Local Acceleration and Loss of Relativistic Electrons in the Earth's Outer Radiation Belt

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British Antarctic Survey

Jim Dungey Celebration
Burlington House, London
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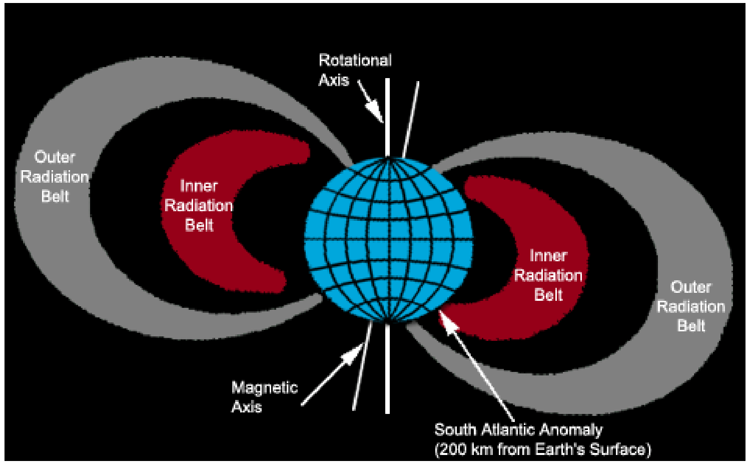
Earth's Radiation Belts

- 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



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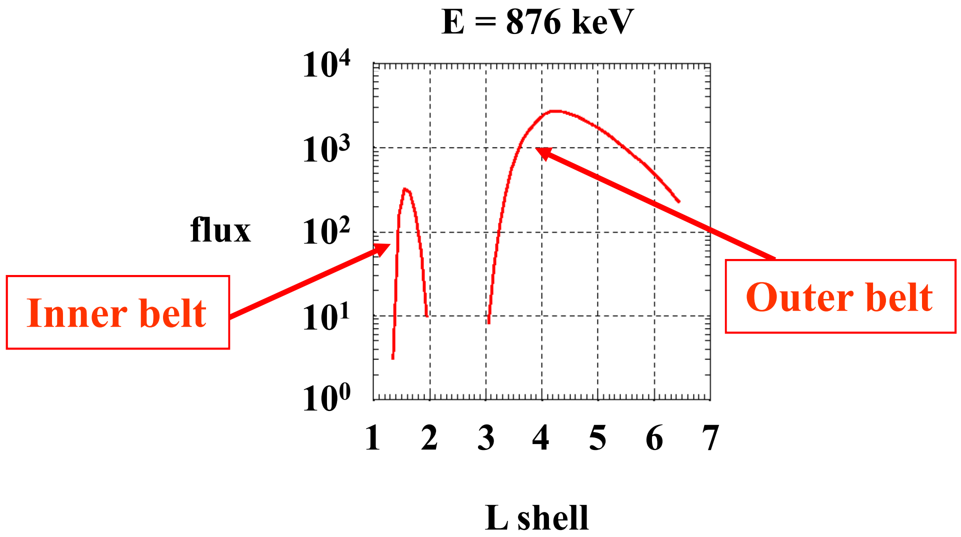

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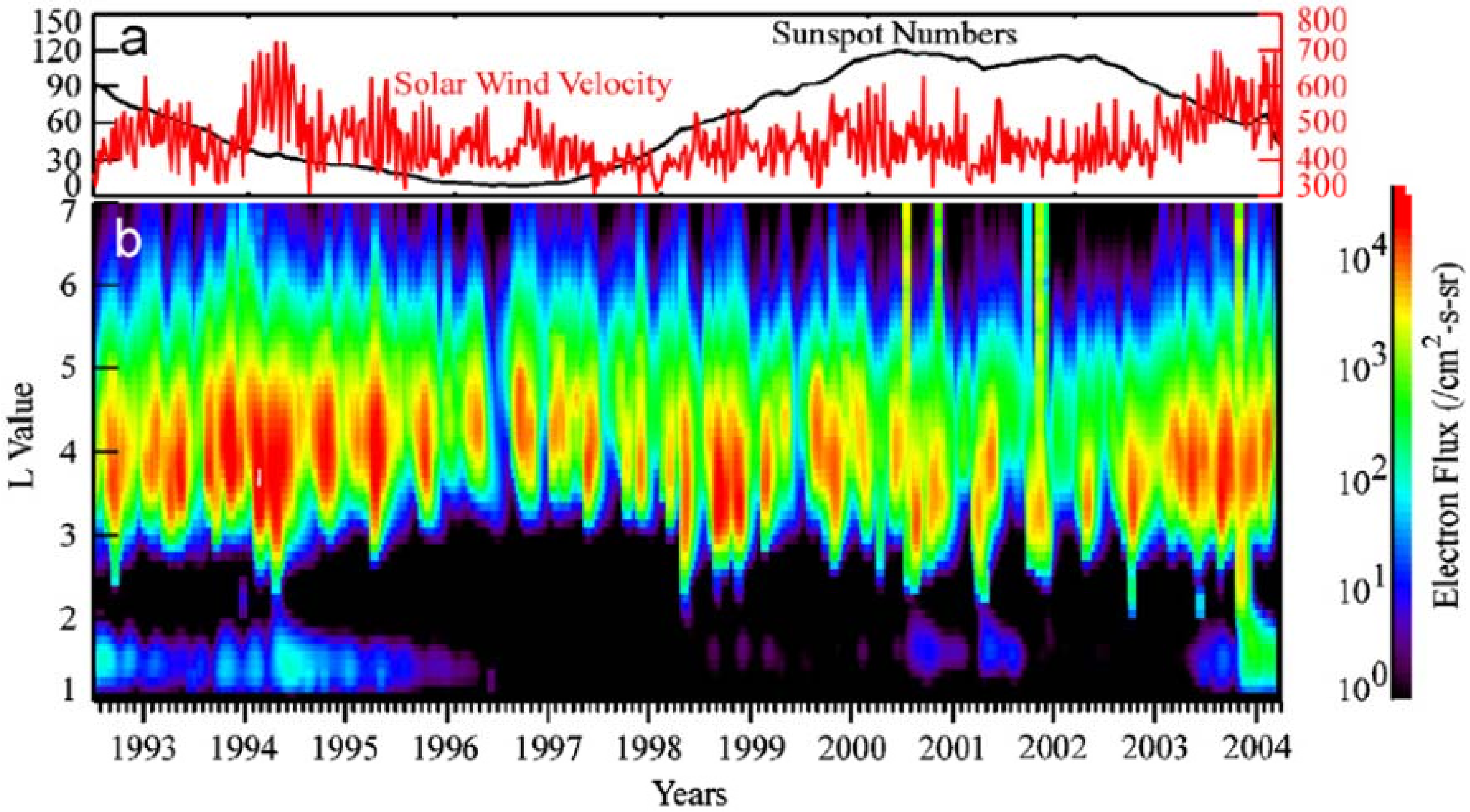
Variability of Outer Radiation Belt Electrons

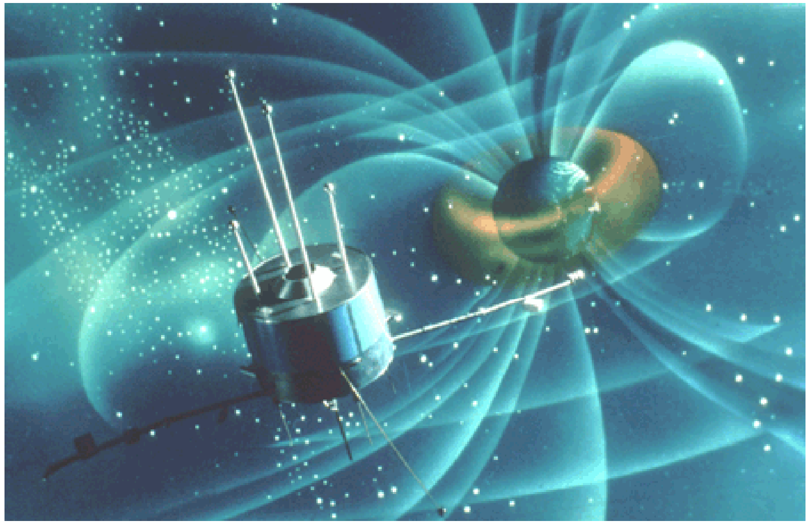


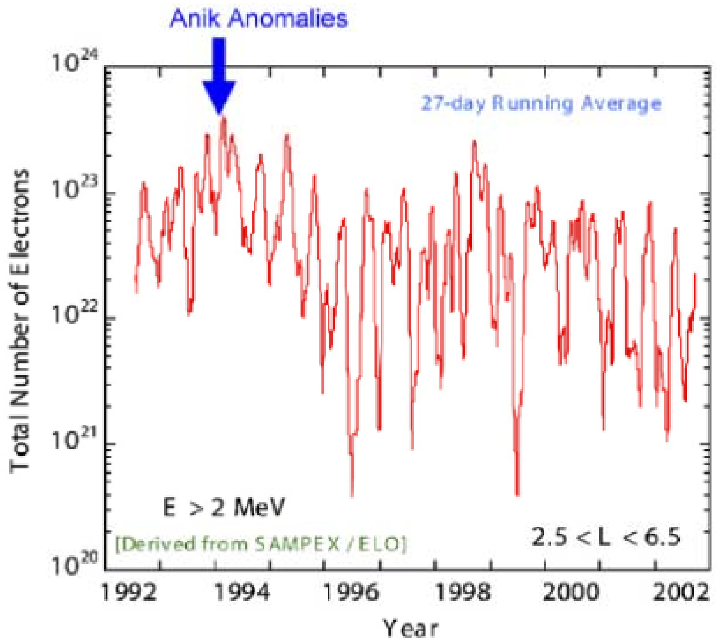
- The flux of relativistic electrons can change by several orders of magnitude on a variety of different time scales

Baker *et al*., AG, 2008

Importance

- Understanding this variability is important since enhanced fluxes of relativistic electrons:
  - damage satellites, e.g.,
    - 1994: Intelsat K, Anik E1, & E2
    - 1997: Telstar 401
    - 2003: Midori 2
  - risk to humans in space





Baker *et al*., AG, 2008

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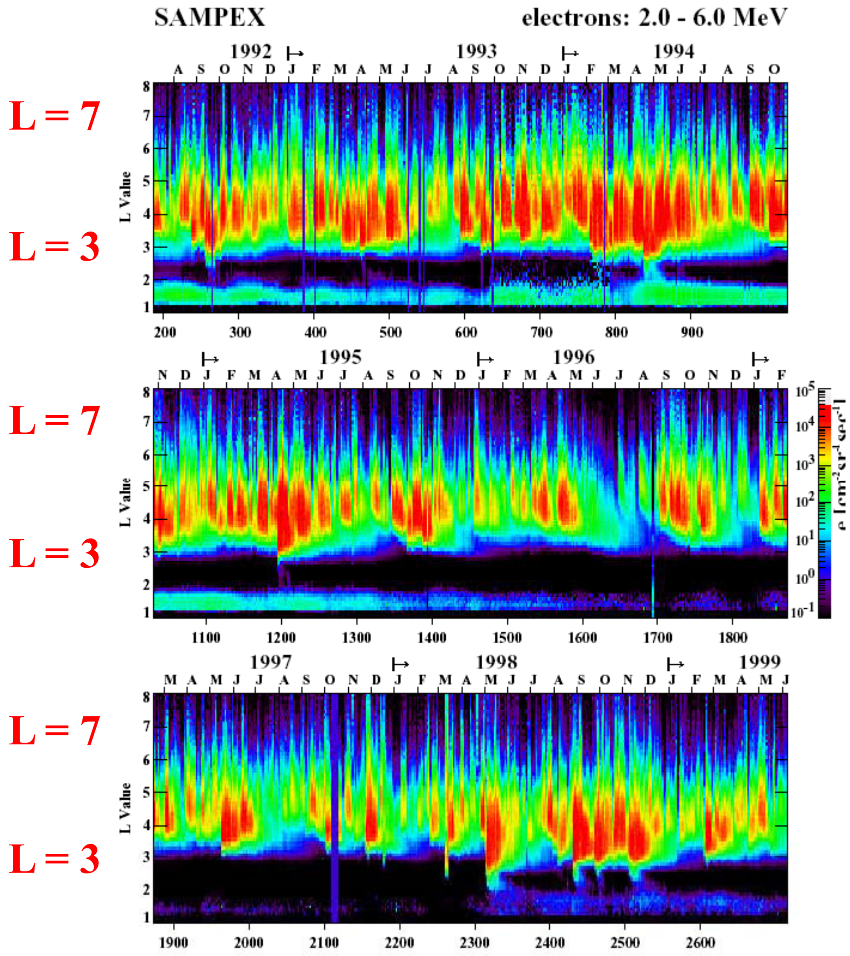
Challenge

- ***Characterise***, ***understand***, and ultimately ***predict*** the variability of outer radiation belt electrons

- Complex problem involving a variety of source, transport and loss processes



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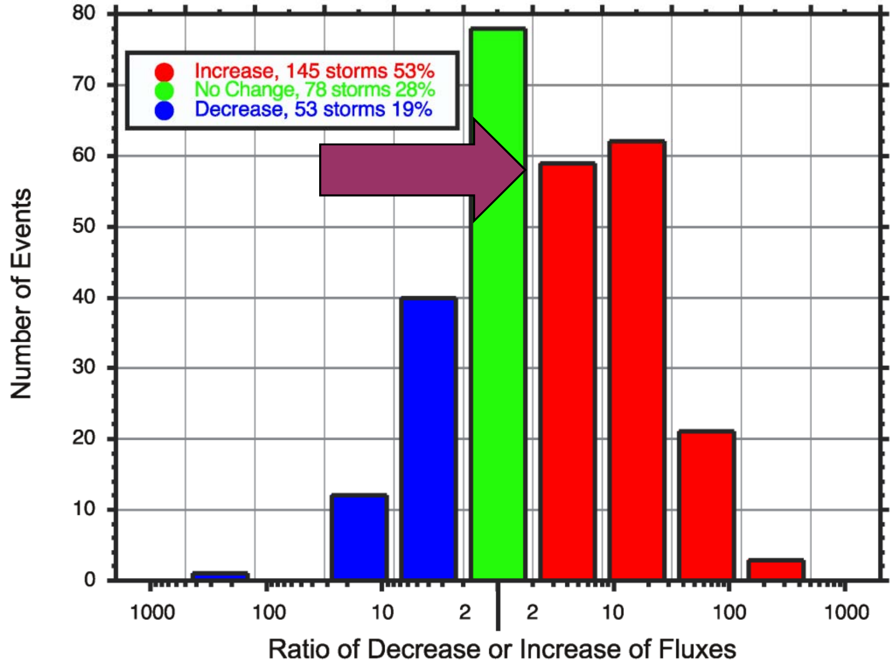
Relativistic Electron Variability

