Electron Acceleration and Loss in the Earth's Radiation Belts: The Contribution of Wave-particle Interactions

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Outline

- Relevance
- Radiation belt variability
- Existing theories
- Evidence for wave-particle interactions
- Future requirements

Tutorial, GEM, Telluride, Colorado, 25 June 2002

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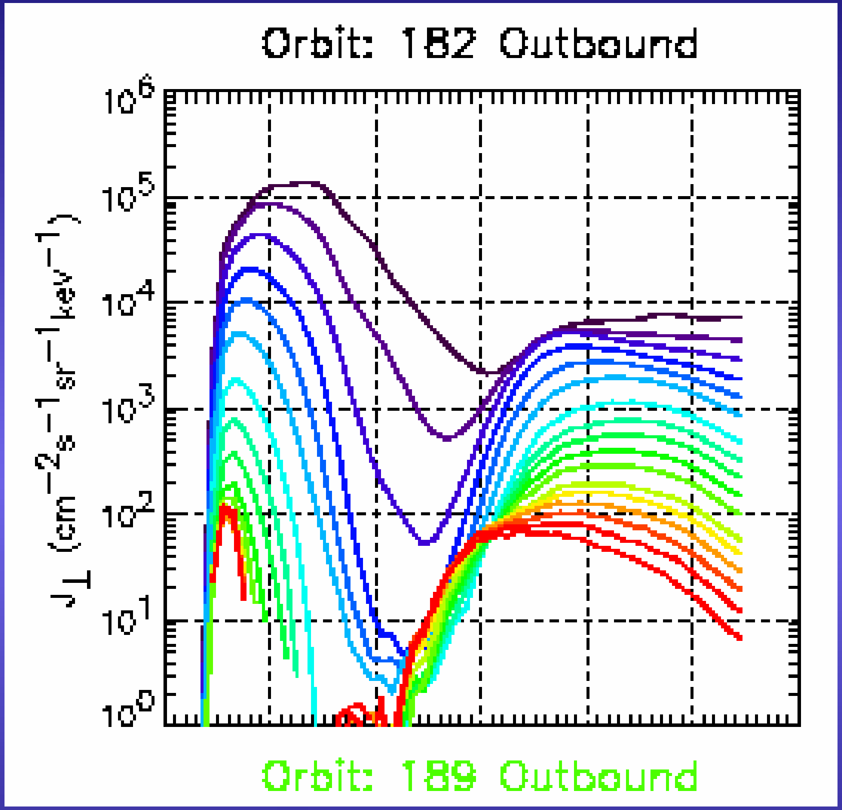
Earth's Radiation Belts

- Discovered in 1958 by James van Allen and his team Iowa
- Trapped electrons and ions
- Only one proton belt
  - 0.1 - several 100 MeV
  - Peak near L = 1.8
- Two electron belts with slot region in between
  - For E > 1MeV peaks near 1.6 and 4.0 Re
- Outer belt highly variable cf inner belt
- Outer belt extends to geostationary orbit
- Hazardous to astronauts and spacecraft



- From Meredith et al. [2002]
- (red = 1.47 MeV)

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Relevance

- Radiation environment damages spacecraft
  - MeV electrons cause internal charging
  - 0.1 – 100 keV cause surface charging
  - MeV ions cause single event upsets
  - Cumulative radiation dose
    - Degradation of performance
    - Swelling of mirror surfaces
    - Darkening of glassy surfaces
    - Solar cell degradation
    - Thermal control degradation
    - Damage electronic components
    - Limits lifetime

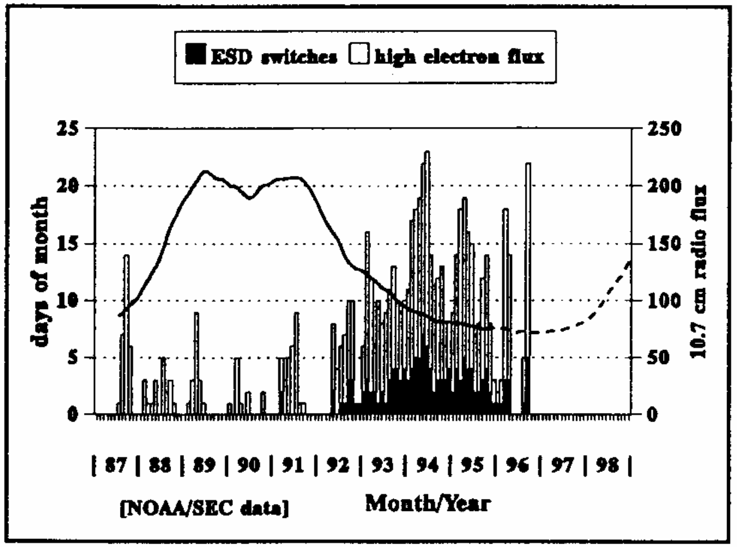

Fig. 5 Monthly number of switches caused by internal charging & days with flux $> 10^8$ cm^{-2} sr^{-1}

Wrenn and Smith [1996]

- ESA study 2001
  - 3 out of 4 satellite designers said that internal charging is now their most important problem [Horne, 2001]
    - MeV electrons

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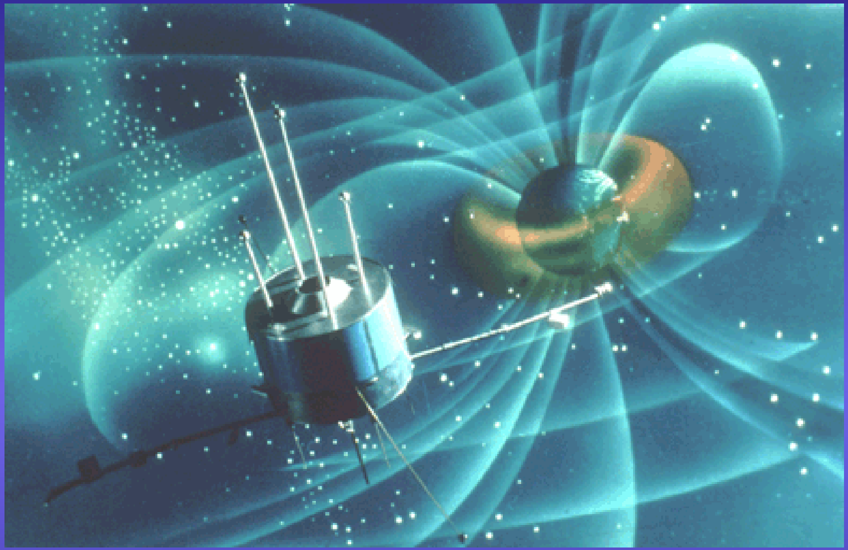
Satellite Losses

- Internal charging and ESD is related to MeV electron flux (variations)
  - more than 20 spacecraft damaged [Wrenn and Smith, 1996]

- Several examples of spacecraft damaged during storms when flux was enhanced, e.g., Baker et al. [1998]
  - 1994: Intelsat K, Anik E1, & E2
  - 1997: Telstar 401
  - 1998: Galaxy IV

  - But whether space weather was the direct cause is controversial

- US National Security Space Architect:
  - 13 satellites lost in 16 years that can be attributed clearly to Space Weather



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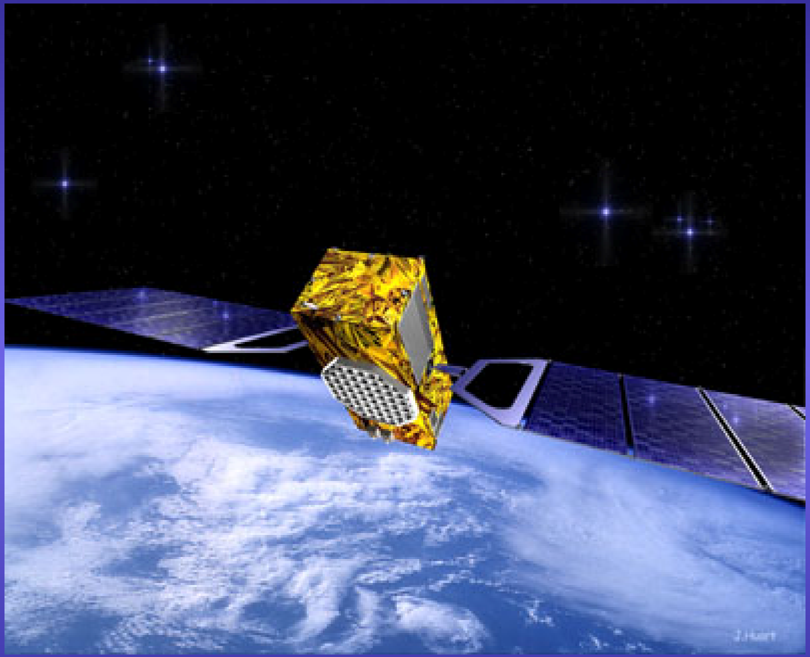
Cost Estimates

- Modern telecommunications spacecraft
  - To build ~ US$200M
  - To launch to GEO ~ $100M
  - To insure each year ~ 3-5%



- About 600 spacecraft launched

- About 250 spacecraft in GEO
  - about 100 insured

- Substantial losses to space insurance
  - 1998: Loss claims $1.6B premiums $850M
  - 2000: Loss claims $1.0B premiums $xx

- Space weather cause or contributor to $500M of loss 1994-97 (US insurance brokers)

- Overall risk is becoming higher:
  - All space claims: 1989 $200M,
  - All space claims: 1998 $1.65B

Future Growth Area

- Telecommunications is a growth area
  - From $20B – to $100B over next 10 years (UK House of Commons, 2000)
    - Internet, direct TV, navigation
- EU – Galileo project 2005-2008
  - 30 spacecraft
  - L = 4.7 and GEO
- US – next generation GPS
- New technology – new risk
- Research on radiation belts is relevant
  - satellite design and construction
  - launch operators
  - service providers
  - space insurance

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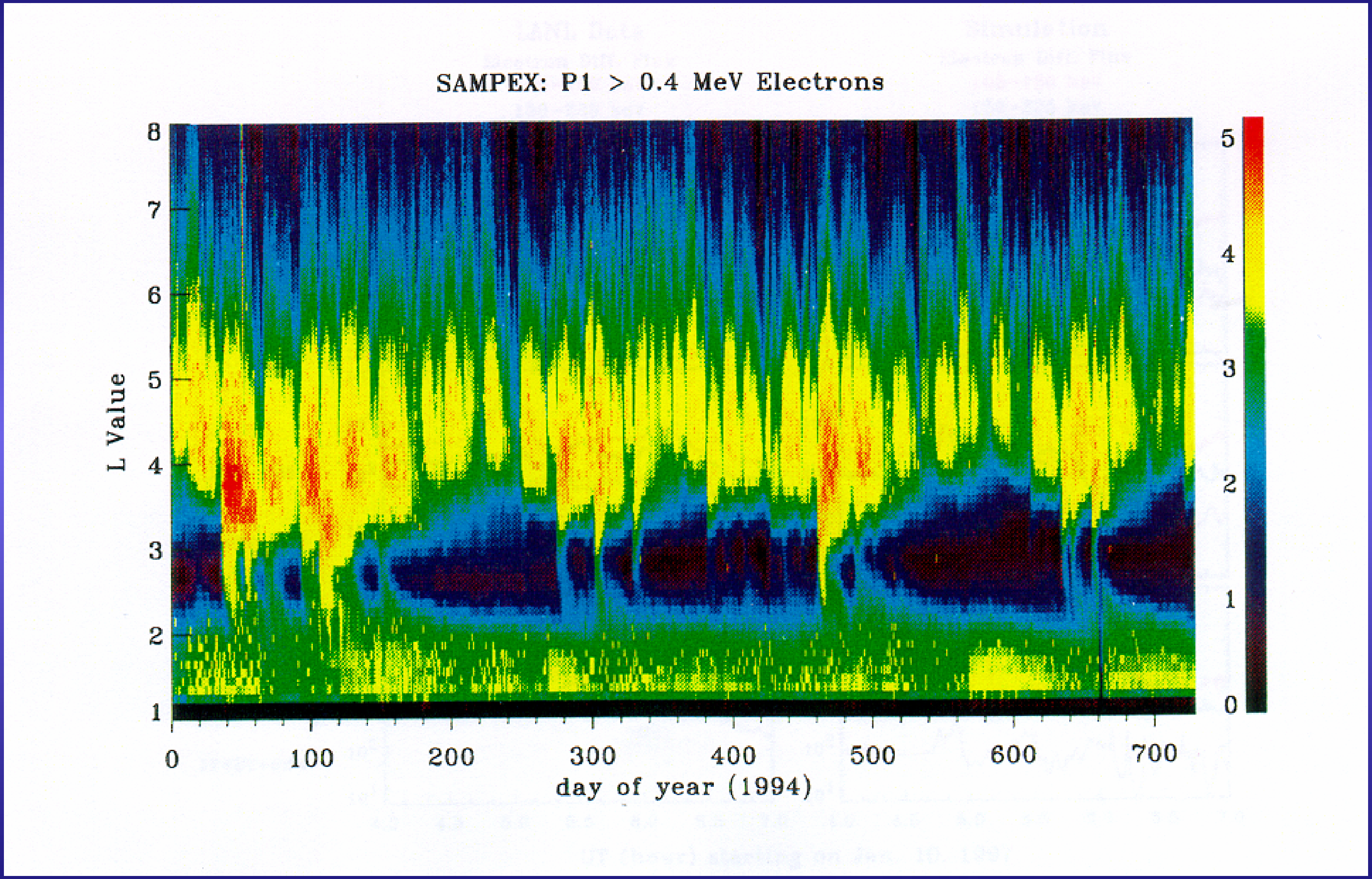
Outer Belt Variability



