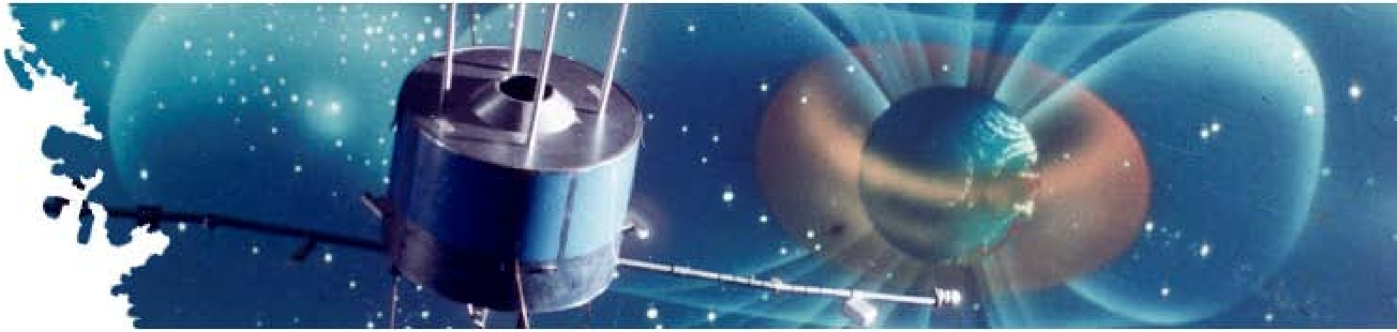


CRRES Plasma Wave Observations

Nigel P. Meredith

British Antarctic Survey

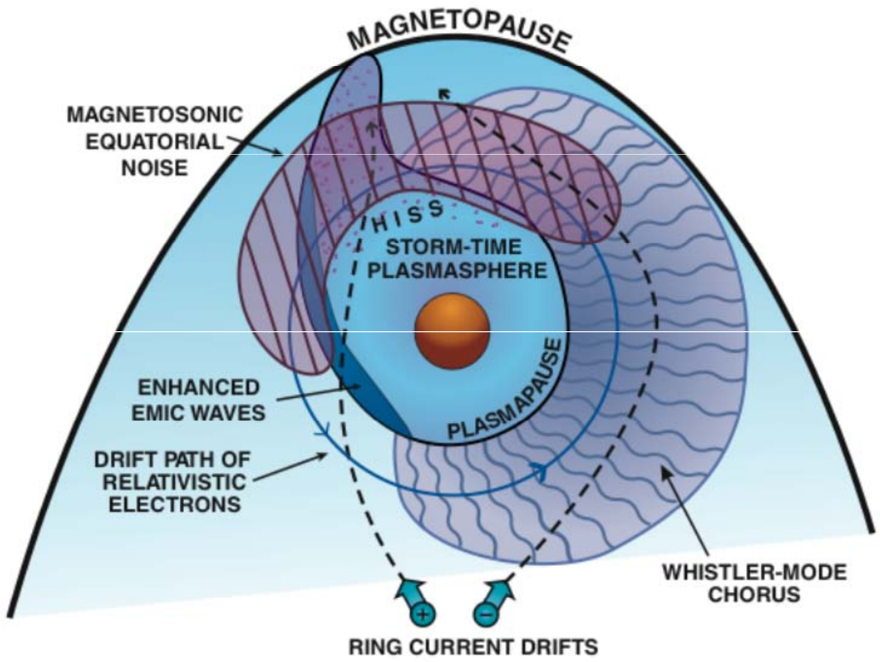
British Antarctic Survey

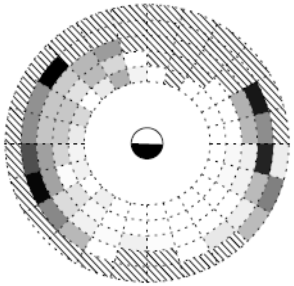
NATURAL ENVIRONMENT RESEARCH COUNCIL

AGU Chapman Conference
St John's, Newfoundland
17th – 22nd July, 2011

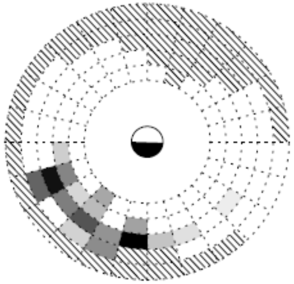
Plasma Waves

- Plasma waves play a fundamental role in the dynamics of the Earth's radiation belts and inner magnetosphere.





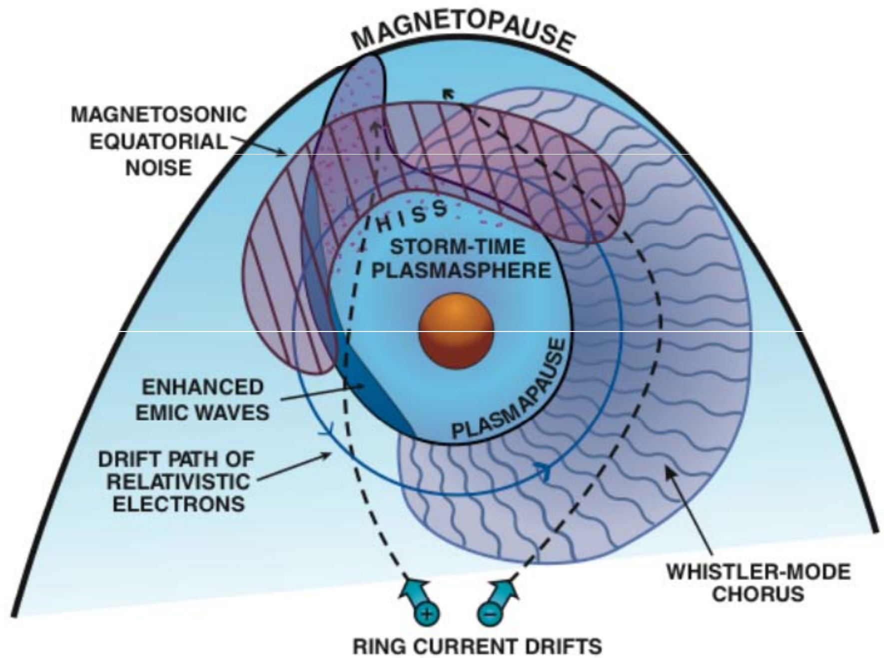
TOROIDAL PC 5 ULF WAVES

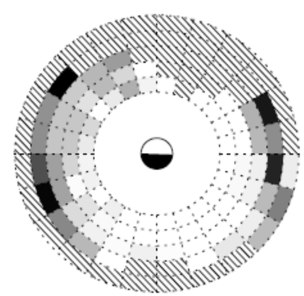


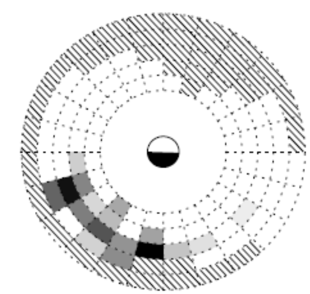
POLOIDAL PC 5 ULF WAVES

Plasma Waves

- Plasma waves play a fundamental role in the dynamics of the Earth's radiation belts and inner magnetosphere.
- They have a major influence on the energization, transport, and loss of ring current and radiation belt particles.




TOROIDAL PC 5
ULF WAVES


POLOIDAL PC 5
ULF WAVES

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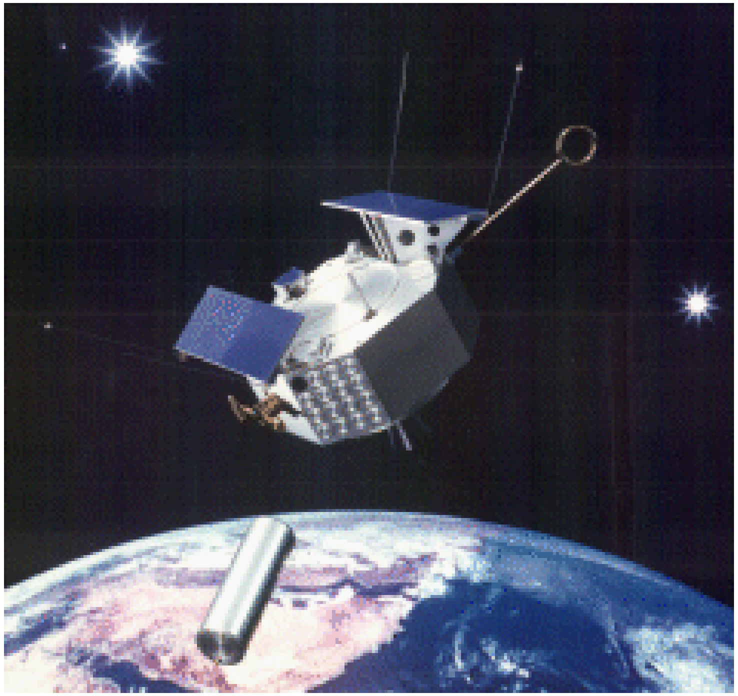
Plasma Waves

- In this presentation I will show how plasma wave observations from CRRES have helped to improve our understanding of the dynamics of the Earth's radiation belts.



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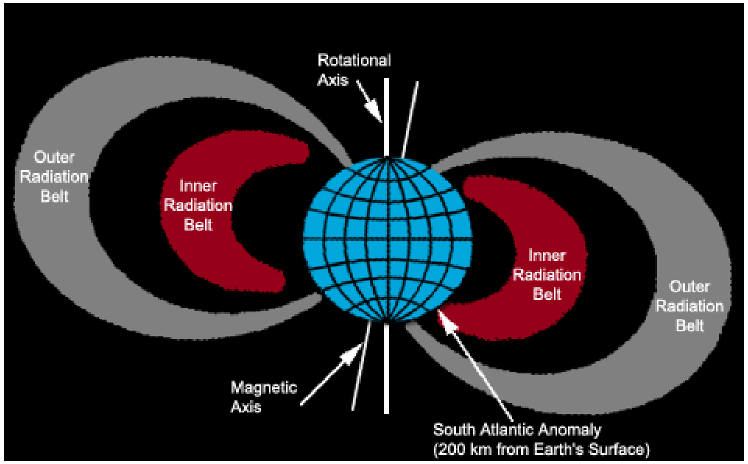
Earth’s Radiation Belts

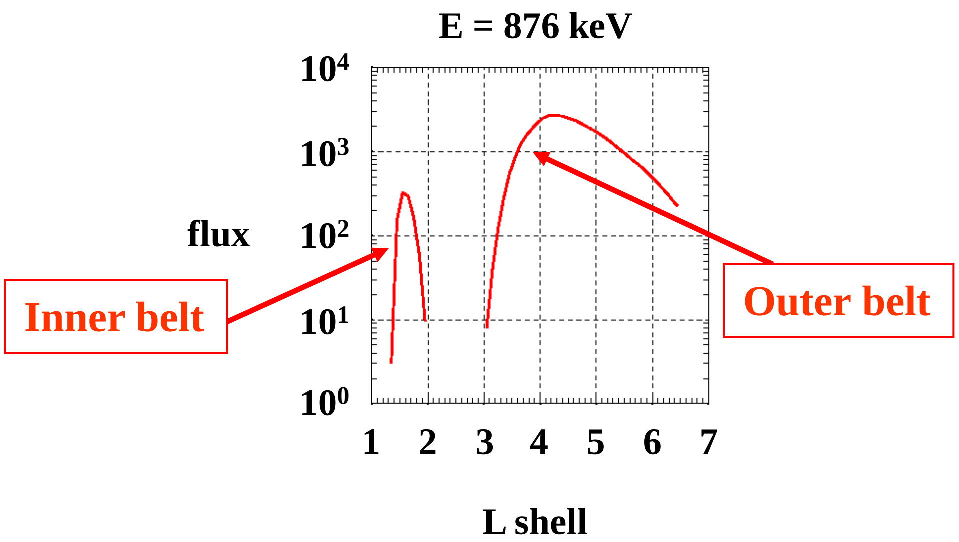
- Energetic electrons (E > 100 keV) in the Earth’s radiation belts are generally confined to two distinct regions.

- Inner radiation belt
  - 1.2 < L < 2
  - exhibits long term stability

- Outer radiation belt
  - 3 < L < 7
  - highly dynamic



NASA



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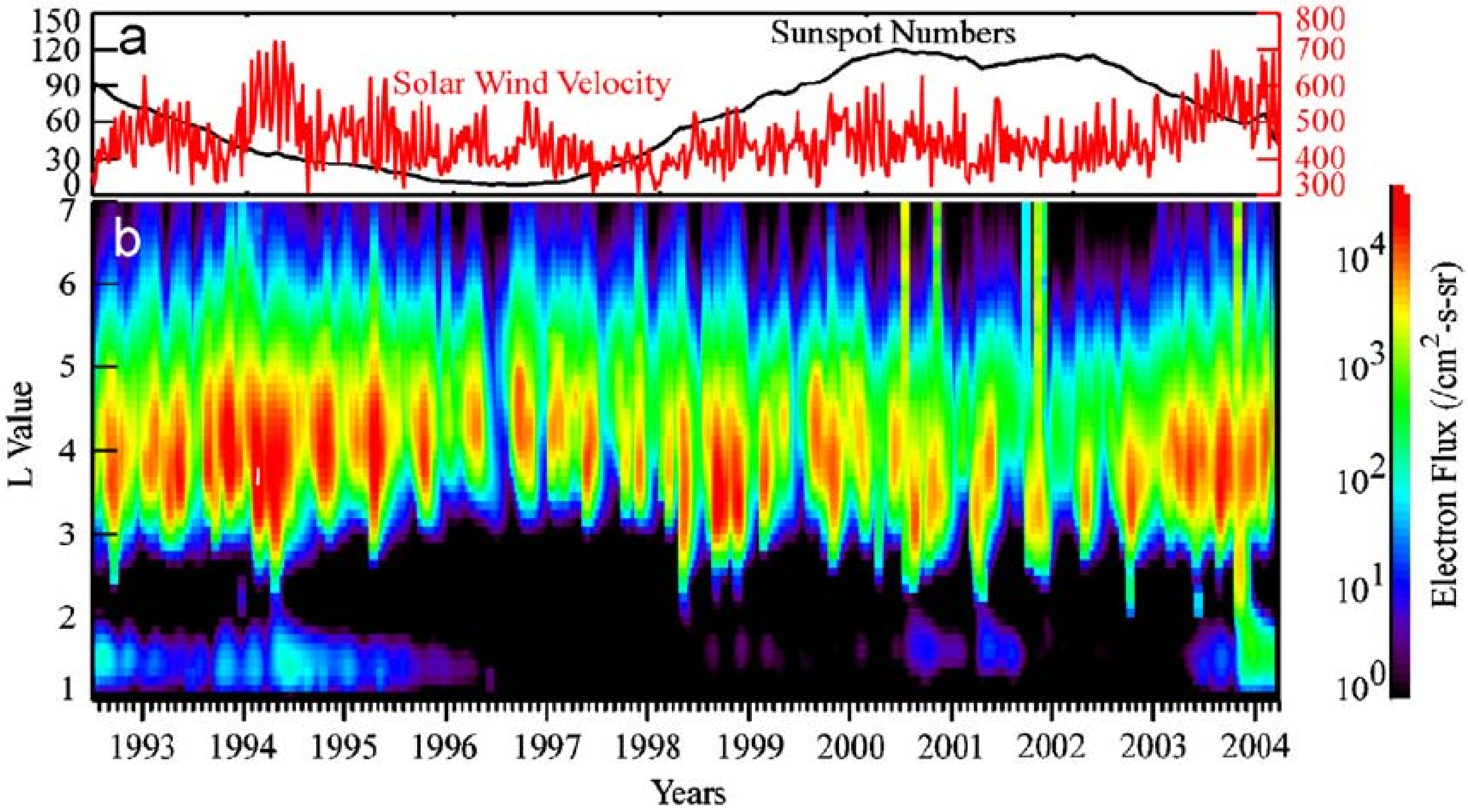
Radiation Belt Dynamics

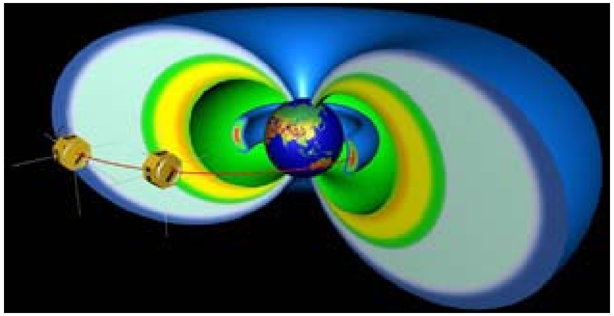


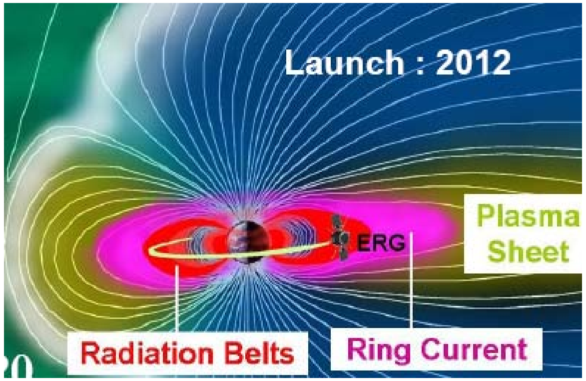
- Fluxes change dramatically on a variety of different time scales.
- Covers a range of over 4 orders of magnitude.

Baker *et al*., AG, 2008

Radiation Belt Dynamics

- Understanding this variability, including determining the dominant acceleration and loss processes, is the primary objective of three new space missions:
  - NASA Radiation Belt Storm Probes Mission
  - Canadian ORBITALS Mission
  - Japanese ERG Mission





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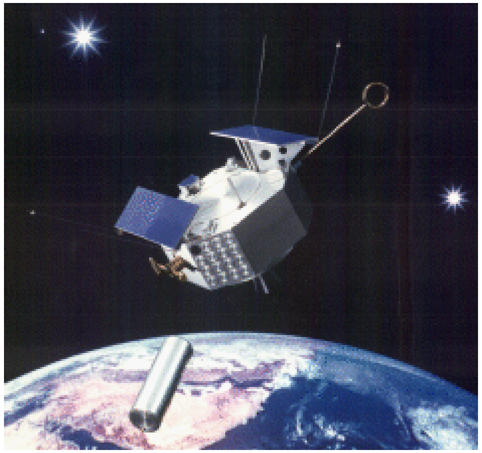
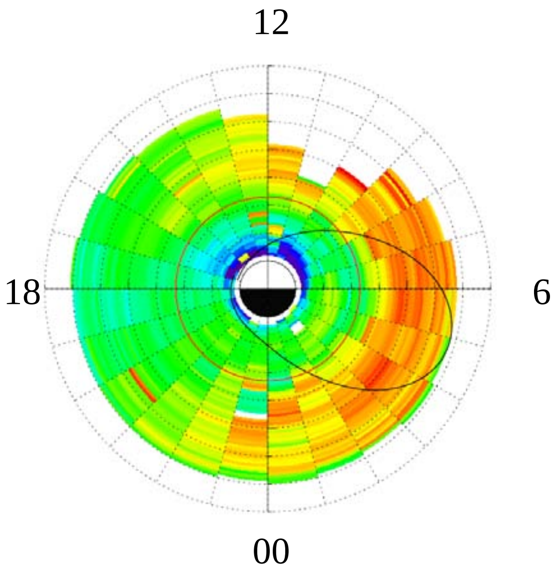
CRRES Orbit

- launched 25th July 1990
- low inclination
- GTO orbit
- period of ~10 hours
- $1.05 < L < 8$
- $-30^o < \lambda_m < +30^o$
- operated until 11th October 1991
- MLT of apogee precessed from ~08:00 through midnight to 13:30 MLT





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Radial Diffusion

Radial diffusion is an important transport process in the Earth's radiation belts:

- driven by fluctuations in the Earth's electric and magnetic fields on timescales of the drift period
- enhanced by ULF waves [e.g., **Hudson *et al*., 1999**; **Elkington *et al*., 1999**]
- conserves the first two adiabatic invariants BUT breaks the third adiabatic invariant

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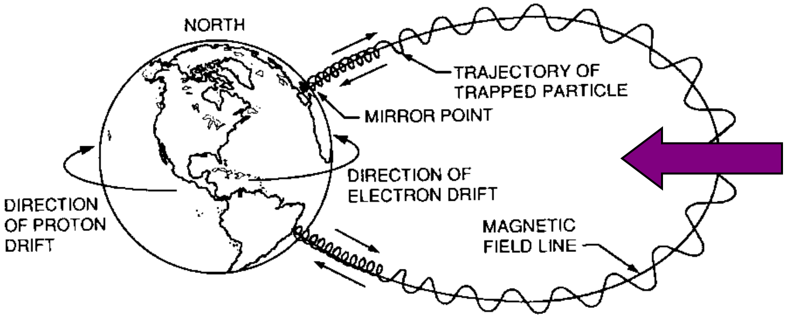
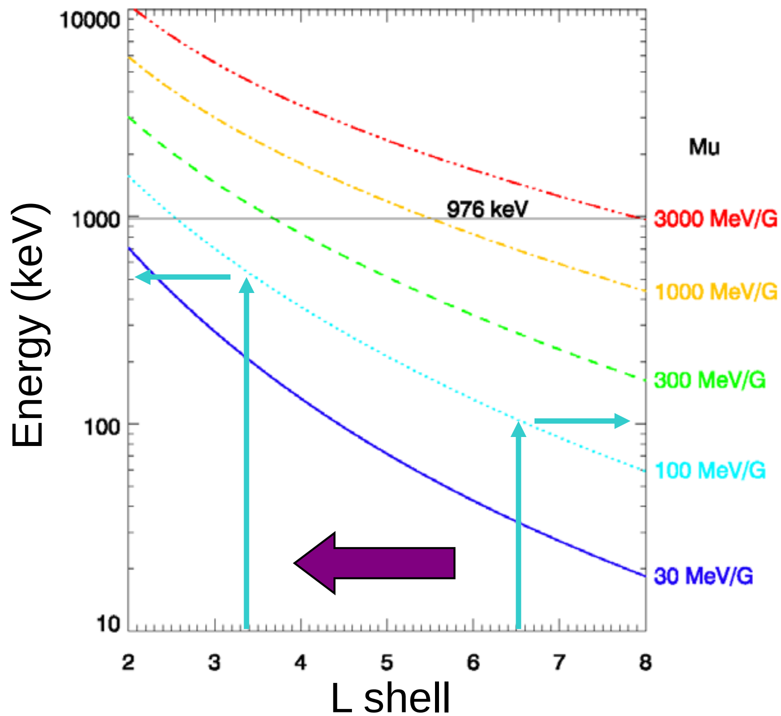
Radial Diffusion

- Conservation of first invariant implies:

$$p_{\perp}^2 = 2m_e B$$

- Inward radial diffusion leads to significant energisation.





courtesy of M. Lam

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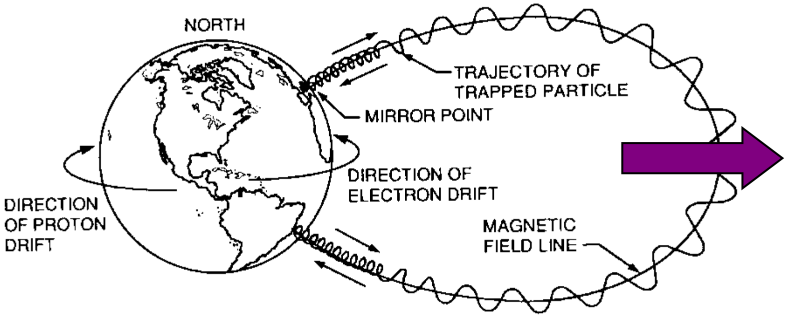
Radial Diffusion

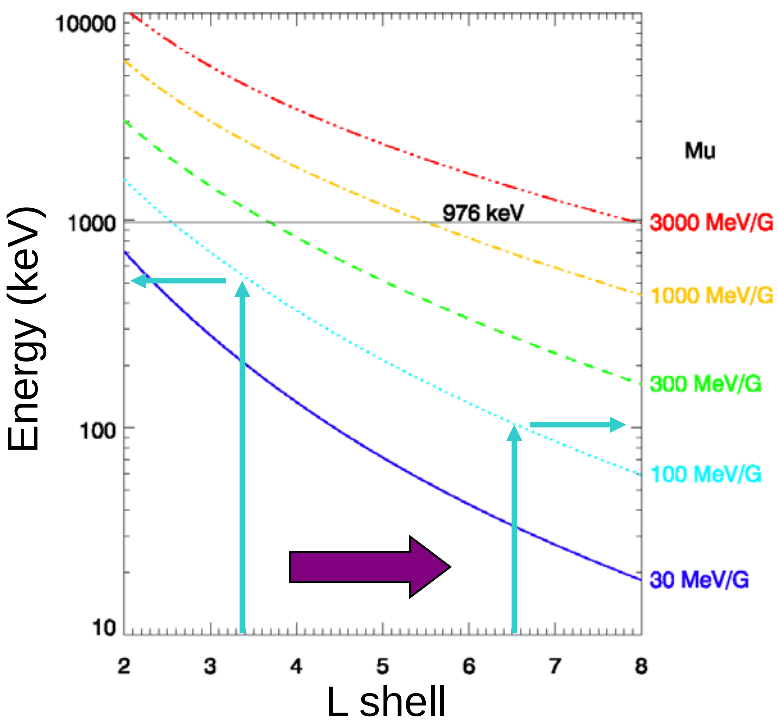
- Conservation of first invariant implies:

$$p_{\perp}^{2} = 2m_{e}B$$

- Inward radial diffusion leads to significant energisation.

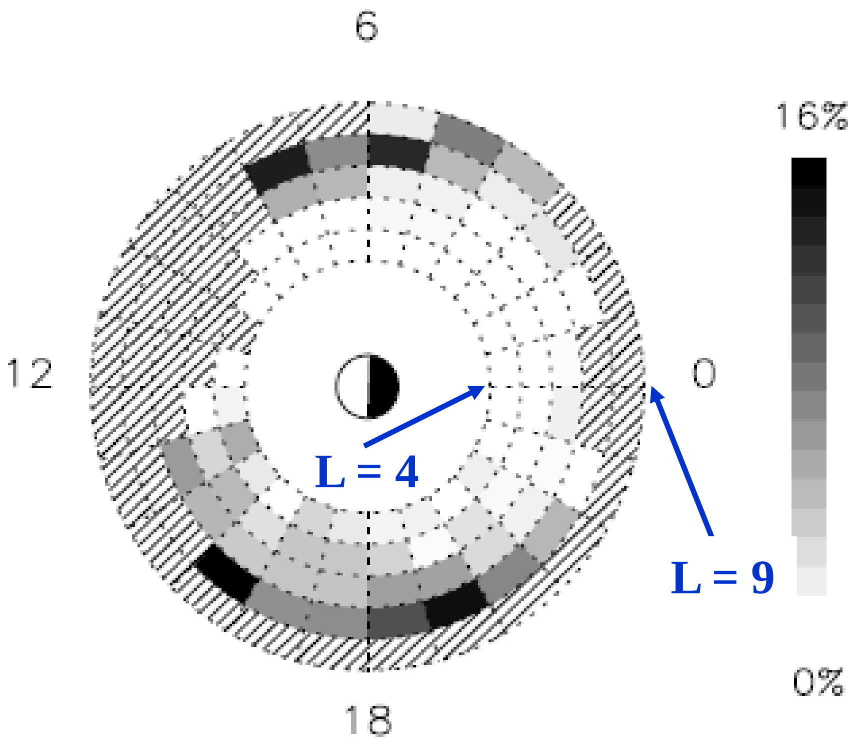
- Outward radial diffusion combined with magnetopause losses can be a significant loss process [**Shprits *et al*., JGR, 2006**].





courtesy of M. Lam

Toroidal Pc 5 ULF Waves Measured by CRRES

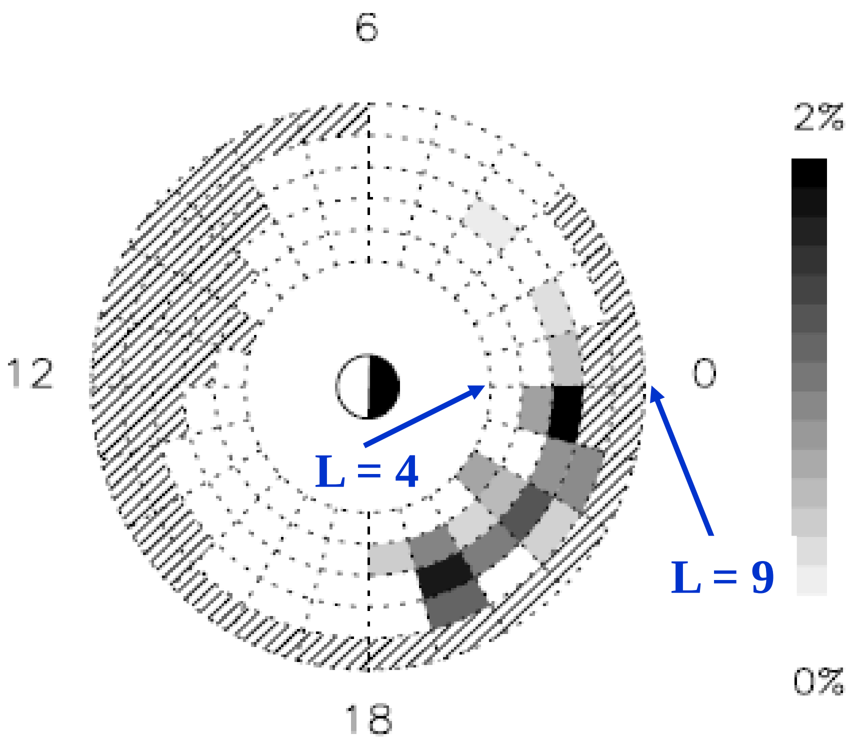


Hudson *et al*., AG, 2004

- CRRES observations show toroidal Pc 5 ULF wave power distributed fairly equally between the dawn and dusk flanks

- consistent with excitation by the Kelvin-Helmholz instability

Poloidal Pc 5 ULF Waves Measured by CRRES



Hudson *et al*., AG, 2004

- In contrast, poloidal Pc 5 ULF waves occur predominantly on the dusk side
- consistent with generation by ring current ions via drift-bounce resonance

Gyroresonant Wave-Particle Interactions

- Gyroresonant wave-particle interactions play a key role in the Earth's radiation belts.

- These interactions can occur when the wave frequency, ω, is Doppler-shifted to a multiple of the relativistic electron gyrofrequency, Ω_e.

$$\omega - k_{\parallel} v_{\parallel} = n\Omega_e/\gamma$$

  - $k_{\parallel}$ is the wave number parallel to the magnetic field
  - $v_{\parallel}$ is the electron velocity parallel to the magnetic field
  - γ is the relativistic factor

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Gyroresonant Wave-Particle Interactions

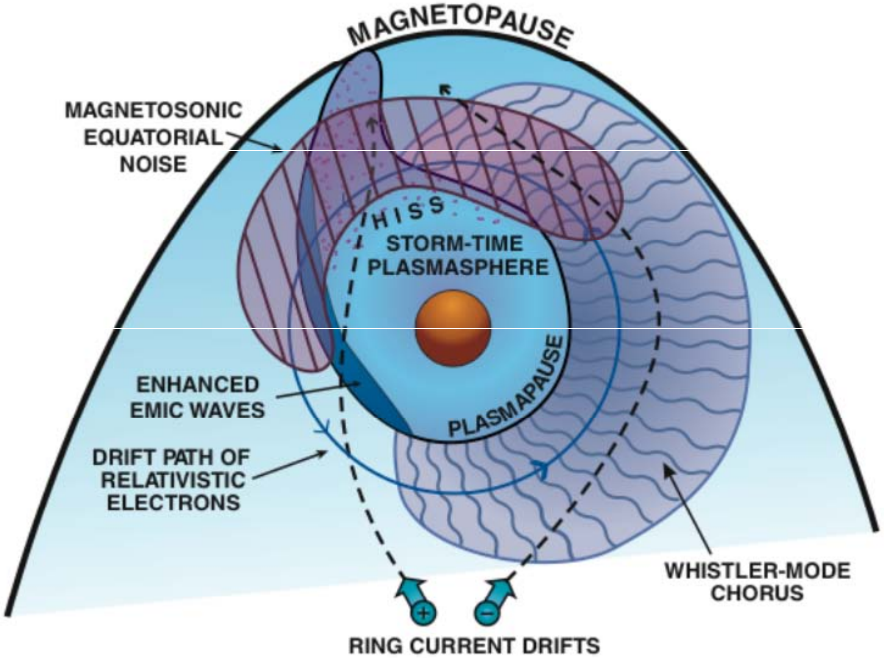
- These interactions break the first and second adiabatic invariants.

- Such interactions lead to:
  - heating and acceleration by the absorption of the waves
  - pitch angle scattering and potential loss to the atmosphere

Radiation Belt Dynamics

• Plasma waves that can lead to efficient gyroresonant wave particle interactions with relativistic electrons include:

- Whistler mode chorus
- Magnetosonic waves
- Plasmaspheric hiss
- EMIC waves.



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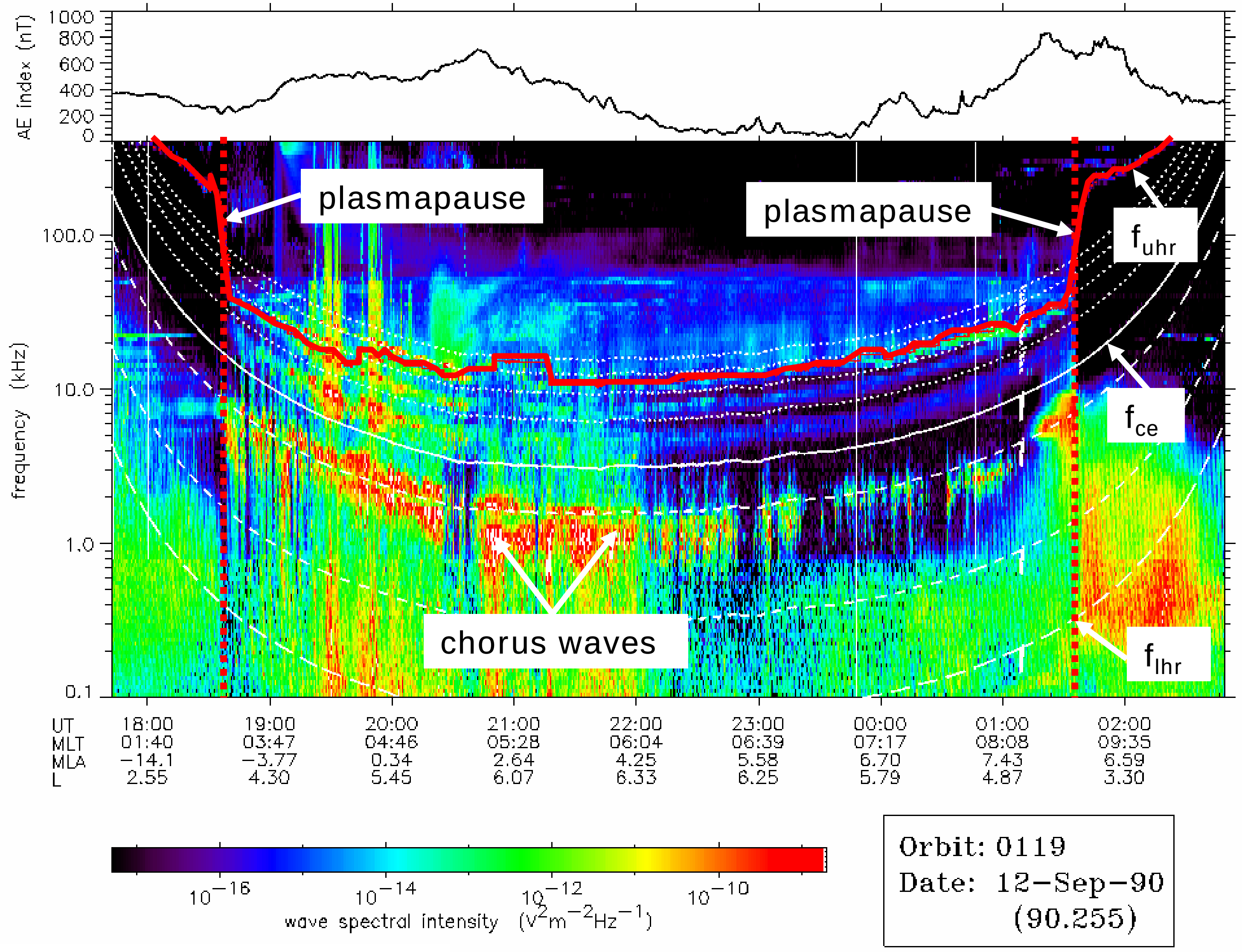
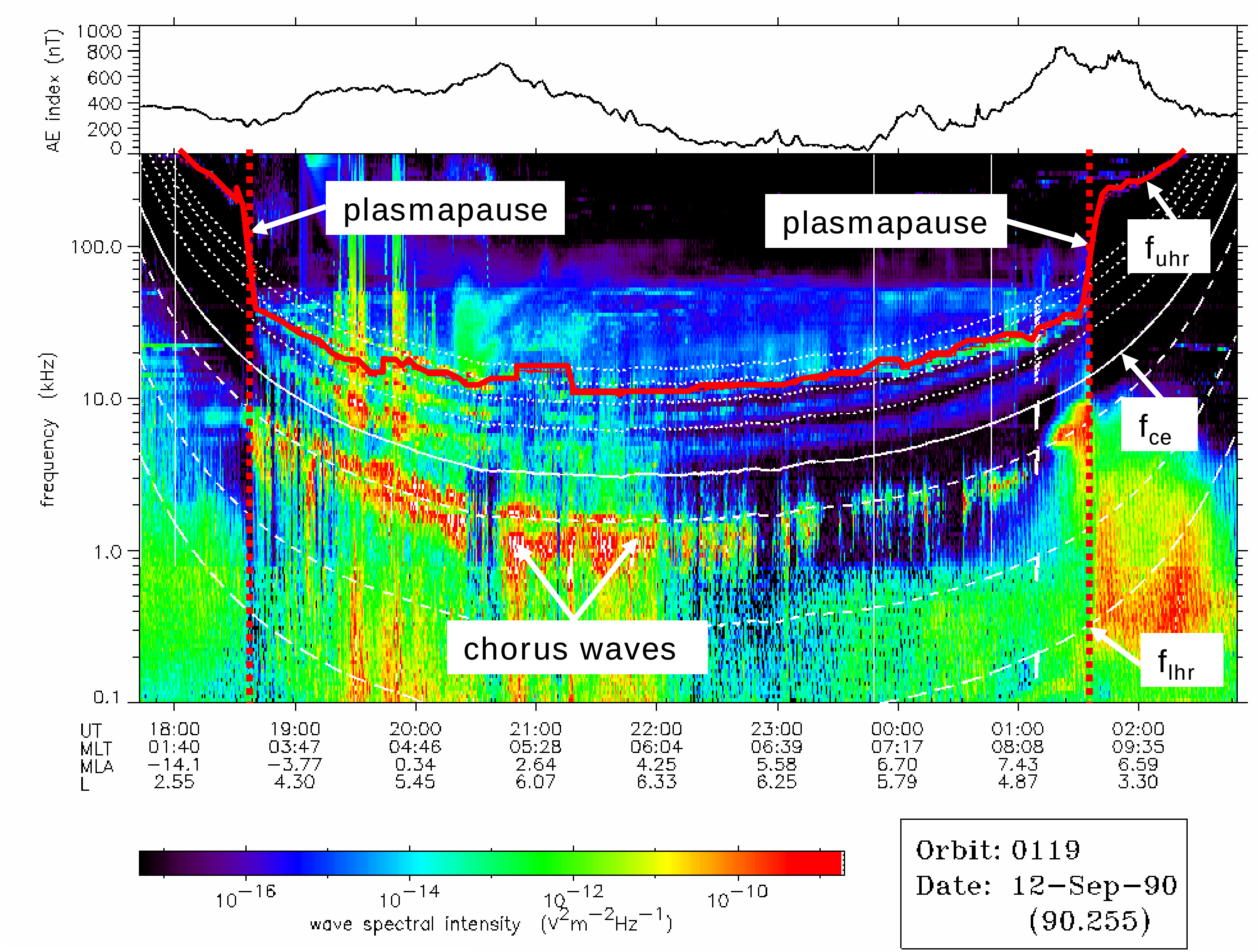
Whistler Mode Chorus



Whistler mode chorus is an intense electromagnetic emission observed outside of the plasmapause in the frequency range 0.1fce < f < 0.8fce.

