Radiation Belt Dynamics: Physical Processes

Richard B. Horne

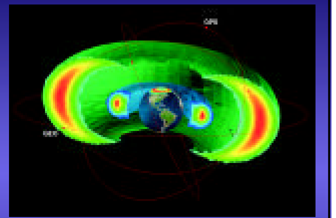
British Antarctic Survey
R.Horne@bas.ac.uk

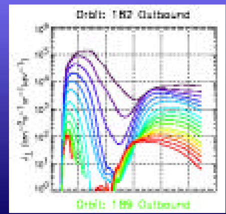
Outline
- Radiation belts and anomalies
- Acceleration
- Losses
- Models

ESWW, Noorwijk 30 November 2004

Earth's Radiation Belts

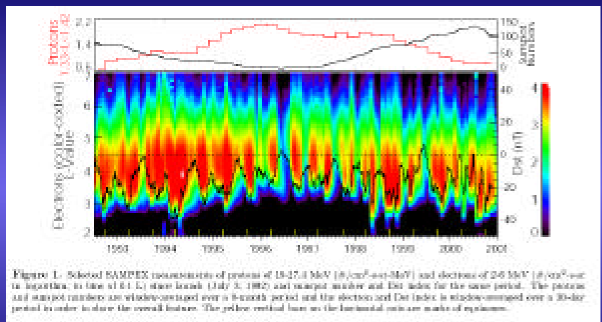
- Energetic electrons (~MeV) trapped by the Earth's magnetic field
- During geomagnetic storms, flux varies by ~1000 over hours to days
- Outer belt highly variable cf inner belt





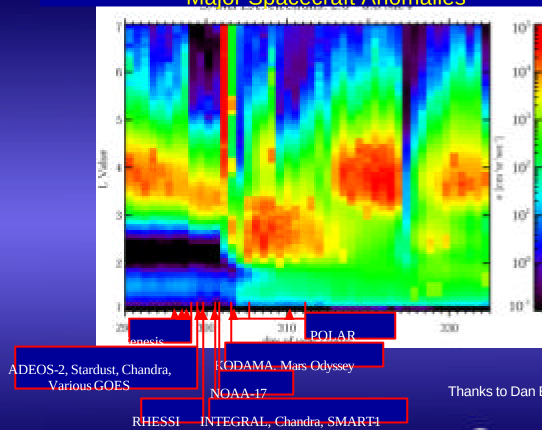
- Outer belt extends to geostationary orbit
- Energetic electrons hazardous to astronauts and spacecraft

Radiation Belt Variability



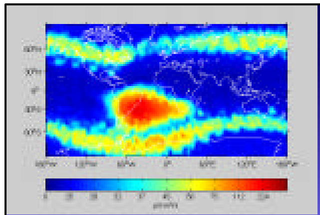
- Li et al., GRL, [2001]

Major Spacecraft Anomalies



Thanks to Dan Baker

South Atlantic Anomaly

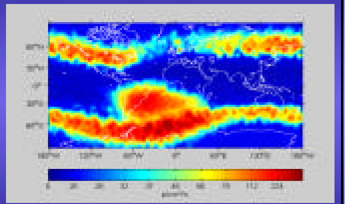


Quiet
15 March 2001

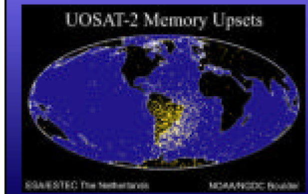
Ecoffet et al. [2002]

Electrons 0.3-6MeV + Protons 8-30MeV

730 km



Magnetic storm
25 March 2001



Anomalies

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Relevance

- ESA study 2001
  - 3 out of 4 satellite designers said that internal charging is now their most important problem
  - [Horne, 2001]
    - MeV electrons the cause
    - Radiation belts important
- Internal charging related to
  - Solar cycle – declining phase
  - Fast solar wind streams
    - Coronal holes

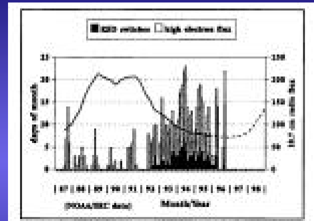

Fig. 5 Monthly number of switches caused by internal charging & days with flux $> 10^8$ cm^{-2} sr^{-1}

Wrenn and Smith [1996]

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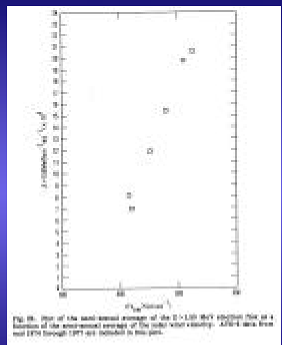
Science Questions

