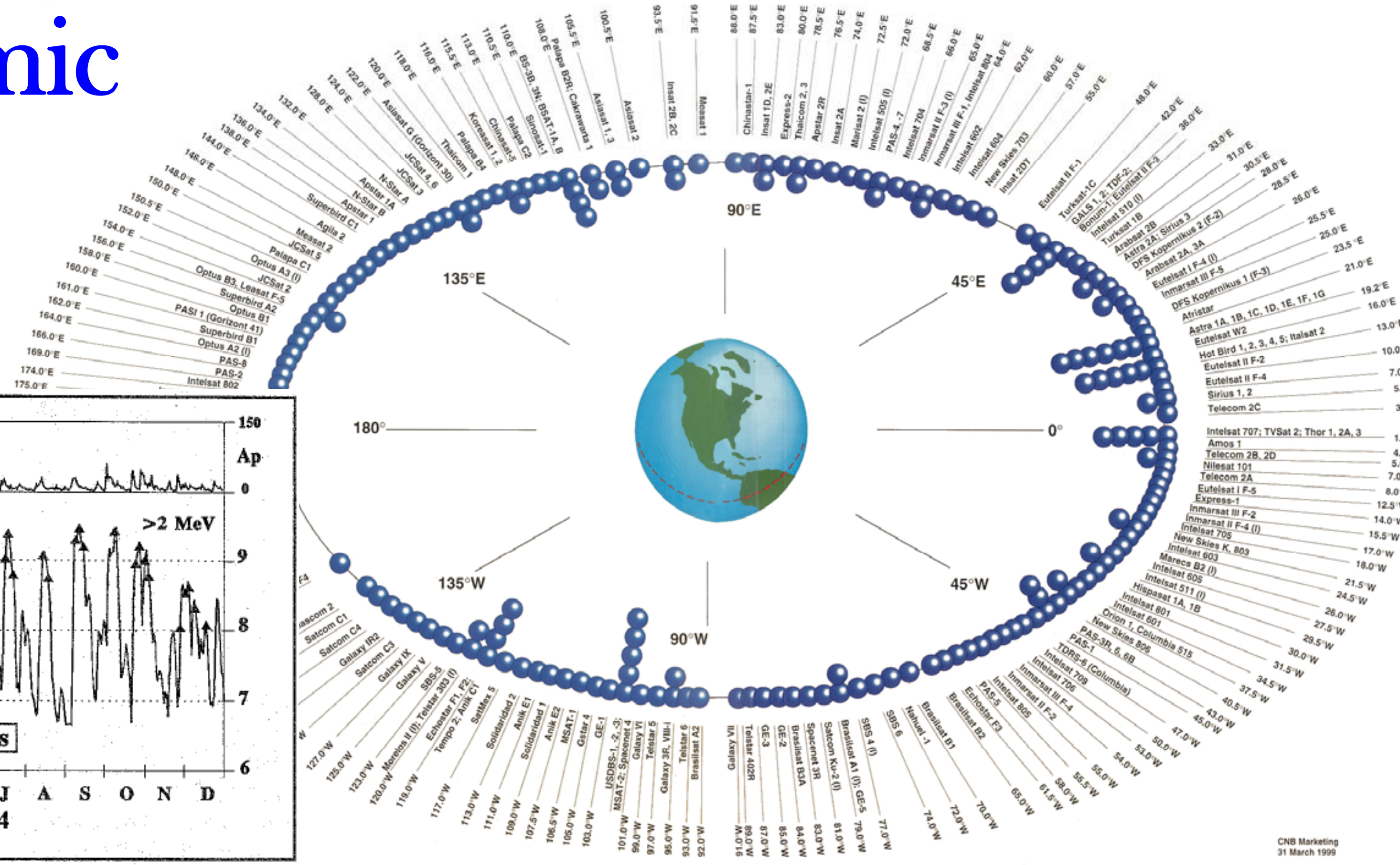
Predictability of outer belt fluxes



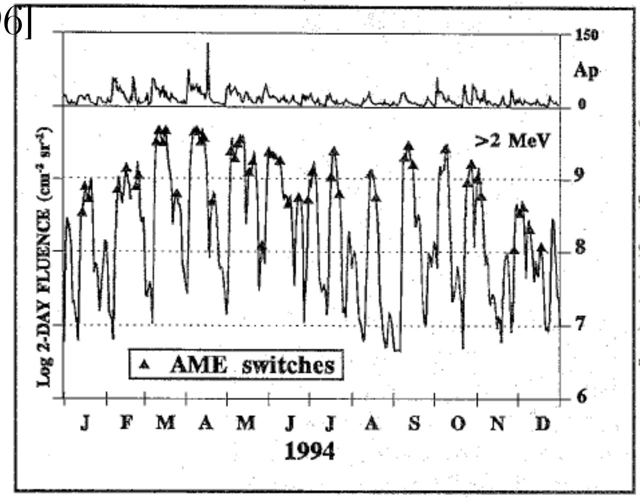
Reeves et al. [2003]

- 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*".

Economic Impact



Wrenn & Smith [1996]

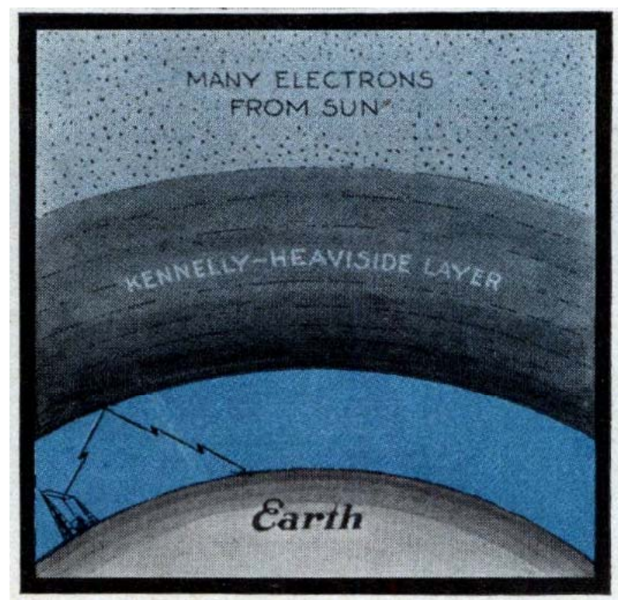


- MeV el: internal charging; 0.1-100keV: surface charging; MeV ions: SEU
- ¾ satellite designers said that internal charging is now their most serious problem, 2001 ESA study [Horne, 2001]
- Examples: Intelsat K, Anik E1 & E2, Telstar 401, Galaxy IV
- Costs: ~$200M build, ~$100M launch to GEO, 3%-5%/yr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

What's wave got to do with it?

Marconi watching associates raise kite antenna at St. John's, December 1901

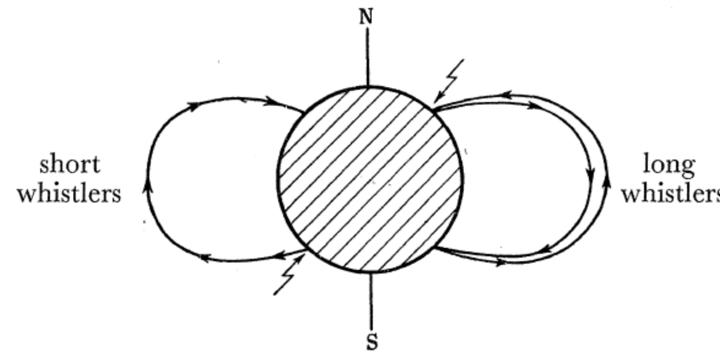
- 1902 Marconi's transatlantic transmission: why are waves not confined to line-of sight?
- Kennelly & Heaviside propose an electrically conductive layer
- Sydney Chapman proposes the layer model of the ionosphere
- Lloyd Berkner is first to measure the height & density of ionosphere



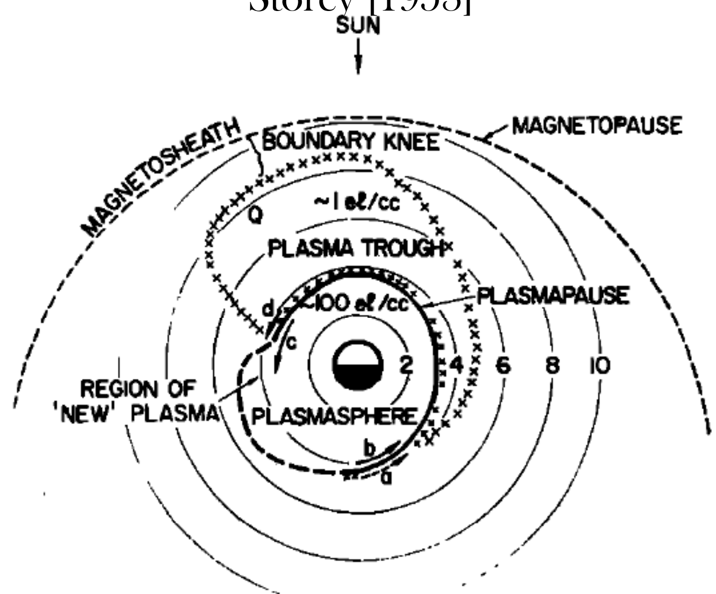
"New discoveries show electricity governs our lives", Modern Mechanix, Feb 1934