Whistler Mode Chorus



The waves are generated by plasma sheet electrons injected during substorms and/or enhanced convection.

Gyroresonant Wave Particle Interactions

- Enhanced storm-time convection electric fields provide a seed population of outer zone electrons with energies up to a few hundred keV [e.g., **Baker *et al*., ASR, 1998; Obara *et al*., EPS, 2000**].

- Gyroresonant wave-particle interactions with whistler-mode chorus then provide a mechanism for accelerating these seed electrons to relativistic energies [e.g., **Horne and Thorne, GRL, 1998**].

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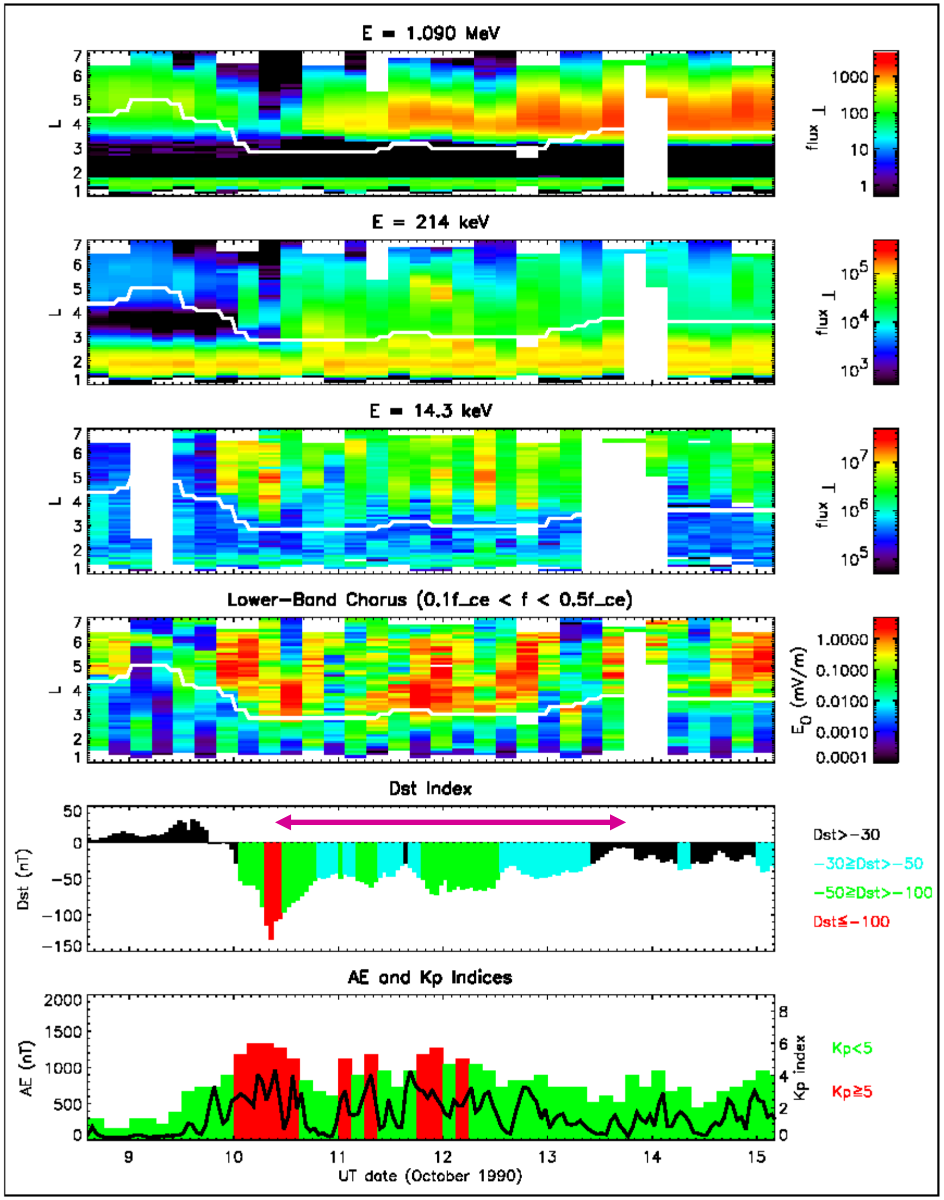
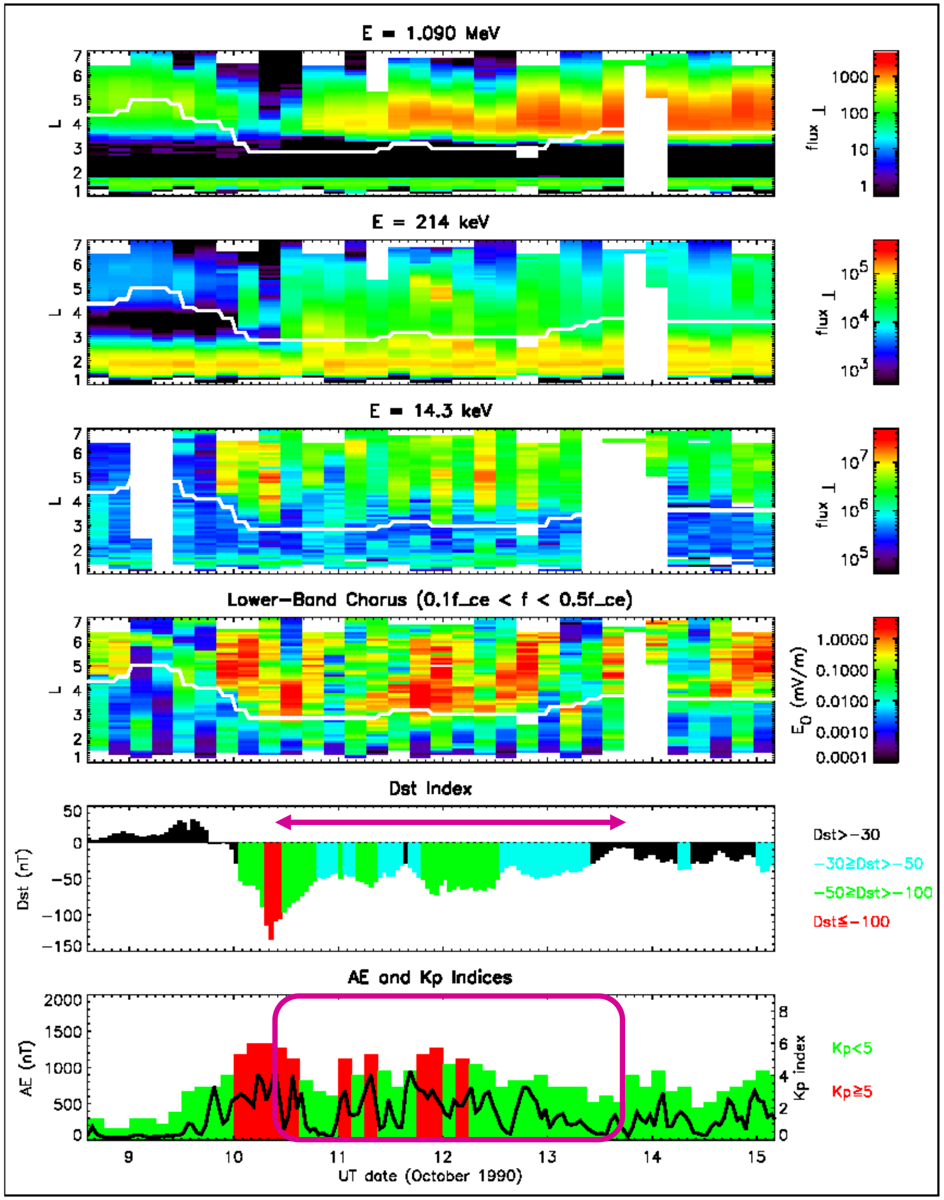
October 9th 1990 Storm



Meredith *et al*., JGR, 2002

Recovery phase associated with:



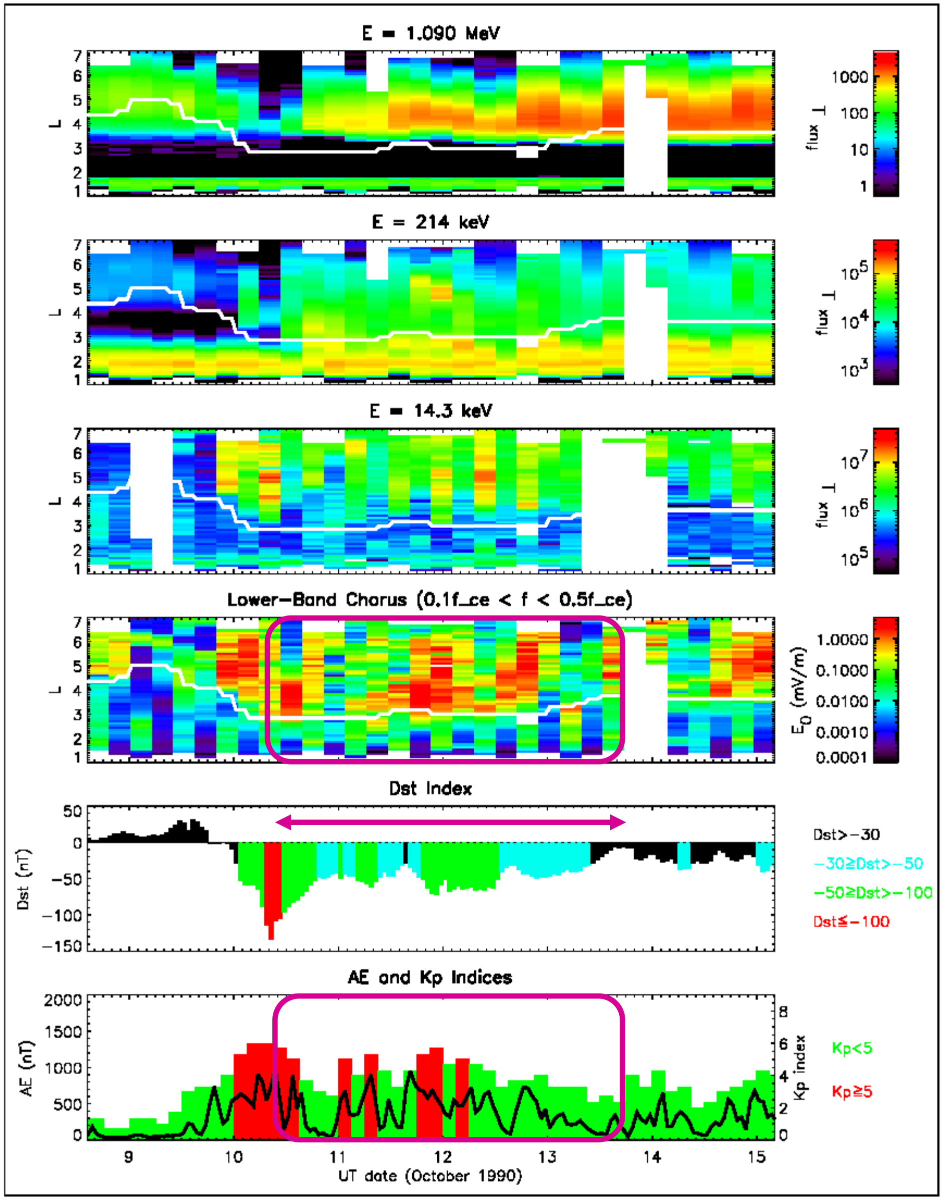
Meredith *et al*., JGR, 2002

October 9th 1990 Storm

Recovery phase associated with:

- enhanced AE activity

October 9th 1990 Storm



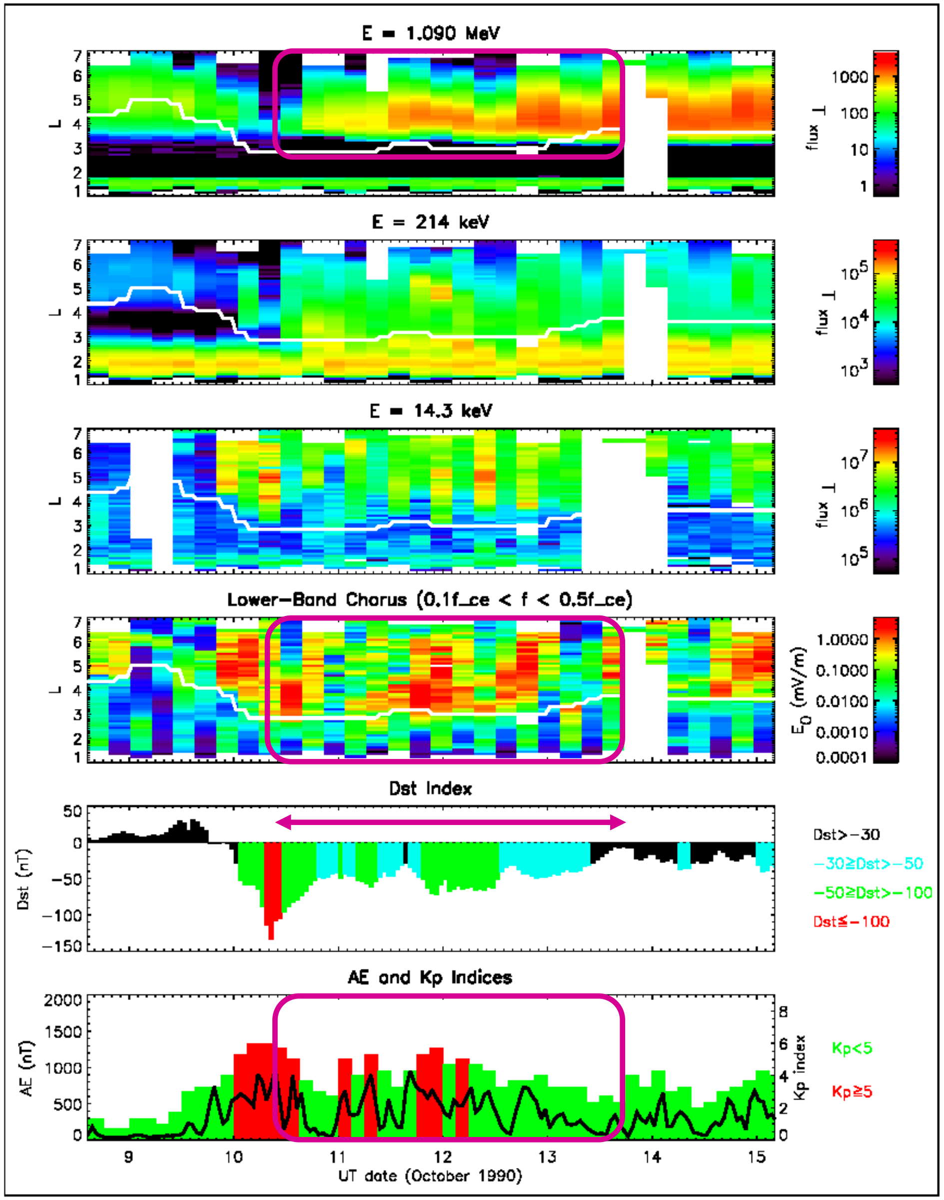
Meredith *et al*., JGR, 2002

Recovery phase associated with:

– enhanced AE activity

– enhanced levels of whistler mode chorus

October 9th 1990 Storm



Meredith *et al*., JGR, 2002

Recovery phase associated with:

- enhanced AE activity
- enhanced levels of whistler mode chorus
- gradual acceleration of electrons to relativistic energies

Phase Space Density Analysis

- Important information on the nature of the acceleration process can be found through phase space density analysis.

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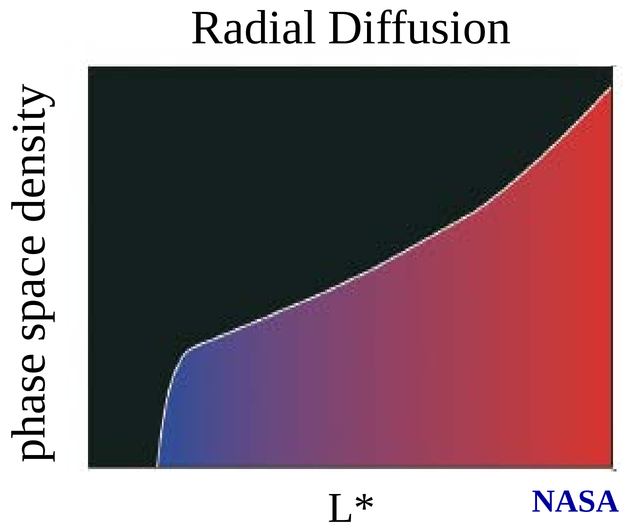
Phase Space Density Analysis

- Important information on the nature of the acceleration process can be found through phase space density analysis.
- Acceleration by inward radial diffusion driven by positive gradients in the phase space density.



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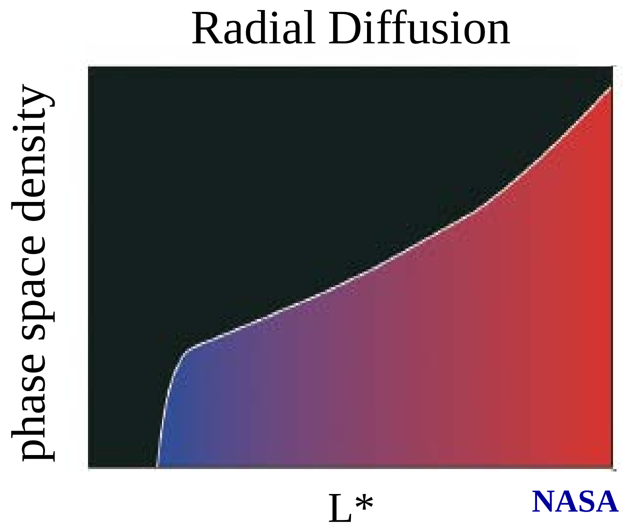
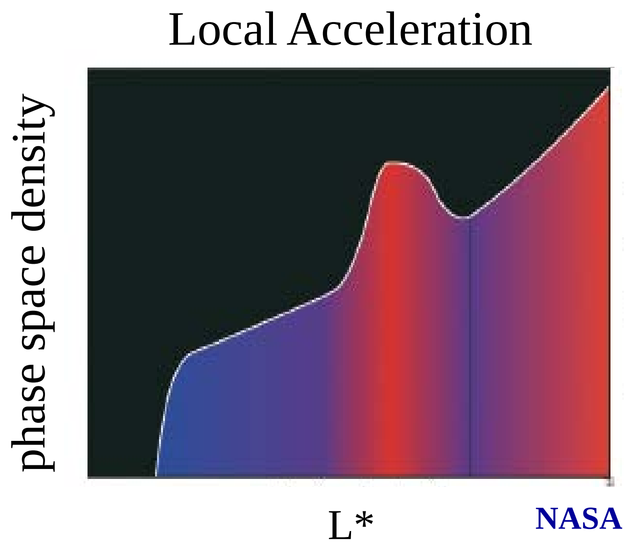
Phase Space Density Analysis

- Important information on the nature of the acceleration process can be found through phase space density analysis.
- Acceleration by inward radial diffusion driven by positive gradients in the phase space density.
- Local acceleration produces peaks in phase space density.





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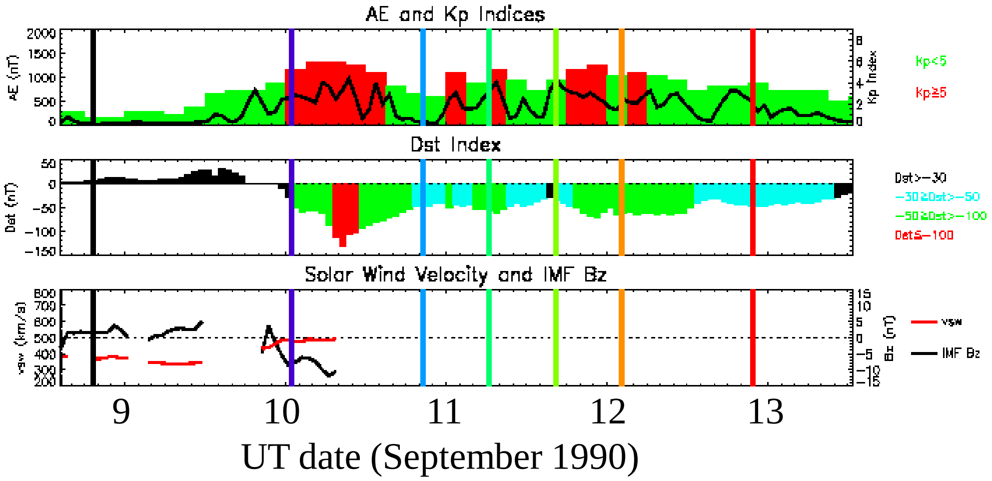
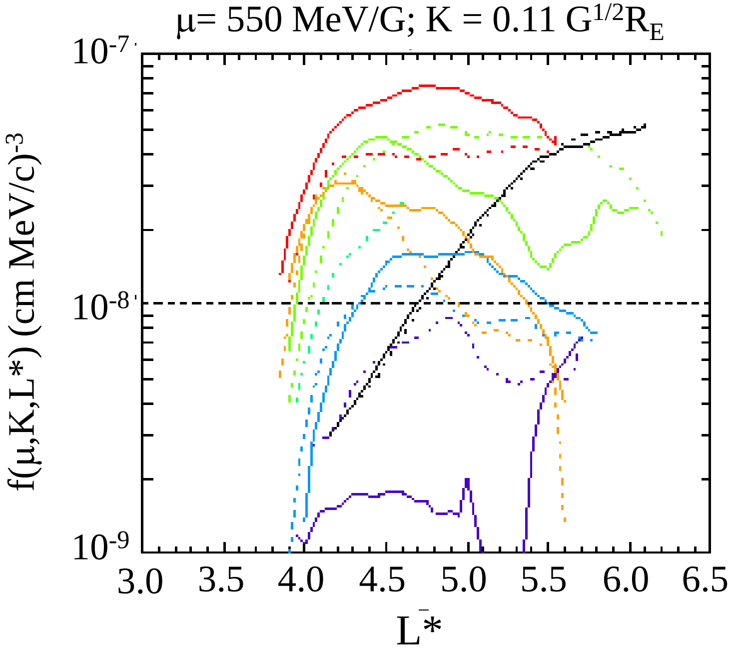
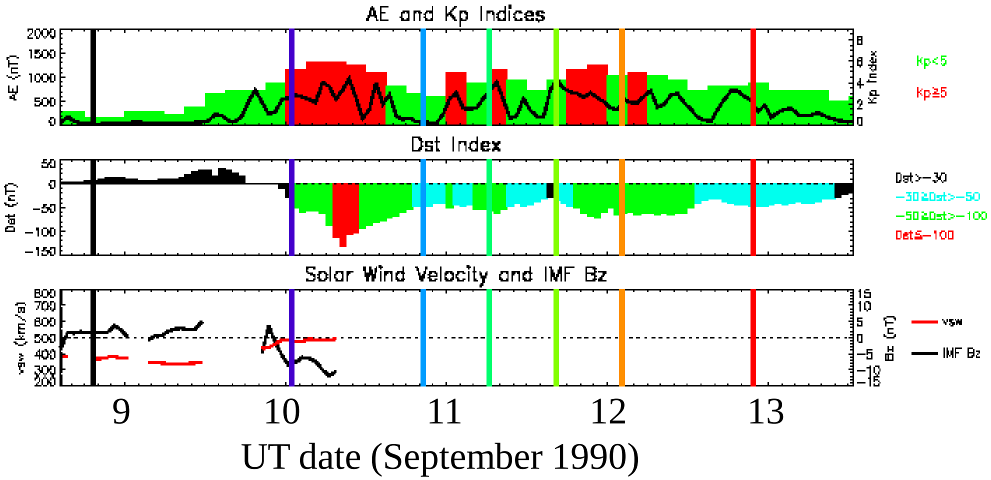
Phase Space Density Analysis

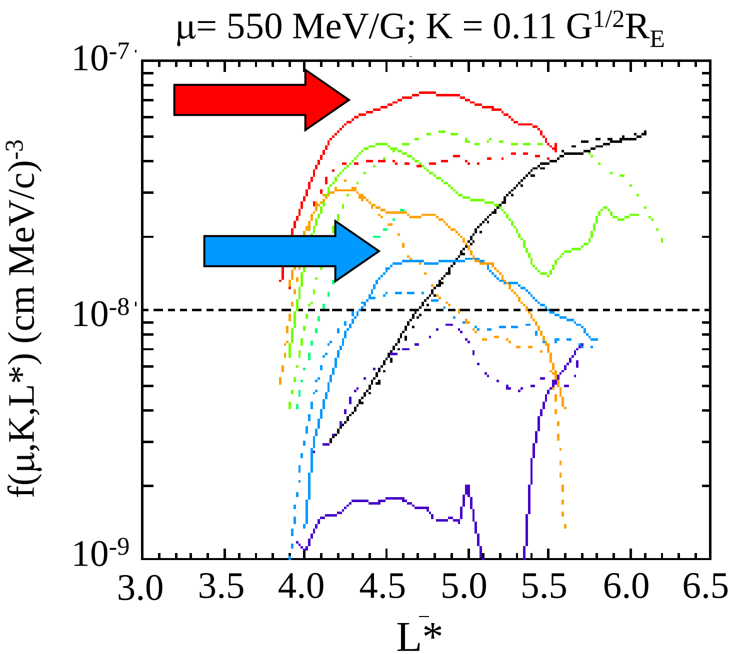




Iles *et al*., JGR, 2006

Phase Space Density Analysis

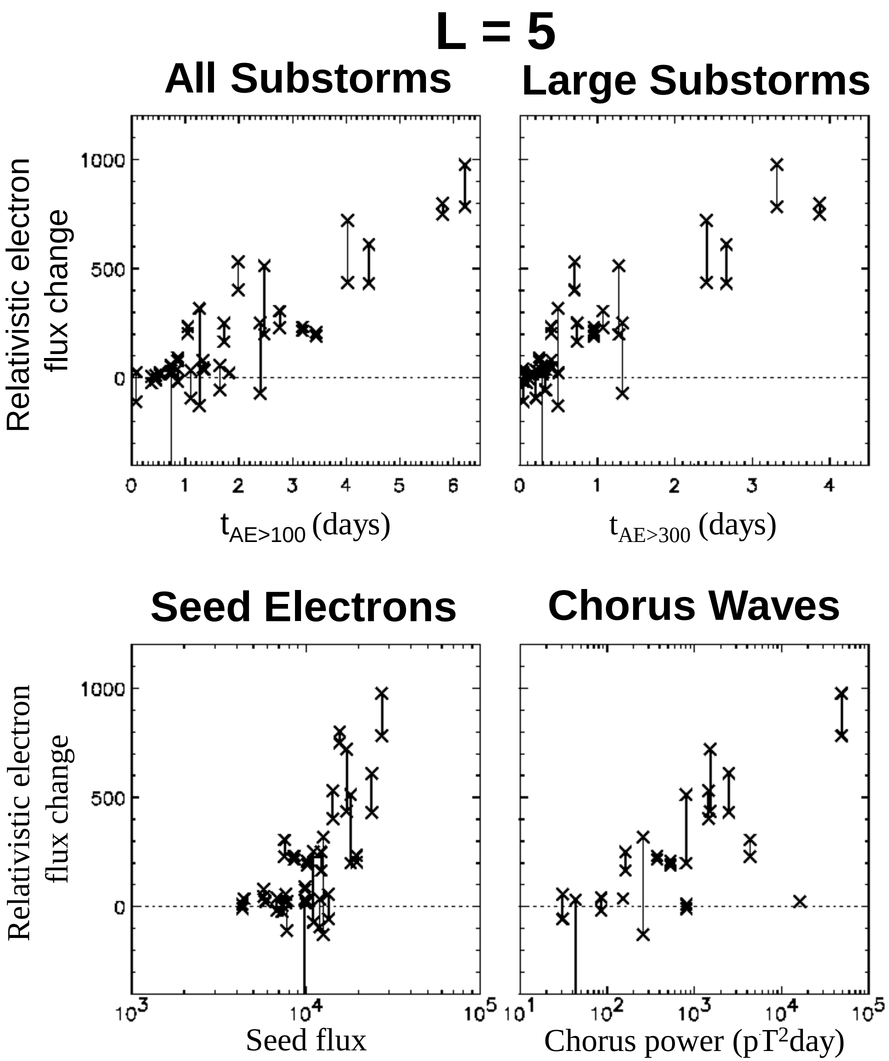




Iles *et al*., JGR, 2006

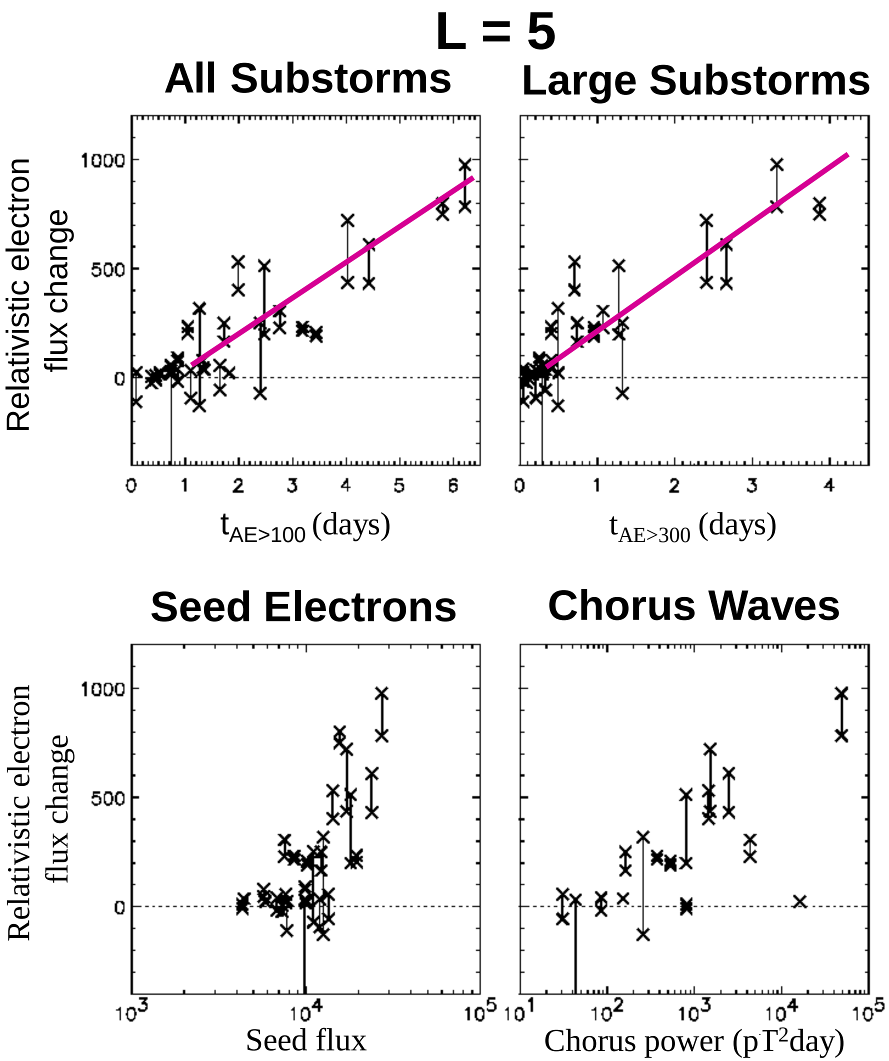
- Evidence for a developing peak in the electron phase space density at ~ MeV energies.
- Local acceleration plays a key role during the recovery phase of this storm.

