

Radiation Belt Dynamics: Physical Processes

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Outline

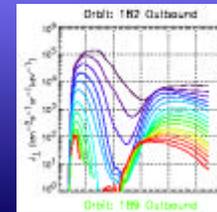
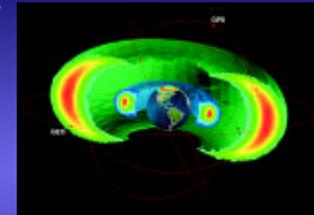
- Radiation belts and anomalies
- Acceleration
- Losses
- Models

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 of inner belt



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



Radiation Belt Variability

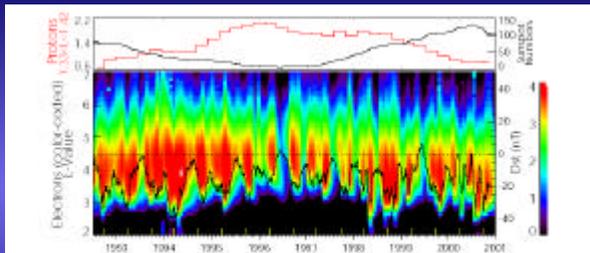
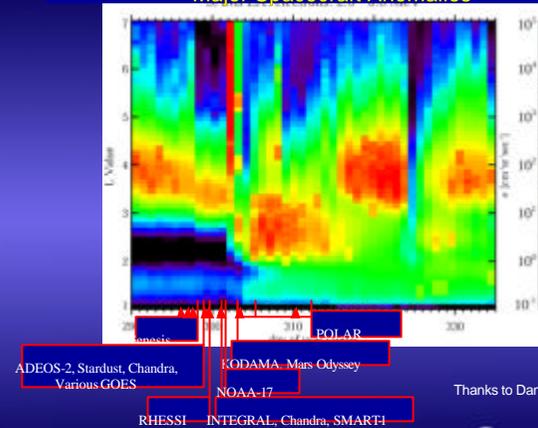


Figure 1. Selected SAMPEX measurements of protons of 10-17.4 MeV ($10^4 \text{ cm}^{-2} \text{ sr}^{-1} \text{ MeV}^{-1}$) and electrons of 2-6 MeV ($10^4 \text{ cm}^{-2} \text{ sr}^{-1} \text{ MeV}^{-1}$) in geostationary orbit at 6.1 L, since launch (July 3, 1992) and merged archive and EDC data for the same period. The proton and electron numbers are window-averaged over a 6-month period and the electron and the proton flux is window-averaged over a 30-day period in order to show the overall features. The yellow vertical bars are the geomagnetic activity index of minimum.

- Li et al., GRL, [2001]



Major Spacecraft Anomalies



Thanks to Dan Baker



South Atlantic Anomaly

Ecoffet et al. [2002]
Electrons 0.3-6MeV + Protons 8-30MeV
730 km

Quiet
15 March 2001

Magnetic storm
25 March 2001

Anomalies

Relevance

- ESA study 2001
 - 3 out of 4 satellite designers said that internal charging is now their most important problem
 - [Home, 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 $> 10^6 \text{ cm}^{-2} \text{ sr}^{-1}$

Wrenn and Smith [1996]

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

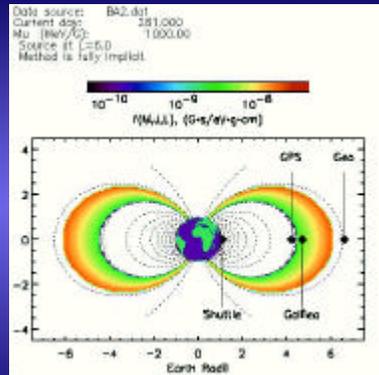
Fig. 16 Plot of the mean radial average of the 0.1-1.00 MeV electron flux at a location of the geomagnetic average of the total solar wind velocity. ATO-4 data from west 87W through 1971 are included in this plot.