- The fluxes of relativistic electrons (E>1 MeV) in the outer zone are enhanced by a factor of 2 or more in ~50% of all moderate and intense storms



Reeves *et al*., GRL, 2003

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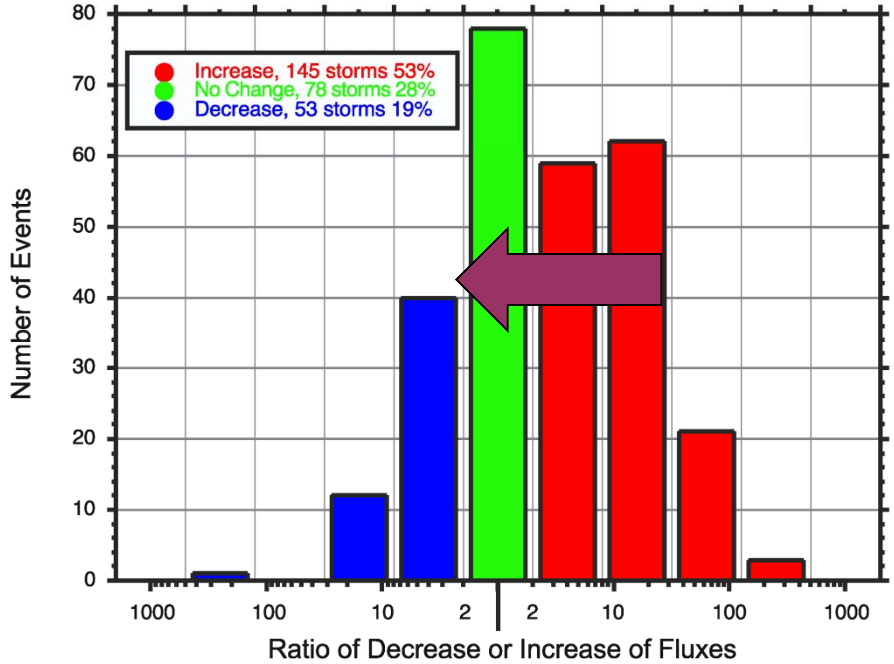
Relativistic Electron Variability

- The fluxes of relativistic electrons (E>1 MeV) in the outer zone are enhanced by a factor of 2 or more in ~50% of all moderate and intense storms
- However, in sharp contrast, ~20% of these storms decrease the fluxes by a factor of 2 or more
- This emphasizes the need to study loss processes as well as acceleration processes



Reeves *et al*., GRL, 2003

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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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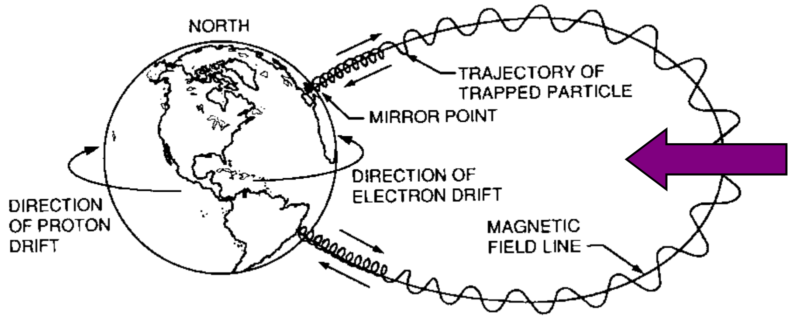
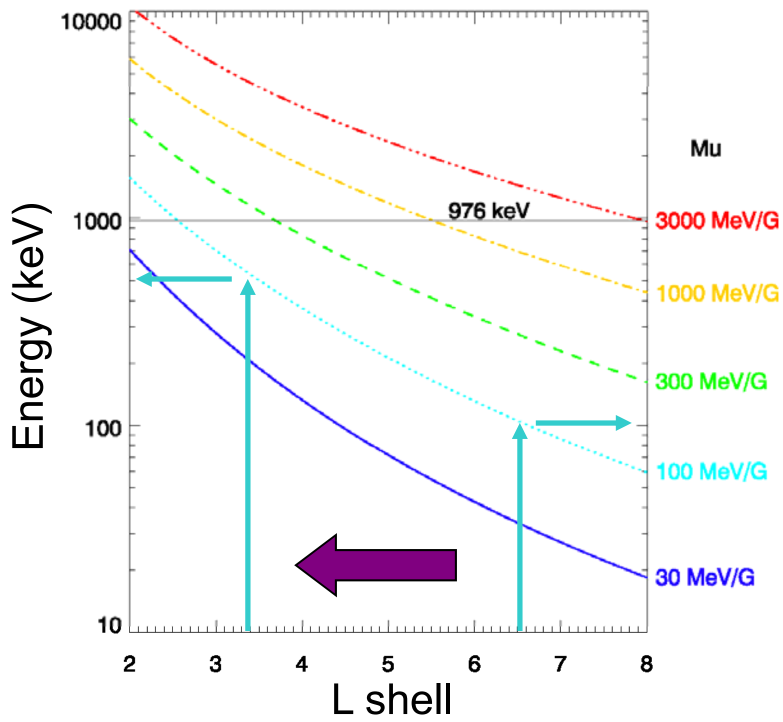
Radial Diffusion

- Conservation of first invariant implies:

$$p_{\perp}^{2} = 2m_eB$$

- Inward radial diffusion leads to significant energisation





courtesy of M. Lam

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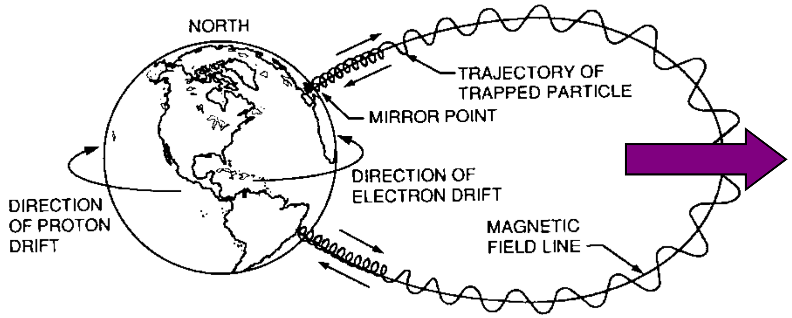
Radial Diffusion

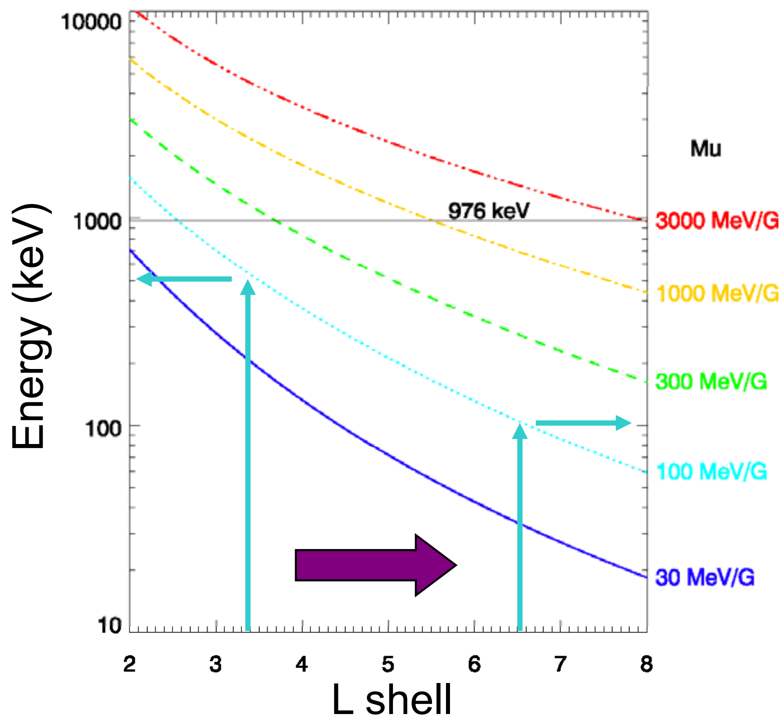
- Conservation of first invariant implies:

$$p_{\perp}^2 = 2m_eB$$

- 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

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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

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

  - $\mathbf{k}_{\parallel}$ is the wave number parallel to the magnetic field
  - $\mathbf{v}_{\parallel}$ is the electron velocity parallel to the magnetic field
  - γ is the relativistic factor

Gyroresonant Wave-Particle Interactions

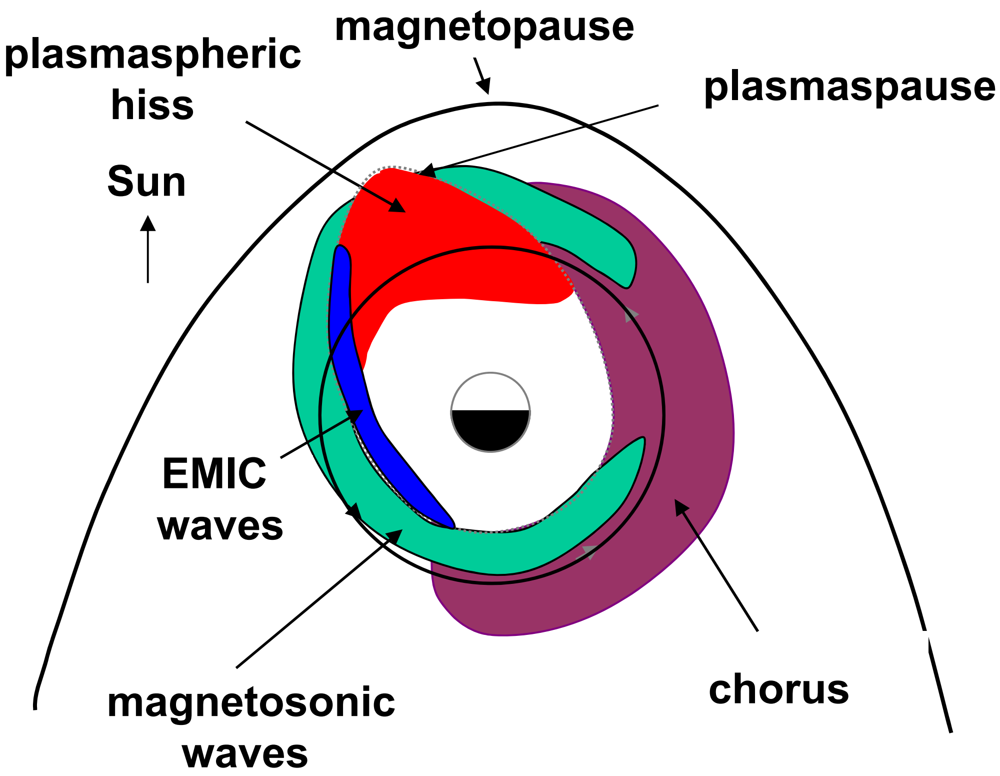
- These interactions break the first and second adiabatic invariants

- Such interactions [e.g., **Kennel and Petschek, JGR, 1966**] lead to:
  - pitch angle scattering and potential loss to the atmosphere
  - energy diffusion