Survey of 26 Geomagnetic Storms



Meredith *et al*., JGR, 2003

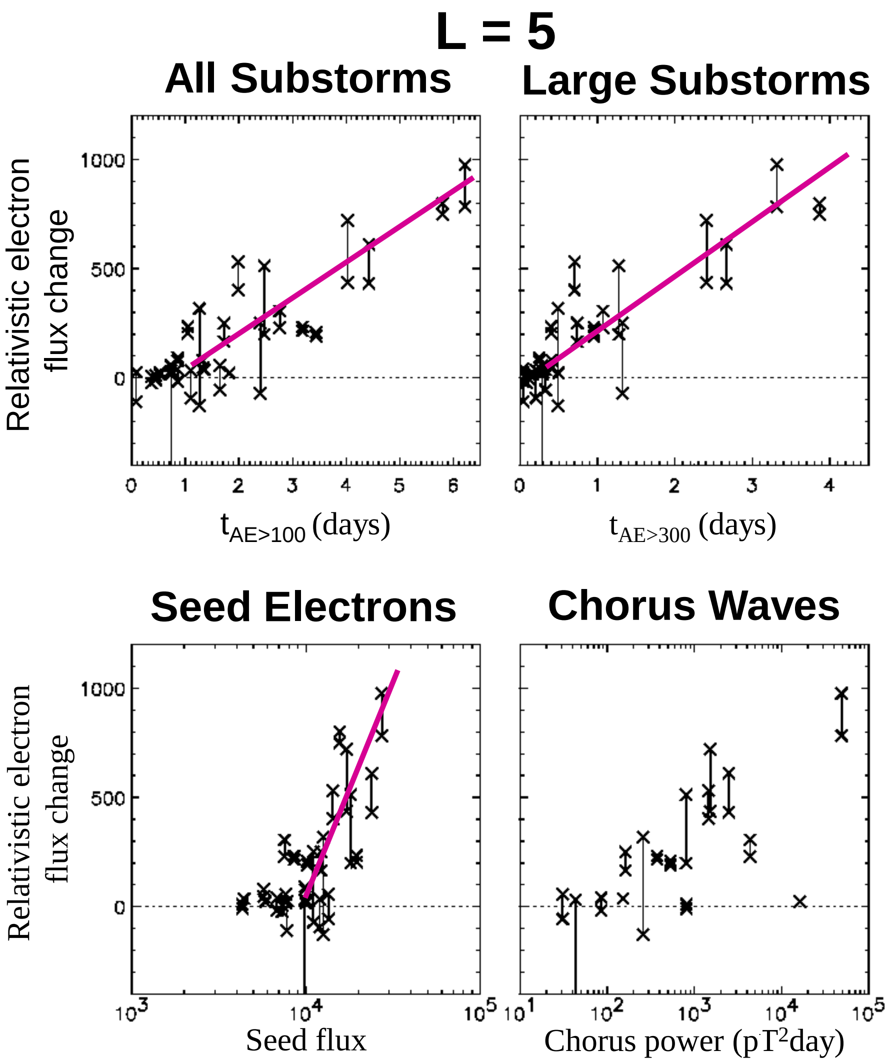
Survey of 26 Geomagnetic Storms



Meredith *et al*., JGR, 2003

- Trend for larger relativistic electron flux enhancements to be associated with:
  - longer durations of prolonged AE activity

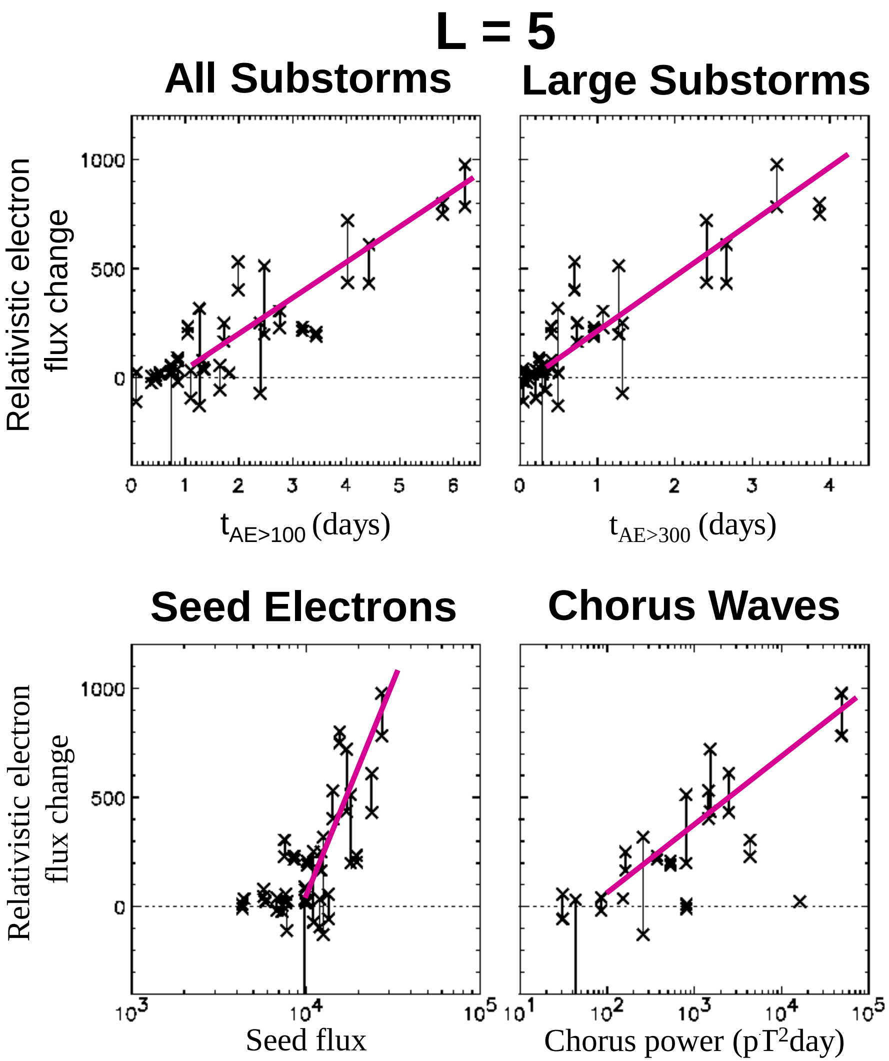
Survey of 26 Geomagnetic Storms



Meredith *et al*., JGR, 2003

- Trend for larger relativistic electron flux enhancements to be associated with:
  - longer durations of prolonged AE activity
  - larger fluxes of seed electrons

Survey of 26 Geomagnetic Storms



Meredith *et al*., JGR, 2003

- Trend for larger relativistic electron flux enhancements to be associated with:
  - longer durations of prolonged AE activity
  - larger fluxes of seed electrons
  - larger integrated lower-band chorus wave power

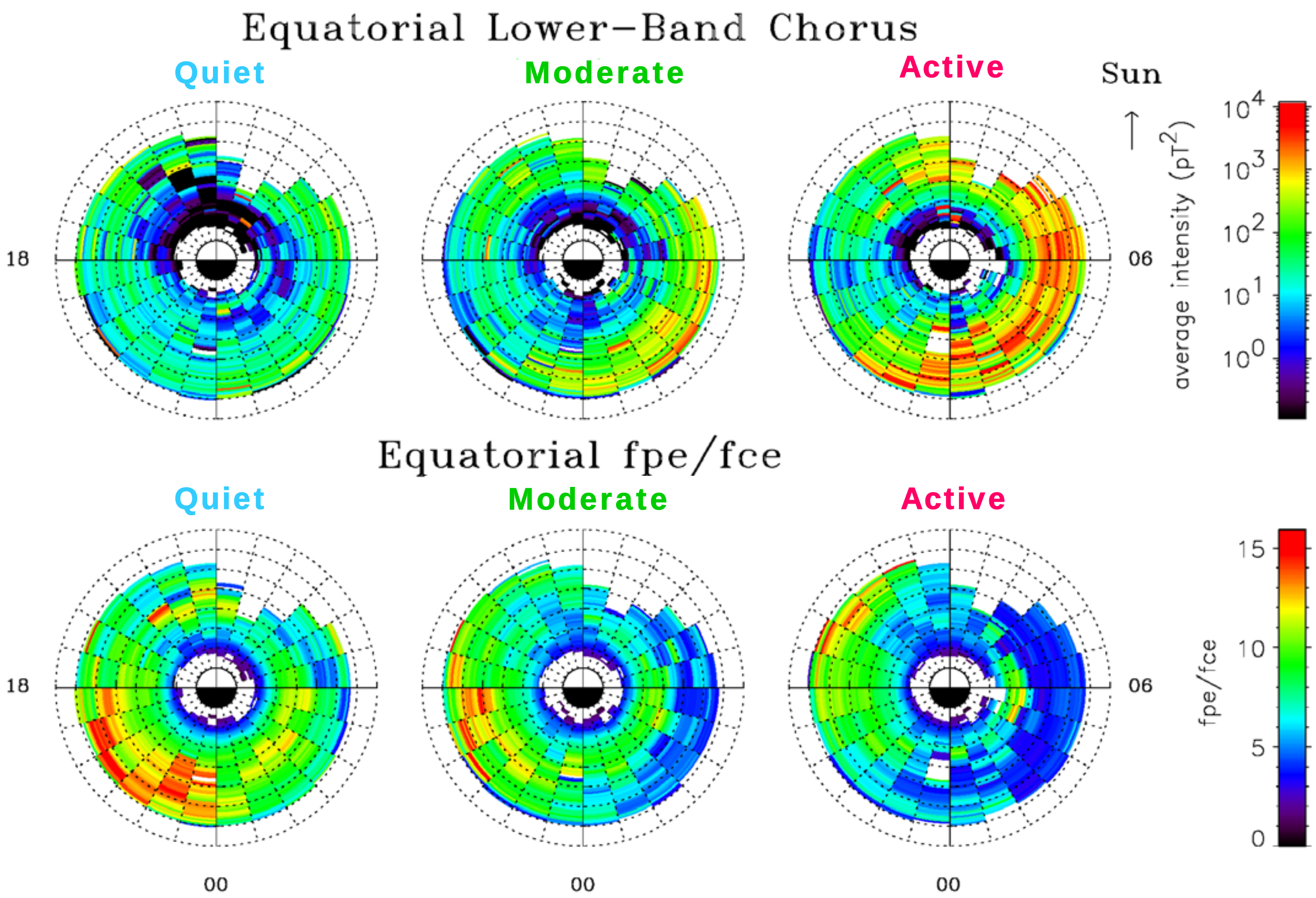
Energy Diffusion

- Pitch angle and energy diffusion rates for scattering by whistler mode waves depend on:
  - the wave magnetic field intensity
  - the frequency distribution of the waves
  - the ratio fpe/fce

- Relativistic electrons interact most readily with lower-band chorus (**Horne and Thorne, GRL, 1998**).

- Energy diffusion is most effective in regions of low fpe/fce (**Summers *et al*., JGR, 1998**).

Equatorial Region (-15° < λ_m < 15°)



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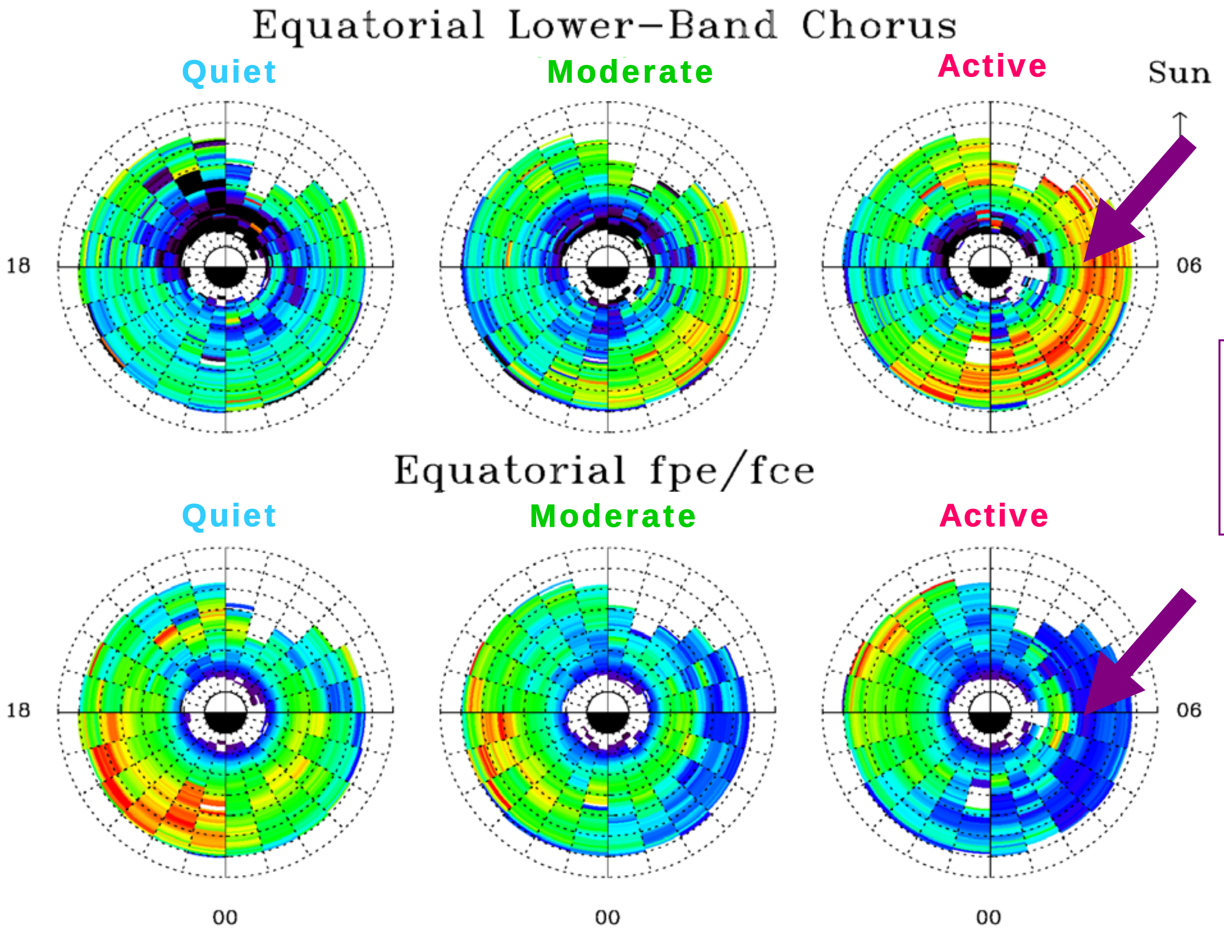
Meredith *et al.*, GRL, 2003

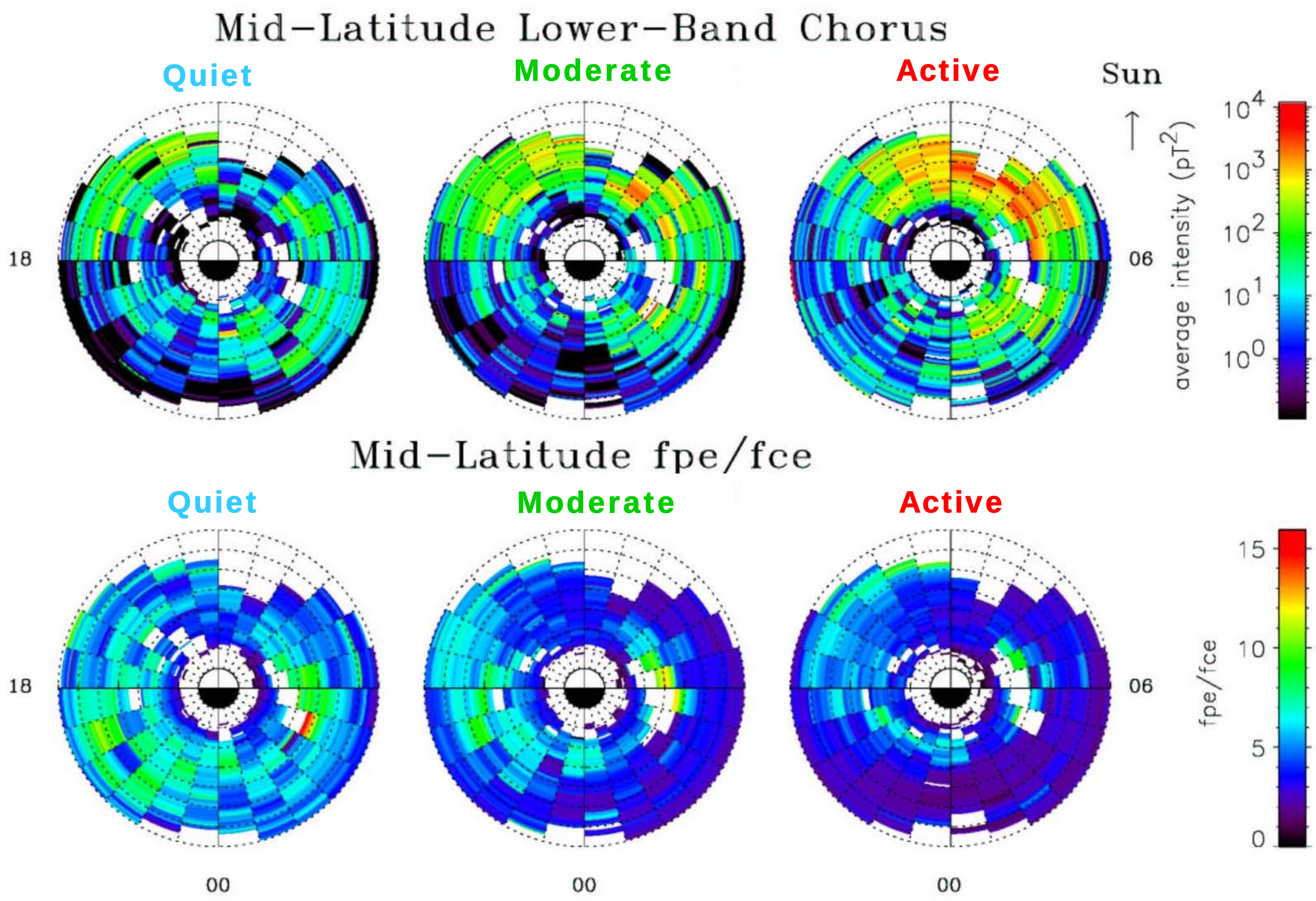
Equatorial Region ($-15^o < \lambda_m < 15^o$)



active conditions
4 < L < 6
23 – 13 MLT

Meredith *et al*., GRL, 2003

Mid-Latitude Region ($15^o < |\lambda_m| < 30^o$)



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Meredith *et al*., GRL, 2003

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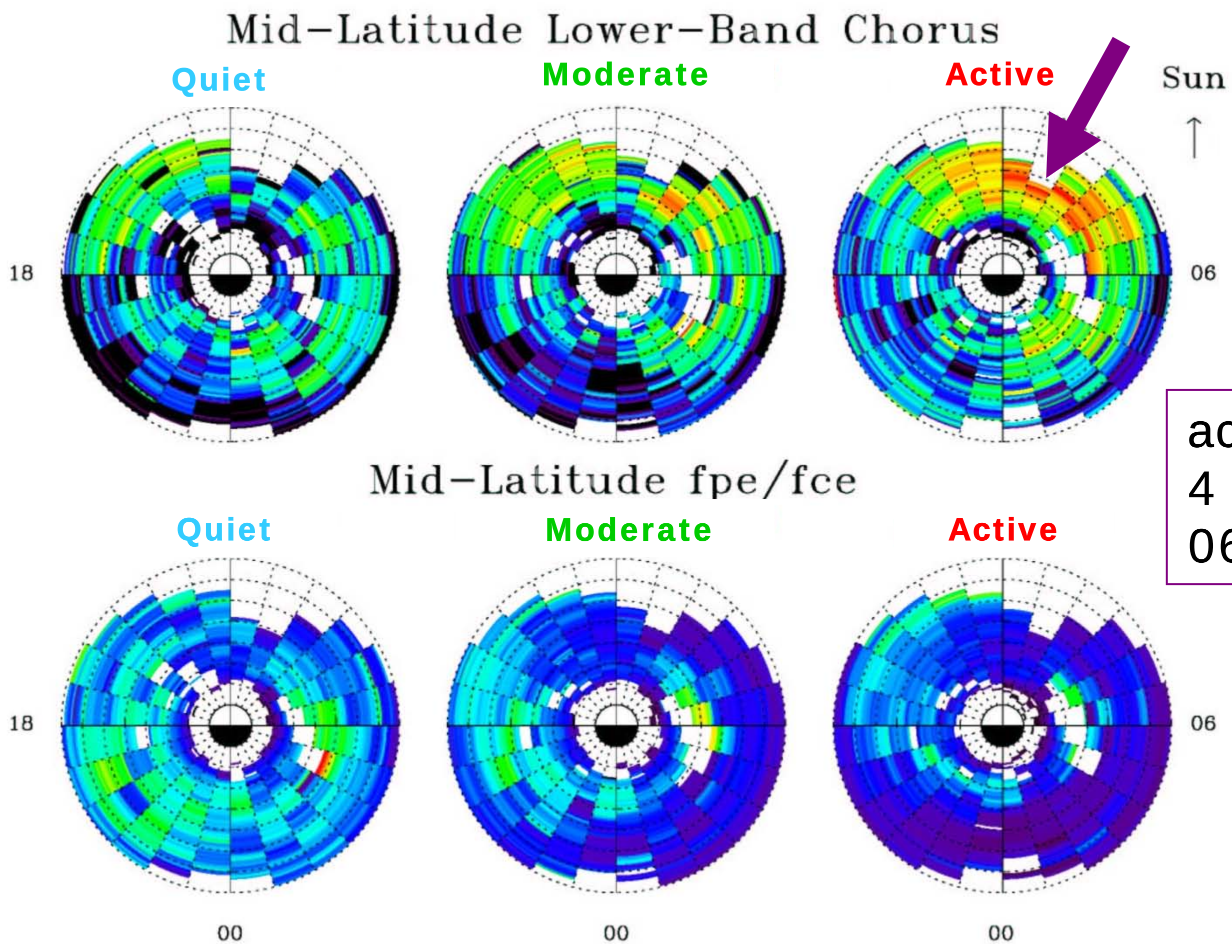

active conditions
4 < L < 6
06 – 14 MLT

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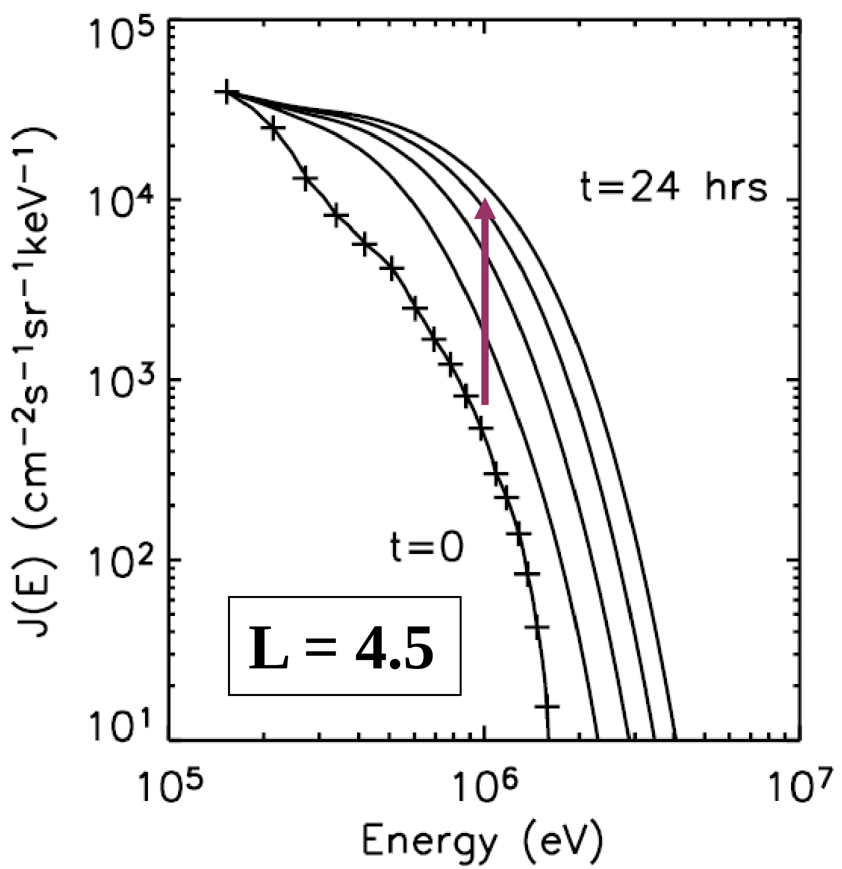
Meredith *et al.*, GRL, 2003

Timescale for Acceleration

- Use 1D Fokker-Planck equation to calculate evolution of particle flux.
- Loss and acceleration by chorus are included using the PADIE code with CRRES wave model.
  - timescale to increase the flux at 1 MeV by an order of magnitude is ~ 1 day.
  - consistent with satellite observations during the recovery phase of storms.



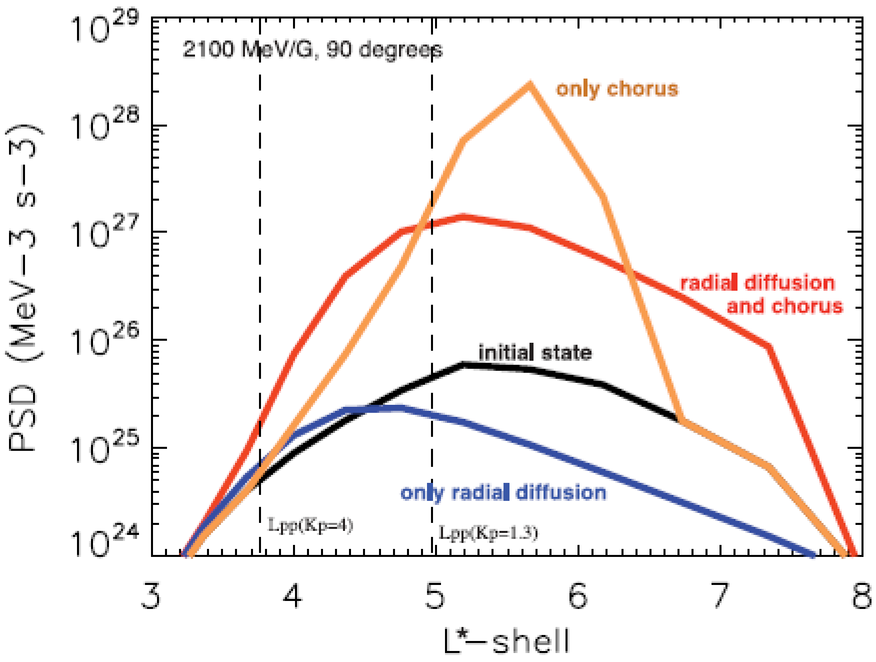
Horne *et al*., JGR, 2005

3D Simulations using Salammbô

- **Varotsou et al., [JGR, 2008]** studied the effects of electron-chorus resonant interactions using the Salammbô code.

- The model included radial diffusion and wave-particle interactions.

- Diffusion rates for resonant chorus waves were calculated using the PADIE code together with a global model of chorus and fpe/fce from CRRES observations.

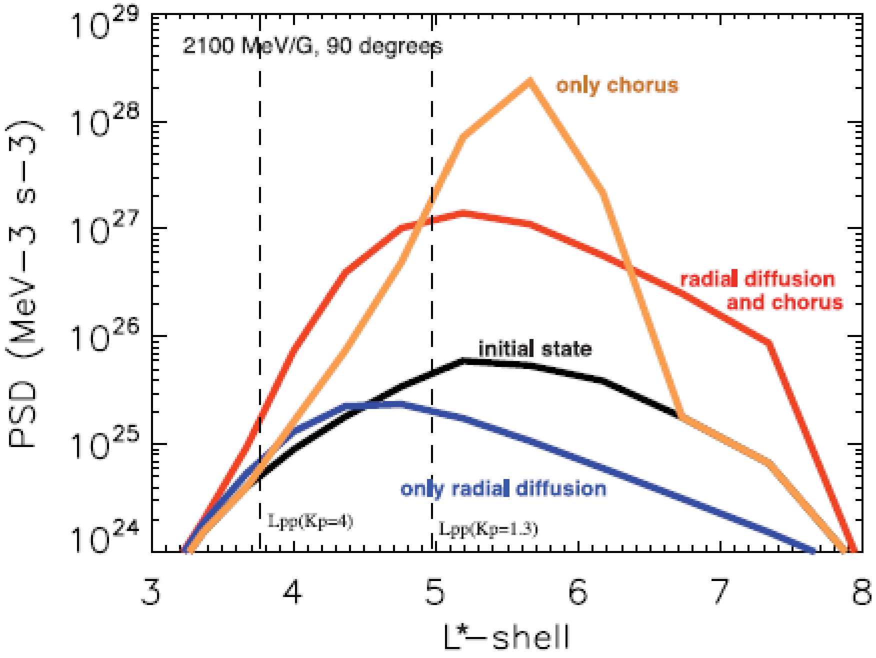


Varotsou *et al*., JGR, 2008

3D Simulations using Salammbô

- The model results show that chorus waves are capable of accelerating electrons to relativistic energies.

- Inward and outward radial diffusion then increases the relativistic electron flux over the entire outer radiation belt.

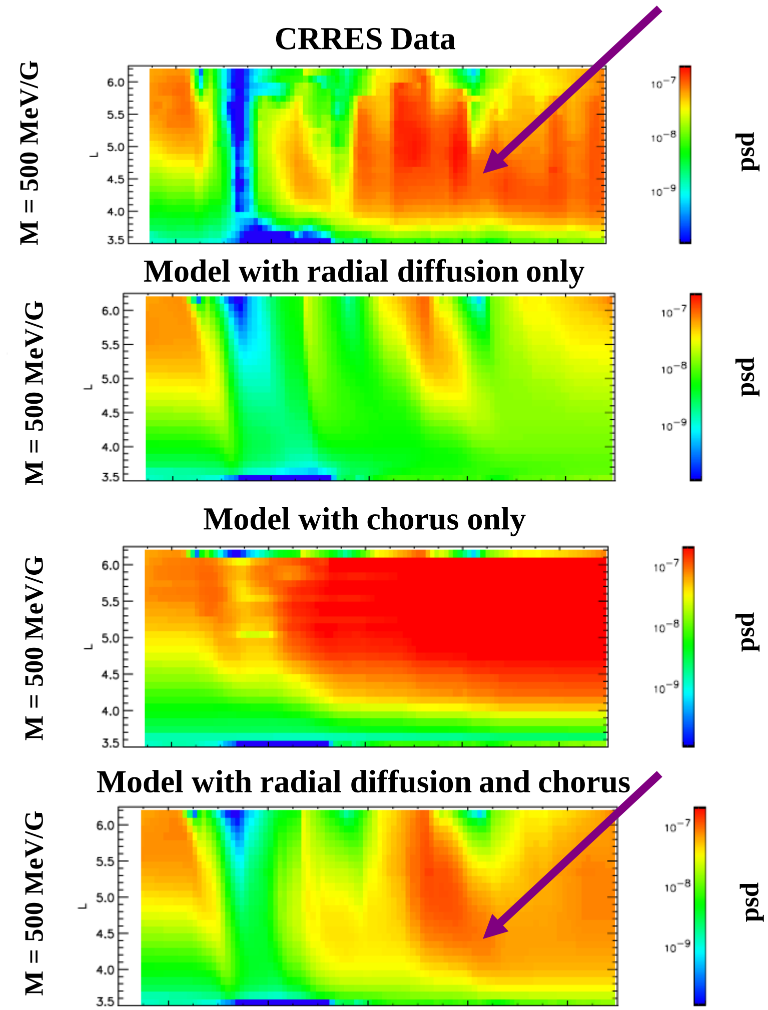


Varotsou *et al*., JGR, 2008

3D Diffusion Simulations
Comparison with Data

- **Albert *et al*. [2009]** modelled the October 9 1990 storm using a 3D code including radial diffusion together with quasi-linear pitch angle and energy diffusion driven by the CRRES chorus wave model.

- They showed that the persistent peaks in phase space density seen during the recovery phase were well explained by a combination of chorus acceleration and radial diffusion.



Albert *et al*., JGR, 2009

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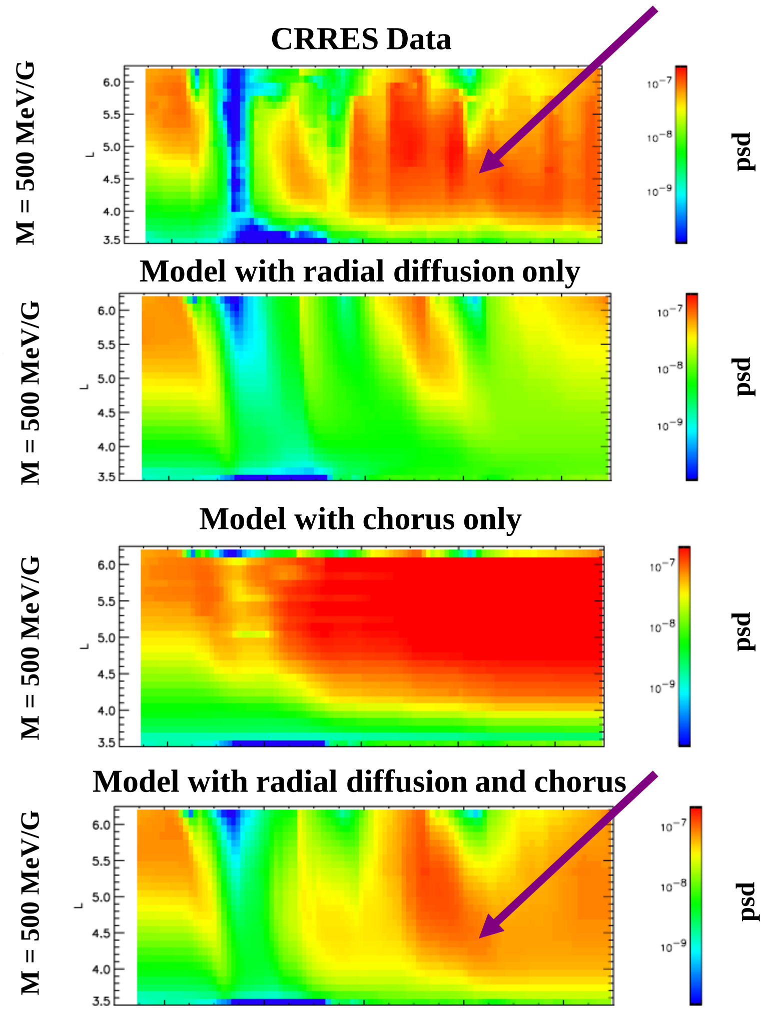
3D Diffusion Simulations
Comparison with Data

- This result suggests that chorus-electron interactions can be well-simulated by quasi-linear diffusion despite the increasingly appreciated nonlinear nature of chorus waves.

- Why does quasi-linear diffusion work so well ?

- What is the role of nonlinear interactions ?



