Wave-Particle Interactions in the Radiation Belts of Earth and Jupiter

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WPI - Plasma Regiemes

- Lab plasmas
  - Controlled experiments possible,
  - limited regiemes – e.g. collisional
- Planetary magnetospheres/ionospheres
  - In situ measurements
- Solar/solar wind/astrophysical
  - Remote sensing
- Earth system
  - Understand physical processes
  - Verify
  - Export knowledge to other areas
    - scaling

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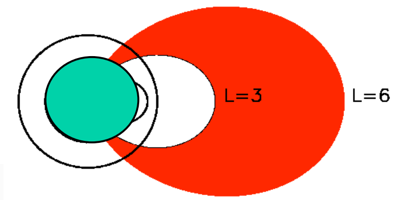
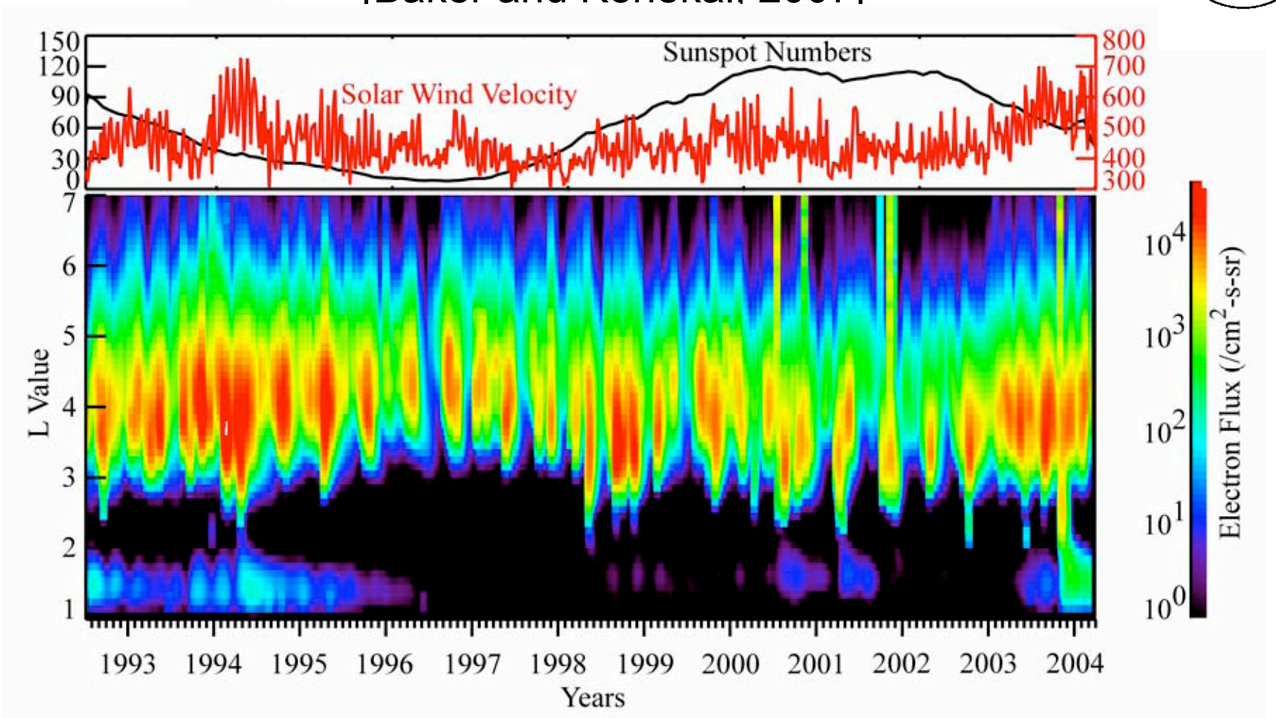
Radiation Belts - The Problem



[Baker and Kenekal, 2007]



- Solar wind velocity related to electron flux variations inside the Van Allen radiation belts
- Flux variations are due to acceleration, transport and loss inside the magnetosphere
- How do you produce >1 MeV electrons from a source of ~ keV electrons?

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Electron Flux During Magnetic Storms

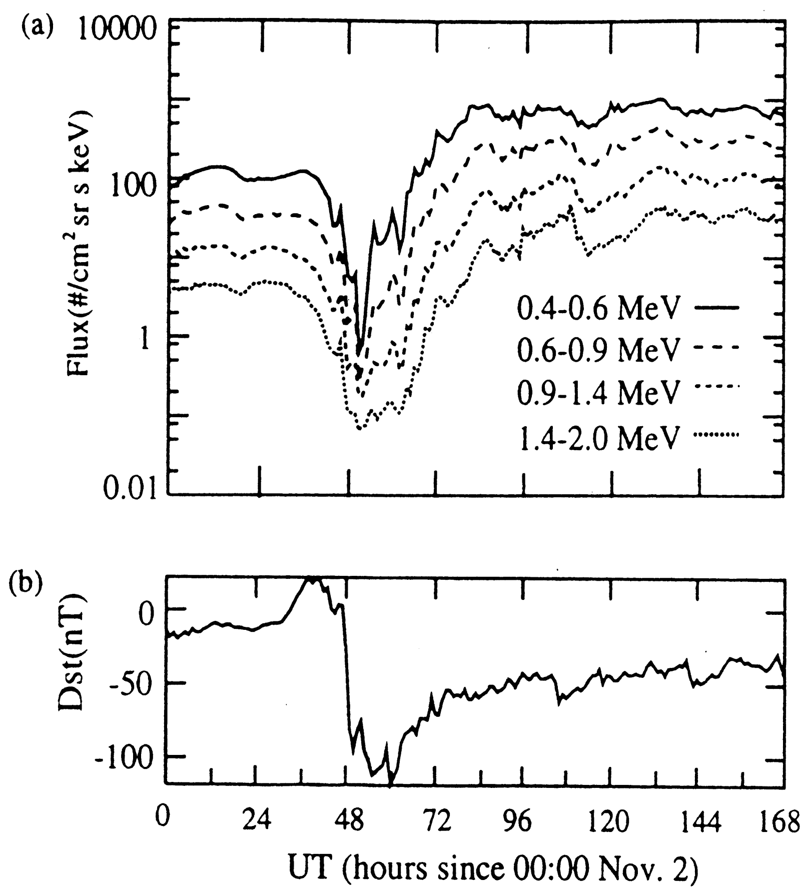

Figure 1. (a) Hourly averaged electron flux variation at GEO for November 2–8, 1993, measured by the CPA instrument on the LANL spacecraft 1984–129 (LT = UT + 0.5) for four high-energy channel and (b) *Dst* variation for the same time period.

- Flux increases above pre-storm level before Dst recovered
- Non adiabatic
- Net acceleration
- Timescale ~ 1-2 days

Kim and Chan, [1997]

Electron Acceleration

By 1998 – Established:

- Acceleration is internal to magnetosphere [Li et al., 1997]
- MeV electron flux correlated to fast solar wind (> 500 km/s)

Two new theories developed:

- Acceleration by ULF waves (breaks 3rd invariant)
  - Hudson et al. [1999]
  - Elkington et al. [1999]

- Acceleration by wave-particle interactions (breaks 1st invariant – all 3)
  - Horne and Thorne [1998]
  - Summers et al. [1998]

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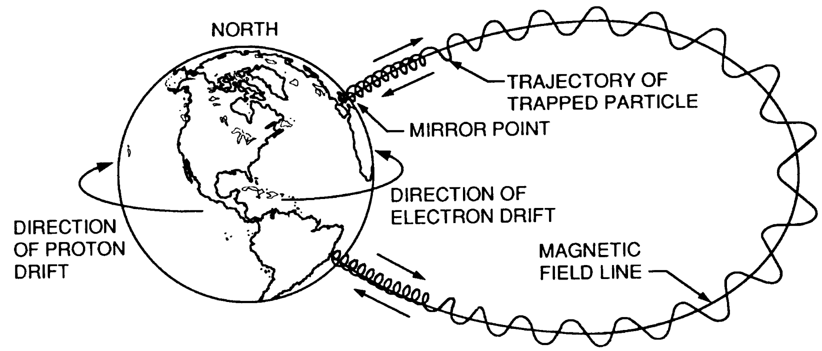
Adiabatic Invariants

$$\mu = M = \frac{p^2 \sin^2 \alpha}{2 m_0 B}$$

$$\mathbf{J}_2 = 2 \oint_{m1}^{m2} p_{\|} dl$$

$$\mathbf{J}_3 = q \int \mathbf{B}.d\mathbf{s} = q\Phi$$



- Cyclic motion
  - 3 adiabatic invariants
- If conserved
  - no net acceleration or loss
- Acceleration requires breaking 1 or more invariant
- Requires E, B fields at frequencies
  - drift ~ 0.1-10 mHz
  - bounce ~ Hz
  - gyration ~ kHz

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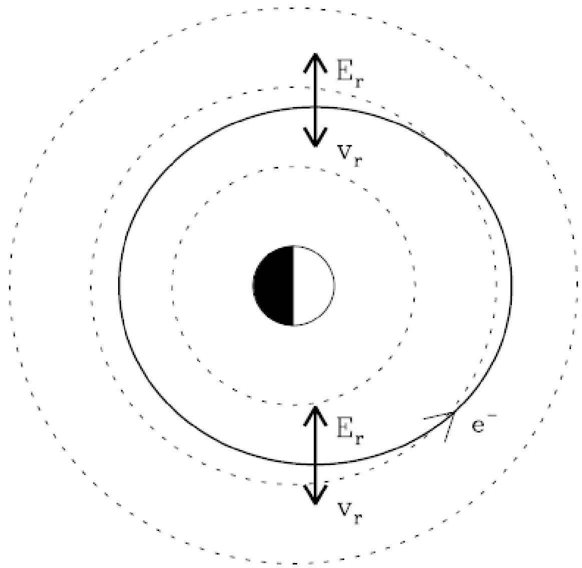
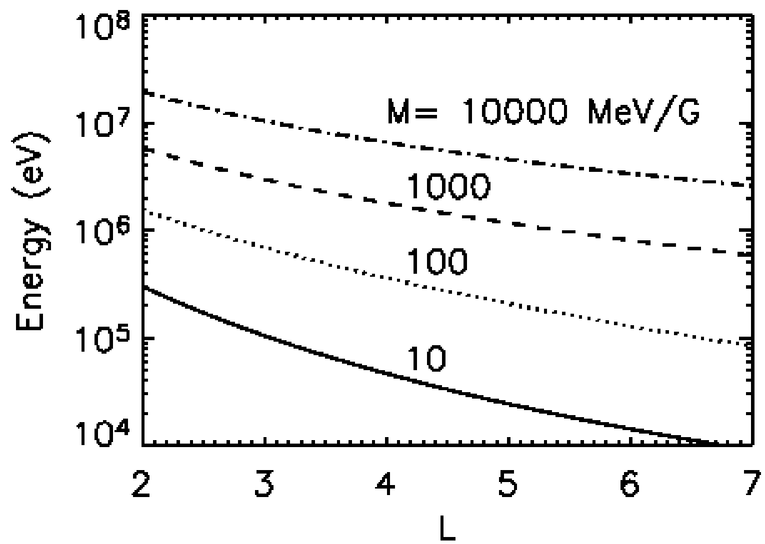
Inward Radial Diffusion





- Fluctuations in E, B fields
  - ULF waves f ~ mHz
  - ~ Pc5
- Gradient in phase space density
  - Transport
- Breaks 3rd invariant
- Conservation of 1st + 2nd invariant
  - Betatron and Fermi acceleration
- Too slow
  - but enhanced by ULF waves at f ~ mHz