Paulikas and Blake [1979]

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

Inward Radial Diffusion

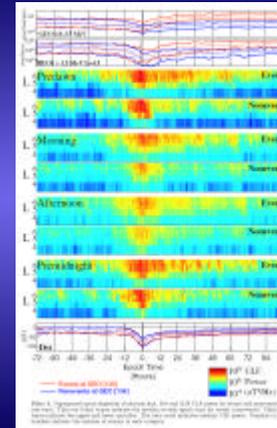


- Source at 6.6Re
- Inward transport

- Fluctuations in Magnetic and Electric field at drift periods of particles
 - mHz
 - Break 3rd invariant
- Gradient - drives diffusion towards the planet
- Conservation of 1st invariant –
 - $M = p^2 \sin^2 \alpha / (2m_e B)$ and J
 - B increases
 - Energy gain



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]

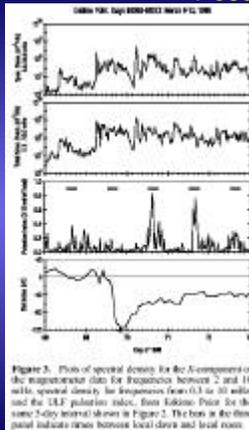


Figure 3. Plots of spectral density for the X-component of the magnetometer data for frequencies between 0.2 and 10 mHz, spectral density for frequencies from 0.1 to 30 mHz, and the 14.15 pulsation index, from Eskimo Point for the same 3-day interval shown in Figure 2. The bars in the time panel indicate times because local days and local nights.

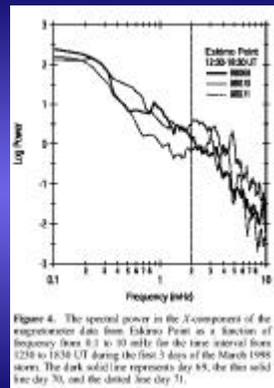
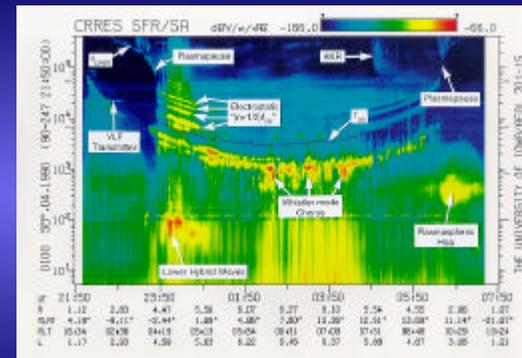


Figure 4. The spectral power in the X-component of the magnetometer data from Eskimo Point as a function of frequency from 0.1 to 10 mHz for the time interval from 0230 to 1930 UT during the first 3 days of the March 1995 storm. The dark solid line represents day 85, the thin solid line day 70, and the dotted line day 71.



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.

$$v_k = \frac{\omega}{k} = \frac{\omega}{k} \left(\frac{1}{\beta} \right) \left(\frac{n^2 - q}{\omega} \right)$$

- 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

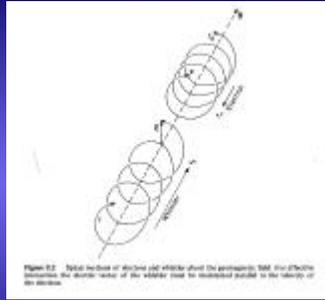
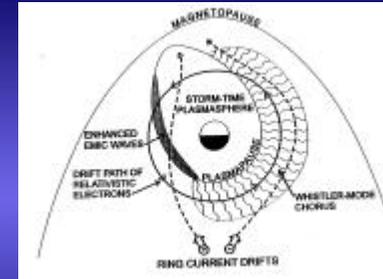


Figure 12 Spatial location of whistler and whistler about the perpendicular B field. The electric field rotates in the same sense as the electron drift in the direction of the magnetic field.



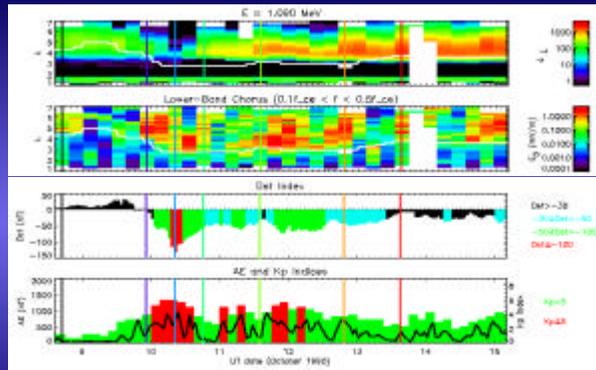
Loss and Acceleration



- 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

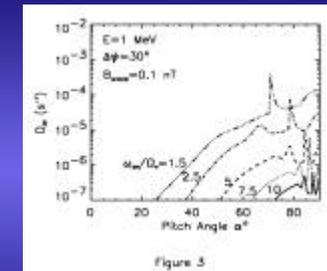
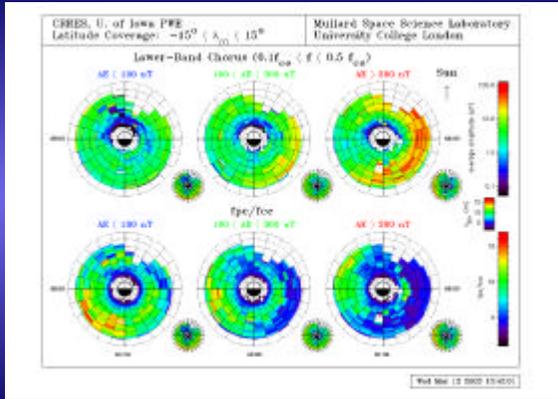