- Relation to solar driver?
  - Fast solar wind streams
  - CMEs
  - 50% of magnetic storms
- How are particles accelerated?
- What is the dominant loss mechanism?
- Effects on atmosphere?
  - Chemistry, ozone
- Physical understanding - better models
  - To specify
  - To predict
  - Analyse past events



Paulikas and Blake [1979]

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Acceleration and Loss Mechanisms

- Acceleration mechanisms
  - Electrons from Jupiter
  - Shock acceleration
  - Radial diffusion
  - ULF enhanced radial diffusion
  - Wave-particle interactions
  - Re-circulation
  - Direct substorm injection
  - Adiabatic effects
  - Cusp injection
- Loss processes
  - De-trapping due to E fields
  - Coulomb Collisions
  - Wave-particle interactions

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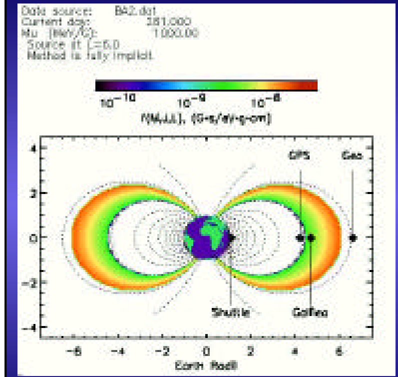
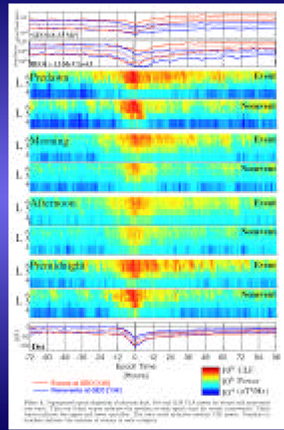
Inward Radial Diffusion



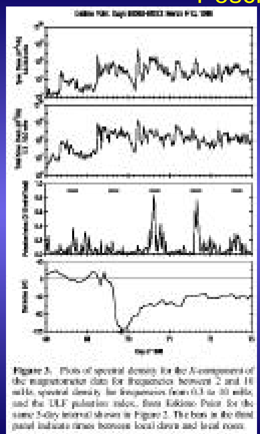
- Fluctuations in Magnetic and Electric field at drift periods of particles
  - mHz
  - Break 3[rd] invariant
- Gradient - drives diffusion towards the planet
- Conservation of 1[st] invariant –
  - $M = p^2 \sin^2 a/(2m_0 B)$ and J
  - B increases
  - Energy gain
- Source at 6.6Re
- Inward transport

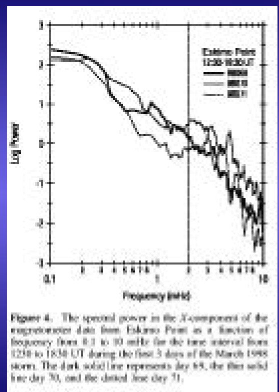
ULF Wave Acceleration



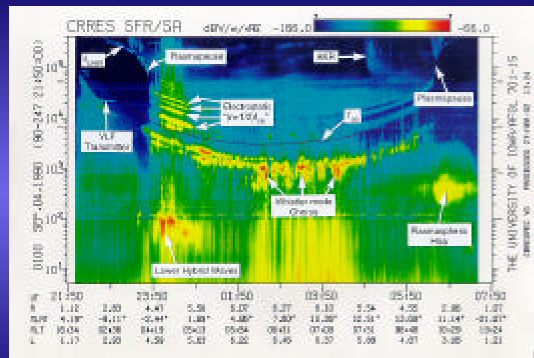
- Radial diffusion too slow
- ULF wave acceleration
  - Hudson et al., Elkington et al.
- ULF wave power increases during storms
- O'brien et al., 2003

Posch et al. [2003]





Wave Acceleration: Which Waves?