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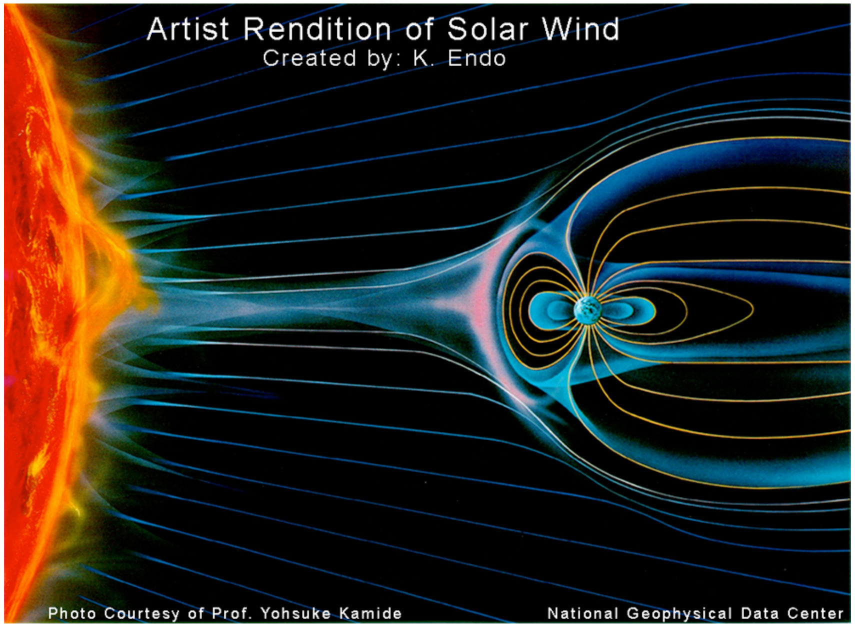
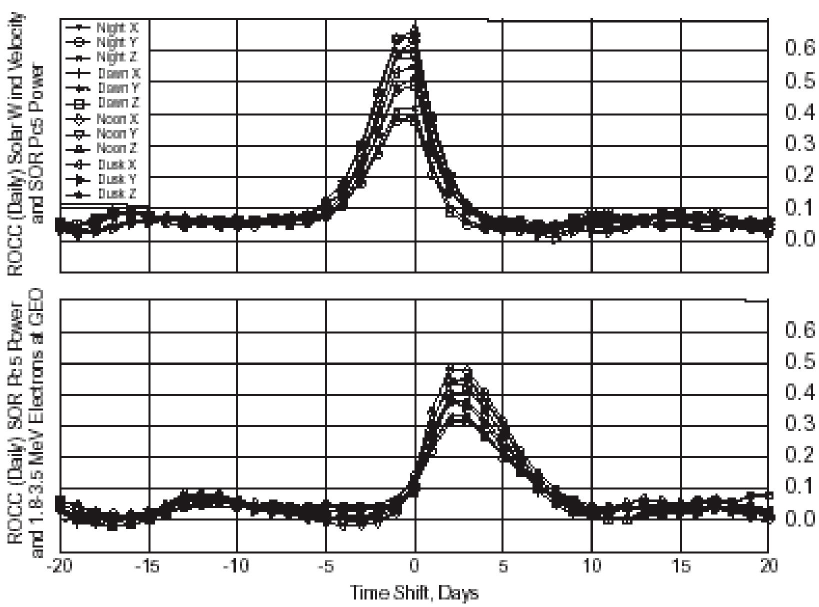


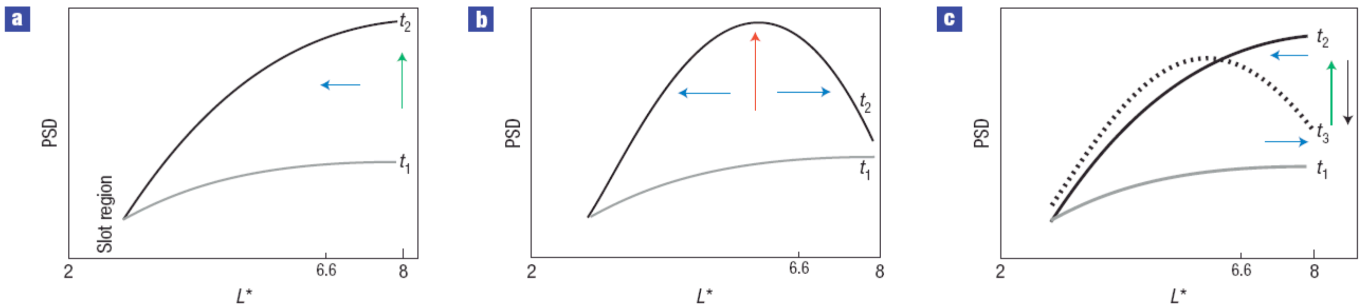
Source of ULF Waves

- Fast solar wind drives Kelvin Helmholtz instabilities
- SW pressure variations
- Both drive ULF wave power inside magnetosphere

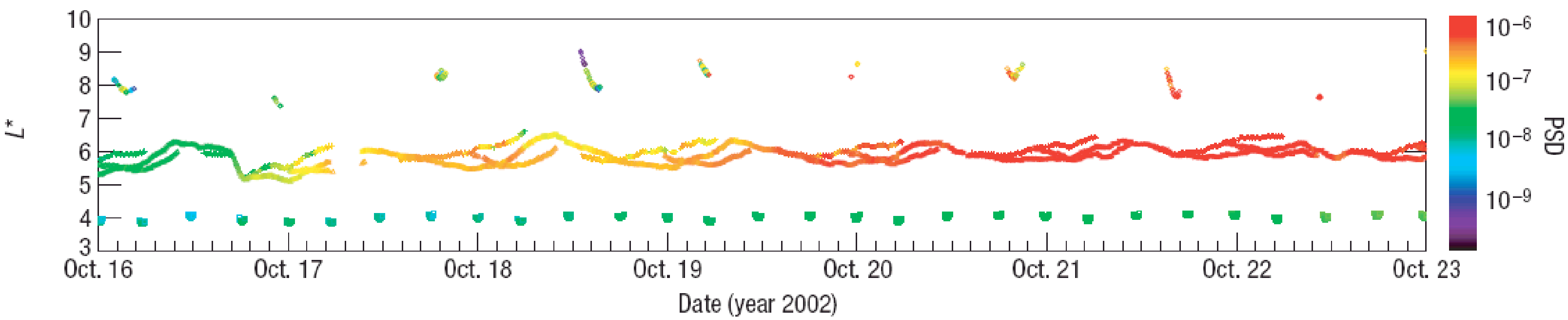


- Solar Wind velocity correlated with ULF (Pc 5) waves [Mann et al., 2004]
- ULF waves (Pc5) correlated with 1.8 MeV electrons (GEO)
  ~ 2 day delay
- Peak correlation during declining phase of solar cycle
  – 1994 - 1995

Evidence for Local Acceleration



- If inward radial diffusion (Fermi and Betratron acceleration) then peak must occur for L > 6.6 Re



- But - peak observed near L = 5.5 first
- So - cannot be inward radial diffusion
- Must be local acceleration (gyro-resonant)

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[Chen et al., Nature Physics, 2007]

Wave Acceleration

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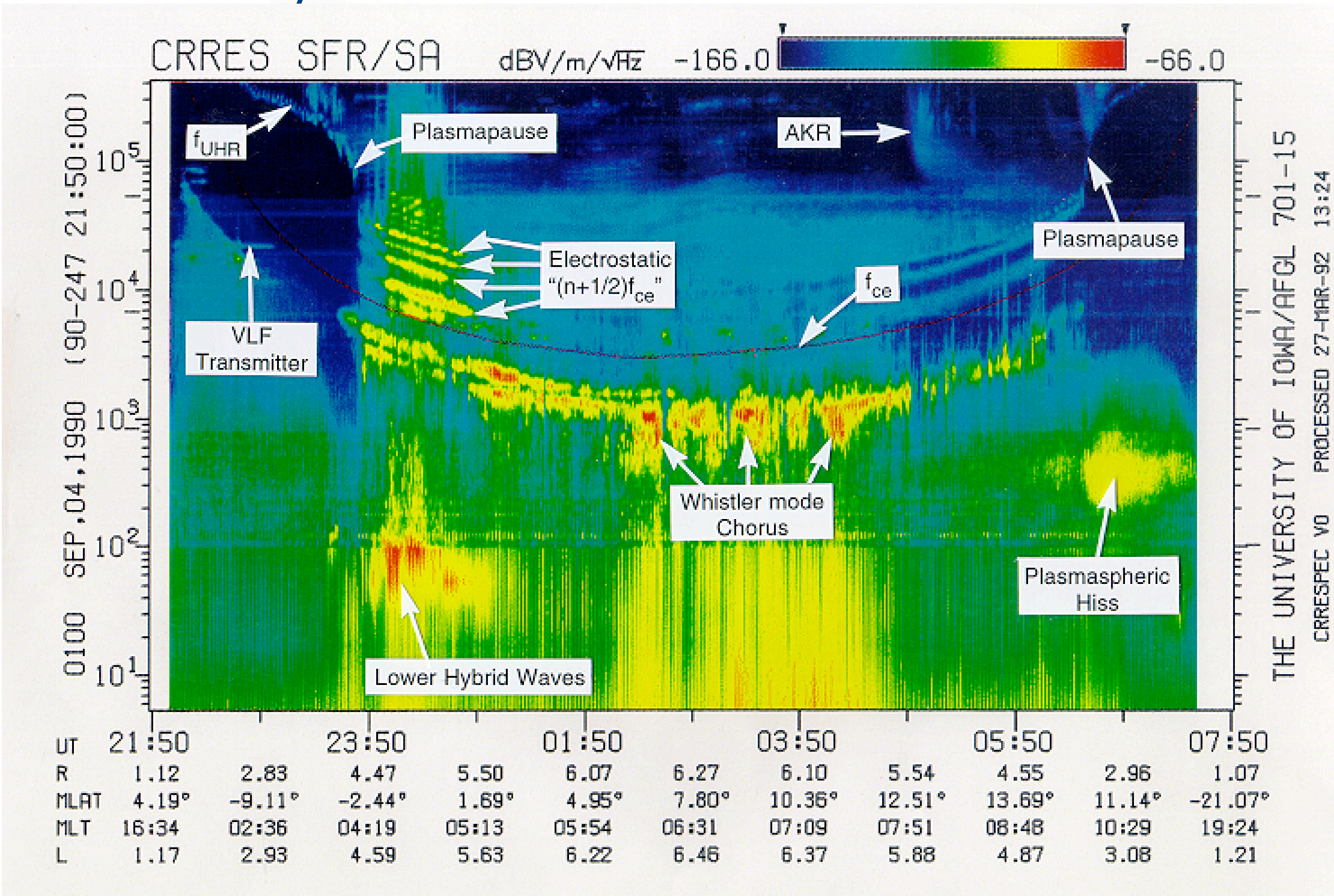
Acceleration by Wave-Particle Interactions: Which Waves?