Important Wave Modes

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

- Chorus waves
- Magnetosonic waves
- Plasmaspheric hiss
- EMIC waves



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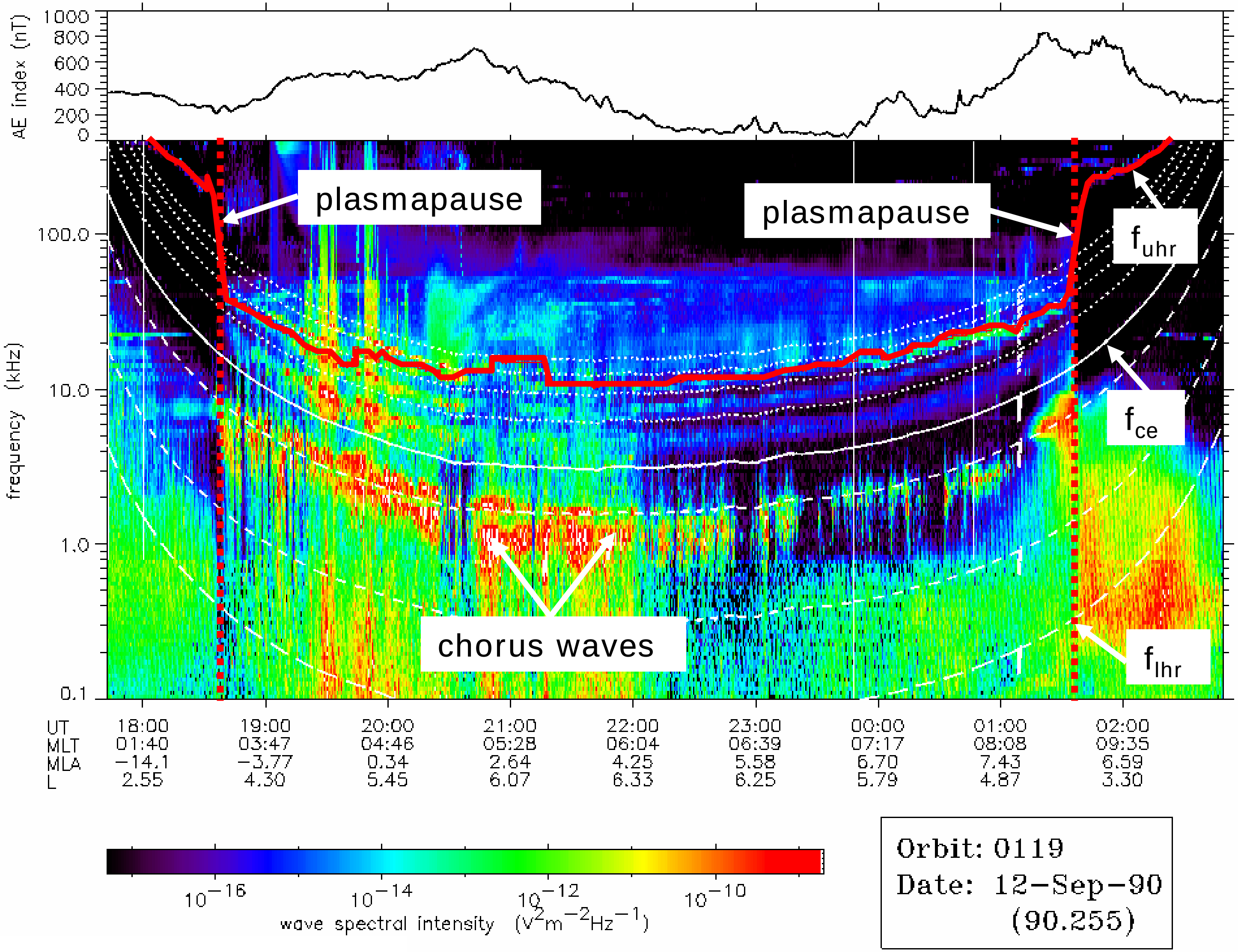
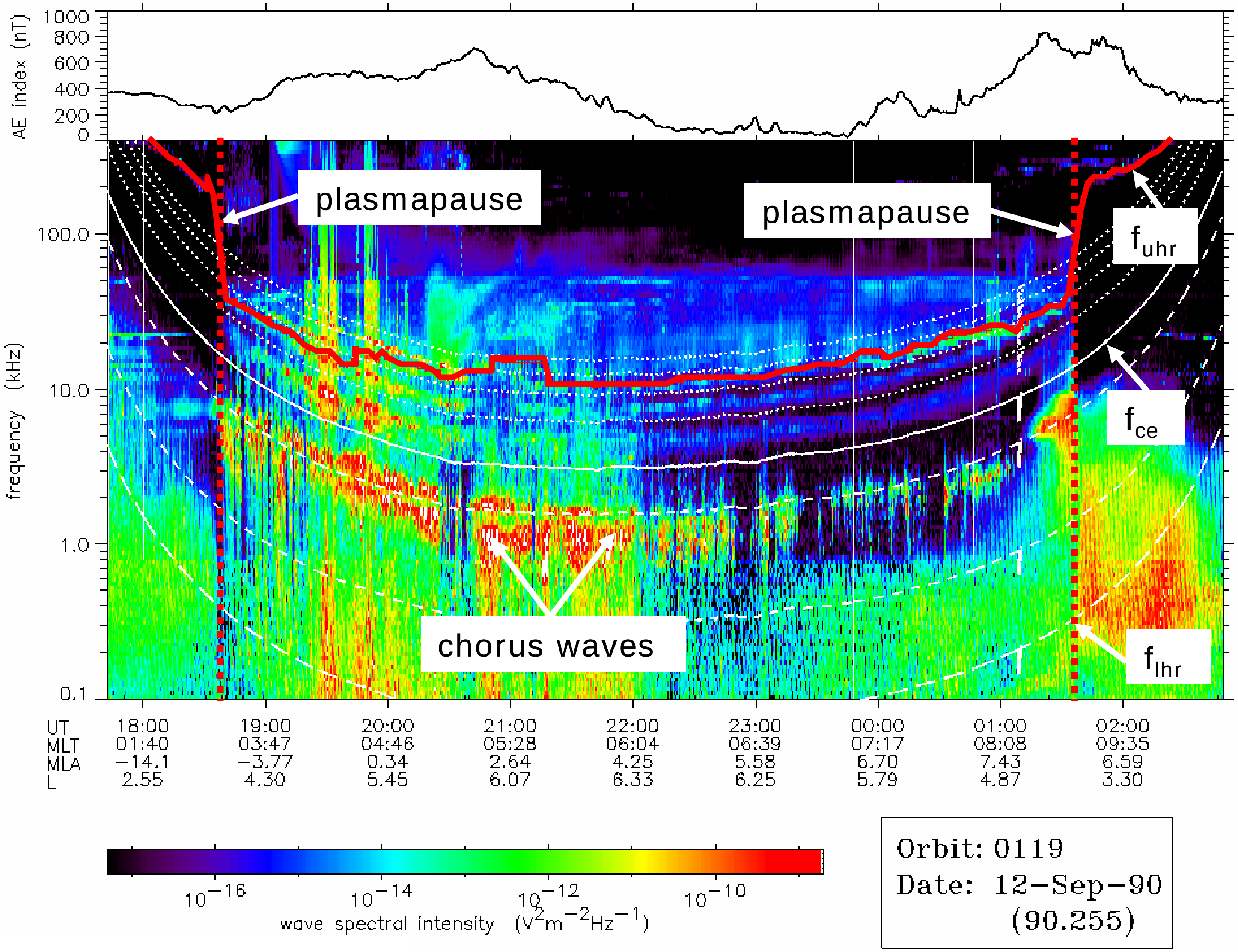
Whistler Mode Chorus



- Chorus is an intense emission, observed outside the plasmapause in the frequency range 0.1-0.8fce

Whistler Mode Chorus

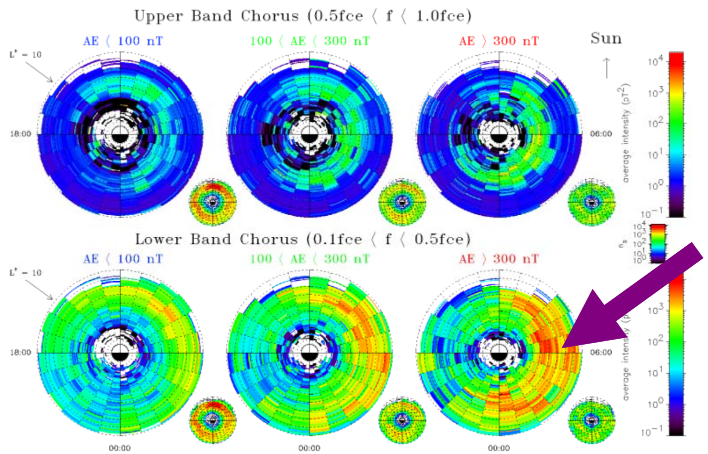


- The waves are generated by plasma sheet electrons injected into the magnetosphere during substorms and/or enhanced convection

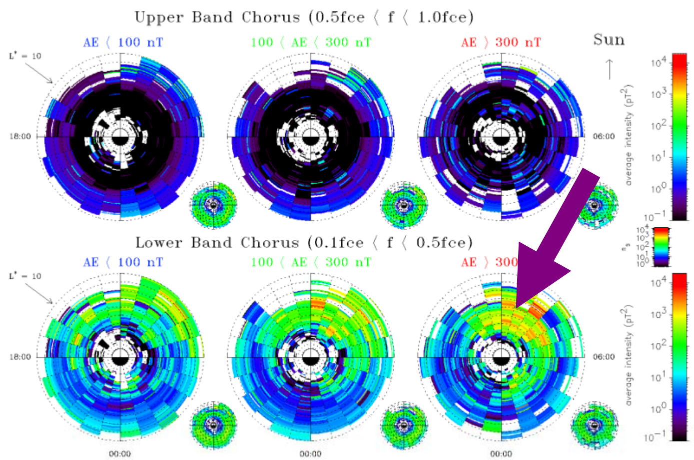
Global Model of Whistler Model Chorus

- Chorus is strongest in the lower band during active conditions
- Equatorial chorus is strongest in the region 4 < L* < 9 primarily on the dawn-side.
- At higher latitudes chorus tends to be strongest on the dayside from 0700 to 1400 MLT

Equatorial Chorus ($|\lambda_m| < 15^o$)



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



Meredith *et al.*, JGR, 2012

Acceleration due to Chorus

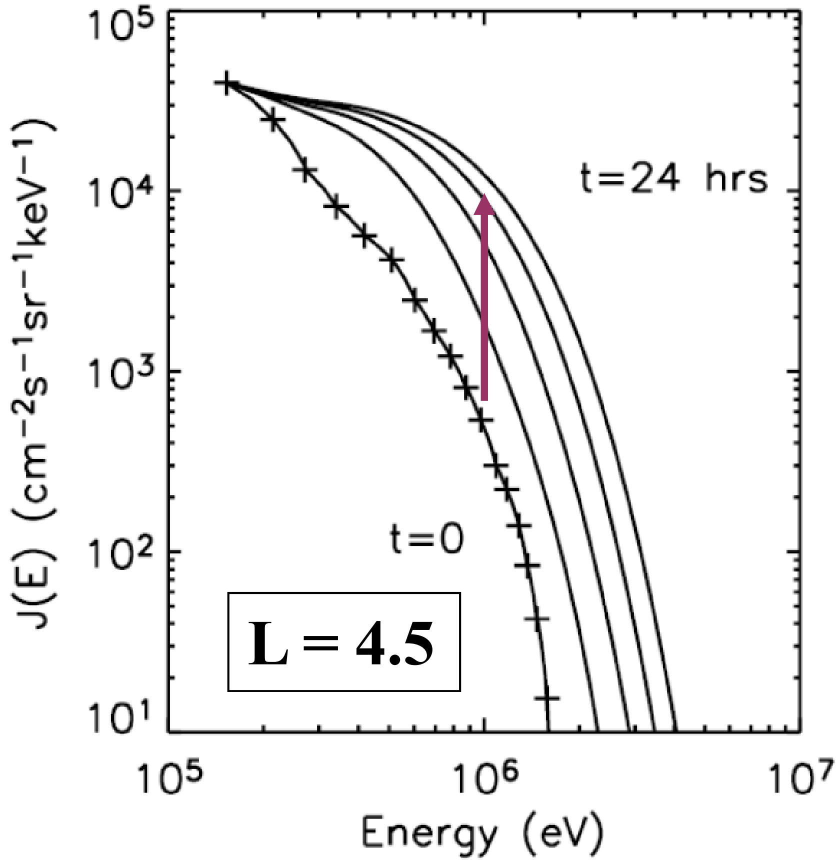
- Use 1D Fokker-Planck equation to calculate evolution of particle flux

- 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

- Numerous studies have since shown that chorus is an important acceleration mechanism

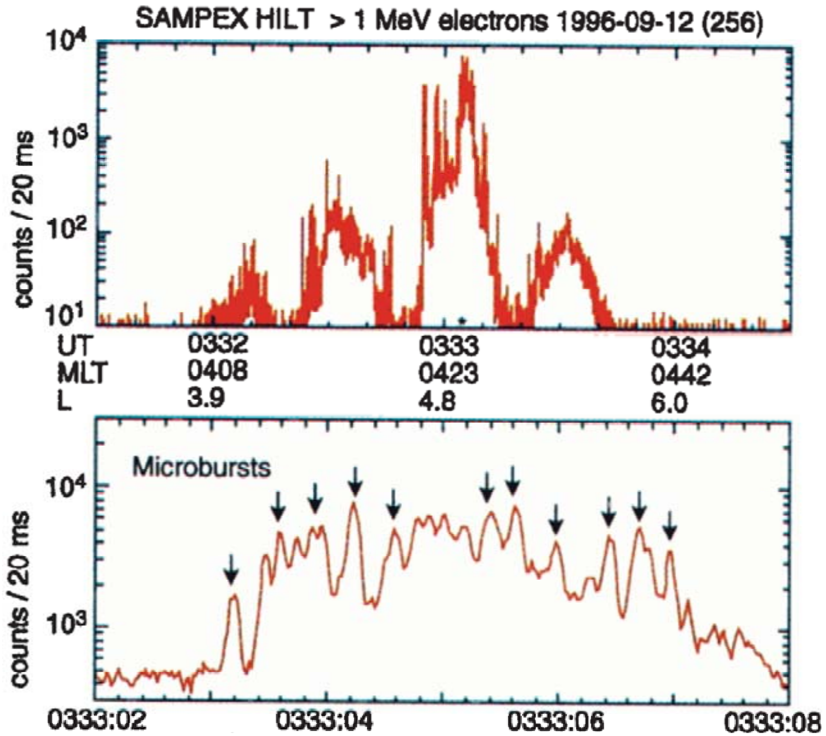


Horne *et al*., JGR, 2005

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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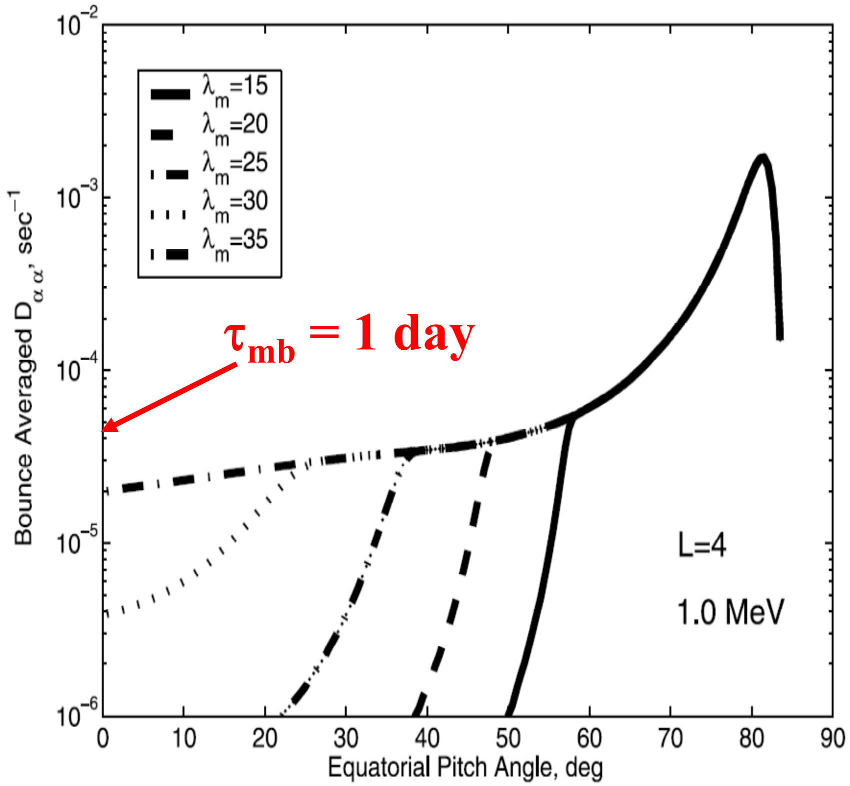
Losses due to Chorus