Li et al. [1997]

Electron Flux During Magnetic Storms

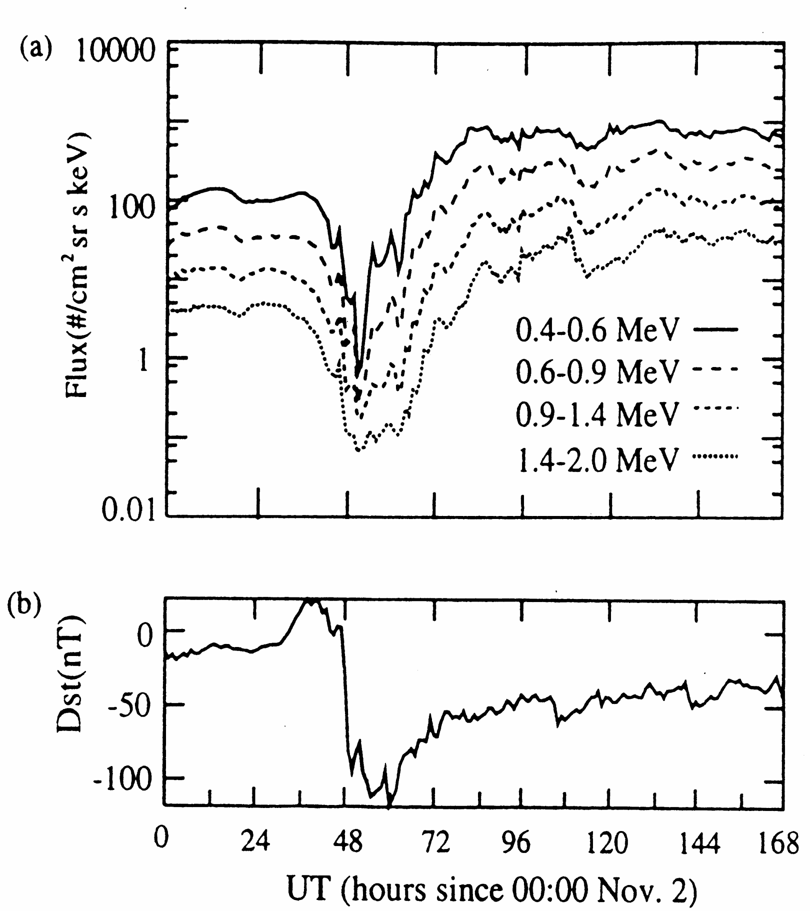
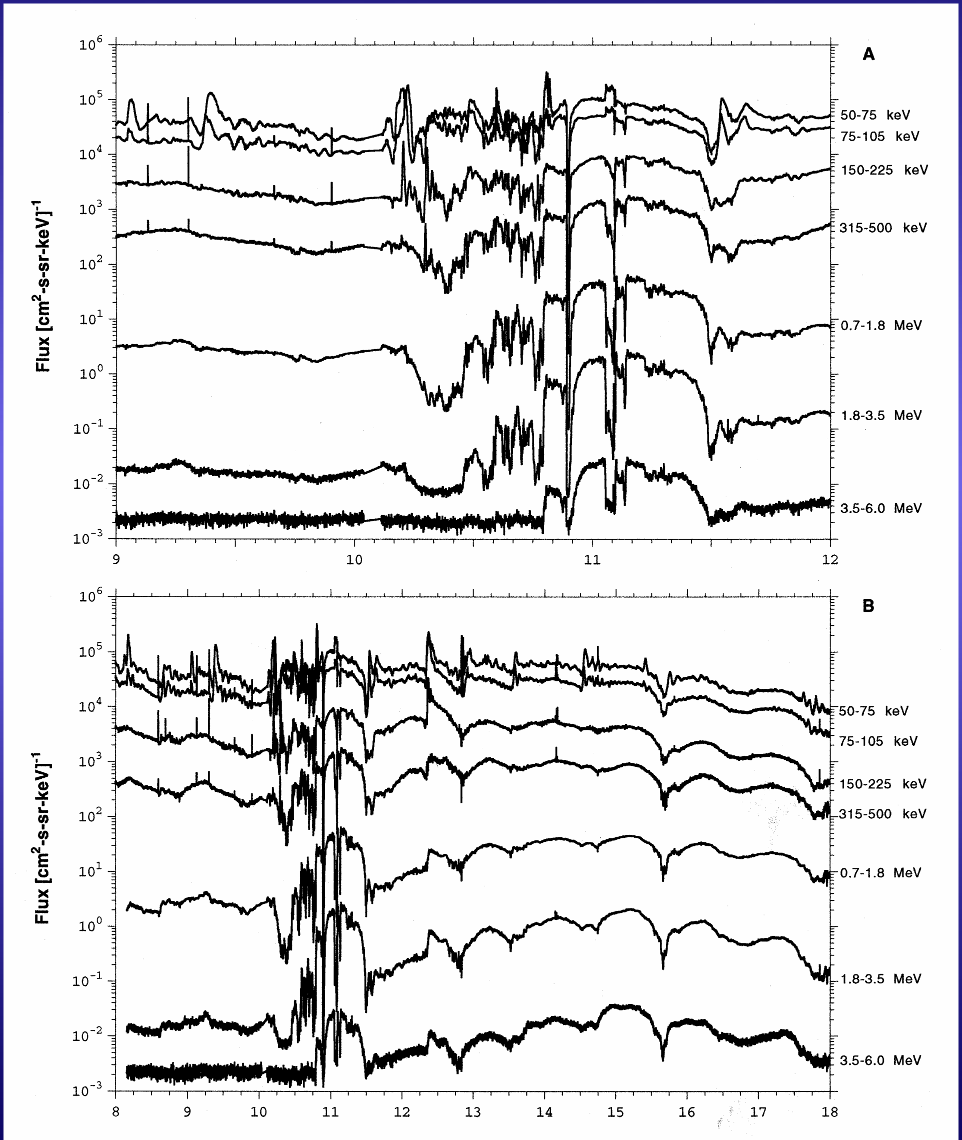


Figure 1. (a) Hourly averaged electron flux variation at GEO for November 2–8, 1993, measured by the CPA instrument on the LANL spacecraft 1984–129 (LT = UT + 0.5) for four high-energy channel and (b) *Dst* variation for the same time period.

- Kim and Chan, [1997]
- MeV flux drops rapidly at storm main phase (as measured by Dst)
- Flux increases during recovery phase
- Flux increases above pre-storm level before Dst recovered
- Net acceleration
- How are electrons accelerated?

Variations in Flux at Geostationary During a CME Event



- Jan 1997 storm CME event [Reeves et al.,1998]
- Rapid variations on periods of hours
- Net increase MeV electrons above pre-storm level over 2-3 days
- 2 timescales

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Magnetic Storm Association

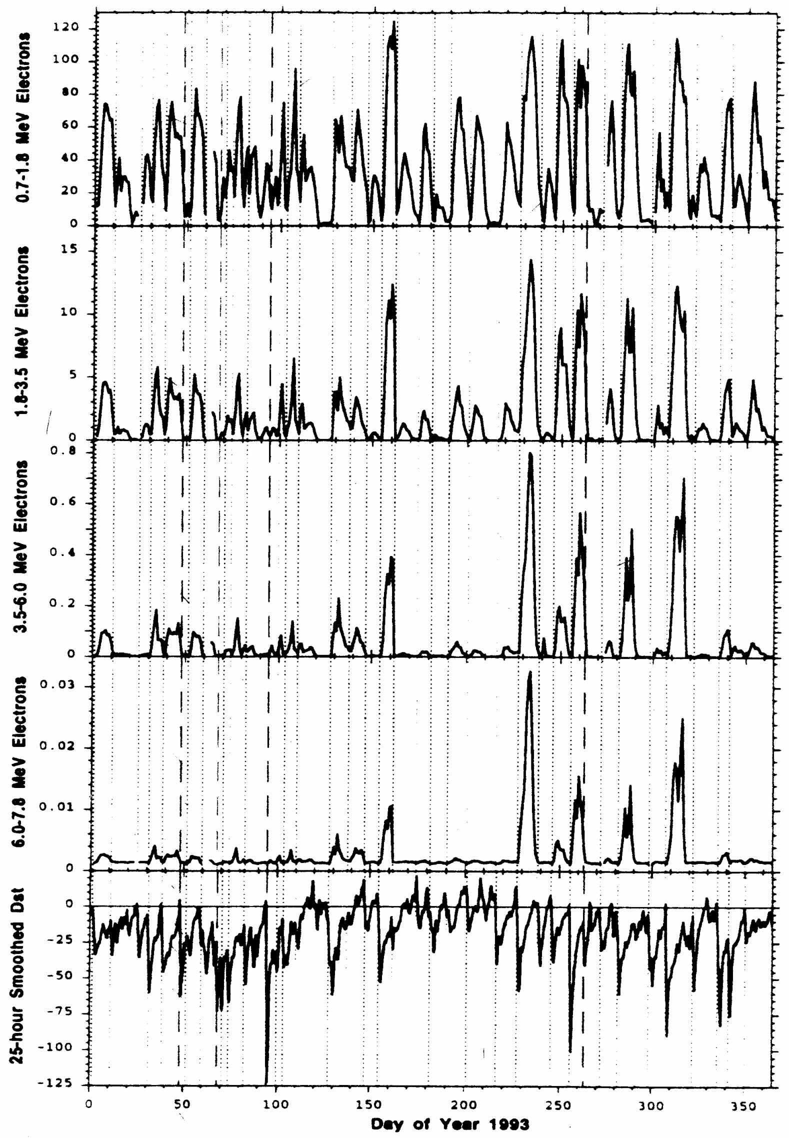

Figure 2. Relativistic electron fluxes (in $[cm^2\text{-}s\text{-}sr\text{-}keV]^{-1}$) in four energy channels from 0.7 to 7.8 MeV and the Dst index for 1993. Thirty five relativistic electron events of varying intensity are indicated with dotted lines. The four storms (Dst decreases) that occurred without significant electron fluxes are marked with dashed lines.

- 90% of magnetic storms associated with flux enhancements Reeves [1998]
- Now 50% !
- Why don't all storms result in acceleration ?
- Some storms result in net loss of electrons

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Fast Solar Wind Streams

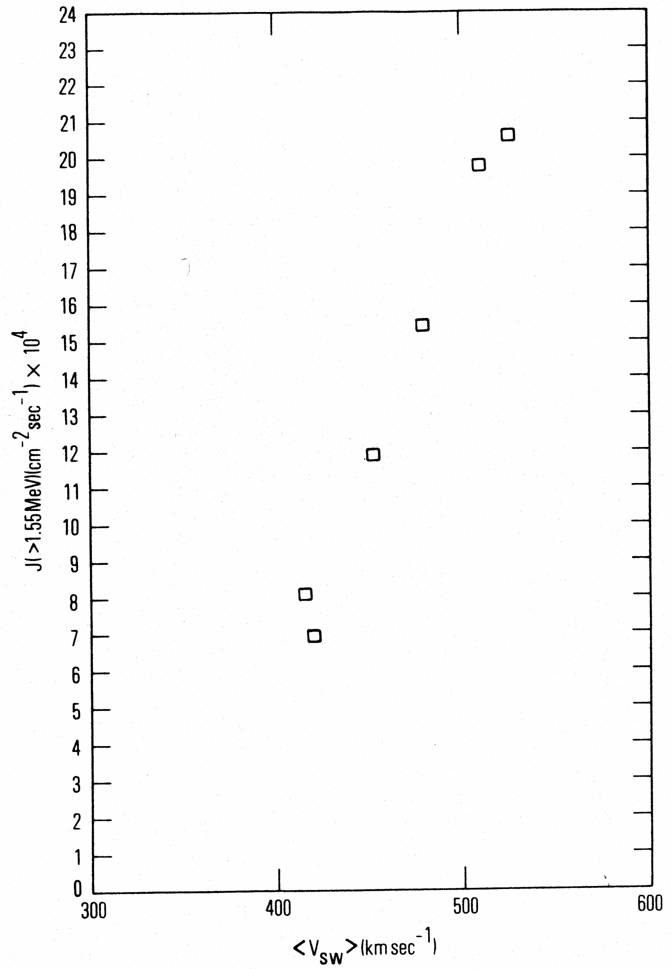

Fig. 20. Plot of the semi-annual average of the E > 1.55 MeV electron flux as a function of the semi-annual average of the solar wind velocity. ATS-6 data from mid 1974 through 1977 are included in this plot.

- Flux enhancements correlated with fast solar wind streams, e.g., Paulikas and Blake [1979] , Baker et al. [1997]; Buhler et al. [1997]

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Summary of Observations

- Electron enhancements in the radiation belts are correlated with:
  - Fast solar wind streams [Paulikas and Blake, 1979].
  - CME events [Li et al., 1993].
  - IMF Bz < 0 [Blake et al., 1997].
  - Magnetic storms [Baker et al., 1986; Reeves, 1998].

- During a magnetic storm, typically:
  - Electron flux rapidly decreases at the beginning of the main phase.
  - Flux increases above pre-storm levels 2-3 days after the main phase.

- Not all magnetic storms or fast solar wind streams result in enhanced electron flux.

- Acceleration must be internal to the magnetosphere
  - Li et al. [1997]

- How are the electrons accelerated ?
- Where are they accelerated ?
- How much loss ?