Natural waves from space

- Barkhausen [1919] heard audible ‘whistles’ whilst spying on allied communication
- Storey [1953], showed whistlers traveled out to 3-4 Re, density ~400 el/cc (much higher than anticipated).
- Other ‘audible’ atmospherics:
  - dawn chorus: “like a rookery heard from a distance”
  - A steady hiss
- Discovery of the plasmapause

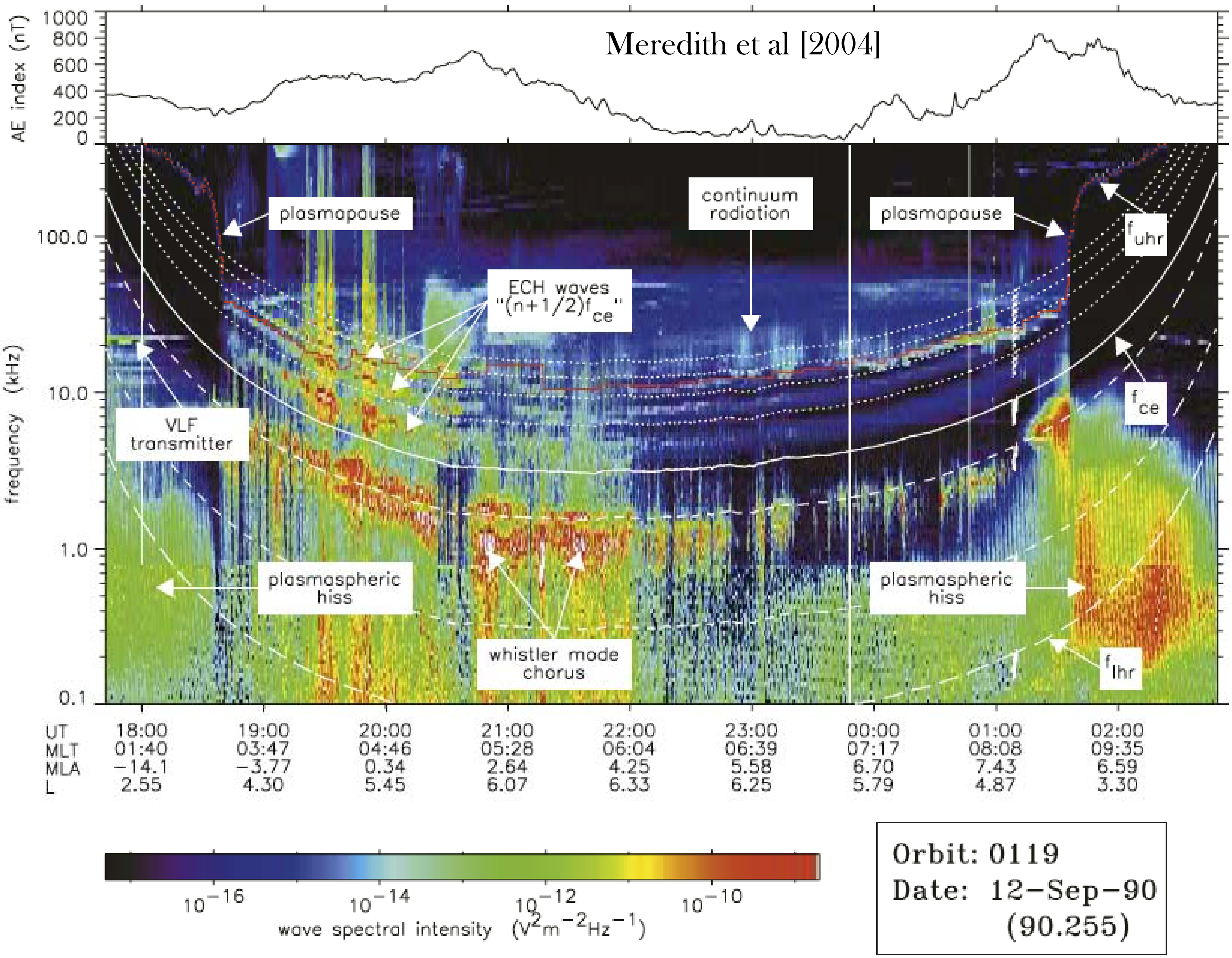


Storey [1953]

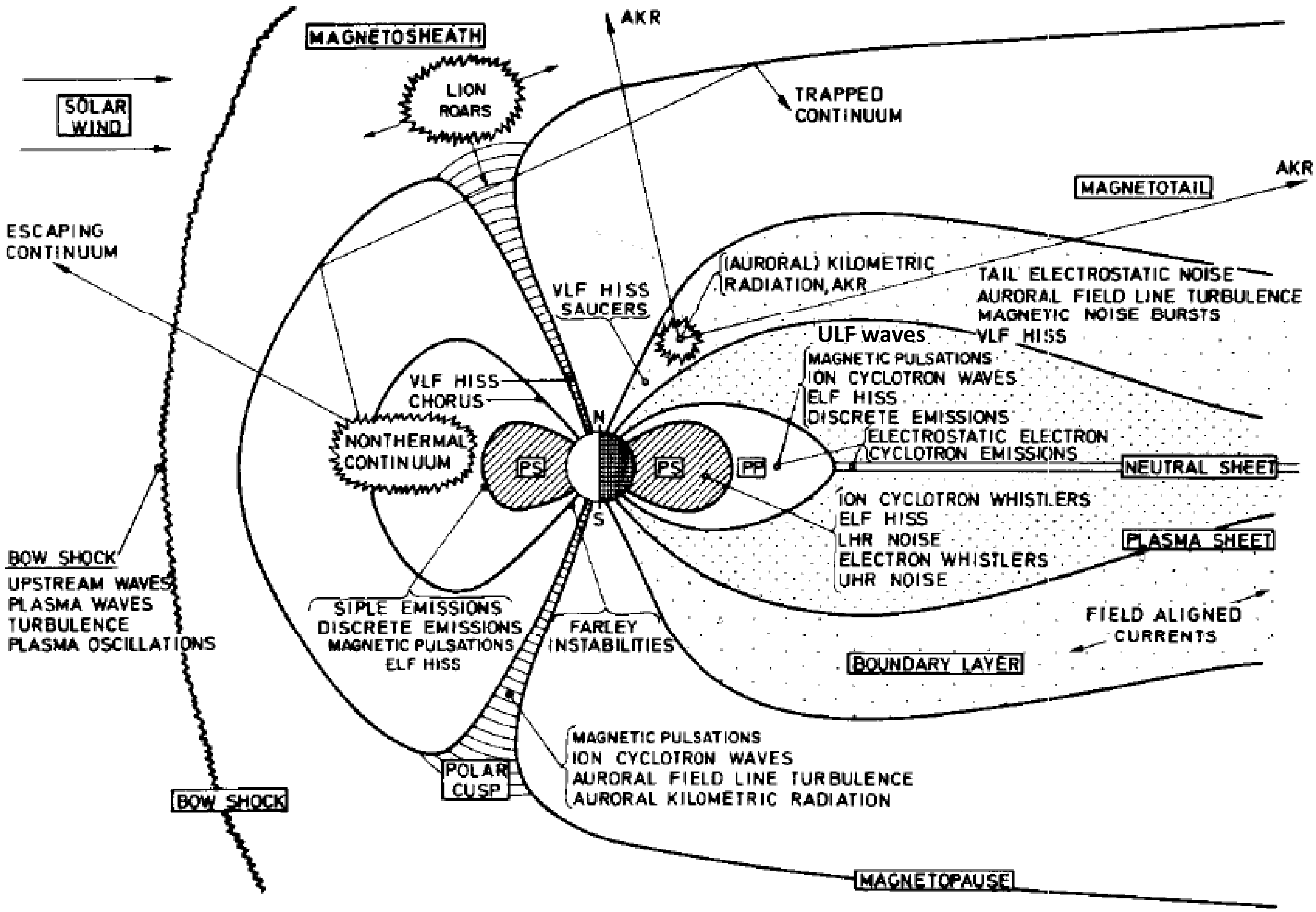


Carpenter [1966]

The wave environment in space



“The menagerie of geospace plasma waves”