- 5 wave modes can accelerate electrons [Horne and Thorne, 1998]
- Whistler mode chorus can resonate with ~ 1 keV – 10 MeV

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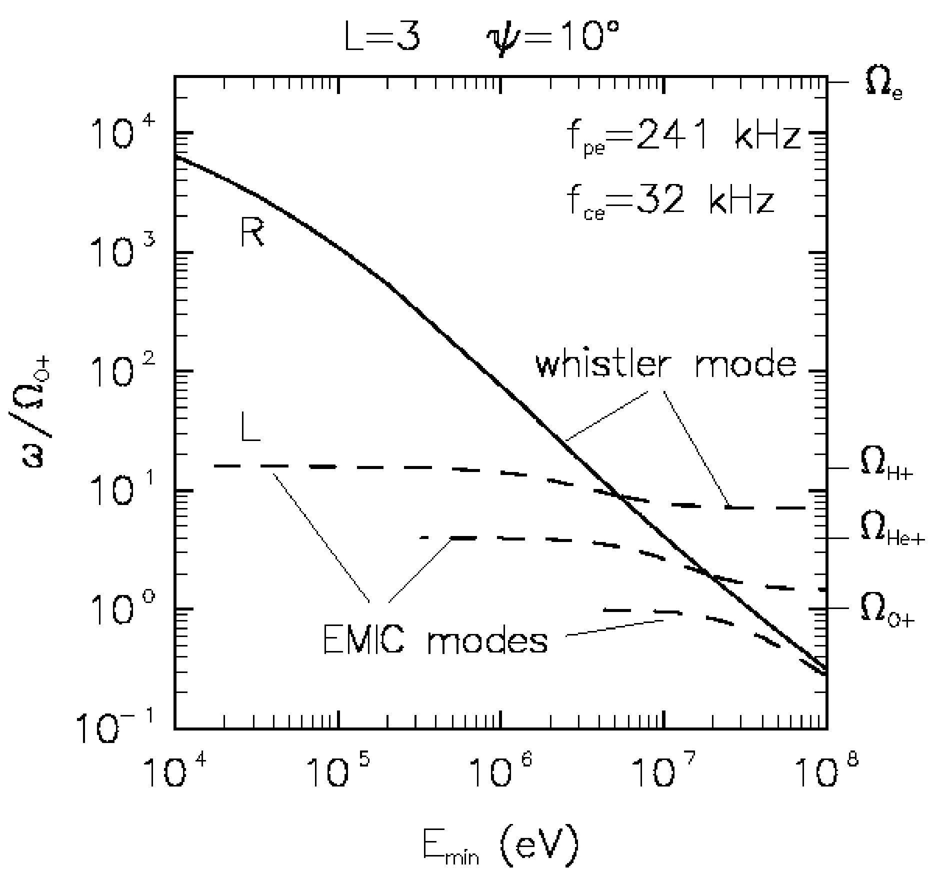
Resonant Energies



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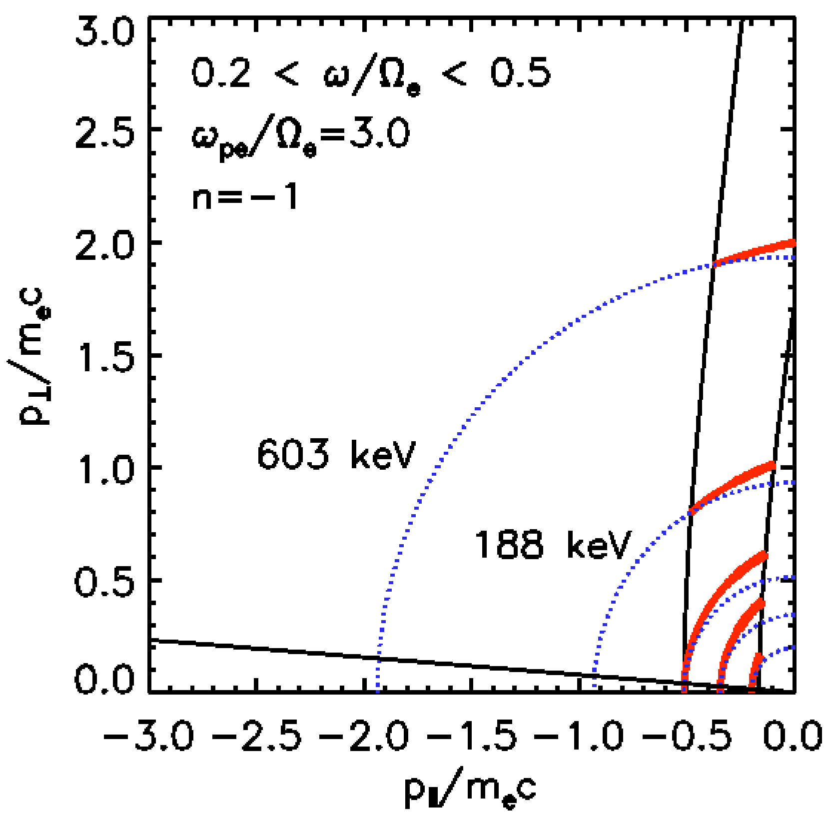
Acceleration by Whistler Mode Waves

$$v_{\parallel} = v_{\parallel res} = \frac{\omega}{k_{\parallel}}\left(1 - \frac{n\Omega_{\sigma}}{\gamma\omega}\right)$$

- Solve Doppler shifted cyclotron resonance with dispersion relation
- Diffusion into loss cone E > ~10 keV
  - Whistler wave growth
- Diffusion at large pitch angles ~ MeV
  - Acceleration
  - Trapping



Horne and Thorne, [1998, 2003, 2005a,b]

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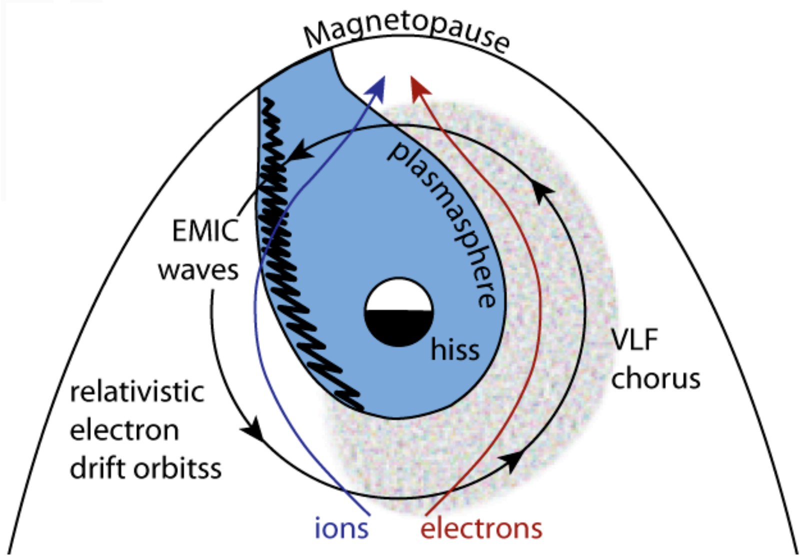
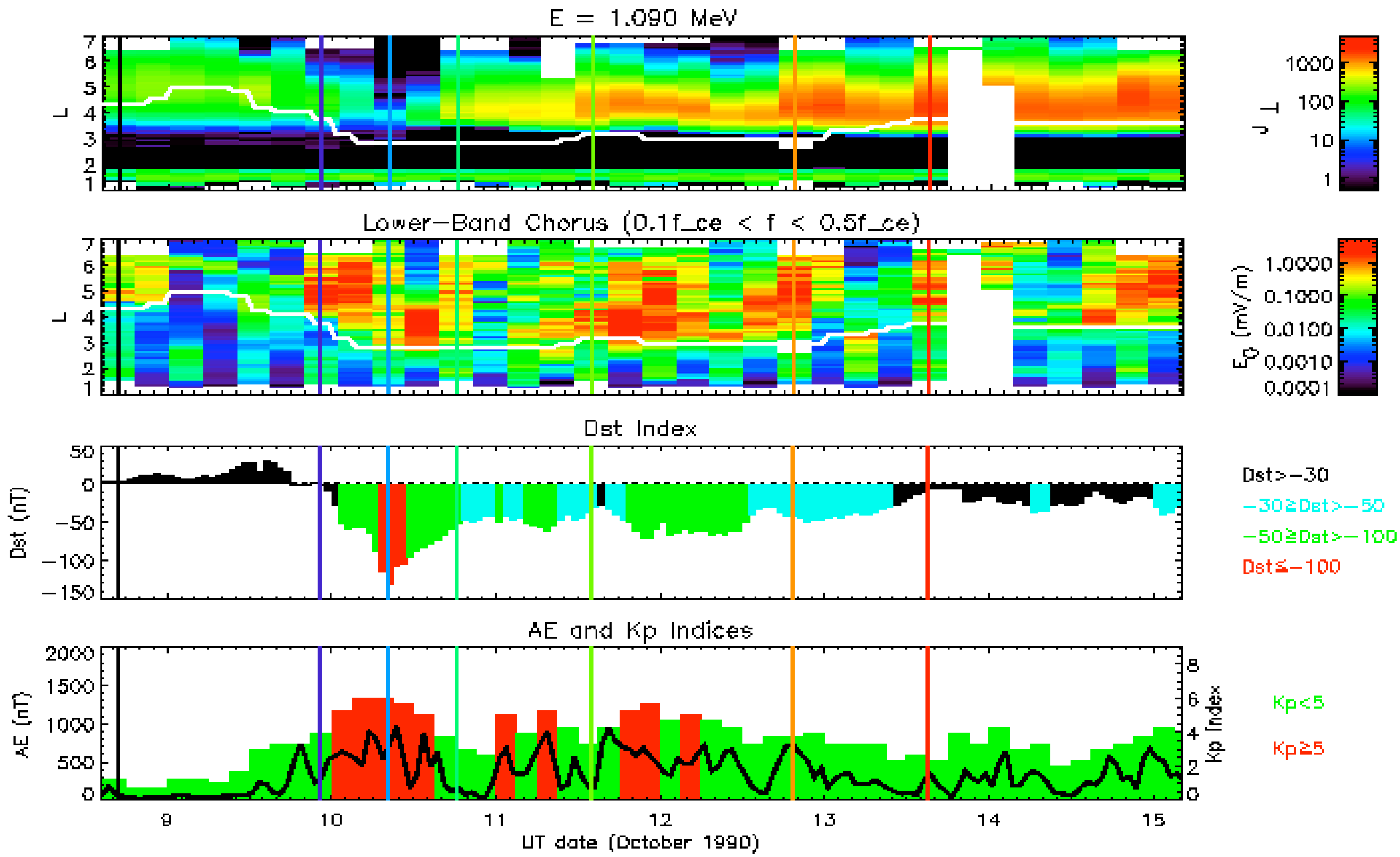
Concept



[Summers et al. [1998]

- Injection of ~1 - 100 keV electrons
  - temperature anisotropy excites whistler mode chorus
- Whistler mode chorus accelerates fraction of population to ~ MeV energies
- Other waves also contribute:
  - Acceleration – chorus and magnetosonic waves
  - Loss to atmosphere – hiss, transmitters, chorus, EM ion cyclotron waves

Whistler Mode Chorus During a Magnetic Storm



Meredith et al. [2002]

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Resonant Diffusion

$$\frac{\partial f_0}{\partial t} = \nabla.(\mathbf{D}.\nabla f_0) =$$

$$\frac{1}{p\sin\alpha}\frac{\partial}{\partial\alpha}\sin\alpha\left(D_{\alpha\alpha}\frac{1}{p}\frac{\partial f_0}{\partial\alpha} + D_{\alpha p}\frac{\partial f_0}{\partial p}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}p^2\left(D_{p\alpha}\frac{1}{p}\frac{\partial f_0}{\partial\alpha} + D_{pp}\frac{\partial f_0}{\partial p}\right)$$

- Broad band of waves

- Adopt quasi-linear diffusion approach
  - Waves uncorrelated
  - Small scattering by each wave
  - Diffusion is proportional to wave power

- Stochastic diffusion

- Obtain timescale, energy range, and pitch angle distribution

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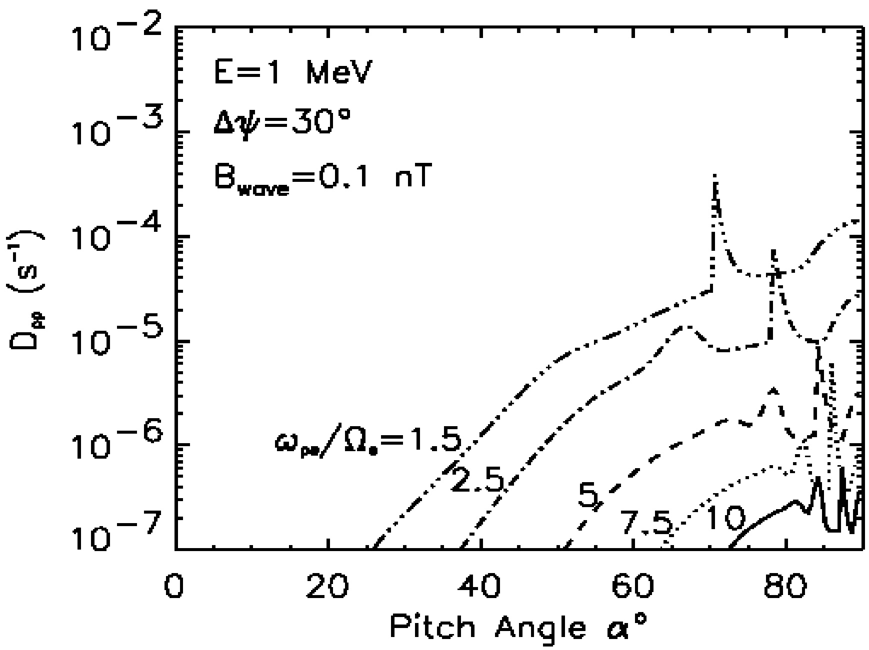
Local Diffusion Coefficients