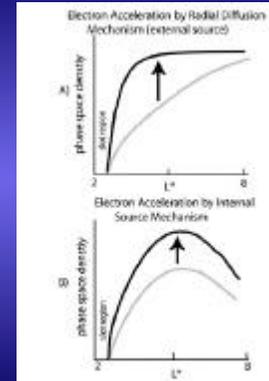
Figure 3
Horne et al. GRL, [2003]



CRRES Survey of fpe/fce



Acceleration: Internal or Radial Diffusion?



- Or could it be losses?

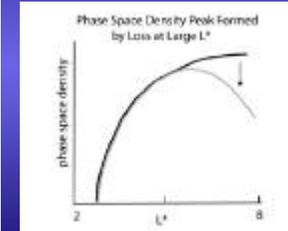
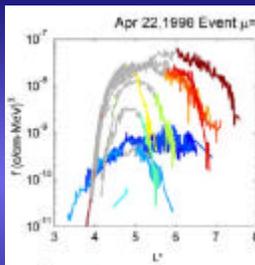


Figure 3. Schematic showing how losses at large L^* cause a peak in the phase space density versus L^* profile.



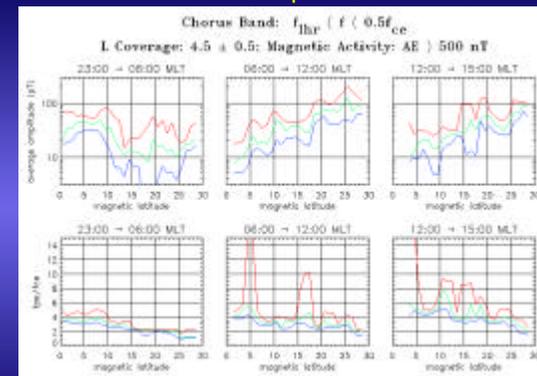
Green and Kivelson 2004



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



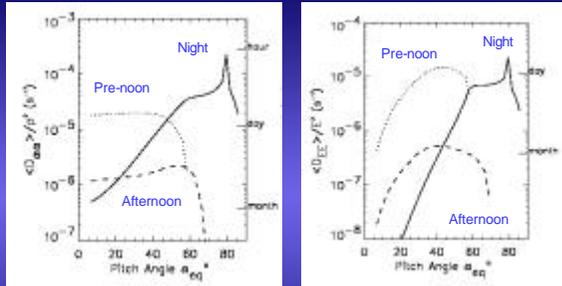
Wave Amplitudes



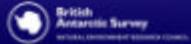
- Green: median
- Red and blue: 75% and 25% quartiles



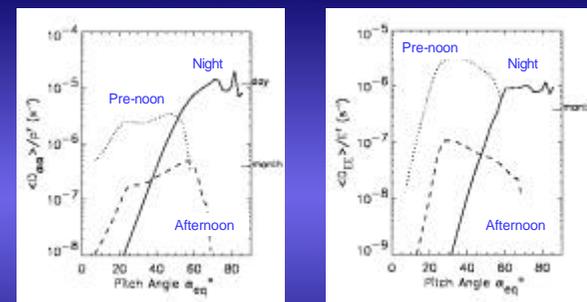
Average over MLT - 300 keV



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



Average over MLT - 1 MeV

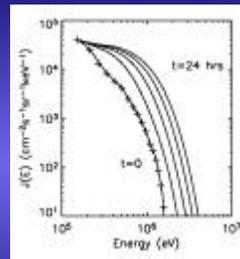


- Timescale for loss ~ 10 days
- Timescale for acceleration ~ 3 days
- Electrons accelerated faster than they are lost



Time Evolution of Flux

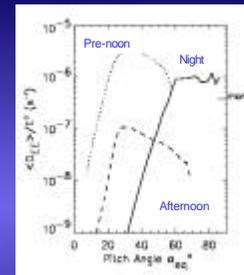
- Solve Fokker-Planck equation for energy only
- Assume whistler mode waves present for ~1 day
- Take CRRES data for $t=0$
- Timescale for flux increase about 12 hours at ~1 MeV
- Timescale consistent with observations (1-2 days)