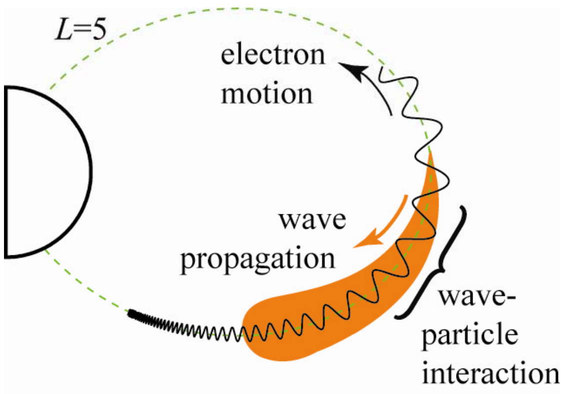
Shawhan [1985]

PS = PLASMASPHERE PP = PLASMAPAUSE

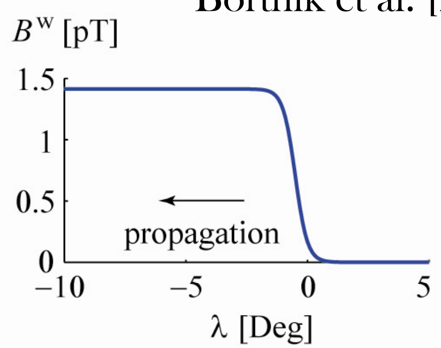
Wave-particle interactions

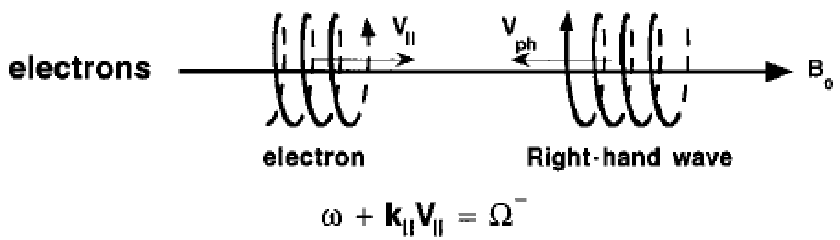
$$\frac{d\mathbf{p}}{dt} = q\left(\mathbf{E_w} + \frac{\mathbf{p}}{m_e\gamma}\times\left[\mathbf{B_0}(\lambda)+\mathbf{B_w}\right]\right)$$

- How does an unstable particle distribution relax in a collisionless plasma?
- Wave-particle interactions
  1. Propagating wave structure
  2. Particle travels through wave
  3. Non-adiabatic changes to particle's invariants



Bortnik et al. [2008]



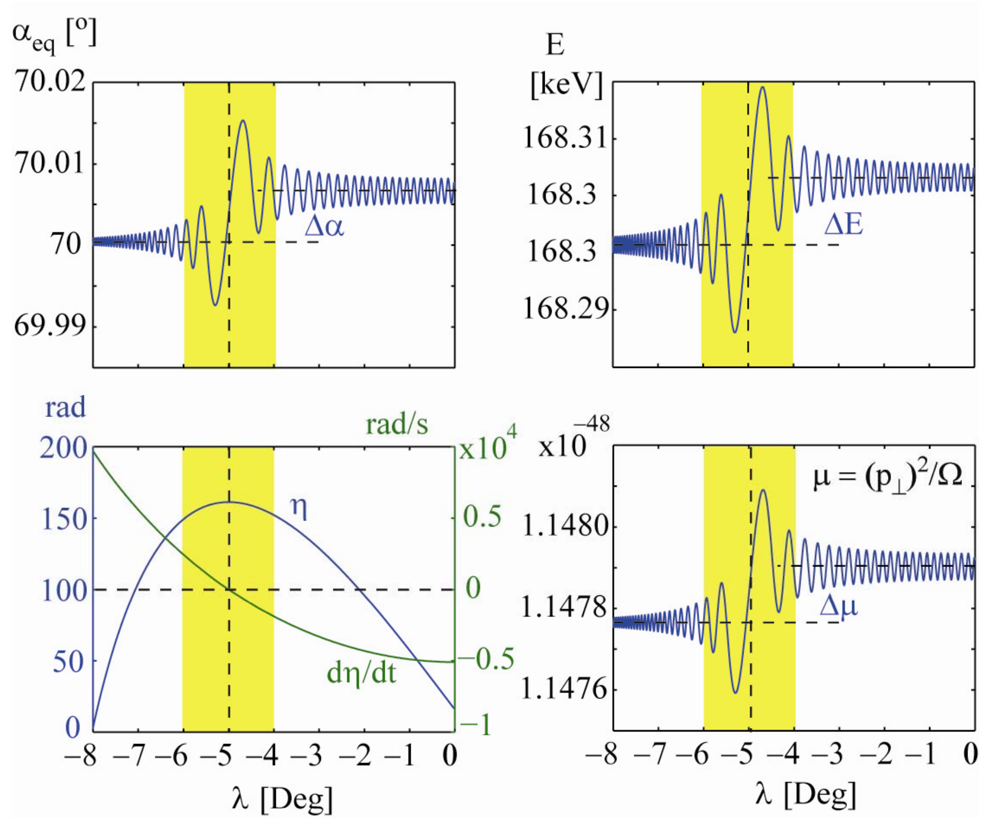


Tsurutani & Lakhina [1997]

Albert [1993; 2000; 2002]; Bell [1984; 1986]; Dysthe [1971]; Ginet Heinemann [1990]; Inan et al. [1978]; Inan [1987]; Matsumoto & Kimura [1971]; Roth et al. [1999]; Shklyar [1986]; and many more.

Test particle equations example

- Non-adiabatic changes occur when η is stationary, i.e., dη/dt ~ 0 (resonance)
- Example equation: (field-aligned, non-relativistic)



wave

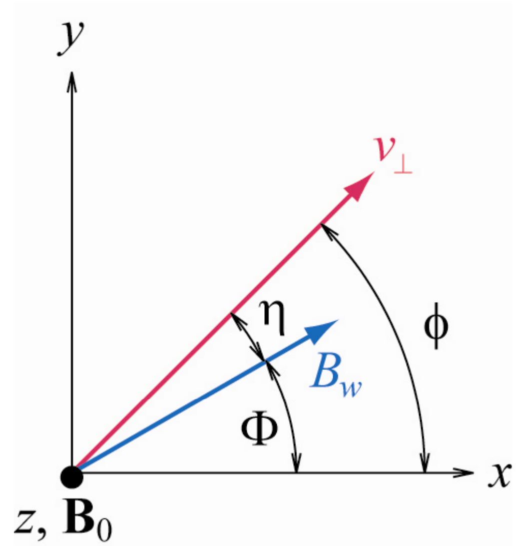
$$\frac{dv_\parallel}{dt} = \left(\frac{qB_w}{m}\right) v_\perp \sin\eta - \frac{v_\perp^2}{2B}\frac{\partial B}{\partial z}$$

adiabatic

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

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

phase



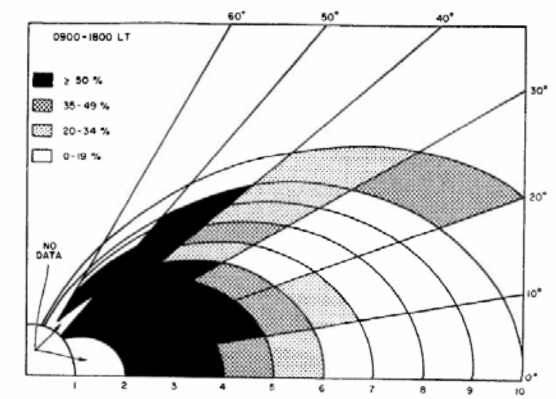
GEM FG: RBWM

- The Radiation Belts and Waves Modeling Focus Group will focus on:
    1. Identifying and quantifying the contributions and effects of various sources of heating, transport, and loss of radiation belt ions and electrons, and developing global and local models of the radiation belts
    2. Which will require the development of physical models of the excitation, propagation, and distribution of the plasma waves that are known to affect the radiation belts
- Co-chairs:
    - Yuri Shprits, Scot Elkington, Jacob Bortnik, Craig Kletzing
- Inner Magnetosphere & Storms, 2010-2014
- 7 challenge questions

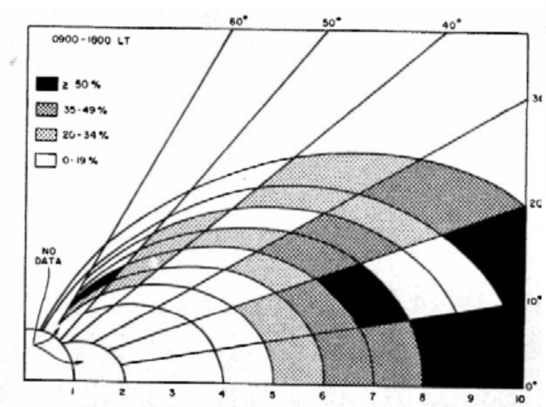
Challenge #1

What is the measured wave distribution and its spatiotemporal variability?