- Whistler mode chorus waves
- Momentum diffusion more efficient for low fpe/fce
  - Higher phase velocity

Horne et al. GRL, [2003]

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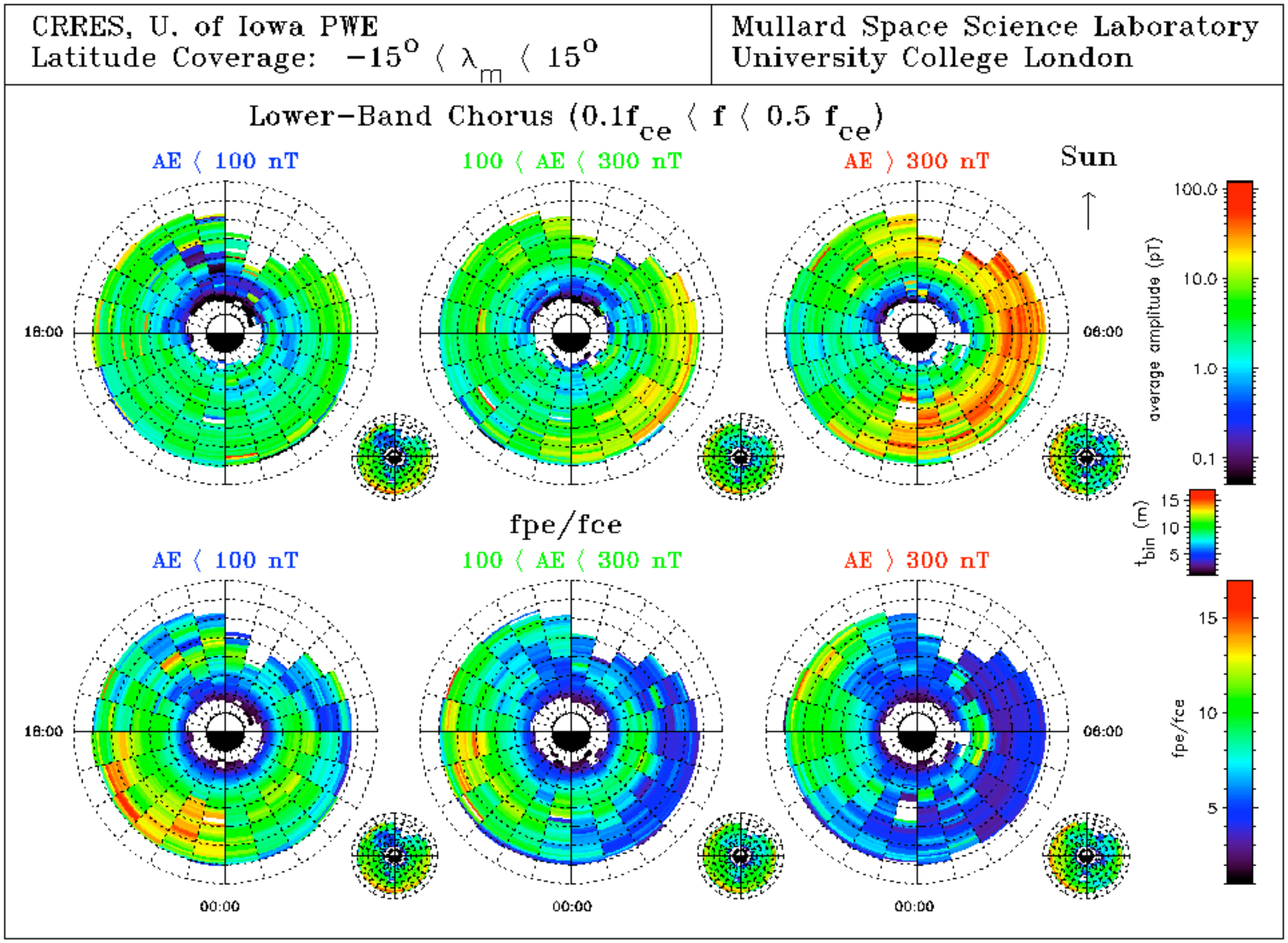
CRRES Survey of fpe/fce



Meredith et al. [2002]

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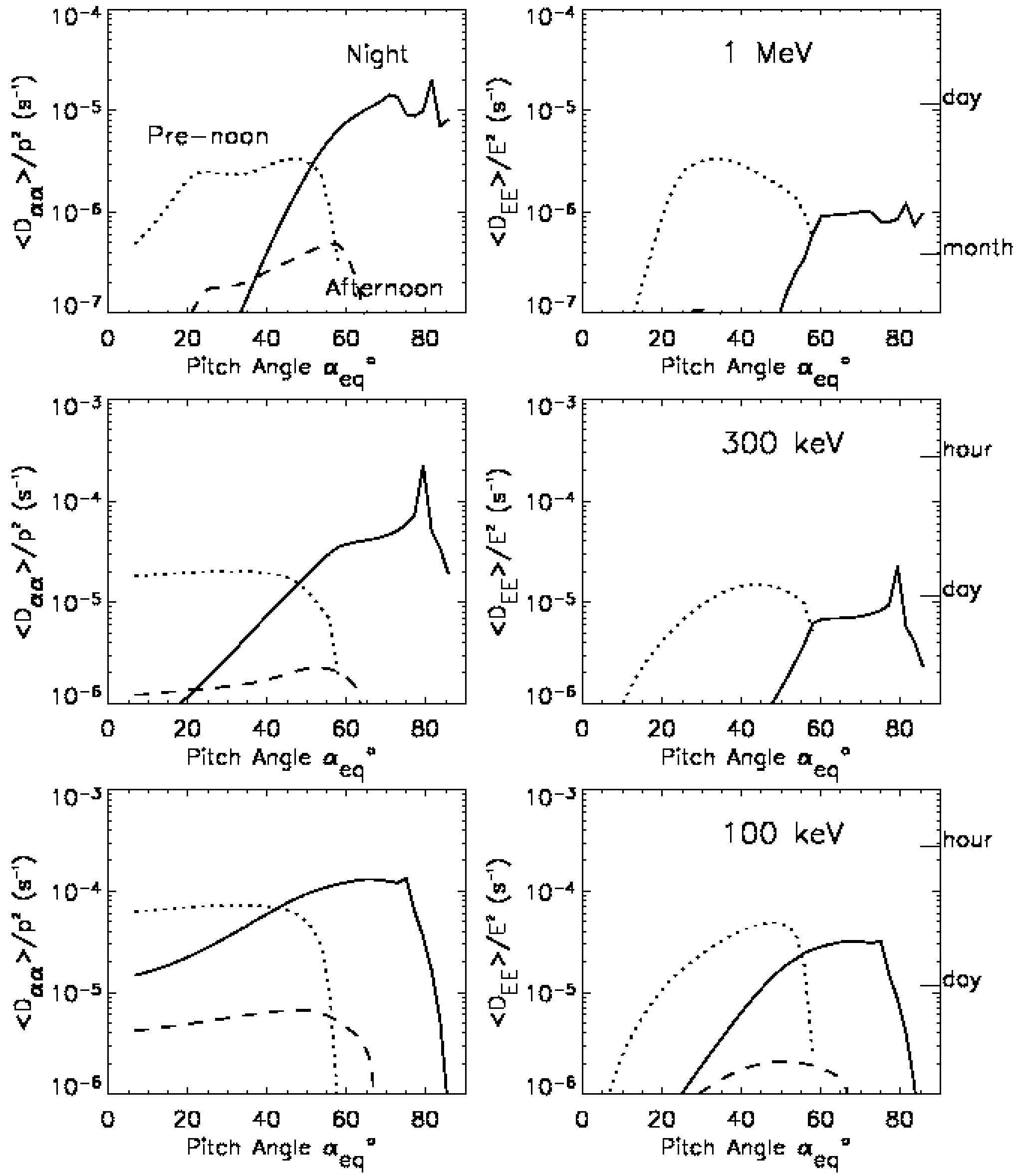

Acceleration cf Loss

- Chorus at different MLT
- E > ~300 keV Energy diffusion faster than pitch angle diffusion

Horne et al. [2005a]

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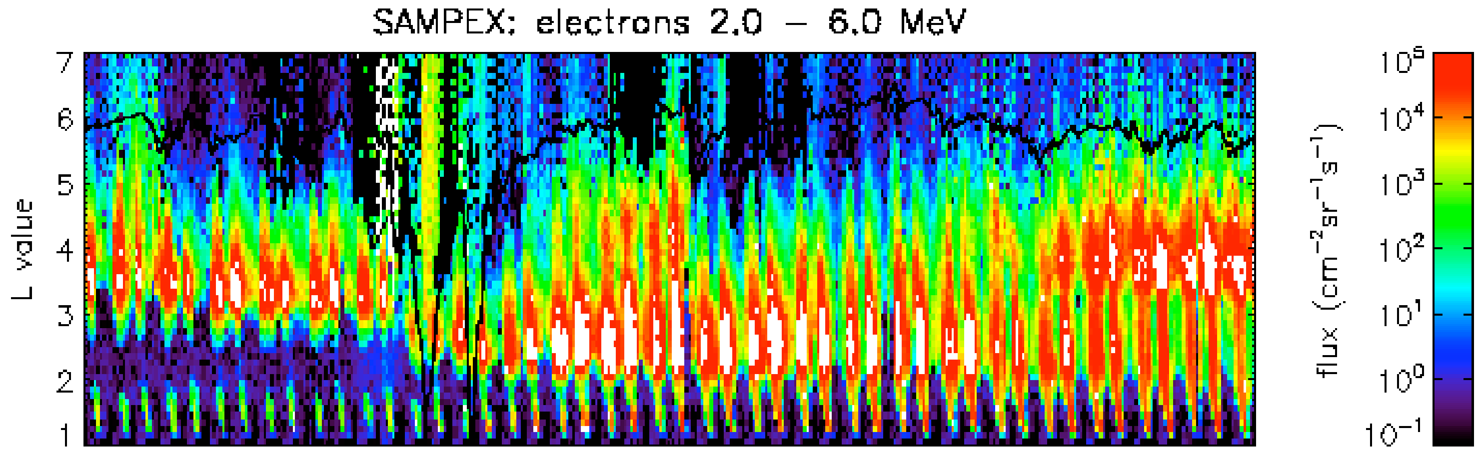
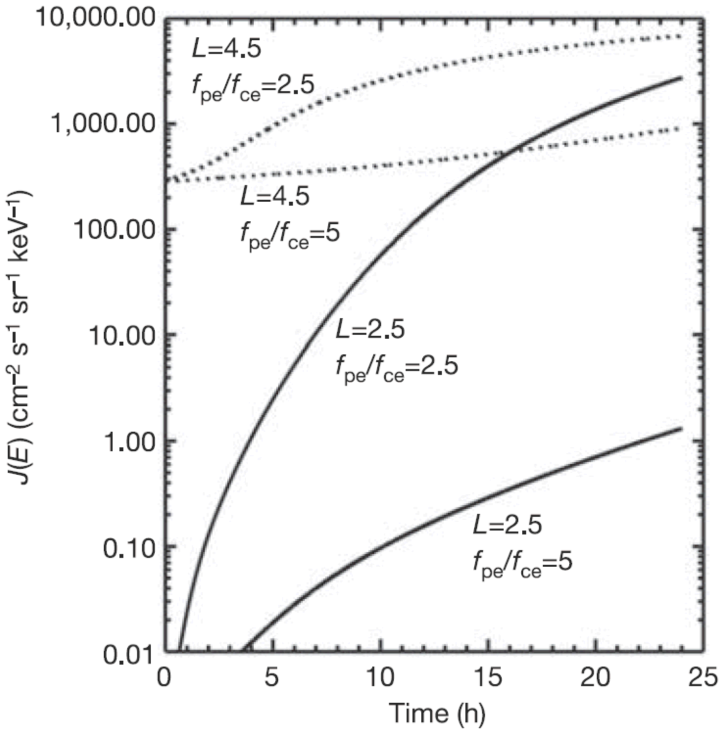
Wave Acceleration During 2003 Hallowe'en Storm