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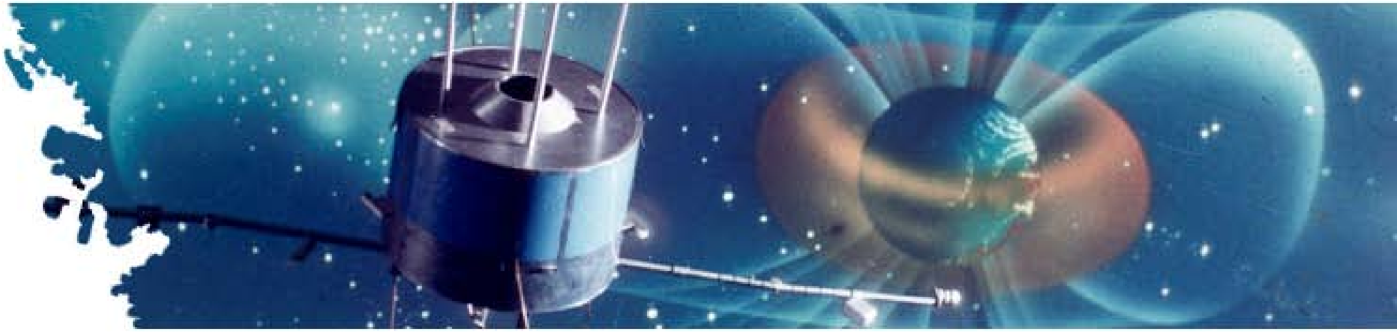
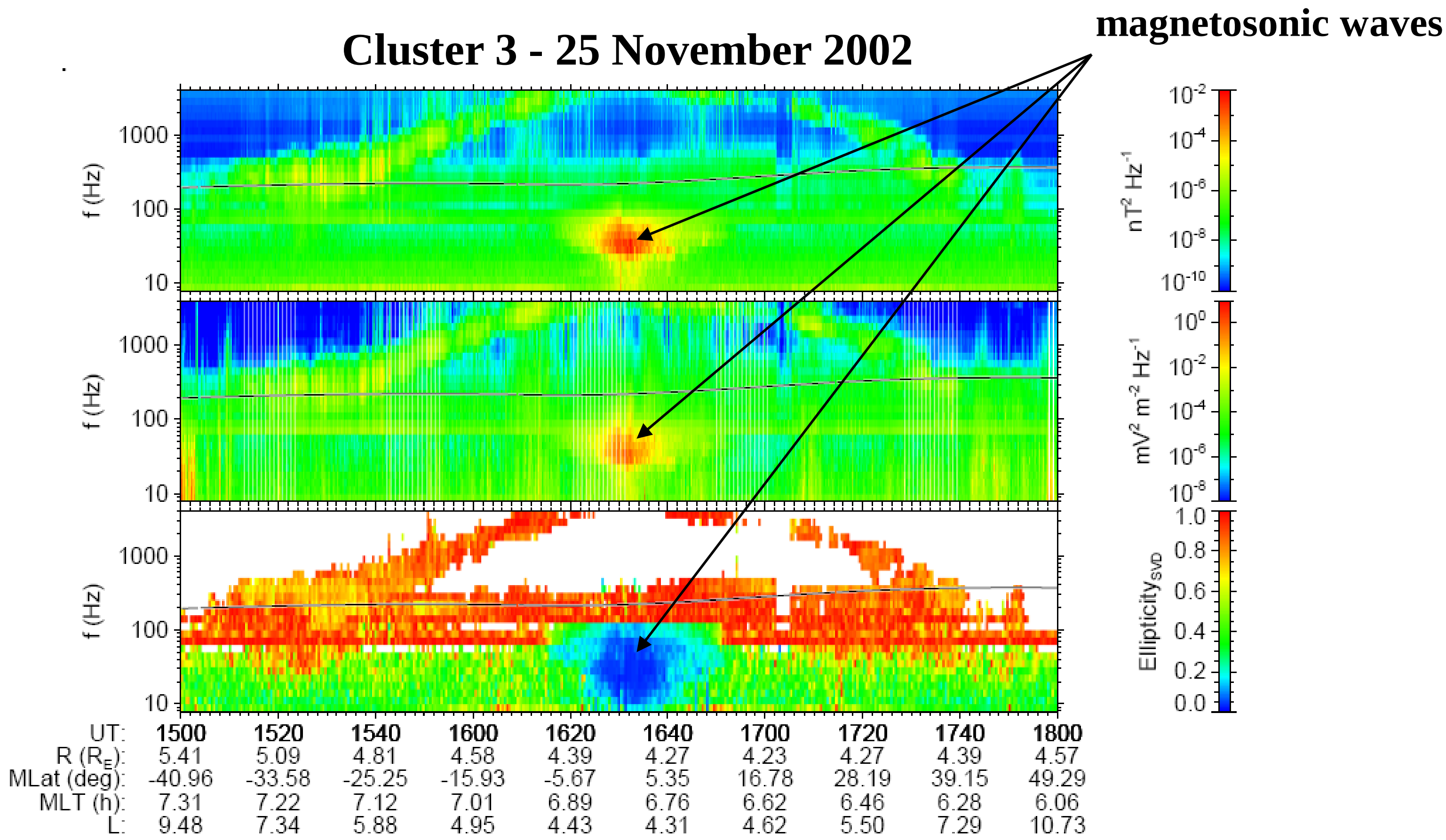
Albert *et al*., JGR, 2009



Paradigm Shift

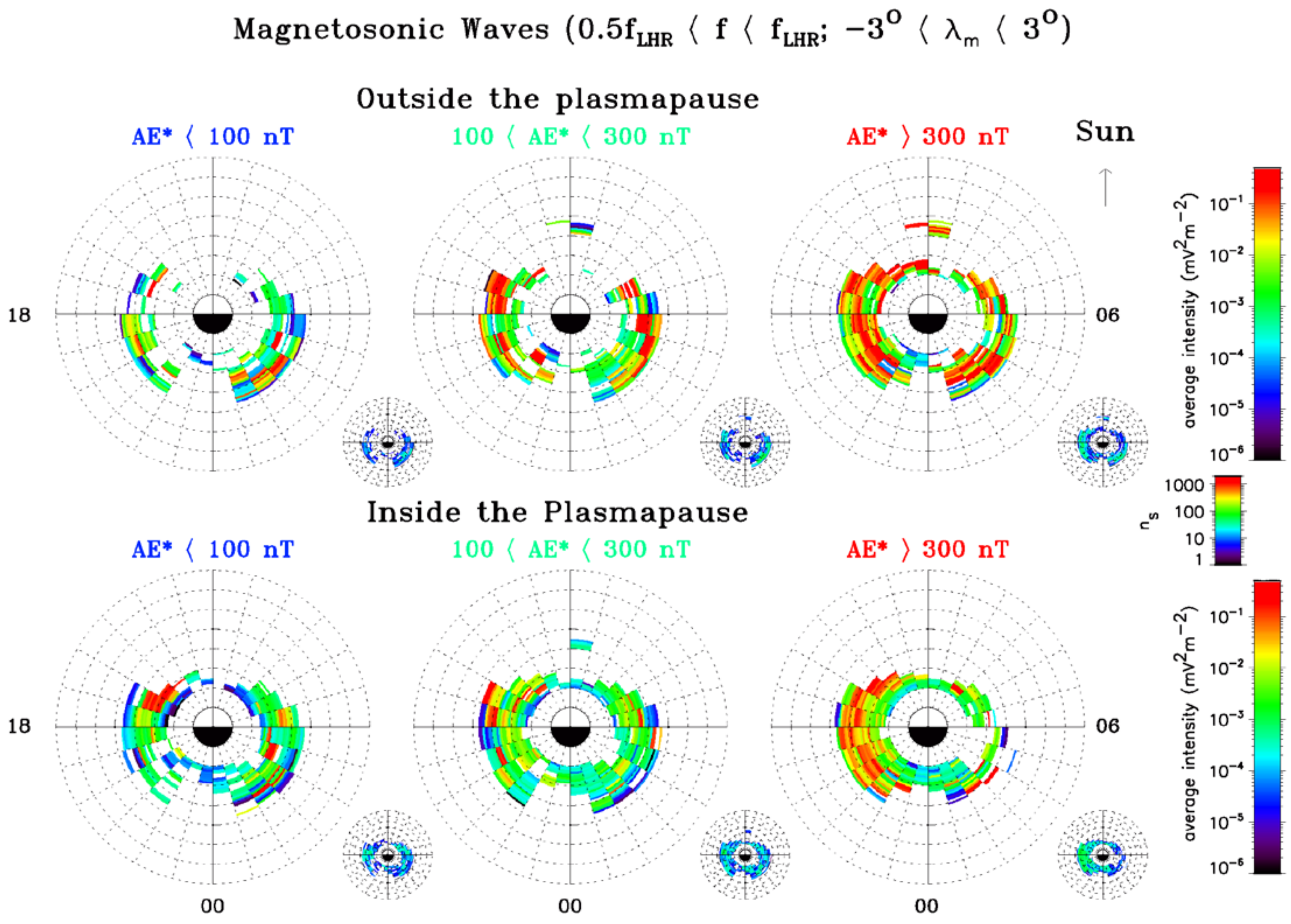
- Local acceleration by **whistler mode chorus** plays a major role in the dynamics of the outer radiation belt during extended periods of enhanced magnetic activity .

Magnetosonic Waves



- intense electromagnetic emissions, fcp < f < flhr
- compressional waves, propagate across B_0
- generated by proton ring distributions [**Boardsen *et al*., JGR, 1992**]

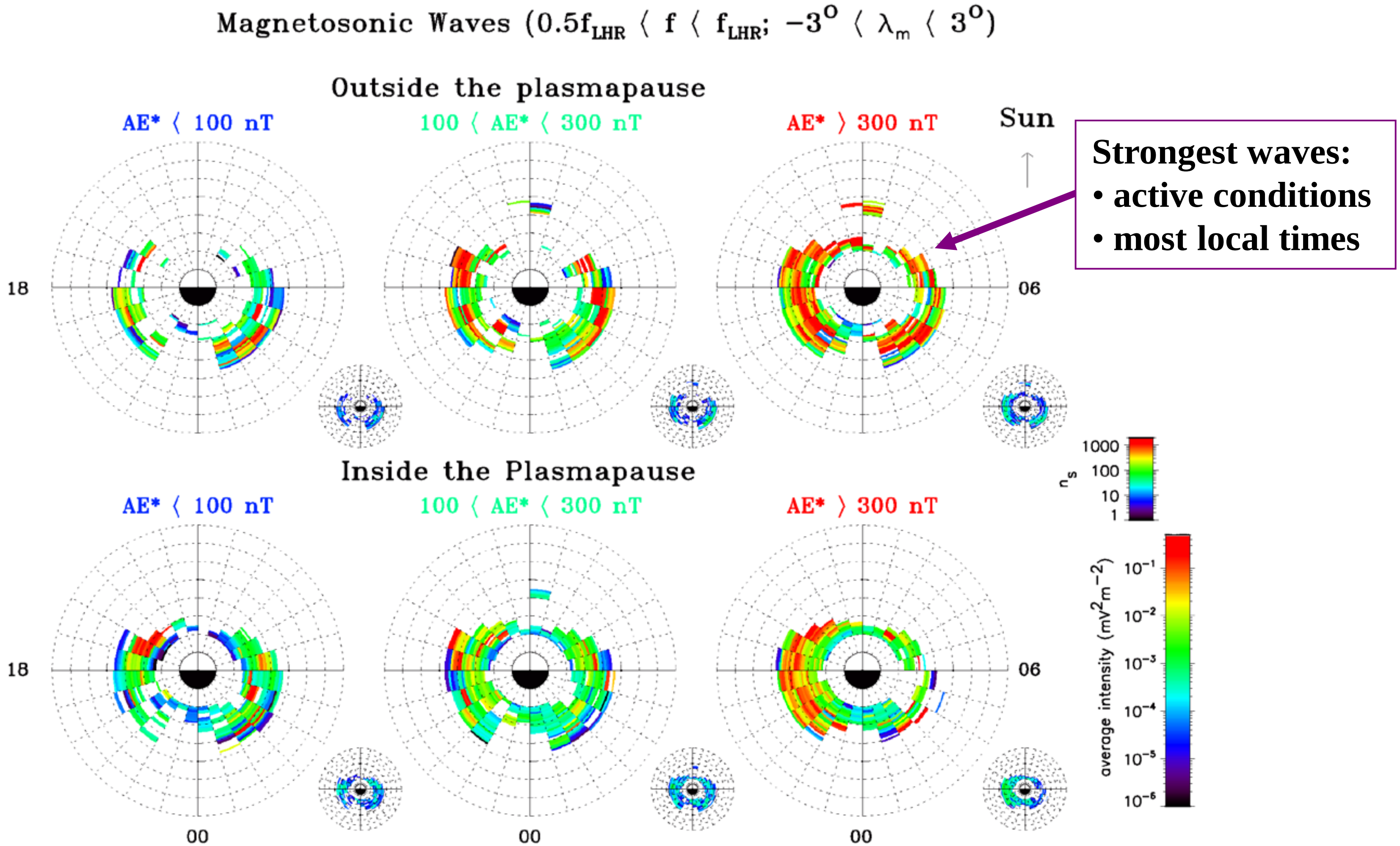
Global Distribution of Magnetosonic Waves



- Note: Low frequency limit of CRRES PWE restricts frequency and L shell coverage.

Meredith *et al*., JGR, 2008

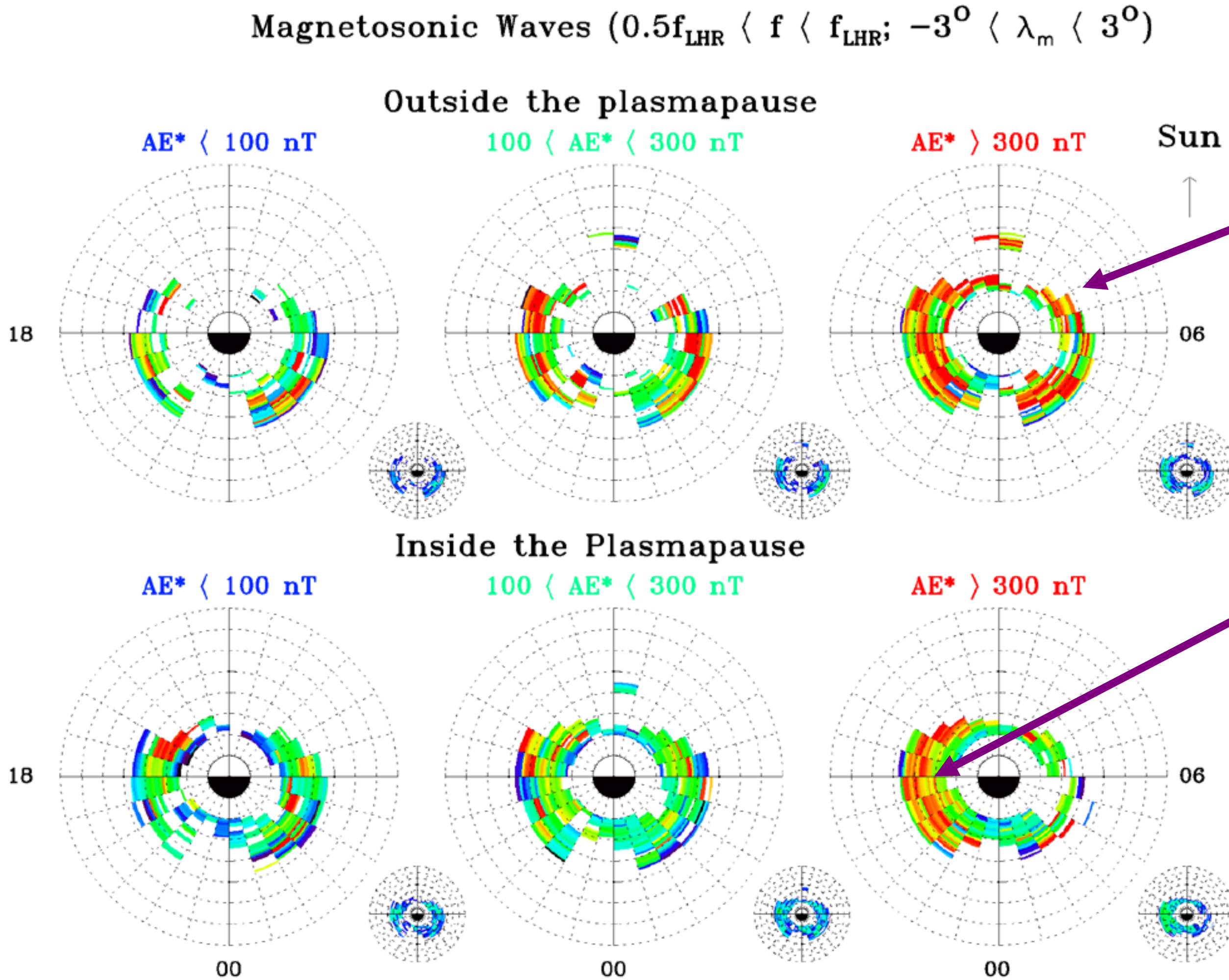
Global Distribution of Magnetosonic Waves



- Note: Low frequency limit of CRRES PWE restricts frequency and L shell coverage.

Meredith *et al*., JGR, 2008

Global Distribution of Magnetosonic Waves



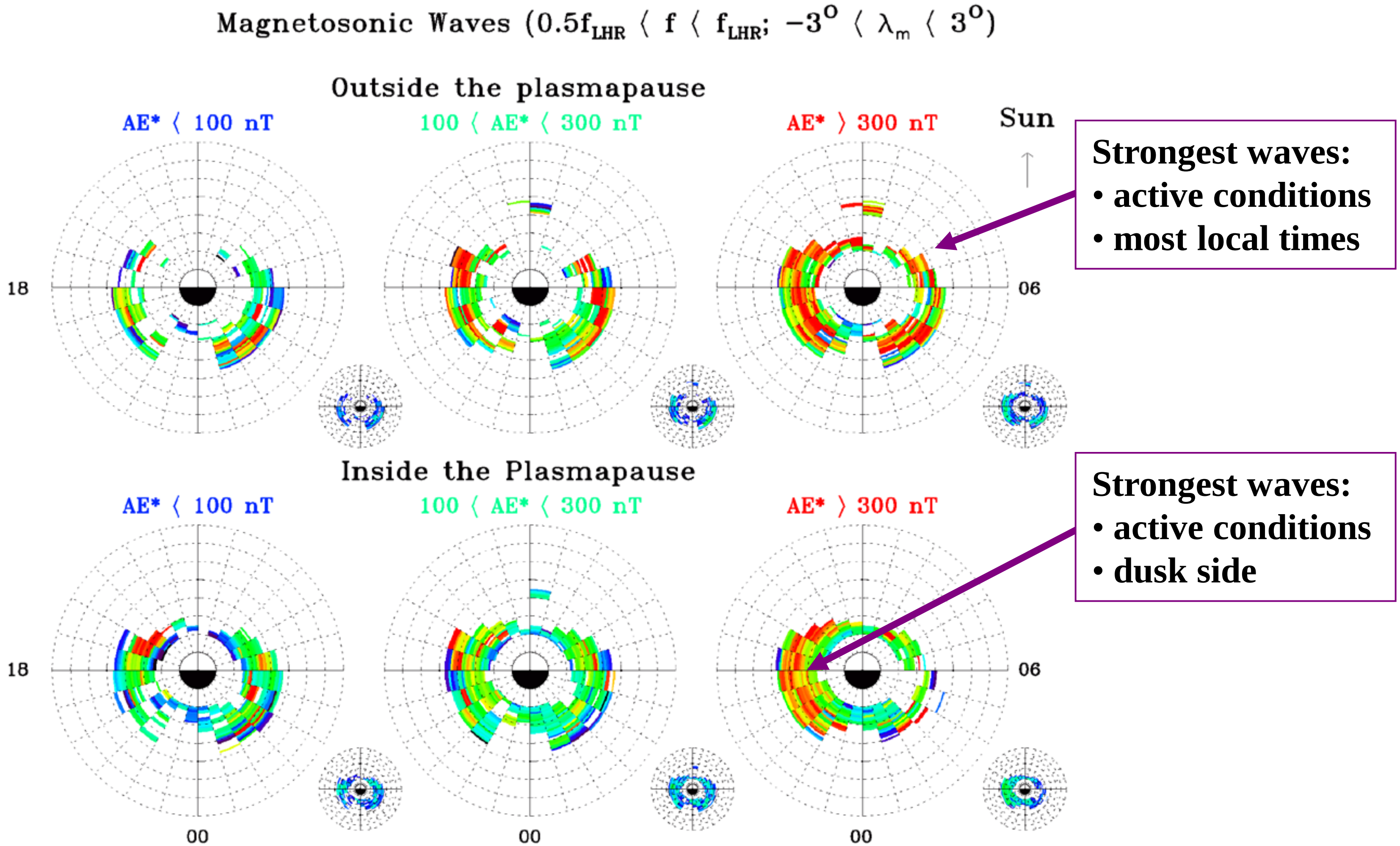
Strongest waves:
- **active conditions**
- **most local times**

Strongest waves:
- **active conditions**
- **dusk side**

- Note: Low frequency limit of CRRES PWE restricts frequency and L shell coverage.

Meredith *et al.*, JGR, 2008

Global Distribution of Magnetosonic Waves



- Wave power increases with increasing magnetic activity suggesting they are related to periods of enhanced convection and/or substorm activity.

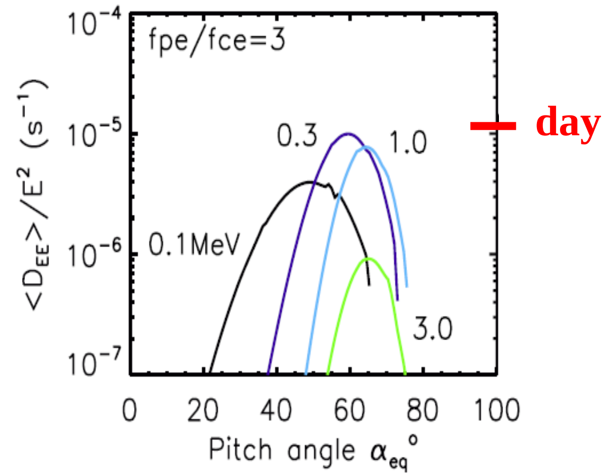
Energy Diffusion Rates at L = 4.5

- Energy diffusion rates have been estimated using Cluster wave observations and the PADIE code.

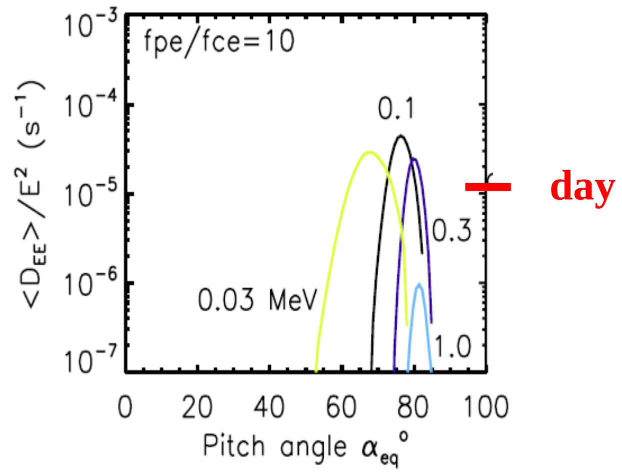
- Timescale of the order of a day
  - 0.3 < E < 1 MeV outside the plasmapause
  - 0.03 < E < 0.3 MeV inside the plasmapause

Magnetosonic waves may provide a significant energy transfer process between the ring current and the outer radiation belt.

Outside plasmapause



Inside plasmapause



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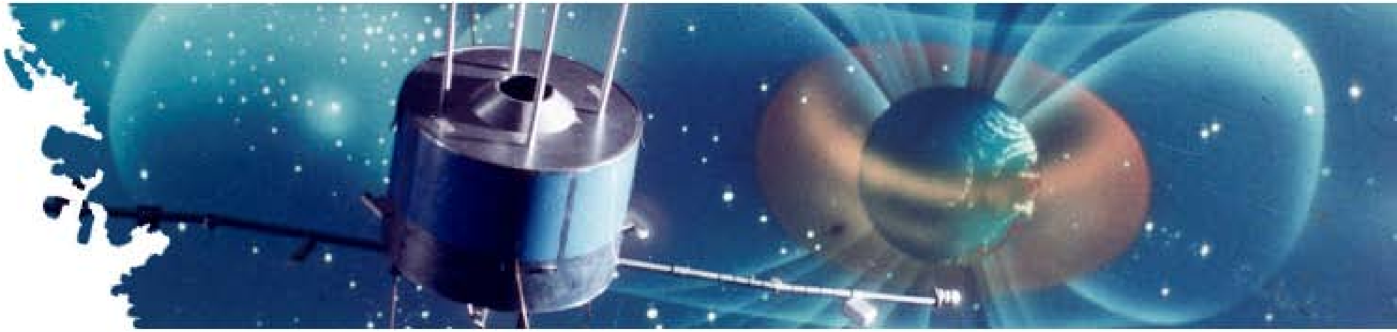
Horne *et al*., GRL, 2007



Local Acceleration by Magnetosonic Waves

- Local acceleration by **magnetosonic waves** may also play an important role in radiation belt dynamics.

- More information on the global distribution and spectral properties of the waves required to quantitatively assess this suggestion.

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Loss Mechanisms

- Several wave modes contribute to pitch angle scattering and subsequent loss to the atmosphere.

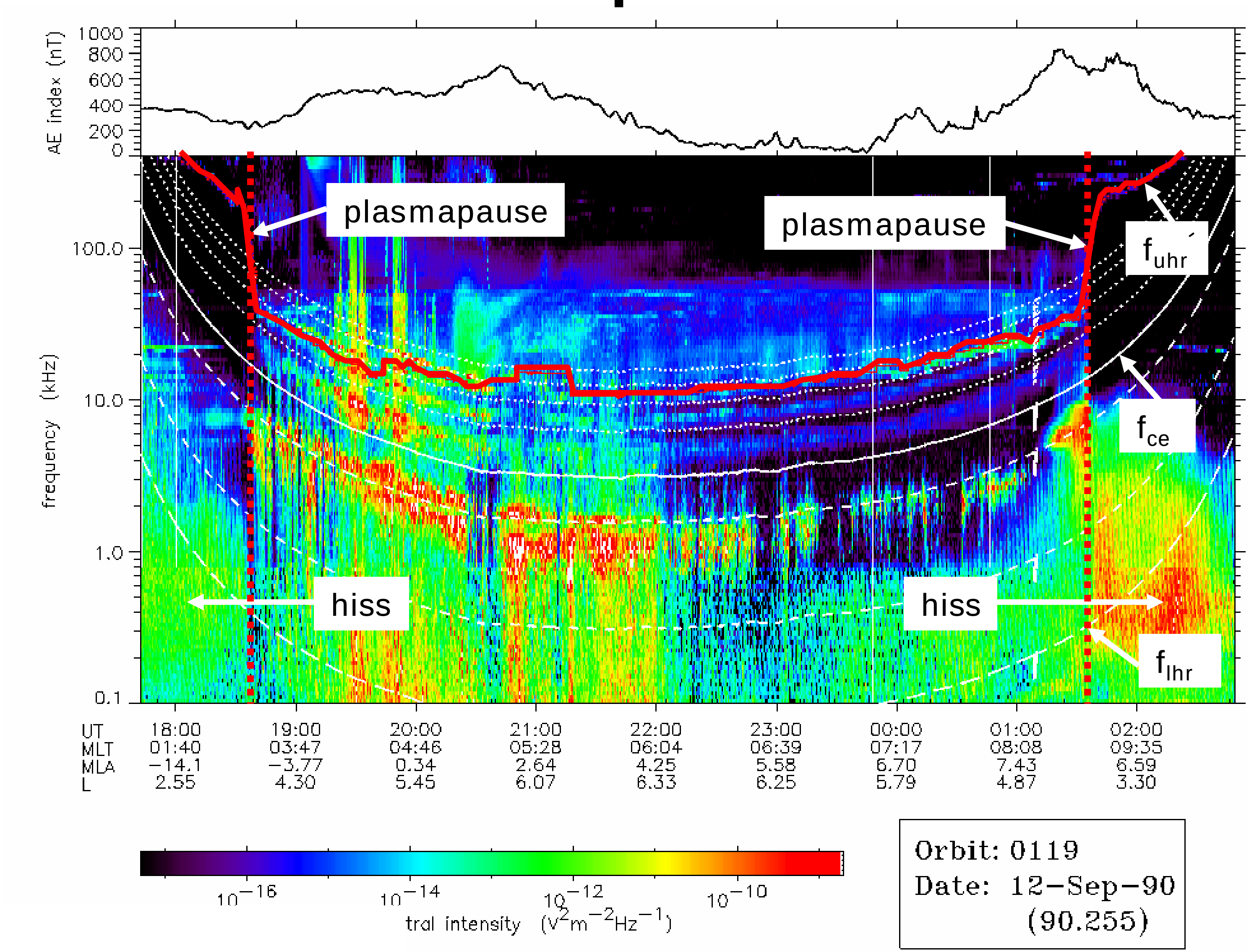
- Three potentially important loss processes – the scattering due to gyro-resonant interactions with:

  - Plasmaspheric hiss

  - Whistler mode chorus

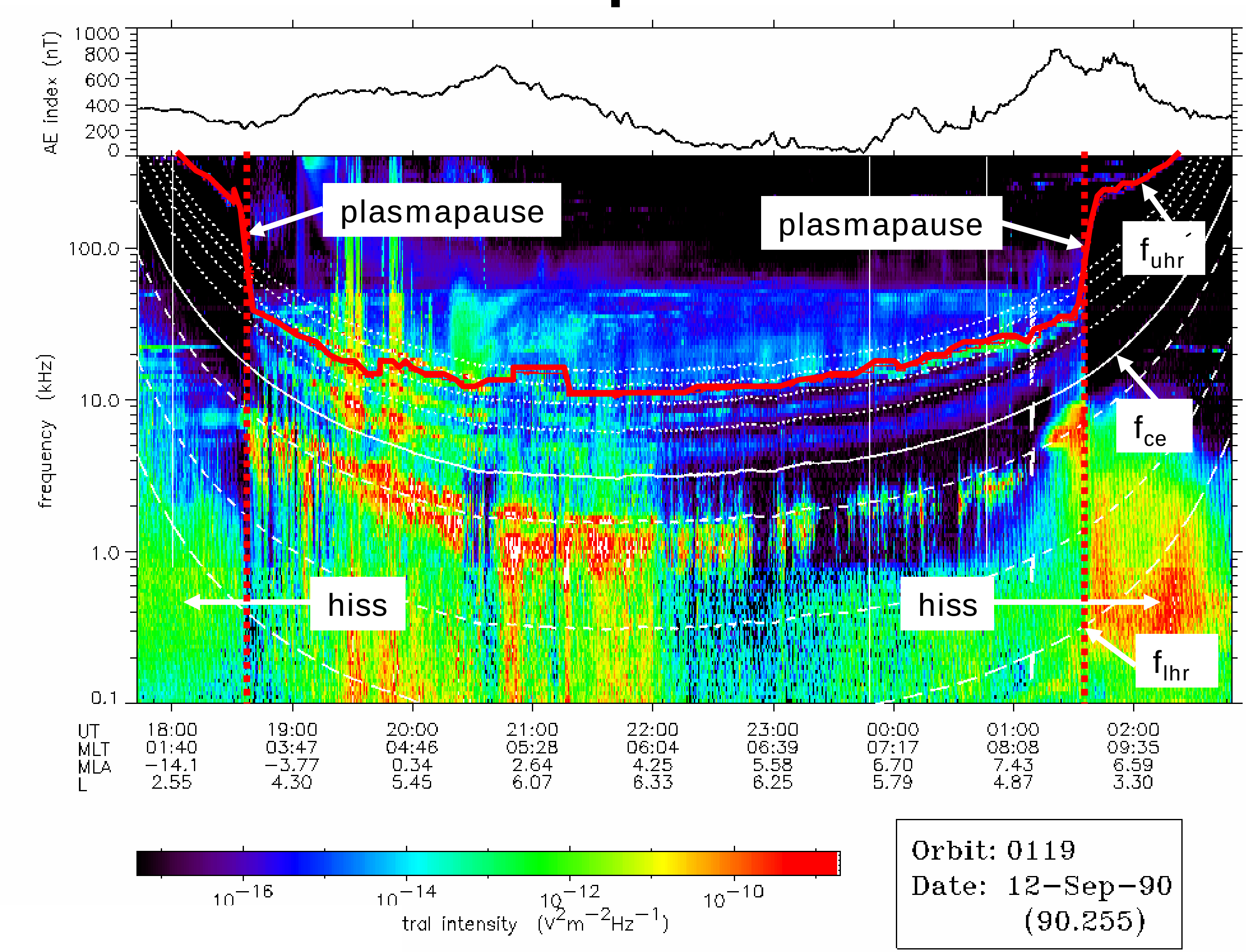
  - EMIC waves

Plasmaspheric Hiss



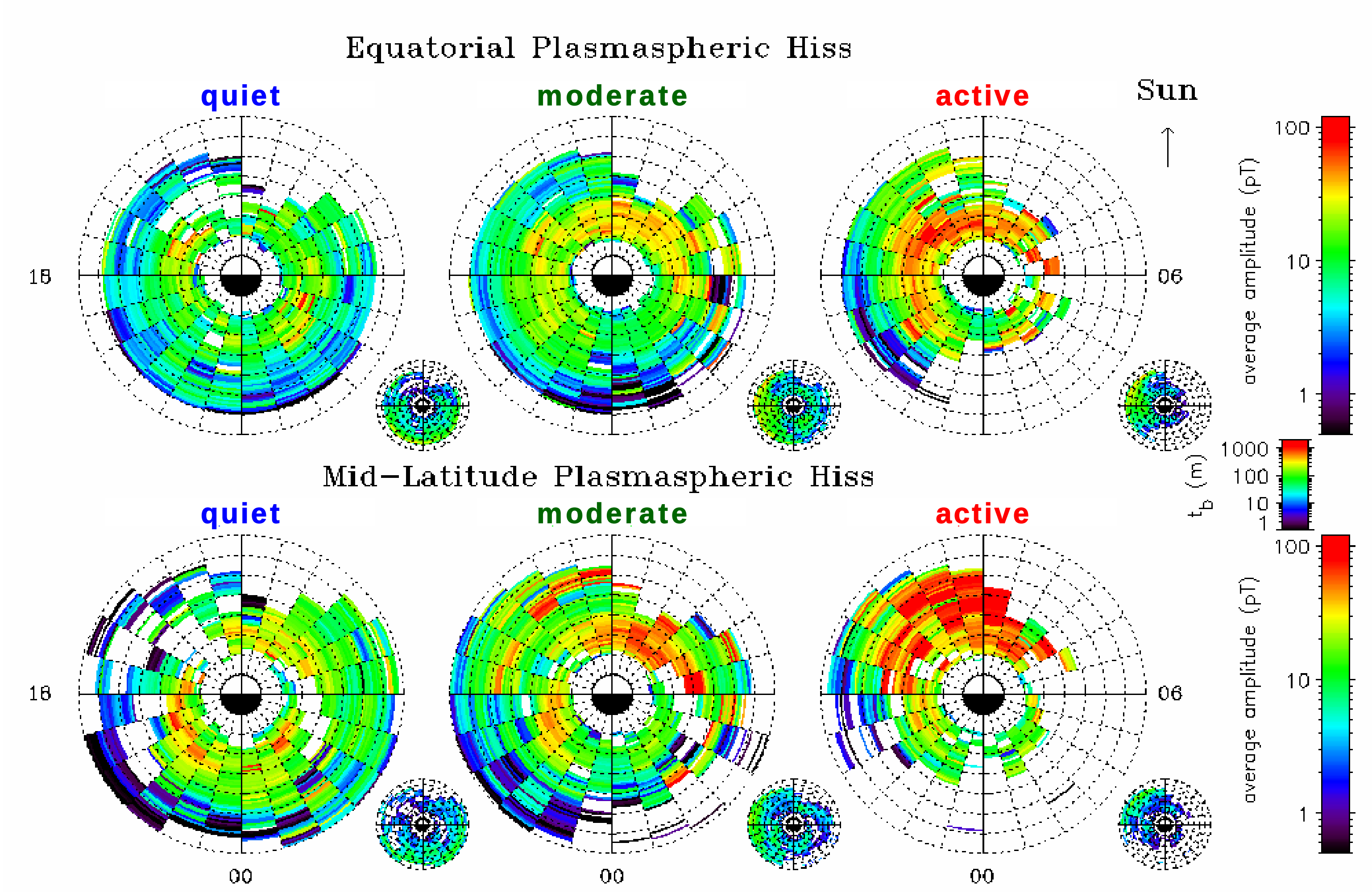
Plasmaspheric hiss is a broadband, structureless, ELF emission that occurs in the frequency range from 100 Hz to several kHz.

Plasmaspheric Hiss



This whistler mode emission is confined to the higher density regions associated with the plasmasphere or plasmaspheric plumes.