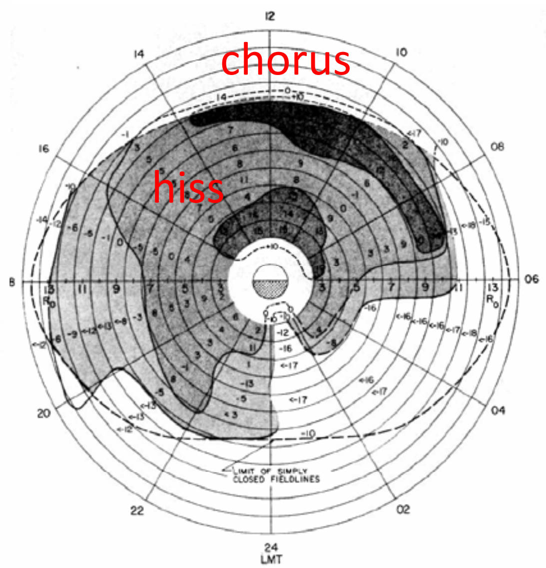
"Steady noise"



"Bursts of noise"

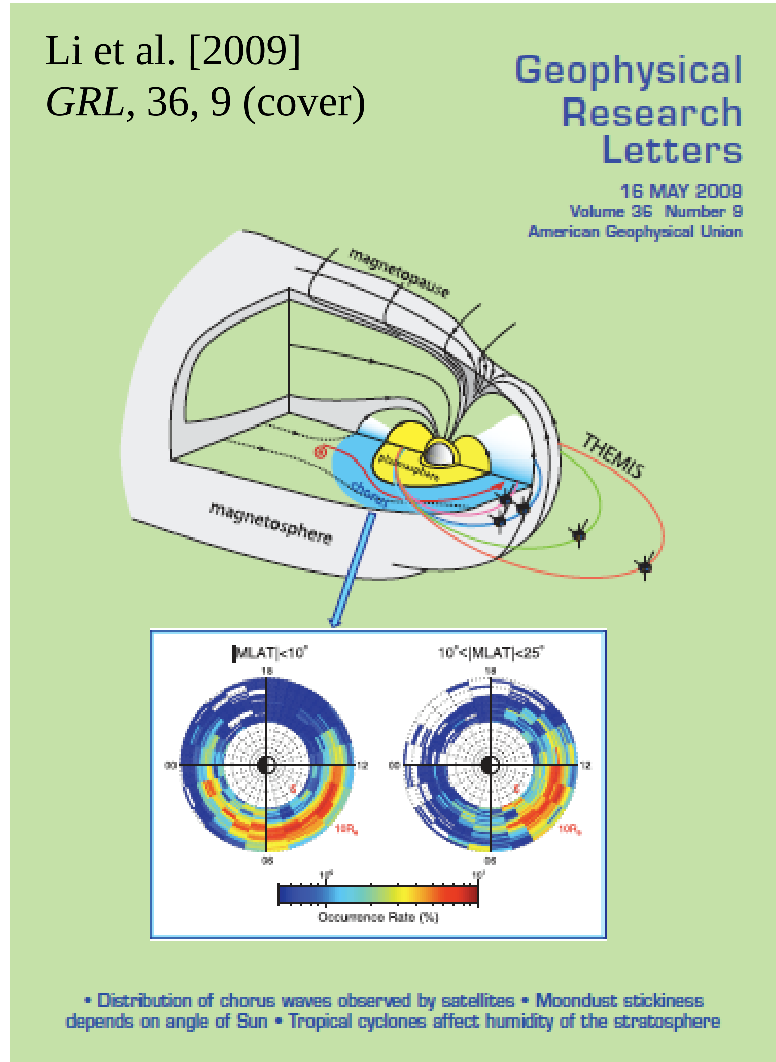


Russell et al. [1969]

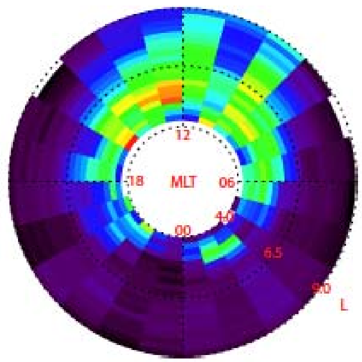


OGO 1 satellite,
f ~0.3 – 0.5 kHz
Dunckel & Helliwell
[1969]

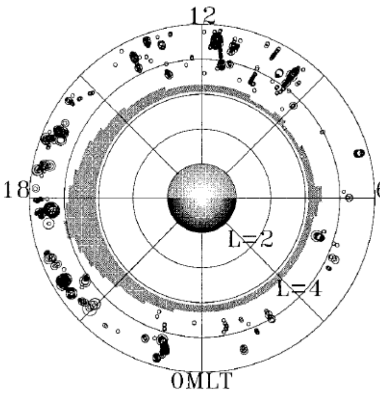
Li et al. [2009]
GRL, 36, 9 (cover)



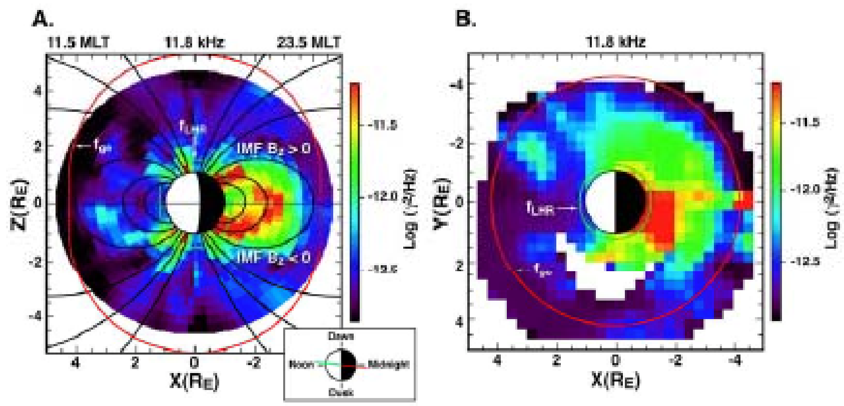
Challenge #1



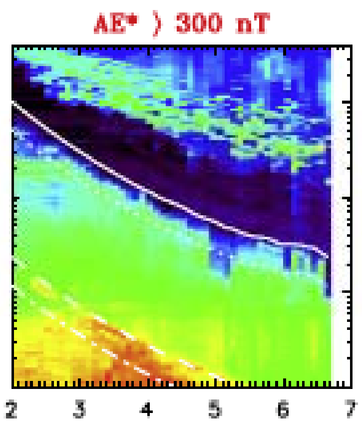
Pokhotelov et al. [2008]
CLUSTER, magnetosonic



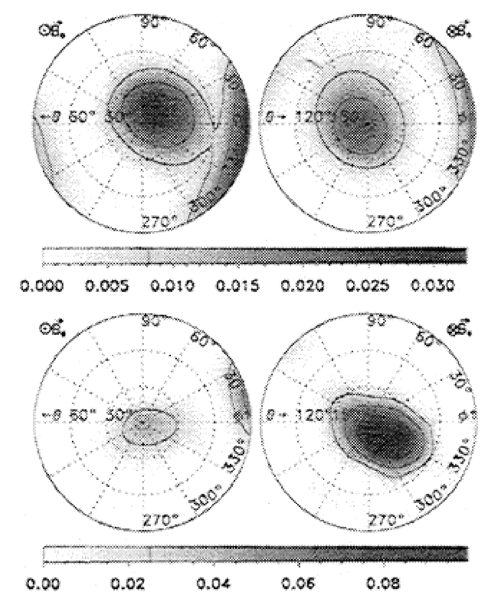
Erlandson & Ukhorskiy [2001], DE 1 EMIC



Green et al. [2005], DE 1 & IMAGE RPI VLF transmitter



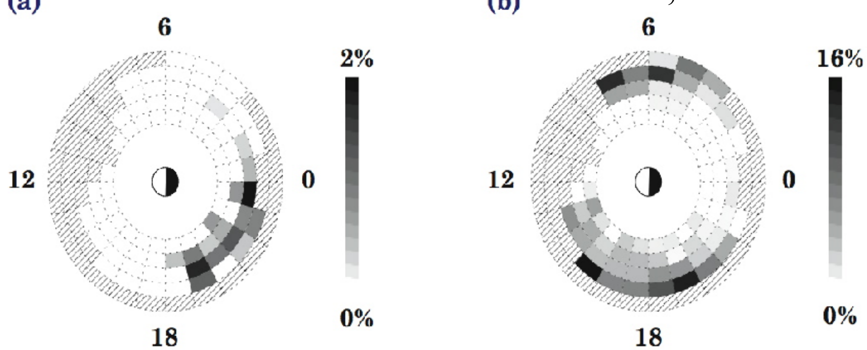
Meredith et al. [2008]
CRRES, magnetosonic