- Bounce-averaged diffusion rates for 100 pT chorus waves at L = 4 show:
  - loss timescales near the loss cone due to chorus can approach 1 day
  - requires chorus at latitudes greater than 30^0



Thorne *et al*., JGR, 2005

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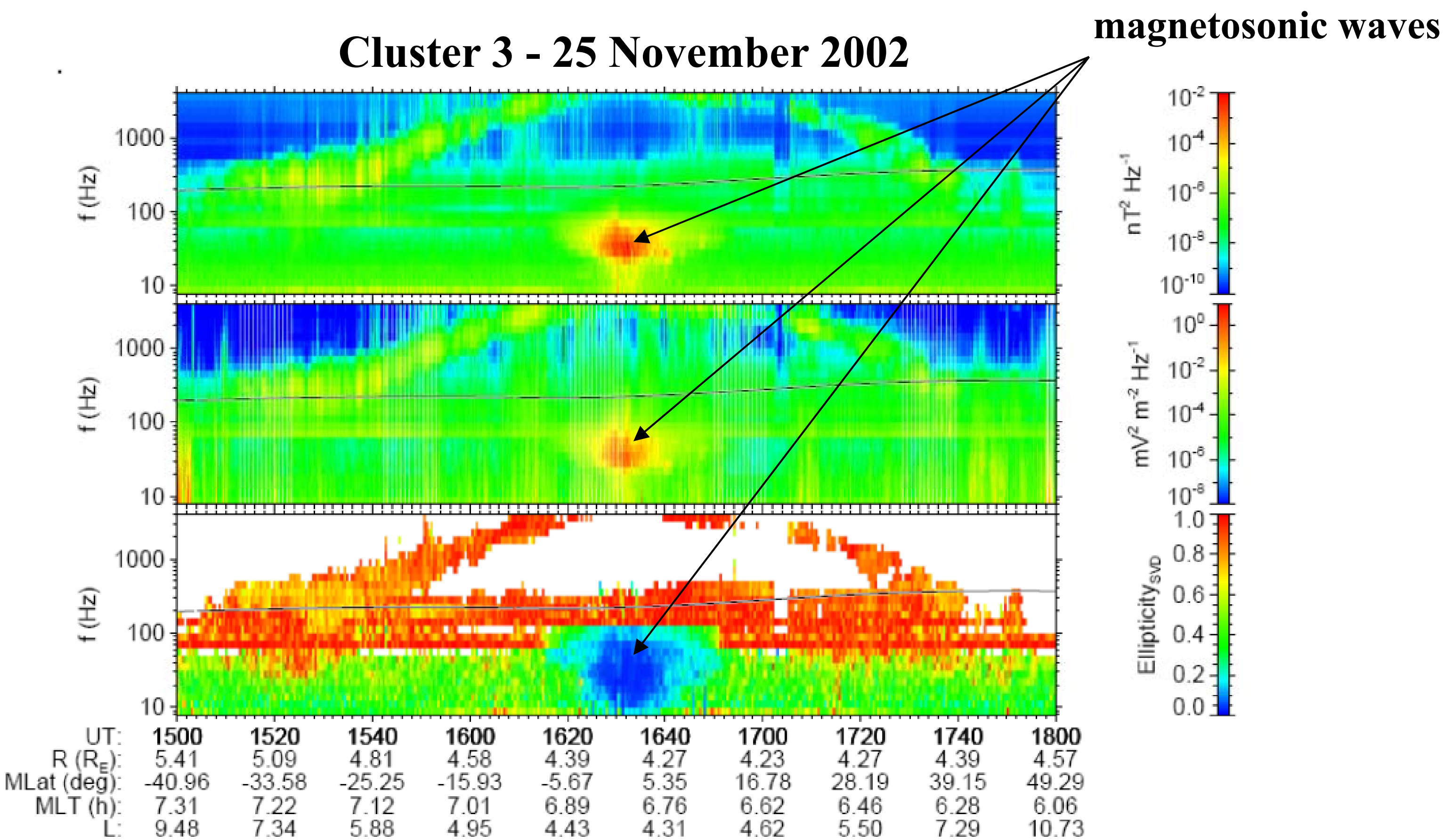
Magnetosonic Waves



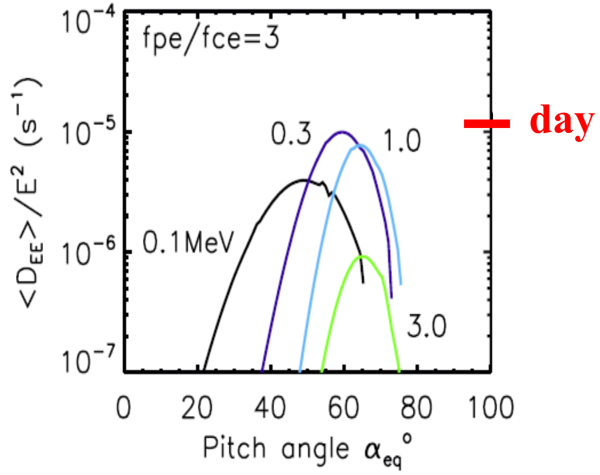
- intense electromagnetic emissions, fcp < f < flhr
- compressional waves, propagate across B_0
- generated by proton ring distributions [**Boardsen *et al*., JGR, 1992**]

Acceleration Due to Magnetosonic Waves

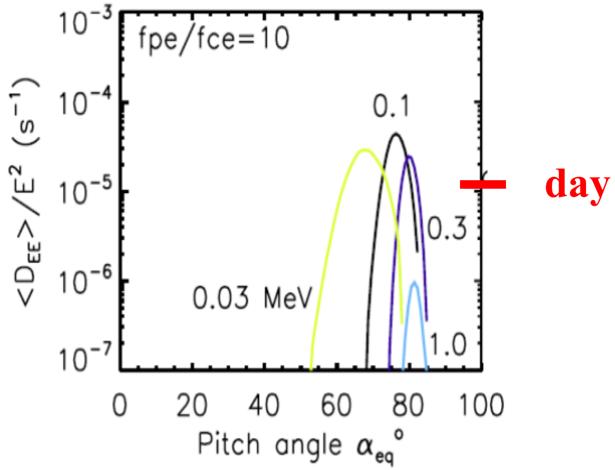
- Energy diffusion rates at L = 4.5 have been estimated using Cluster wave observations and the PADIE code
- Timescale of the order of a day
  - 0.3 < E < 1 MeV outside the plasmapause
  - 0.03 < E < 0.3 MeV inside the plasmapause

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

Outside plasmapause



Inside plasmapause



Horne *et al.*, GRL, 2007

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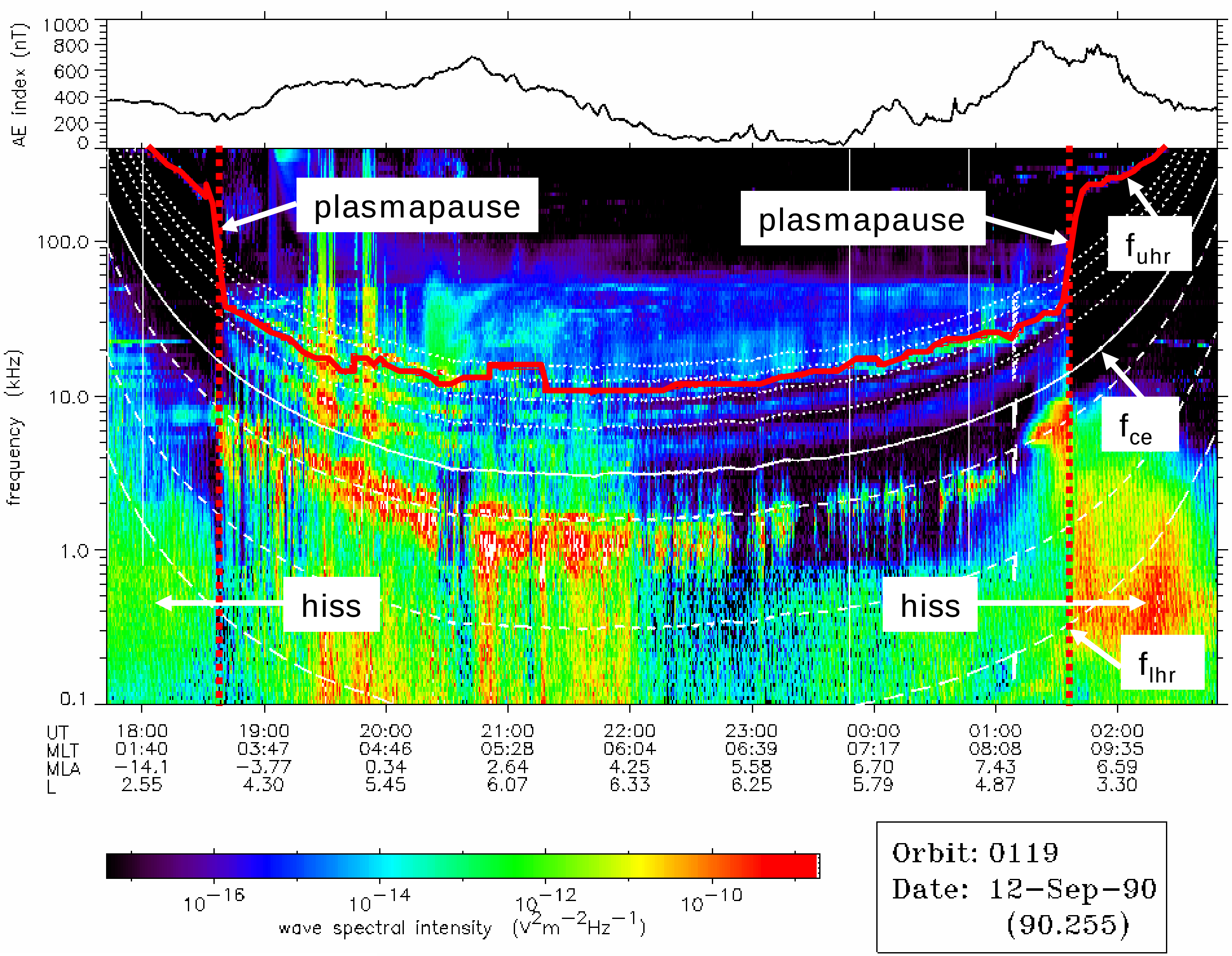
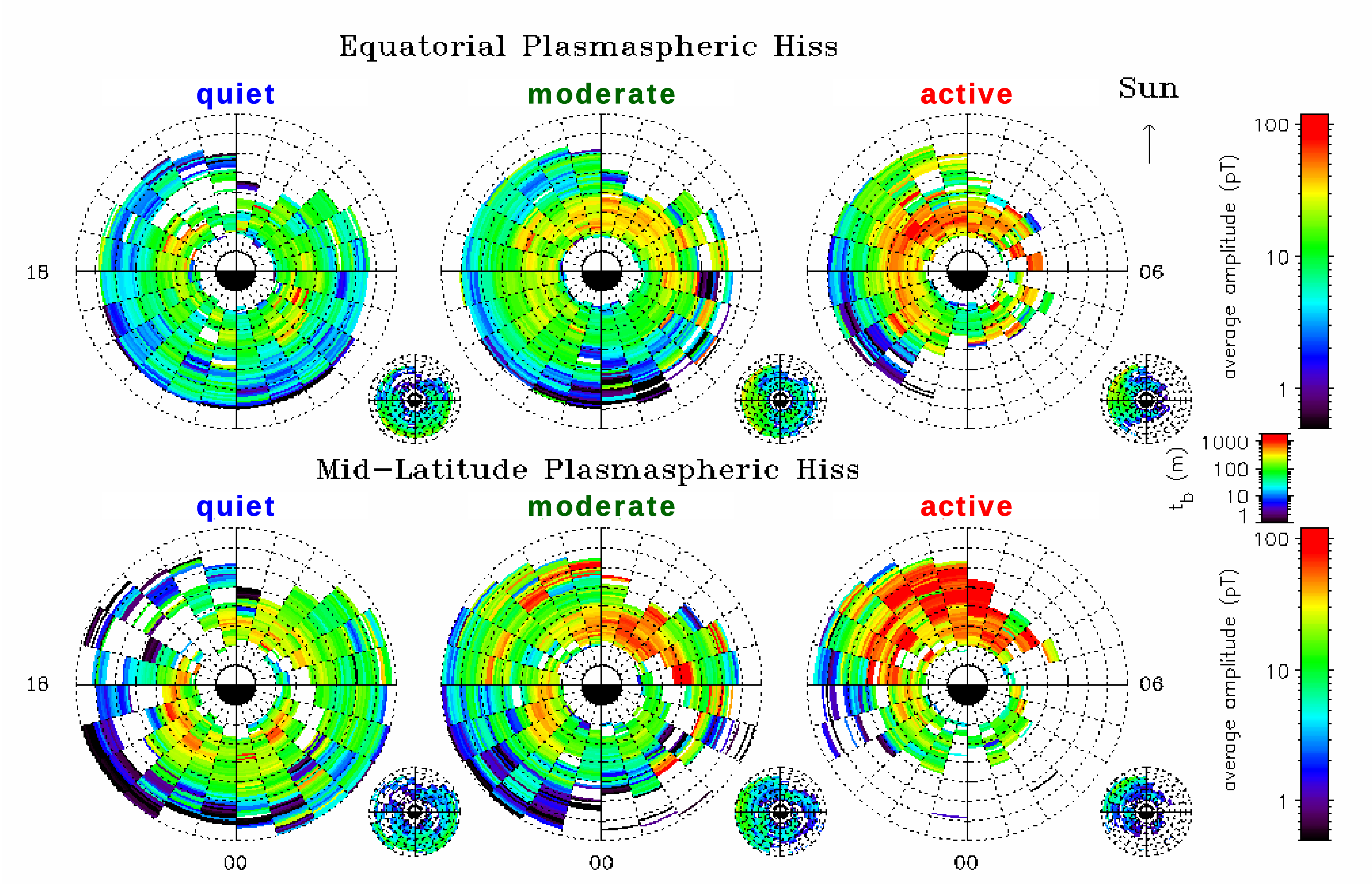
Plasmaspheric Hiss



