Sources or Losses? The cause and effect of low-frequency magnetospheric pulsations in the Van Allen belts.

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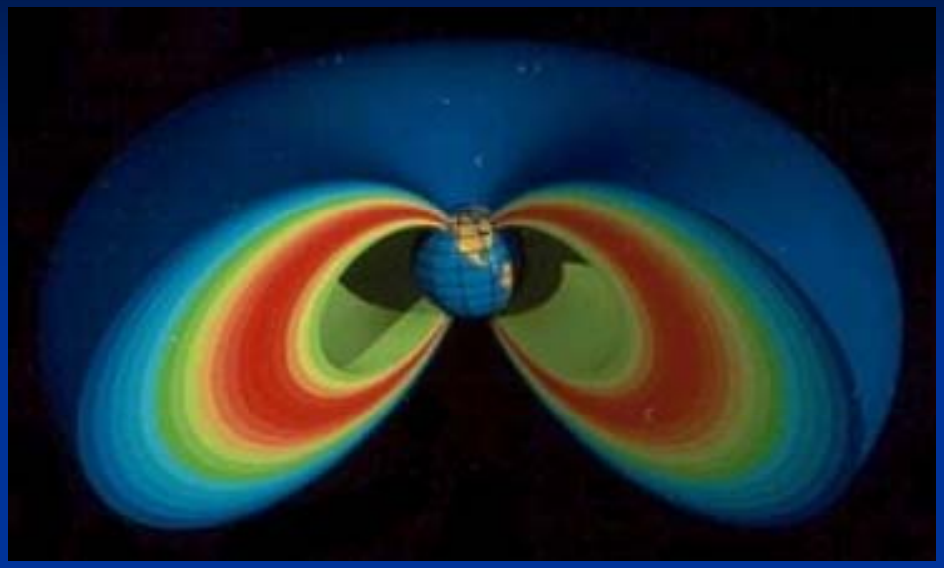
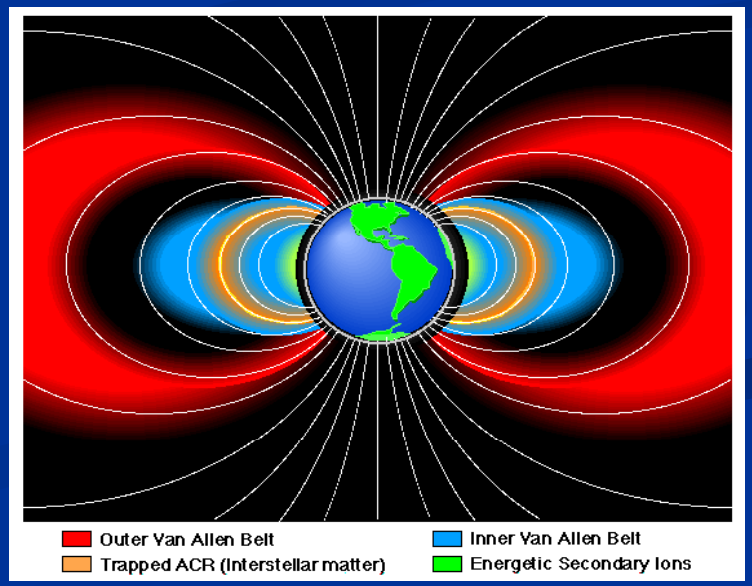
The Van Allen Radiation Belts

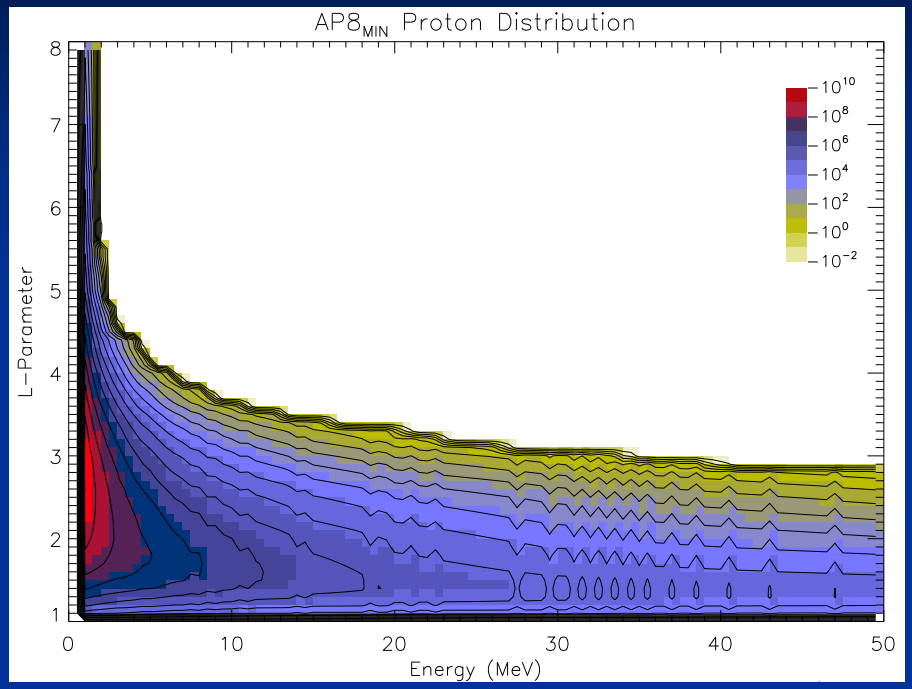


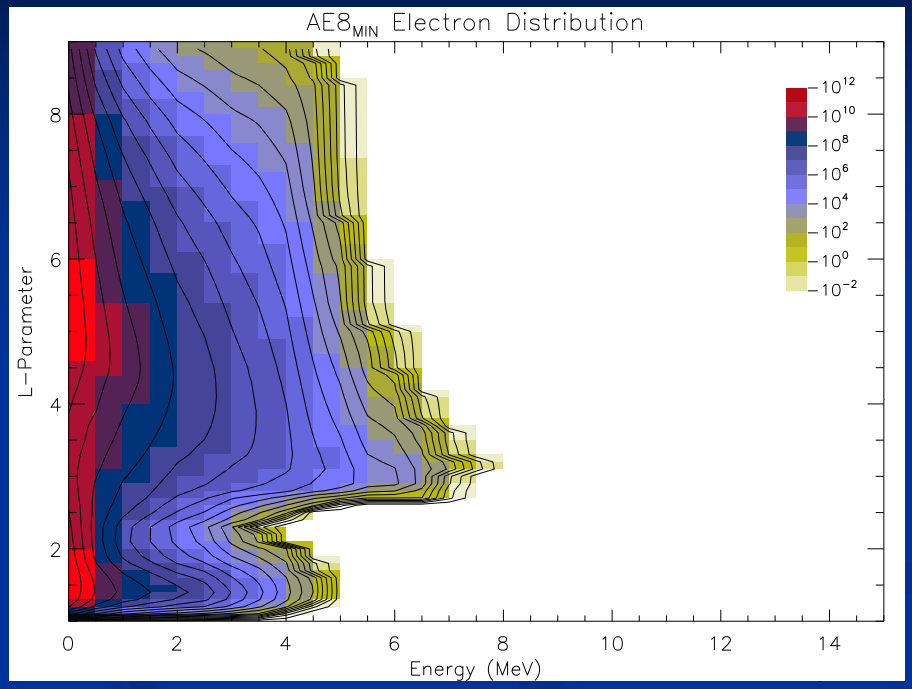
Earth's space radiation environment was first discovered by James Van Allen in 1958, using results from a simple Geiger counter flown aboard the spacecraft *Explorer I*.

- Trapped electrons and ions drifting in orbits encircling Earth.
- Two spatial populations: inner zone and outer zone.
- Energies from ~200 keV to > several MeV (VERY ENERGETIC).



The radiation belts





Ions:

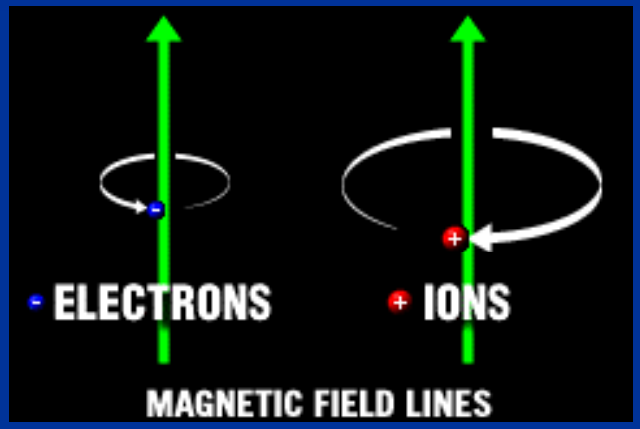
- Composed largely of protons.
- Confined to inner regions of magnetosphere, L<3.
- Energies: W > 10 MeVs.

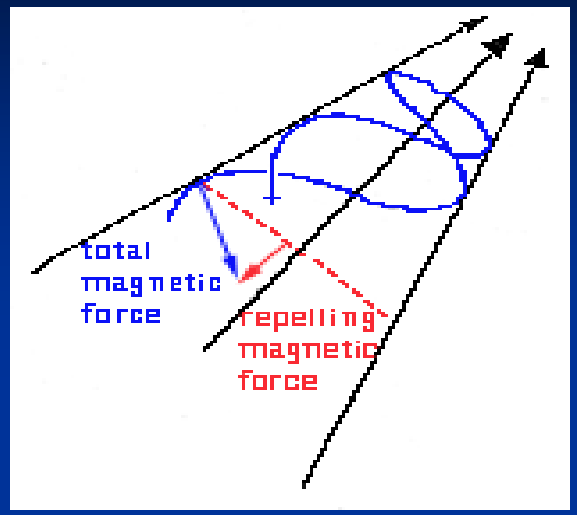
Electrons:

- Two distinct regions: inner and outer zone
- Energies: W < 10 MeV
- Steep power law: $W^{-(5-8)}$

Charged particle motion in the magnetosphere

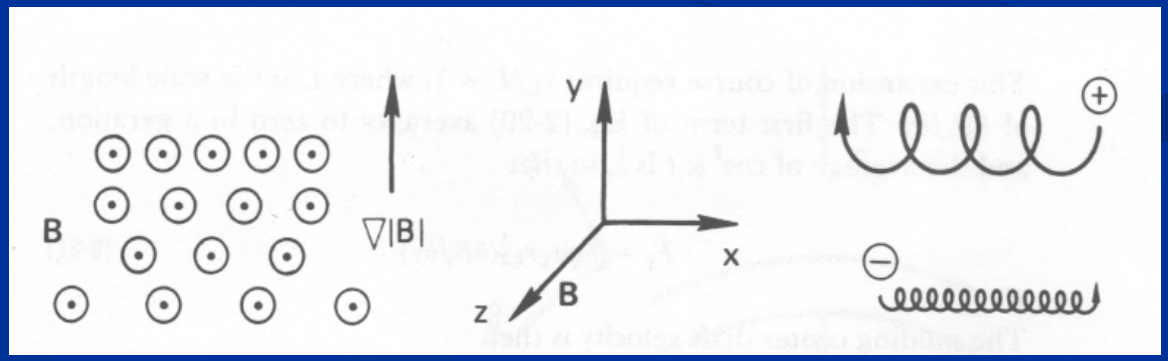
A charged particle in motion in a magnetic field will tend to gyrate about the magnetic field line. *The radius depends on the magnetic field strength.*



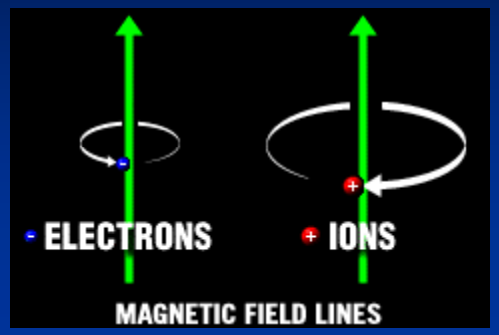


Gradients parallel to the field will cause particles to move away from the high field regions…

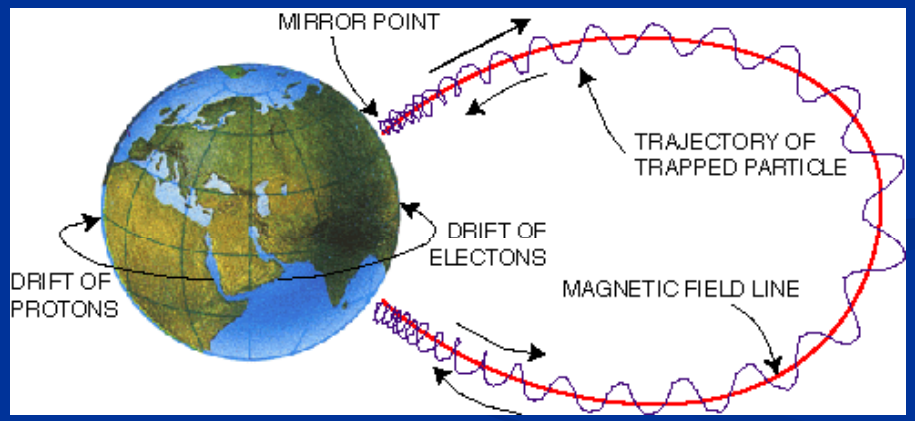
…while gradients perpendicular to the magnetic field will cause the particle to drift across field lines.

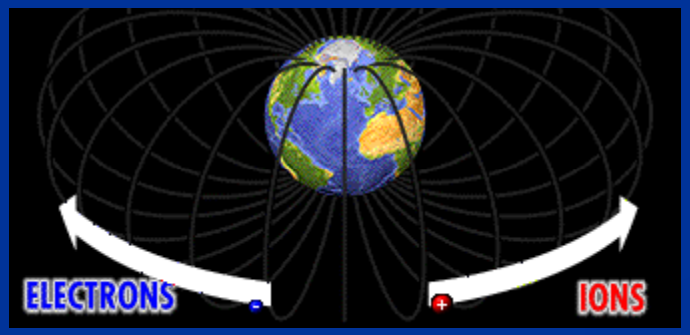


Charged particle motion in the Earth's magnetosphere



The Earth has an intrinsic magnetic field that is roughly a dipole. Charged particles moving under the influence of the Earth's magnetic field therefore execute three distinct types of motion.

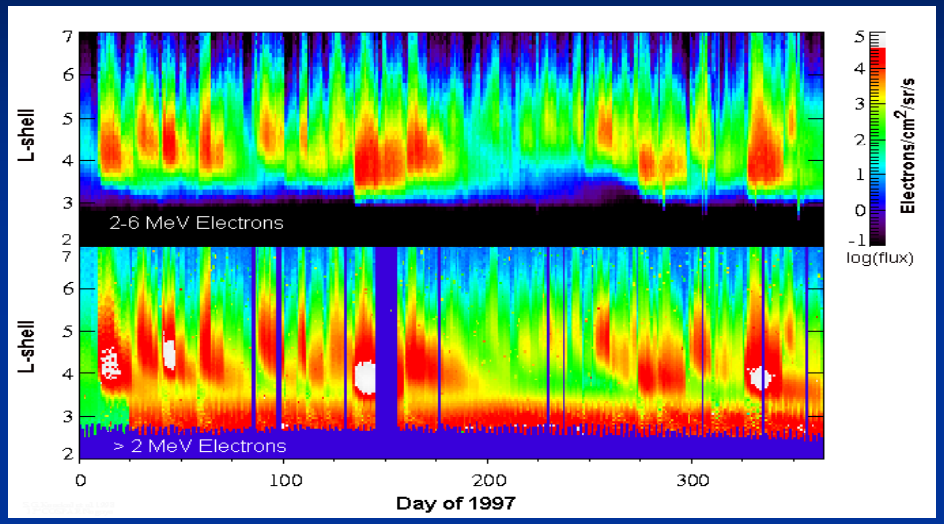




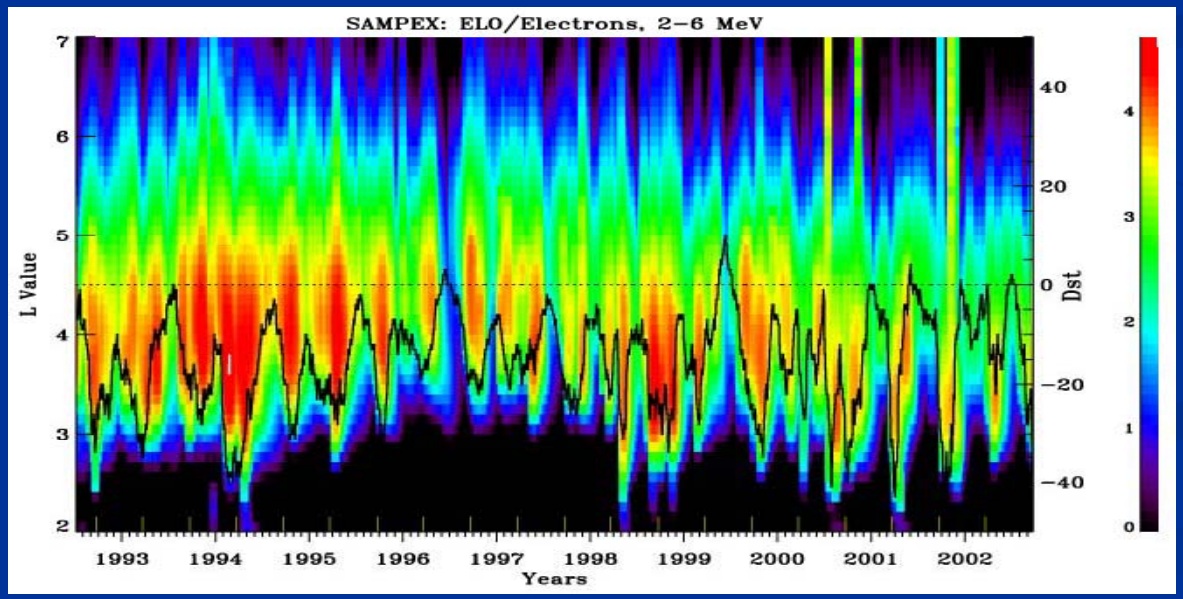
Characteristic time scales:

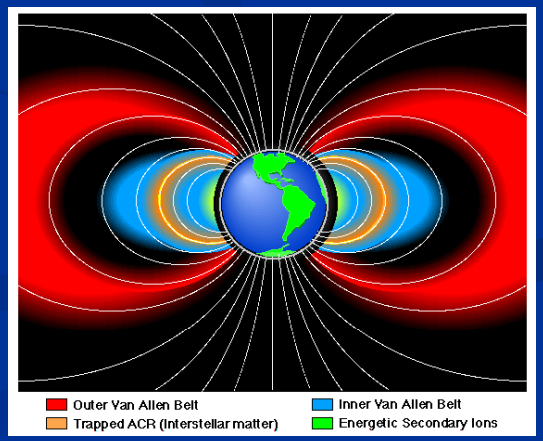
- Gyro: ~ millisecond
- Bounce: ~ 0.1-1.0 s
- Drift: ~ 1-10 minutes

Radiation in the belts is highly variable!