Santolik et al. [2001],
POLAR hiss wavenormals

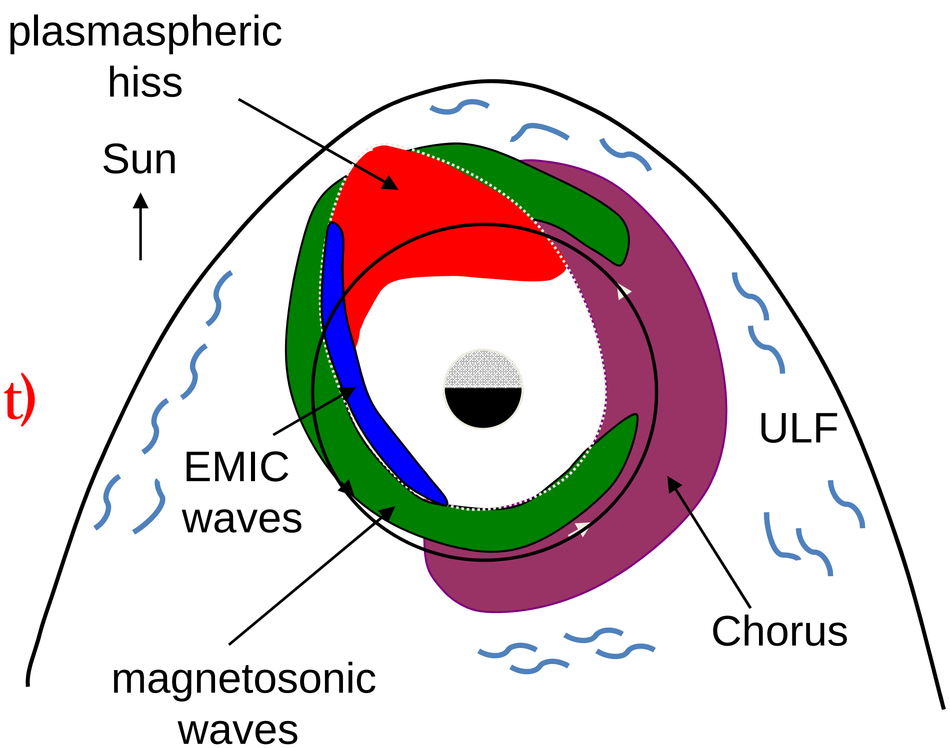
Hudson et al. [2004]
CRRES, ULF

(a) (b)



Challenge #1

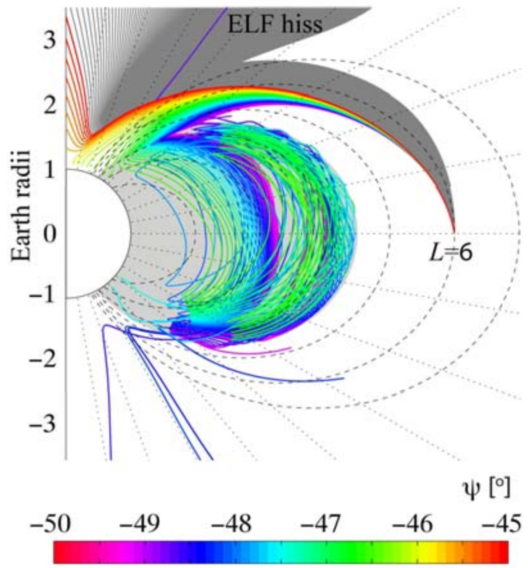
- Wave power distribution:
  W(L, MLT, lat, *f*, ψ, ϕ, M, D, t)
  - L: L-shell
  - MLT: Magnetic Local Time
  - Lat: geomagnetic latitude
  - *f*: wave frequency
  - ψ: wave normal angle, zenith
  - ϕ: wave normal angle, azimuth
  - M: ULF, EMIC, magnetosonic, hiss, chorus, whistlers, ECH, ...)
  - D: Duty cycle, i.e., % of actual occurrence
  - t: Storm/substorm phase?
- LANL wave database (Reiner Friedel)
- NASA VWO (Shing Fung); Also ViRBO for particle data



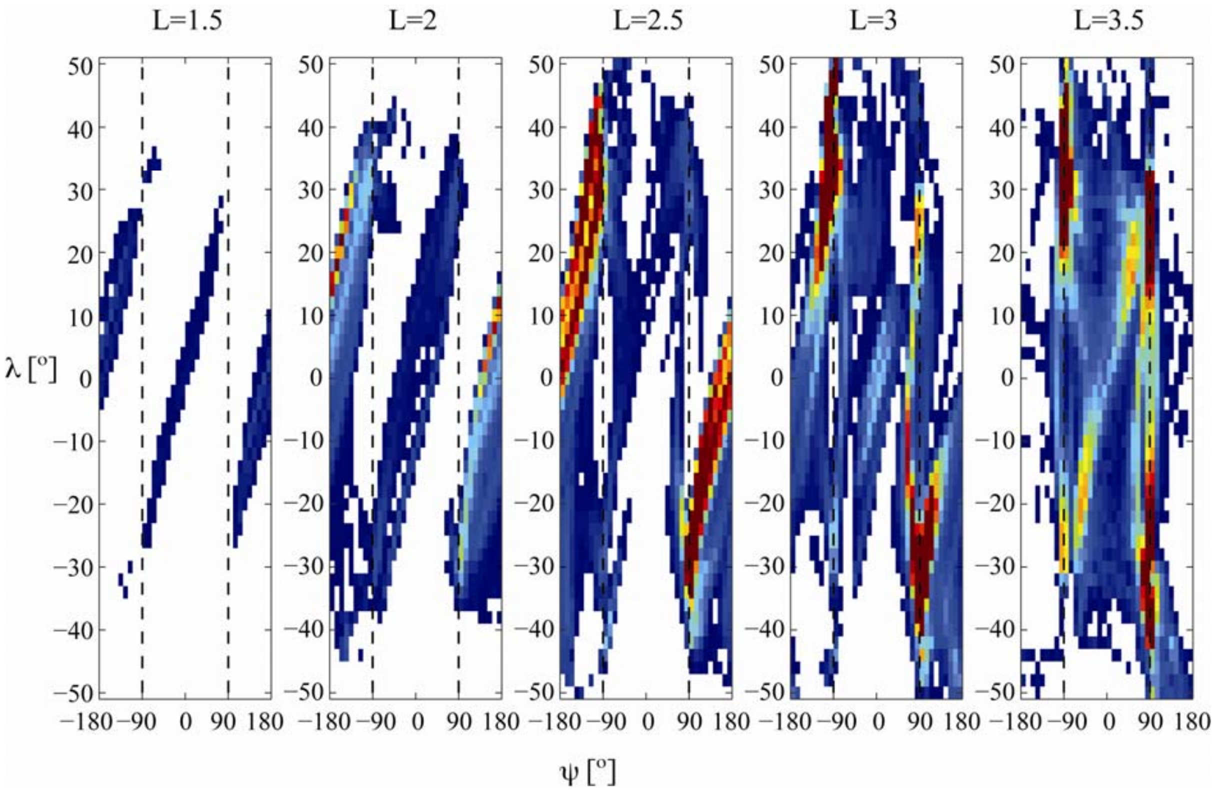
Meredith et al. 2008 GEM tutorial

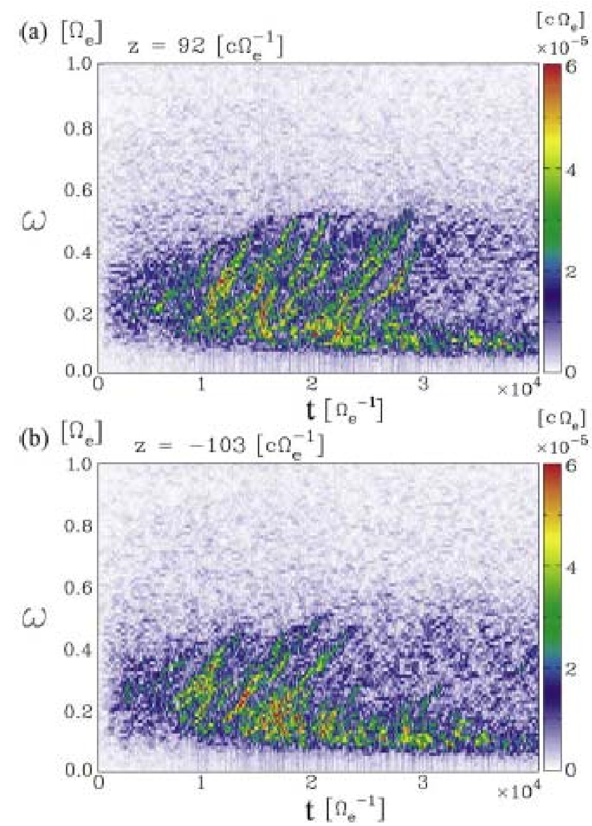
Challenge #2

What is the excitation, propagation, and distribution of waves? (modeling)