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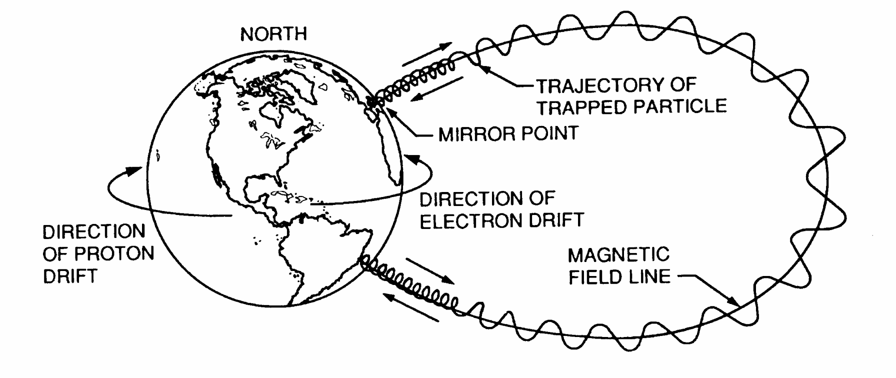
Adiabatic Invariants



- Particles trapped by magnetic field
- Conservation of all 3 invariants results in flux changes – but no net acceleration or loss
- Flux observed above pre-storm level before Dst recovered
- Acceleration requires breaking 1 or more invariants
  - E, B fields at frequencies comparable to drift, bounce and cyclotron frequencies

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

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

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

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Accelerations Mechanisms

- Inward radial diffusion
  - [Schulz and Lanzerotti, 1974]
- Re-circulation model
  - [Nishida, 1976; Fujimoto and Nishida, 1990]
- Dayside compression (inductive E field)
  - [Li et al., 1993; Hudson et al., 1997]
- ULF enhanced radial diffusion
  - [Hudson et al., 1999; Elkington et al., 1999]
- Wave particle interactions
  - [Temerin et al., 1994; Li et al., 1997; Horne and Thorne, 1998; Summers et al., 1998]
- Cusp trapping and diffusion of energetic electrons
  - [Sheldon, 1998]
- Substorm injection
  - [Kim et al., 2000; Fok et al., 2001]
- ULF and whistler mode waves
  - [Liu et al., 1999]

Radial Diffusion

- Schulz and Lanzerotti [1974]
- Inward radial diffusion requires:
  - Spatial gradients in the phase space density
  - Fluctuations in B and (electrostatic) E fields
  - Breaks the 3rd adiabatic invariant

- Acceleration occurs by inward transport into larger B and conservation of
  - $M = p^2 \sin^2 a/(2m_0 B)$ and J

$$\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L}\left[D_{LL}\frac{1}{L^2}\frac{\partial f}{\partial L}\right]$$

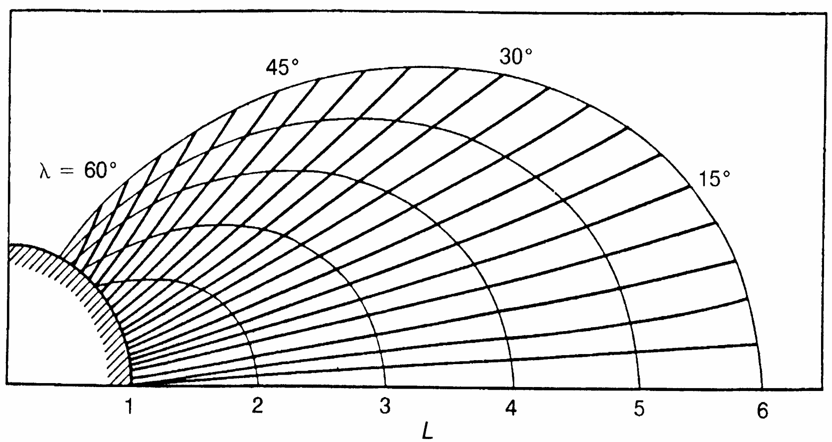

Figure 8.1. Diffusion paths of the mirroring points of trapped particles undergoing radial diffusion conserving the first and second adiabatic invariants.

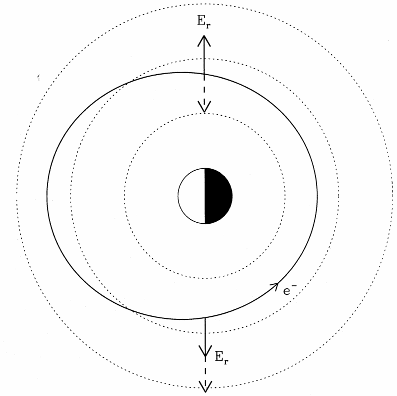

Figure 2. Sketch of an electron drift path in a compressed dipole, with electric fields indicated for an m=2 mode. Solid arrows indicate the electric field at t=0 for an electron starting at dusk, while the dashed arrows indicate the electric field direction half a drift period later.

- OK for quiet times
- Too slow for disturbed times

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ULF Enhanced Radial Diffusion

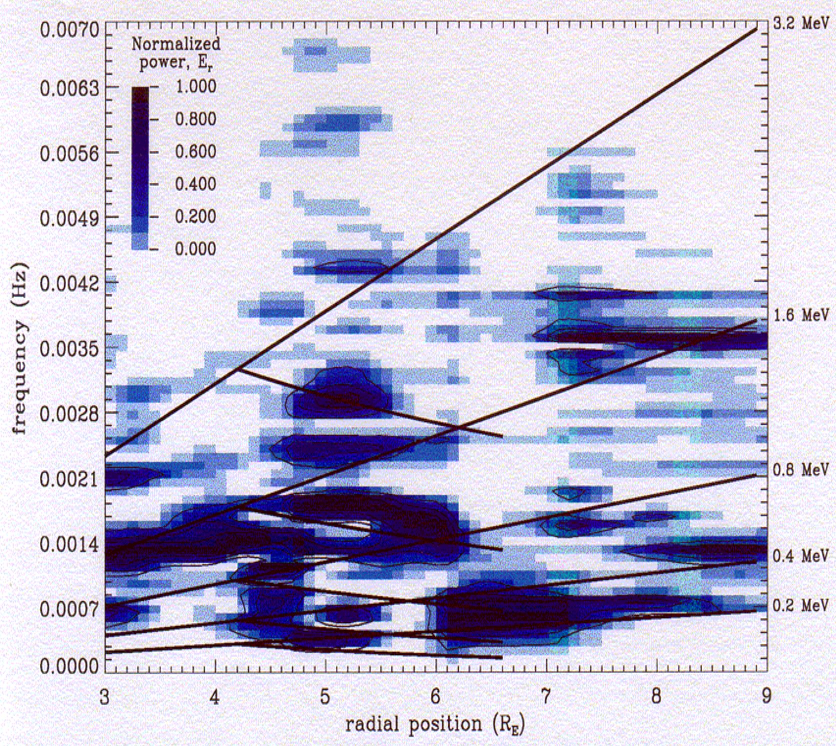

Figure 1. Power spectrum of the toroidal component of the simulated electric field in the period between 0900 and 1200 UT on January 10, 1997, at midnight MLT. The ascending black lines indicate the dipole drift frequency as a function of L for the indicated energies, while the descending lines between 4.2 and 6.6 R_E give the drift frequencies of particles at constant first adiabatic invariant.

- Radial diffusion rate enhanced by ULF waves [Hudson et al., 1999; Elkington et al., 1999; Mathie and Mann, 2000]

- Pc-3-5 waves observed during electron events
- Wave period is comparable to drift period of MeV electrons
- Propose electrons are accelerated by drift bounce resonance with toroidal-mode ULF waves
- Breaks 3rd invariant, but 1st and 2nd are conserved
- Important mechanism

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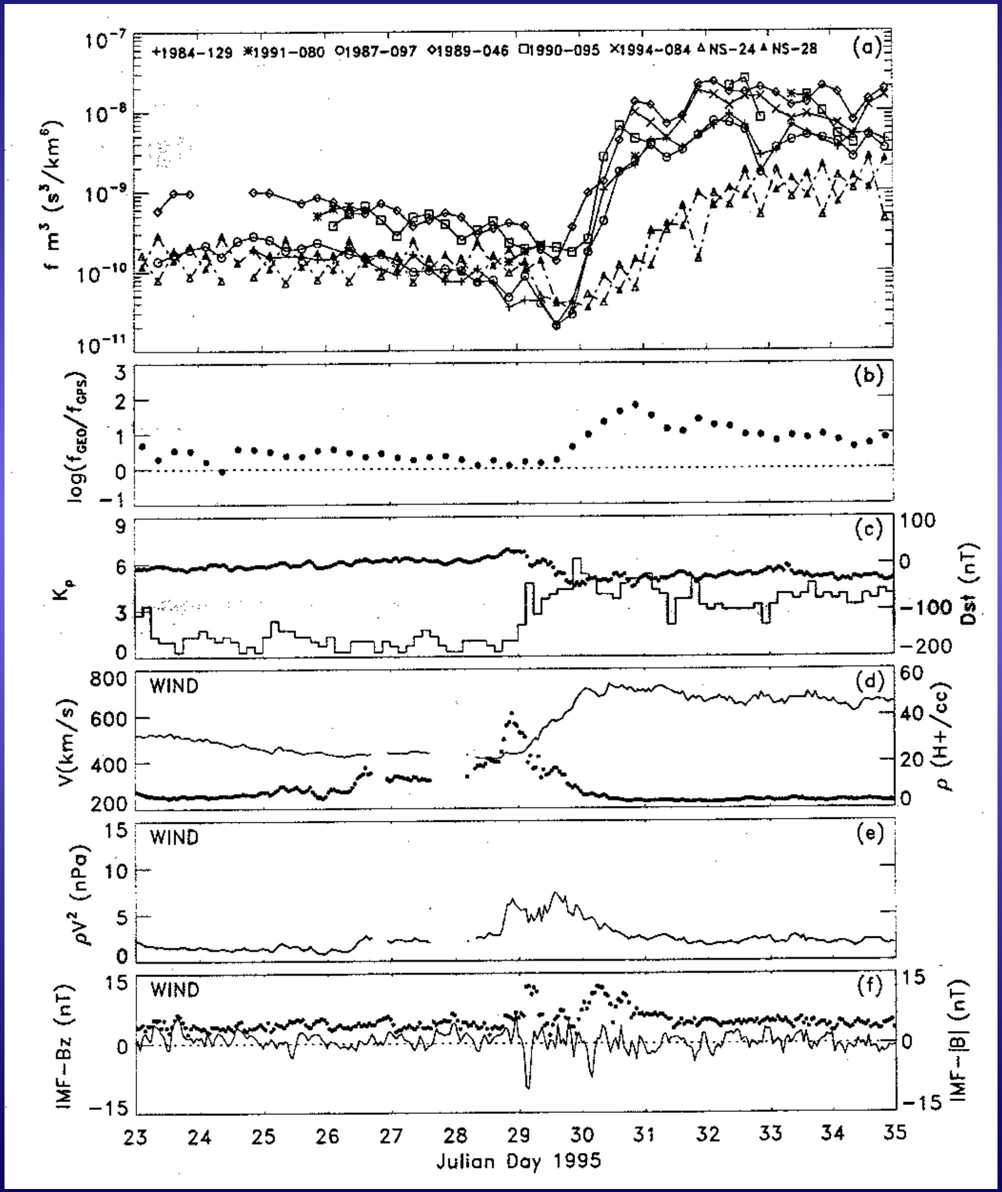
Evidence for Radial Diffusion



- Hilmer et al. [2000]
- Fast solar wind stream and Kp > 3
- Flux increases first at L=6.6, then L = 4.7
- Consistent with inward radial diffusion
- Showed that radial diffusion driven by electric field fluctuations was main contributor

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Problems With Radial Diffusion

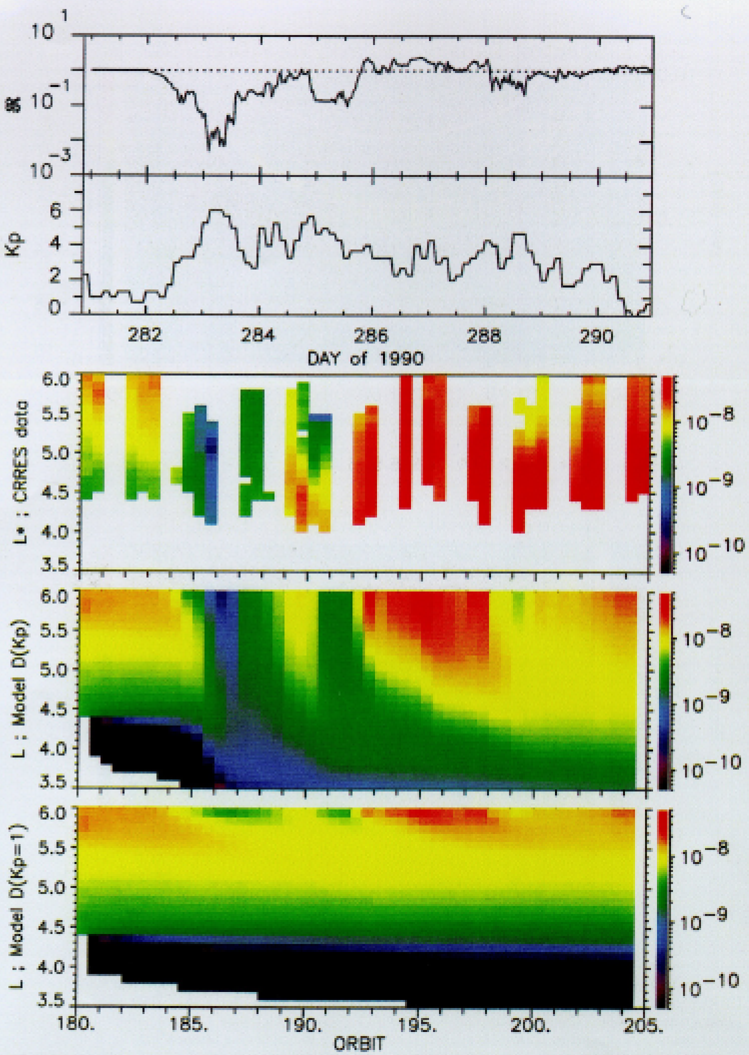

Plate 3. Modeling results survey for electrons with M=1000 MeV/G, with format identical to that of Plate 2. The top panel is a plot of the time-dependent scale factor $\Re_{geo}(E,t)$, for the energy range 0.75-1.10 MeV.