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

Global Distribution of Plasmaspheric Hiss



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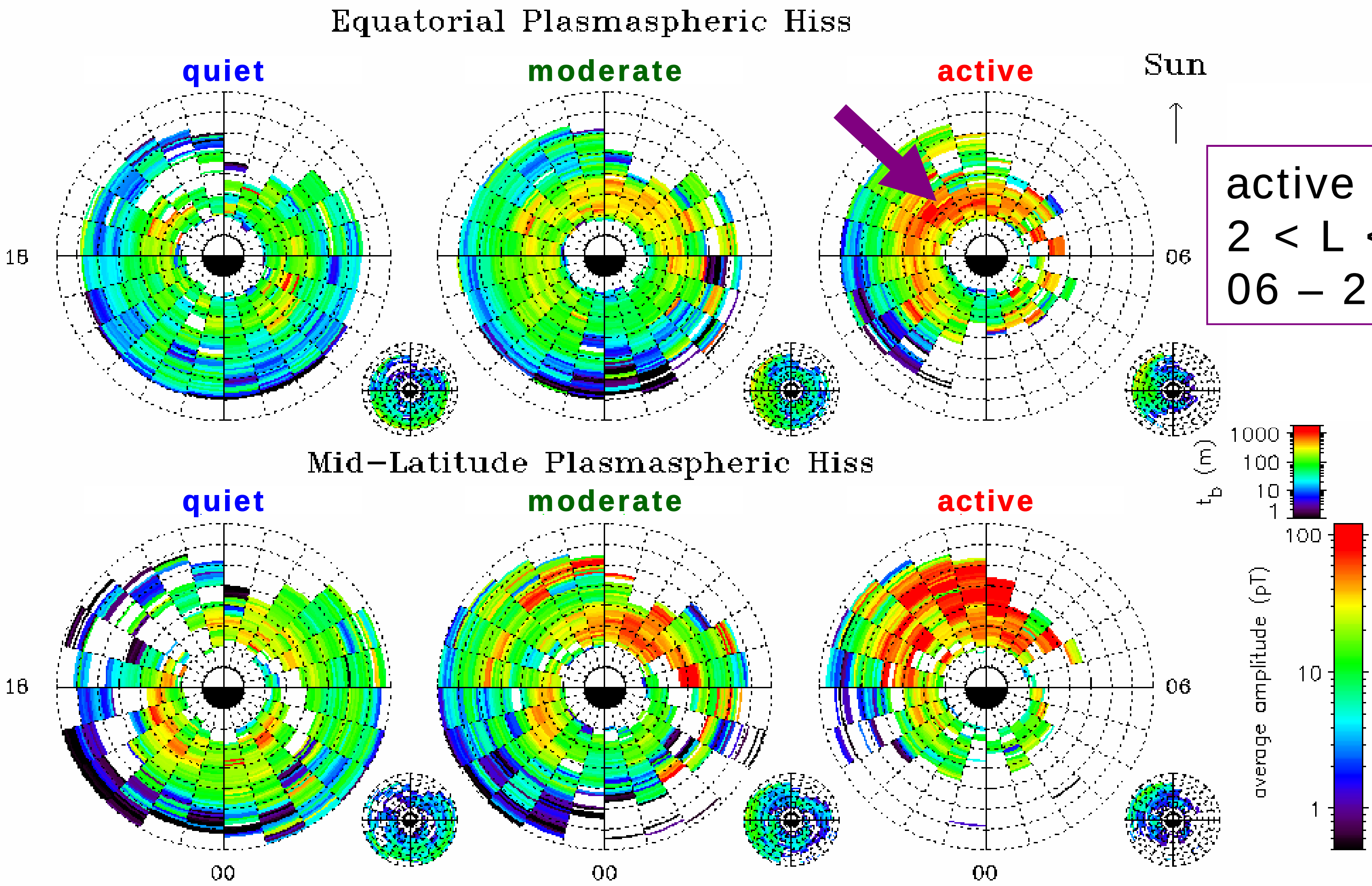
Meredith *et al.*, JGR, 2004

Global Distribution of Plasmaspheric Hiss



active
2 < L < 4
06 – 21 MLT

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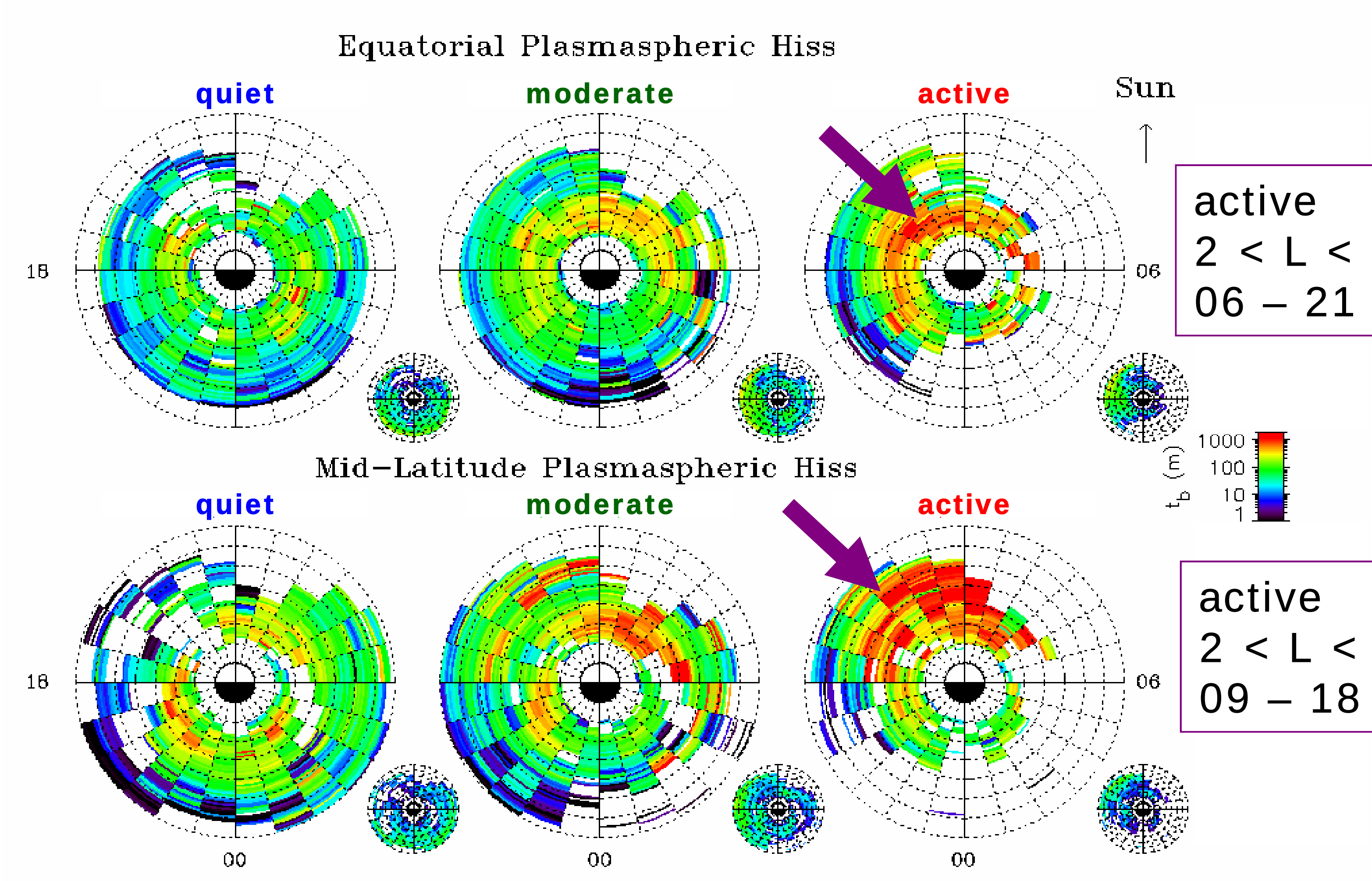
Meredith *et al.*, JGR, 2004

Global Distribution of Plasmaspheric Hiss



active
2 < L < 4
06 – 21 MLT

active
2 < L < 4
09 – 18 MLT

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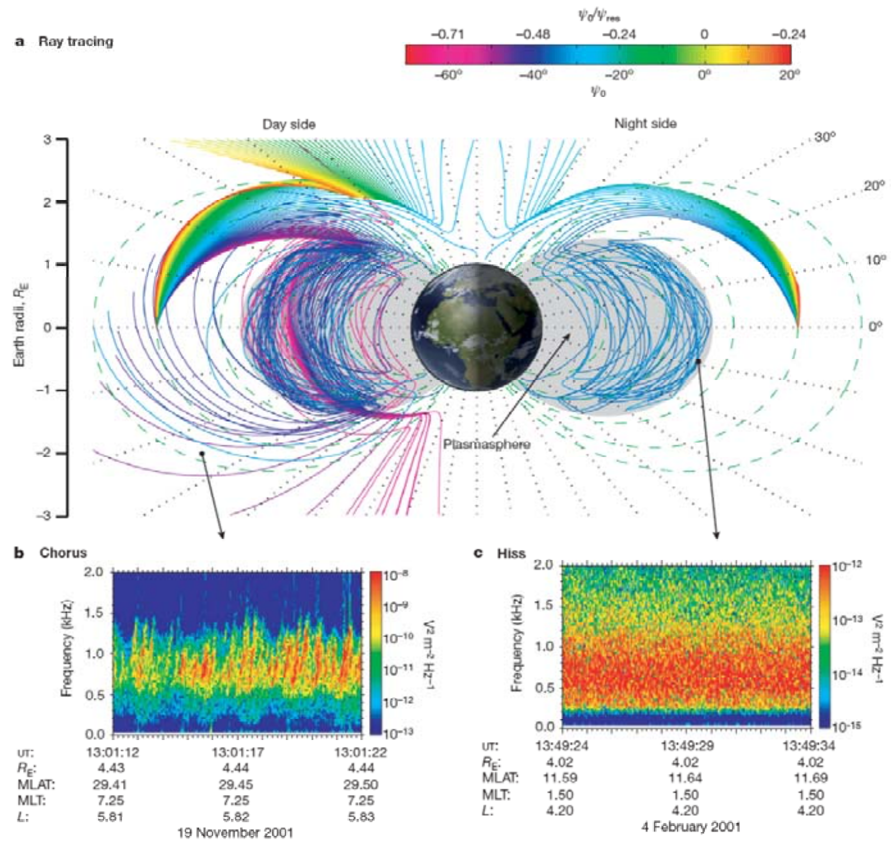
Meredith *et al*., JGR, 2004

Origin of Plasmaspheric Hiss

- Ray tracing studies show that chorus waves can propagate into the plasmasphere and evolve into plasmaspheric hiss

- Results account for the essential features of hiss



Bortnik *et al*., Nature, 2008

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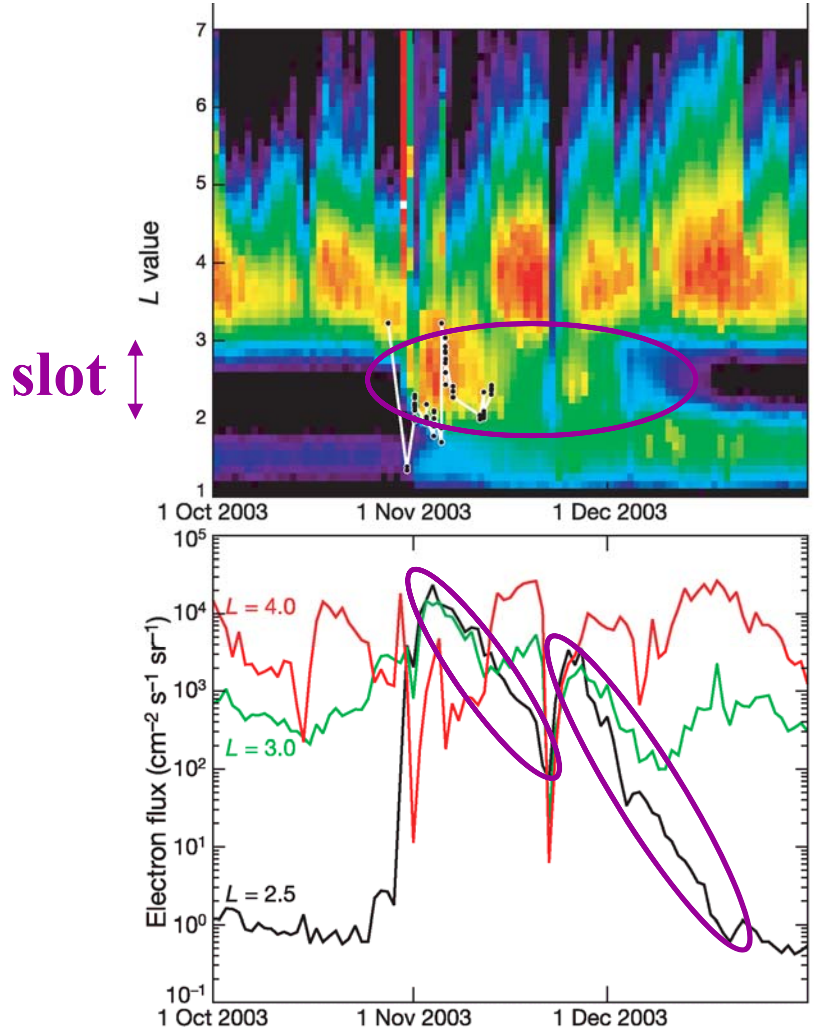
Slot Region Loss Timescales