Bortnik et al. [2009]

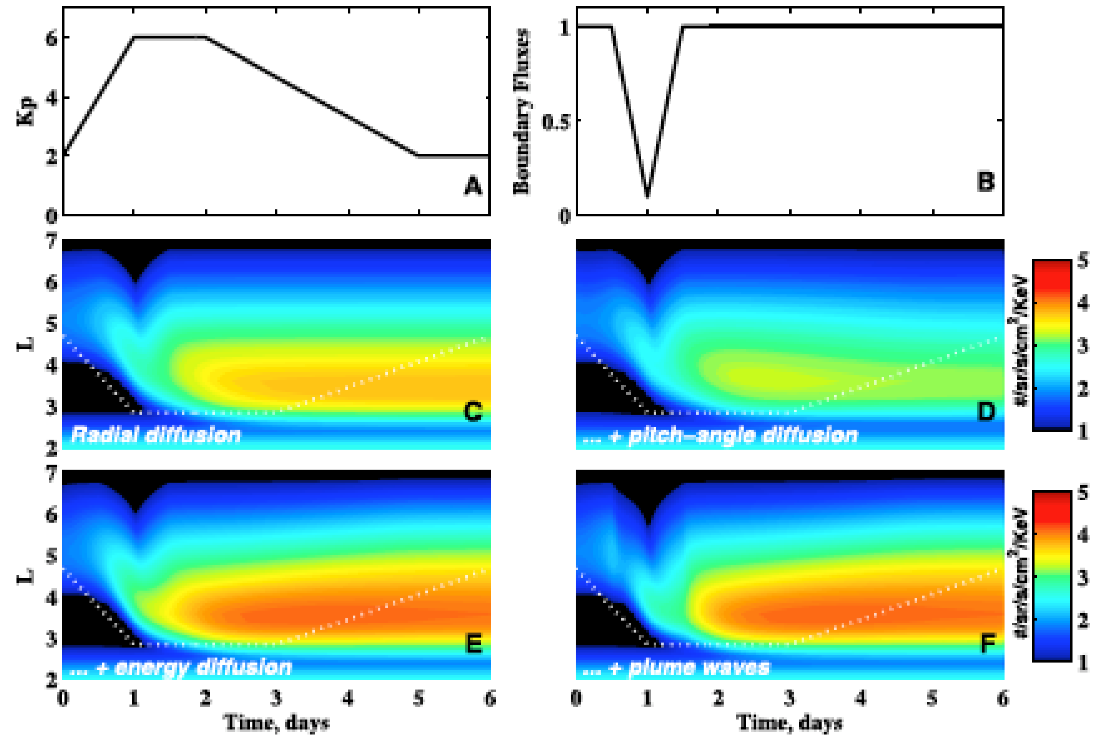




Katoh & Omura [2008], chorus

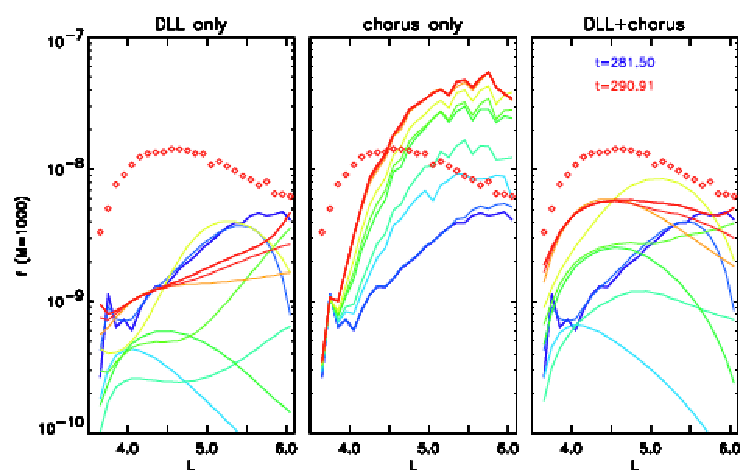
Challenge #3

What is the effect of different waves on radiation belt dynamics?
(quasilinear theory)



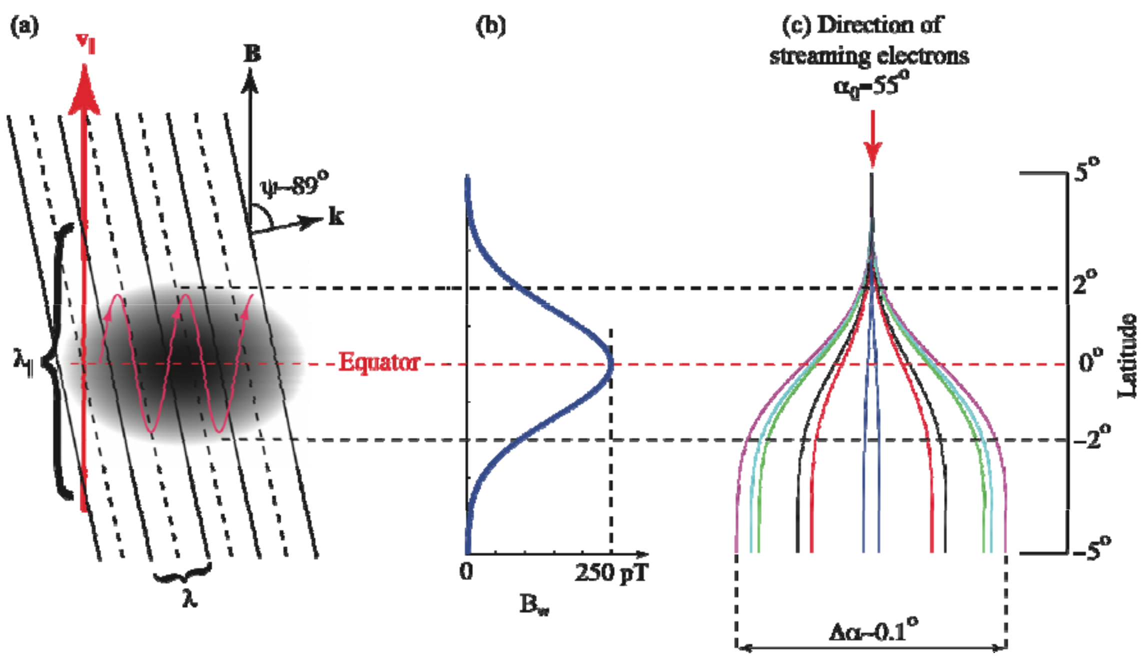
Shprits et al. [2009], 3D VERB

Albert et al. [2009], 3D, Oct. 9, 1990



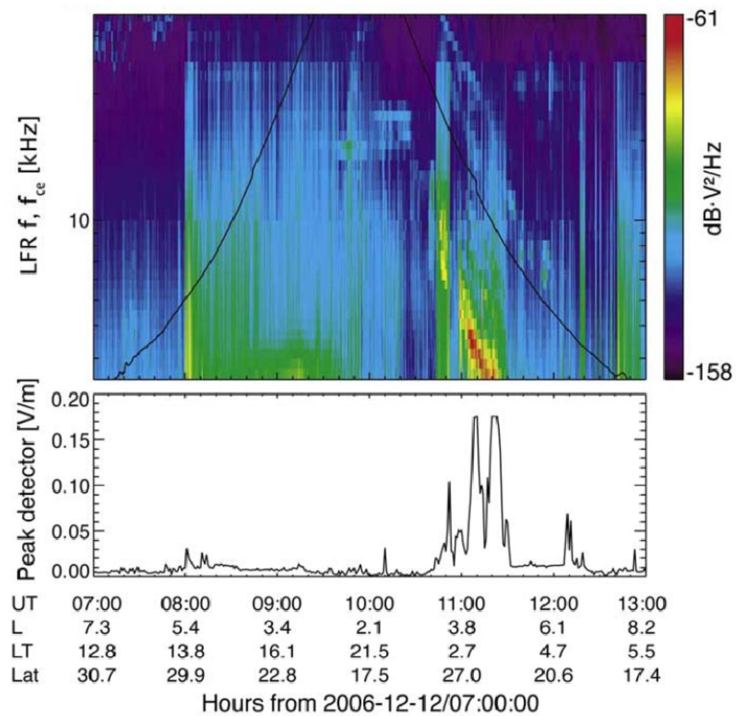
Challenge #4

What is the effect of non-diffusive processes?