Global Distribution of Plasmaspheric Hiss



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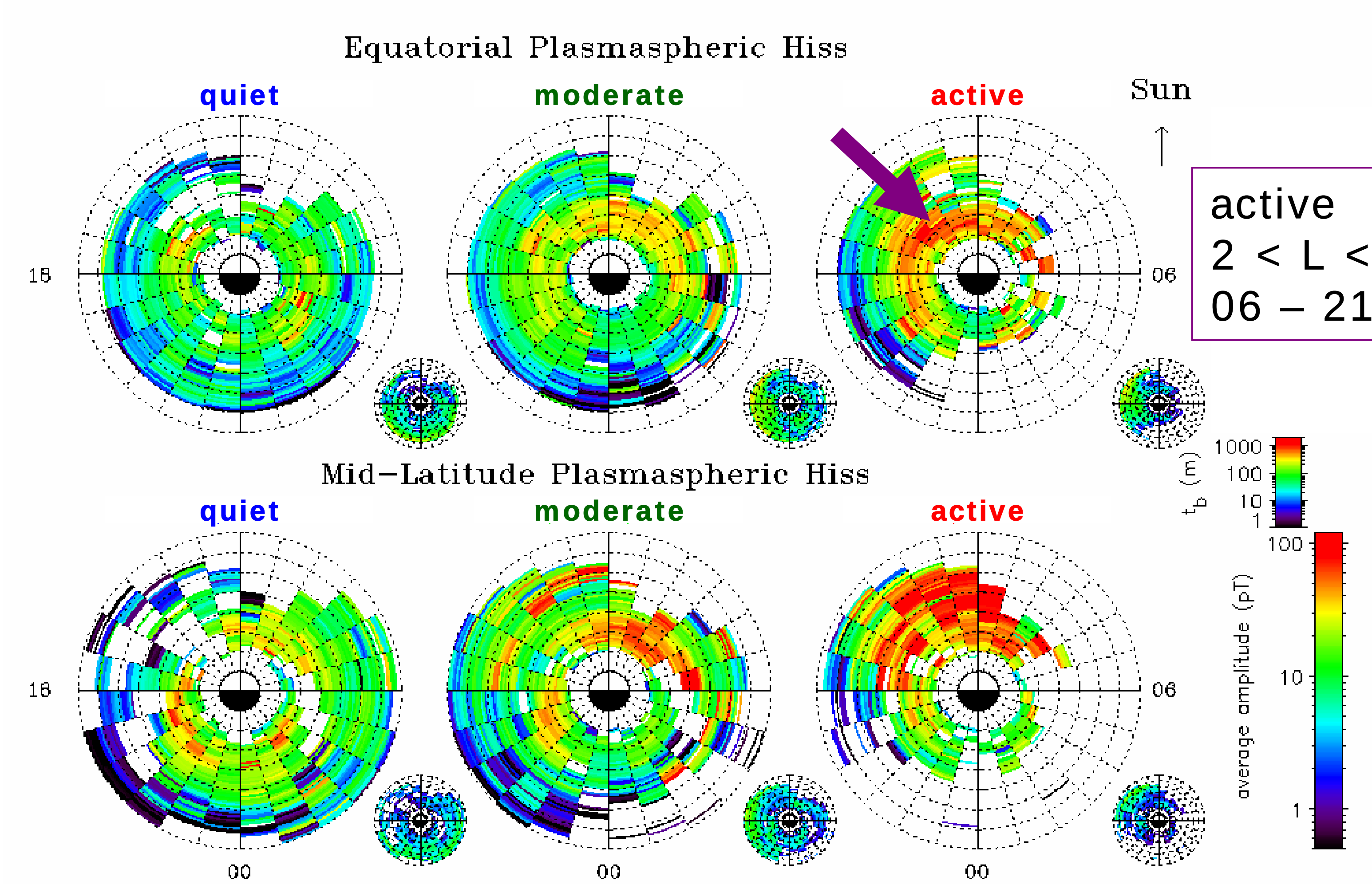
Meredith *et al*., JGR, 2004

Global Distribution of Plasmaspheric Hiss



active
2 < L < 4
06 – 21 MLT

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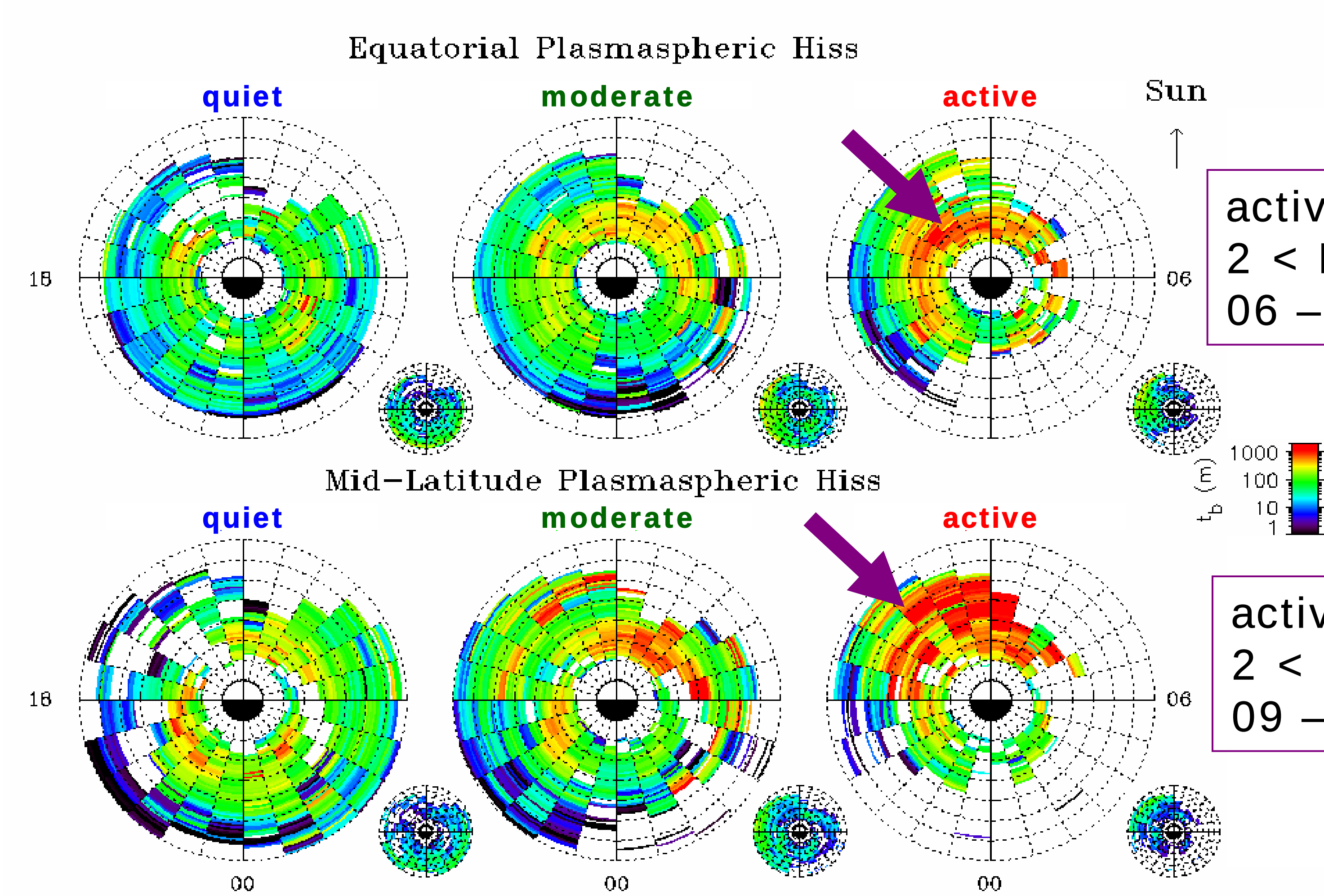
Meredith *et al.*, JGR, 2004

Global Distribution of Plasmaspheric Hiss



active
2 < L < 4
06 – 21 MLT

active
2 < L < 4
09 – 18 MLT

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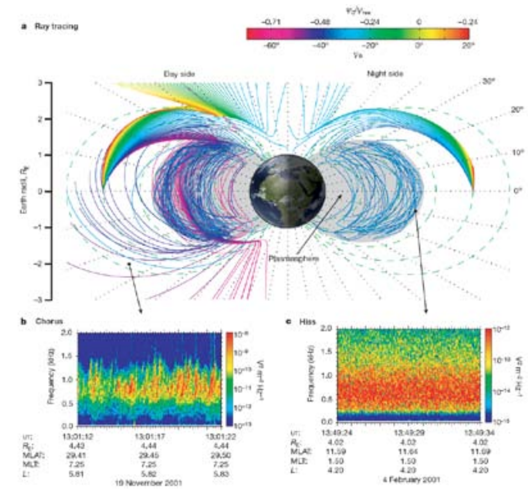
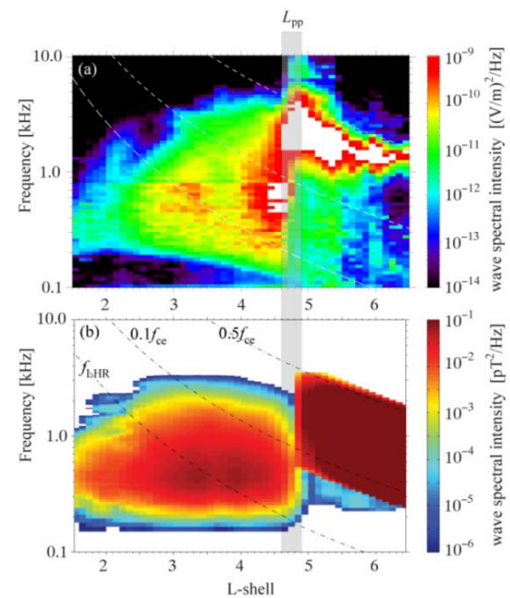
Meredith *et al*., JGR, 2004

Origin of Plasmaspheric Hiss

- Ray tracing studies show that chorus waves can propagate into the plasmasphere and evolve into plasmaspheric hiss.
- Results reproduce the observed spatial and spectral distributions of plasmaspheric hiss.



Bortnik *et al*., Nature, 2008



Bortnik *et al*., GEM, 2011

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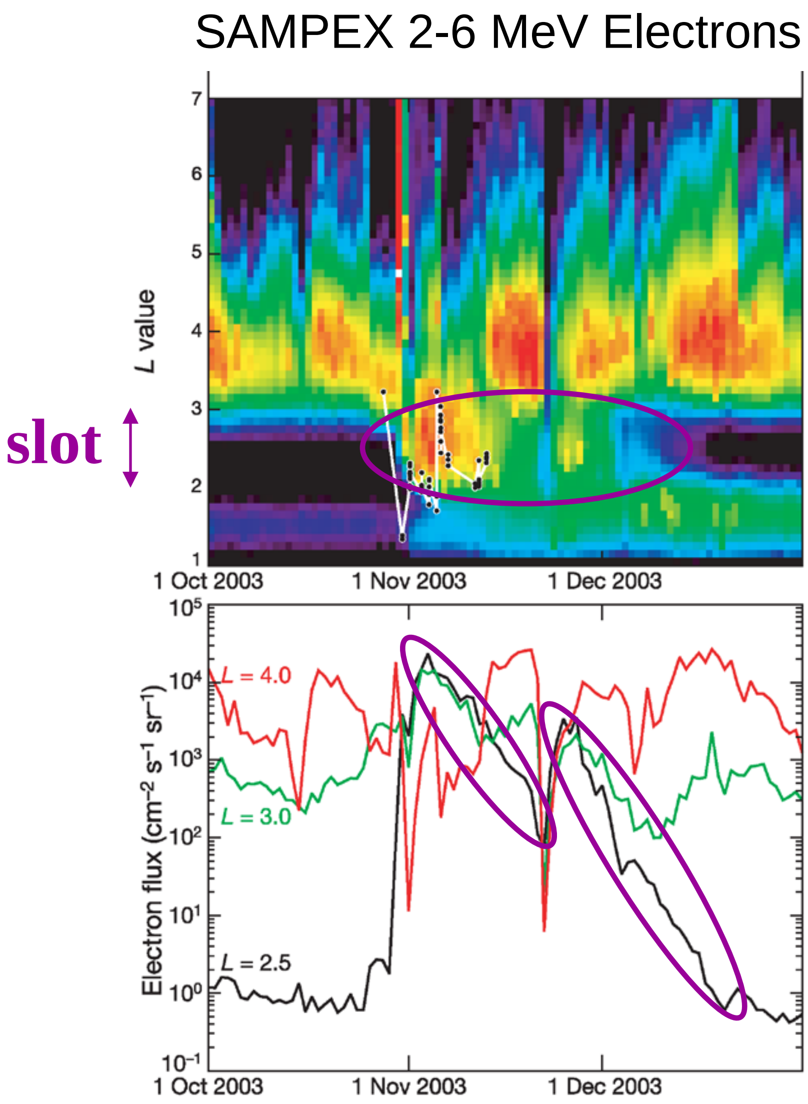
Slot Region Loss Timescales

- Slot region can become filled during exceptionally large storms such as the Halloween Storms of 2003.
- Slot region subsequently reforms.
- Loss timescales for 2-6 MeV electrons at L = 2.5 estimated to be of the order of 2.9 – 4.6 days.
- The dominant loss process must be able to explain this decay.



Baker *et al*., Nature, 2004

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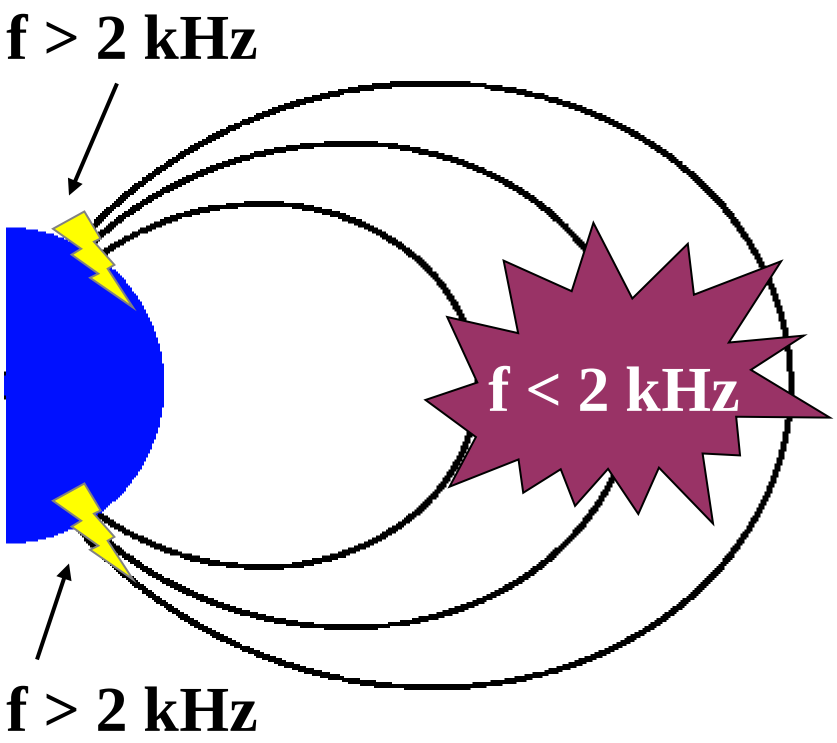
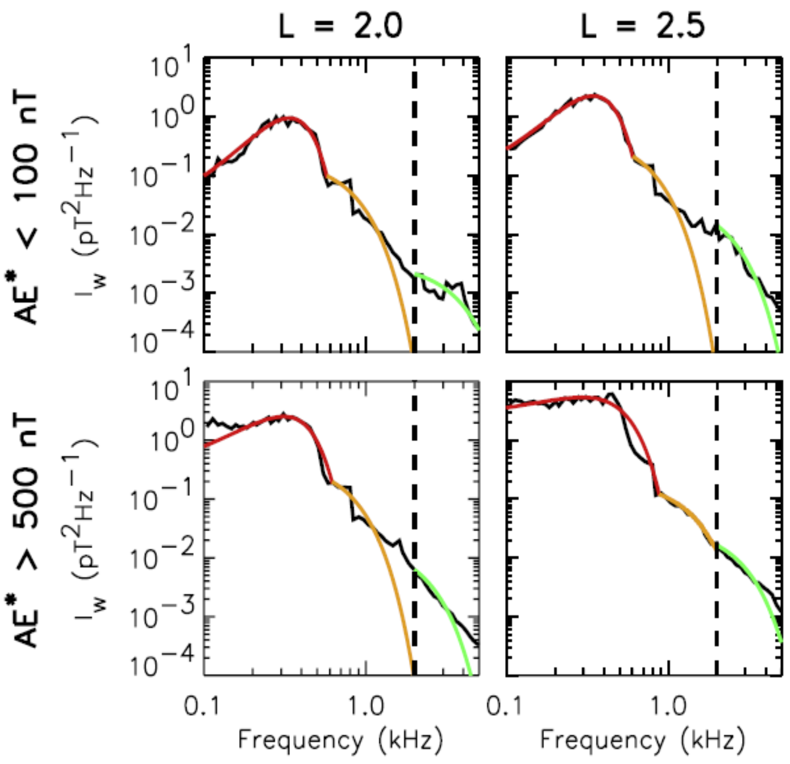
Broadband Plasmaspheric Emissions

- Broadband plasmaspheric emissions can be split into two categories [***Meredith et al*., 2006**]:
  - Plamaspheric hiss
    - 100 Hz < f < 2 kHz
    - generated by whistler mode chorus
  - MR whistlers
    - 2 kHz < f < 5 kHz
    - produced by thunderstorms on Earth



Calculation of Losses Due To Hiss

- Use global models of the wave spectral intensity based on CRRES observations.
- Calculate bounce-averaged pitch angle rates using the PADIE code.
- Loss timescale calculated using the 1D pitch angle diffusion equation following **Lyons *et al.*, [1972]**.

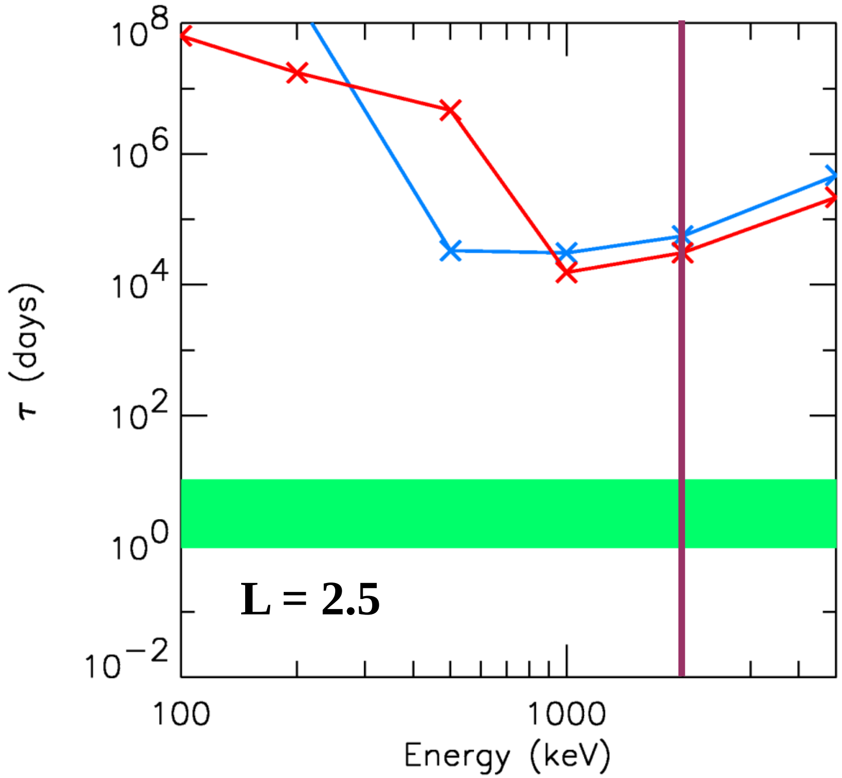


Meredith *et al.*, JGR, 2007

Slot Region Loss Timescales

MR Whistlers

- Loss timescales due to MR whistlers are prohibitively long.



Quiet Conditions (AE* < 100 nT)

Active Conditions (AE* > 500 nT)

Meredith *et al*., JGR, 2007

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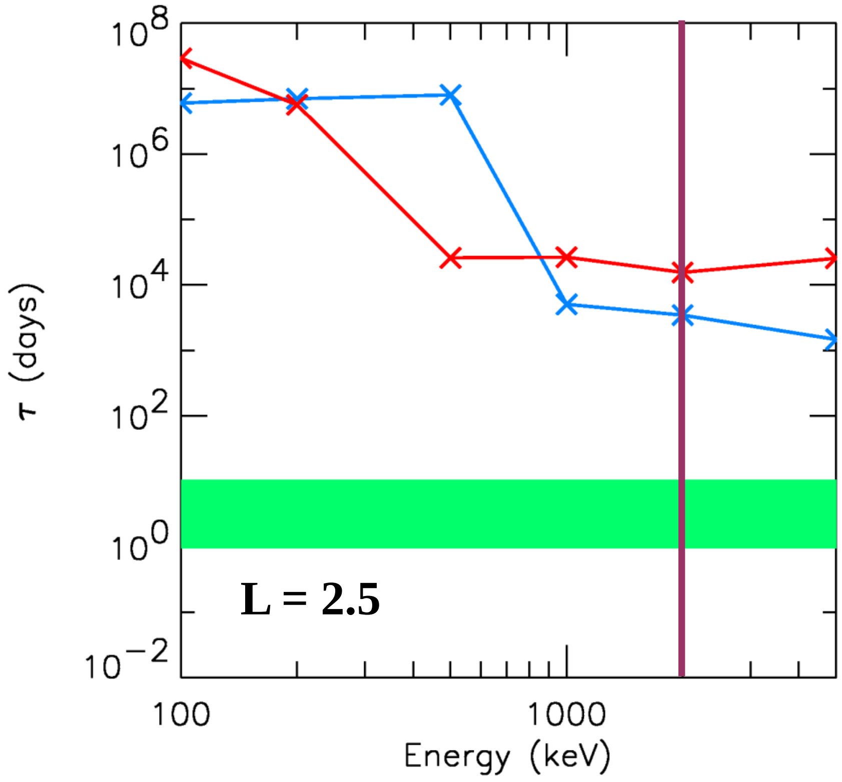
Slot Region Loss Timescales

- Loss timescales due to hiss propagating at large wave normal angles are also prohibitively long.

Hiss (ψ_m = 80°)



Quiet Conditions (AE* < 100 nT)

Active Conditions (AE* > 500 nT)

Meredith *et al*., JGR, 2007

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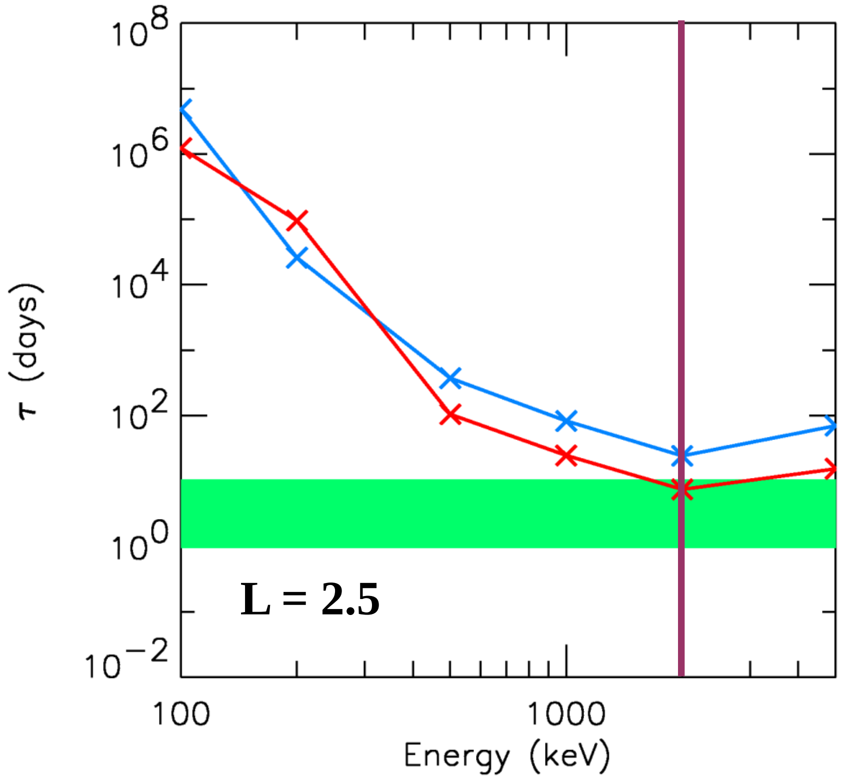
Slot Region Loss Timescales

- Hiss propagating at medium wave normal angles can lead to loss timescales of the order of 10 days during active conditions.

Hiss ($\psi_m = 52^o$)



Quiet Conditions (AE* < 100 nT)

Active Conditions (AE* > 500 nT)

Meredith *et al*., JGR, 2007

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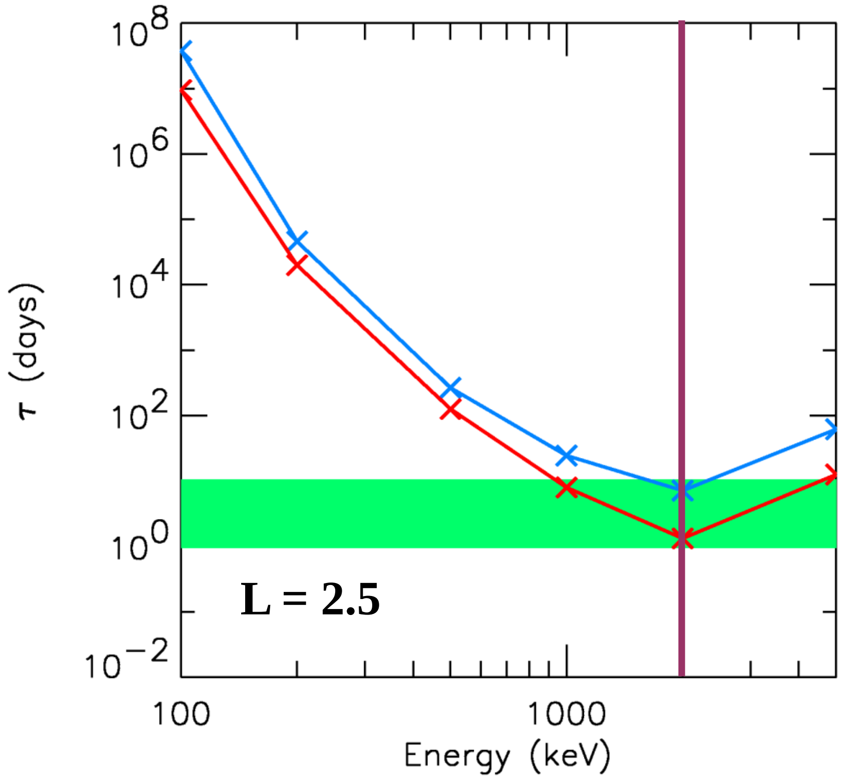
Slot Region Loss Timescales

- Hiss propagating at small wave normal angles can lead to loss timescales of the order of 1 – 10 days depending on magnetic activity.
- Hiss propagating at small wave normal angles is largely responsible for the formation of the slot region.

Hiss ($\psi_m = 0^o$)



Quiet Conditions (AE* < 100 nT)

Active Conditions (AE* > 500 nT)

Meredith *et al*., JGR, 2007

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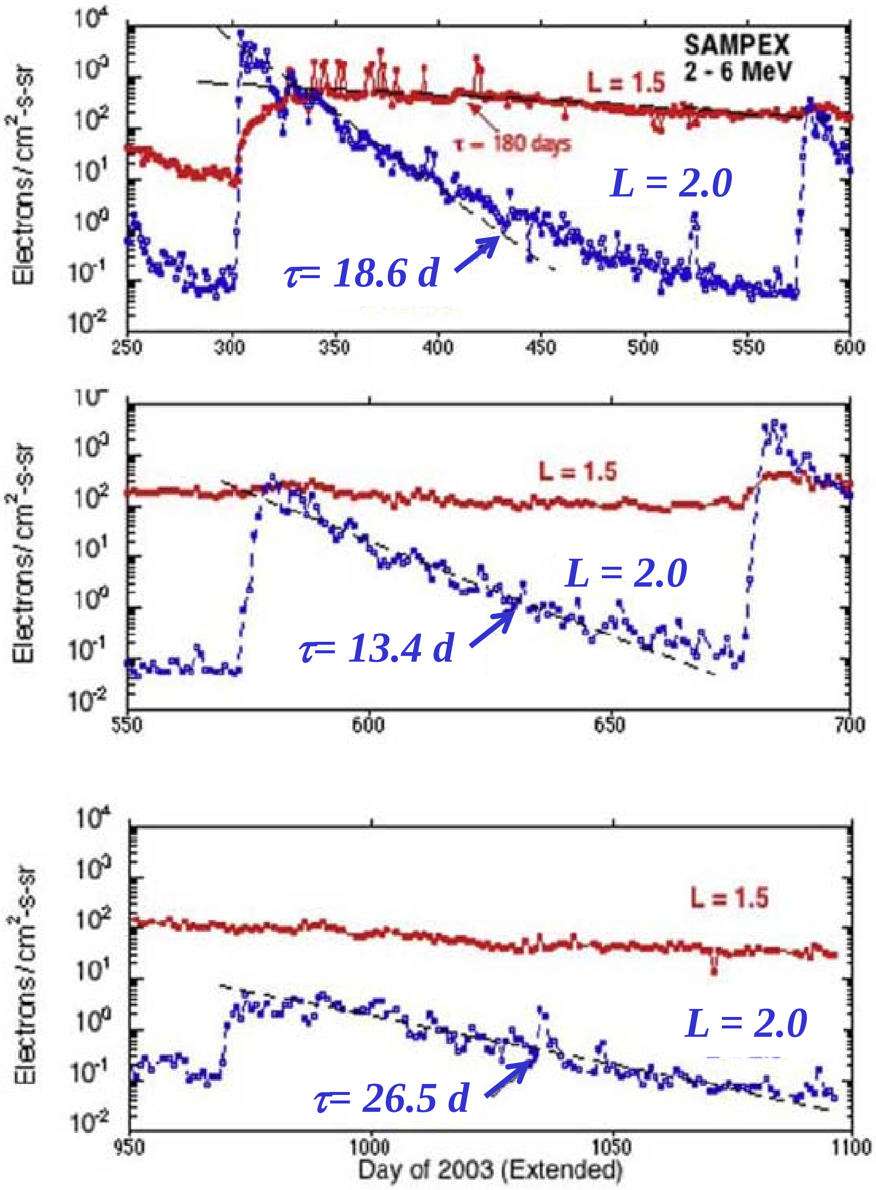
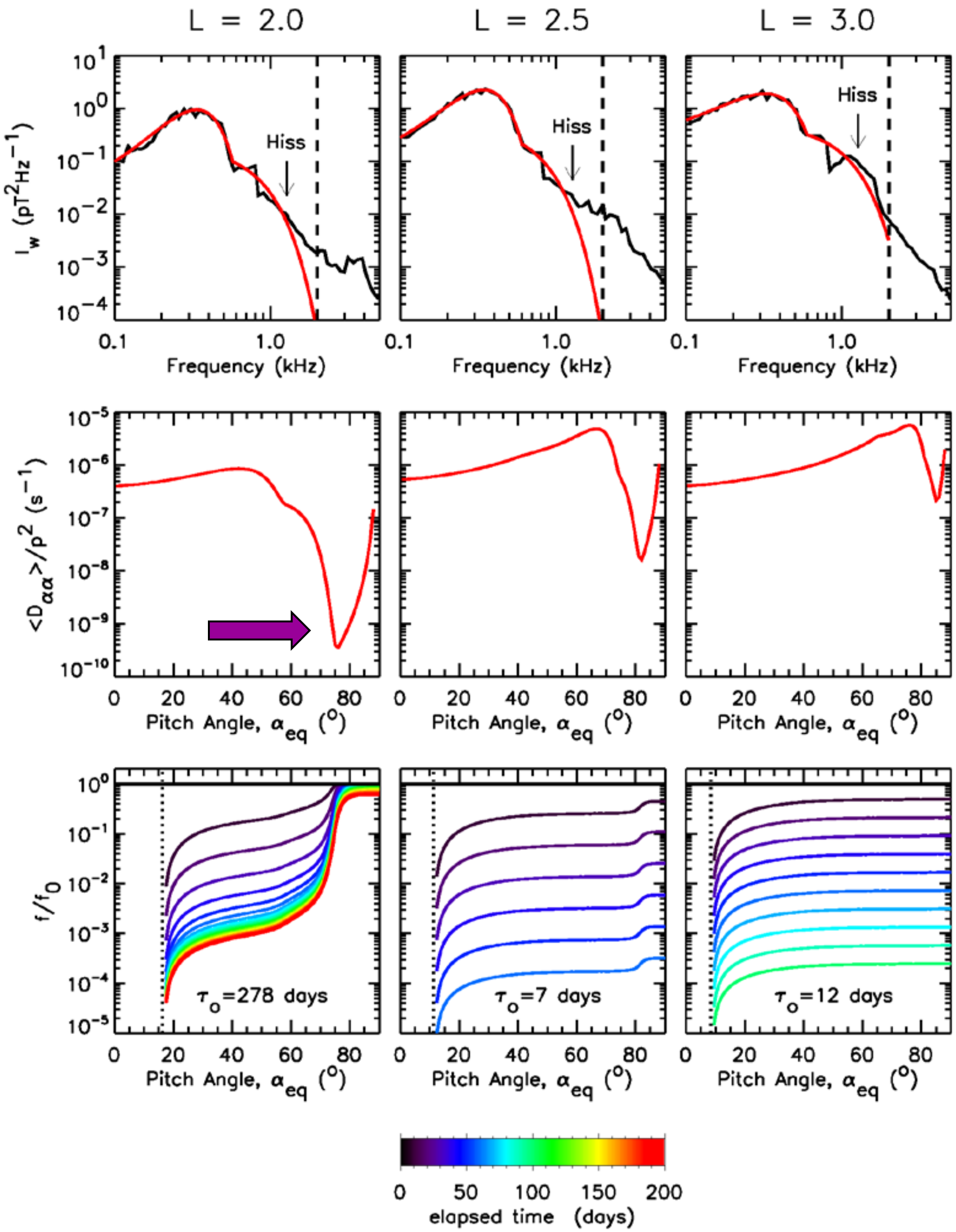
Loss Timescales at Inner Edge of the Slot



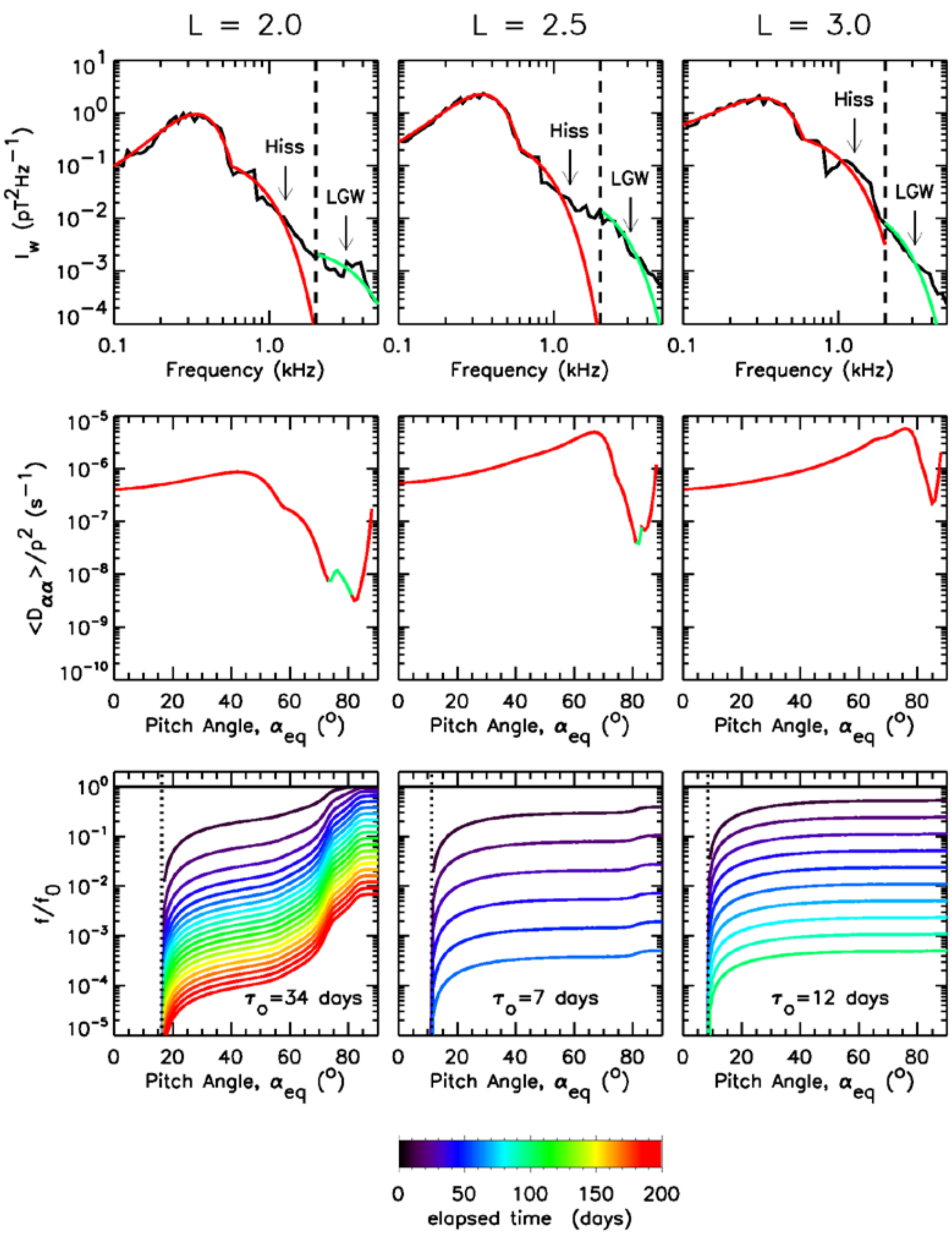
- More recently **Baker *et al.* [2007]** reported an experimental lifetime of ~20 days at L = 2.0.
- This lifetime is much shorter than the theoretical estimates of a few hundred days as a result of losses due to plasmaspheric hiss alone. **[Meredith *et al.*, 2007]**.

Lifetimes due to Hiss



- At L = 2.0 there is a very deep minimum in the diffusion rate.
- This dramatically effects the evolution of the PAD:
  - The decay is pitch angle dependent.
  - The distribution initially decays more rapidly at smaller pitch angles.
- Once an equilibrium shape is reached the entire distribution decays with a timescale of 278 days.