- 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

SAMPEX 2-6 MeV Electrons



Baker *et al*., Nature, 2004

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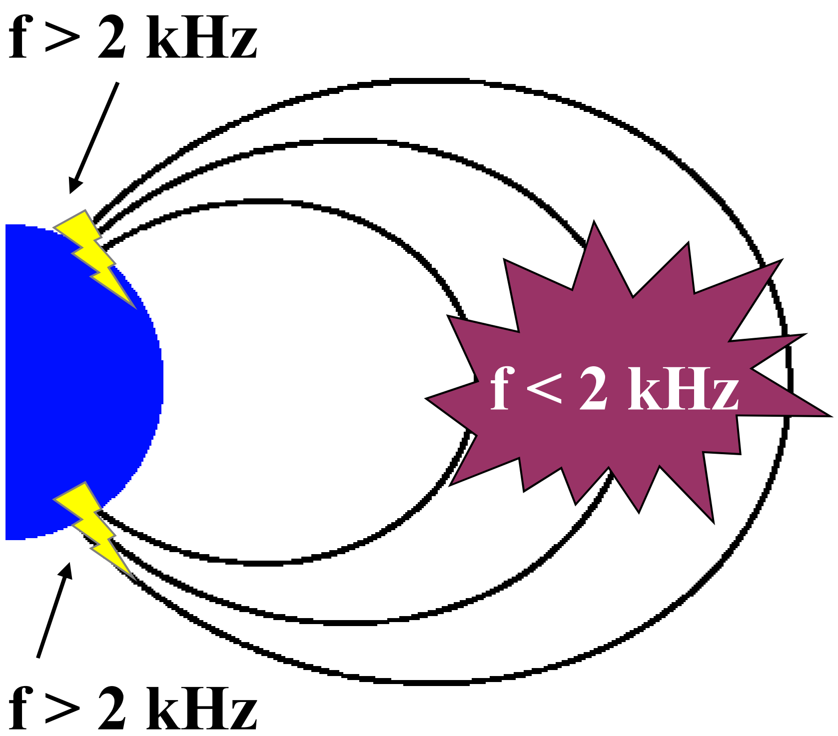
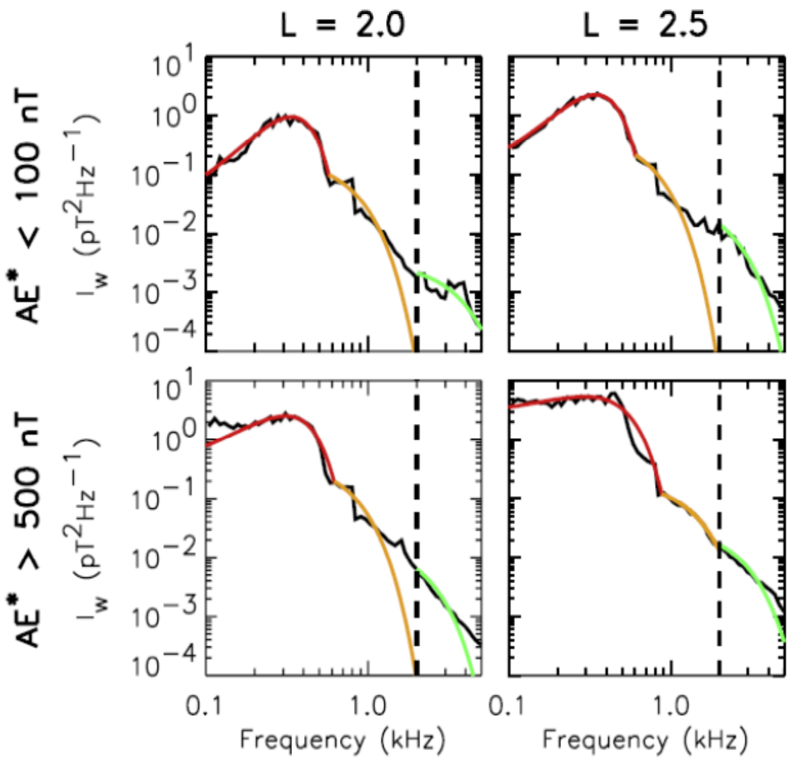
Broadband Plasmaspheric Emissions

- Broadband plasmaspheric emissions can be split into two categories [**Meredith *et al*., 2006**]:
  - Plamaspheric hiss
    - 100 Hz < f < 2 kHz
    - from chorus outside the plasmapause
  - 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]**

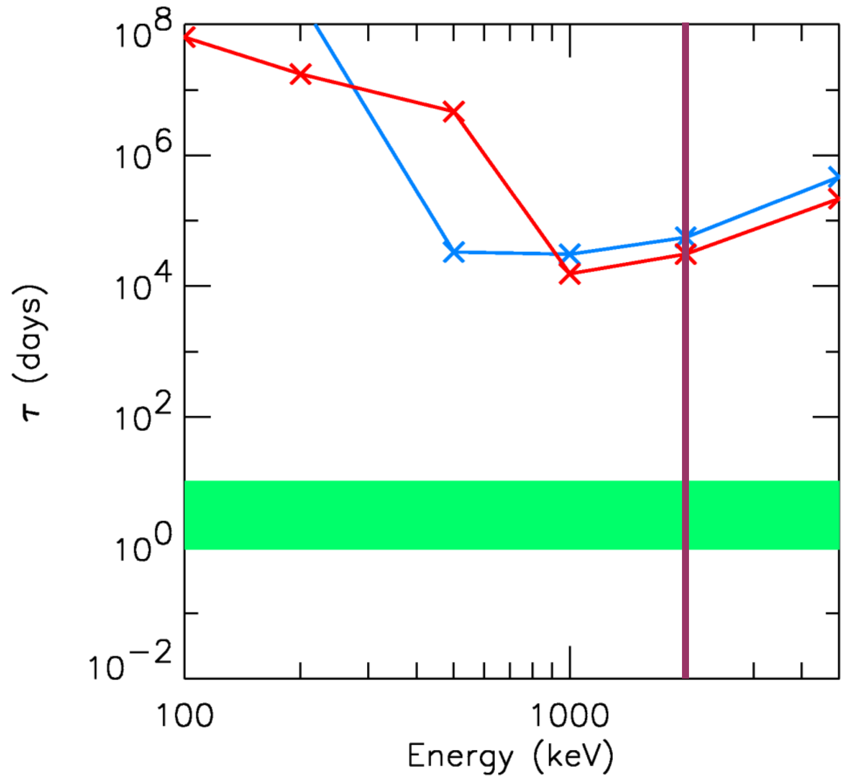


Meredith *et al*., JGR, 2007

Slot Region Loss Timescales

- Loss timescales due to MR whistlers are prohibitively long

MR Whistlers



Quiet Conditions (AE* < 100 nT)

Active Conditions (AE* > 500 nT)

Meredith *et al.*, JGR, 2007

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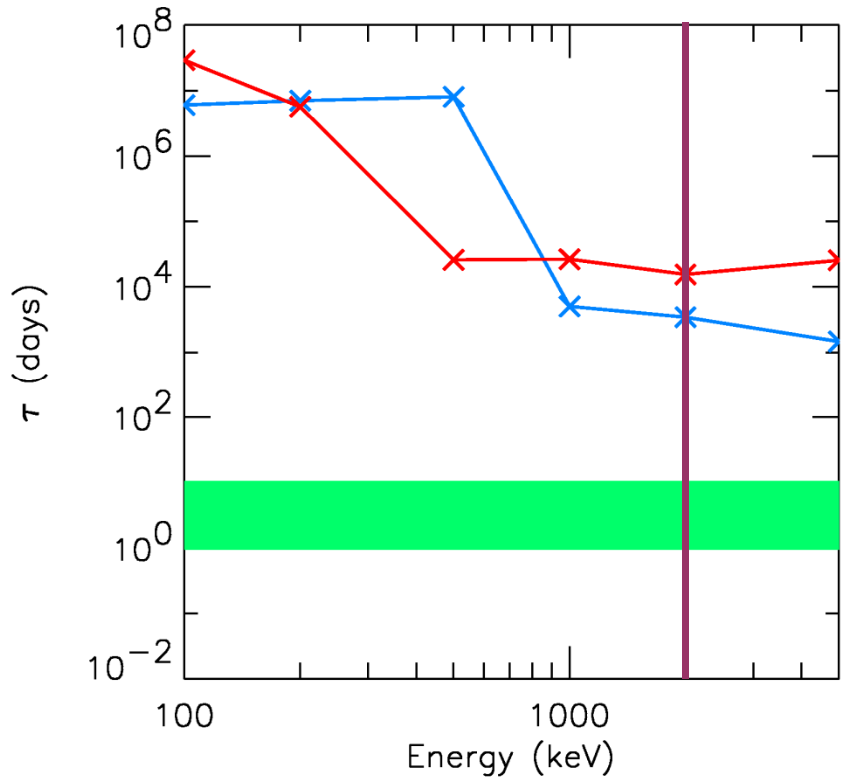
Slot Region Loss Timescales

- 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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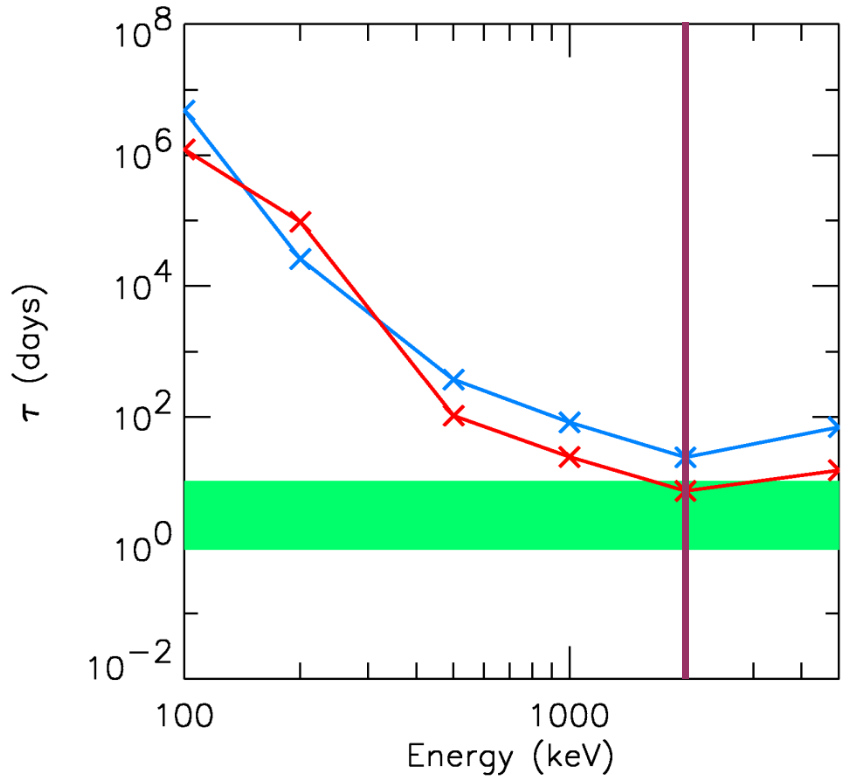
Slot Region Loss Timescales

- 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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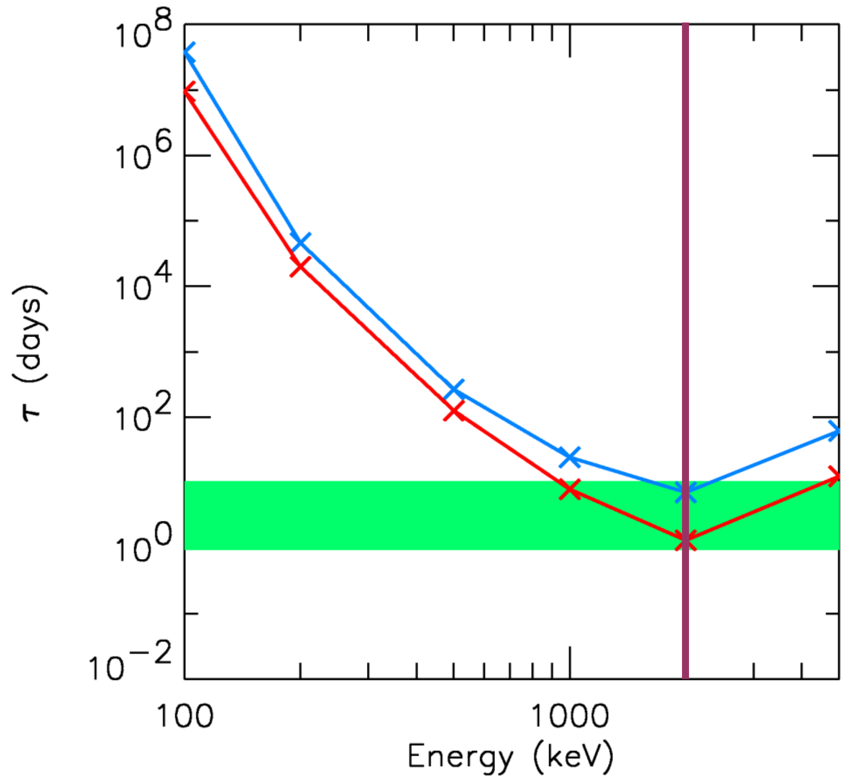
Slot Region Loss Timescales

- 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 (ψ_m = 0°)



Quiet Conditions (AE* < 100 nT)

Active Conditions (AE* > 500 nT)