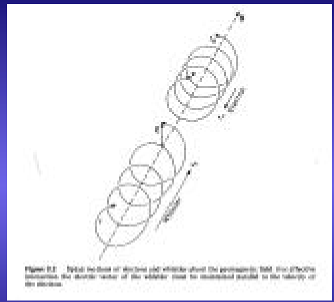
- 5 wave modes for acceleration
- [Horne and Thorne, 1998]

Acceleration by Whistler Mode Waves

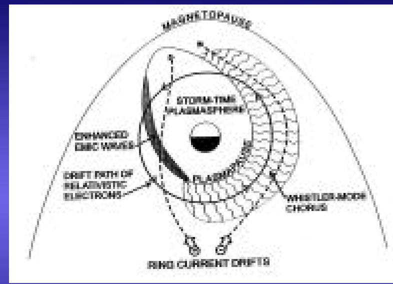
- Wave frequency is Doppler shifted by motion along B.

vk = ! kk Ã 1 ¡ n- q ° ! !

- Electric field rotates in same sense as electrons
- E field remains in phase with particle
- Broad band waves - pitch angle and energy diffusion
  - Acceleration
  - Loss to atmosphere

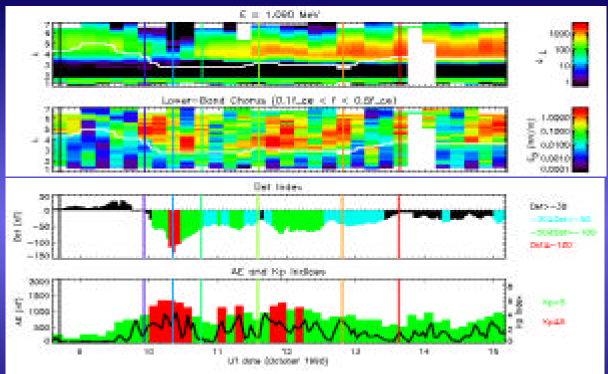


Loss and Acceleration



- Substorms inject ~1 - 100 keV electrons
- Electrons drift and excite whistler mode chorus
- Chorus accelerates fraction of population to ~MeV energies
- Chorus+hiss+EMIC waves contribute to loss

Magnetic Storm

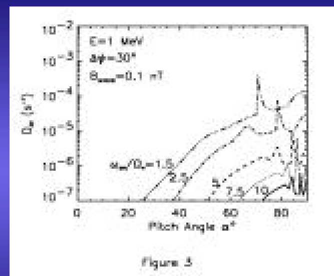


Meredith et al. [2002]

- Substorm injection of keV electrons
- Excitation of chorus
- Chorus accelerates a fraction to MeV energies

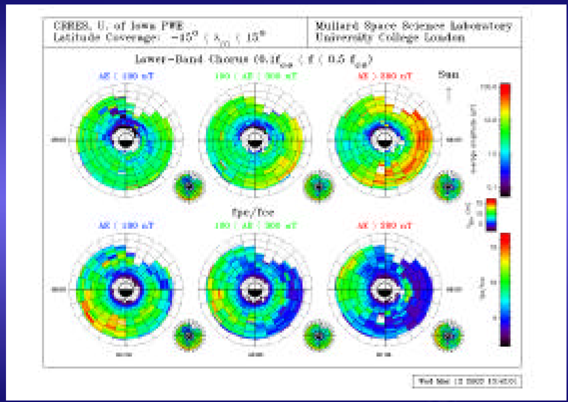
PADIE Diffusion Code

- Calculate pitch angle and energy diffusion
- Momentum diffusion more efficient for low plasma density
- Most effective in the heart of the radiation belt L ~ 4
- Suggests outside the plasmapause during storms
- Possibly high latitudes

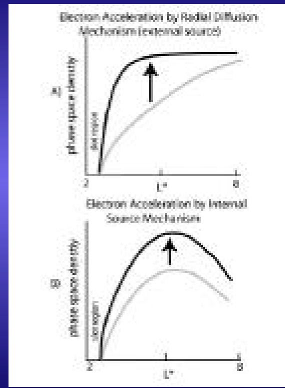


Horne et al. GRL, [2003]

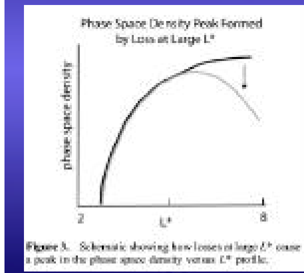
CRRES Survey of fpe/fce



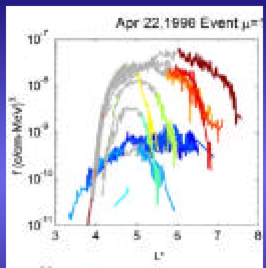
Acceleration: Internal or Radial Diffusion?



- Or could it be losses?