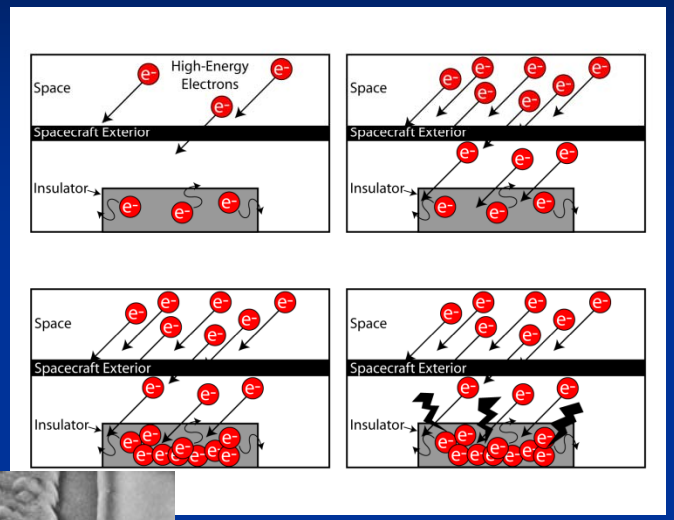
- Storm commencement: minutes
- Storm main phase: hours
- Storm recovery: days
- Solar rotation: 13-27 days
- Season: months
- Solar cycle: years

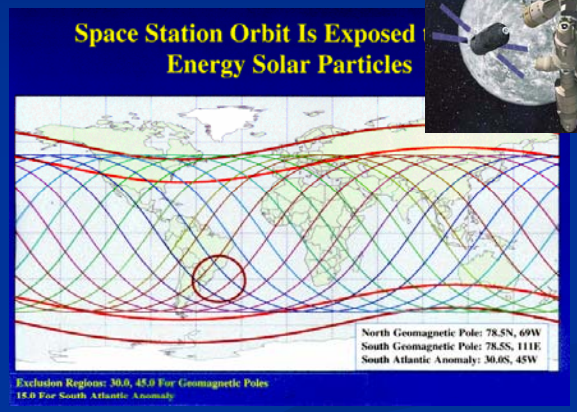




Effects of radiation belt particles

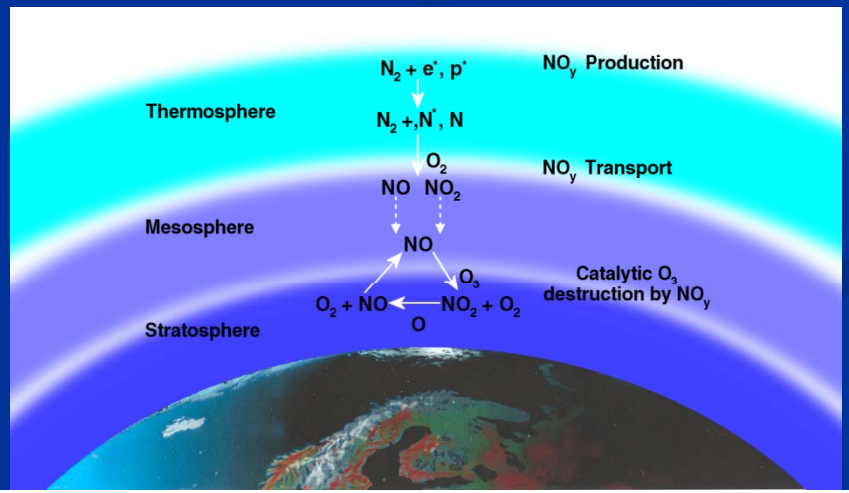
Damage to spacecraft





Hazardous to humans in space

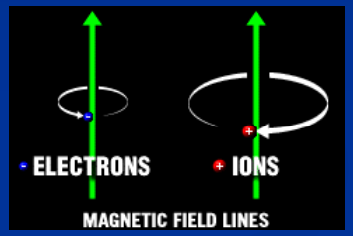
Terrestrial effects: atmospheric chemistry, ozone depletion



Adiabatic Invariants

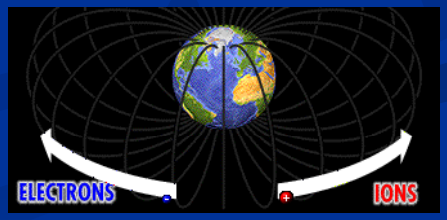
Each characteristic type of trapped particle motion can be characterized by one of three "adiabatic invariants", which remain constant if the fields don't vary much over the motion.

- The "first invariant", *M*, is related to the magnetic field contained within the gyro-orbit. Conserving *M* means that a particle's perpendicular energy increases as the magnetic field increases.
- The "second invariant", *K*, is related to the bounce motion of the particle. A particle conserving *K* will try to bounce along field lines of the same length.
- The "third invariant", *L*, is related to the field contained within the drift orbit. In a dipole field, *L* is the radial distance of the orbit as it crosses the equatorial plane.



~0.001s

~0.1s



~10 min

Violating the 3rd, conserving the first

Field perturbations occurring on time scales of a few minutes can violate the third invariant, while conserving the first.

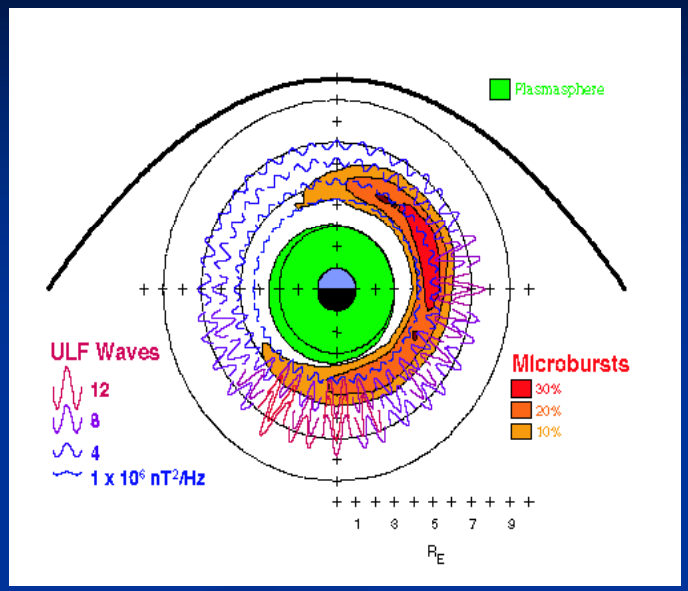
- Violation of the third invariant will cause particles to move radially to regions of higher or lower field strength.
- Conservation of the first invariant will cause the energy to change as the particle moves into regions of higher or lower field strength.

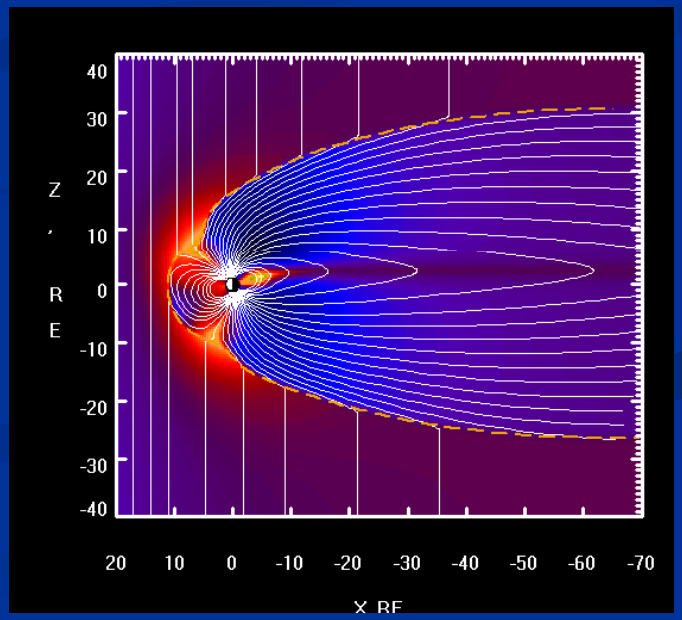
➢ We can energize particles by moving them around the magnetosphere.

Processes operating in the radiation belts

There are a host of important processes acting in the radiation belts. Among them:

- Heating/transport by interaction with low-frequency waves
- Heating by interaction with high-frequency waves
- Convective motion due to large-scale magnetospheric circulation
- Injection by substorm dipolarization
- Injection by CME/SSC
- Losses due to scattering into the atmosphere
- Losses due to interaction with the magnetopause
- Etc….



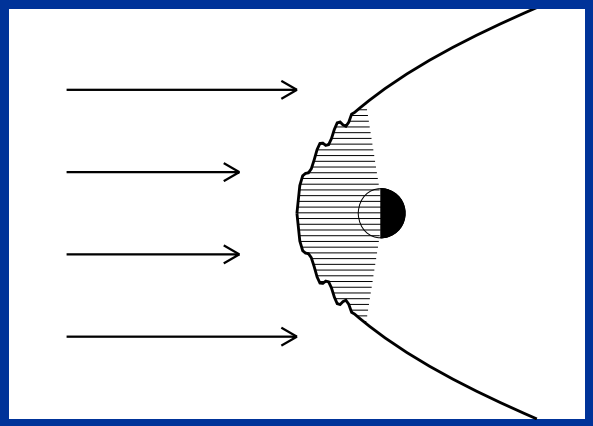


To paraphrase a statement made by another radiation belt researcher, "Anything that can happen in the radiation belts, probably does. The task is determining the relative importance of each process".

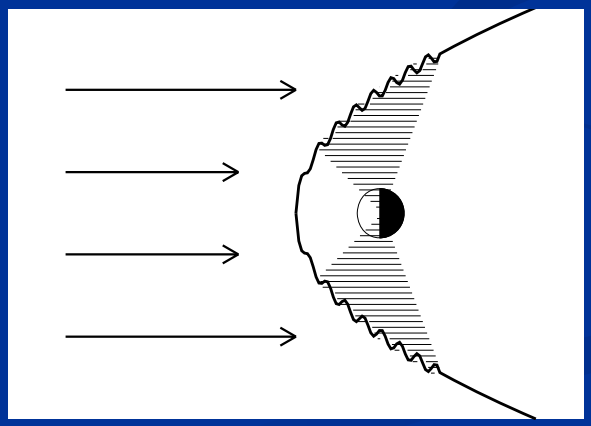
Pc5 ULF waves in the magnetosphere

Pc5 ULF waves are defined as the continuous magnetospheric pulsations that occur at mHz frequencies, which happens to be *commensurate with the drift frequency of relativistic electrons* in the outer zone radiation belts.

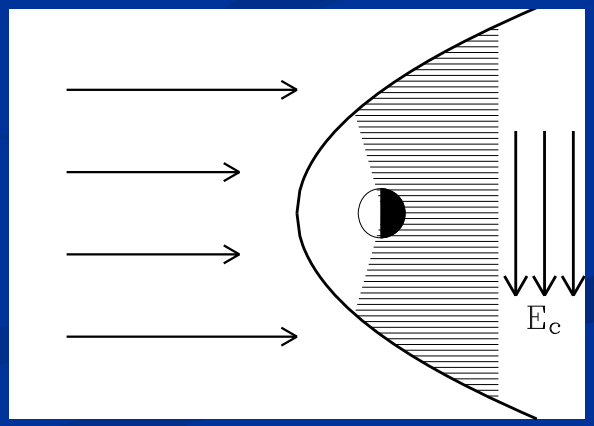
- Internally-driven: high azimuthal mode number (>20), via ring current instablilities
- Externally-driven: low azimuthal mode number (<10), via solar wind interactions…



Impulsive variations in the solar wind

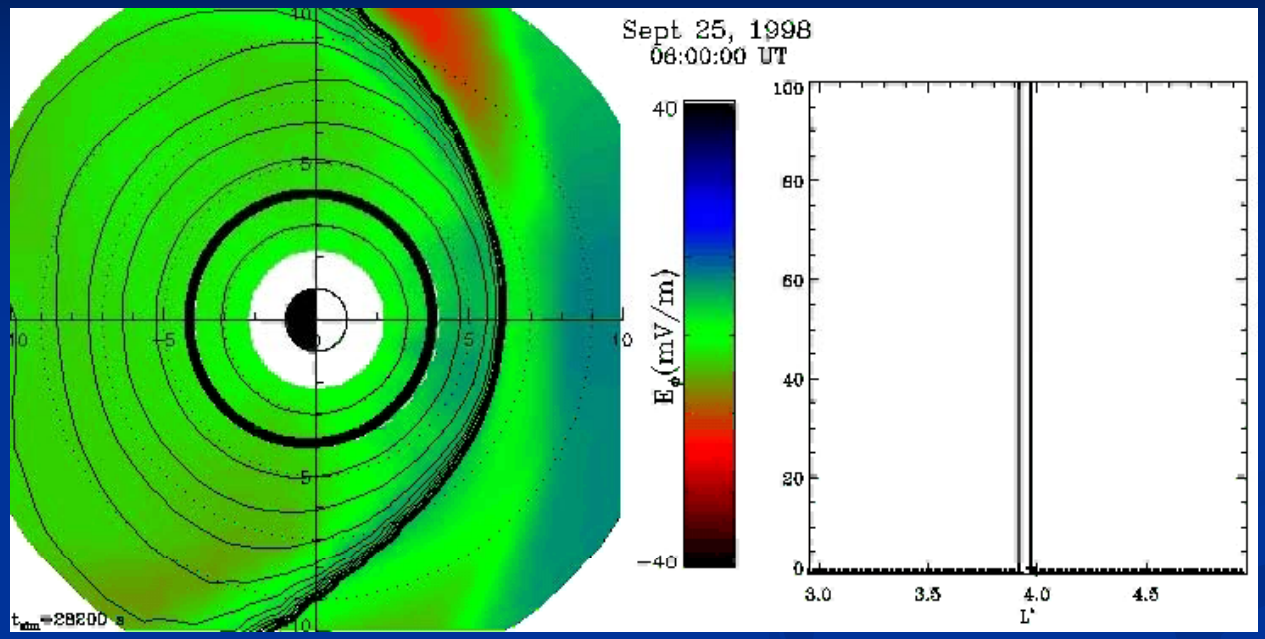


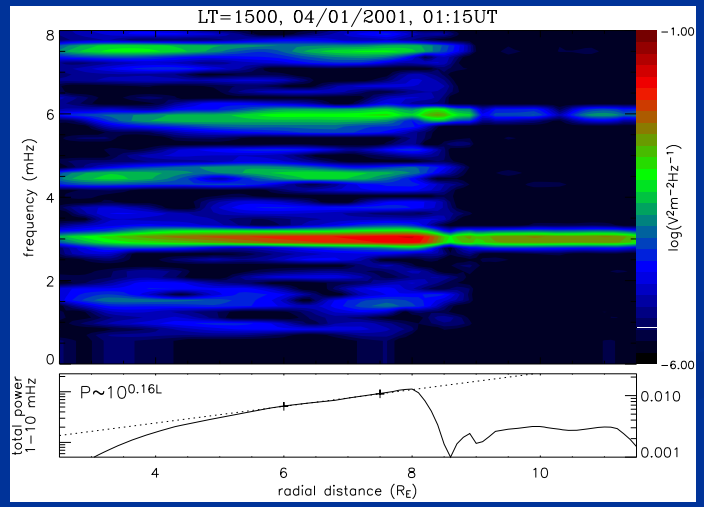
Shear waves on the flanks

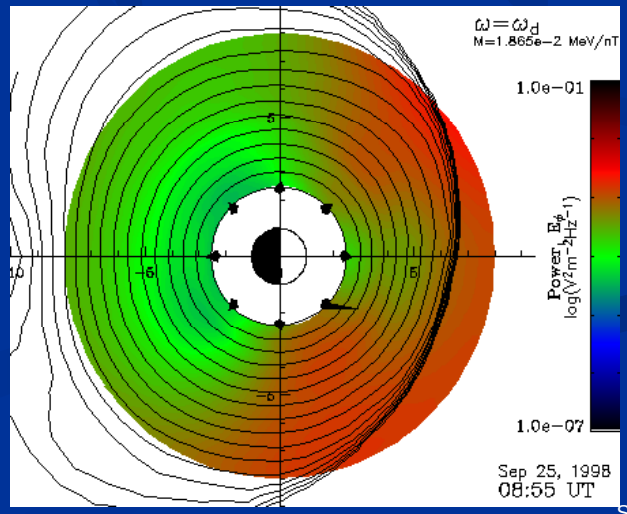


Variations in the convection electric field

Example: Pc5 waves due to solar wind fluctuations





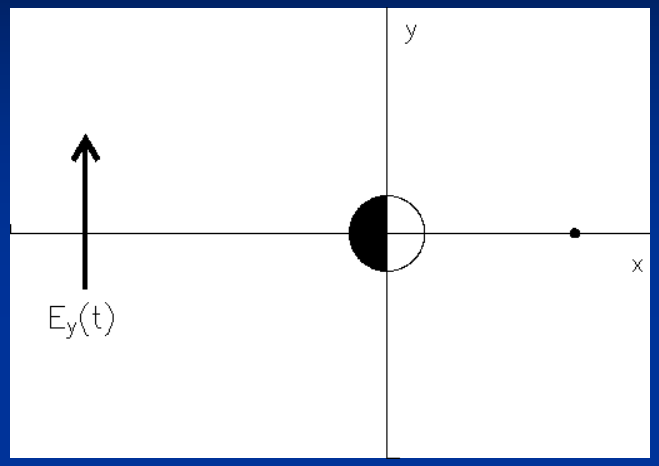


S. Elkington, March 25, 2010

Energization and Pc5 ULF waves

Energy of an electron moving in a dipole magnetic field with slowly-varying dawn-dusk convection electric field