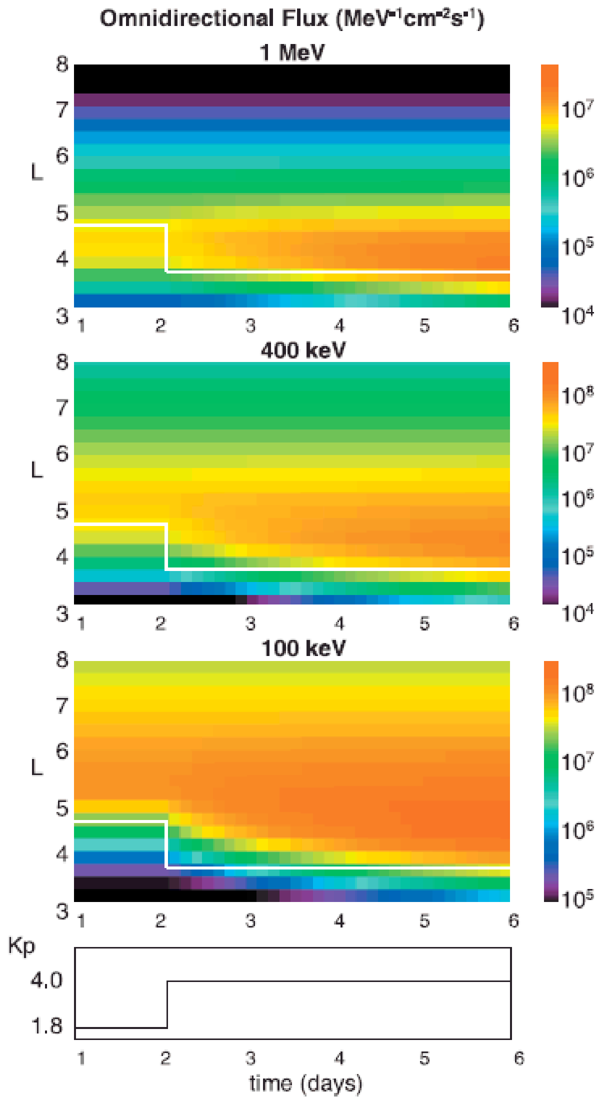




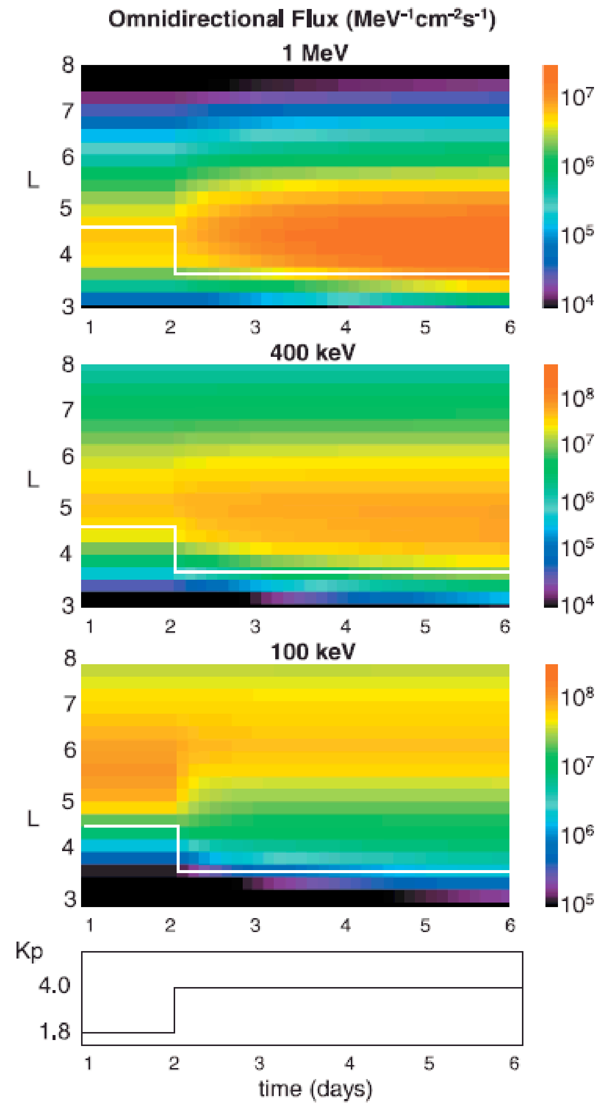
- **Horne et al., *Nature* [2005b]**
- Plasmapause eroded to L < 2.0
- Chorus waves detected by CLUSTER, and in Antarctica
- Efficient wave acceleration in low density region L~2.5

Global Radiation Belt Modelling

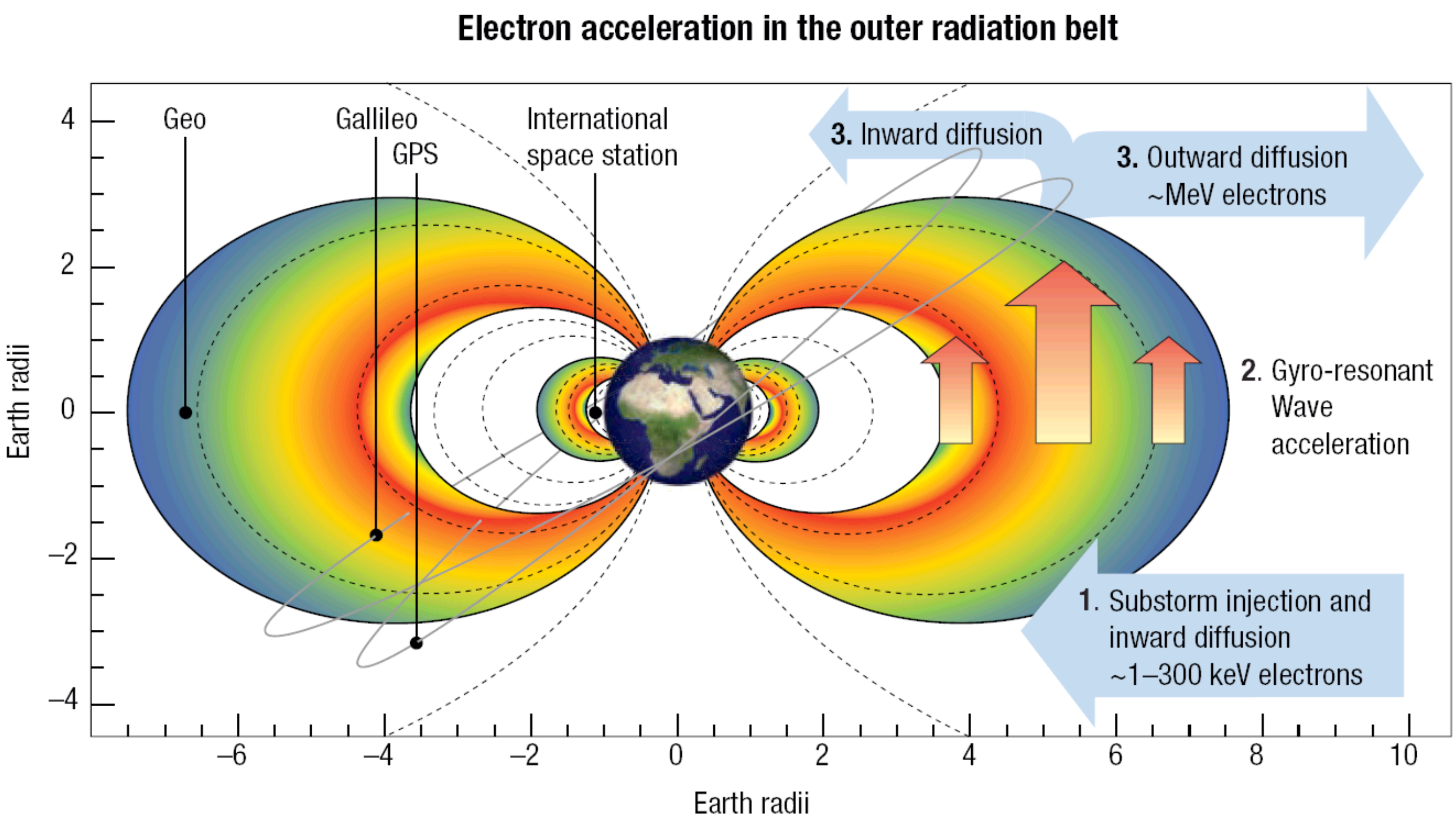
- Radial Diffusion only



- RD and wave acceleration



Wave Acceleration Concept



Horne, Nature Physics [2007]

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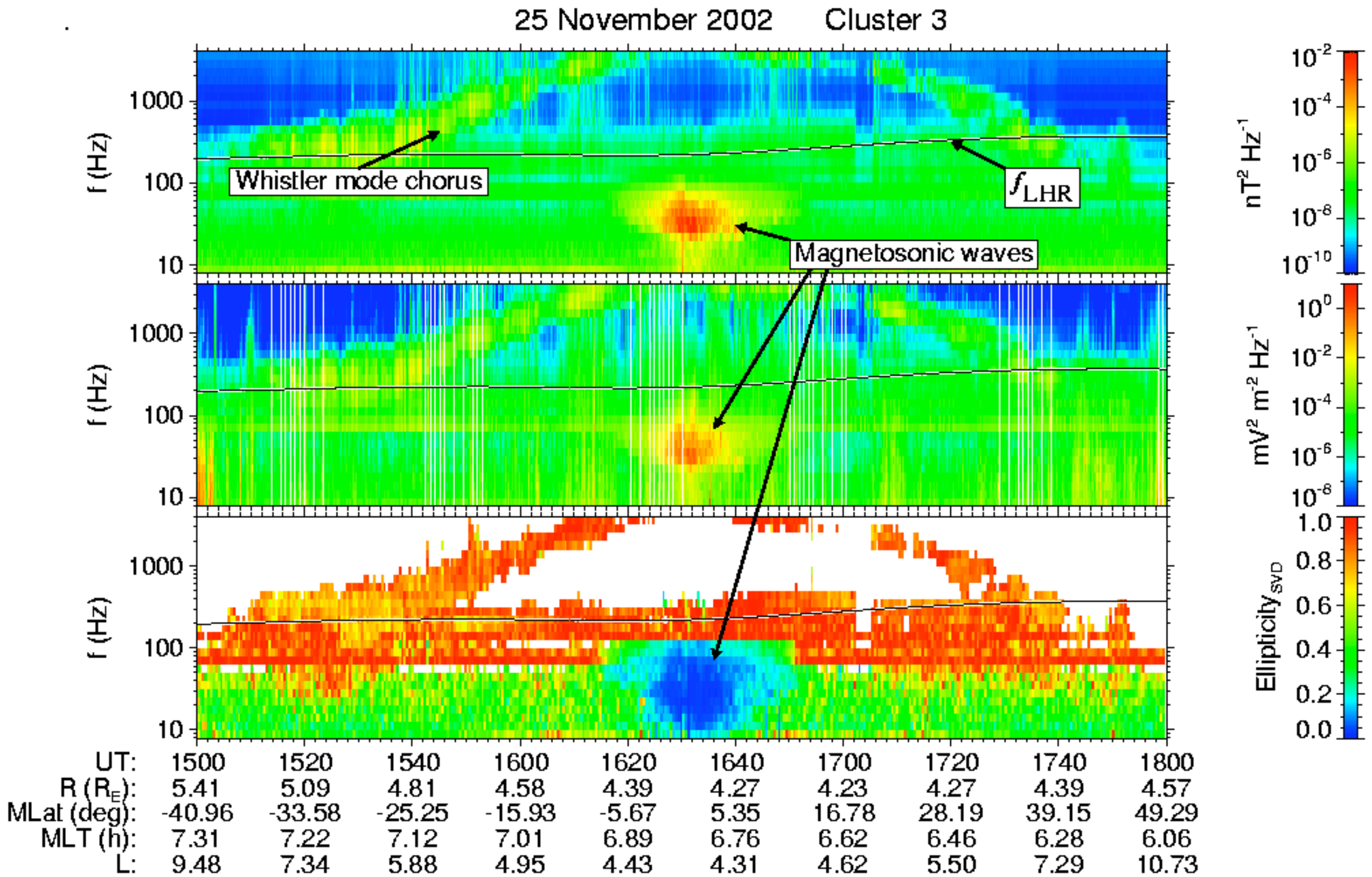
Magnetosonic Waves