Meredith *et al*., JGR, 2009

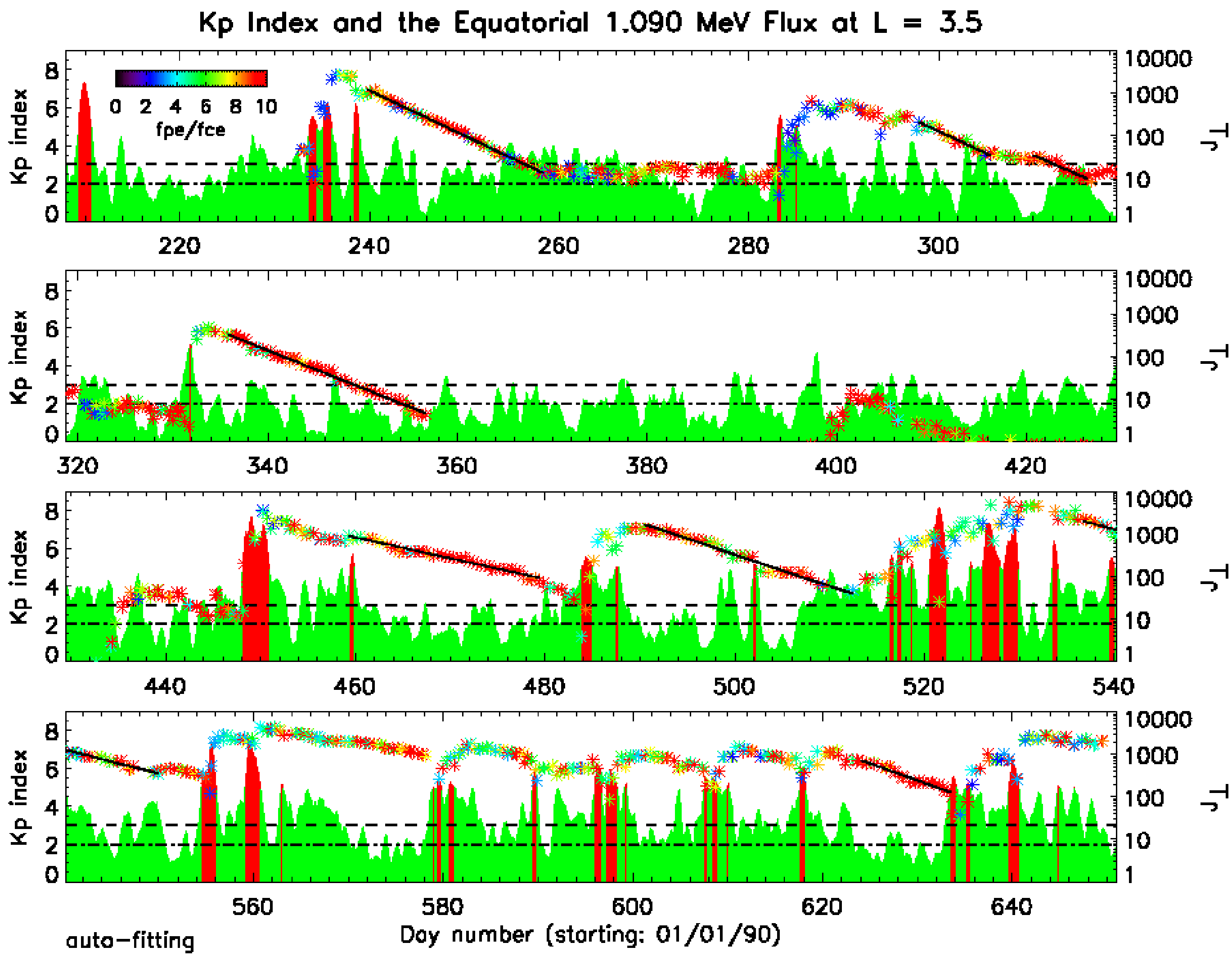


Losses due to Hiss and LGWs

- At L = 2.0, the effect of the additional wave power is to increase the diffusion rates in the deep minimum.
- The distribution now evolves more quickly to an equilibrium state and decays with a lifetime of 34 days.
- Hiss and LGWs can explain the observed lifetime at the inner edge of the slot

Meredith *et al*., JGR, 2009

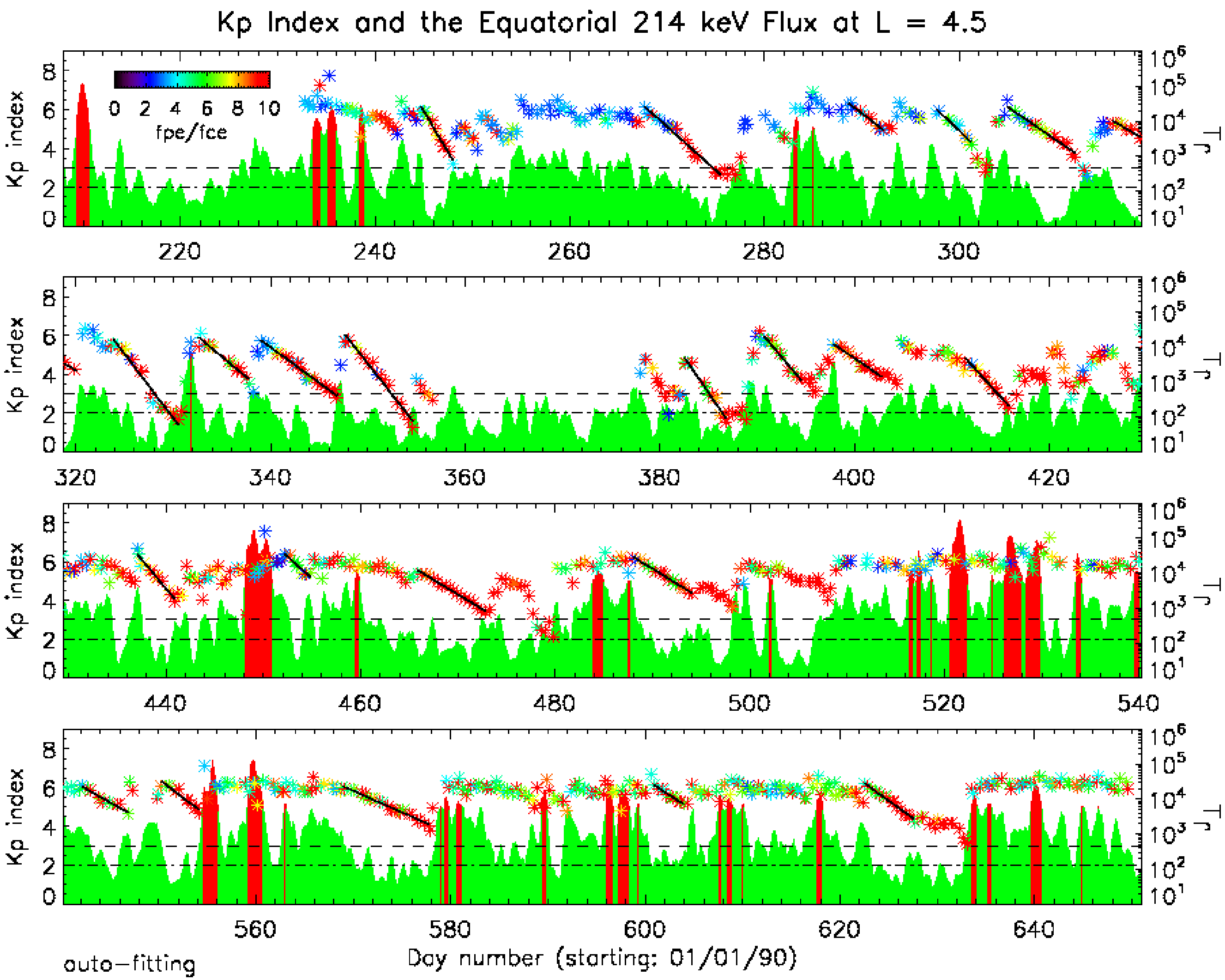
Quiet-time Decay in the Outer Radiation Belt



Experimental loss timescale is 5.7±0.6 days

Meredith *et al*., JGR, 2006

Quiet-time Decay in the Outer Radiation Belt



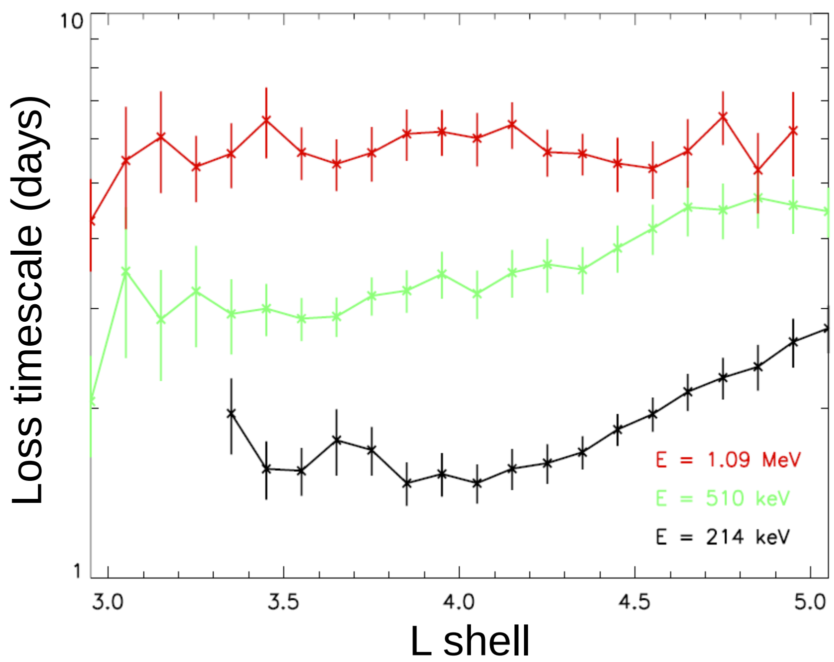
Experimental loss timescale is 2.0±0.1 days

Meredith *et al*., JGR, 2006

Quiet Time Loss Timescales

- Quiet time loss timescales in the outer radiation belt increase with increasing energy.
- Loss timescales range from
  - 1.5 – 3.5 days for 214 keV electrons
  - 5.5 – 6.5 days for 1.09 MeV electrons

Loss Timescale versus L shell



Meredith *et al*., JGR, 2006

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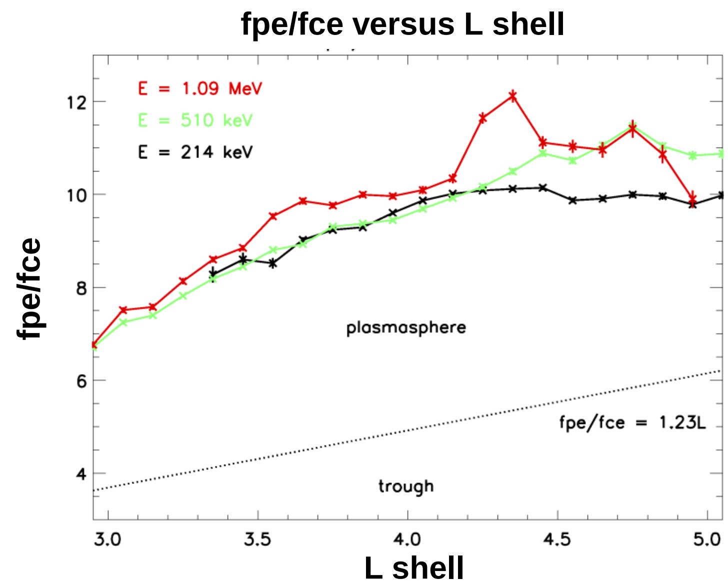
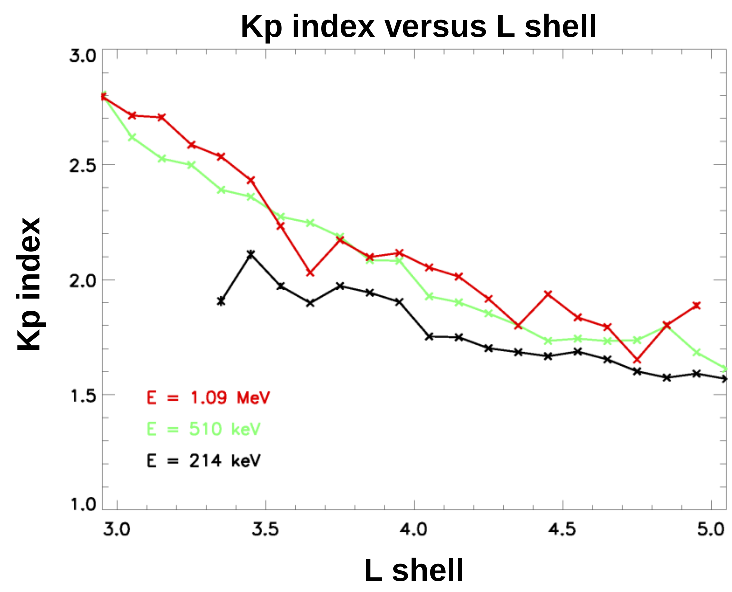
Quiet Time Loss Timescales

- Quiet-time decay associated with:
  - Large values of fpe/fce (> 7)
  - $\langle Kp \rangle < 3^{-}$





Meredith *et al*., JGR, 2006

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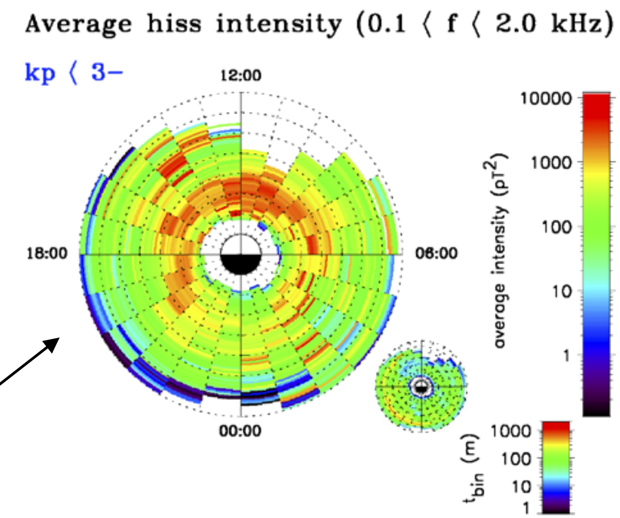
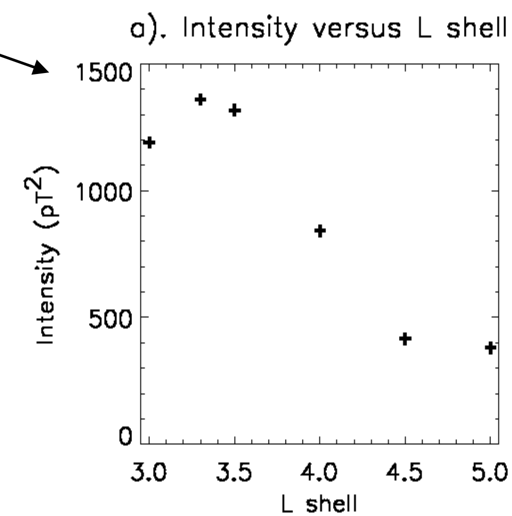
Calculation of Quiet Time Losses Due To Hiss

- Use the PADIE code and the 1D pitch angle diffusion equation.
- Use a wave model based on CRRES observations for $Kp < 3^-$.

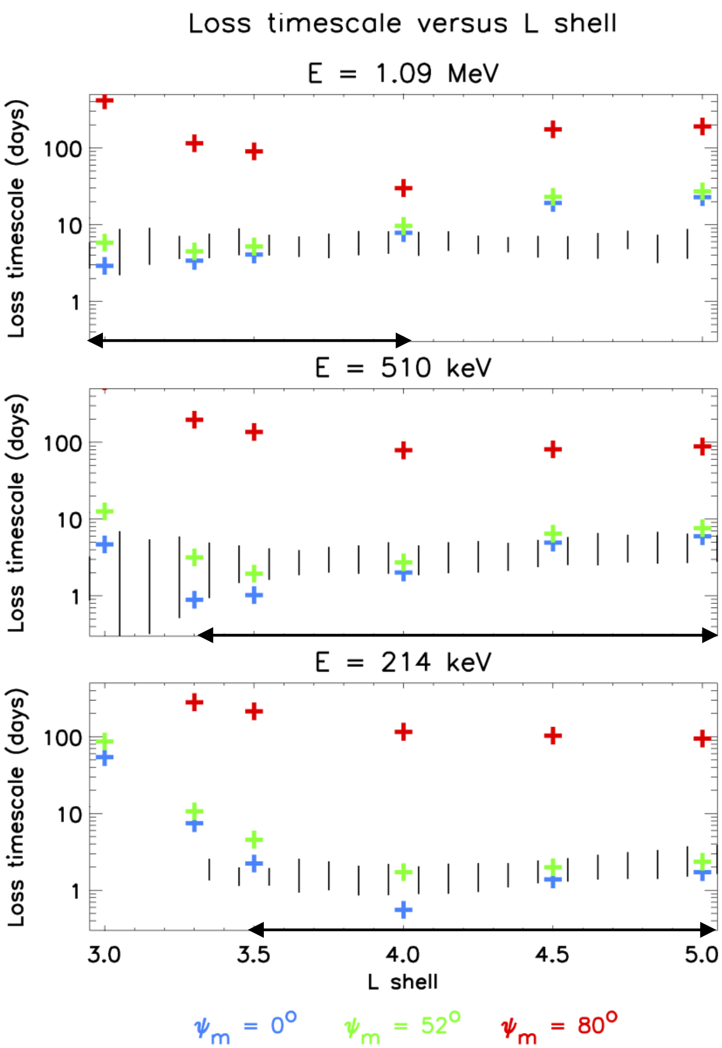




Meredith *et al*., JGR, 2006

Comparison with QL Diffusion due to Hiss

- Plasmaspheric hiss propagating at small and/or medium wave normal angles can explain much of the observed quiet time decay.
- Plasmaspheric hiss propagating at large wave normal angles does not contribute to the loss rates



Meredith *et al*., JGR, 2006

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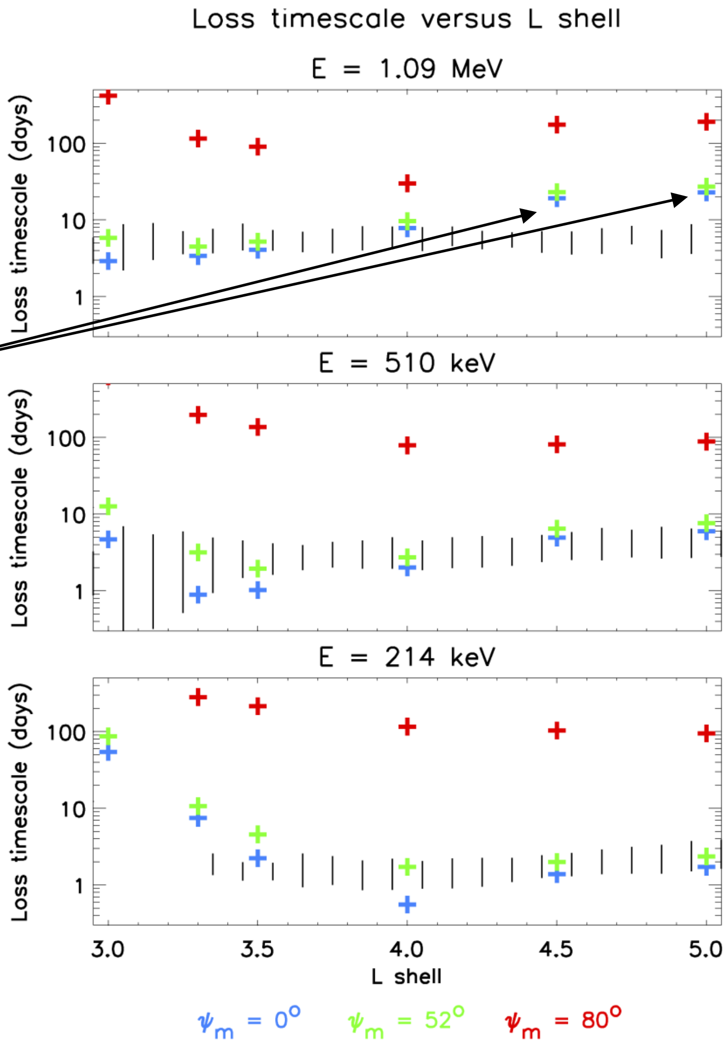
Comparison with QL Diffusion due to Hiss

- MeV loss timescales overestimated by a factor of 5 in region 4.5 < L < 5.0.

- EMIC waves may play a role in this region.



Meredith *et al*., JGR, 2006

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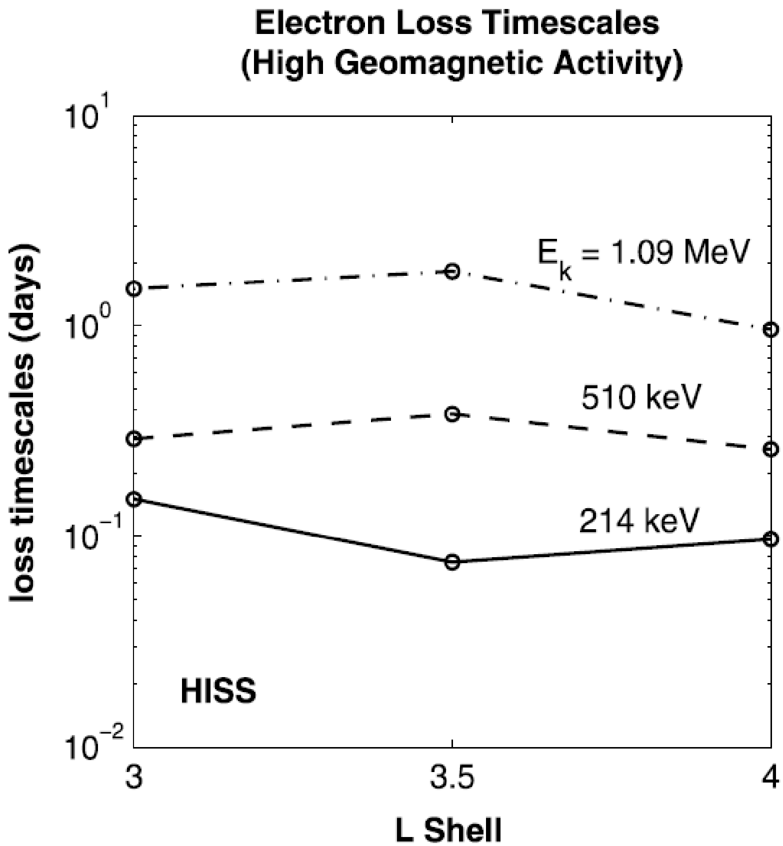
Loss Timescales During Active Conditions

- During active conditions loss timescales can be of the order of a day or less in the region 3.0 < L < 4.0
- Plasmaspheric hiss could thus play an important role in the loss of energetic electrons in the inner region of the outer radiation belt during enhanced magnetic activity.



Summers *et al*., JGR, 2007

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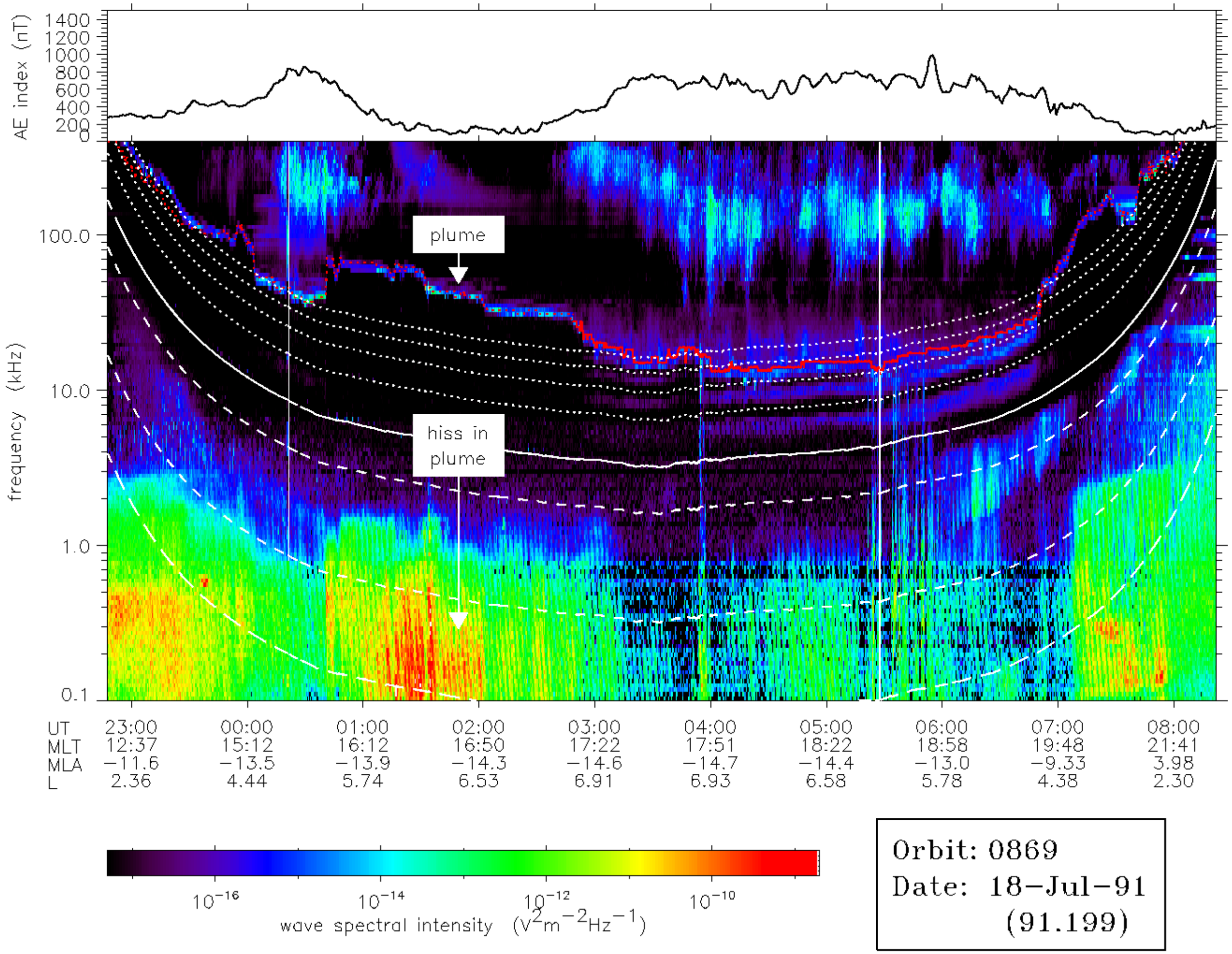
Hiss in Plasmaspheric Plumes

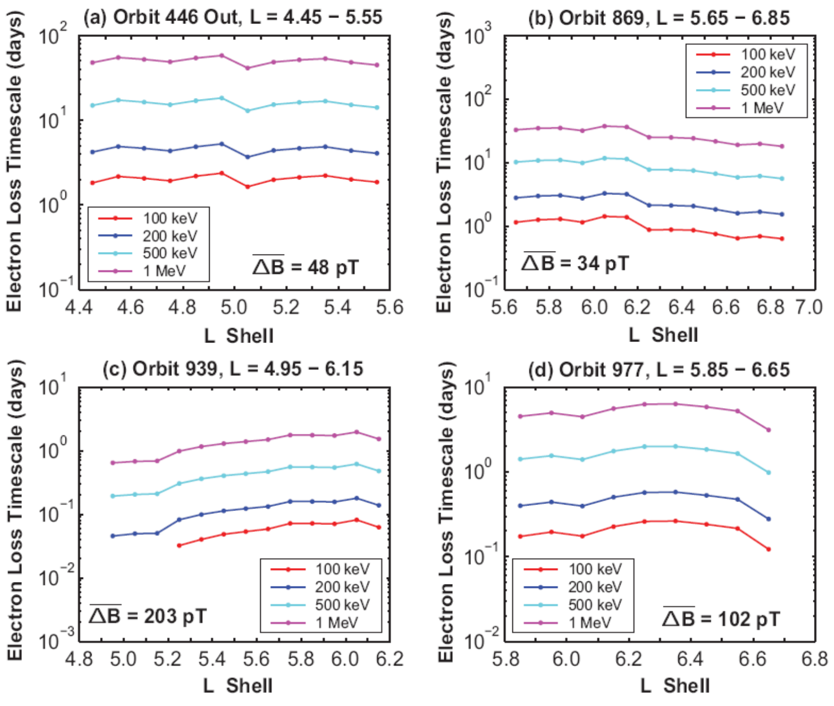


- Plasmaspheric hiss is also observed in plasmaspheric plumes

Summers *et al*., JGR, 2008

Loss Timescales in Plasmaspheric Plumes

- Loss timescales estimated to be:
  - days to tens of days at 1 MeV
  - hours to a day at 100 keV
- Hiss in plumes can efficiently scatter energetic electrons.



Summers *et al.*, JGR, 2008

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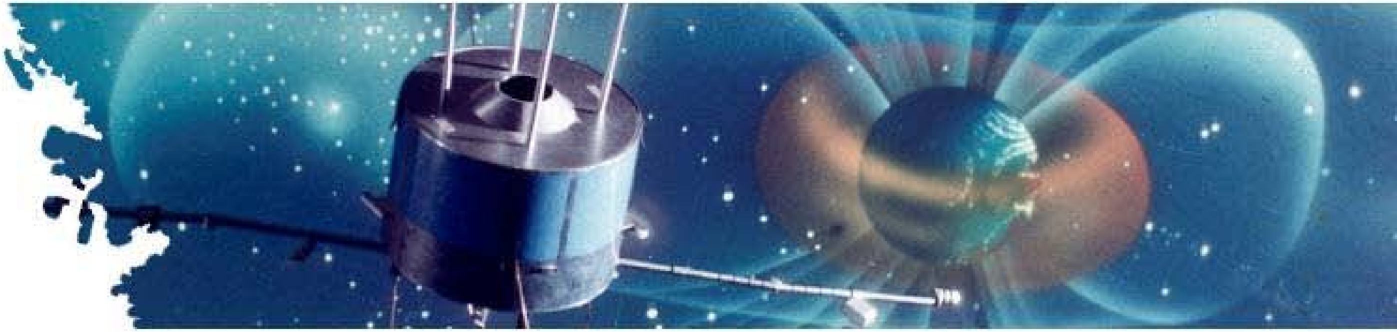
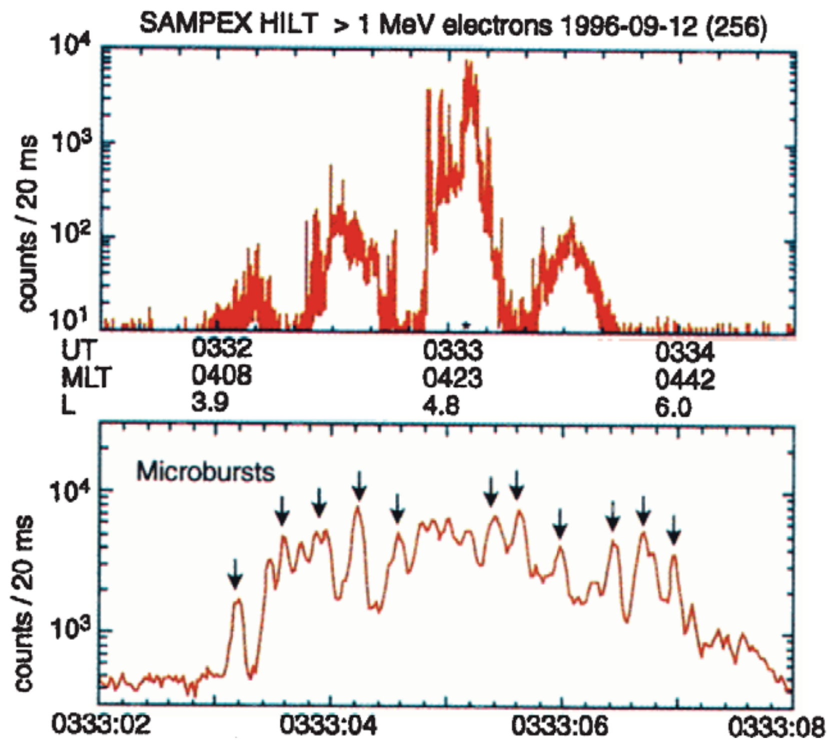


Role of Plasmaspheric Hiss

- **Plasmaspheric hiss** plays an important role in the formation of the slot region, the quiet time decay of the outer radiation belt and in electron loss during geomagnetic storms

Losses due to Chorus

- Relativistic electrons near the loss cone can also resonate with chorus at high geomagnetic latitudes.
- Bursty nature of chorus leads to < 1 second intensifications of precipitation known as microbursts.



Lorentzen *et al*., JGR, 2001

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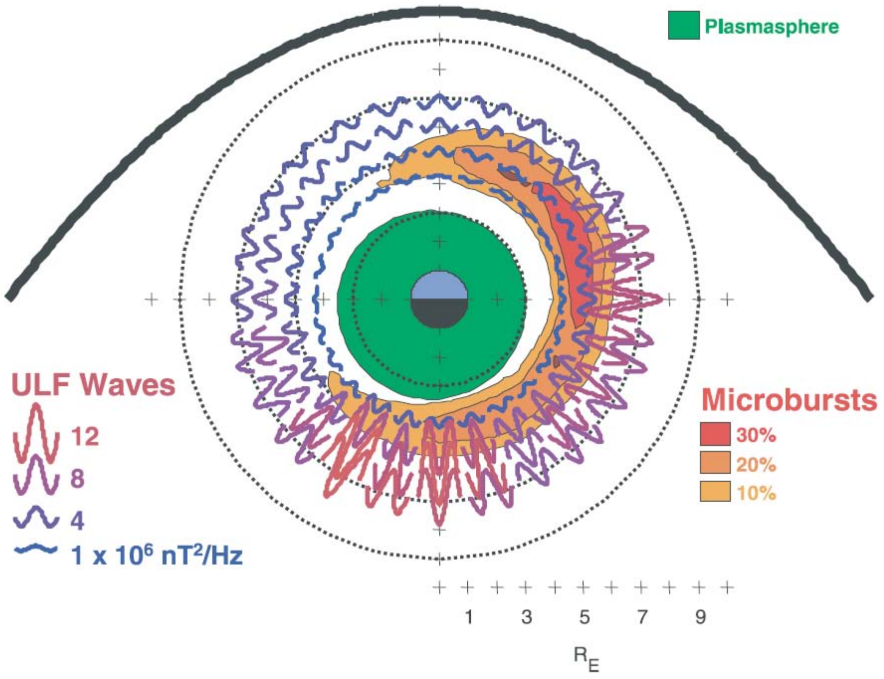
Microburst Precipitation

- Microburst precipitation observed by SAMPEX
  - outside the plasmapause
  - on the dawnside
  - near L = 5.
- Peak rates in the dawn to noon sector.
- Similar to the distribution of high latitude chorus waves.



O'Brien *et al*., JGR, 2003

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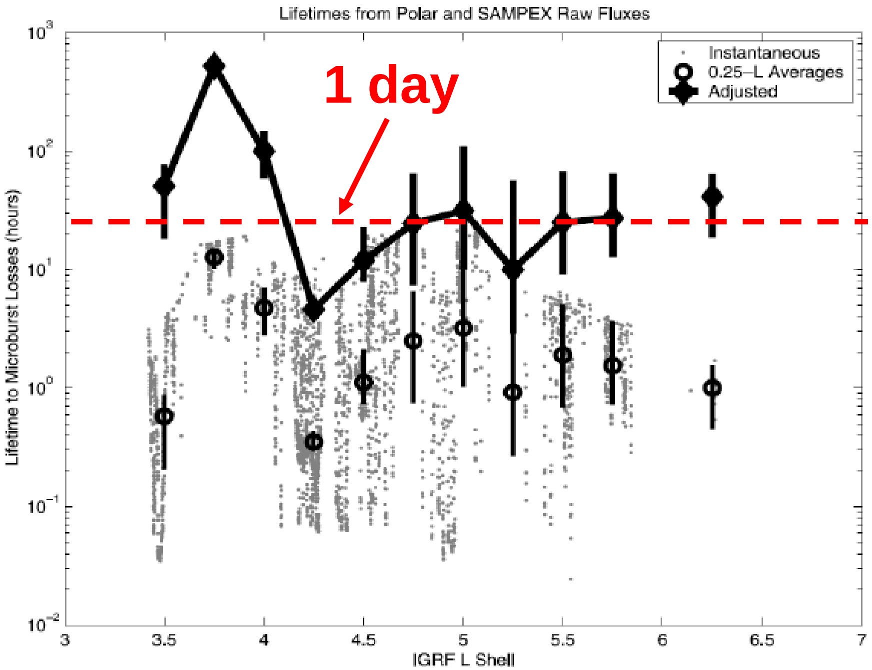
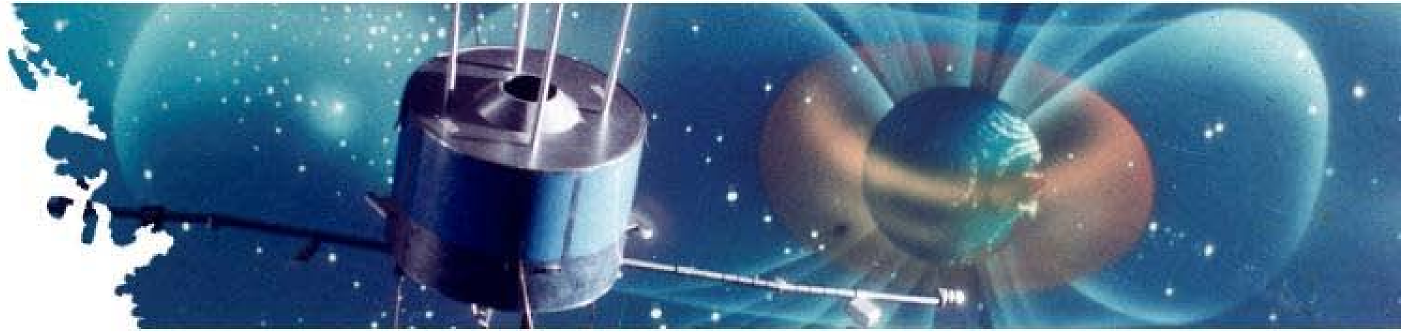
Microburst Loss Rates – Case Study

- Comparison between precipitating flux observed by SAMPEX and the trapped flux measured by Polar.
- Effective lifetimes are of the order of 1 day.



Thorne *et al*., JGR, 2005



Dual Role of Whistler-Mode Chorus

- W**histler mode chorus** plays a dual role in both the local acceleration and loss of radiation belt electrons.