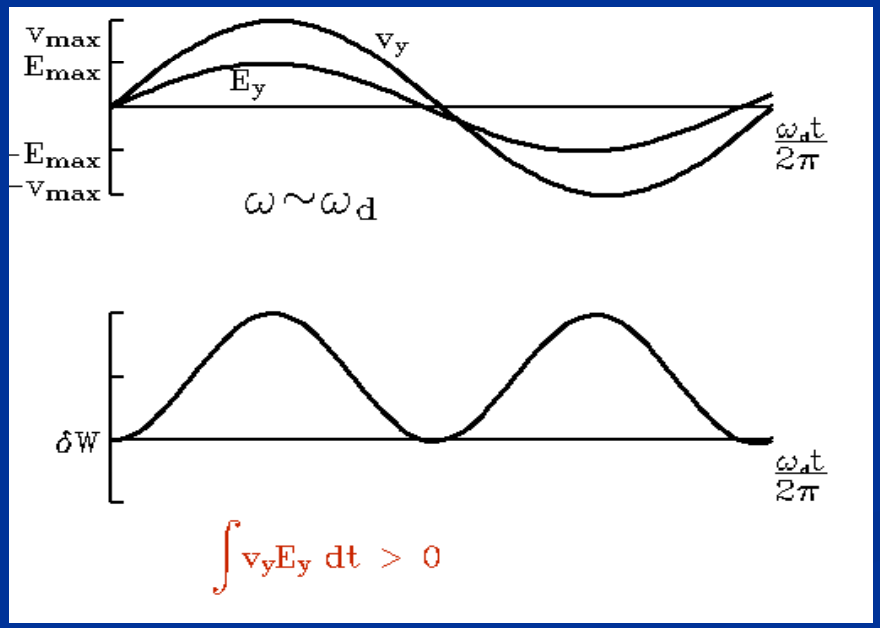
$$\frac{dW}{dt} = q\,\vec{v}_D \cdot \vec{E} + \frac{M}{\gamma}\frac{\partial B}{\partial t}$$

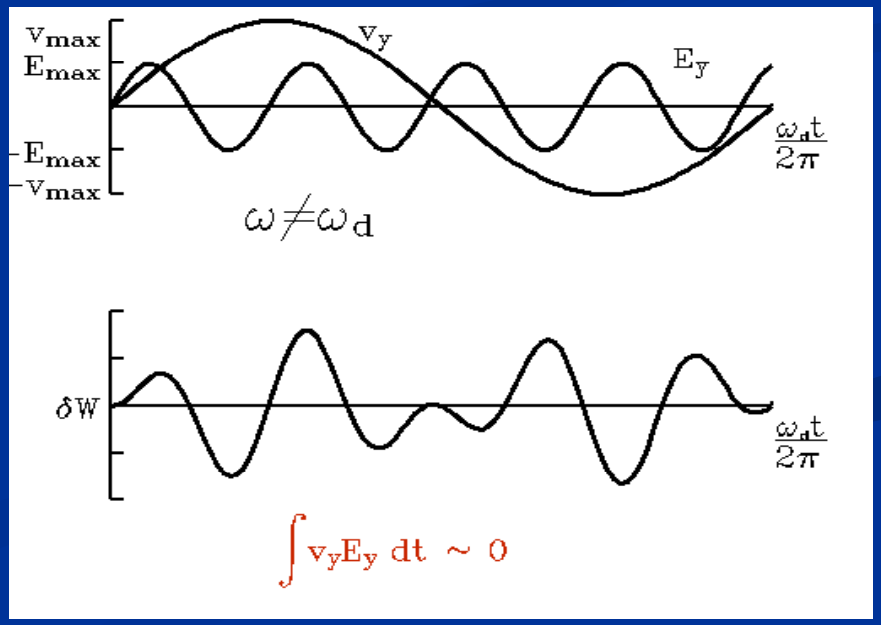


- f_D~mHz ⇨ ULF waves.
- Only need consider resonant frequencies

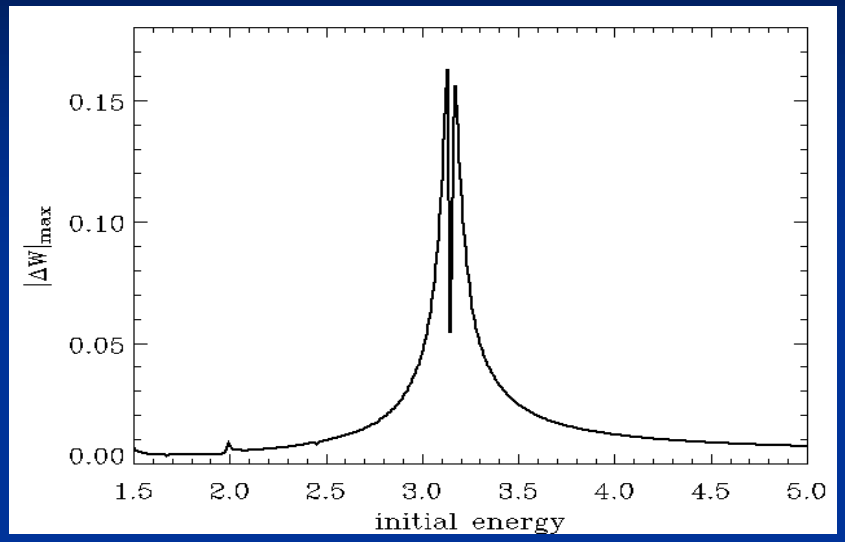
$$E = E_0 \cos(m\varphi - \omega t + \xi)$$

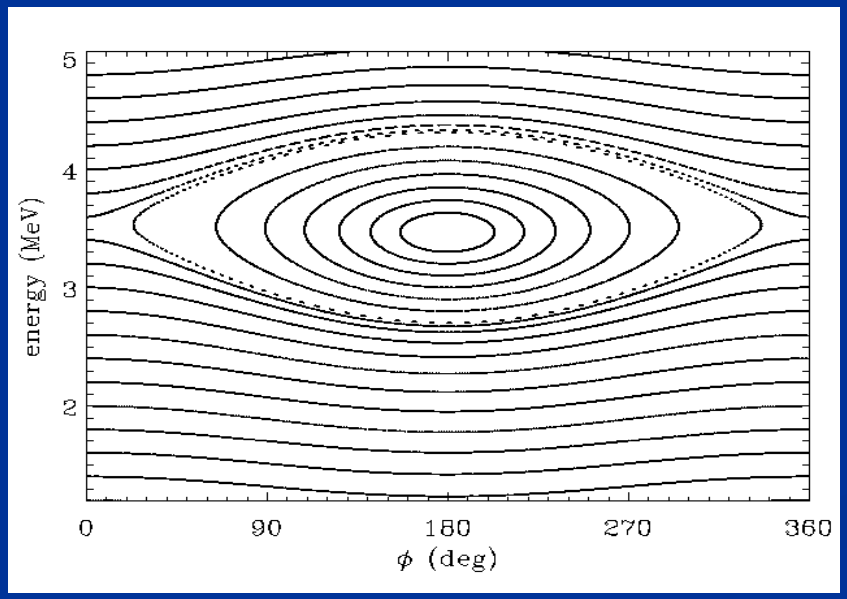
$$\omega = m\omega_D$$

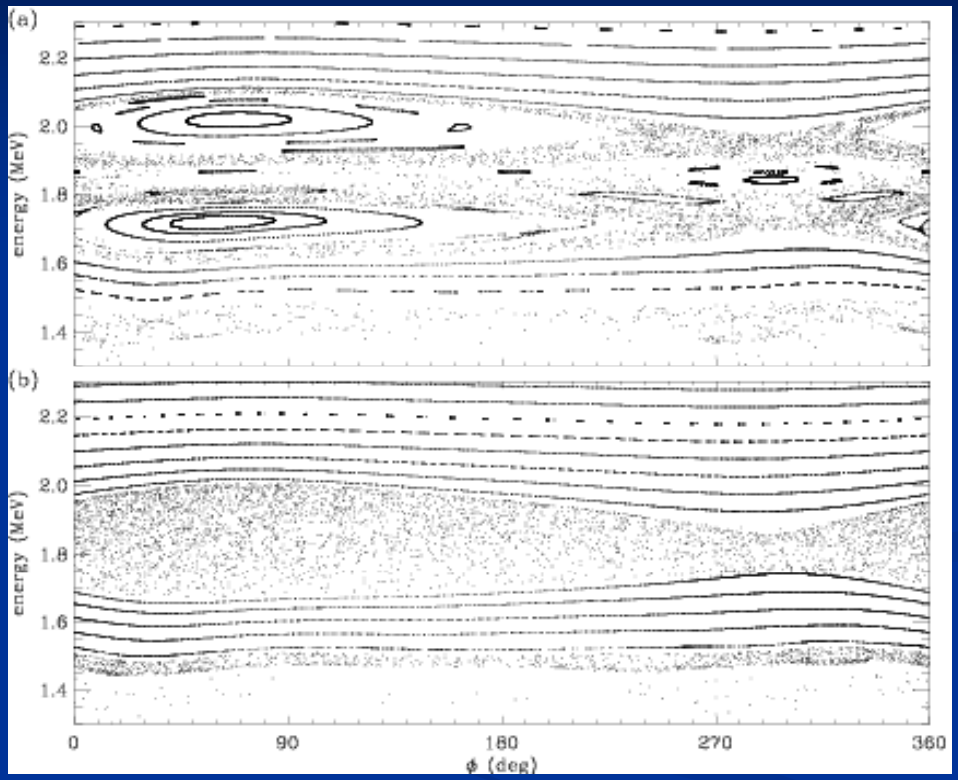




Multiple Pc5 frequencies: radial diffusion

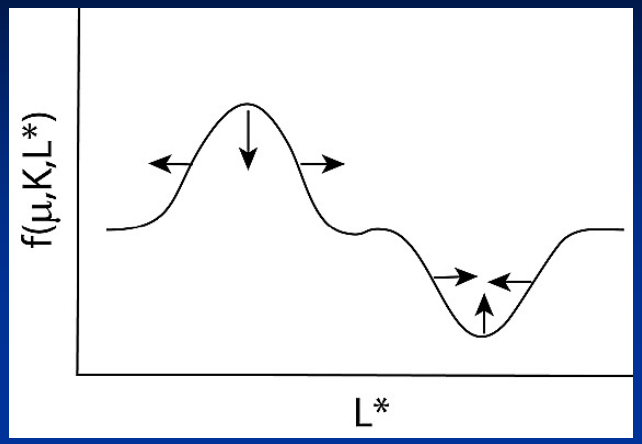


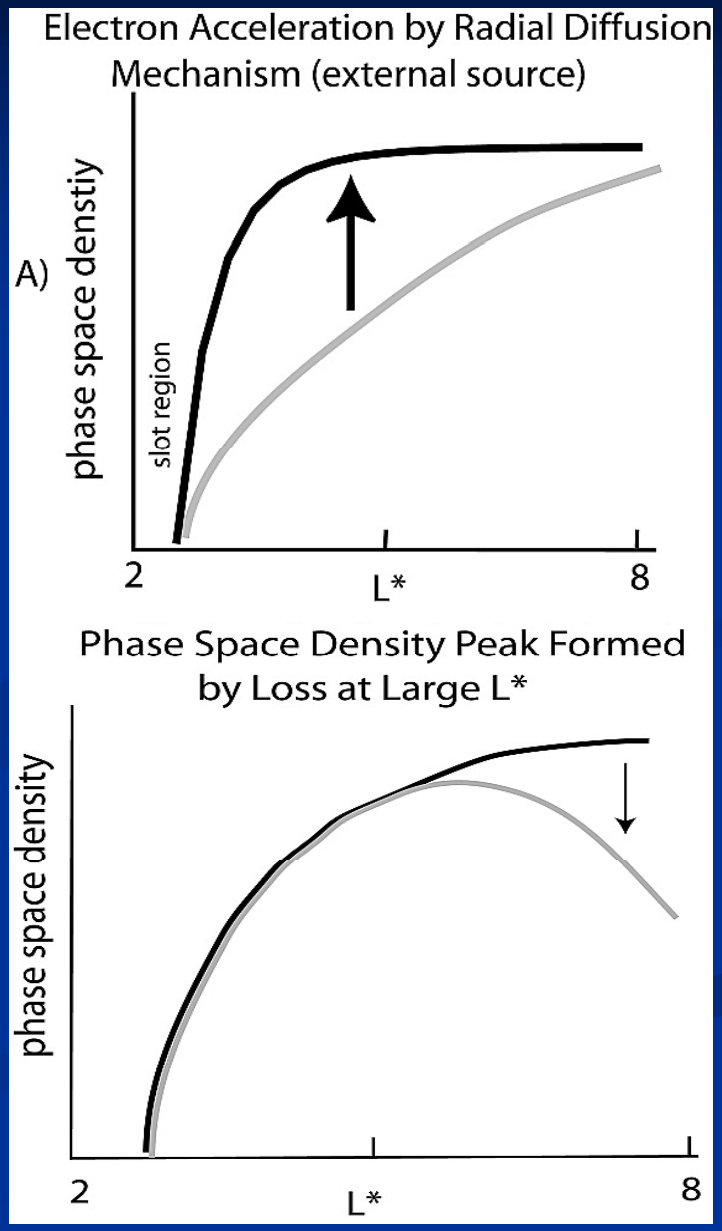




Under conditions where particles are acted on by multiple (or a continuum) of frequencies, stochastic motion of the particle results in diffusion in L.

Stochastic transport: Fick's law

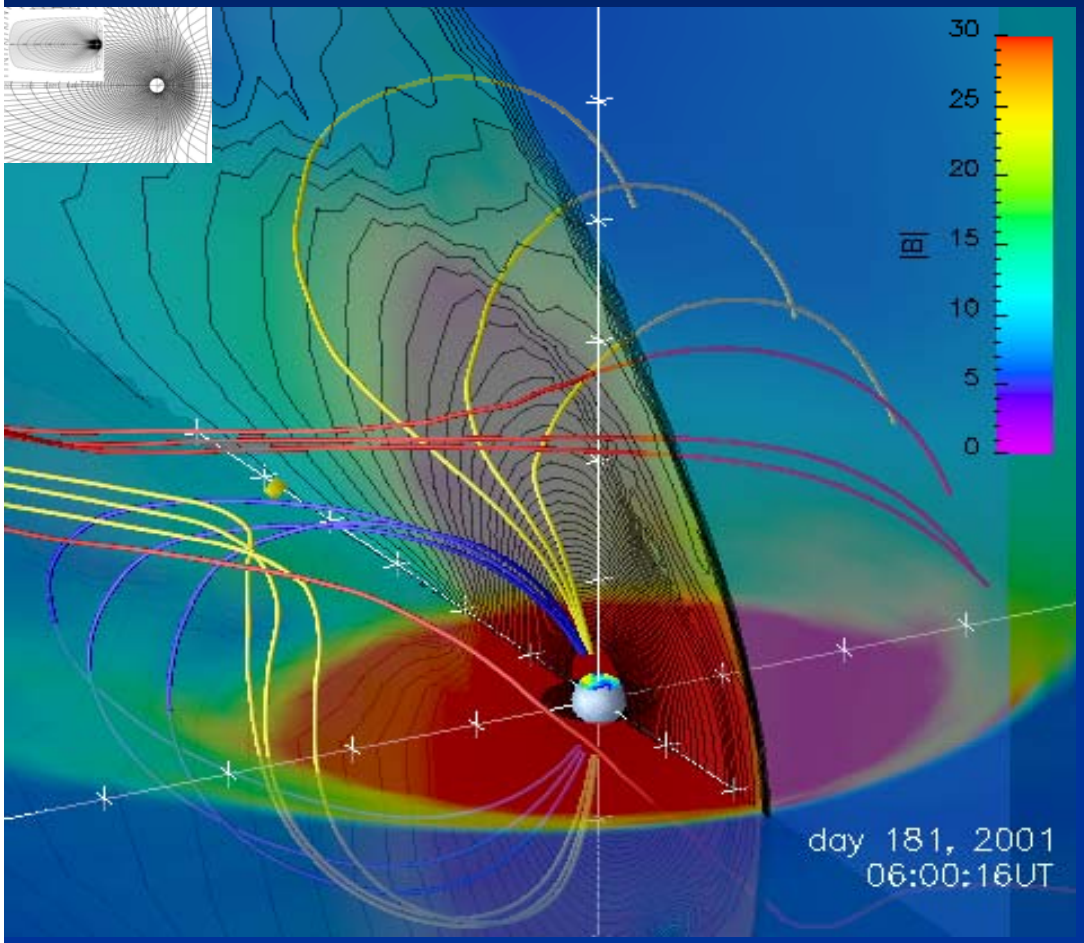




Diffusion will act to *smooth out gradients* in the distribution function. In the radiation belts, the net effect of radial diffusion depends on the phase space gradient in *L*:

- High *f* at outer boundary, acts as a source.
- Low *f* at outer boundary, may act as a loss.

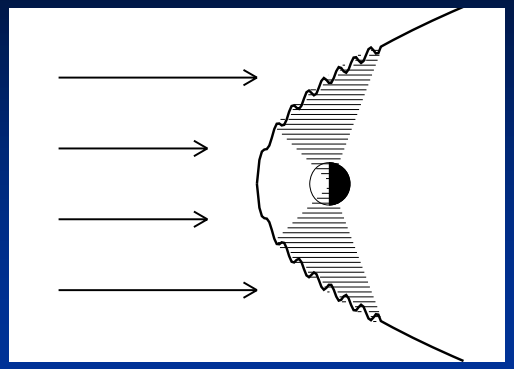
Global MHD simulations of the magnetosphere

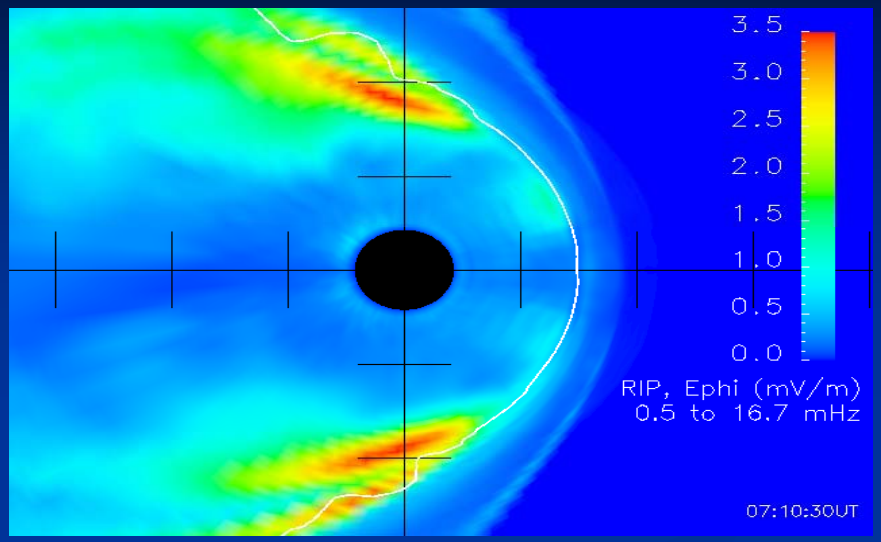


- MHD treats magnetospheric plasma as magnetized fluid
- Driven by upstream boundary conditions
- Includes reconnection, convection, external contributions to B, etc.
- Does not include
  - High frequency waves
  - Multiple plasma species
  - Kinetic effects
  - Hall physics
  - Etc…

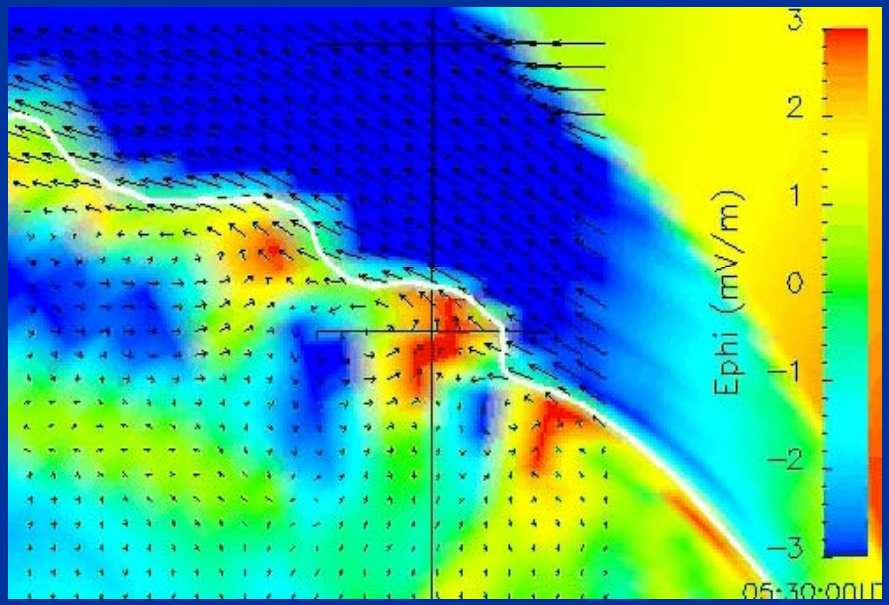
The Lyon-Fedder-Mobarry is under active development via the NSF Science Technology Center (STC) program and the *Center for Integrated Space Weather Modeling*, a 10-year, $40M program designed to construct an integrated physical model of the entire Sun-Earth system.