- Magnetosonic waves propagate across Bo, fcH < f < fLHR
- Intense
- Generated by proton ring distributions [e.g., Boardsen et al. 1992]

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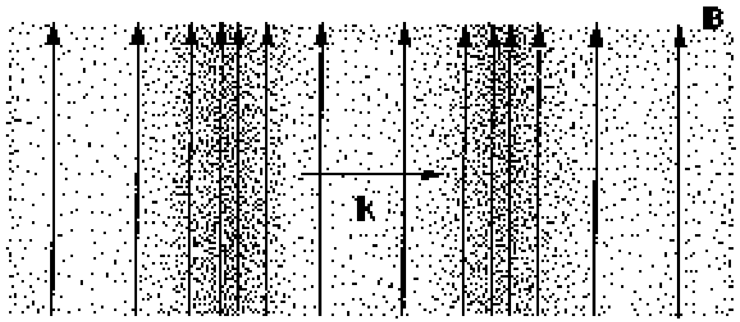
Low Frequency Propagation Perpendicular to B

fcH < f < f LHR



- Fast compressional magnetosonic wave
  - B field and plasma compressions
- B is along Bo
- E is almost perpendicular to Bo and k

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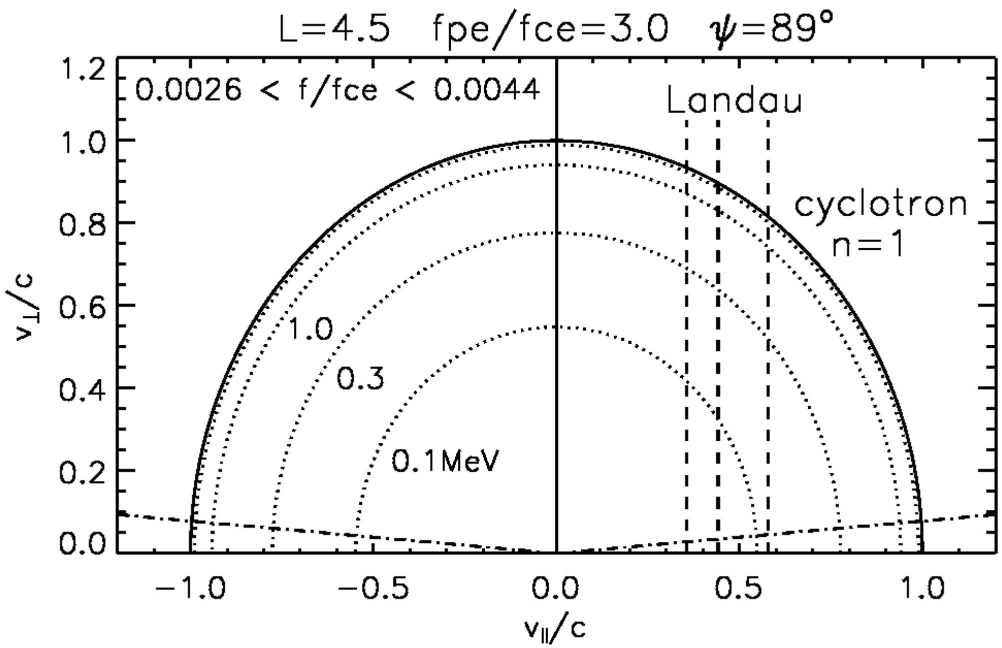
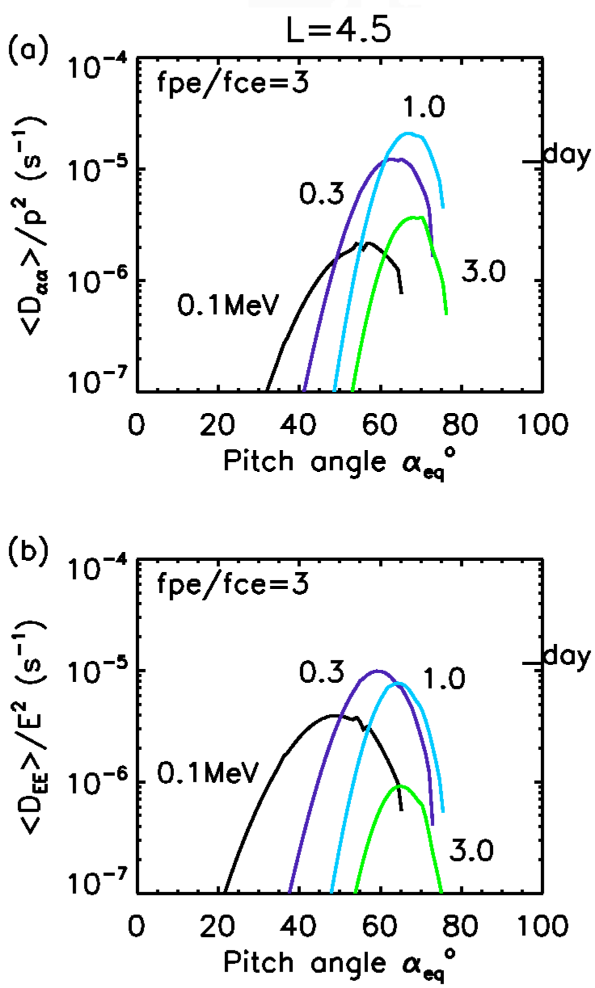
Resonant Diffusion



$$\omega - n\Omega_\sigma/\gamma - k_\parallel v_\parallel = 0$$

- Solve with dispersion relation
  - Not field-aligned !
- Cyclotron resonance >3 MeV
  - unlikely to contribute
- Landau resonance possible
  - Energy diffusion
- Consider a band of waves with spread of directions
  - Diffusion rates

Diffusion Rates – Magnetosonic Waves



- No loss to atmosphere
- Acceleration from ~ 100 keV to a few MeV
- Timescale ~ 1-2 days
- Energy transfer from protons to electrons

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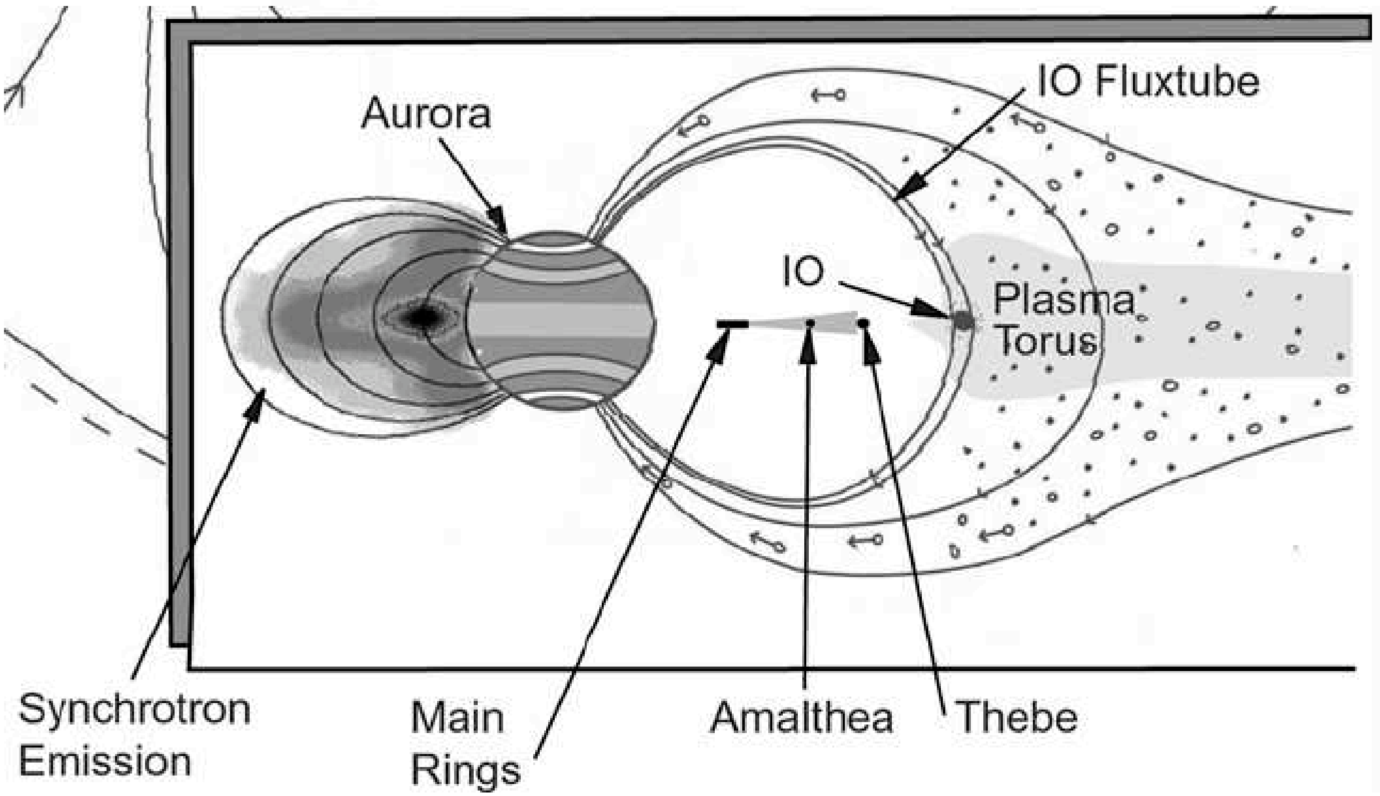
Application to Jupiter's Radiation Belts