EMIC Waves

- EMIC waves are low frequency waves (0.1-5 Hz) which are excited in bands below the proton gyrofrequency.
- They are generated by medium energy (1-100 keV) ring current ions injected during storms and substorms.
- They are able to resonate with MeV electrons causing pitch angle scattering and loss to the atmosphere.

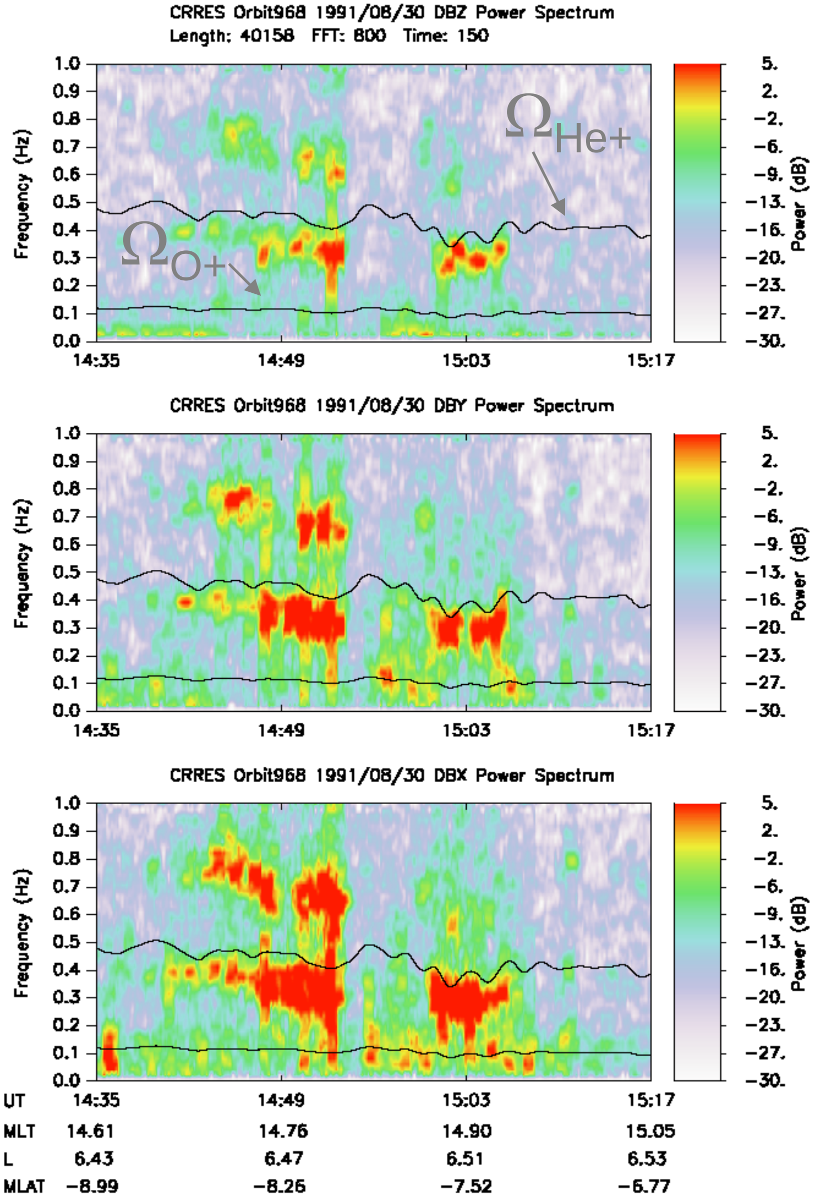


Figure courtesy of Brian Fraser

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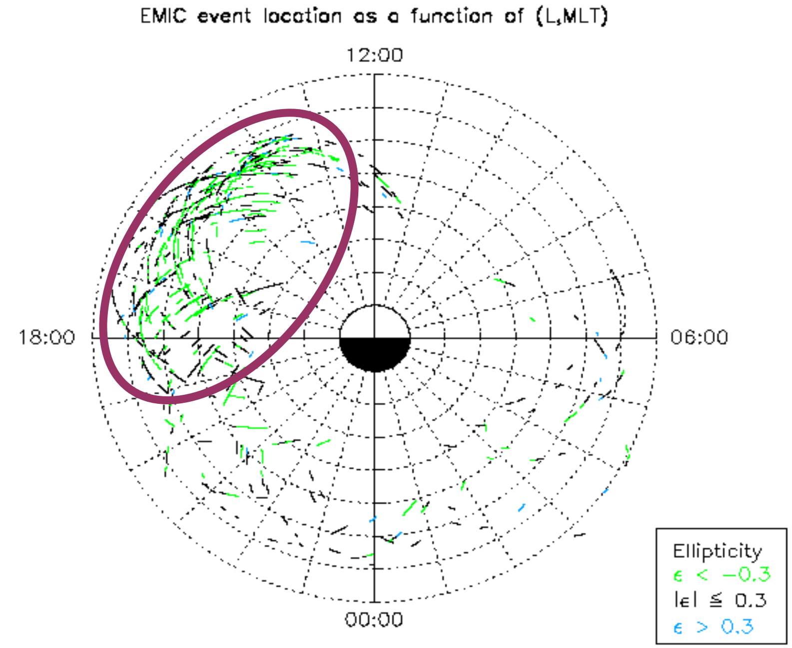
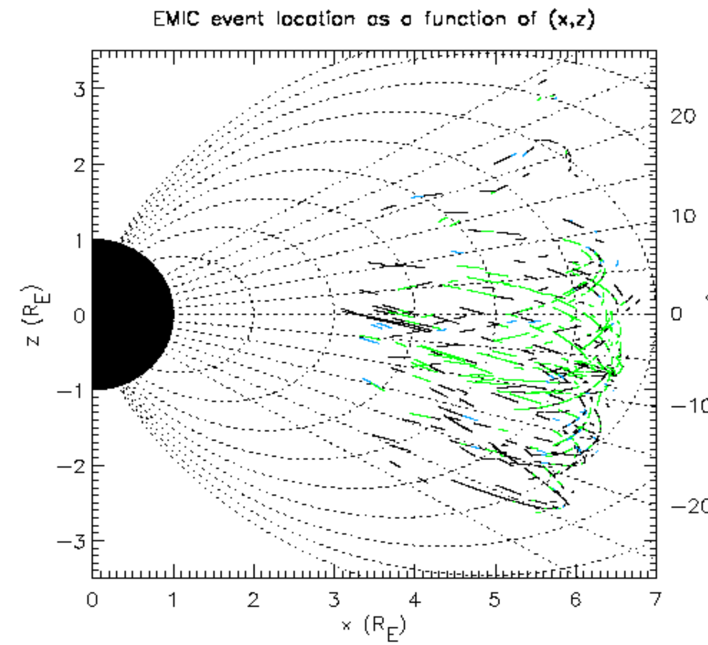
Location of Events

- EMIC waves are primarily observed between 13:00 and 19:00 MLT over a range of L shells > 3.





Meredith *et al*., JGR, 2003

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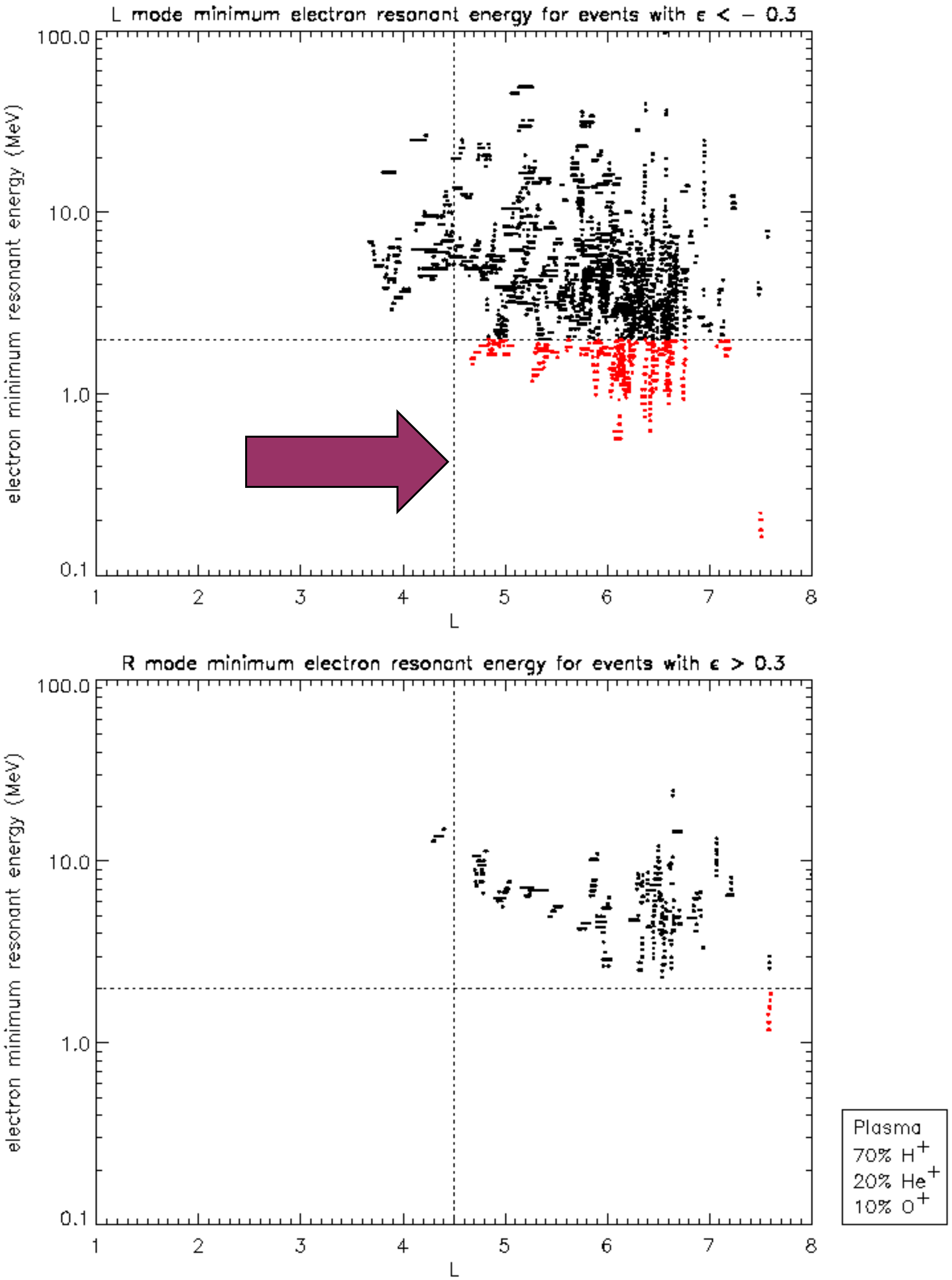
Spatial Distribution

- The L-mode minimum resonant energies fall below 2 MeV during ~12.5 % of the observations.
- These lower energy events occur outside L=4.5.
- The R-mode minimum resonant energies tend to be greater than 2 MeV.



Meredith *et al*., JGR, 2003

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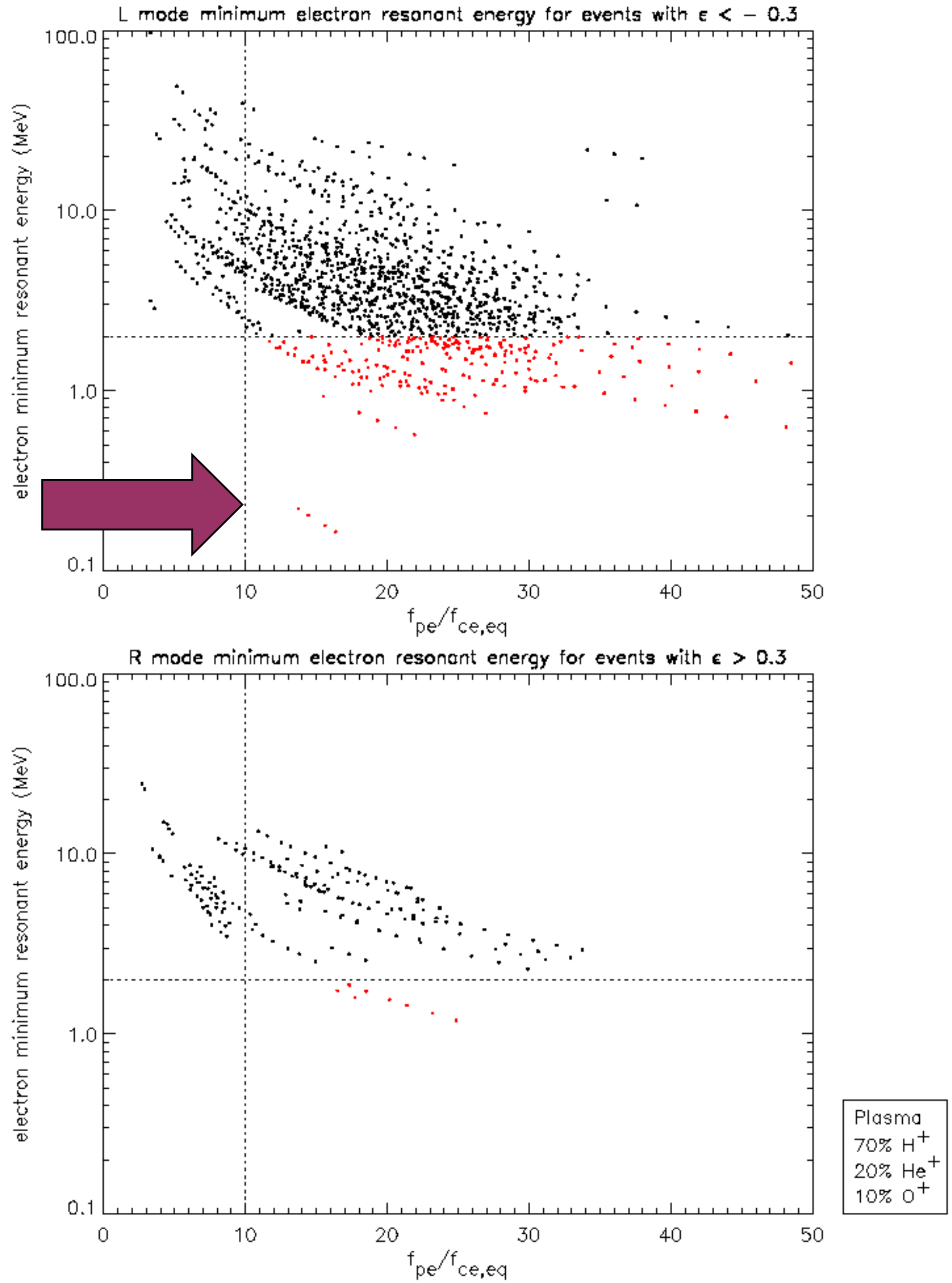
Dependence on fpe/fce

- The L-mode minimum resonant energies fall below 2 MeV in high density regions where fpe/fce > 10.
- Such conditions are found in regions of high plasma density and low magnetic field such as the dusk-side plasmasphere or plasmaspheric plumes.



Meredith *et al*., JGR, 2003

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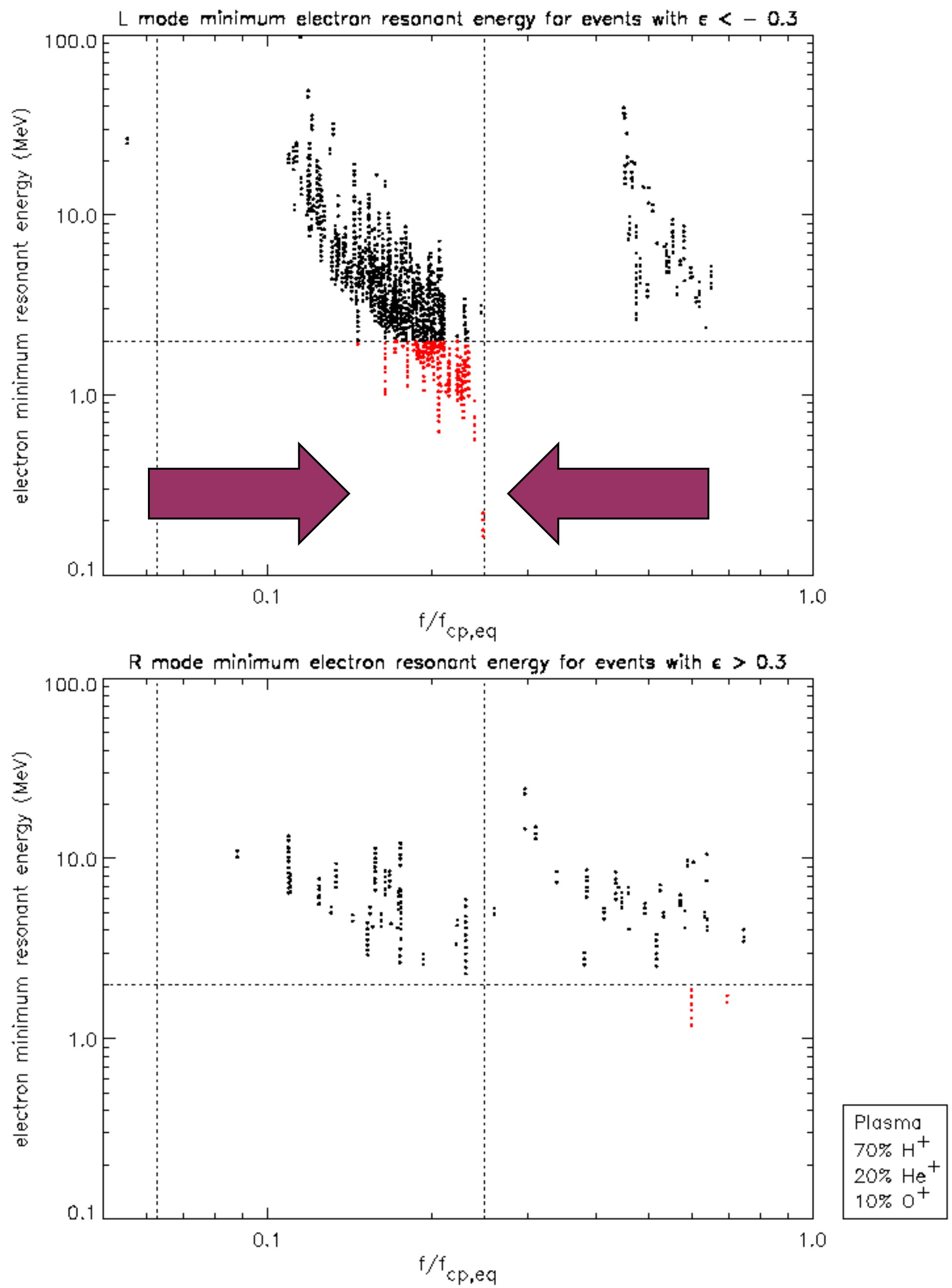
Dependence on Frequency

- The L-mode minimum resonant energies are sensitive to the normalised frequency.

- The lower energy events occur over a range of frequencies below the helium ion gyrofrequency.



Meredith *et al.*, JGR, 2003

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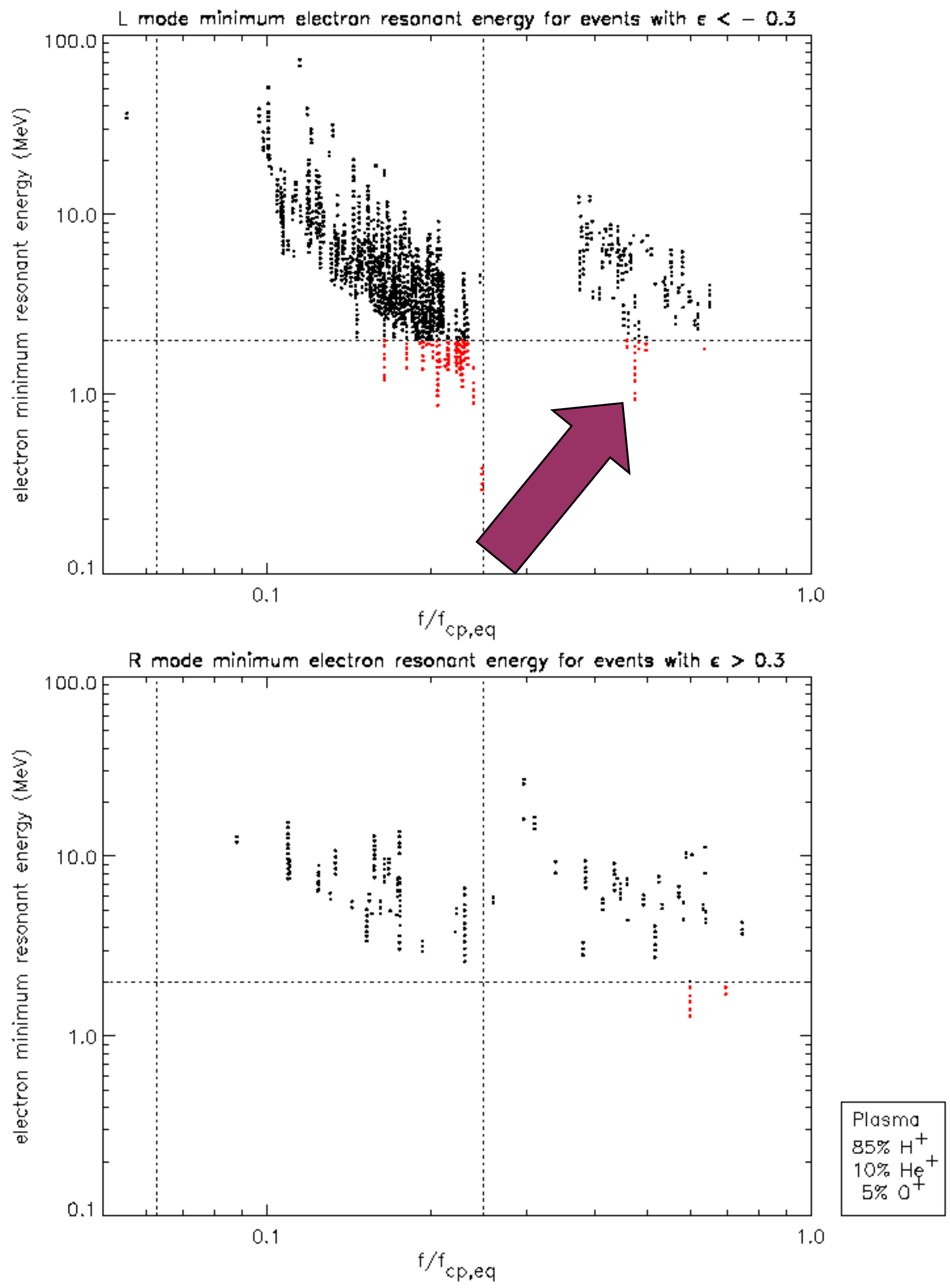
Dependence on Frequency

- For lower concentrations of heavy ions the lower energy events can also occur over a range of frequencies below the hydrogen ion gyrofrequency.



Meredith *et al*., JGR, 2003

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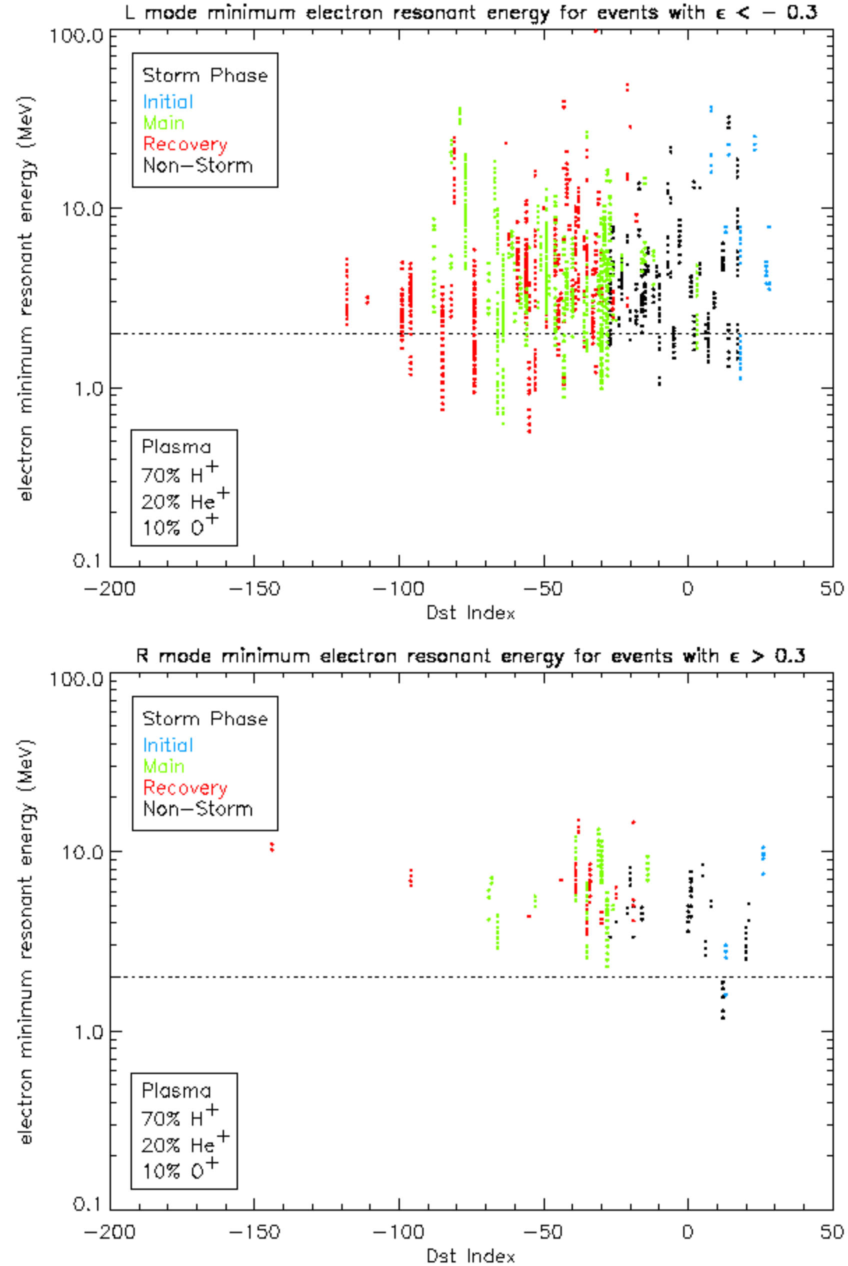
Dependence on Dst Index

- The L-mode electron minimum resonant energies may fall below 2 MeV for almost any value of the Dst index.



Meredith *et al*., JGR, 2003

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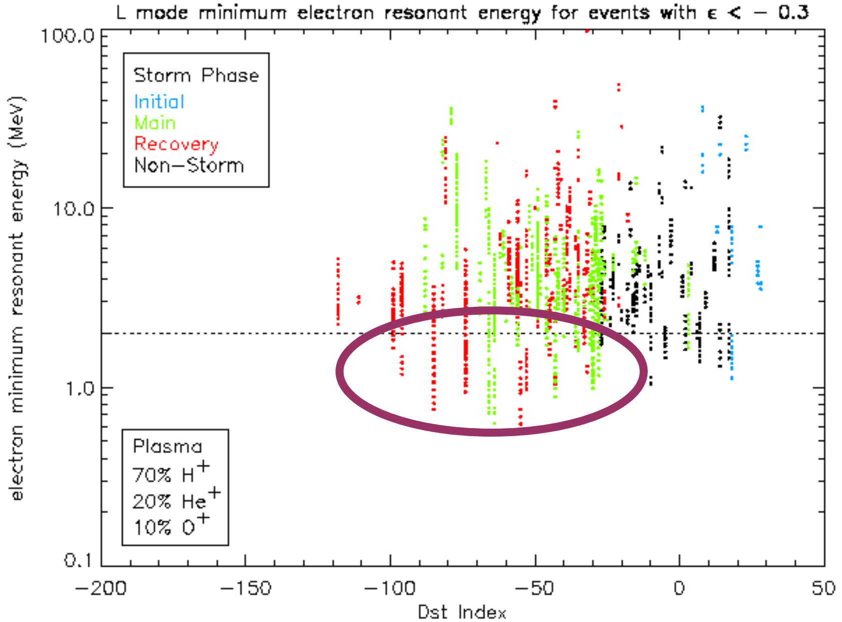
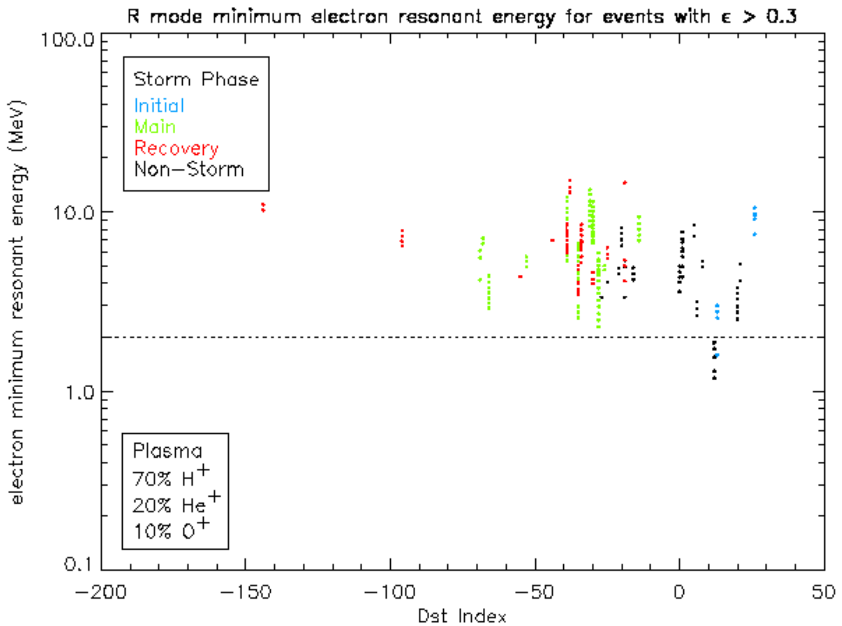
Dependence on Dst Index

- The L-mode electron minimum resonant energies may fall below 2 MeV for almost any value of the Dst index.
- The majority (84%) of the lower energy events occur during storms.
- The L-mode minimum electron resonant energies can fall below 2 MeV during the initial phase of a storm when the Dst index is positive.





Meredith *et al*., JGR, 2003

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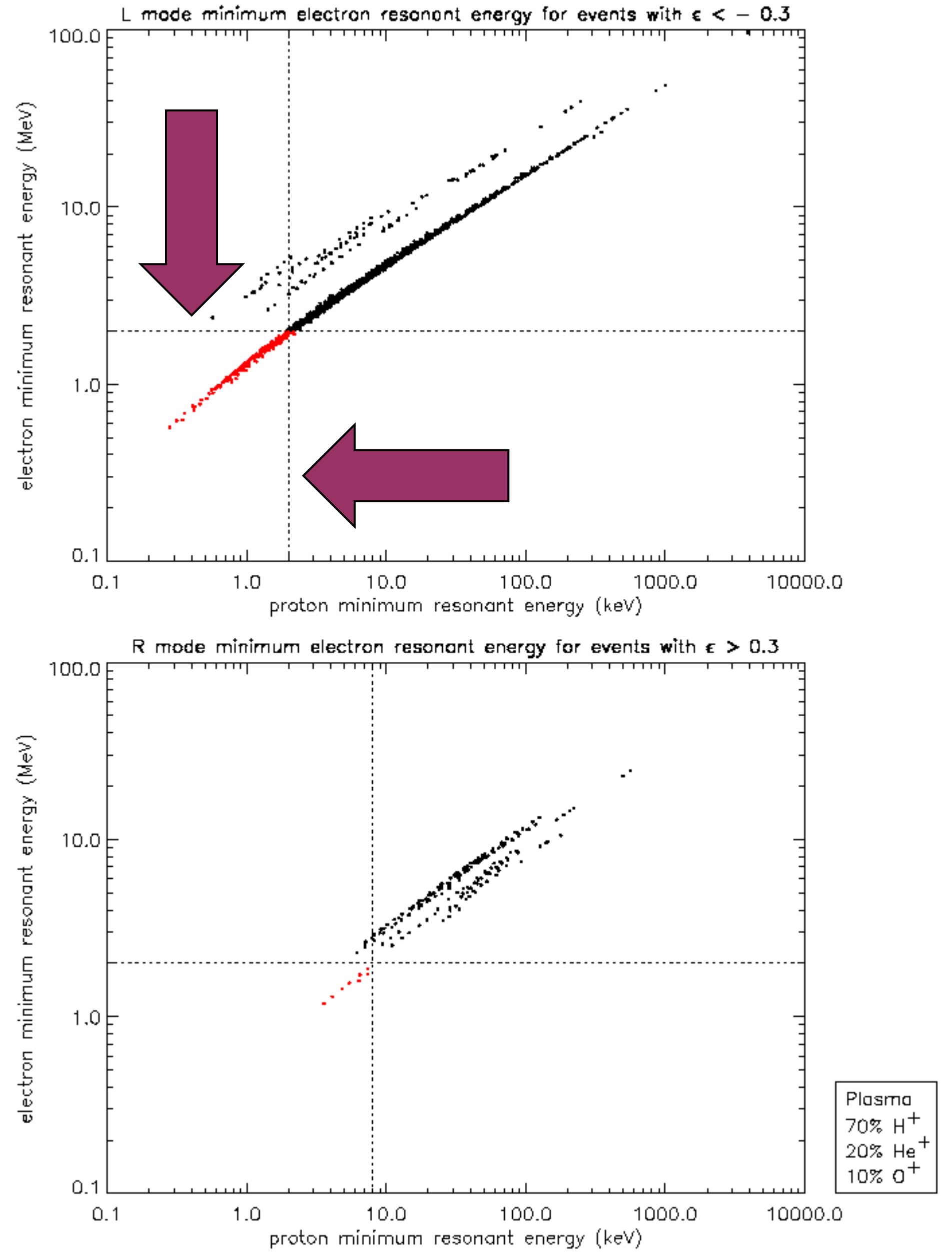
Proton Minimum Resonant Energies

- Electron minimum energies below 2 MeV are associated with proton minimum resonant energies below 2 keV.
- EMIC waves which resonate with ~MeV electrons are produced by ~keV protons.



Meredith *et al*., JGR, 2003

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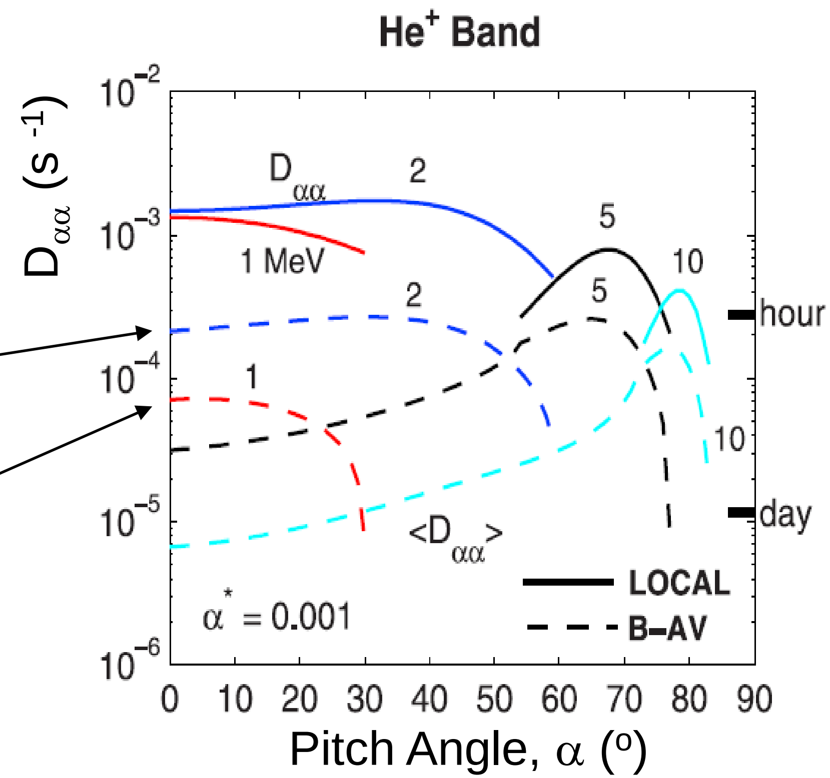
Scattering Rates in the Helium Band

- Loss timescale near equatorial loss cone:
  - ~1 hour for 2 MeV electrons.
  - several hours for 1 MeV electrons.