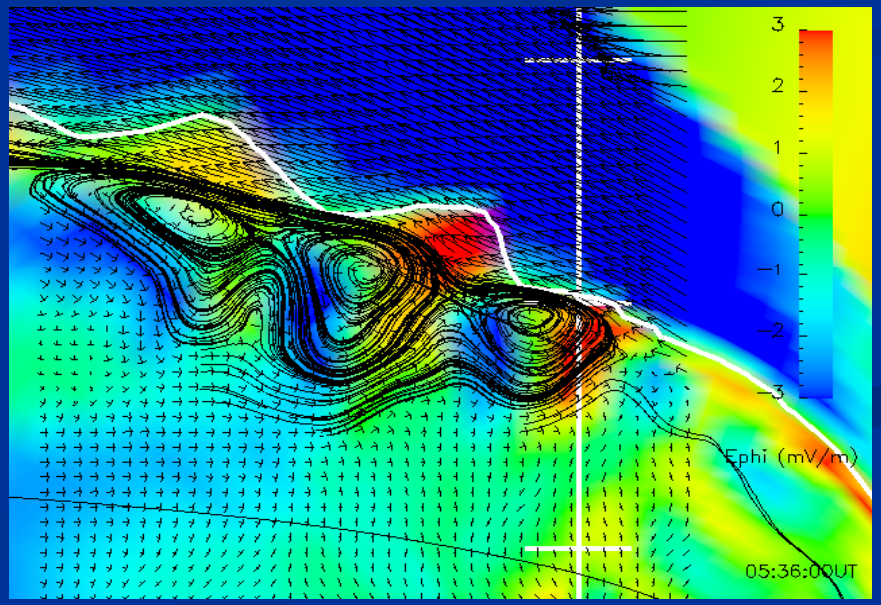
Basic drivers of Pc5: shear interactions





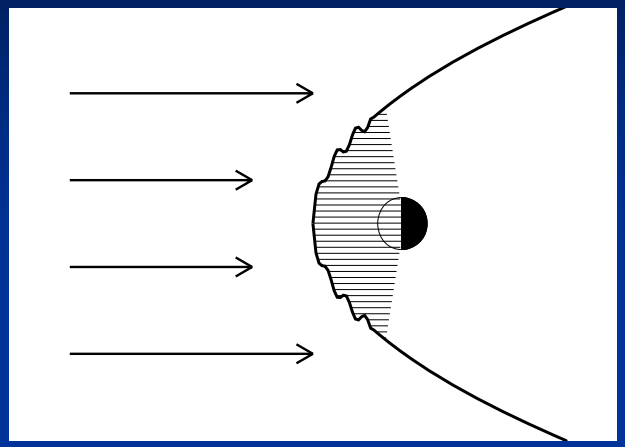
ULF activity characterized as a function of solar wind velocity for KH waves on the flanks of LFM MHD.





Claudepierre et al., *JGR* 113, 10.1029/2007JA012890, 2008.

Basic Drivers: Pressure variations



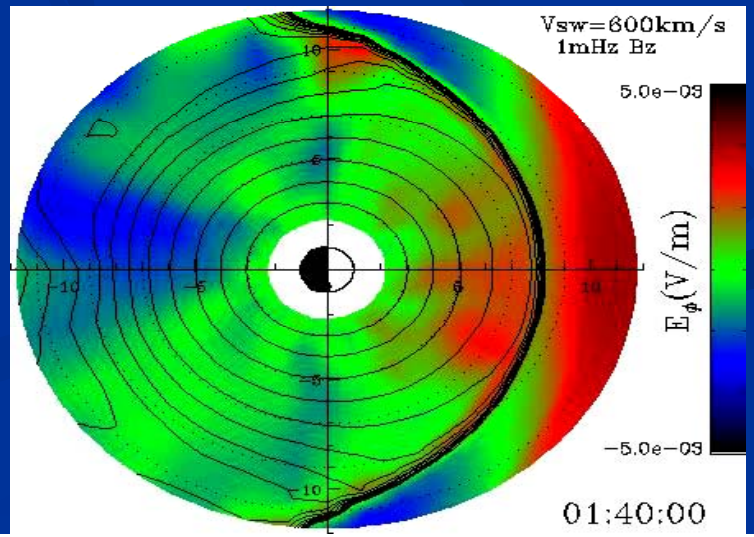
We also wish to characterize the effect of pressure variations during the ascending Vsw phase of HSSW storm. We introduce density perturbations of the form

$$n(t) = n_0 + C\sin(\omega t)$$

We also introduce the appropriate out of phase oscillation in the input sound speed so that the thermal pressure is constant in the input conditions (Pth ~ n C_s^2):

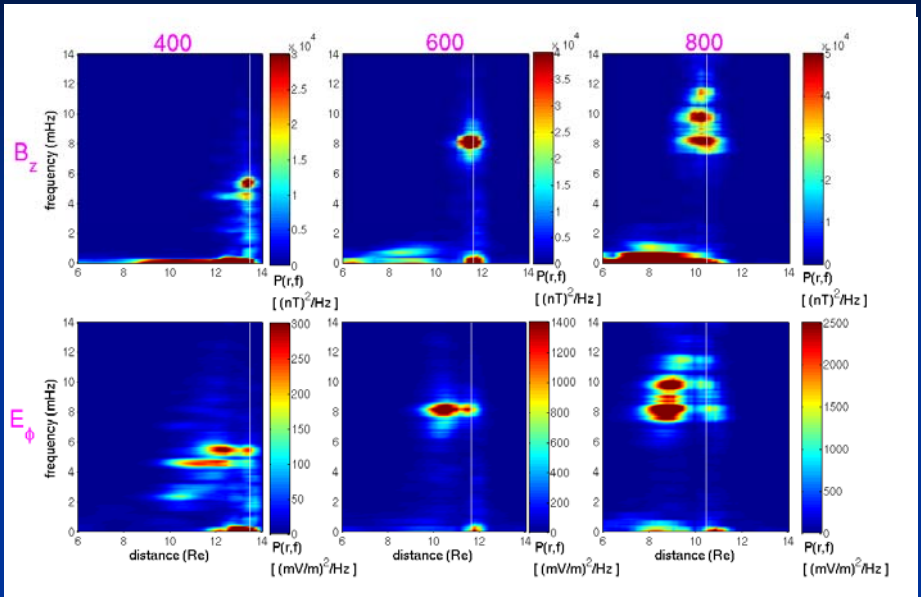
$$c_s(t) = c_{s,0}\sqrt{\frac{n_0}{n_0 + C\sin(\omega t)}}$$

We wish to understand the response of the magnetospheric cavity as a function of frequency; we may use both monochromatic frequencies as well as broadband runs.

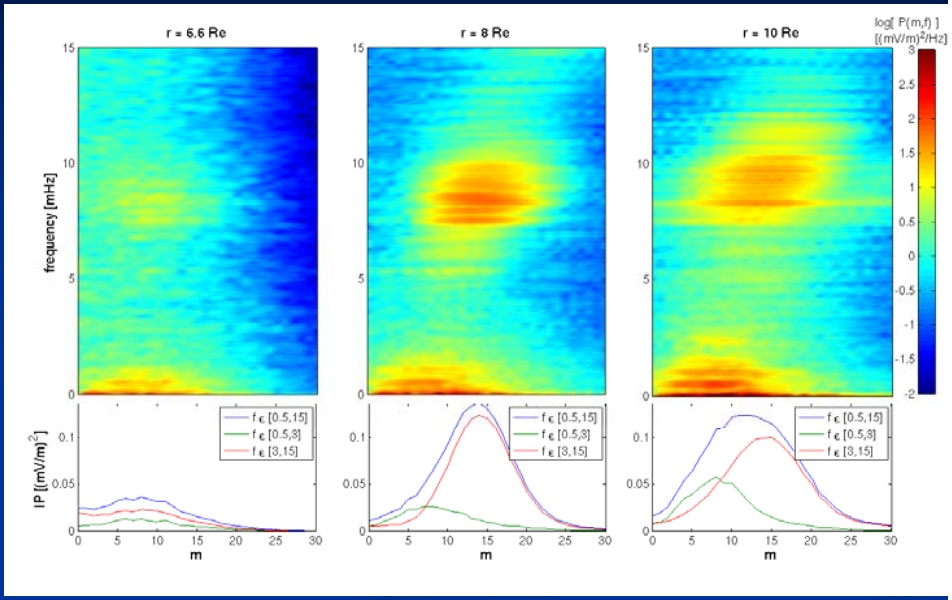


Pc5 wave analysis

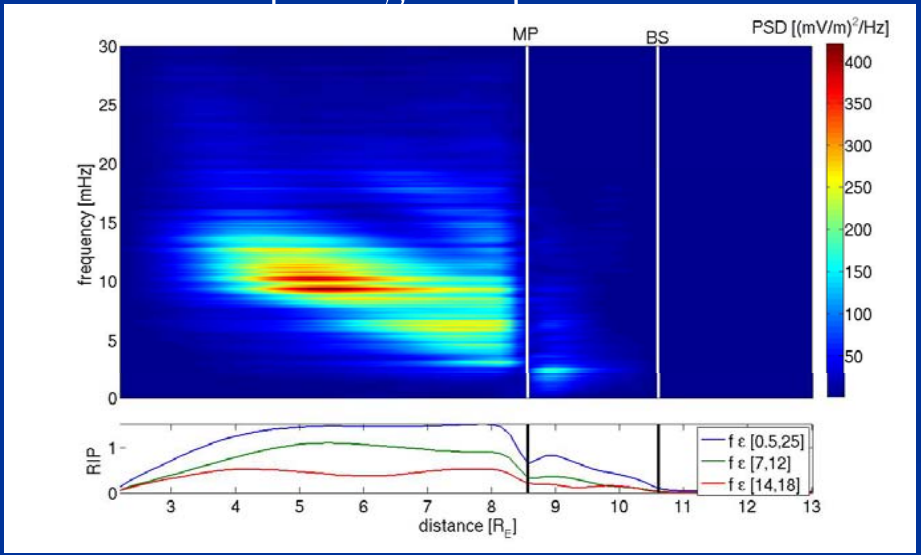
Frequency, sheer waves



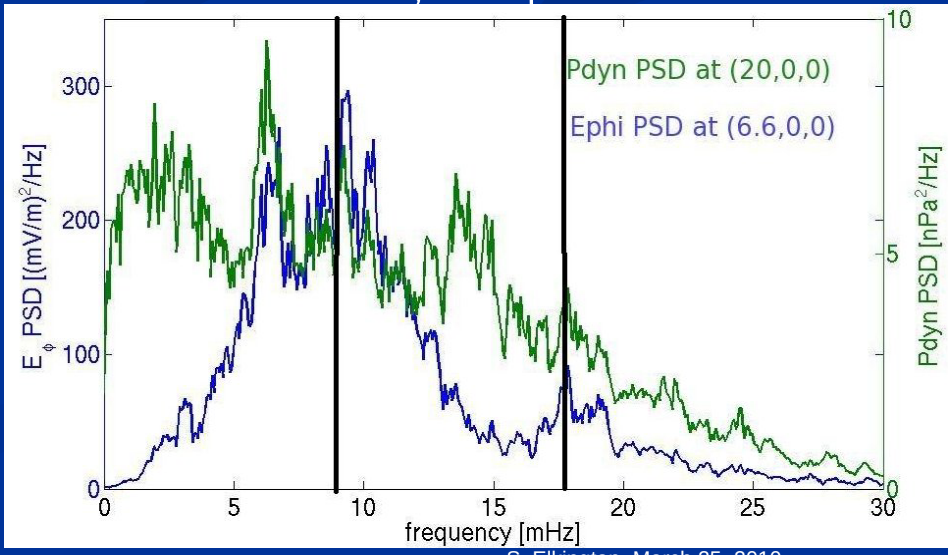
Mode structure, shear waves



Frequency, compressional waves



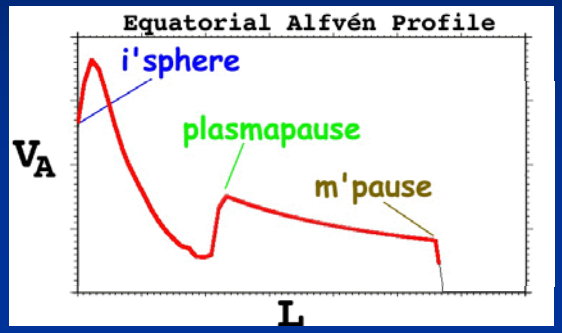
Power at GEO, compressional waves



Can Pc5s be inferred from solar wind conditions?

We wish to understand the relationship between ULF wave power in the solar wind and the distribution of ULF wave power in the magnetosphere.

- Reflections from Alfven gradients
- Field line resonances
- Local time distribution



For a given magnetospheric configuration, we assume that there exists a mapping function that relates the distribution of ULF wave power in the magnetosphere to the driving conditions in the solar wind.

$$P_{mag}(L,\phi,m,f;t) = \Lambda(L,\phi,m,f;\ldots)\cdot P_{sw}(f;t)$$

where Λ may be a function of the independent variables v_{sw}, B_{sw}, δB_{sw}, ρv^2, $\delta(\rho v^2)$, …

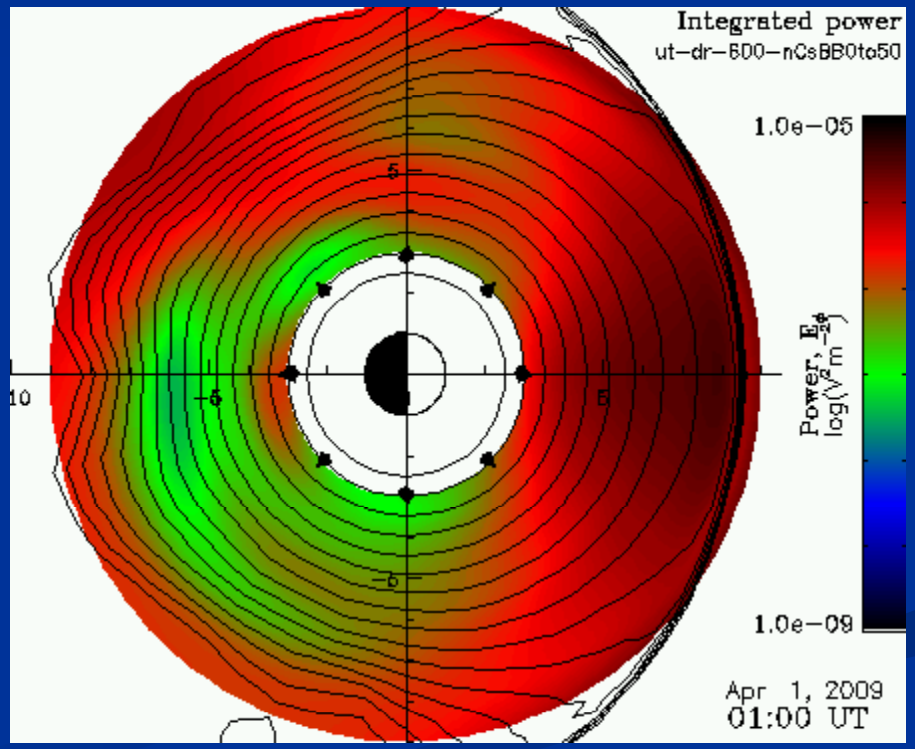
We wish to investigate the functional dependence of Λ on these variables.

Magnetospheric Pc5 scaling with solar wind ULF wave power

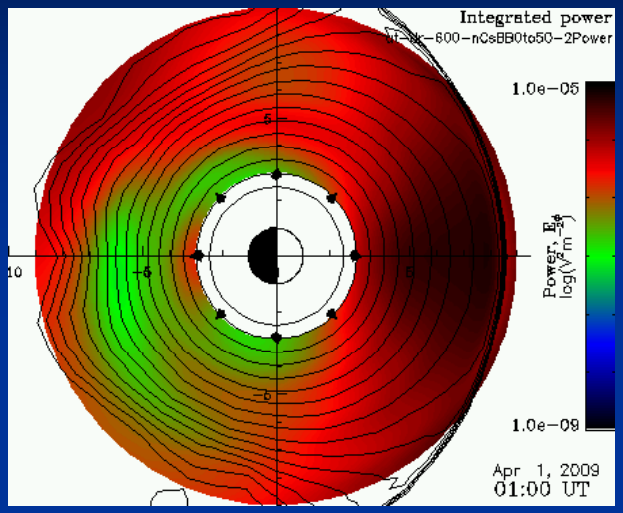
We wish to test the dependence of magnetospheric ULF wave power on the magnitude of the driving perturbations in the solar wind.