Meredith *et al.*, JGR, 2007

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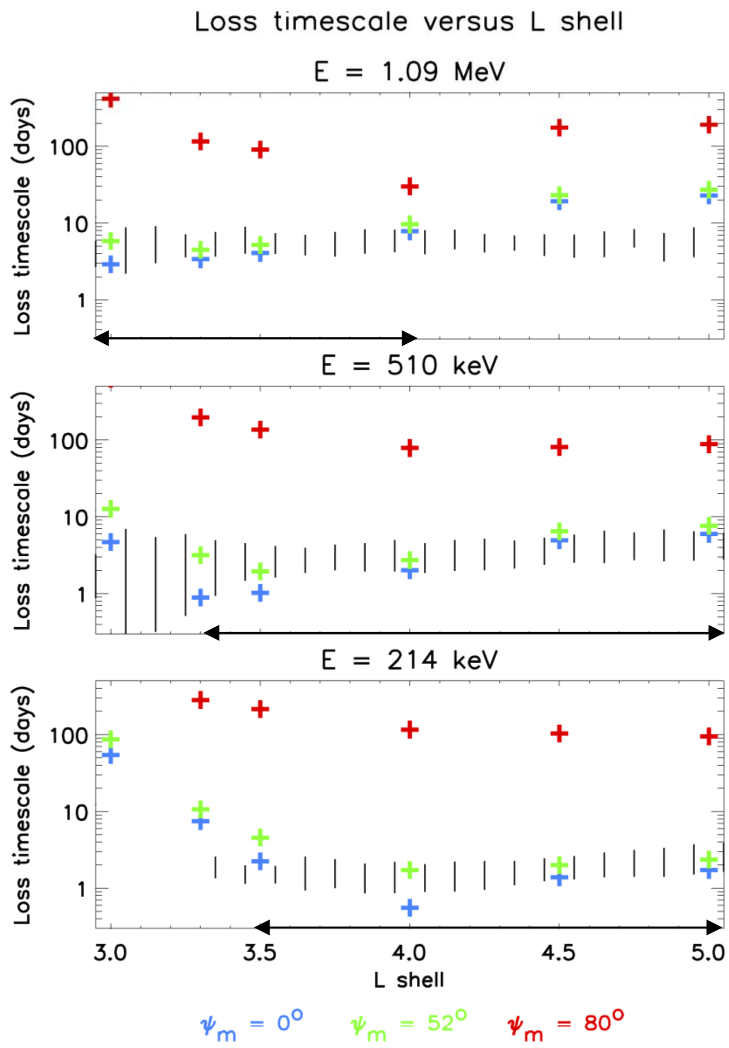
Comparison with QL Diffusion due to Hiss

- 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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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

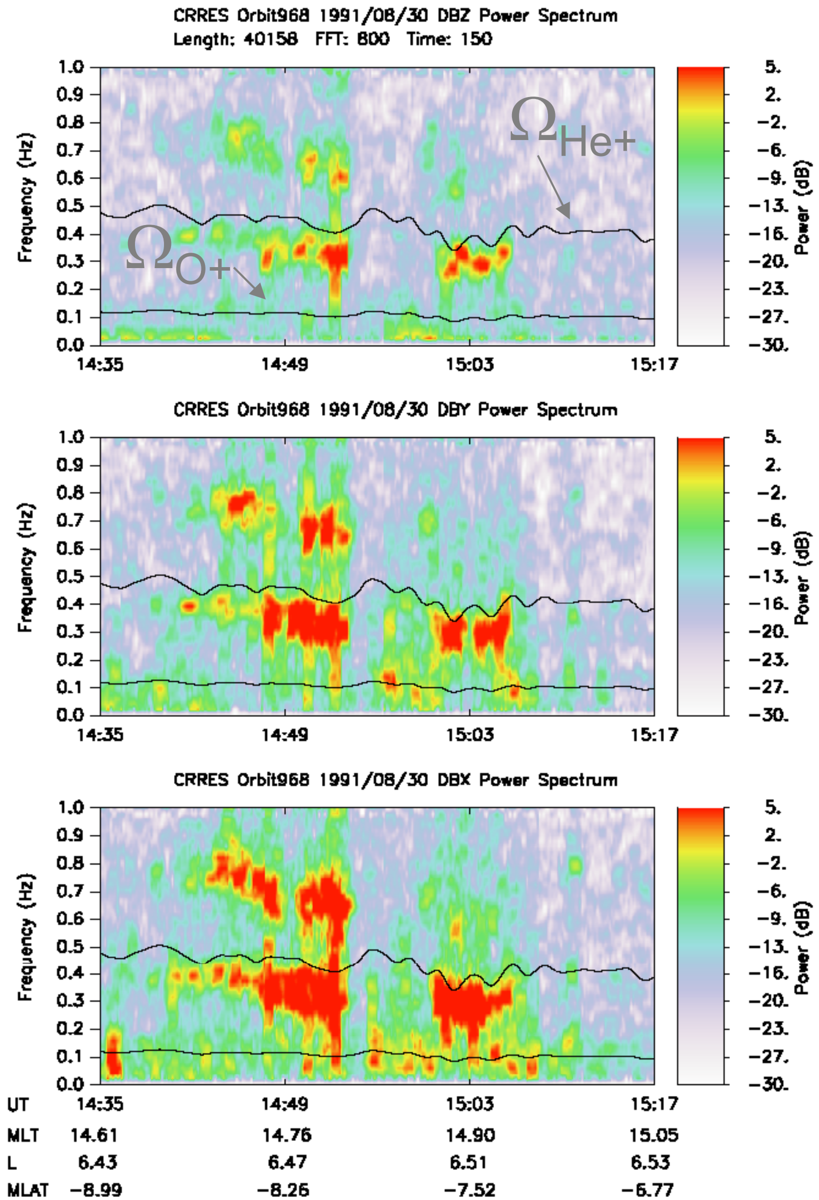

Figure courtesy of Brian Fraser

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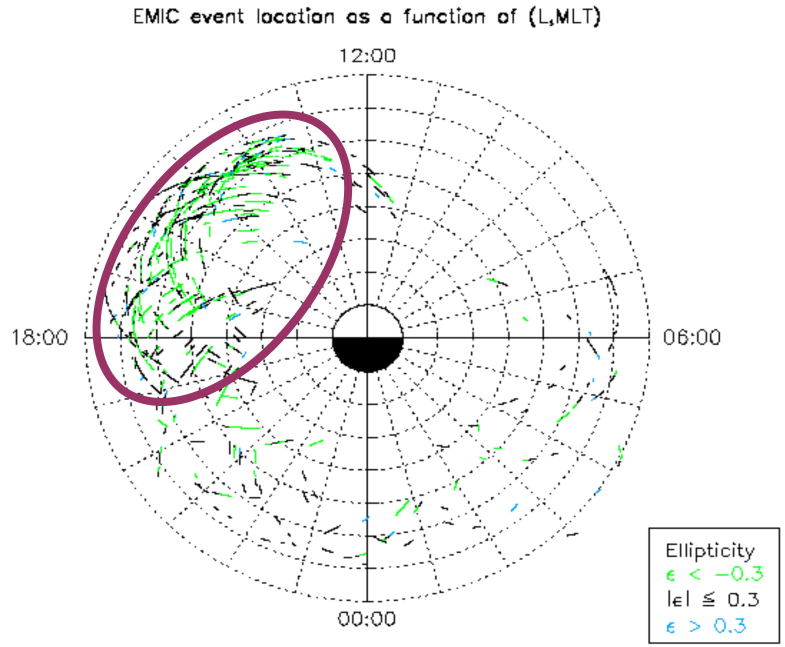
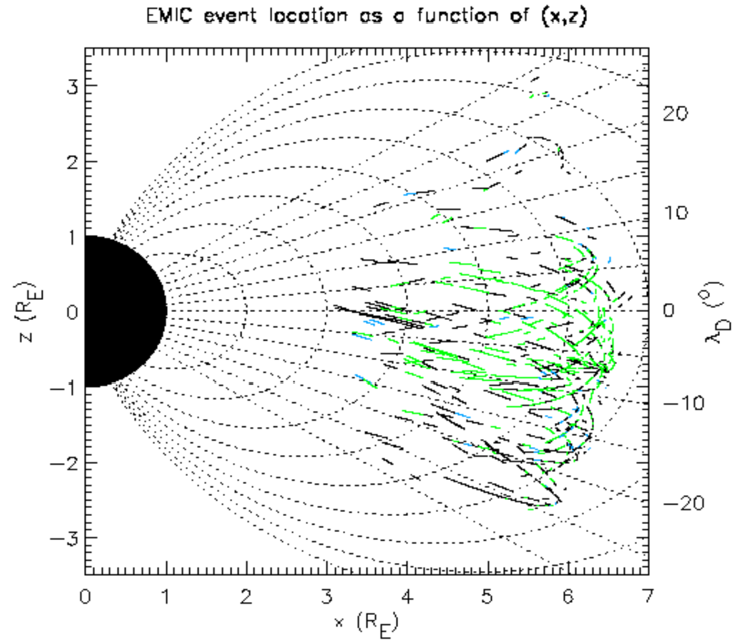
Location of Events

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





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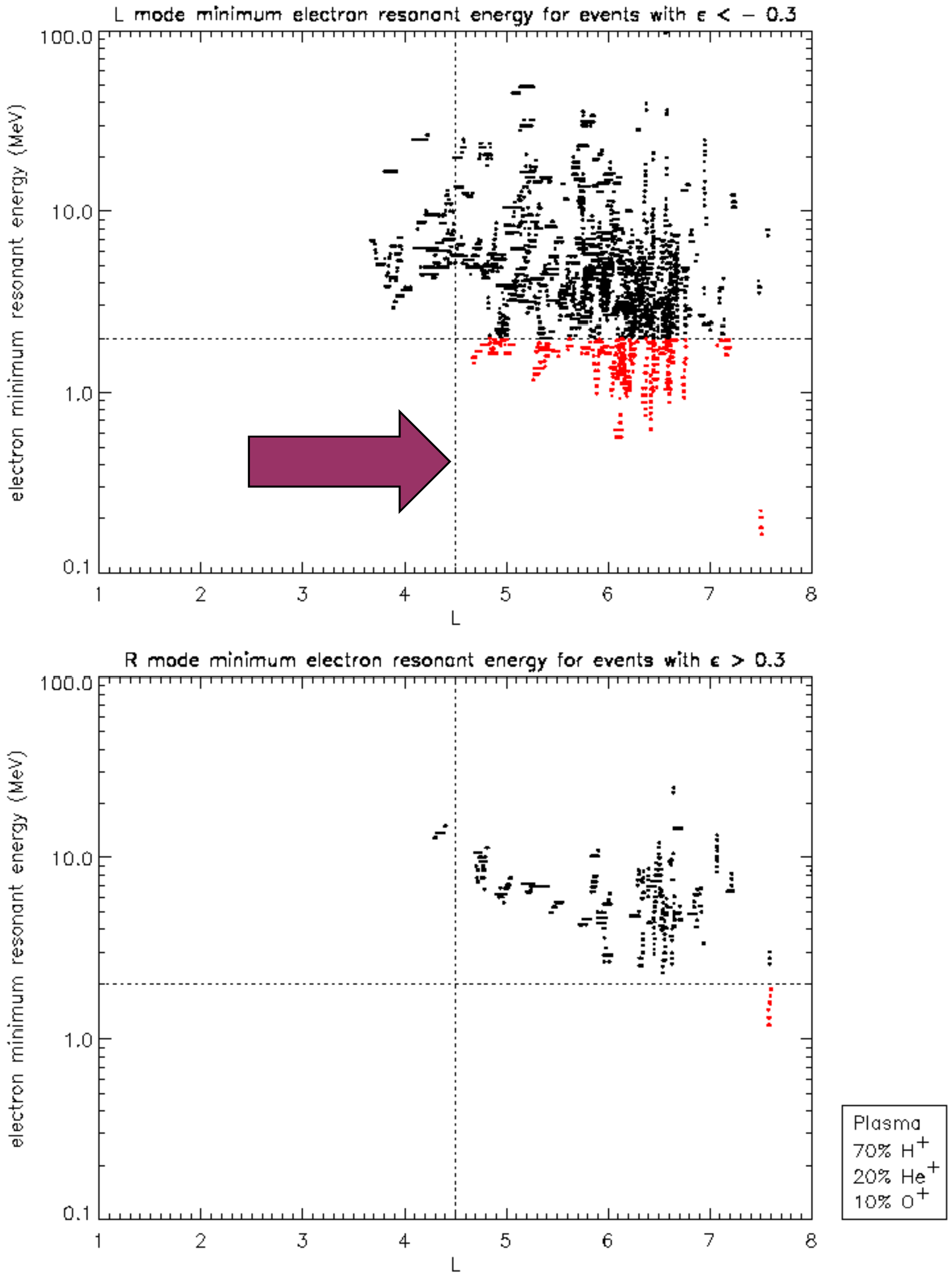
Meredith *et al*., JGR, 2003

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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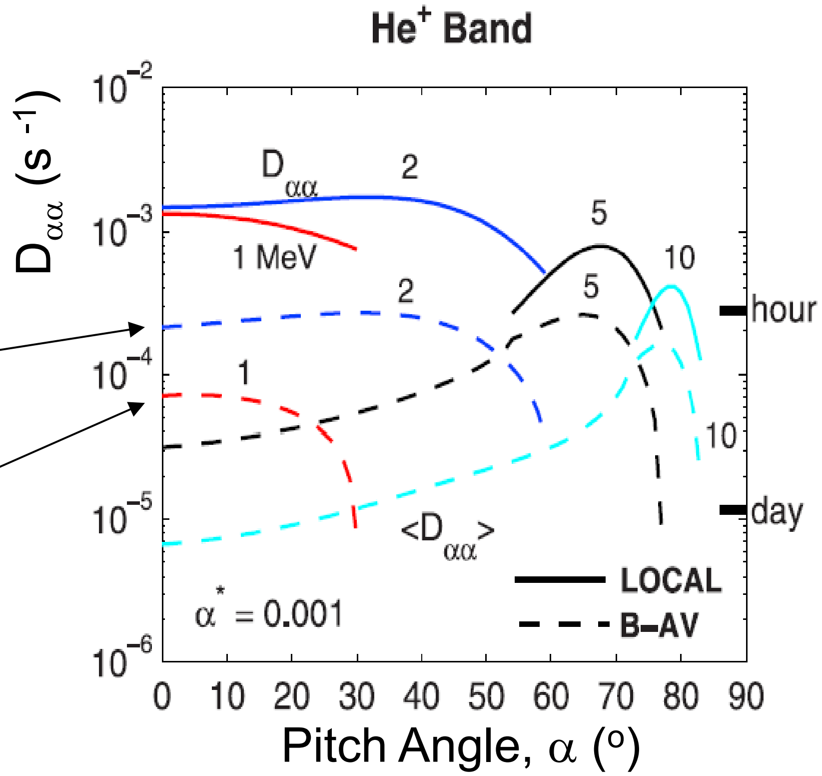
Scatterring Rates in the Helium Band