Brautigam and Albert [2000]

- Modelled Oct 1990 storm using CRRES data
- Model, Kp dependent, boundary conditions at GEO

Concluded:

- Radial diffusion underestimates flux by factor at 1000 MeV/G by factor of 5 near L=4
- Peak flux observed near L=4

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Problems With Radial Diffusion

- Storm times - Important for E < 500 keV, but underestimates the flux at > MeV near L=4
- Direction of diffusion is outward during main phase of storm
  - Electron deceleration
- Peak in phase space density near L=4 suggests local acceleration
  - Miyoshi et al. [2002], Brautigam and Albert [2000], Selesnick and Blake [2000], McAdams et al. [2001]
- Long timescales for inward diffusion to L = 4
  - Thorne et al. [2002]

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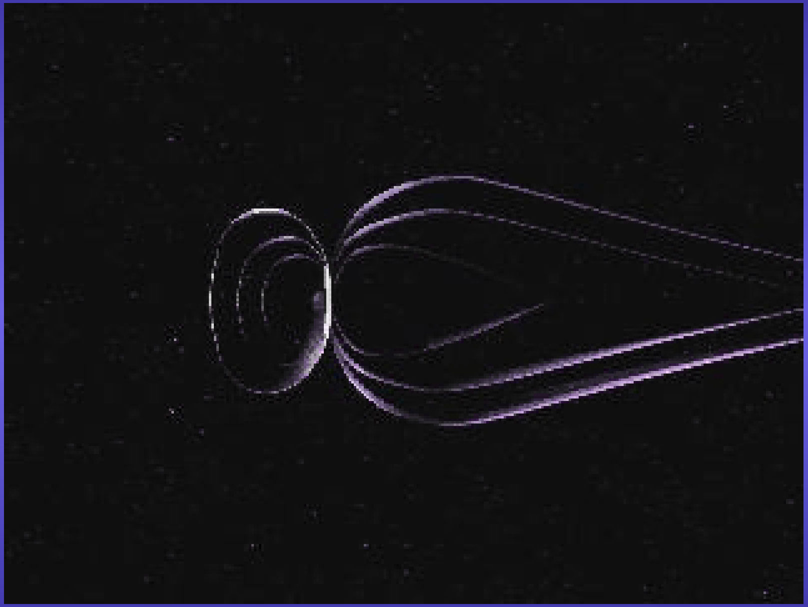
Substorm Injection



Thanks to N. Fox for simulation

- Acceleration by substorm injection [e.g., Kim et al., 2000; Fok et al., 2001]
- But
- Injected particles are usually < 500 keV
- Substorms may play an important role supplying the seed population

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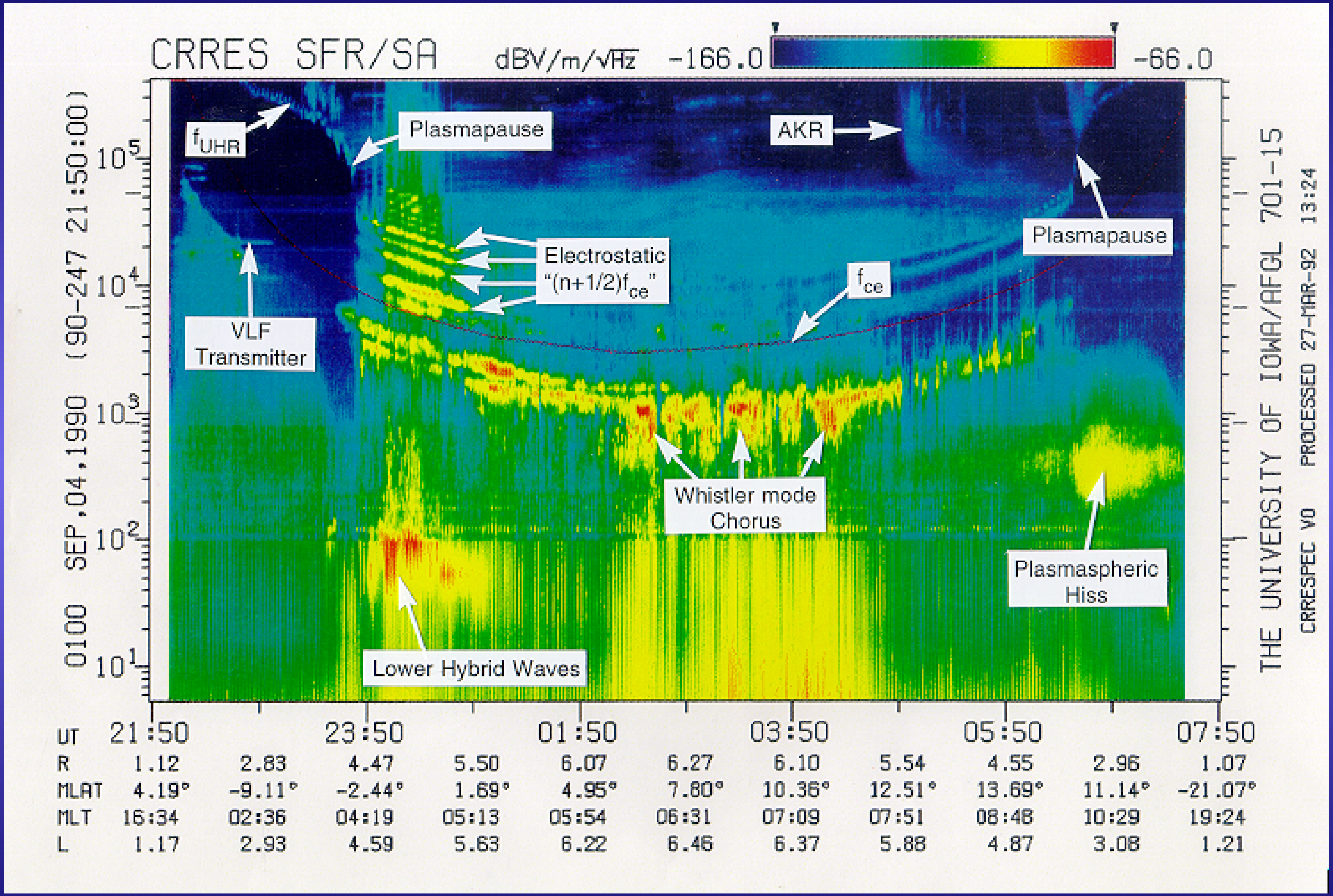
Contribution of Wave-Particle Interactions



- Waves at frequencies that break the 1st invariant (and hence all 3)

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Evidence for Particle Loss by Waves

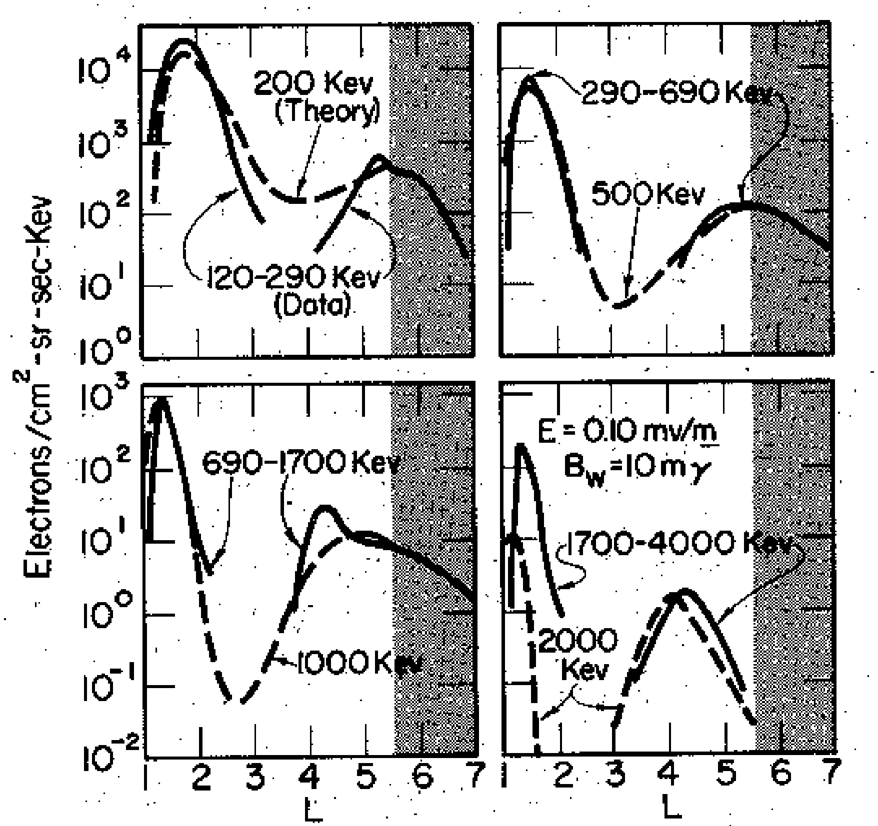

Fig. 3. Theoretical flux profiles for $E = 0.10$ mv/m and $B_W = 10$ mγ are compared with quiet time solar minimum observations [*Pfitzer et al.*, 1966].

- Lyons and Thorne [1973]
- Quiet time radiation belts
- Balance of inward radial diffusion with losses due to whistler mode hiss
- High density region
- Agrees well with observed radiation belt structure
- Strong evidence for wave-particle losses by Doppler shifted cyclotron resonance

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Doppler Shifted Cyclotron Resonance

- For resonance with electrons, wave frequency is Doppler shifted by motion along B.

$$v_{||} = \frac{\omega}{k_{||}}\left(1 - \frac{n\Omega_q}{\gamma\omega}\right)$$

- For propagation along B, whistler waves and electrons must propagate in opposite directions
- Electric field rotates in same sense as electrons
- E field remains in phase with particle
- Efficient exchange of energy

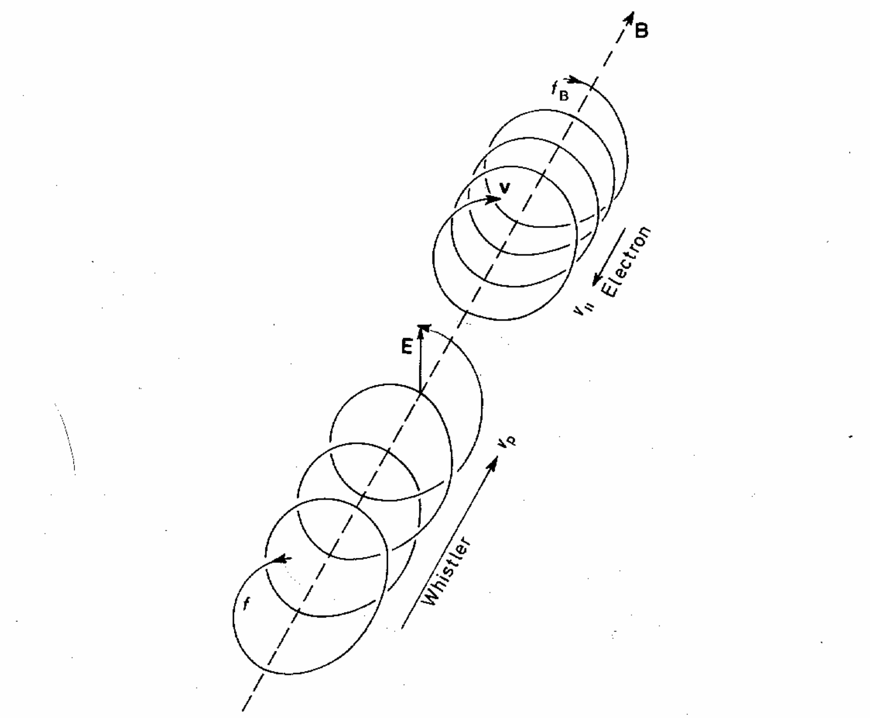

Figure 9.2 Spiral motions of electron and whistler about the geomagnetic field. For effective interaction the electric vector of the whistler must be maintained parallel to the velocity of the electron.