- We begin with a baseline run using a constant background solar wind density n_0 of 5 cm^{-3}, constant solar wind velocity of 600 km/s, and a broadband perturbation spectrum δn of 0.05 cm^{-3} applied at frequencies between 0 and 50 mHz at 0.1 mHz intervals.

- We conduct a second, identical simulation where the density perturbation spectrum has been increased such that the power spectrum of pressure fluctuations in the solar wind is twice our baseline run.

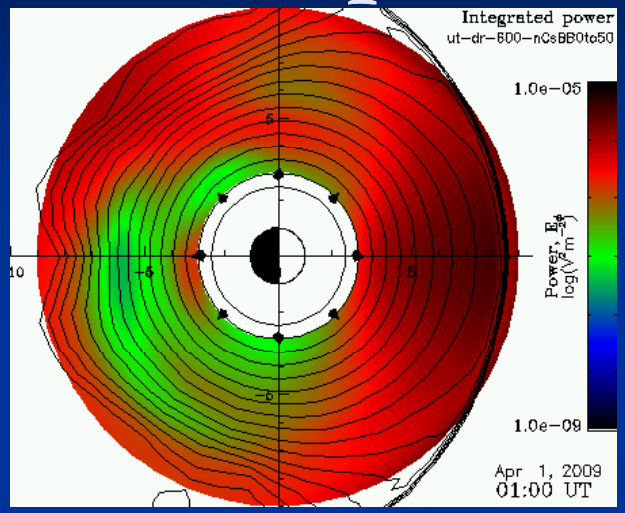


Magnetospheric Pc5 scaling with solar wind ULF wave power



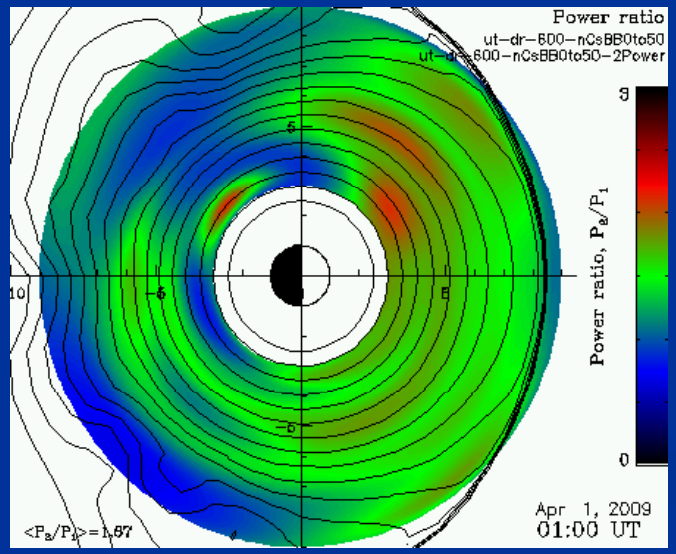
SW pert = $2\delta n$

÷



SW pert = δn

=



- Average ratio of integrated, noonside magnetospheric ULF wave power between 4 and 7 R_E is 1.87
- Average ratio of integrated solar wind pressure power at 15 R_E is 2.0

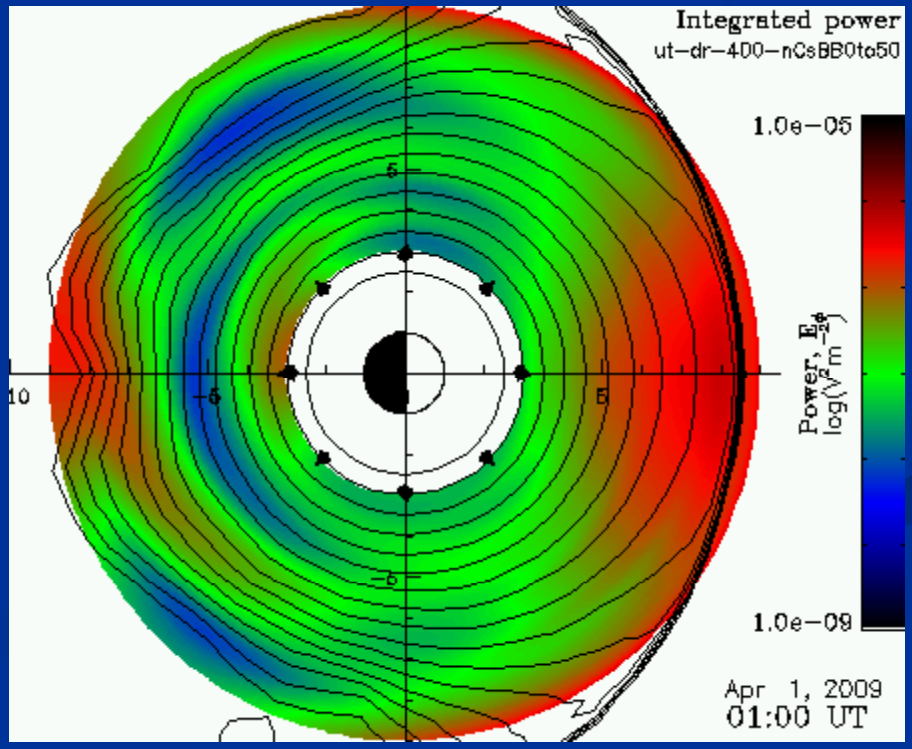
- Suggests a linear, 1:1 correspondence between solar wind pressure PSD and magnetospheric ULF PSD.

Magnetospheric Pc5 scaling with solar wind speed

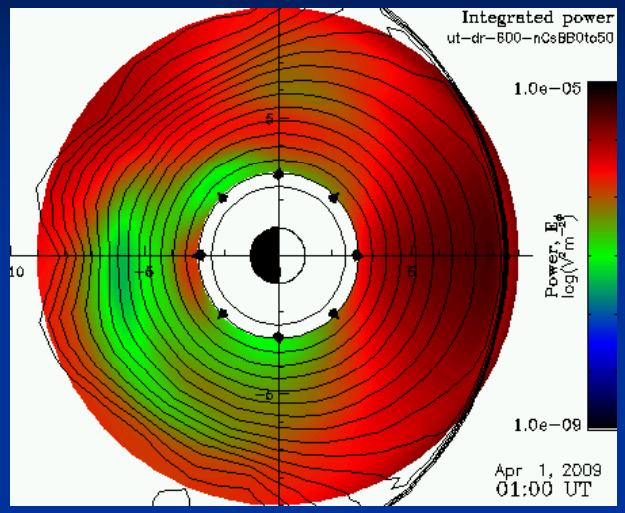
It is well known that magnetospheric ULF power increases with increasing solar wind velocity. Is this a function of larger pressure perturbations associated with higher solar wind velocity (e.g. *Huang et al., JGR 2009*), or a change of magnetospheric state (e.g. onset of magnetospheric waveguide, *Mathie & Mann, JGR 2001*)?

- We use the previous 600 km/s run as a baseline.

- We conduct a second run at 400 km/s with the same input perturbation spectrum, δn = .05 cm^{-3}, but with the background solar wind density n_0 increased by $(600/400)^2$ so that the background dynamic pressure is the same between the two events.

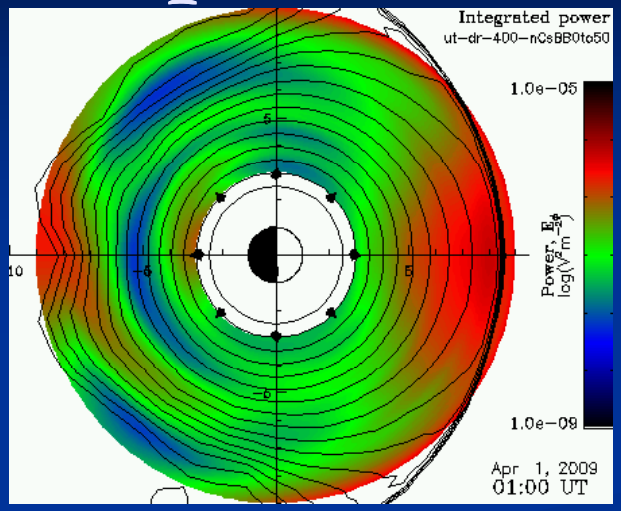


Magnetospheric Pc5 scaling with solar wind speed



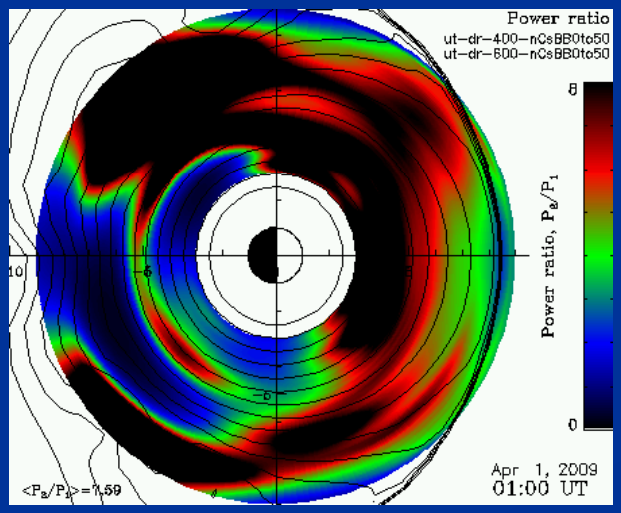
Vsw = 600 km/s

÷



Vsw = 400 km/s

=

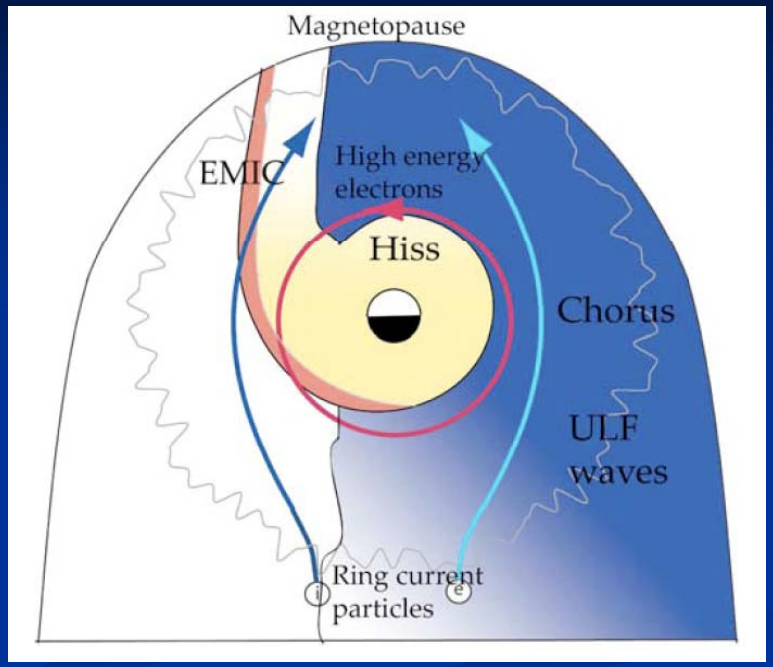


- Average ratio of integrated, noonside magnetospheric ULF wave power between 4 and 7 R_E is 7.59
- Average ratio of integrated solar wind pressure power at 15 R_E is 1.97
- i.e. normalized by solar wind power, this 50% increase in solar wind velocity leads to a 4x increase in magnetospheric wave power.

Pc1-2 ULF waves: EMIC

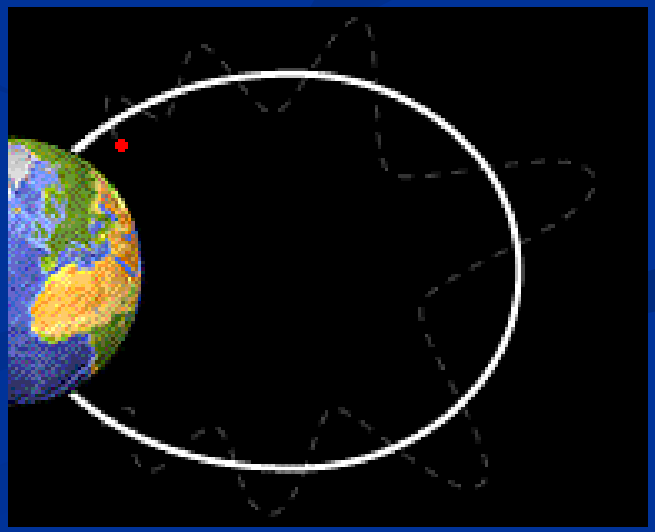
Electromagnetic Ion Cyclotron (EMIC) waves:

- Left-hand circular E/M waves.
- ~0.1-5 Hz frequencies.
- Driven by temperature anisotropies among keV ions, $T_{\perp} > T_{\parallel}$.
- Growth rate depends on cold plasma background.
- Heavy ions may modify EMIC growth and propagation.



EMIC interactions with radbelt electrons:

- Sufficient parallel velocity changes polarization in e- frame.
- Resonant interaction causes diffusion in pitch angle.
  - Loss: precipitation into atmosphere.
  - Acceleration: requires additional VLF wave activity (e.g. Summers et al., chorus)



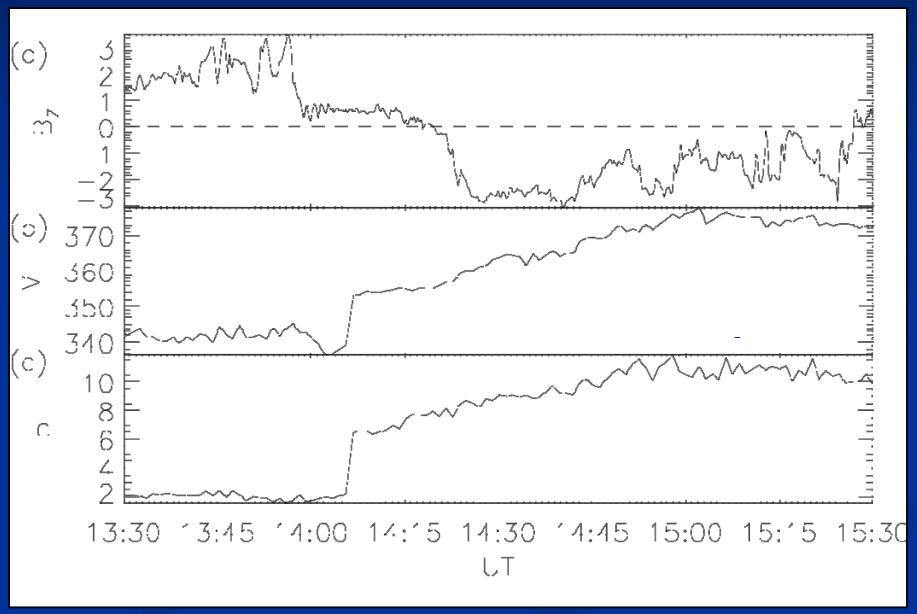
Compression-related EMIC activity

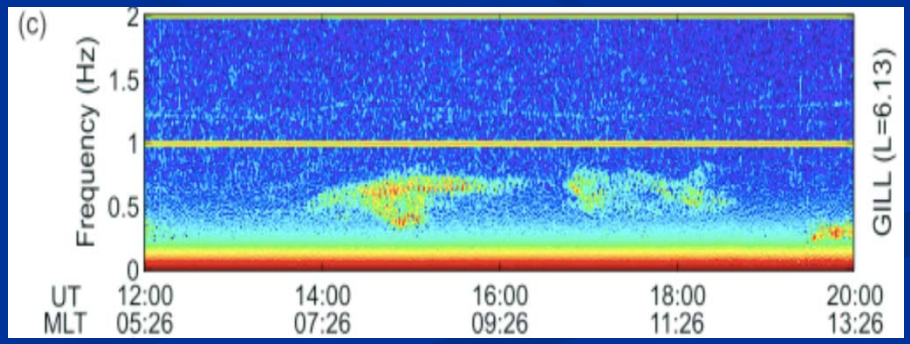
Some EMIC events are clearly associated with increases in solar wind pressure.

- Confined largely to dayside.
- Most activity at L>5.

June 29, 2007 EMIC event *(Usanova et al., GRL 2008):*

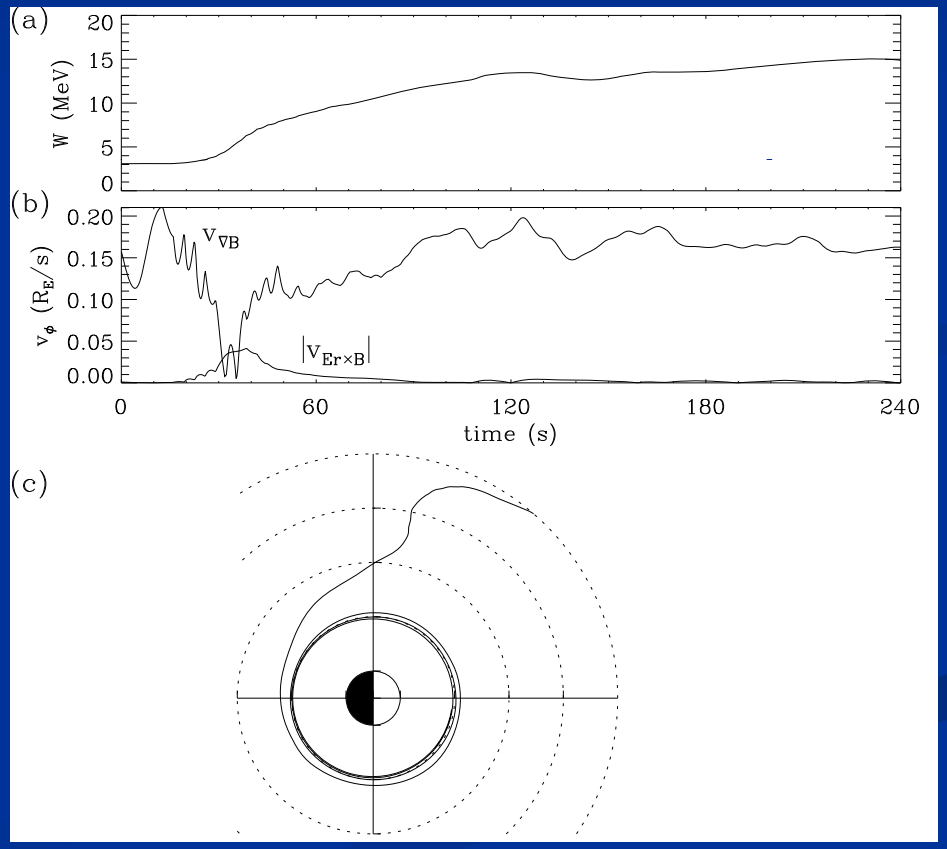
- Simultaneous THEMIS and CARISMA observations.
- Waves observed in narrow band between L~5-7.
- >2h duration.
- Spanned several hours of local time.