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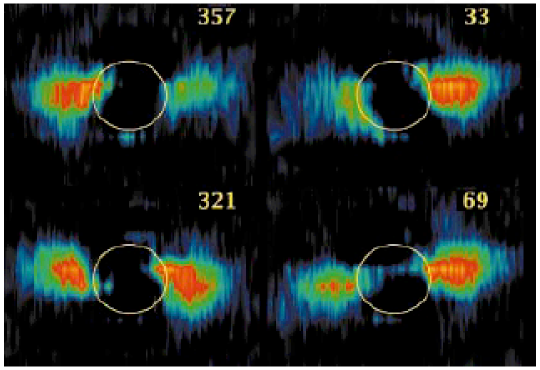
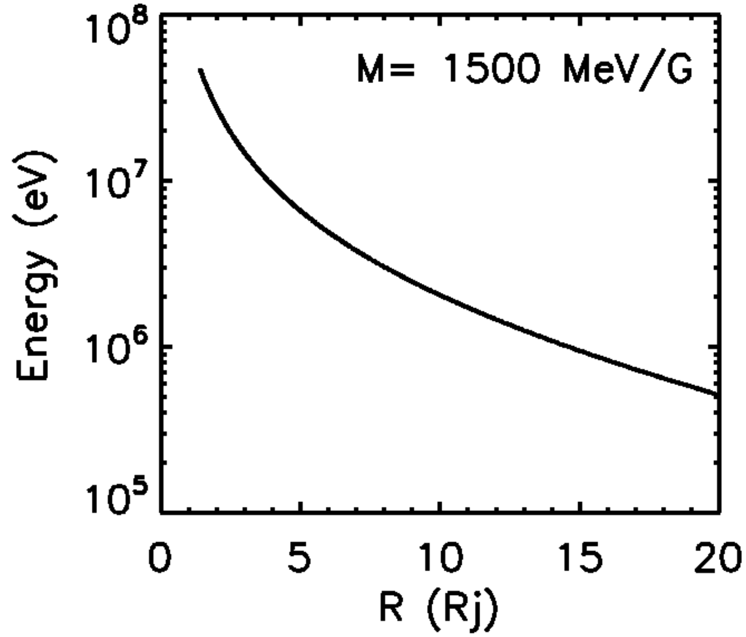
The Problem



[Bolton et al., Nature, 2002]



- Synchrotron radiation (13.8 GHz) indicates:
  - 50 MeV electrons at L=1.4
- Current theory
  - Betatron and Fermi acceleration by inward transport
- Requires a source
  - > 1 MeV at 10 – 15 Rj

- How do you produce ~1 MeV electrons at L ~ 15?

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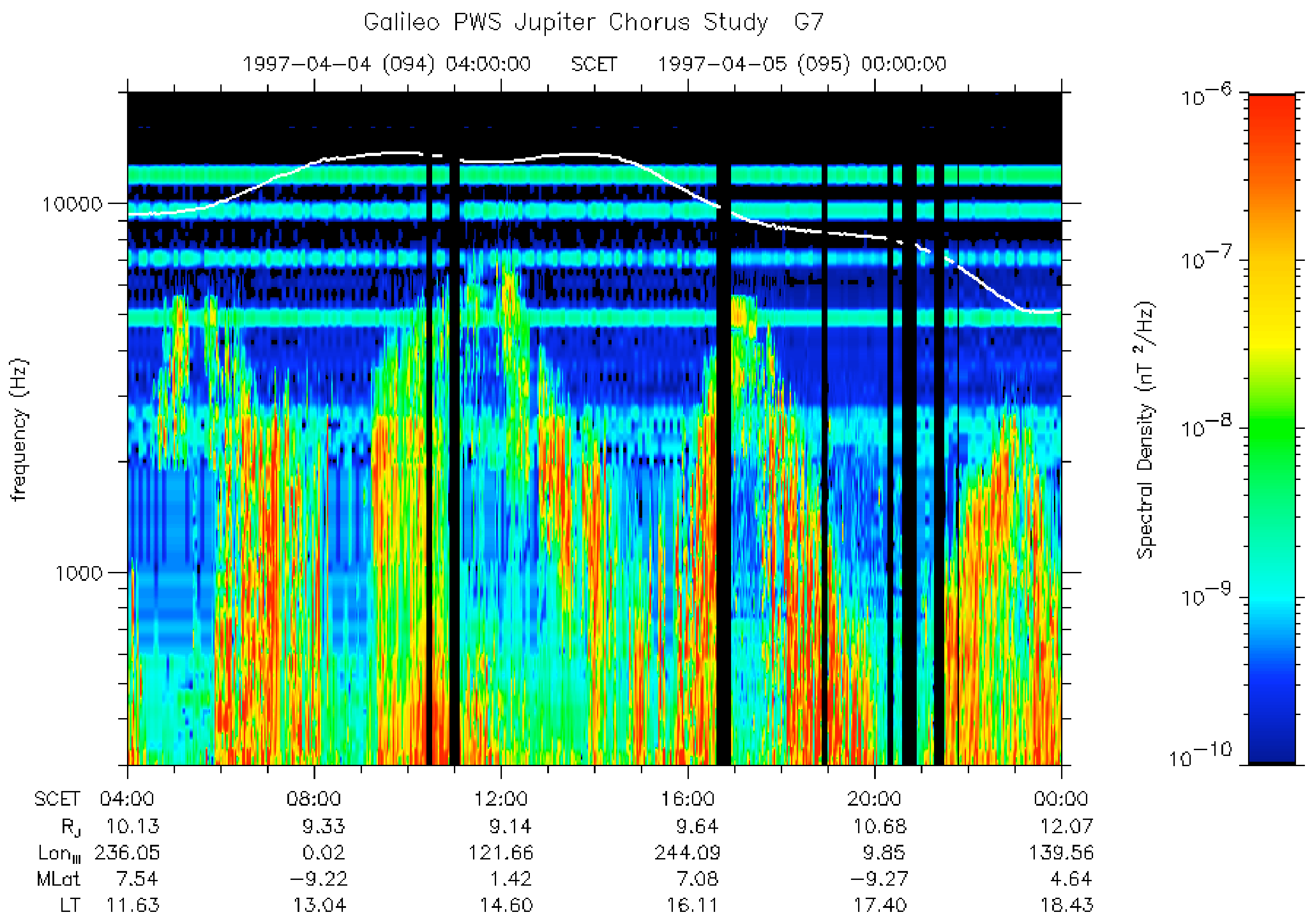
Whistler Mode Waves at Jupiter



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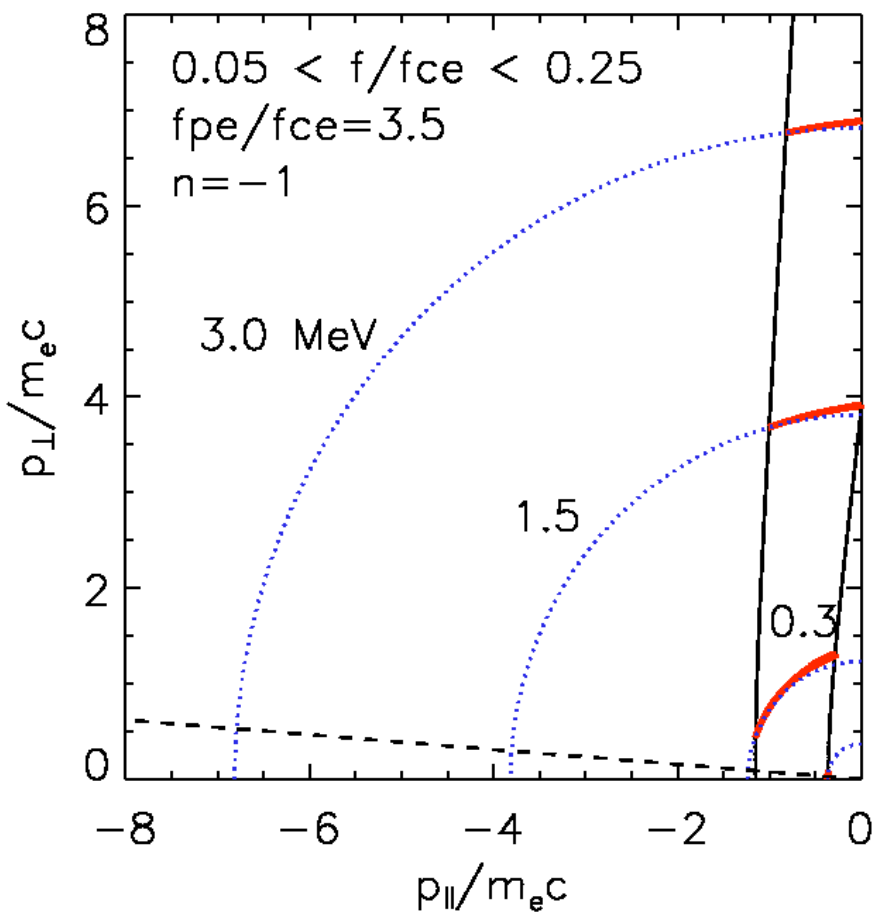
Resonant Diffusion



- Scaling similar to Earth
- Energy transfer via whistler mode waves from low to high energy

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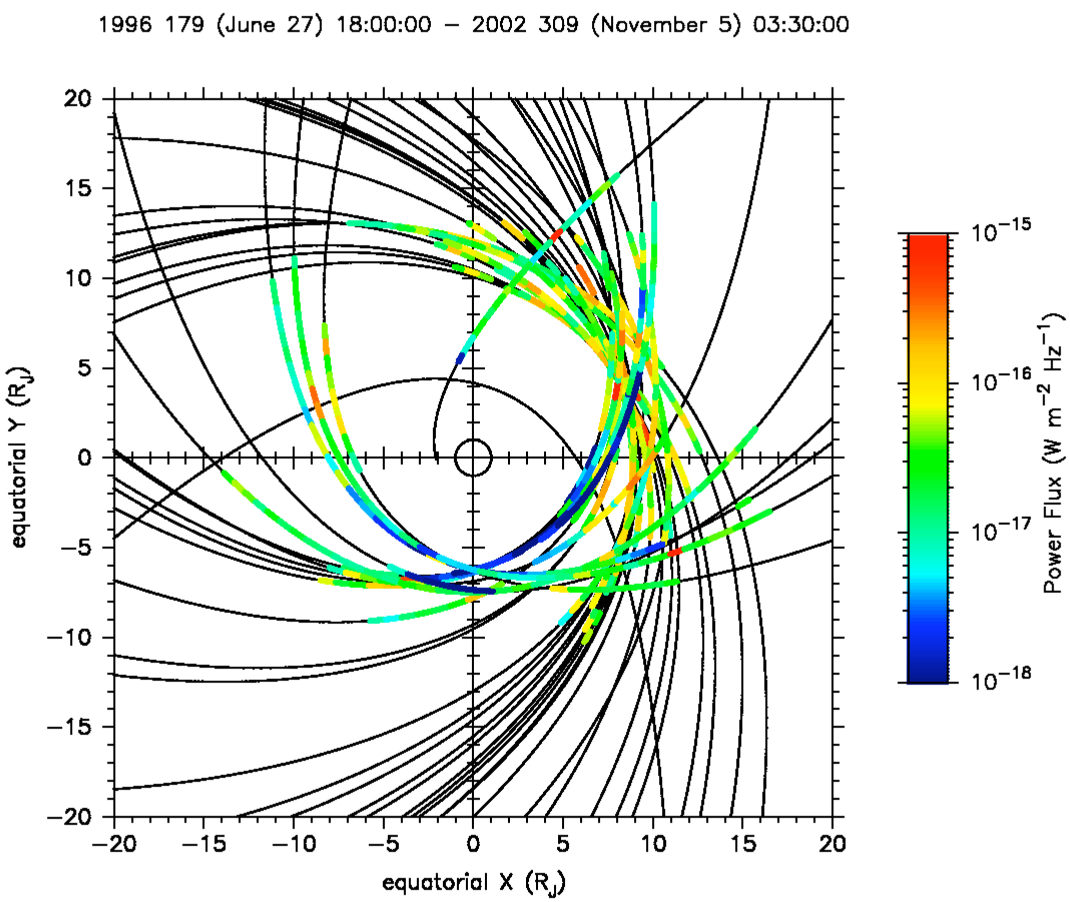
Galileo Wave Data



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Wave Acceleration

- Chorus wave power peaks outside orbit of Io
  - Waves generated by flux interchange instabilities
- Calculate electron energy diffusion using PADIE code
  - Model wave spectrum from Galileo 13:20-13:30 SCET
  - 30º angular spread of waves
  - Landau +-5 cyclotron resonances
  - Bounce average over 10º latitude
  - Dipole field + density model
- Energy diffusion peaks outside Io
  - Wave acceleration