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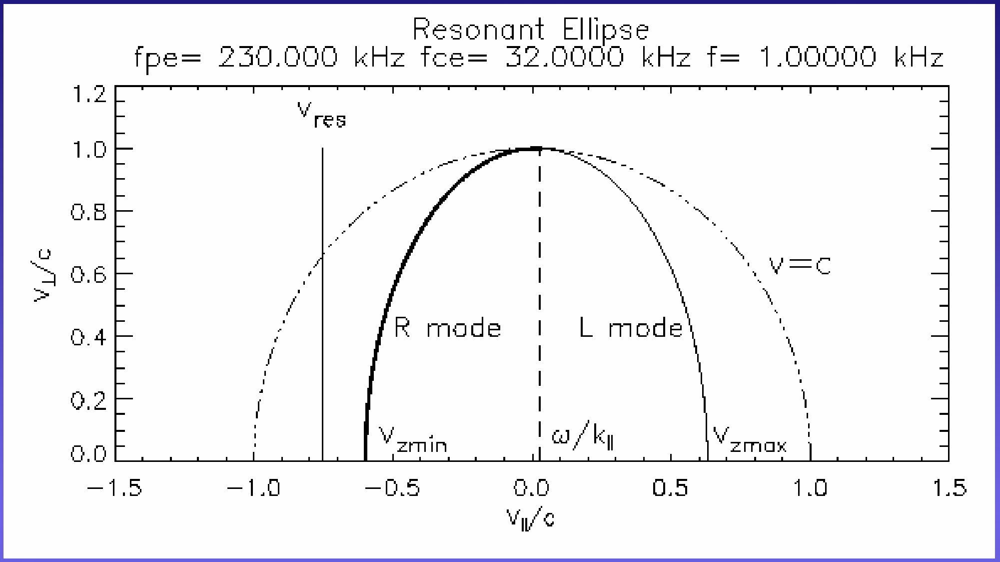
Resonant Ellipse

- In the relativistic case, the resonance condition is an ellipse
- The minimum resonant energy (Eres) is where the ellipse crosses the vz axis
- To solve - require the phase velocity – obtained from the dispersion relation
- Dependence on
  - Plasma frequency fpe
  - Gyro-frequency fce
  - Propagation angle
  - Wave frequency



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

- For f < fce, Eres smaller for R mode
- For f < fci, Eres smaller for L mode

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Resonant Diffusion
Single Wave Characteristics

- Gendrin [1981] showed that small amplitude waves diffuse particles along constant energy surfaces

Force on an electron

$$F = q(\mathbf{E} + \mathbf{v}\times(\mathbf{B_0} + \mathbf{B}))$$

For transverse plane waves

$$k \times E = \omega B,$$

Transform to wave frame – fields at rest

$$F = q((\mathbf{v} - \mathbf{v_{ph}})\times(\mathbf{B_0} + \mathbf{B}))$$

Force is orthogonal to electron displacement – no net transfer of energy

In the *wave frame* the particle energy is conserved

Resonant Diffusion
Single Wave Characteristics

- In the wave frame:

$$v_{\perp}'^2 + v_{\|}'^2 = v_0^2$$

- Particles scattered along circles in velocity

- Transform back to lab frame:

$$v_{\perp}^2 + \left(v_{\|} - \frac{\omega}{k_{\|}}\right)^2 = const$$

- Single wave characteristics are circles centred on the phase velocity along which the particles are scattered

- Can determine pitch angle and energy scattering due to *single waves*

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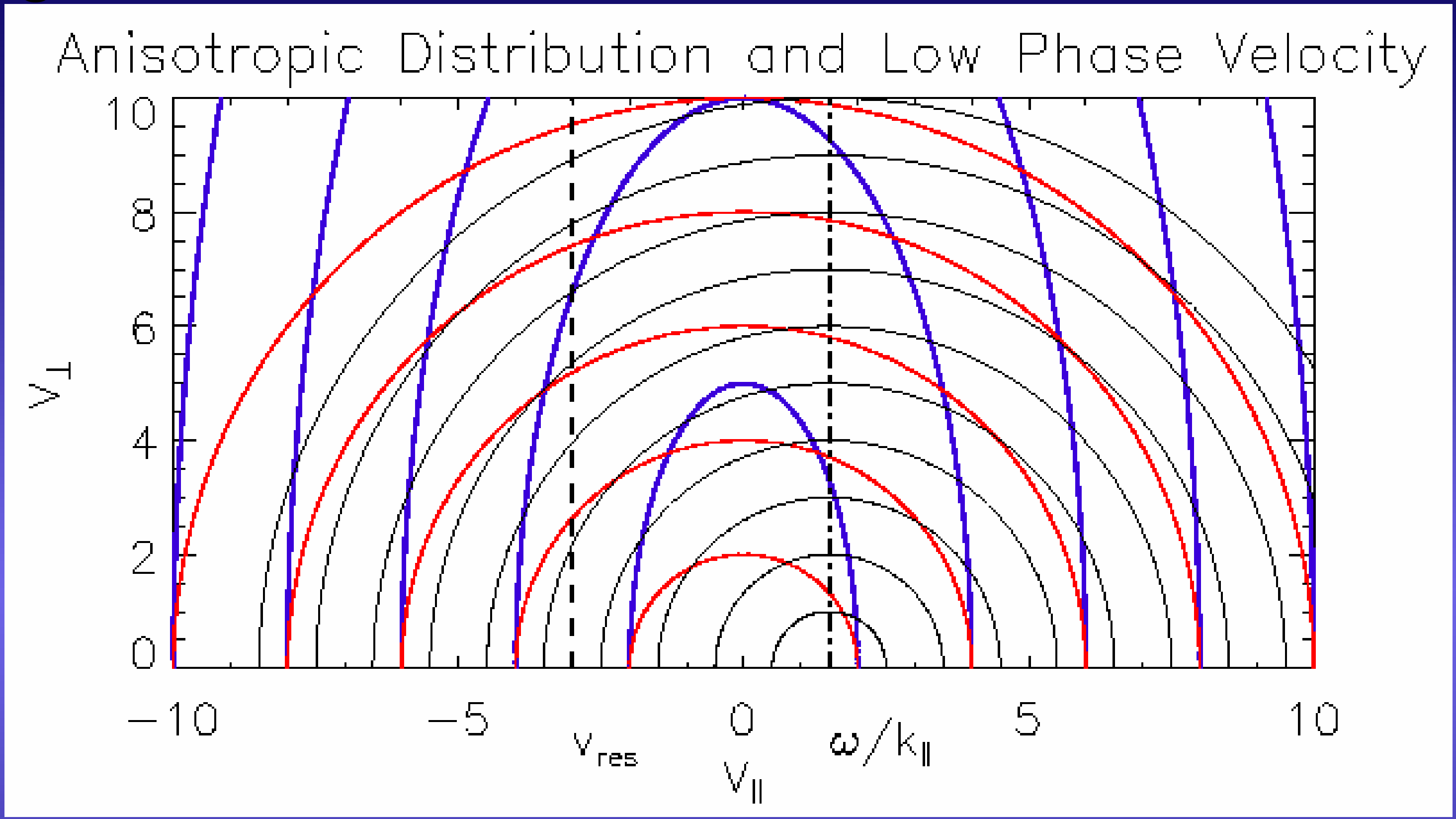
Single Wave Characteristics – Low Phase Velocity



- Particle distribution (blue) anisotropic Tp > Tz (red = constant energy)
- Particle diffusion along single wave characteristics (black)
  - To lower phase space density
- At Vres, direction must be anti-clockwise
- Scattered mainly in pitch angle
- Small energy gain or loss for low phase velocity

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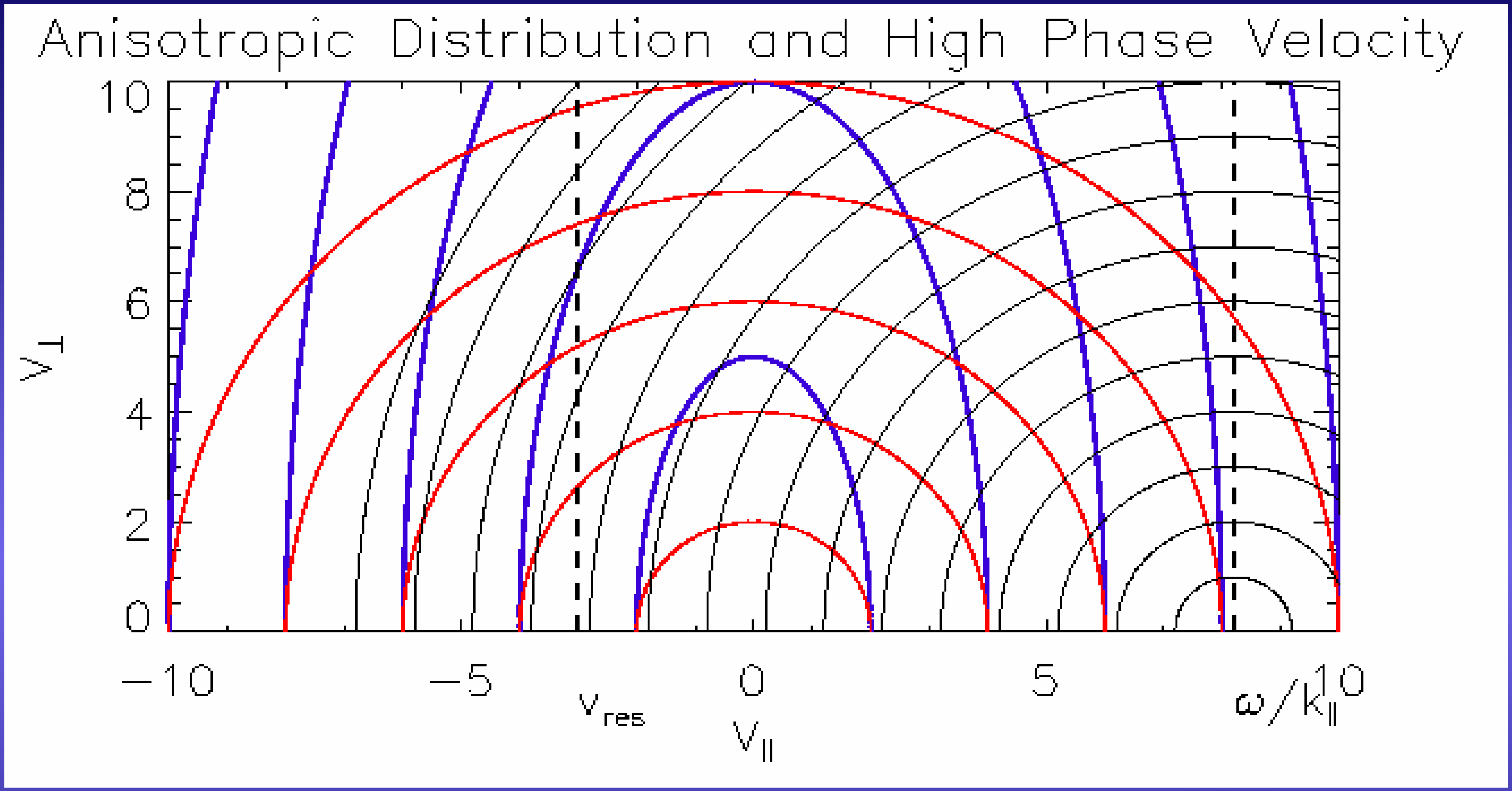
Single Wave Characteristics – High Phase Velocity



- Particle distribution (blue) anisotropic Tp > Tz (red = constant energy)
- Particle diffusion along single wave characteristics (black)
  - To lower phase space density
- At Vres, direction must be anti-clockwise
- Scattered in pitch angle and energy (energy loss)
- Contribute to wave growth

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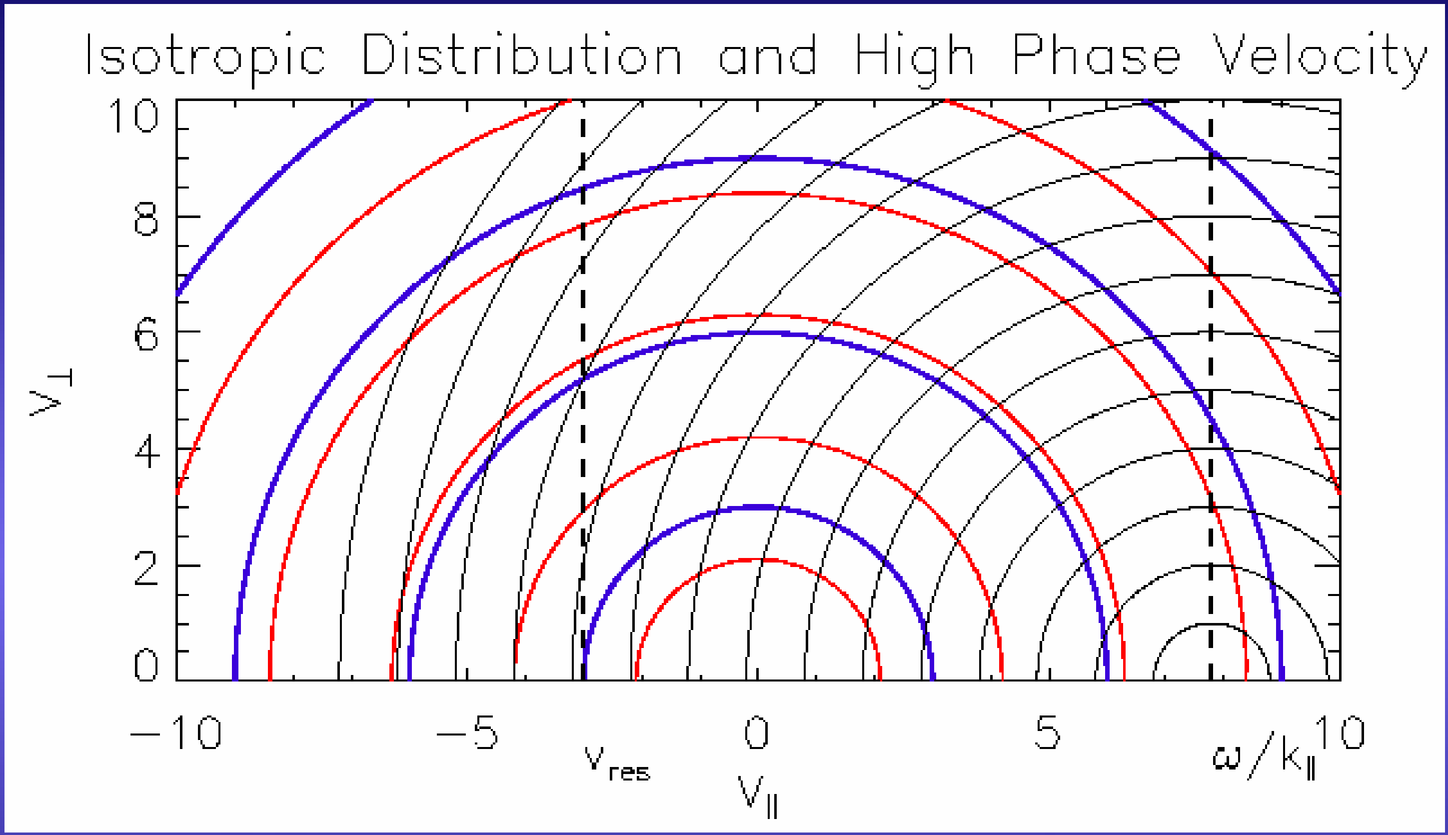
Single Wave Characteristics – High Phase Velocity