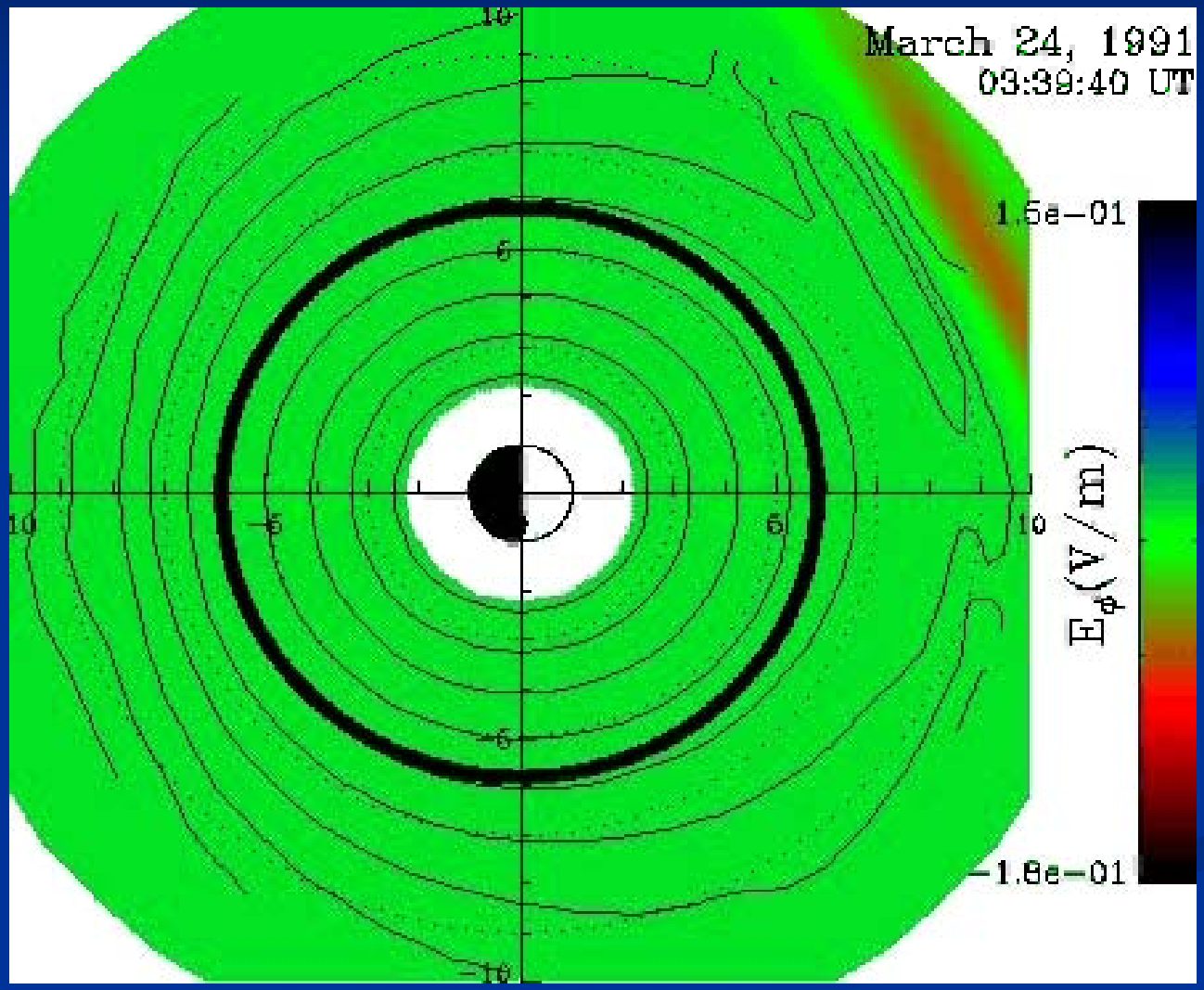


Understanding energetic particle dynamics: test particle simulations

"Test particle" simulations track the equations of motion for a charged particle moving in a model electric and magnetic fields, in an attempt to better understand the physics and dynamics of the energetic particle environment.



March 1991: MHD/particle simulations



Test particle simulations of EMIC growth potential

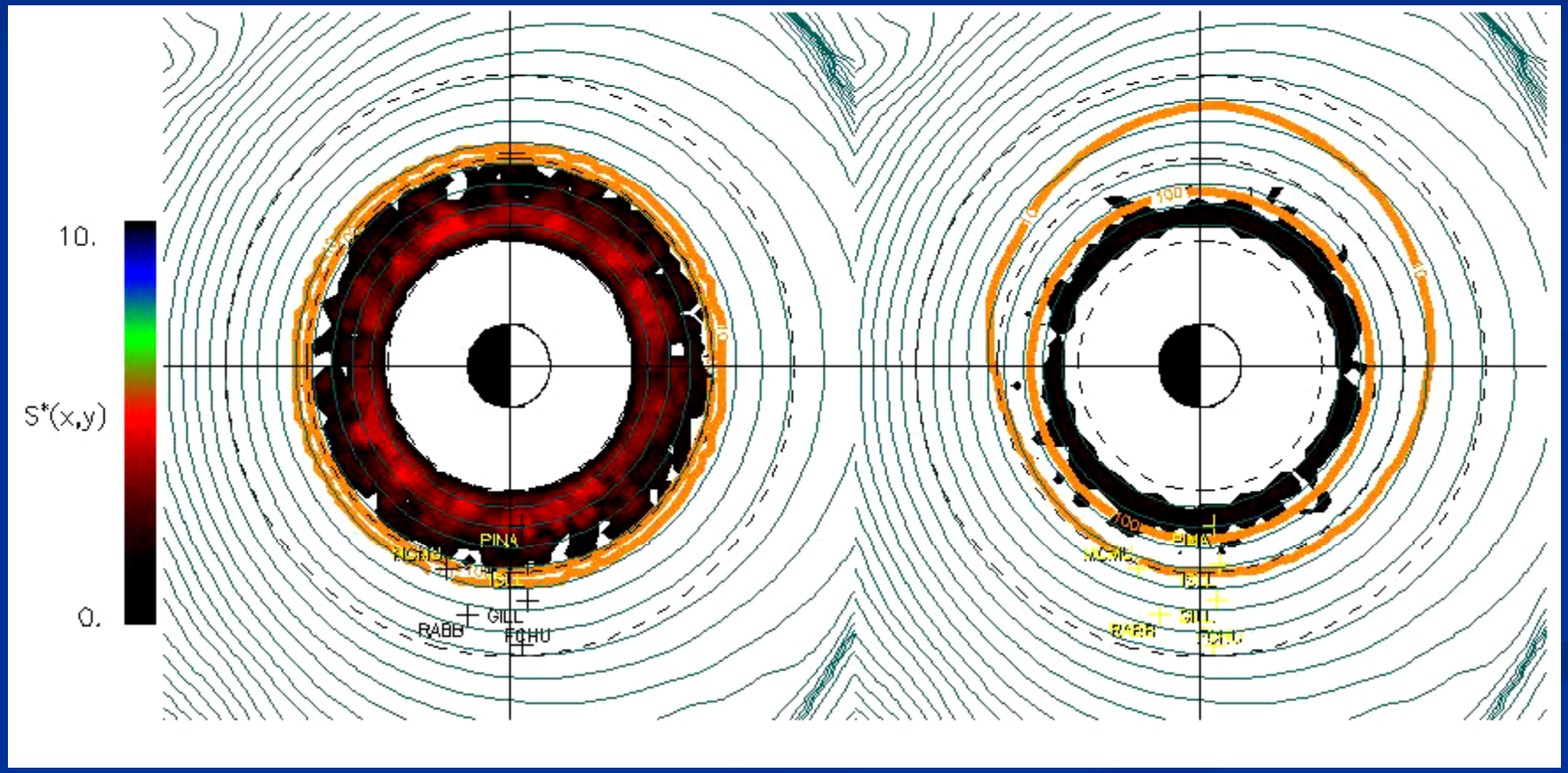
Ideal MHD simulations do not allow for calculation of temperature anisotropies, and do not include wave activity at Pc1-2 frequencies.

Is there a numerically-tractable way to study the global development of EMIC waves in a dynamic, time-dependent fashion?

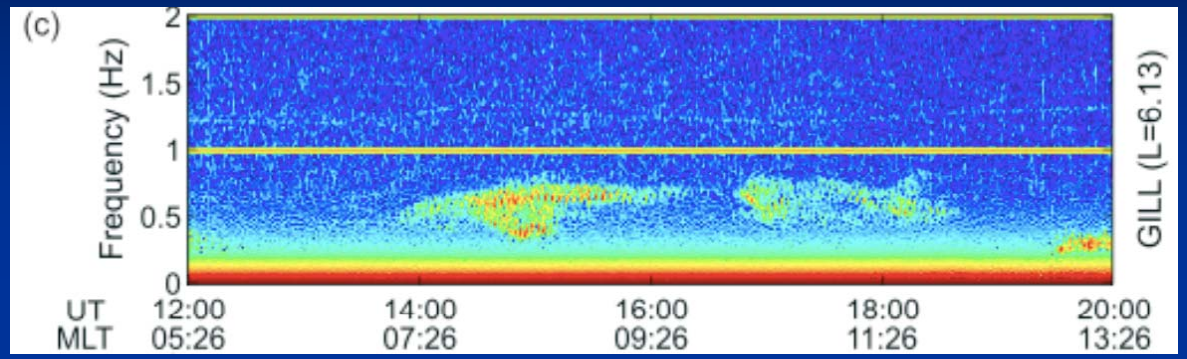
Test particle simulations:

- Use MHD/particle method to track trajectories of warm heavy ions (H^+, He^+, O^+) in response to compressions in the solar wind.
- Calculate bulk quantities $T_\perp$,$T_{||}$ for the ensemble; apply empirical cold plasma model.
- Calculate EMIC wave *growth rate* to infer where, when, and spectral properties of EMIC waves (e.g. a la *Kozyra et al.* [1984]).

EMIC growth rate calculations from MHD/particle simulations

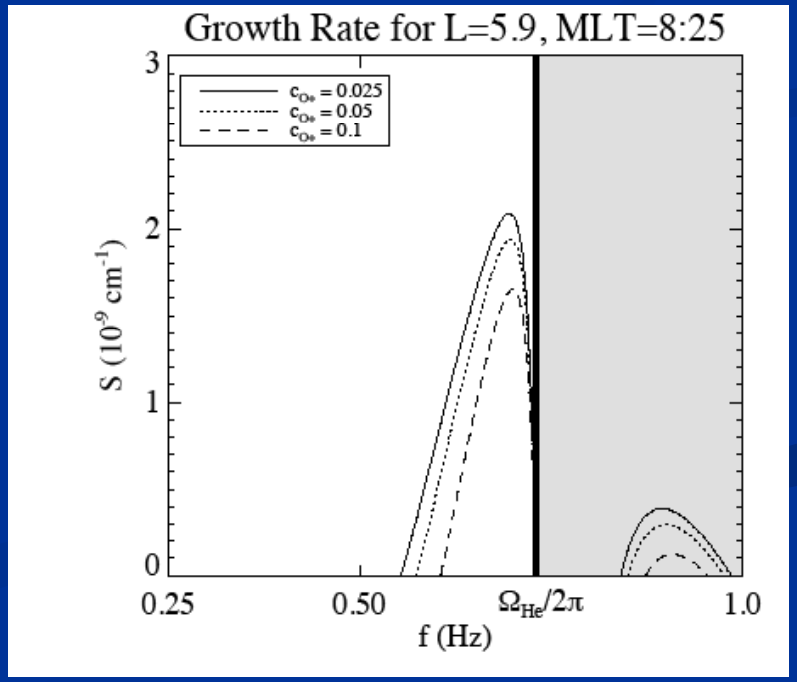


Spectral characteristics



The Spectrogram for the Gillam magnetometer station in Canada for 29 June 2007

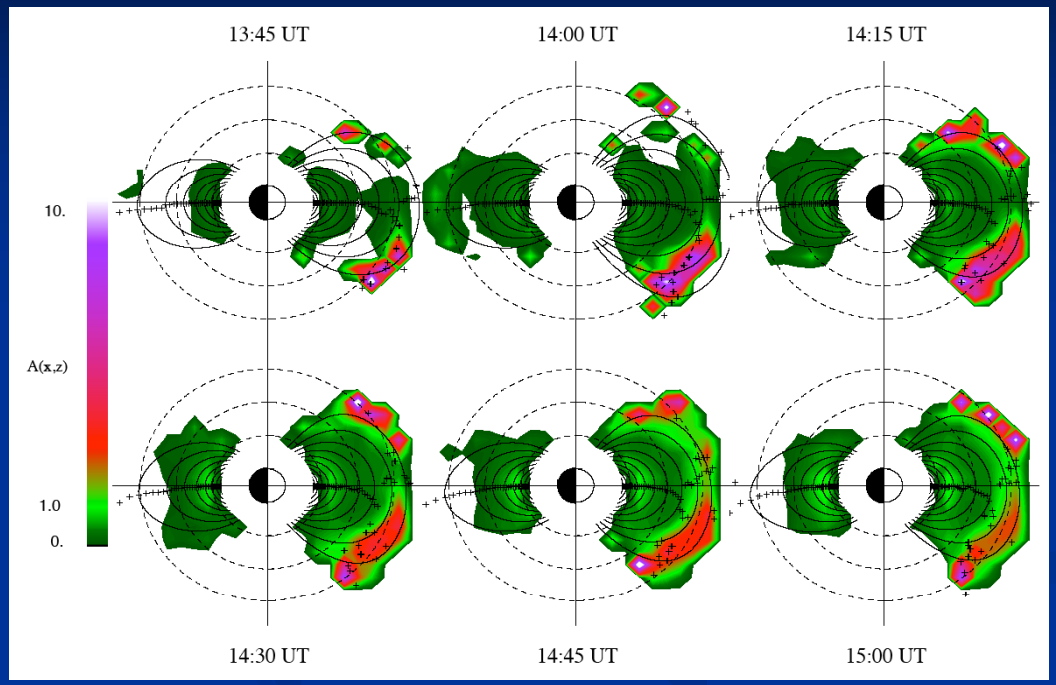
- This is $S(\omega)$ for L=5.9 and MLT=8:25
- The vertical line indicates the local He^+ gyrofrequency.
- Notice the peak frequency is around 0.7 Hz and there is growth a good deal beyond 1.0 Hz.
- Any further discrepancy with the spectrograms from CARISMA and THEMIS are likely due to ionospheric ducting and uncertainties in cold and hot ion composition.

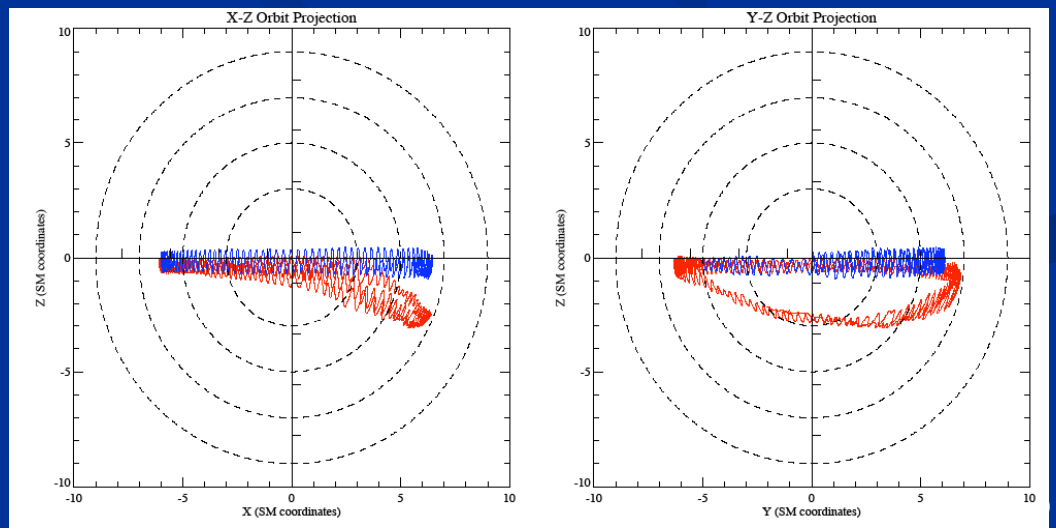


Compressionally-driven EMIC: Shabansky orbits?

Dayside compression of the magnetosphere can lead to off-equatorial magnetic minima, modifying the drift trajectory of the particles in this region [*Shabansky, 1971*].

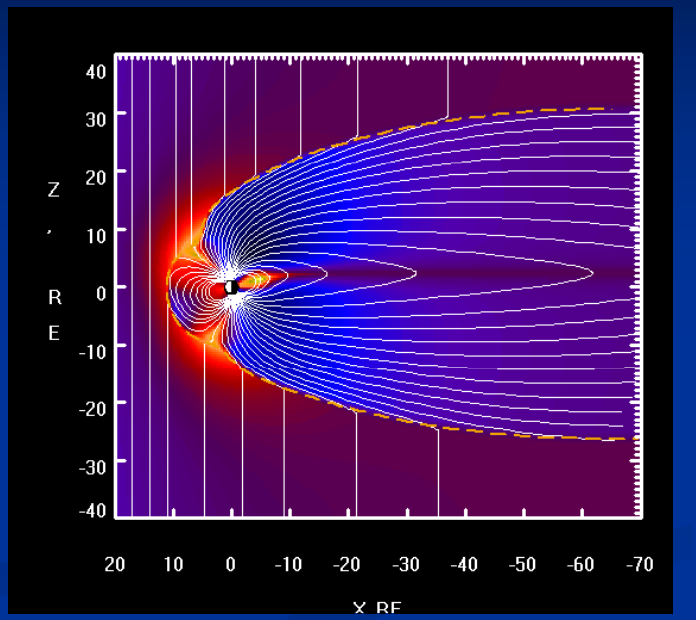
- High initial EPA particles mirror without passing through the equator; low initial EPA particles pass through but with higher EPAs; this leads to a temperature anisotropy at the equator.
- Lower initial EPA particles have roughly unchanged pitch angles at higher latitudes, but on top of that population is the high initial EPA particles; this leads to temperature anisotropy off the equator.
- Drift shell splitting may exacerbate the anisotropy off the magnetic equator.