B_w = 1 nT
1% drift averaging

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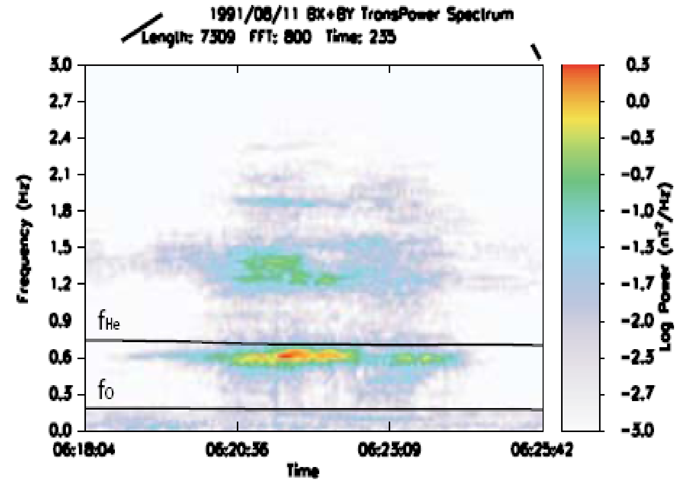
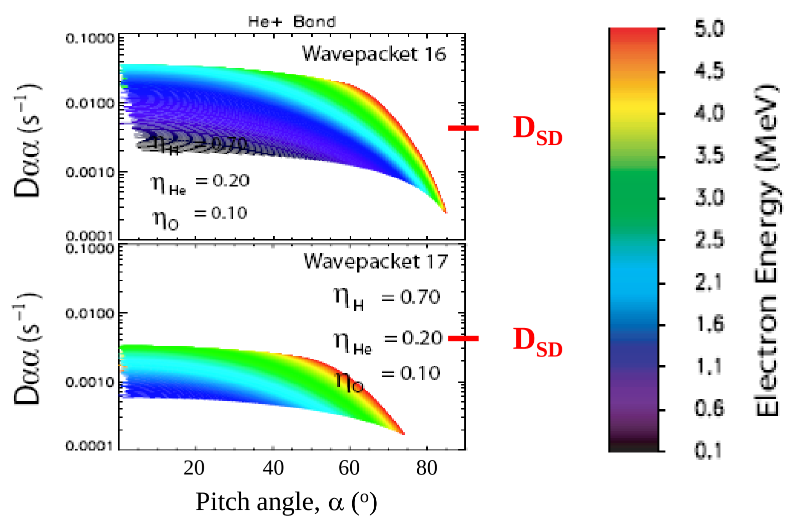
Summers *et al.*, JGR, 2007

Case Study – EMIC Wave Event

- Analysis of an EMIC wave event on CRRES at the start of the main phase of a storm show:
  - E_{min} falls in the 1-2 MeV range
  - $D_{\alpha\alpha}$ is comparable to SD limit
  - suggesting enhanced MeV precipitation.





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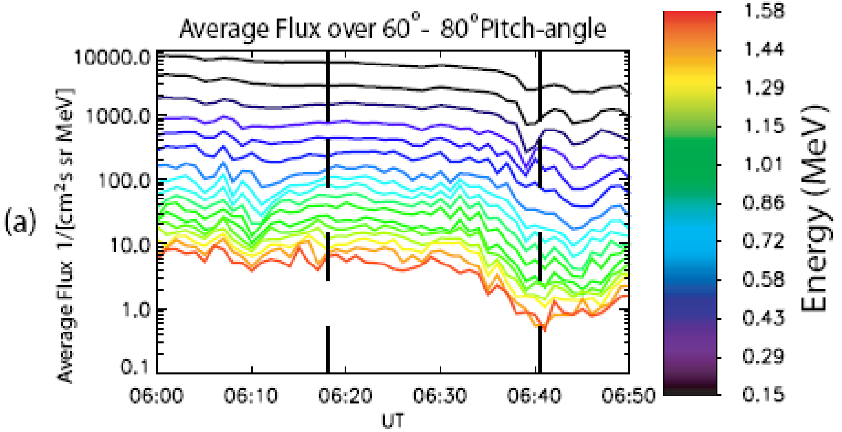
Loto'aniu *et al*., JGR, 2006

Case Study – EMIC Wave Event

- Relativistic electrons observed to drop by an order of magnitude during the event.
- Results consistent with the suggestion that EMIC waves may lead to substantial loss of relativistic electrons during the main phase of geomagnetic storms.



Loto'aniu *et al*., JGR, 2006

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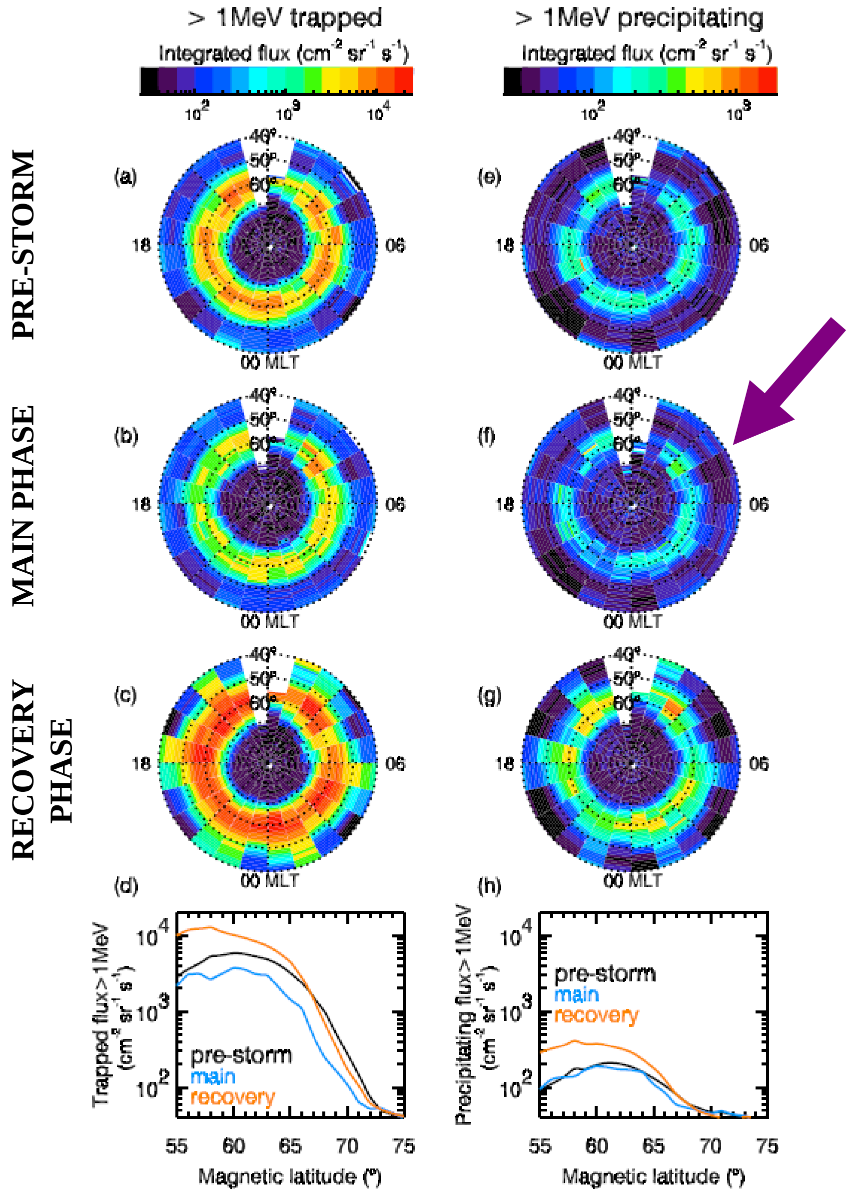
Do EMIC Waves Cause MeV Flux Dropouts ?

- No evidence for enhanced MeV precipitation during the main phase of CME driven storms in POES data.

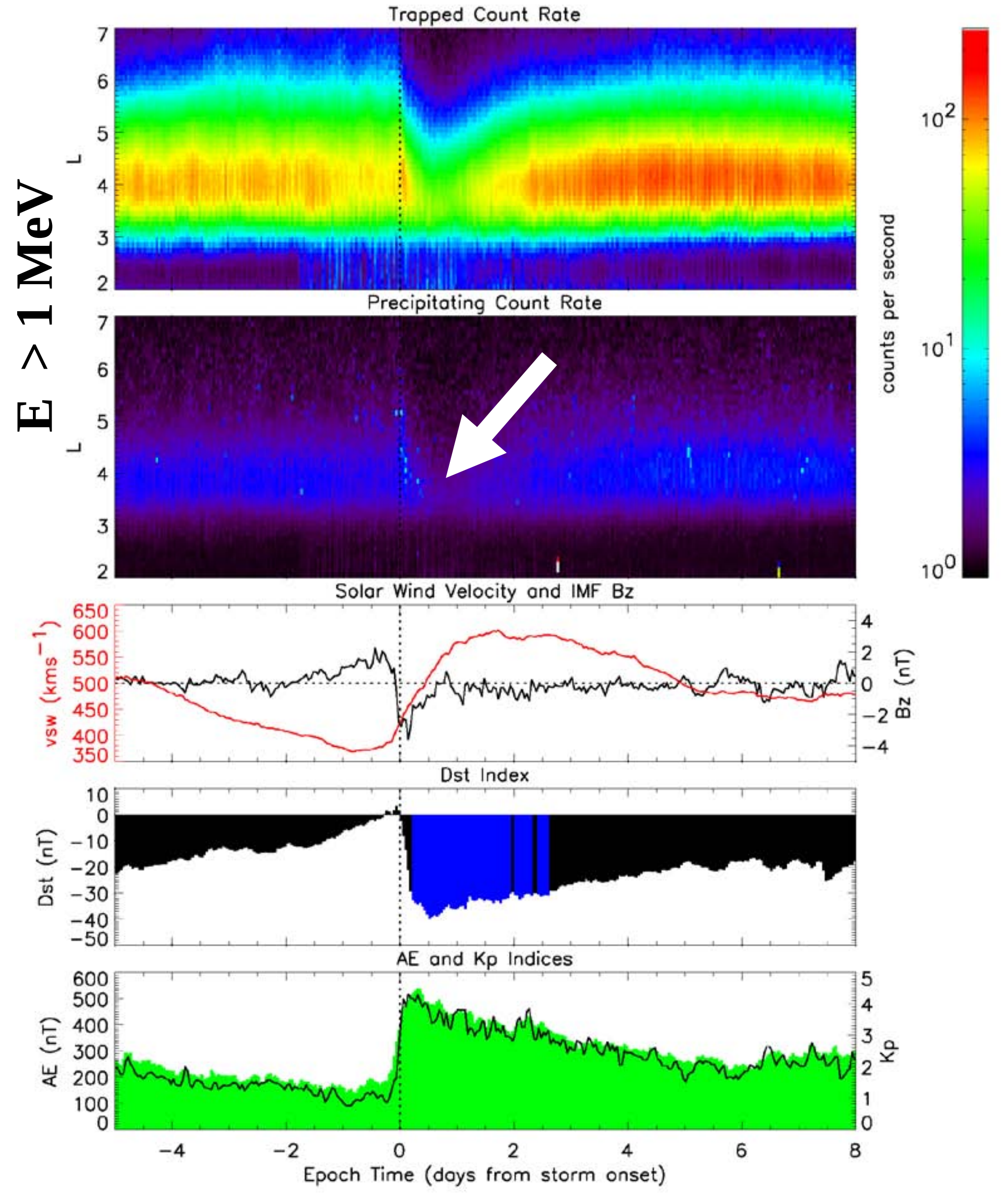


Horne *et al*., GRL, 2009

Do EMIC Waves Cause MeV Flux Dropouts ?

- No evidence for enhanced MeV precipitation during the main phase of CME driven storms in POES data.

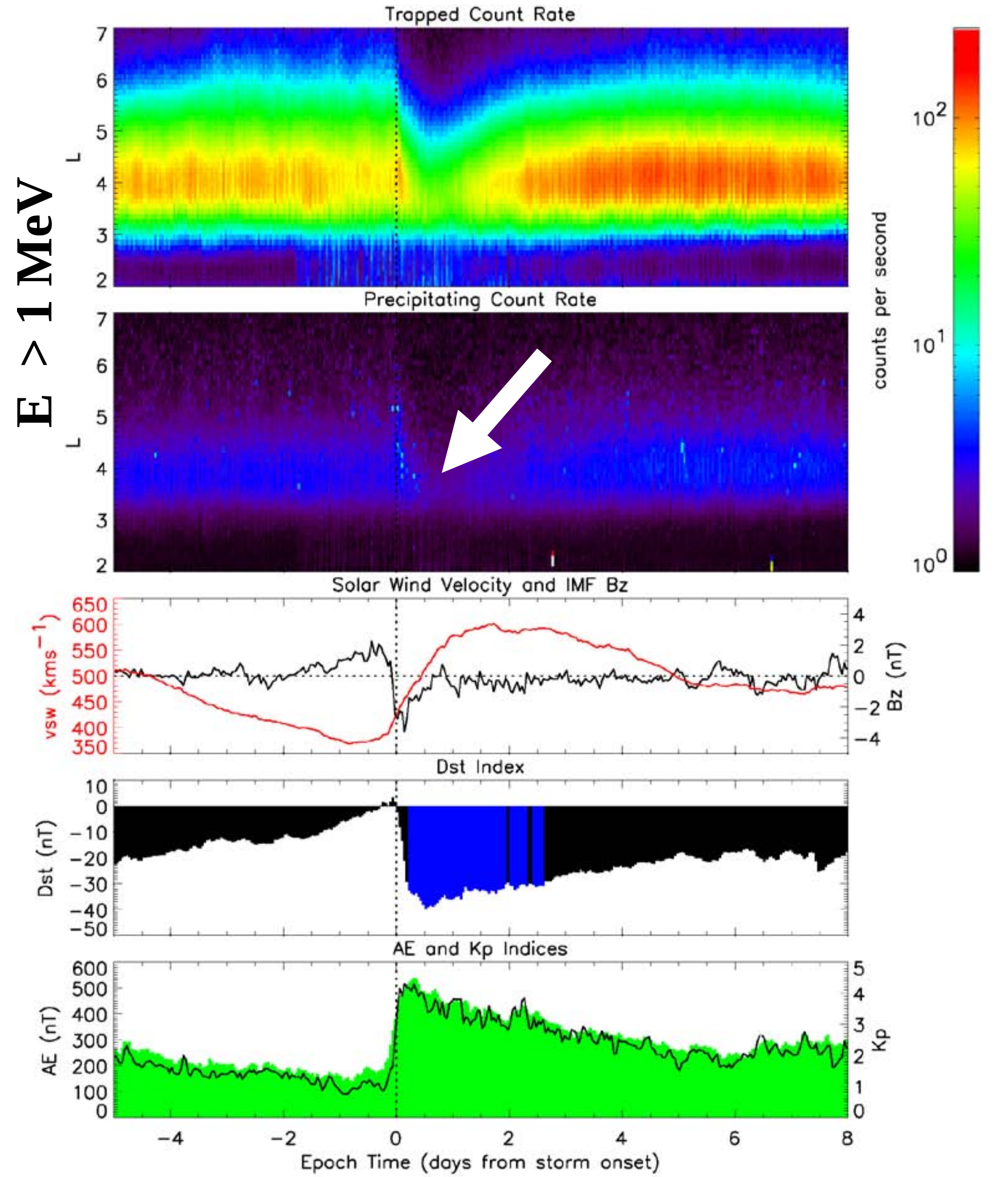
- No evidence for enhanced count rates of precipitating electrons during the main phase of HSS-driven storms



Meredith *et al*., JGR, 2011

Do EMIC Waves Cause MeV Flux Dropouts ?

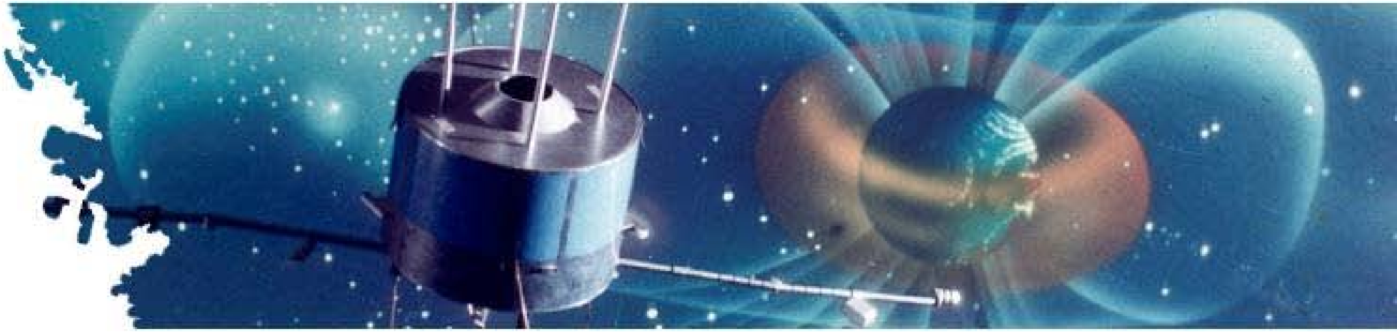
- No evidence for enhanced MeV precipitation during the main phase of CME driven storms in POES data.
- No evidence for enhanced count rates of precipitating electrons during the main phase of HSS-driven storms
- MeV flux drop outs during the main phase of geomagnetic storms not due to pitch angle scattering and subsequent loss to the atmosphere.



Meredith *et al.*, JGR, 2011

What causes MeV Flux Dropouts ?

- Other processes may be more important, including:
  - adiabatic changes associated with the decrease in Dst
  - outward radial diffusion and loss to the magnetopause
  - non-linear decreases in energy



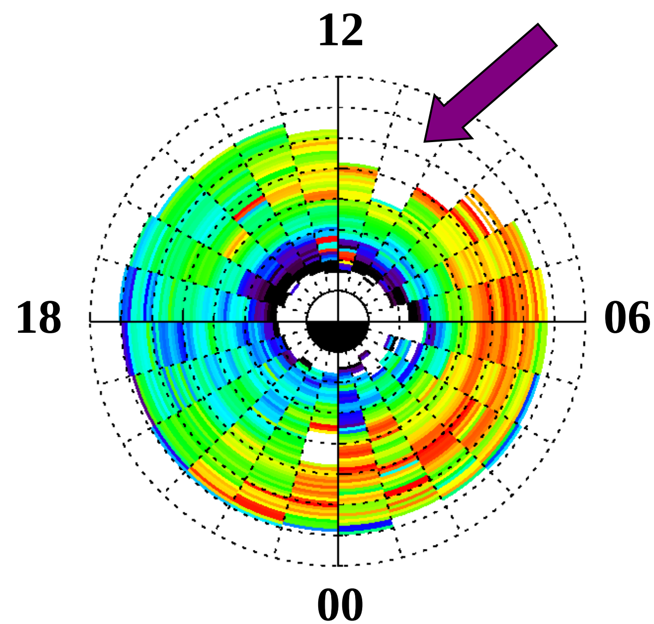
Role of EMIC Waves

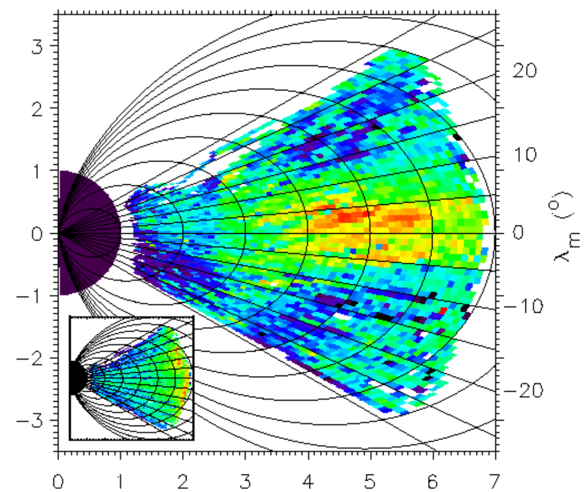
- **EMIC waves** contribute to electron loss at MeV energies but are not responsible for MeV flux dropouts.

- More information on the global distribution and spectral properties of the waves required for an accurate assessment of their role in radiation belt dynamics.

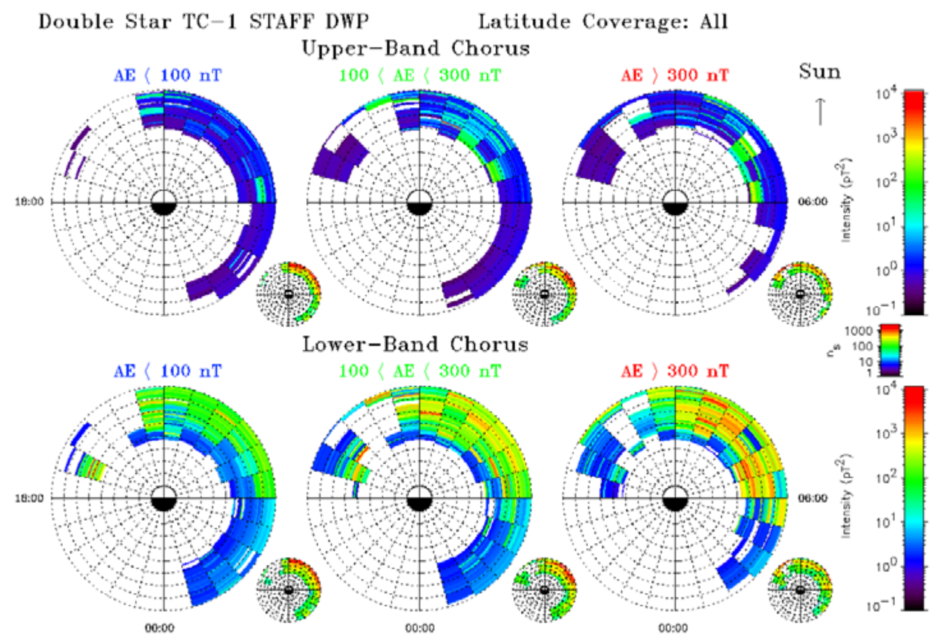
Limitations of the CRRES Wave Models

- Wave models derived from CRRES observations have a number of limitations:
  - limited coverage in L, particularly on the dayside
  - no coverage beyond $\lambda_m = 30^o$
  - no wave B field measurements from the PWE
  - no information on wave normal angle distribution
  - only ~14 months coverage around solar maximum





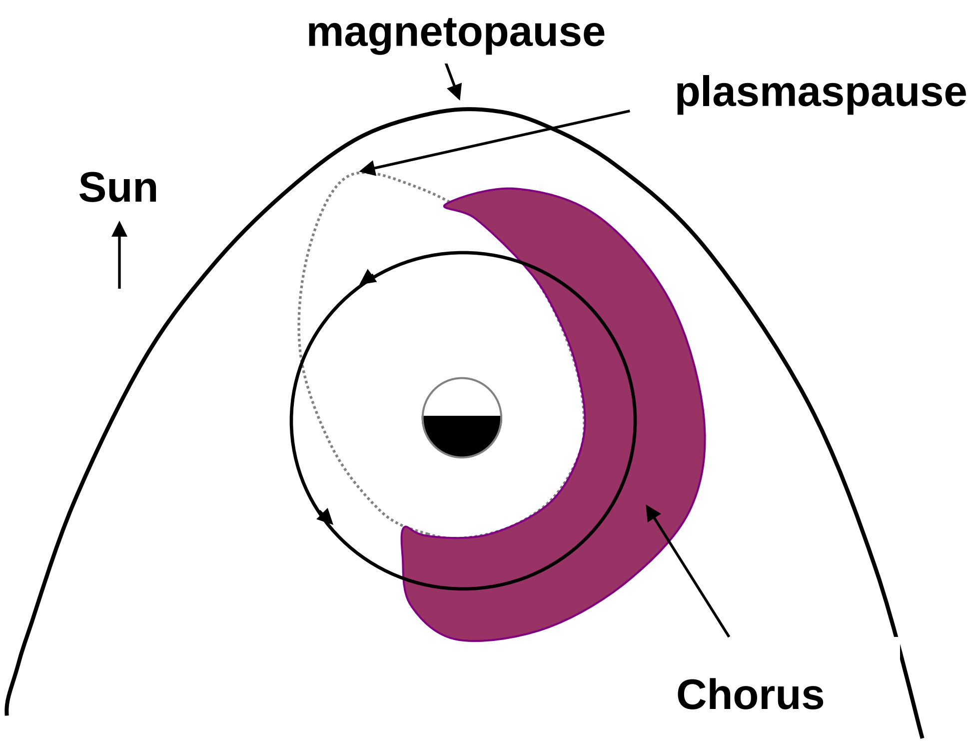
- Spacecast is a new EU FP7 project to model and forecast high energy particle radiation.
- For this project we are developing improved plasma wave models by combining CRRES plasma wave data with data from other satellites to improve the statistics and fill in gaps in the CRRES coverage.
- First 6 months of Double Star data fills in a gap in CRRES coverage on the day-side.



COOPERATION

Conclusions

• ***Chorus waves*** are an important acceleration and loss mechanism for radiation belt electrons.



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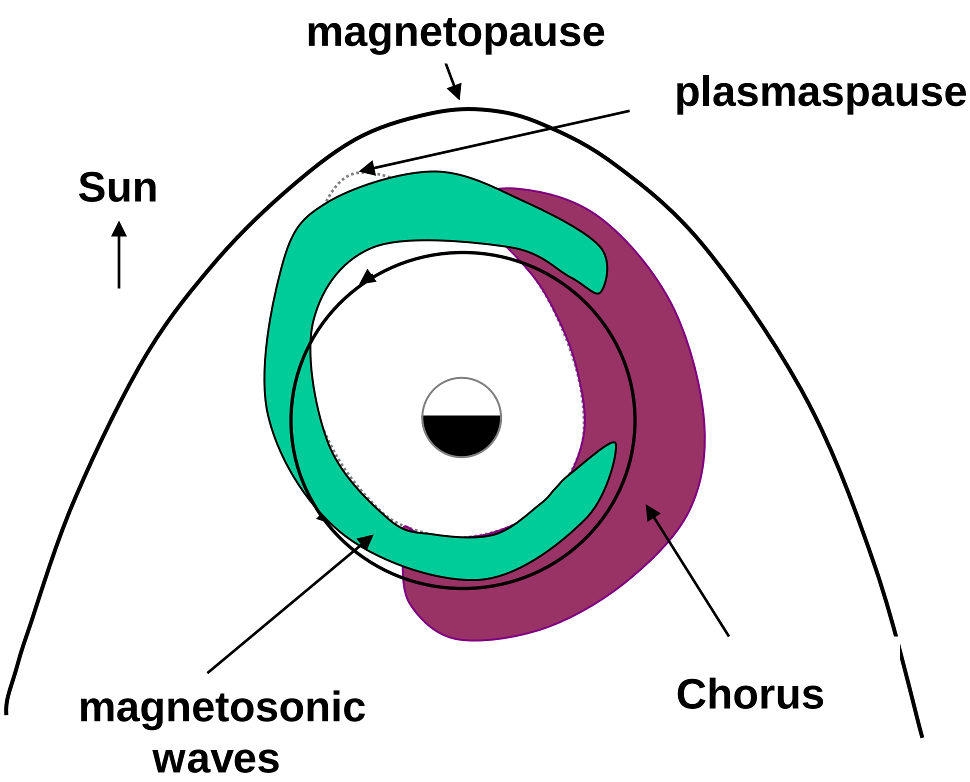
Conclusions

• ***Chorus waves*** are an important acceleration and loss mechanism for radiation belt electrons.

• ***Magnetosonic waves*** may be an important acceleration mechanism.



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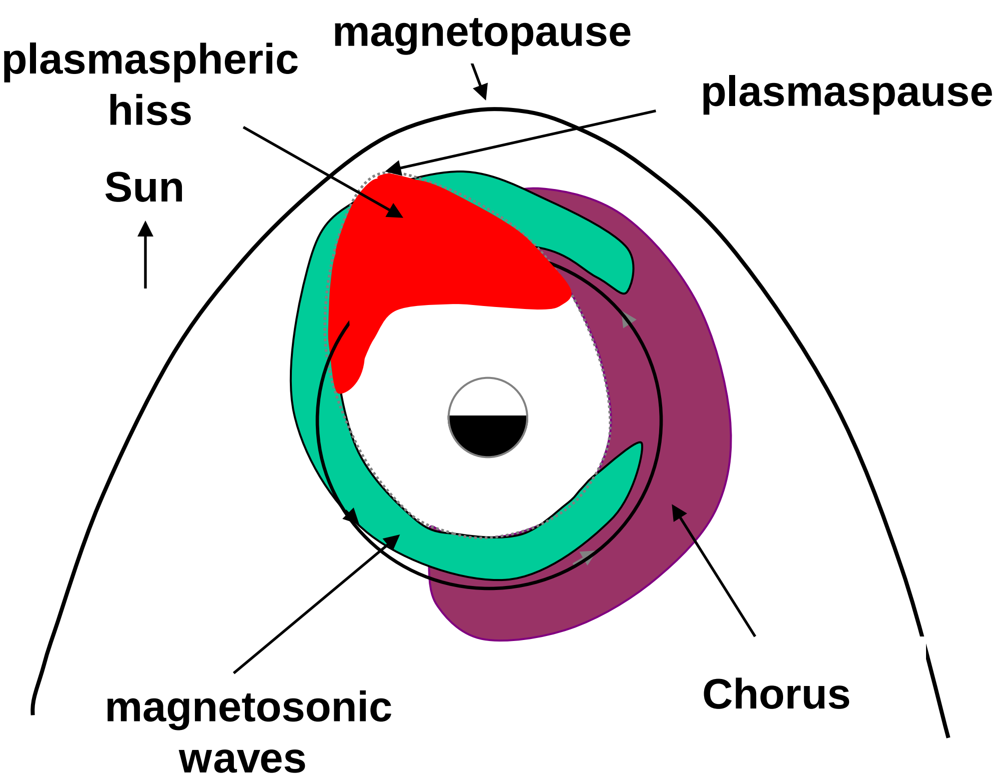
Conclusions

• ***Chorus waves*** are an important acceleration and loss mechanism for radiation belt electrons.

• ***Magnetosonic waves*** may be an important acceleration mechanism.

• ***Plasmaspheric hiss*** is a major loss process for radiation belt electrons



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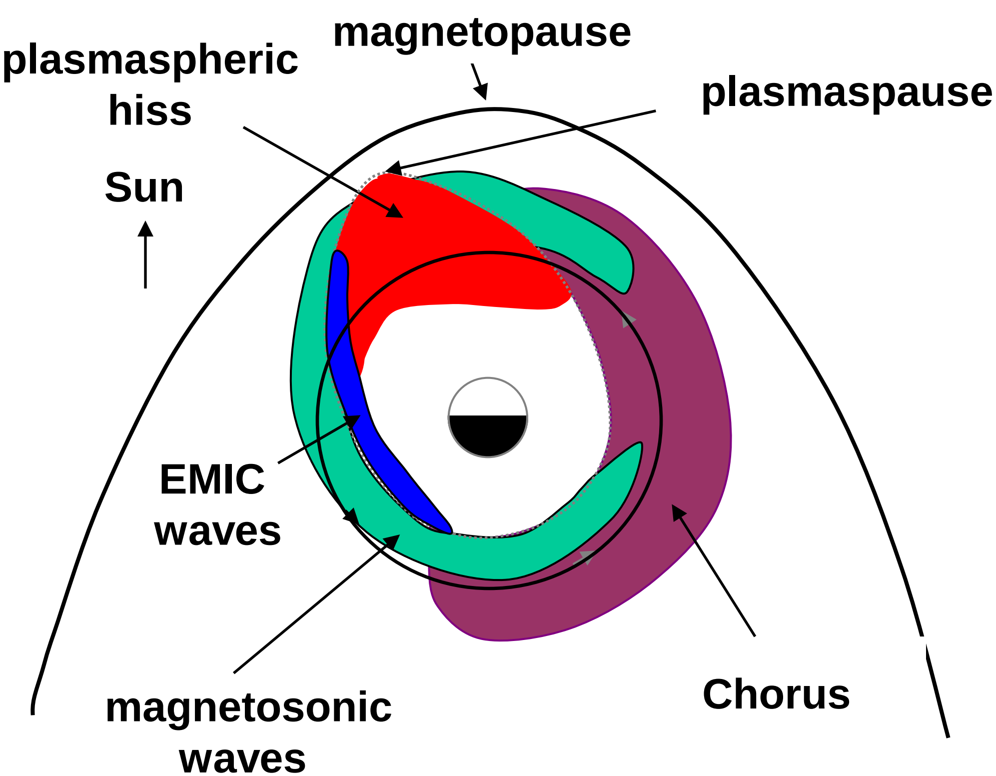
Conclusions

• ***Chorus waves*** are an important acceleration and loss mechanism for radiation belt electrons.

• ***Magnetosonic waves*** may be an important acceleration mechanism.

• ***Plasmaspheric hiss*** is a major loss process for radiation belt electrons

• ***EMIC waves*** may be an important loss mechanism for electrons with energies > ~ 1 MeV



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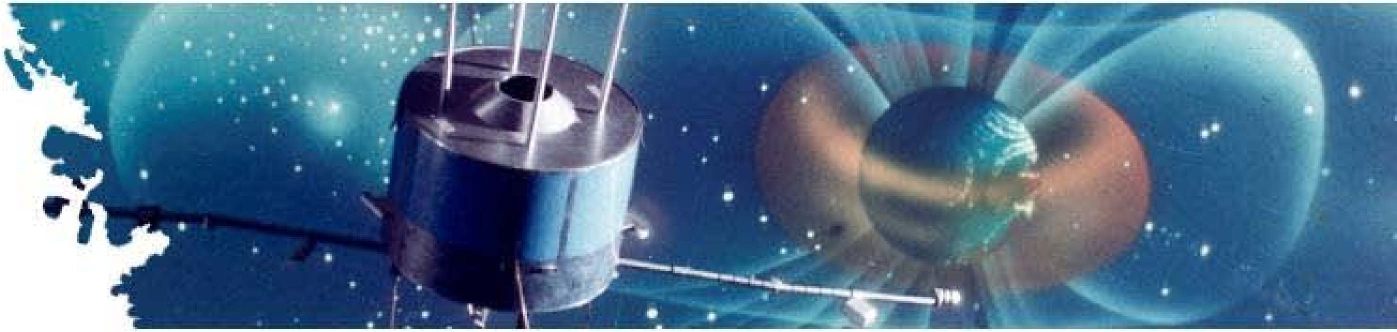
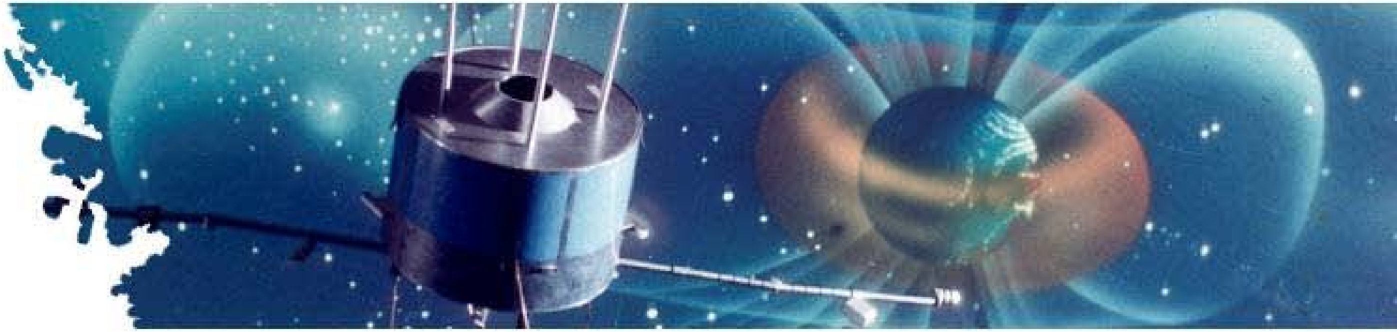


Key Science Questions

1. ***What are the relative roles of the following processes in the acceleration of outer radiation belt electrons ?***

   – ***Inward radial diffusion***

   – ***Local acceleration by:***
     - ***whistler mode chorus***
     - ***magnetosonic waves***
     - ***Z mode waves***

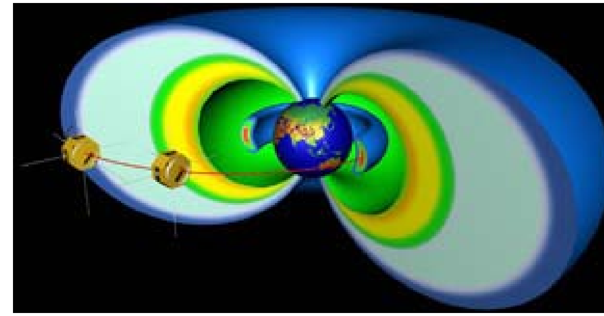


Key Science Questions

2. What are the relative roles of the following processes affecting the loss of outer radiation belt electrons ?

- *Outward radial diffusion and loss to the magnetopause*
- *Losses due to gyroresonant wave particle interactions with:*
  - *EMIC waves*
  - *plasmaspheric hiss*
  - *whistler mode chorus*

Future Satellite Missions



- These key questions will be addressed by ongoing studies using existing datasets and new satellite missions:
  - NASA Radiation Belt Storm Probes Mission (*proposed launch: 2012*)
  - Canadian ORBITALS Mission (*proposed launch: 2012-?)*
  - Japanese ERG Mission (*proposed launch:* 2013)