- Particle distribution (blue) isotropic Tp = Tz (red = constant energy)
- Particle diffusion along single wave characteristics (black)
  - To lower phase space density
- At Vres, direction must be clockwise
- Scattered in pitch angle and energy (energy gain)
- Contribute to wave damping

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Broad Band Waves

- Single wave characteristics provide insight

- Real world
  - Broad band waves
  - Overlapping resonances

- Quasi-linear diffusion approach
  - Waves uncorrelated
  - Small scattering with each wave
  - Large enough bandwidth
  - Diffusion is proportional to wave power

- Stochastic diffusion

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Energy Gain by Whistler Mode Waves

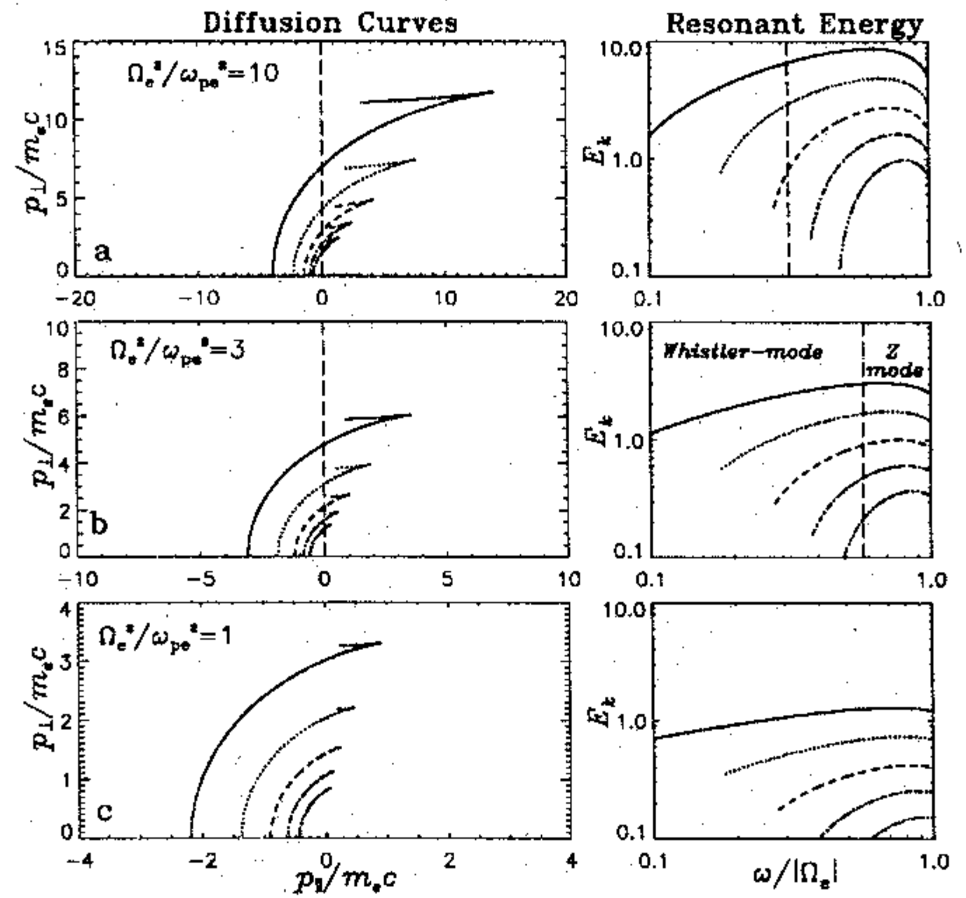

Figure 3. (left) Relativistic resonant diffusion curves in momentum space for electron cyclotron resonance with R mode waves in a low-density plasma. (right) Profiles of the resonant energy (in MeV) along each diffusion curve. In this case, the change in energy along each diffusion curve can be considerable.

- Summers et al [1998]
- Included bandwidth of waves for resonant diffusion
- Assume a bandwidth of resonant waves
- Scatter to larger pitch angles (left) also results in energy gain (right)
- Energy gain more effective in low density
- Whistler and Z mode effective

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Electron Loss by EMIC Waves

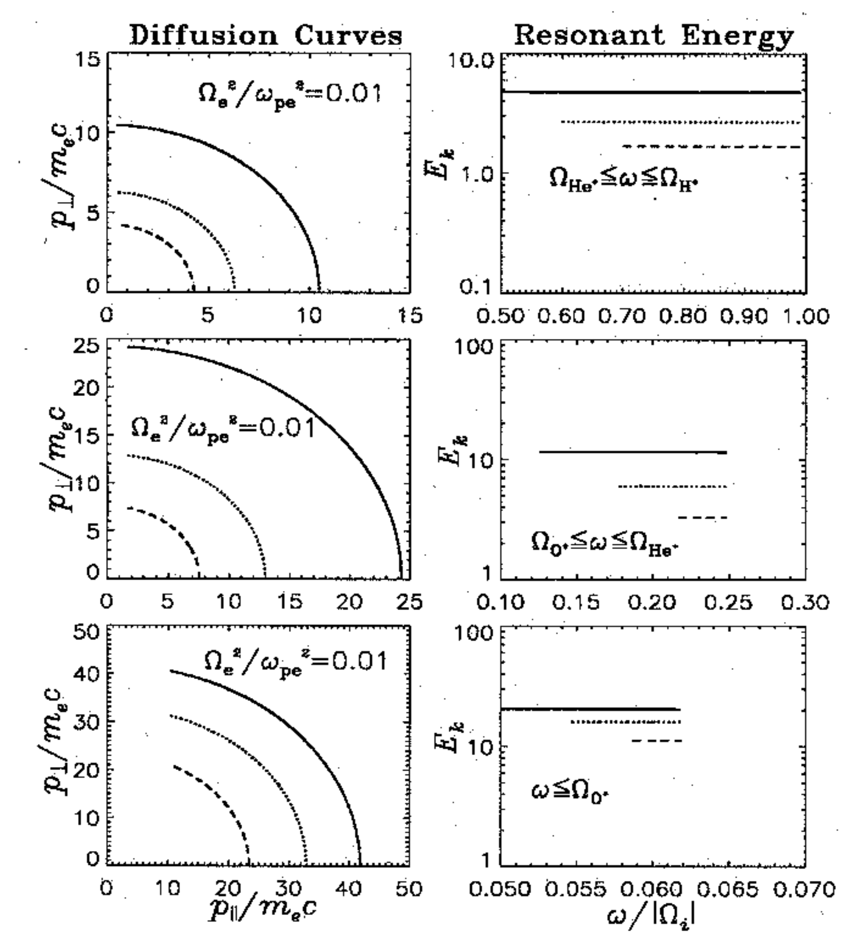

Figure 4. (left) Relativistic resonant diffusion curves for electron cyclotron resonant interaction with L mode EMIC waves in a high-density plasma. (right) Profiles of the resonant energy (in MeV) along each diffusion curve. Here changes in resonant energy are insignificant along each diffusion curve.

- Summers et al [1998]
- Electromagnetic ion cyclotron (EMIC) waves
- Scatter in pitch angle
- Almost no energy gain or loss
- Not effective for acceleration
- Contribute to electron loss from the radiation belts

Acceleration by Doppler Shifted Cyclotron Resonance

- Seed population with E ~100 keV provided by substorm injection and inward diffusion
  - Fast solar wind streams with IMF Bz <0 fluctuations
- Waves are generated by unstable electron (or ion) distributions at E ~ 100 keV
  - Pitch angle scattering and loss of particle energy at low energies
  - But, energy gain by particles possible at higher energies
- As waves propagate the phase velocity changes and the waves resonate with ~ MeV electrons
- Electron acceleration takes place, ***as the waves are absorbed,*** via Doppler shifted cyclotron resonance
- Wave absorption heats the tail distribution function, producing enhanced flux

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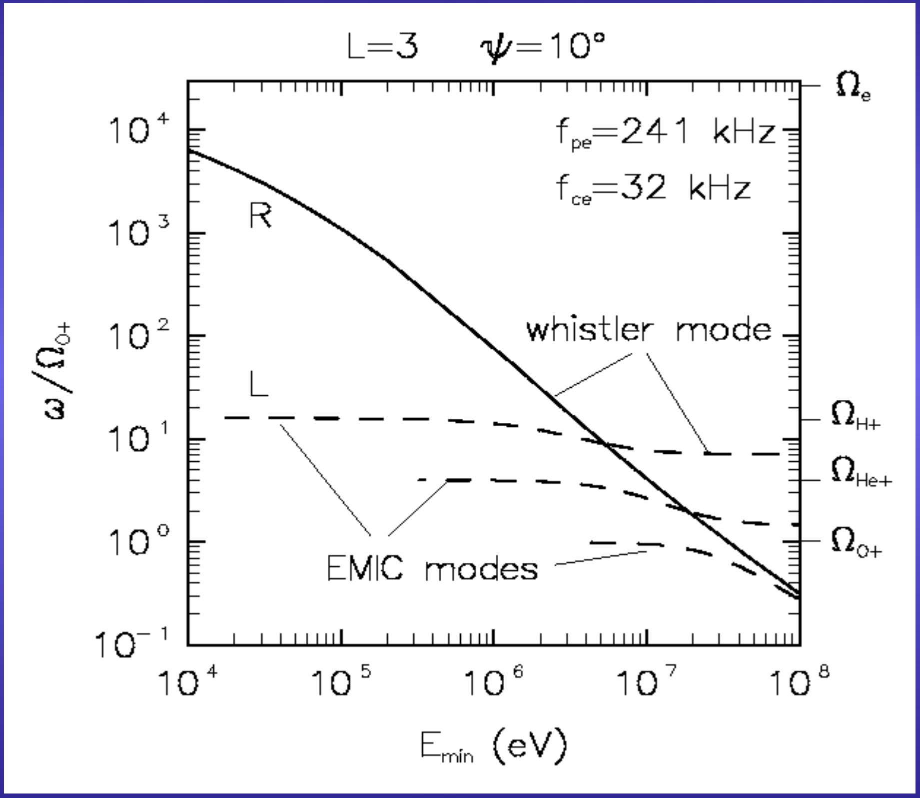
Resonant Energies



- Horne and Thorne [1998]
- To accelerate electrons waves must be able to resonate with 0.1-few MeV electrons

- Found 5 wave modes
  - Whistler mode
  - Magnetosonic
  - Z mode
  - RXZ
  - LO

- Whistler mode is a prime candidate for acceleration (and loss)