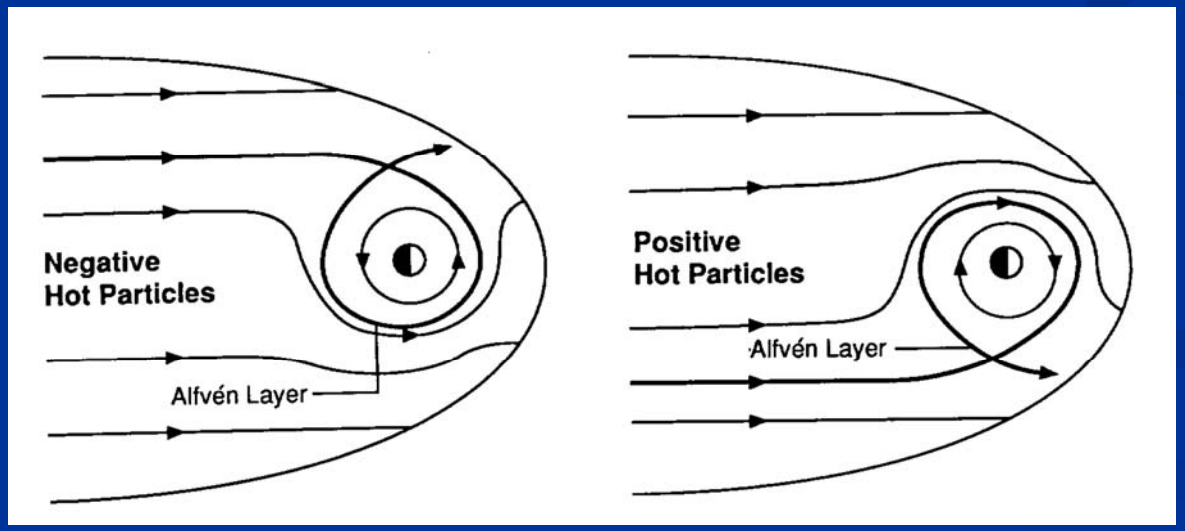




Sources or Losses: boundary conditions?

- Lower-energy particles in the tail are driven Earthward as a result of convection driven by reconnection.
- As they approach Earth, the stronger magnetic fields heat the particles and cause them to begin to drift in orbits around the Earth.
- Particles are those that approach close enough to cross the 'Alfven layer' may be trapped, and subsequently heated to higher energies.

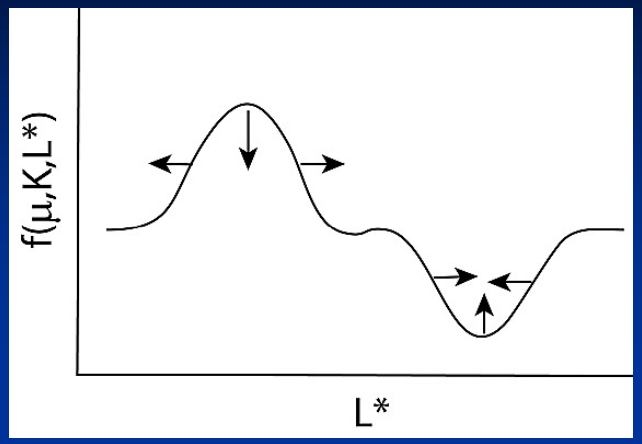


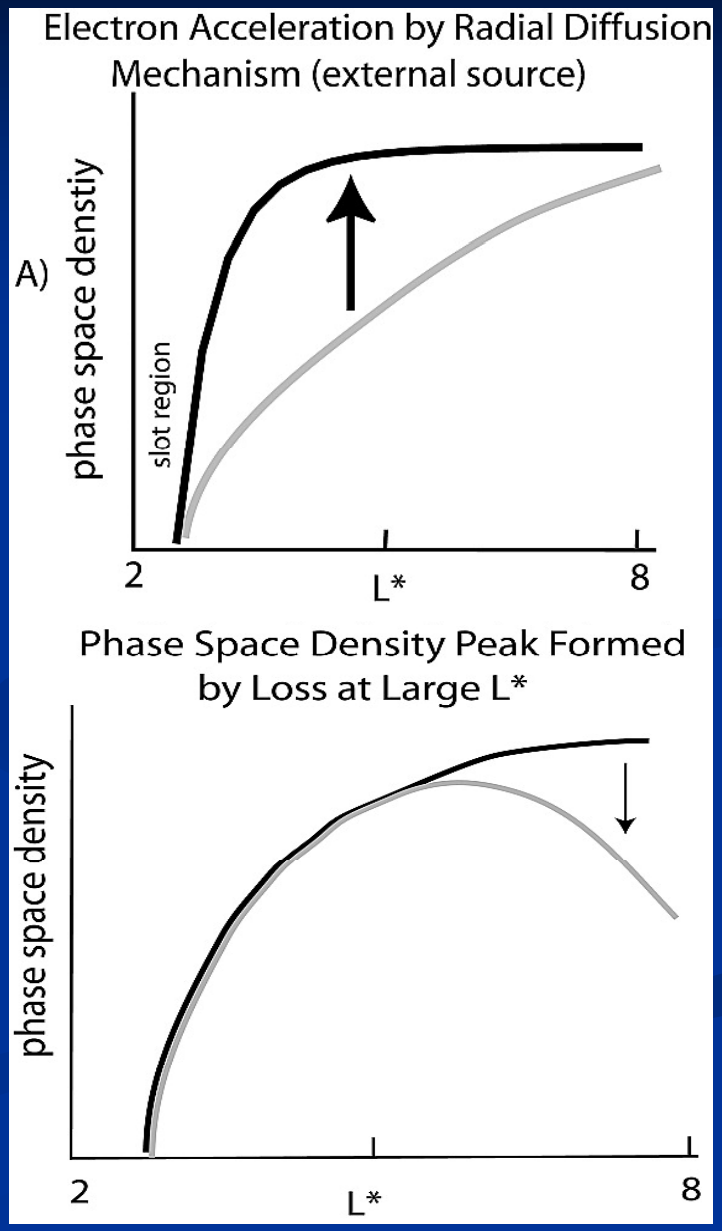


$$r_0 = L_0 R_E = \left[\frac{3\mu B_0 R_E^3}{|q| E_0} \right]^{\frac{1}{4}}$$

- $r_0 \sim 20\ R_E$ for $M \sim 1$ MeV geosynchronous electron
- W for r_0=6.6RE is 50 keV.
- Does diffusion always act as a loss process?

Stochastic transport: Fick's law



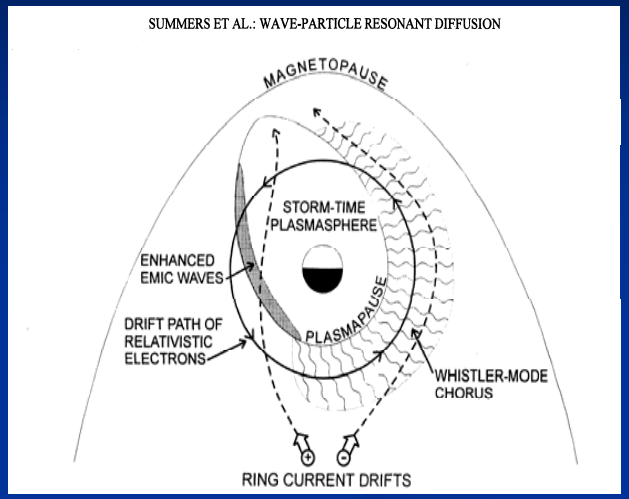


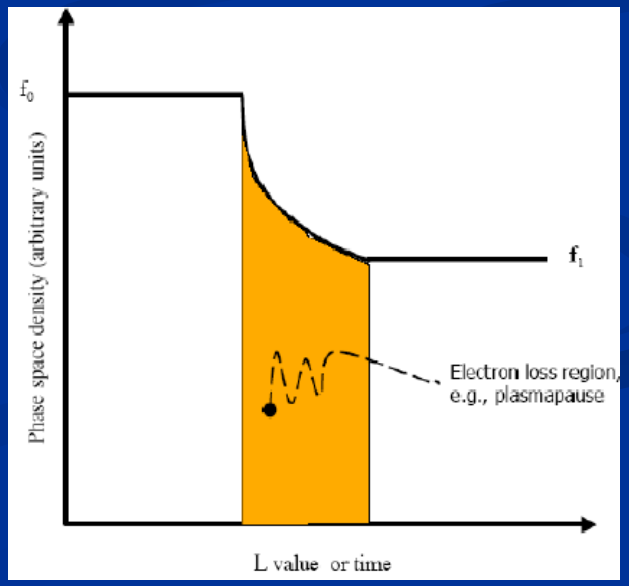
Diffusion will act to *smooth out gradients* in the distribution function. In the radiation belts, the net effect of radial diffusion depends on the phase space gradient in *L*:

- High *f* at outer boundary, acts as a source.
- Low *f* at outer boundary, may act as a loss.

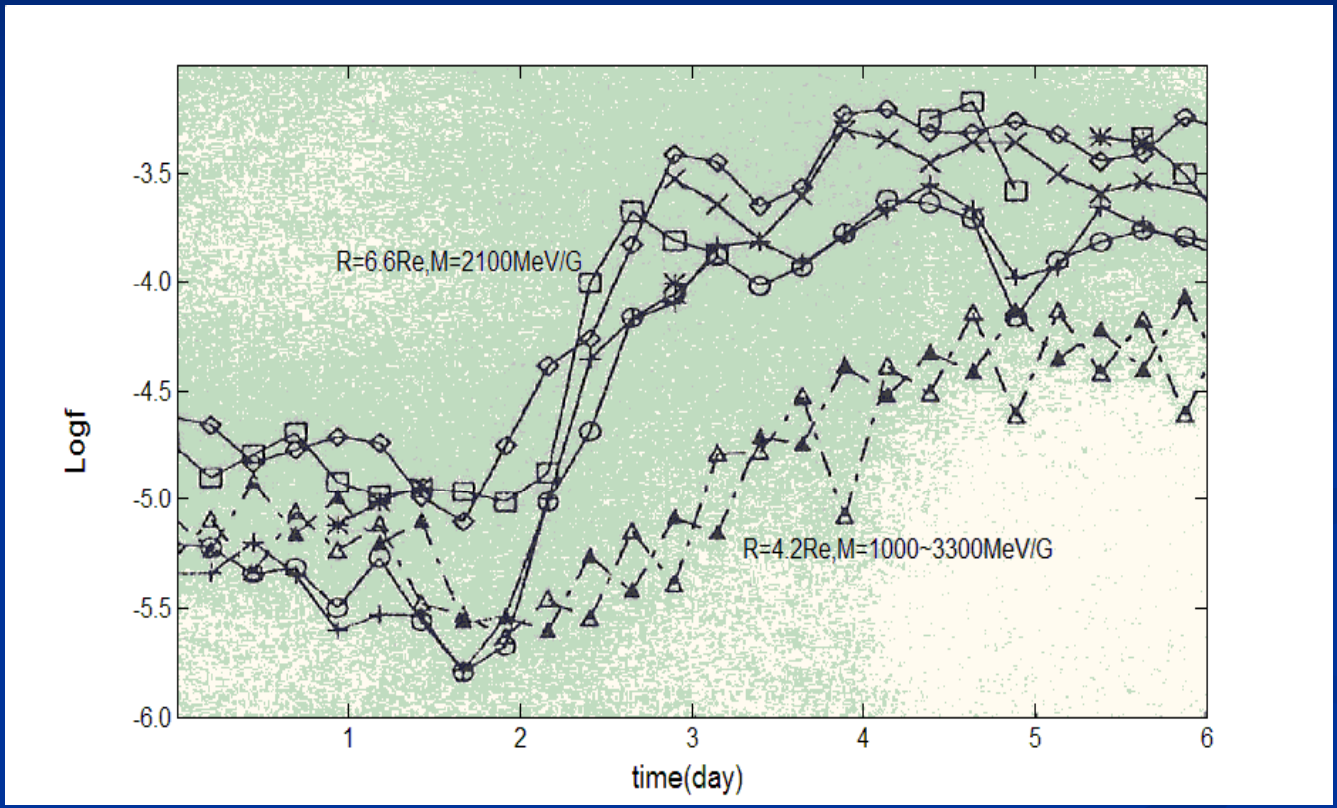
Test particle simulations: Incorporating losses due to EMIC

Interactions with non-MHD waves may be accounted for in an ad hoc way by appropriately adjusting the phase space density along each trajectory when the particles pass through regions where such waves occur (e.g. the plasmapause).



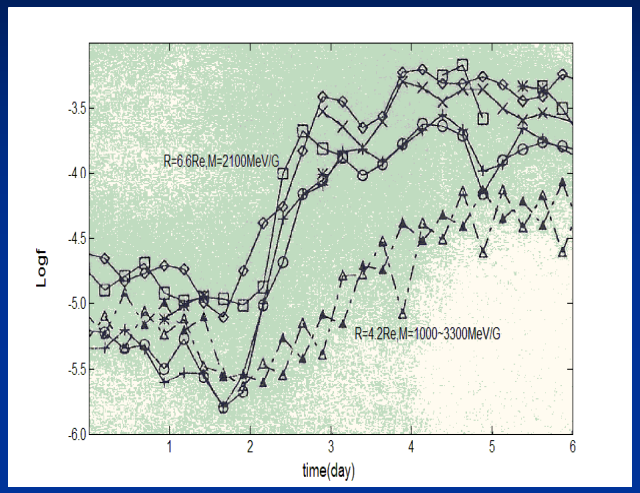


January 1995 storm: radbelt response at GEO (6.6Re) and GPS (4.2Re)



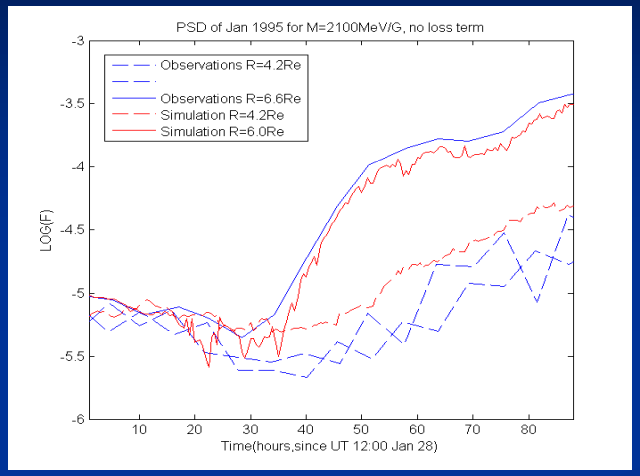
Hilmer et al., *[JGR, 2000]* examined energetic electrons at geosynchronous and GPS altitudes for the January 1995 event, concluding that the observations were consistent with a source at/beyond geosynchronous.

Test particle simulations of the georadiation environment: January 1995



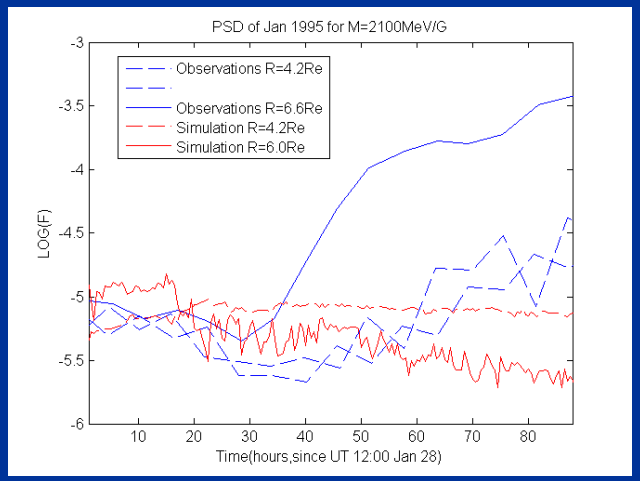
Observations *[Hilmer et al., JGR 2000]*

(b)



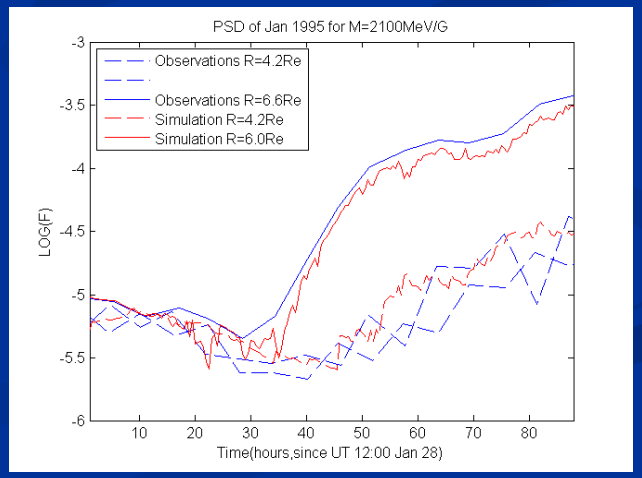
Simulations: GEO boundary, infinite lifetime (*f* too high at GPS).

(a)



Simulations: free boundary, infinite lifetimes (pretty much sucks).

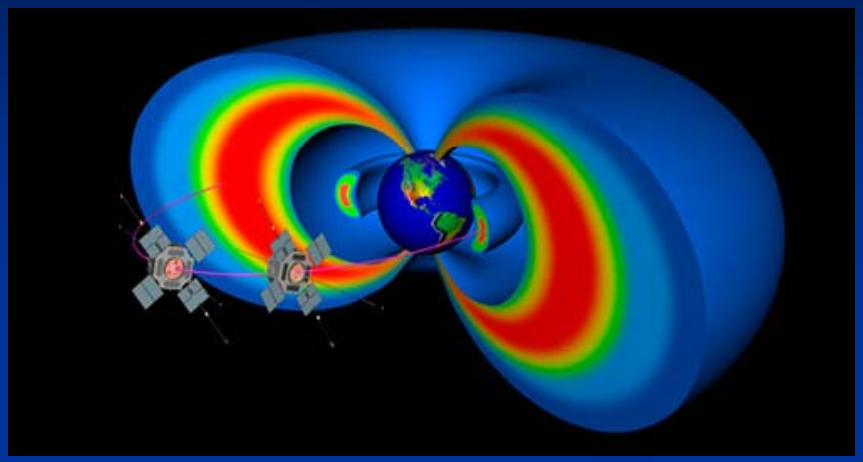
(c)

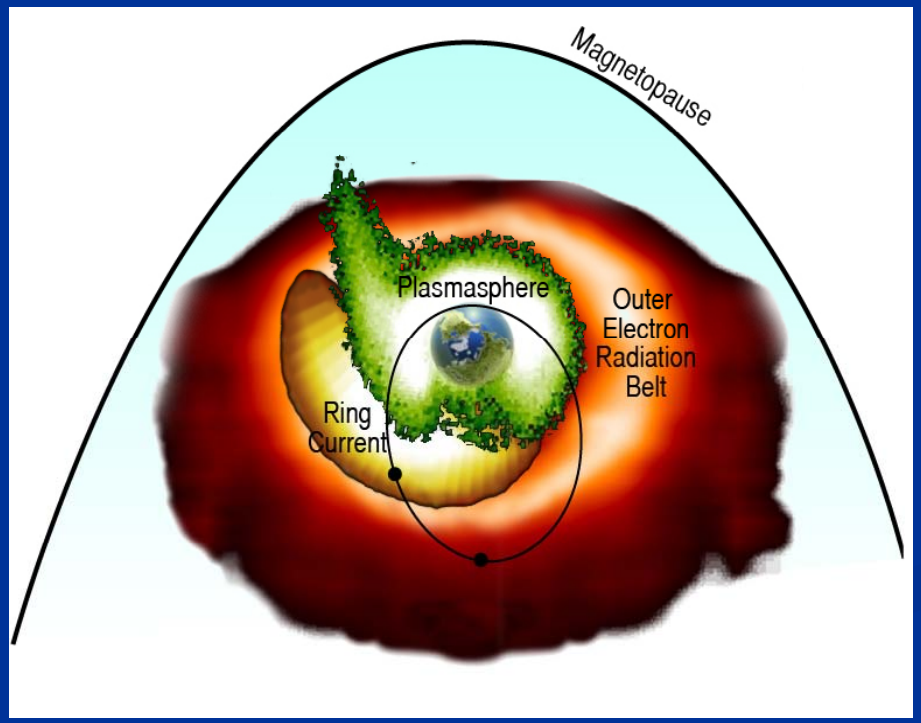


Simulations: GEO boundary, EMIC-limited lifetime (not bad!)