Non-resonant (but linear) scattering by magnetosonic waves

Bortnik and Thorne [2010]



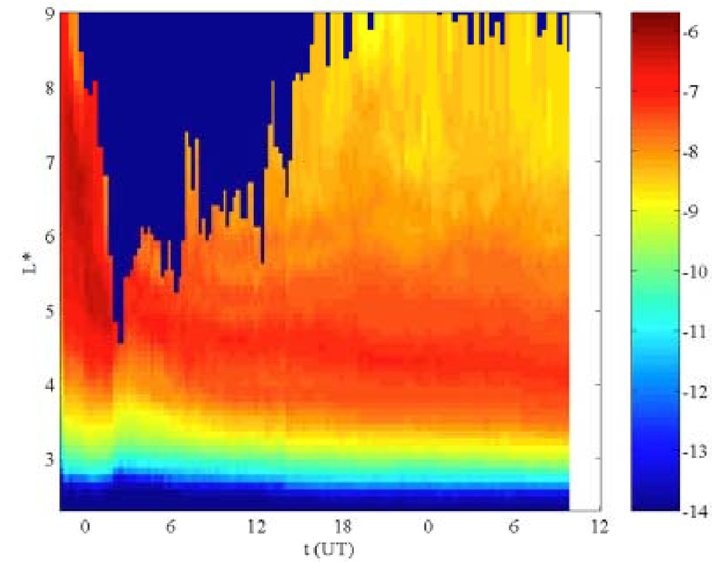
Large amplitude chorus

Cattell et al. [2008], STEREO B

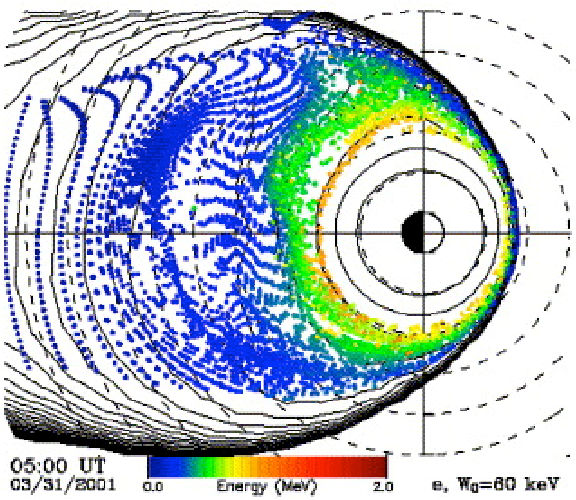
Challenge #5

What is the effect of radial transport via ULF waves?

1. Diffusive
   – Inward radial diffusion? [e.g., Schulz & Lanzerottti, 1974]
   – Redistribution of local peaks in f?
   – Outward radial diffusion? (loss to magnetopause) [Shprits et al., 2006]
   – Drift resonance [Elkington et al., 1999]
2. Non-diffusive
   – Shock-drift [Li et al., 1993; Hudson et al., 1997; Kress et al., 2007]
   – Ukhorskiy et al. [2006, 2008]



Fei et al. [2006]

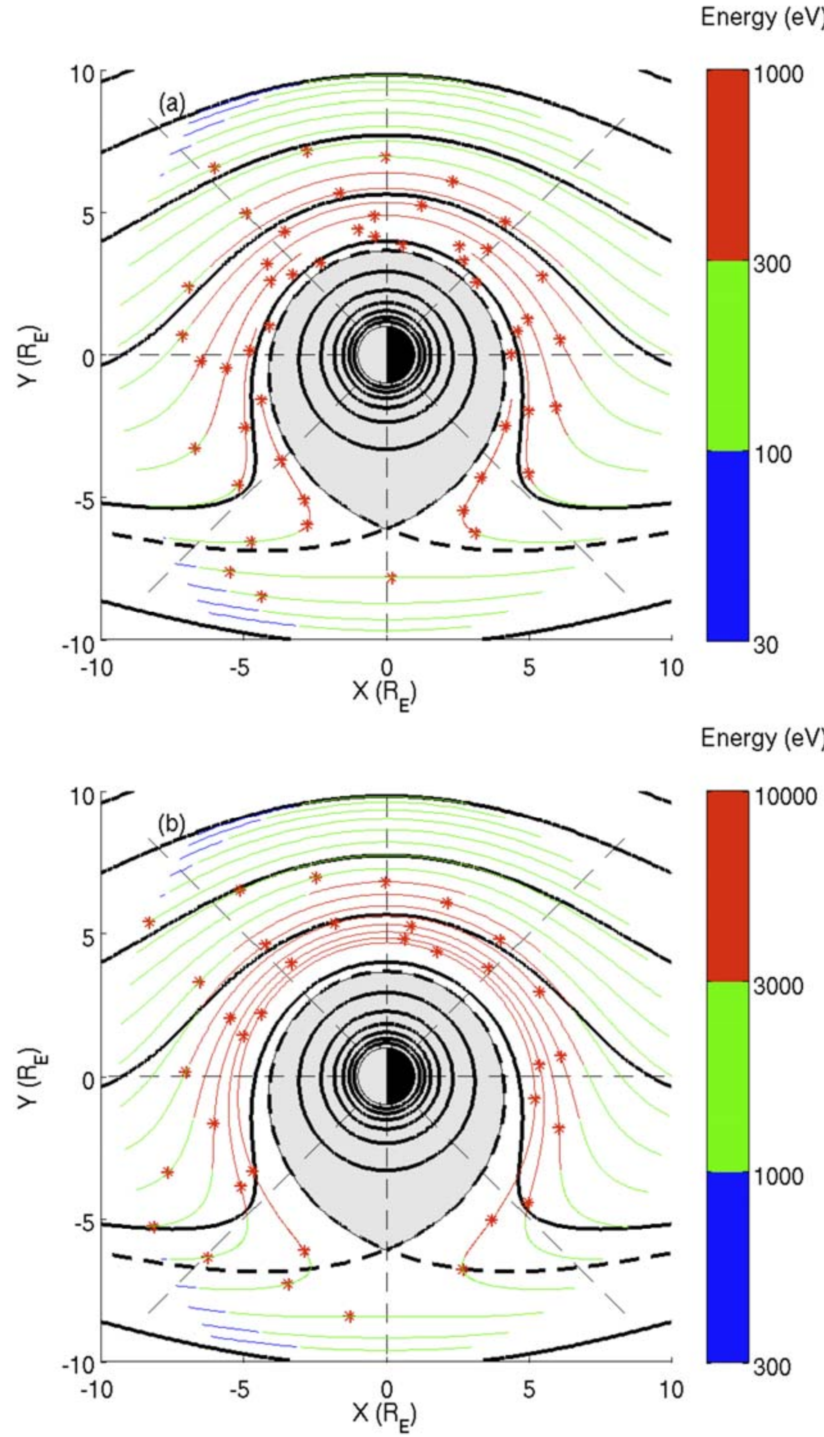


Elkington et al. [2004]

Challenge #6

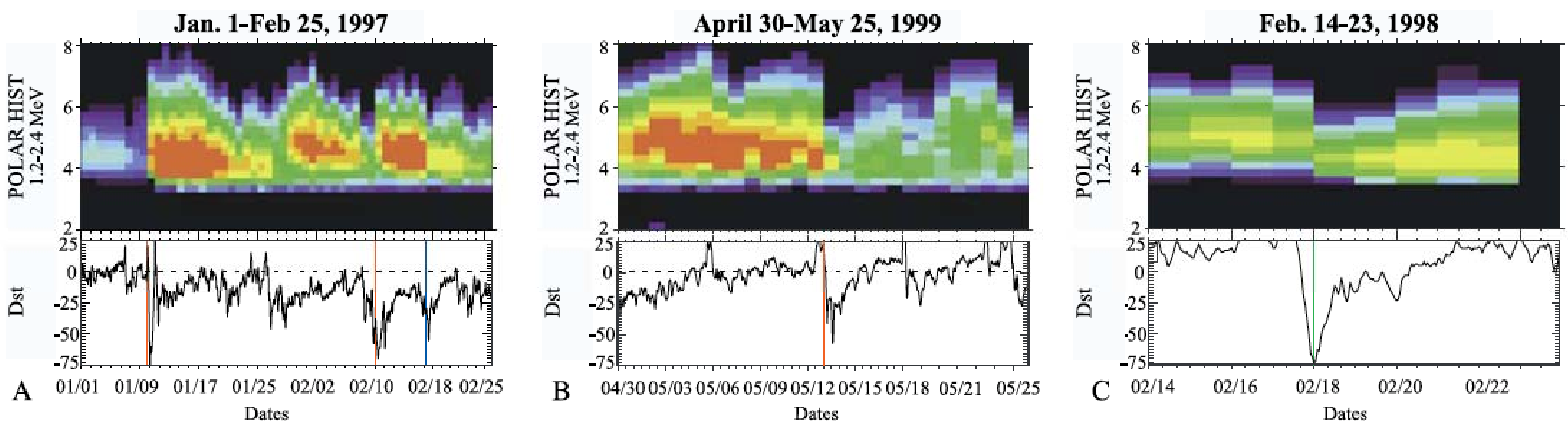
What is the role of (plasmasheet) seed populations?