- Electromagnetic ion cyclotron waves (EMIC) contribute to loss

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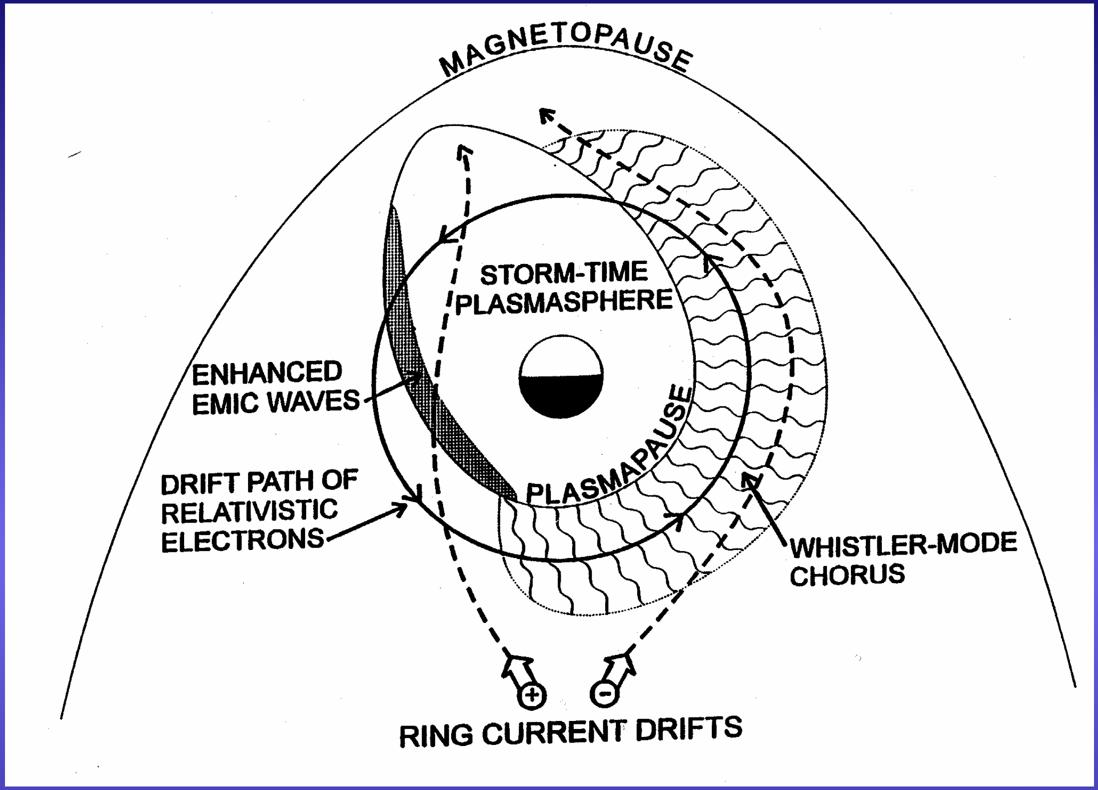
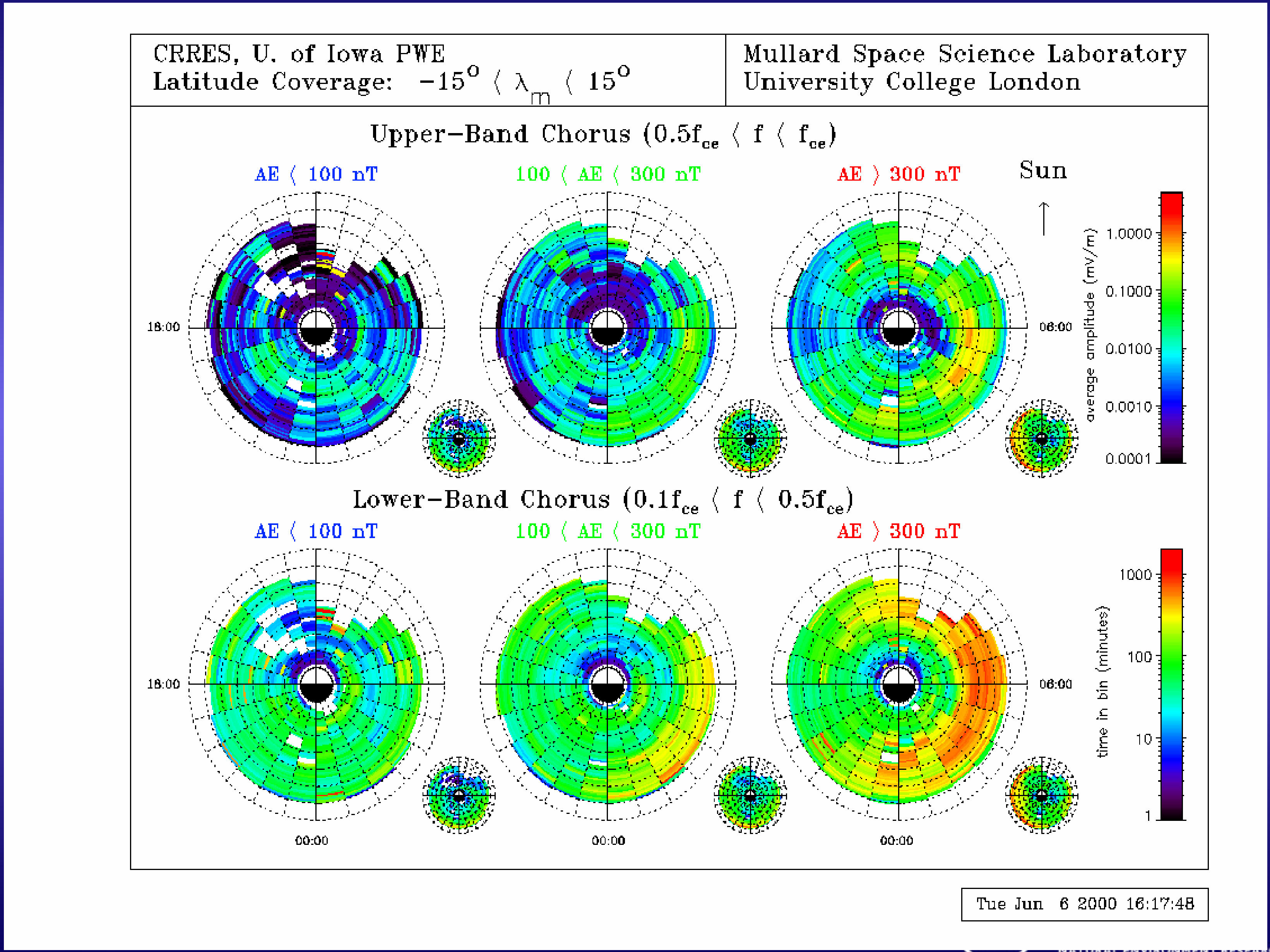
Loss and Acceleration



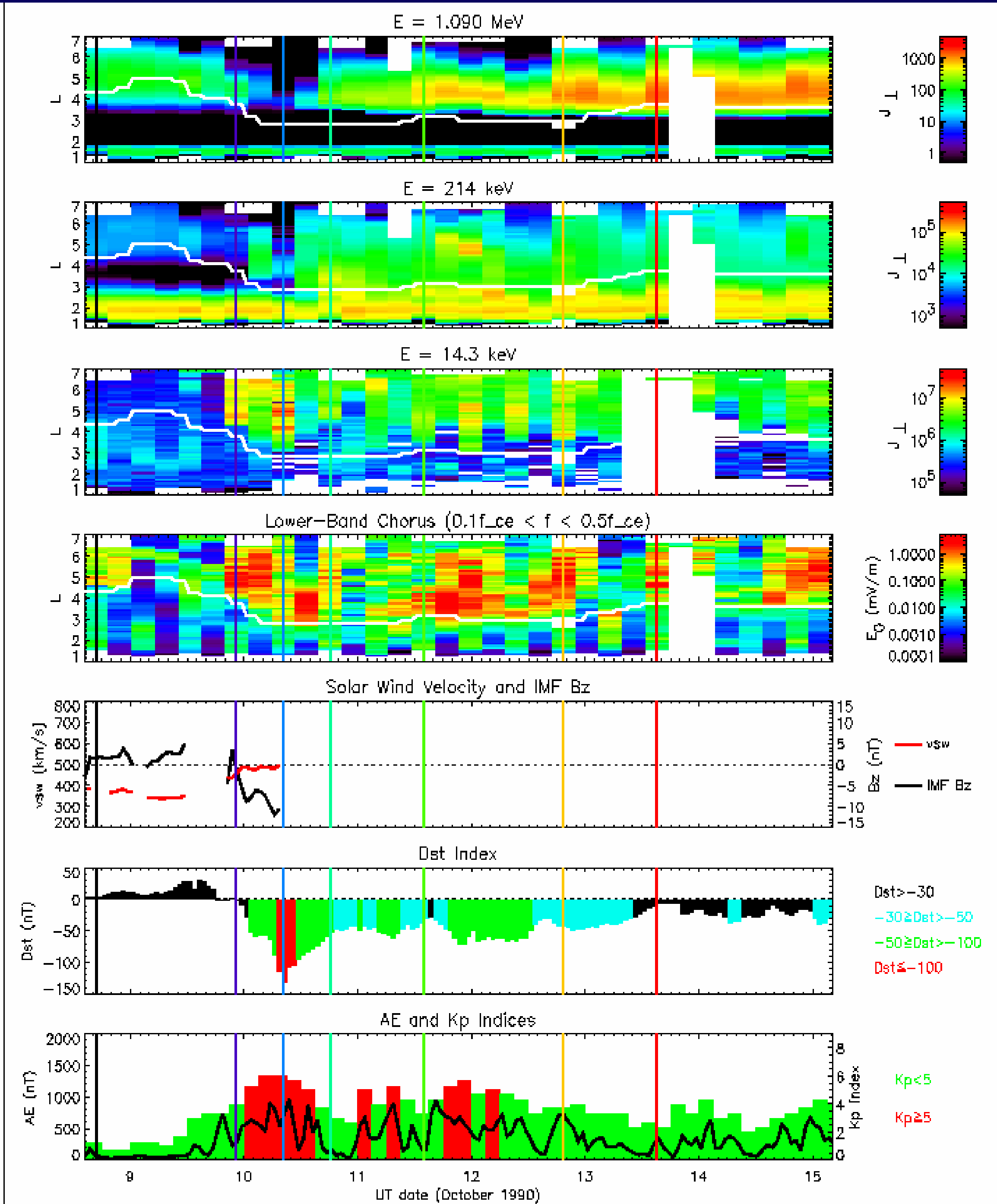
- Waves contribute to loss (EMIC) and acceleration
- Acceleration (by all mechanisms) must overcome the losses
- How much loss ?
  - De-trapping by large scale fields
  - Wave losses

Meredith et al., JGR [2001]

Whistler waves enhanced during substorms



Oct 1990 storm



E=1.09 MeV

214 keV

14.3 keV

- High AE activity
- Electron injection
- Enhanced waves
- Electron flux enhancements

Lower band Chorus

V Solar wind & Bz

Dst

AE & Kp

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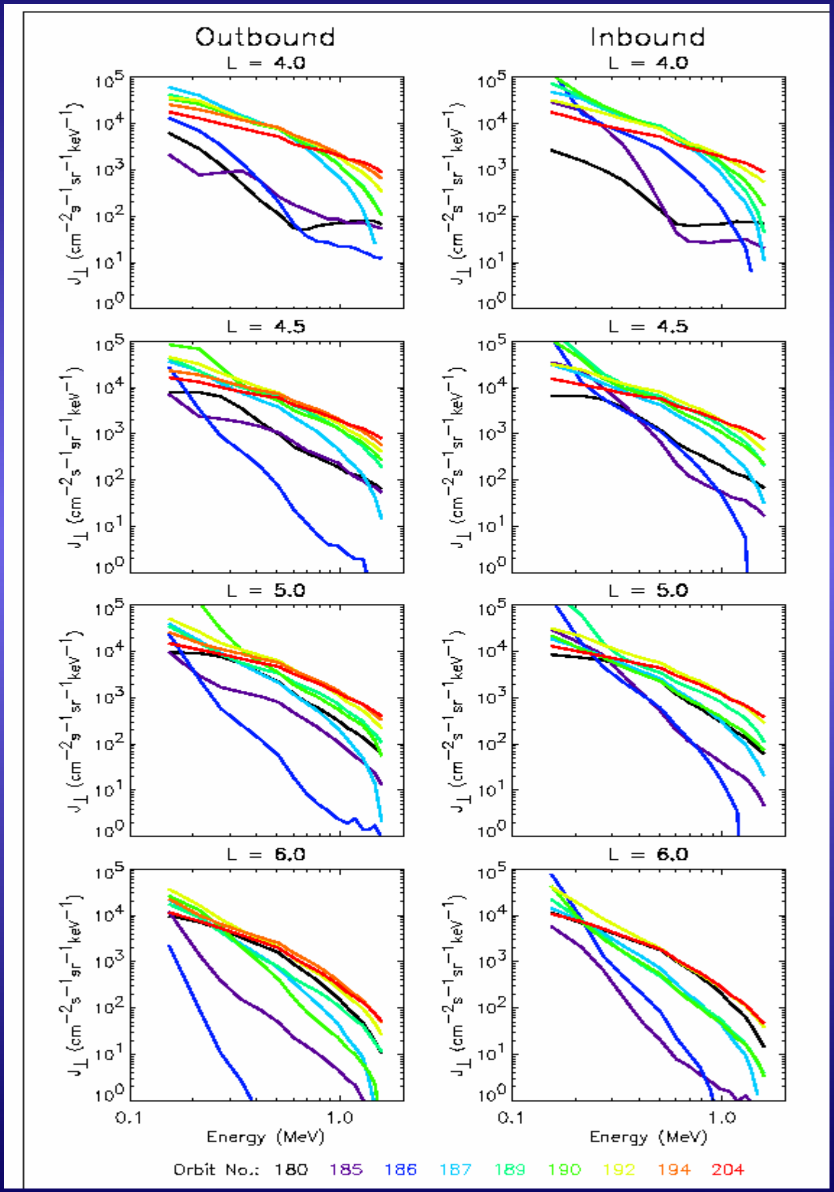
Spectral Hardening



- Meredith et al. [2002]
- Requires enhanced level of substorm activity to pump the low energy (< 100 keV) electrons
- Spectral hardening near L=4 during the recovery phase
- Acceleration is observed to be energy dependent
  - Consistent with wave acceleration

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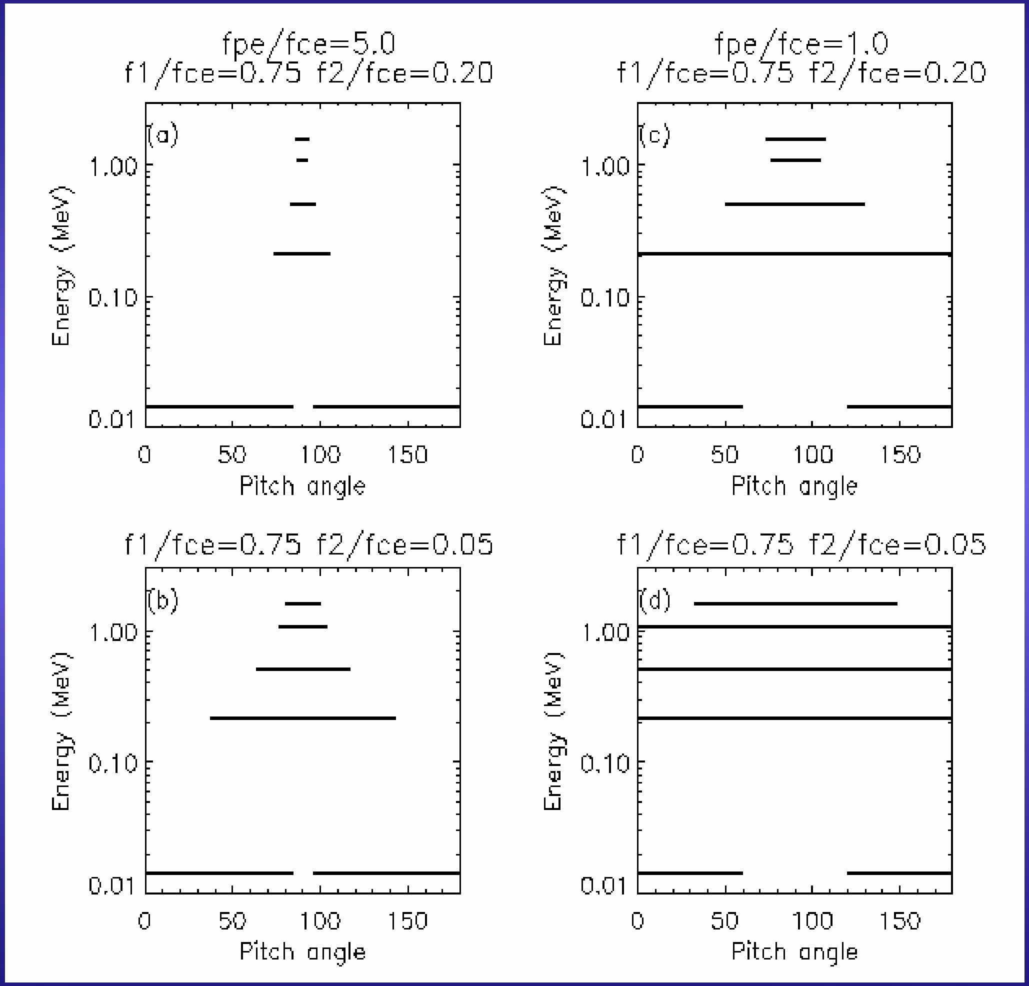
Resonant Pitch Angles