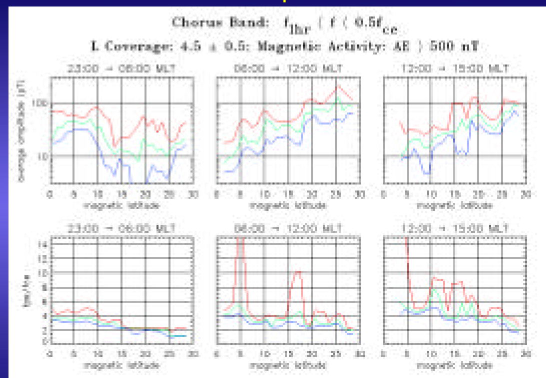


Green and Kivelson 2004



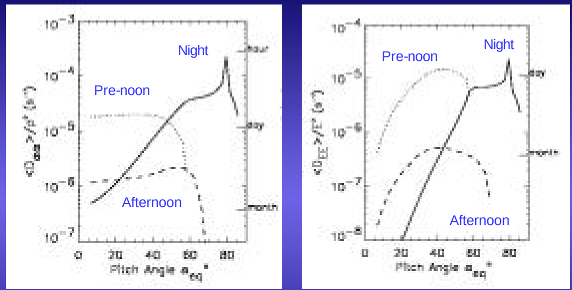
- Peak in phase space density suggests local (wave) acceleration
- Time evolution rules out peak due to losses in outer region

Wave Amplitudes



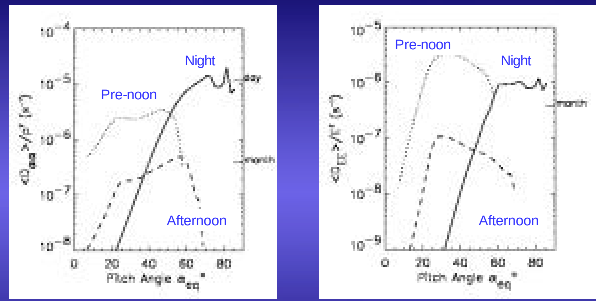
- Green: median
- Red and blue: 75% and 25% quartiles

Average over MLT - 300 keV



- Timescale for loss ~ 0.5 day
- Timescale for acceleration ~ 0.5 day
- Balance between loss and acceleration

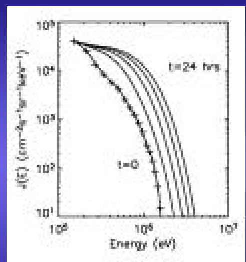
Average over MLT - 1 MeV



- Timescale for loss ~ 10 days
- Timescale for acceleration ~ 3 days
- Electrons accelerated faster than they are lost

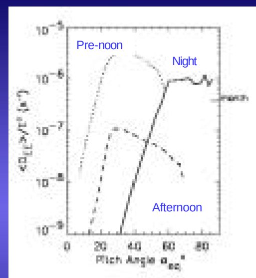
Time Evolution of Flux

- Solve Fokker-Planck equation for energy only
- Assume whistler mode waves present for ~1 day
- Take CRRES data for t=0
- Timescale for flux increase about 12 hours at ~1 MeV
- Timescale consistent with observations (1-2 days)

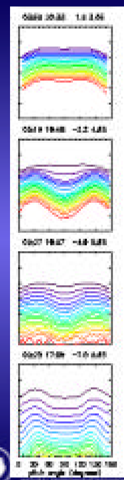


- Time evolution of electron flux at 4.5 Re at the equator

CRRES Orbit 857

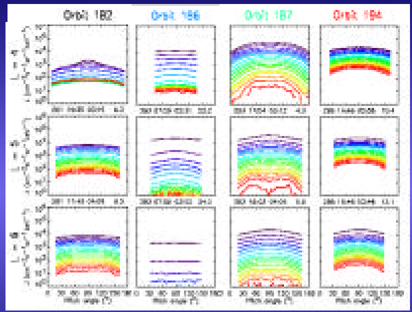


- L=3.65
- Lat = 1.8
- L=4.65
- Lat = -2.2
- L=5.65
- Lat = -4.9
- L=6.65
- Lat = -7.0



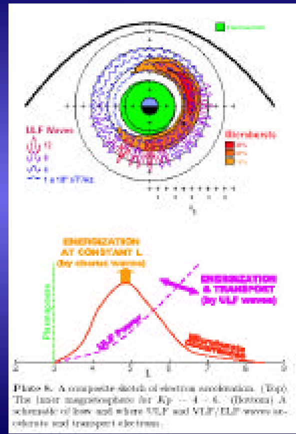
- If dayside chorus dominant
  - Acceleration above equator
  - Model predicts butterfly distributions
- At L = 4 – 5
  - Magnetopause shadowing not expected
  - Nor significant drift shell splitting