1. As the population to be accelerated
2. As the energy source for wave growth
3. As the energy sink for wave damping (shaping the spatial distribution of waves)



Challenge #7

Why do some storms cause increase, decrease, no-net change?
i.e., predictability



Reeves et al. [2003]

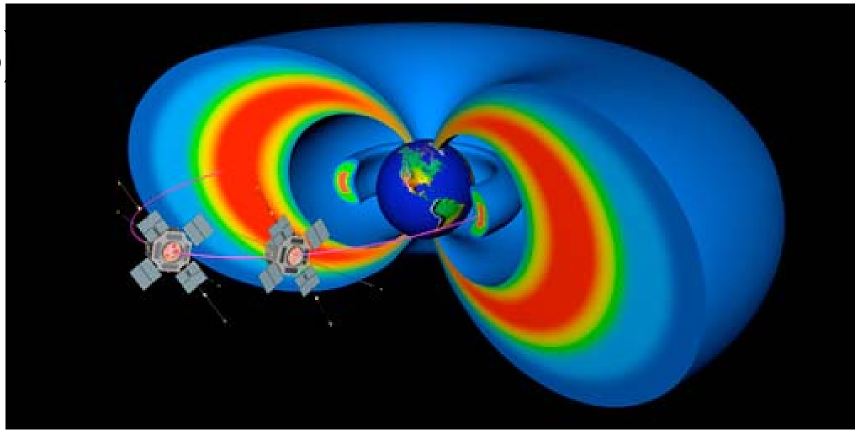
Challenge summary

1. What is the measured wave distribution and its variability?
2. What is the modeled wave excitation, propagation, distribution?
3. What are the effects of different wave types?
4. What is the effect of non-diffusive scattering?
5. What is the role ULF waves?
6. What is the role of the seed population?
7. Why do some storms cause increases, decreases, or no changes in the flux?

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.

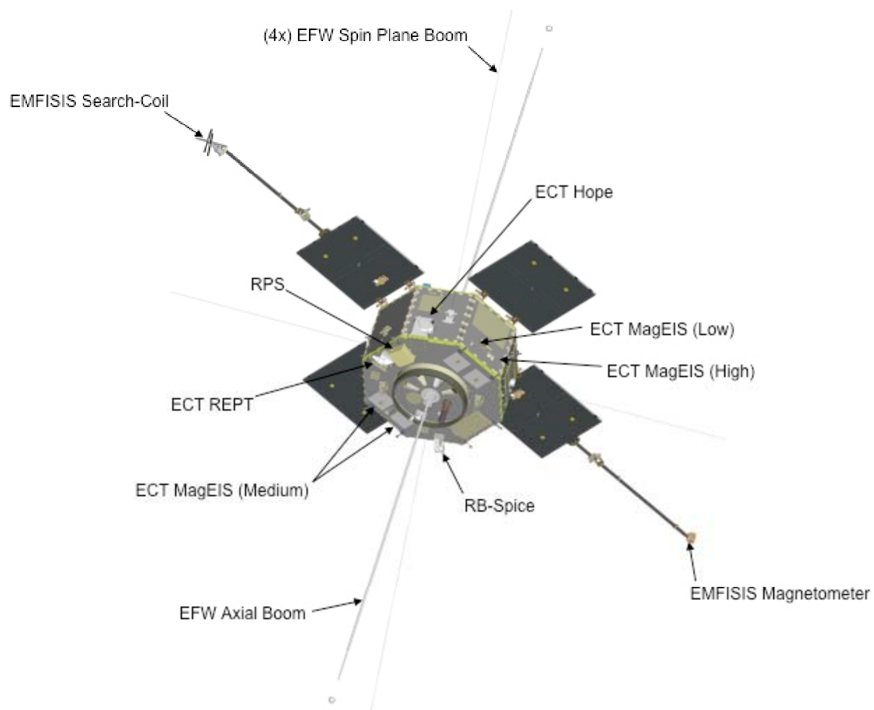
- NASA Living With a Star (LWS
- Launch May 18, 2012
- 2 probes, <1500 kg for both
- ~10° inclination, 9 hr orbits
- ~500 km x 30,600 km



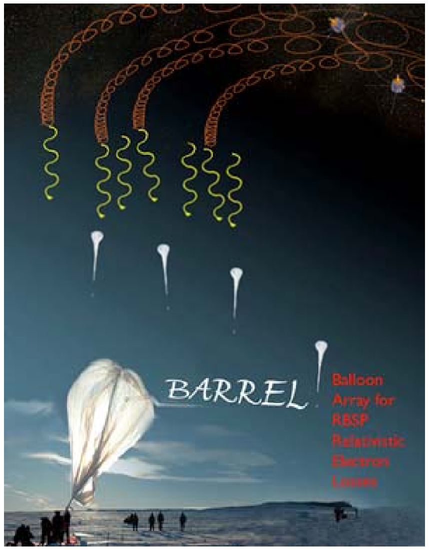
RBSP Instrumentation

Will measure: E & α spectra, ~1 eV to 10's MeV (e^-), 2 GeV (H^+), ion composition & spectra; Waves ~0-12 kHz, E & B, 3-channel, spectra & wave normals, polarization; E-field (1 channel) to 400 kHz;

1. Energetic Particle, Composition, and Thermal Plasma Suite (ECT)
   H. Spence, University of New Hampshire
2. Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS)
   C. Kletzing, University of Iowa
3. Electric Field and Waves Suite (EFW)
   J. Wygant, University of Minnesota
4. Radiation Belt Storm Probes Ion Composition Experiment (RBSPICE)
   L. Lanzerotti, NJ Institute of Technology
5. Relativistic Proton Spectrometer (RPS)
   D. Byers, National Reconnaissance Office

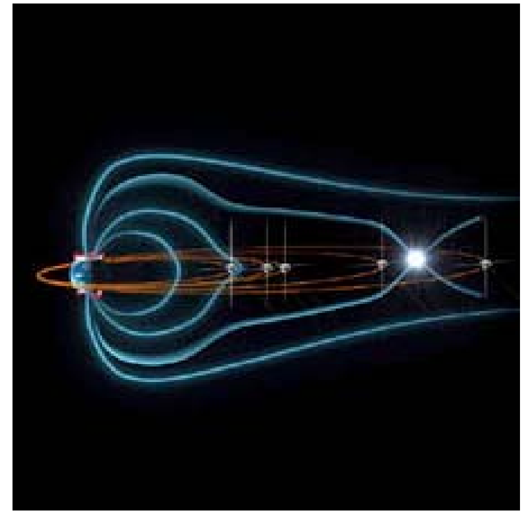


Coordination with other programs

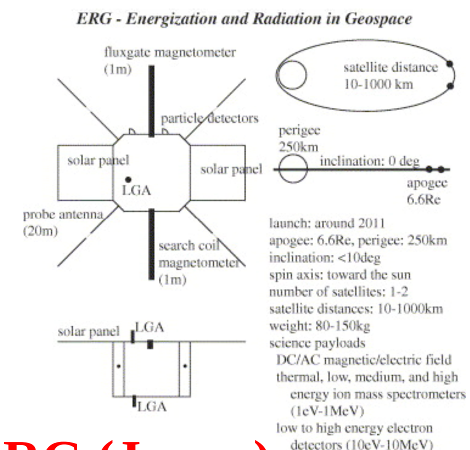


BARREL (NASA)
Launch ~2012
2 campaigns, 5-8 balloons each

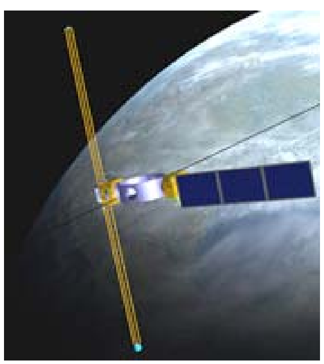
RESONANCE (Russia)
Launch ~2012-14, 4-spacecraft
Orbit:1800x30,000km, ~63° incl.



THEMIS (NASA)
Launch Feb 17, 2007
5 identical probes (3)



ERG (Japan)
Launch ~2013, GTO



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

ORBITALS (CSA)
Launch 2011-2013
Orbit(?) ~L=2 to L=6

Summary

- We started in 1950 and returned in 2010, IGY to RBSP.
- Radiation belts are important scientifically & practically
  - 1951-1960: 16
  - 1961-1970: 150
  - 1971-1980: 428
  - 1981-1990: 358
  - 1991-2000: 392
  - 2001-2010: 647 (401 in past 5 years)
- New GEM FG, RBWM: 7 challenges, 2010-2014
- RBSP mission – to resolve the fundamental physical processes affecting the radiation belts.
- "Grand scale" science project: fundamental theory, modeling, wave & particle distributions, complementary project coordination