- Assume parallel propagation of whistler mode
- Dominant n=-1 resonance
- Compute resonant ellipse for a band of waves
- Compute range of pitch angles for given energy
- Wave growth by scattering and loss at low energies
- Energisation by scattering of trapped electrons at large pitch angles
- Consistent with flat top distributions

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Timescales

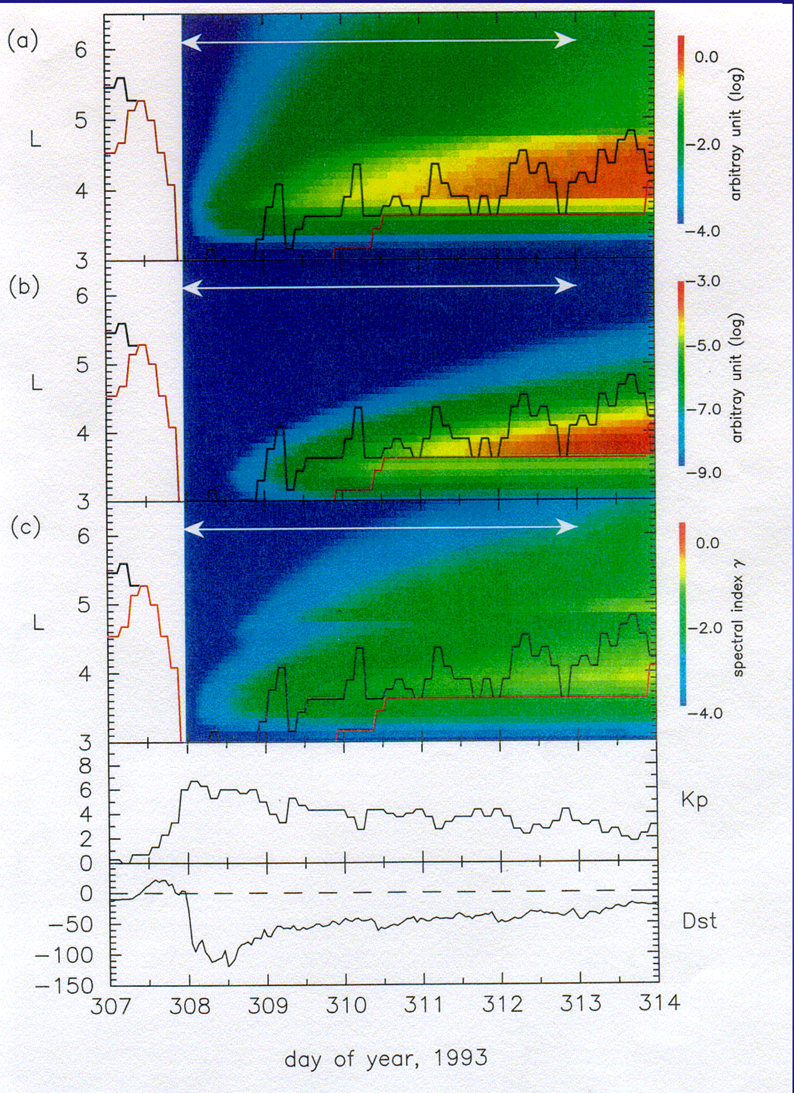

Fig.9 Miyoshi et al.[2001]

- [Summers and Ma [2000]
- Developed Fokker Planck equation for evolution of f(v) due to waves
- Energy diffusion more effective at lower L
- Simulation by Miyoshi et al [2002]
  - Constant wave amplitude of 50pT
  - Seed electrons at 30 keV injected
  - Spectral hardening just outside plasmapause
  - (a) 300 keV electrons, then (b) 2500 keV
  - Timescale – 1-2 days

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Evidence for Doppler Shifted Cyclotron Resonance

- Evidence to support:
- 5 wave modes can resonate with 0.1 – few MeV electrons
- Local acceleration near L=4
  - Whistler mode wave amplitudes enhanced just outside plasmapause where electron flux is observed to be enhanced
- Whistler wave amplitudes enhanced by repeated substorm injection during storm recovery phase
  - consistent with acceleration events
  - consistent with fast solar wind streams and IMFBz < 0
- Pitch angle distributions are flat topped
  - consistent with pitch angle scattering
- Particle spectrum is energy dependent
  - consistent with limited range of resonant energies

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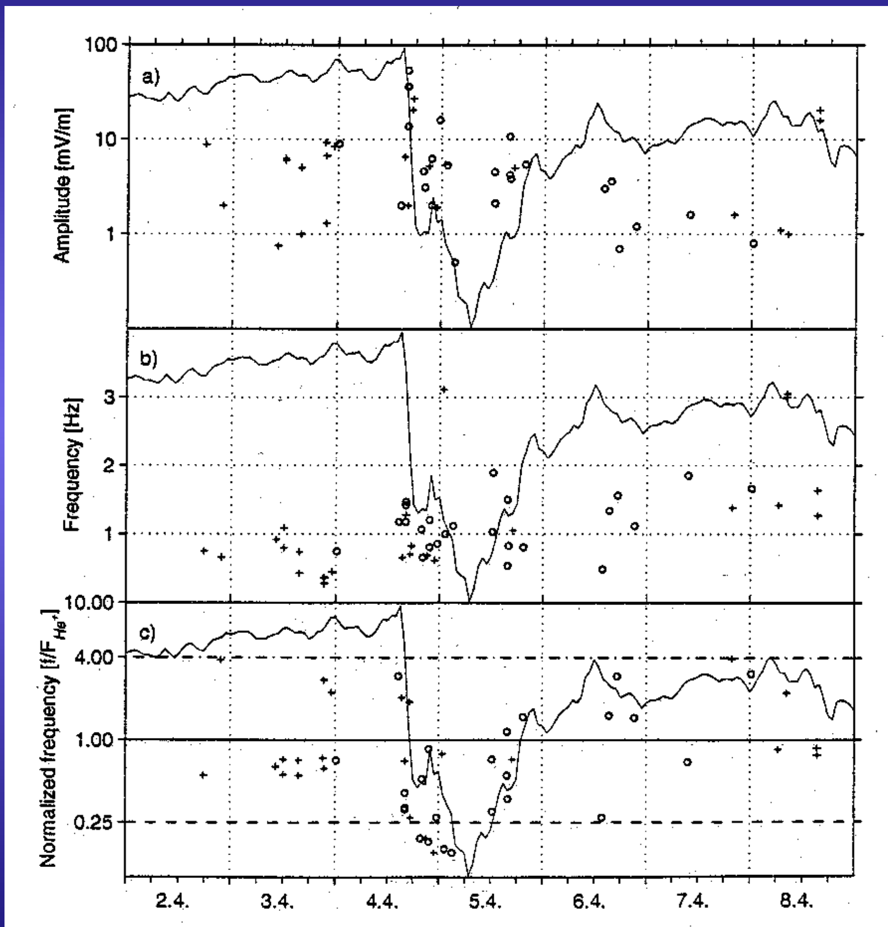
Electron Loss

- Loss to the magnetopause
  - Magnetopause can be compressed inside L=6.6
  - De-trapping of particles and drift outwards to magnetopause
  - How much loss ?

- Loss to the atmosphere
  - Pitch angle scattering into the loss cone
  - Observations of precipitating particles
  - How much loss ?

Evidence for EMIC Waves



- Braysy et al [1998]
- Evidence for EMIC waves during magnetic storms
- Amplitudes enhanced during storm main phase
- Driven by injected ring current H+
- Scattering and loss of protons and MeV electrons

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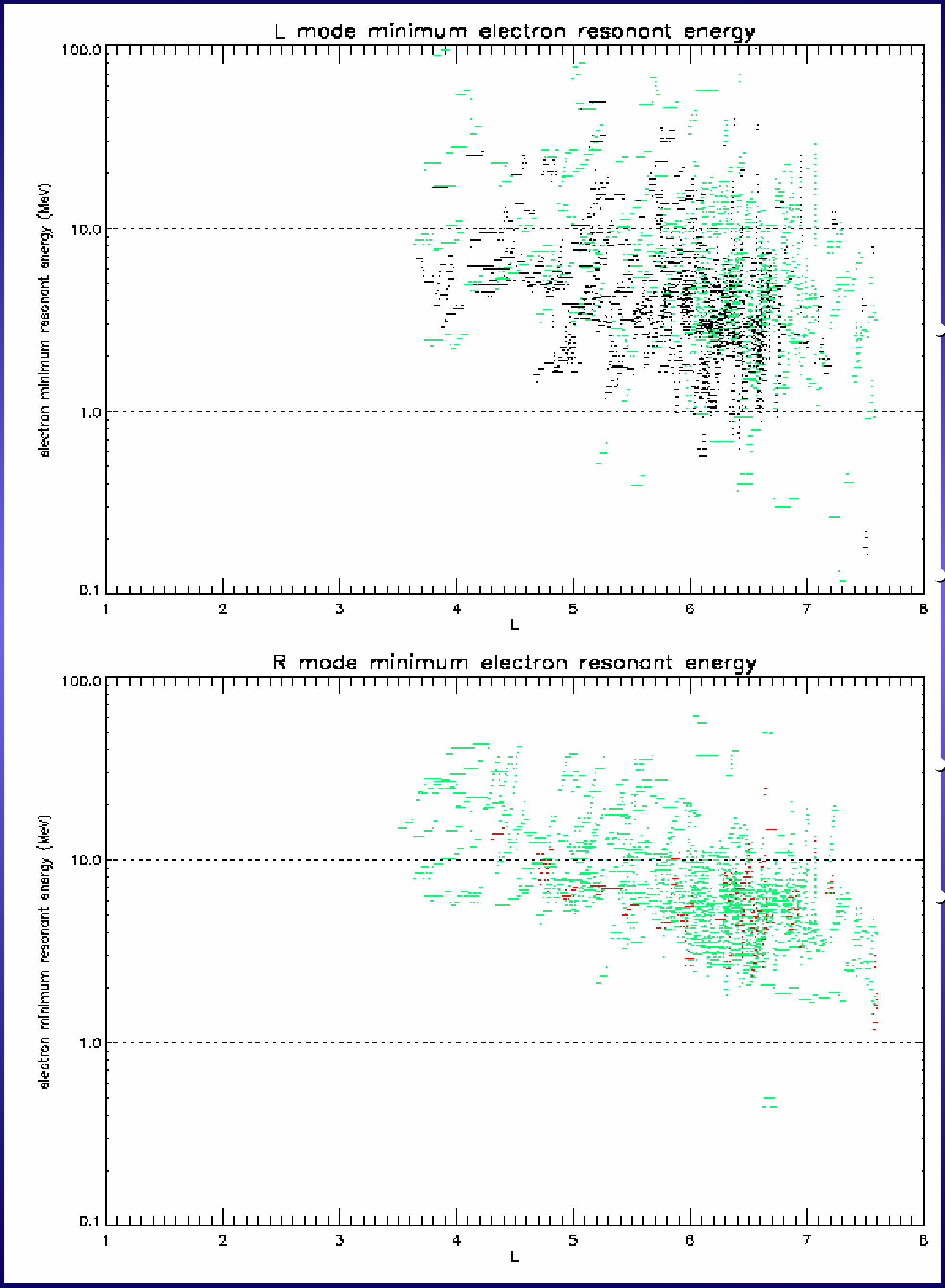
EMIC Resonant Energies



- EMIC wave minimum resonant energies from CRRES (Brian Fraser)
- L mode (top) resonates with ~ 1MeV electrons
- R mode (bottom) > 1 MeV
- Experimental evidence for scattering and contribution to electron loss

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Summary

- Research on the radiation belts is relevant
- Electron acceleration has several complex features
- Experimental evidence to support several theories
  - Wave-particle interactions contribute to acceleration and loss
- Difficult to exclude any (internal acceleration) theories based on existing analysis

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Future Needs

- Quantify losses
  - Sets constraints on acceleration required
- Need to identify conditions to test theories, e.g.,
  - Location of acceleration
  - Direction of diffusion
  - Timescales
- Need better models
  - Magnetic field
  - Diffusion coefficients – need better measurements
- Characterise the seed population
  - Outer trapping region – radial diffusion
  - L ~ 4 waves
- Need for more observations – ILWS – GPS - Galileo
  - Multi-point
  - Combined waves and particles
  - Ground based

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