Signatures in Pitch Angle Distributions



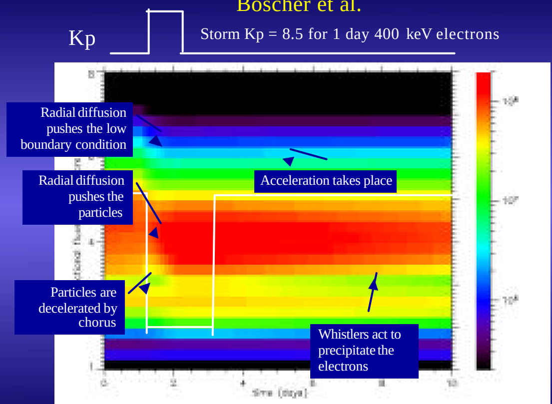
- Measured pitch angle distributions [Horne et al., 2003]
- Flat topped during acceleration L~4
- Width is energy dependent

Dual Acceleration



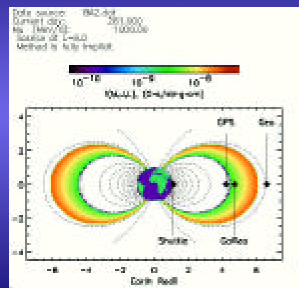
- General concept
- Radial diffusion dominates in the outer region L > 5
- Whistler mode acceleration dominates near L = 3 - 5

Salambo Model – Including Chorus Waves
Boscher et al.

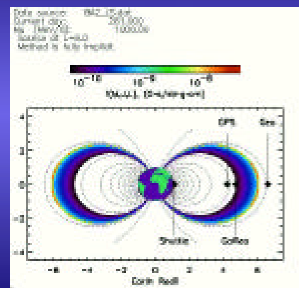


9 Oct 1990 Storm Simulation
How Effective Are Wave Losses?

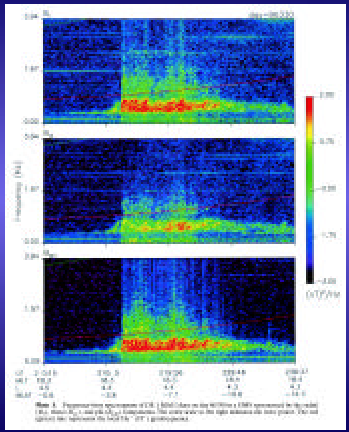
- No losses due to waves



- With maximum theoretical loss due to waves

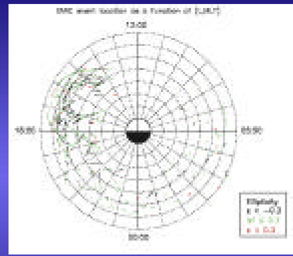


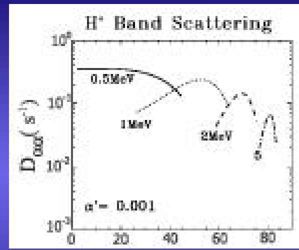
EMIC Waves



- Erlandson and Ukhorskiy [2001]

Losses EMIC waves





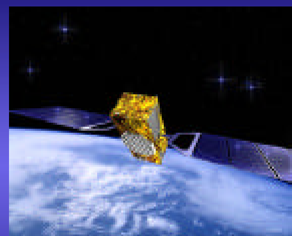
- Very efficient
- MLT distribution?

Needs

- Quantify particle losses to atmosphere
- Measure diffusion coefficients
  - Radial diffusion
  - Pitch angle diffusion
- Quantify most important modes
  - Whistler, Z, LO, RX, magnetosonic, EMIC
  - ULF - Poloidal, torroidal, compressional
- Determine effects on atmospheric chemistry
- Global models need
  - Source particle distribution
  - diffusion coefficients
  - wave amplitudes
  - frequency spectra
  - angular distribution
  - density model
  - magnetic field model
  - MLT, L, magnetic index
  - Relation to solar wind driver
  - Boundary conditions

Conclusions

- Wave acceleration and loss control radiation belt dynamics
- ULF waves L > 5
  - electron transport
  - acceleration
- Whistler mode waves L < 5
  - precipitation
  - acceleration
- Need to incorporate wave acceleration and loss into global models
  - Salambo



- Better specify and predict
- Orbits where there is little data