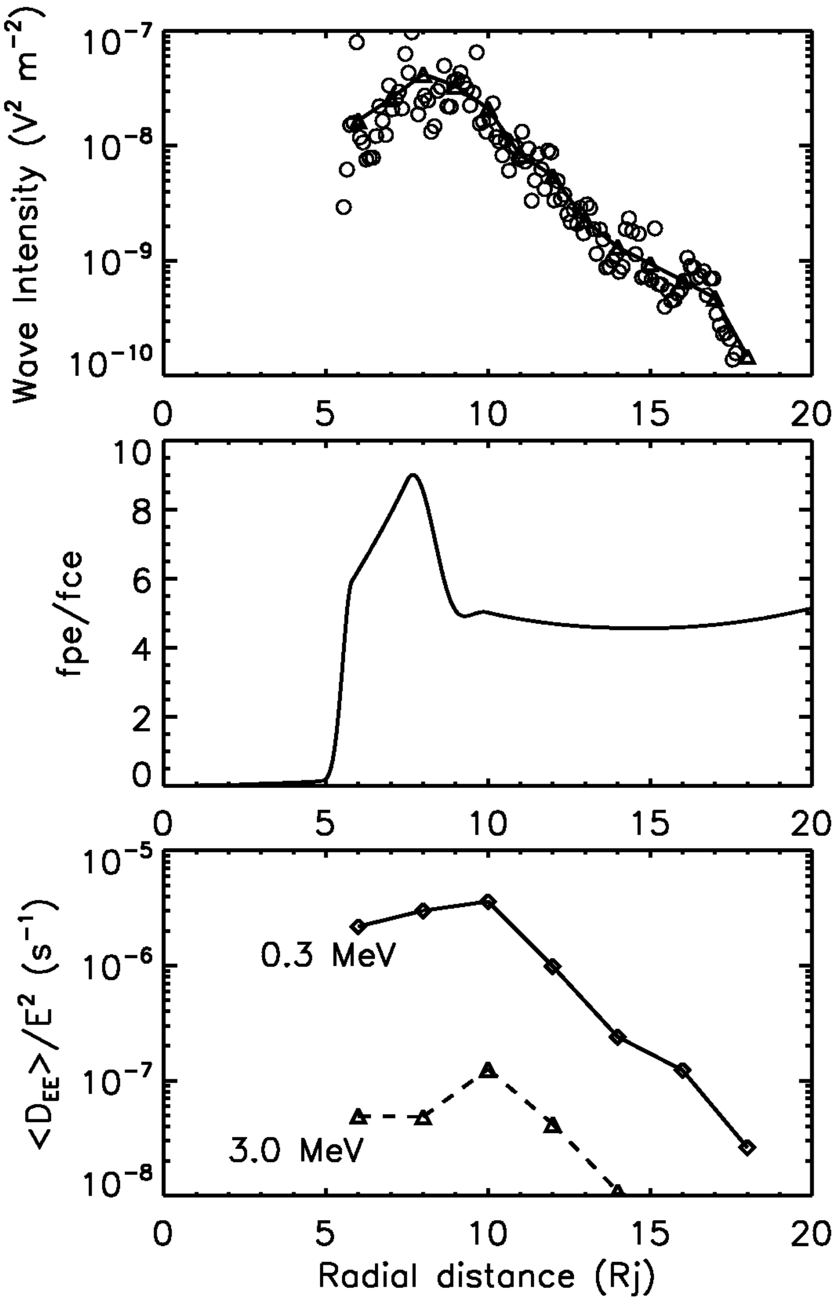

Figure_3.ps

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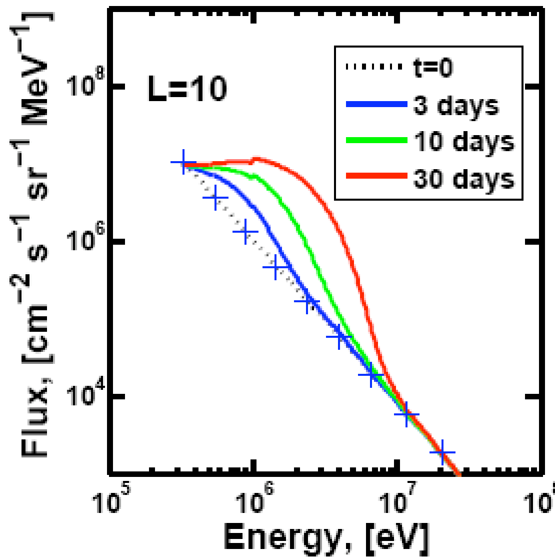
Wave Acceleration at Jupiter

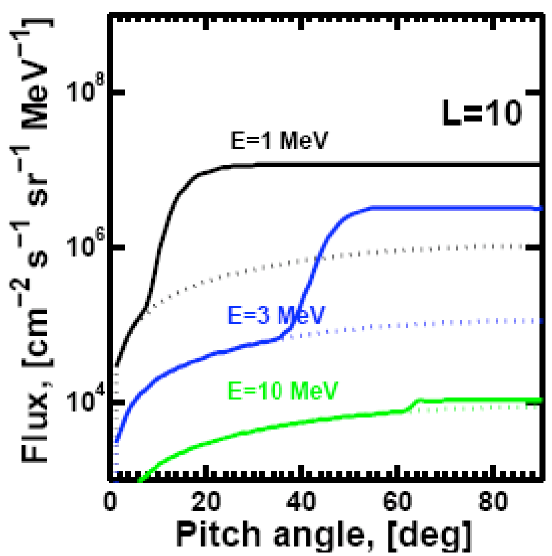
- 2-d Fokker Planck code
  - Diffusion in pitch angle and energy
- Initial flux from Divine and Garrett [1983]
- Fixed boundary conditions at 0.3 and 100 MeV
- Flux=0 inside loss cone and flat gradient at 90

- Timescale ~ 30 days for flux of 1 - 6 MeV electrons to increase by a factor of 10

- Timescale is comparable to transport timescale (20 - 50 days) for thermal plasma

- Peaks in flux would be reduced by transport and losses





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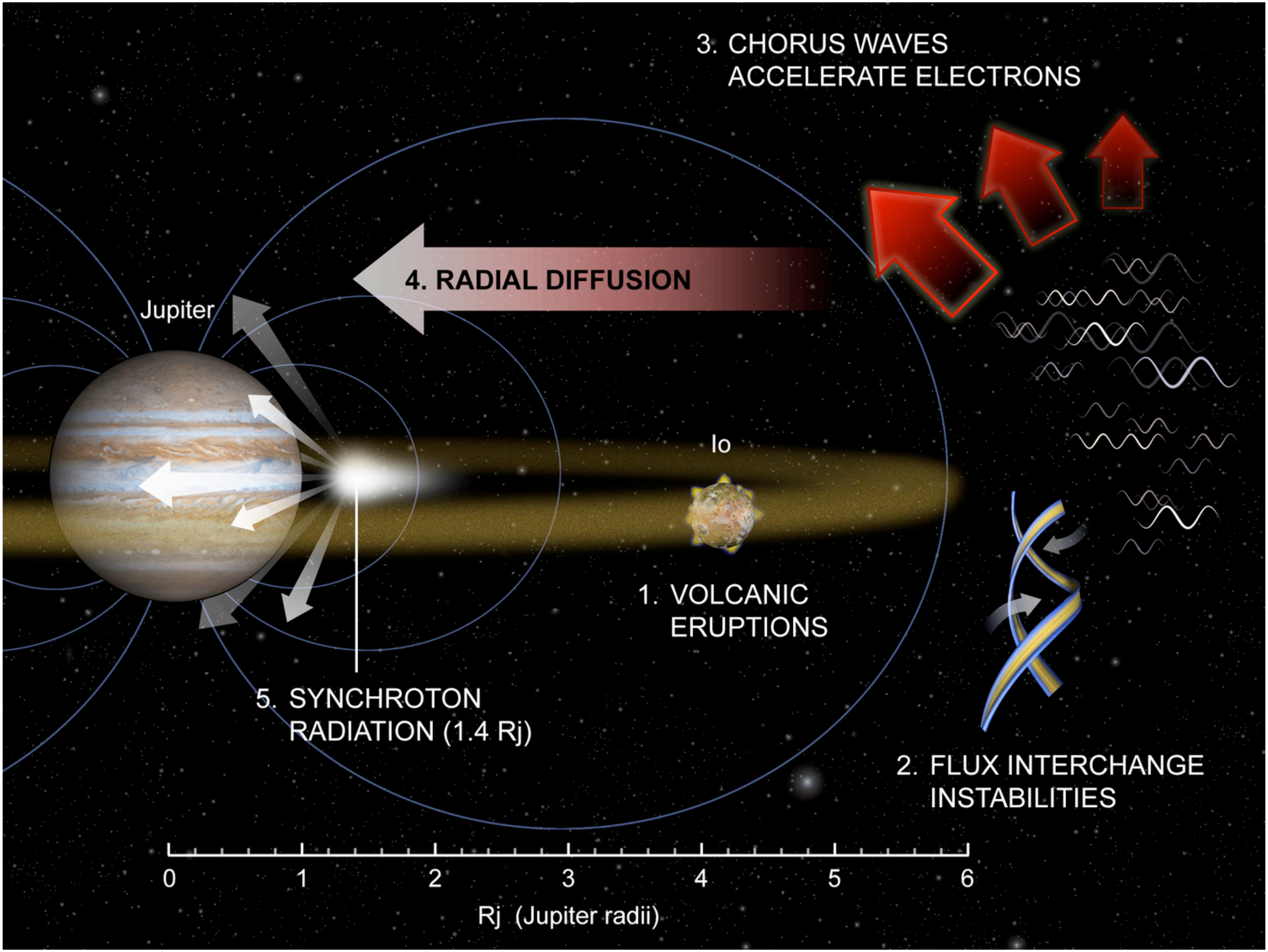
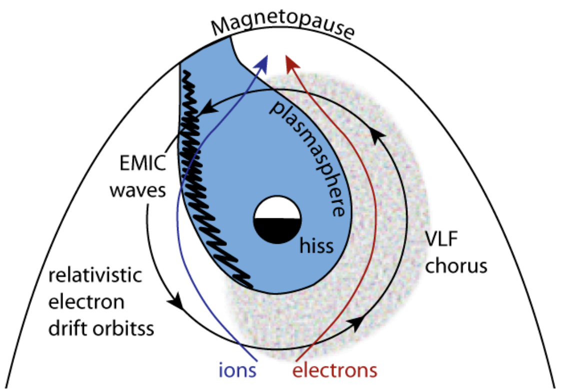

3. CHORUS WAVES
ACCELERATE ELECTRONS
4. RADIAL DIFFUSION
Jupiter
Io
1. VOLCANIC
ERUPTIONS
5. SYNCHROTON
RADIATION (1.4 Rj)
2. FLUX INTERCHANGE
INSTABILITIES
0
1
2
3
4
5
6
Rj (Jupiter radii)

Wider Applications

- Earth
  - Quantify loss and acceleration due to 5 wave modes:
    - Whistler, Magnetosonic, Z mode, LO, RX, EMIC,
- Jupiter
  - Is wave acceleration a key process?
- Saturn, Uranus, Neptune………..exoplanets
  - Is wave acceleration important?
- Solar applications X ray flares
  - E ~ 0.1 – 10 MeV
  - Is whistler mode acceleration key?
- Does particle precipitation affect planetary atmospheres?
  - Change chemistry
  - Affect temperature via chemistry?



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The End

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Acceleration

- Betatron acceleration
  - Energy increase due to a slow increase in magnetic field strength (relative the gyro-period) while conserving the 1st adiabatic invariant. The changing magnetic field induces an electric field which increases the momentum of the particle.

- Fermi acceleration
  - Energy increase due to particle reflection by a magnetic mirror