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

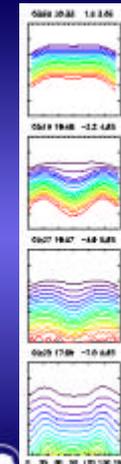


CRRES Orbit 857

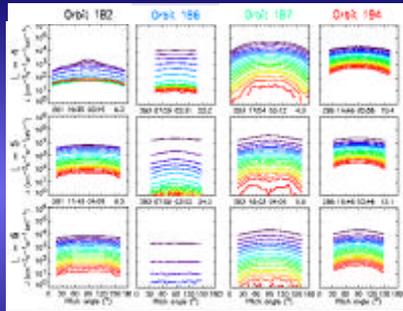


- If dayside chorus dominant
 - Acceleration above equator
 - Model predicts butterfly distributions
- At $L = 4 - 5$
 - Magnetopause shadowing not expected
 - Nor significant drift shell splitting

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



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

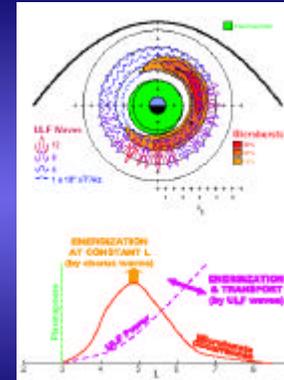


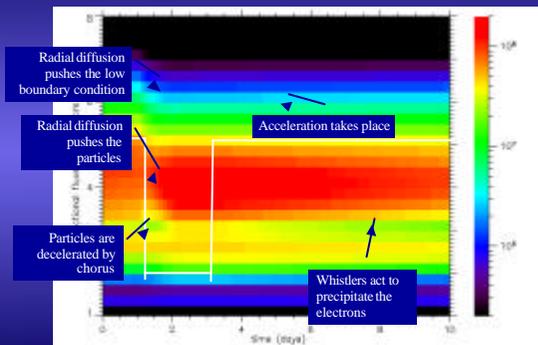
Figure 8. A composite diagram of electron acceleration. (Top) The inner magnetosphere for $K_p = 4 - 6$. (Bottom) A schematic of how and where ULF and VLF/ELF waves accelerate and transport electrons.

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



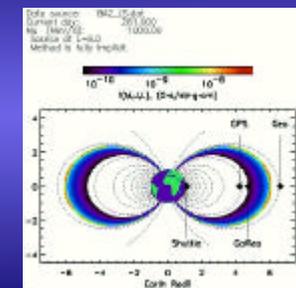
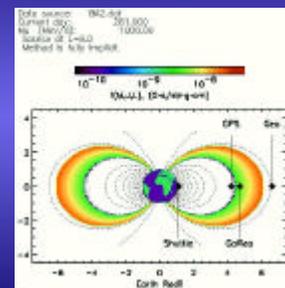
Salambo Model – Including Chorus Waves Boscher et al.

K_p Storm $K_p = 8.5$ for 1 day 400 keV electrons

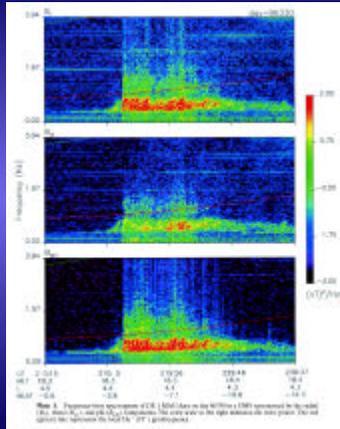


9 Oct 1990 Storm Simulation How Effective Are Wave Losses?

- No losses due to waves
- With maximum theoretical loss due to waves



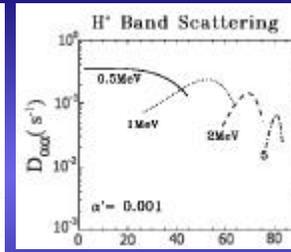
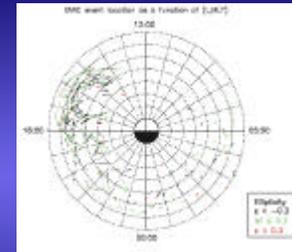
EMIC Waves



- Erlandson and Ukhorskiy [2001]



Losses EMIC waves



- Very efficient
- MLT distribution?



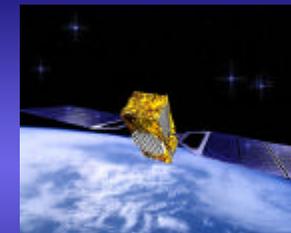
Needs

- 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, toroidal, 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