Radiation Belt Storm Probes (RBSP)

RBSP is a NASA mission designed to study the radiation belts and the waves which drive their dynamics. It consists of two spacecraft, each identically instrumented to provide field and energetic particle information along their orbit.

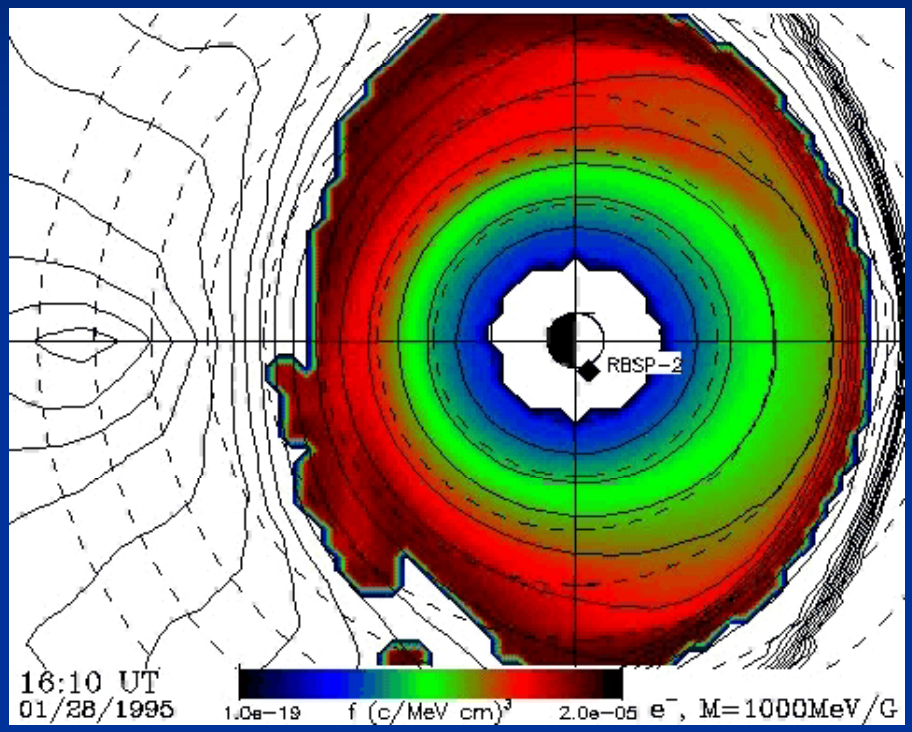




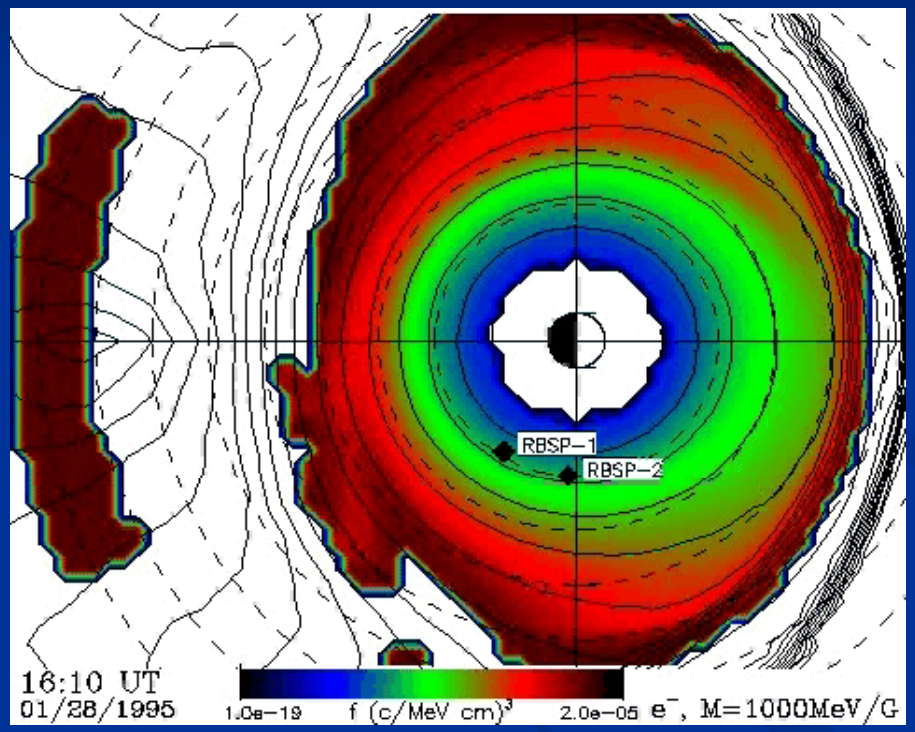
- RBSP Nominal Orbit:
  - **'String of pearls' configuration**
  - **Perigee: ~500 km**
  - **Apogee: 5.8 R_E (altitude 30,615km +/-350km**
  - **Inclination: 10 deg +/- 0.1 deg**
  - **Lapping rate: twice in one local time quadrant (~ 4-5 times/year).**

Global PSD simulations of the January 1995 event

Interval 1, 2

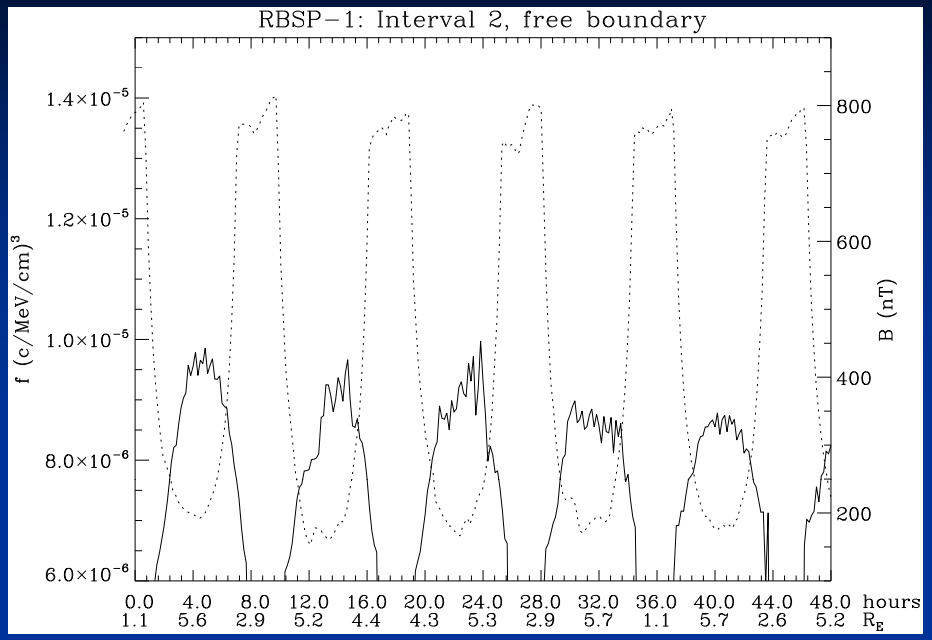


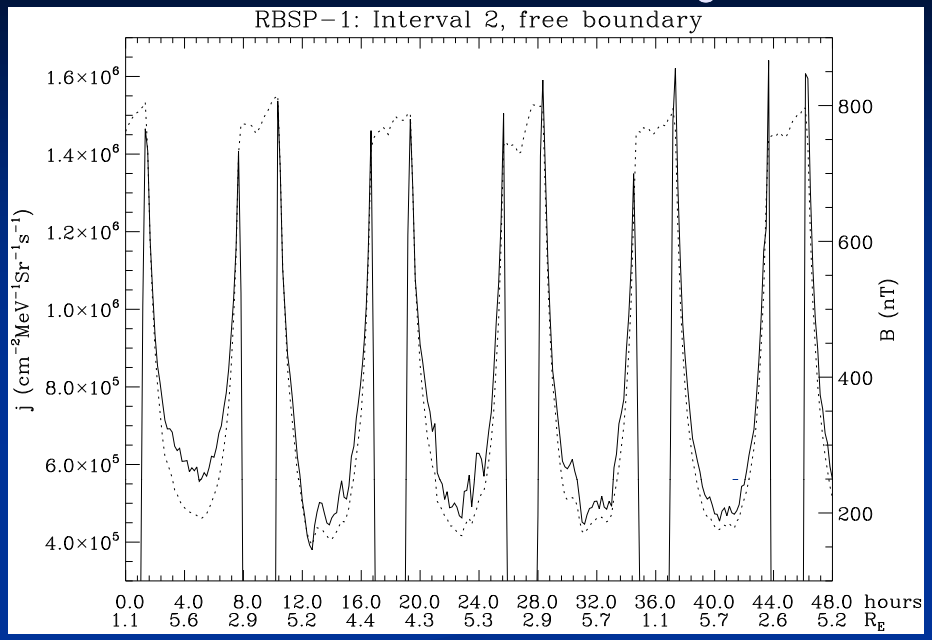
Interval 3



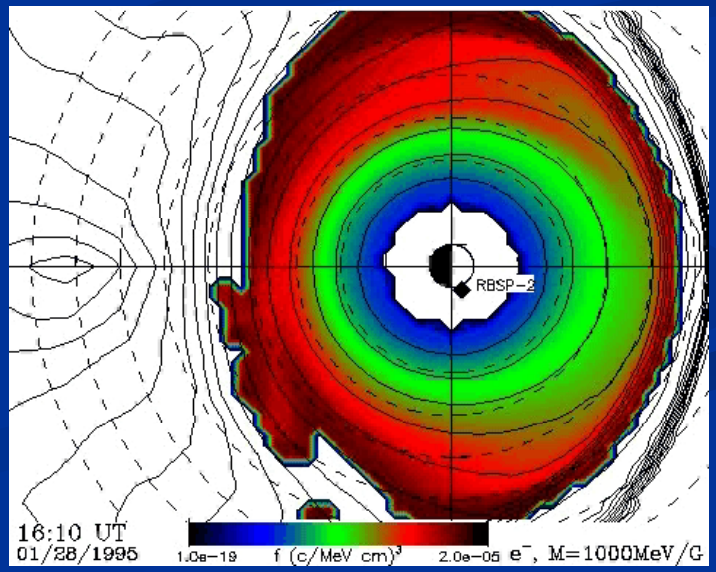
- Global 3d MHD (via LFM) driven by upstream BC from WIND.
- 3 R_E inner boundary.
- 1000 MeV/G electrons.
- Trapped inner belt population; trapped population + plasmasheet population at 19 R_E.

RBSP observations: free boundary

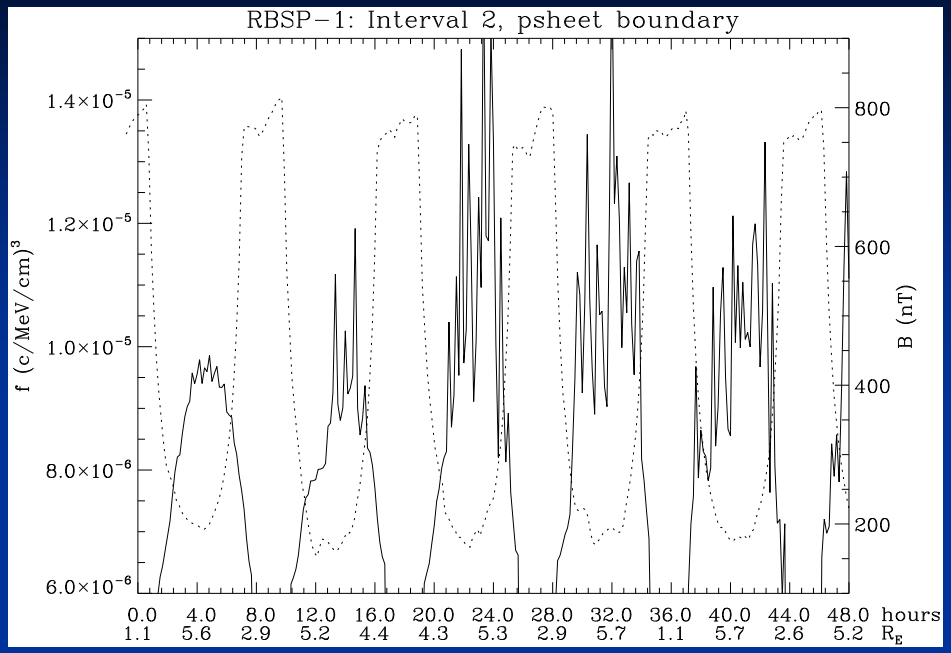


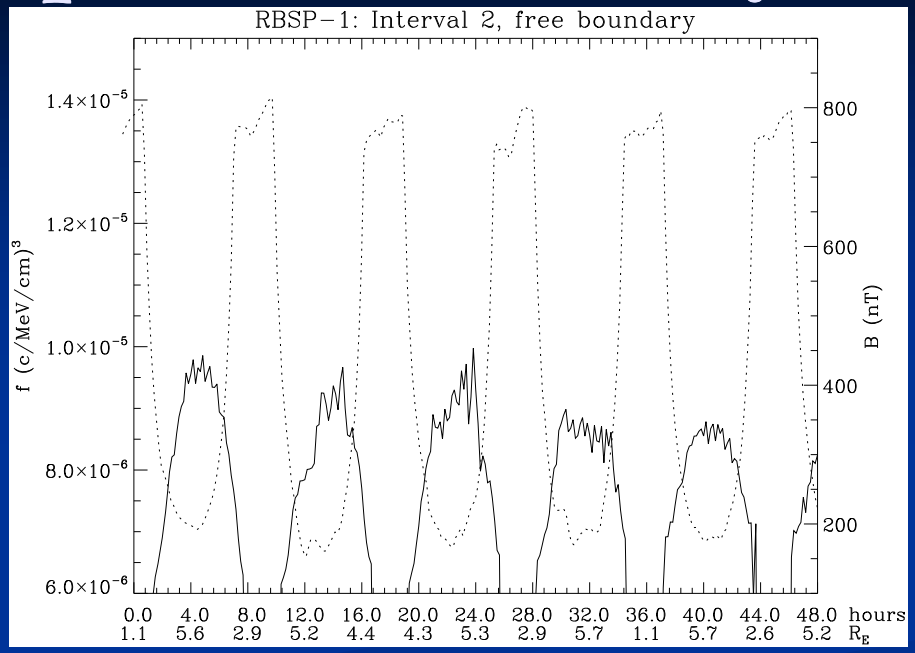


- Phase space density at apogee decreases in time.
- Flux may show some affects of variations in magnetic field.
- RBSP-1 and -2 show nearly identical variations in time in this interval.

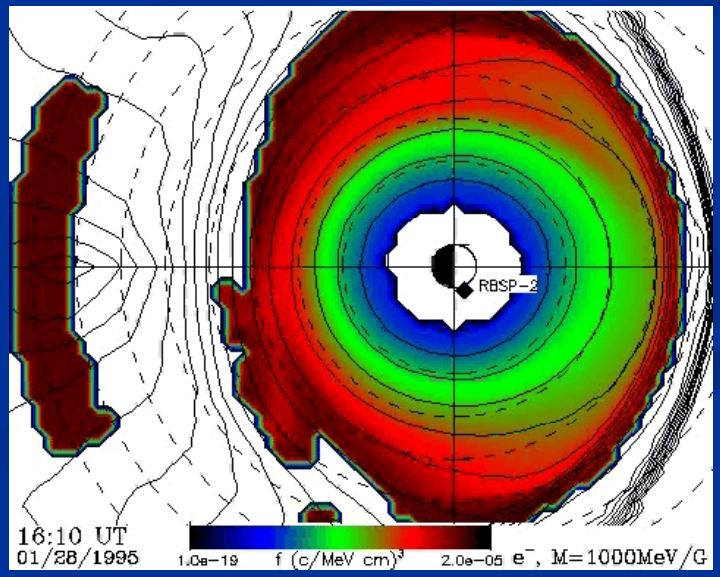


RBSP observations: psheet boundary





- Phase space density increases during periods where plasmasheet particles have access to the inner magnetosphere.
  - Clear injections after orbit 1
  - Alfven layer outside last trapping shell after orbit 3.



Summary/Conclusions

ULF waves are capable of modifying radiation belt dynamics in the outer zone radiation belts.

- Global Pc5 waves:
  - Driven by pressure fluctuations, shear interactions at the m'sphere flanks, and/or Alfvenic fluctuations in the solar wind.
  - mHz frequencies.
  - Acts as a source or loss in the radbelts, depending on boundary conditions.
  - Can we predict or infer Pc5 activity based on solar wind conditions?
- Pc1-2 EMIC waves:
  - Driven by temperature anisotropies among warm (keV) ions in the inner magnetosphere; cold plasma density is critical for growth rate.
  - Hz frequencies.
  - Generally acts to deplete the radiation belts by bouncing particles into the atmosphere.
  - New evidence for Shabansky generation of EMIC waves (McCollough, 3:30pm, 3/29)
- MHD/particle simulations provide a powerful tool for examining the collective effect of ULF waves on radiation belt dynamics.

Thank you.