- 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

Summers *et al.*, JGR, 2007

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BAS Radiation Belt Model

- BAS has developed a physical model of the Earth's radiation belts [**Glauert *et al*., in prep.**]

- The model is based on the solution of a diffusion equation for phase-space density

- Time-dependent Fokker Planck equation in pitch-angle (α), energy (E) and L* (L)

- The values of the diffusion coefficients D_{LL}, $D_{\alpha\alpha}$ and D_{EE} must be calculated

pitch angle diffusion ***energy diffusion***

$$\frac{\partial f}{\partial t} = \frac{1}{g(\alpha)}\frac{\partial}{\partial \alpha}\bigg|_{E,L}\left(g(\alpha)D_{\alpha\alpha}\frac{\partial f}{\partial \alpha}\bigg|_{E,L}\right) + \frac{1}{A(E)}\frac{\partial}{\partial E}\bigg|_{\alpha,L}\left(A(E)D_{EE}\frac{\partial f}{\partial E}\bigg|_{\alpha,L}\right)$$
$$+ L^2\frac{\partial}{\partial L}\bigg|_{\mu,J}\left(\frac{1}{L^2}D_{LL}\frac{\partial f}{\partial L}\bigg|_{\mu,J}\right) - \frac{f}{\tau(\alpha,E)}$$

radial diffusion ***loss term***

$$g(\alpha) = \sin 2\alpha\left(1.3802 - 0.3198\left(\sin\alpha + \sin\alpha^{1/2}\right)\right)$$
$$A(E) = (E + E_0)\left(E(E + 2E_0)\right)^{1/2}$$

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BAS Radiation Belt Model

- For radial diffusion we use the magnetic radial diffusion coefficients of **Brautigam and Albert [2000]**
- Pitch angle and energy diffusion coefficients are calculated using the PADIE code [**Glauert and Horne, 2005**]
- They are based on CRRES statistical maps of lower band chorus, plasmaspheric hiss and lightning generated whistlers scaled by Kp [**Meredith *et al.*, 2003; 2007**]

$$\frac{\partial f}{\partial t} = \frac{1}{g(\alpha)}\frac{\partial}{\partial \alpha}\bigg|_{E,L}\overbrace{\left(g(\alpha) D_{\alpha\alpha}\frac{\partial f}{\partial \alpha}\bigg|_{E,L}\right)}^{\textit{pitch angle diffusion}} + \frac{1}{A(E)}\frac{\partial}{\partial E}\bigg|_{\alpha,L}\overbrace{\left(A(E) D_{EE}\frac{\partial f}{\partial E}\bigg|_{\alpha,L}\right)}^{\textit{energy diffusion}}$$

$$+ L^2\frac{\partial}{\partial L}\bigg|_{\mu,J}\underbrace{\left(\frac{1}{L^2} D_{LL}\frac{\partial f}{\partial L}\bigg|_{\mu,J}\right)}_{\textit{radial diffusion}} - \underbrace{\frac{f}{\tau(\alpha,E)}}_{\textit{loss term}}$$

$$g(\alpha) = \sin 2\alpha\left(1.3802 - 0.3198\left(\sin\alpha + \sin\alpha^{1/2}\right)\right)$$

$$A(E) = (E + E_0)\left(E(E + 2E_0)\right)^{1/2}$$

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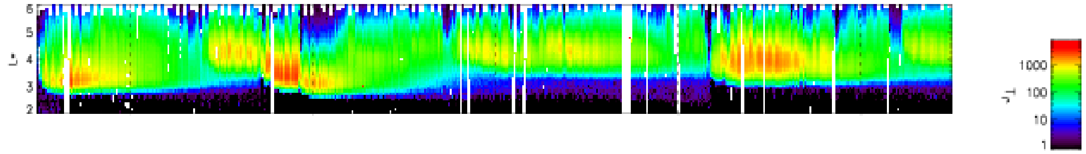
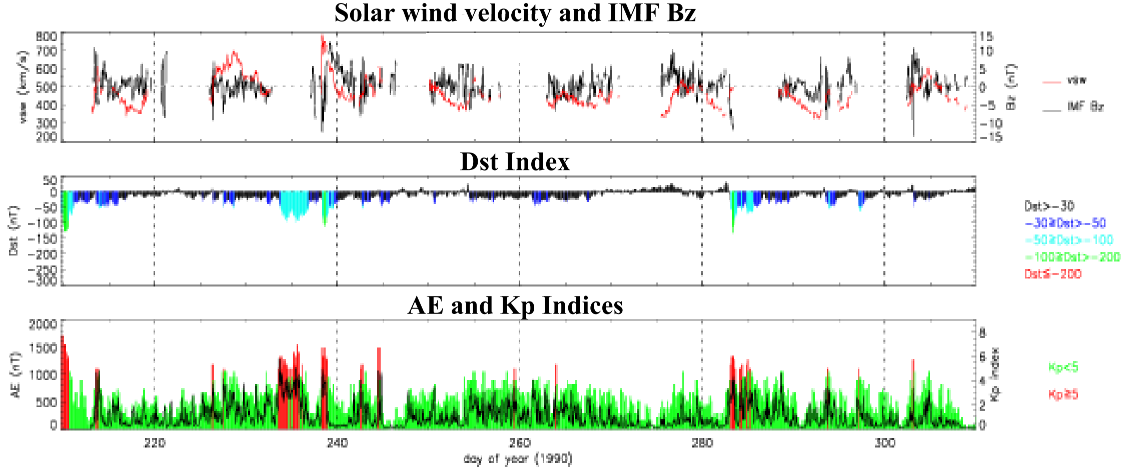
Simulation of a long time period

- Model 100 days during the CRRES mission

E = 1.09 MeV

CRRES Data





Glauert *et al*., JGR, in prep

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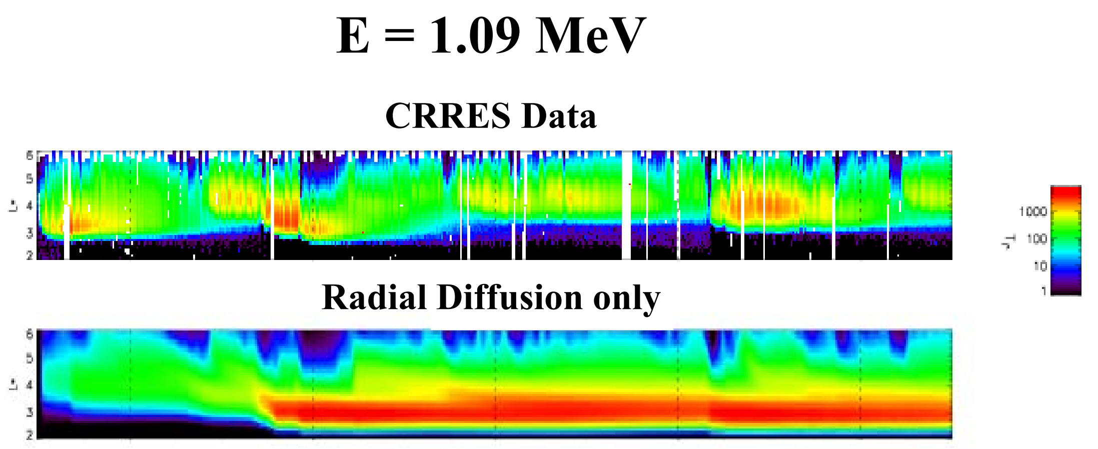
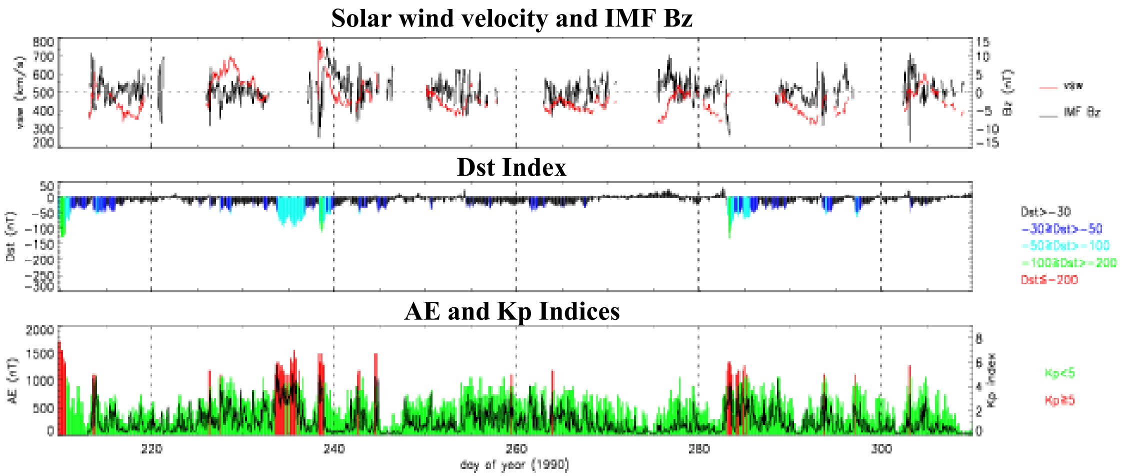
Simulation of a long time period

- Model 100 days during the CRRES mission

- Radial diffusion alone overestimates flux and does not predict the slot





Glauert *et al*., JGR, in prep

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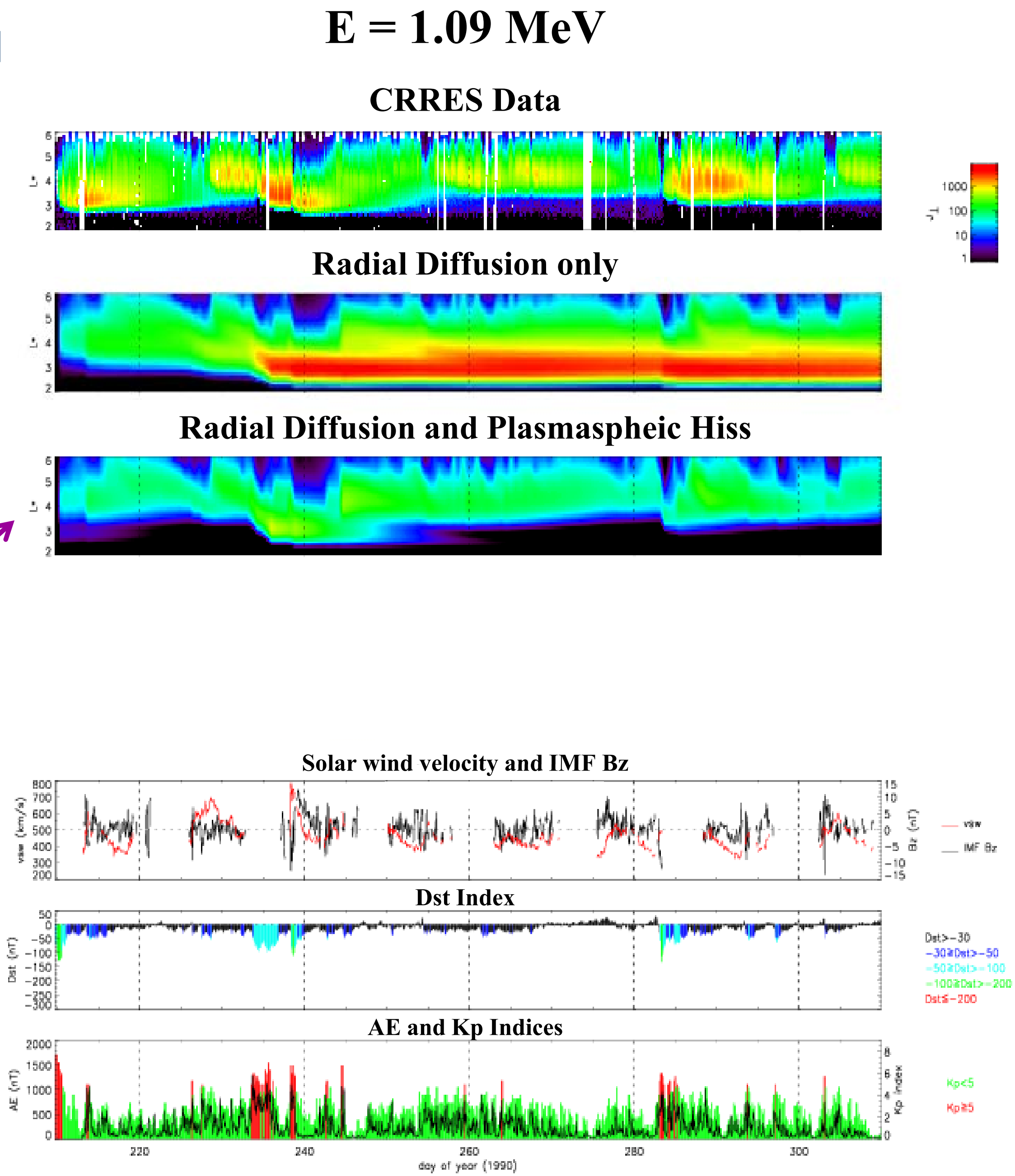
Simulation of a long time period

- Model 100 days during the CRRES mission
- Radial diffusion alone overestimates flux and does not predict the slot
- Radial diffusion and hiss predicts the slot but underestimates flux due to lack of local acceleration



Glauert *et al.*, JGR, in prep

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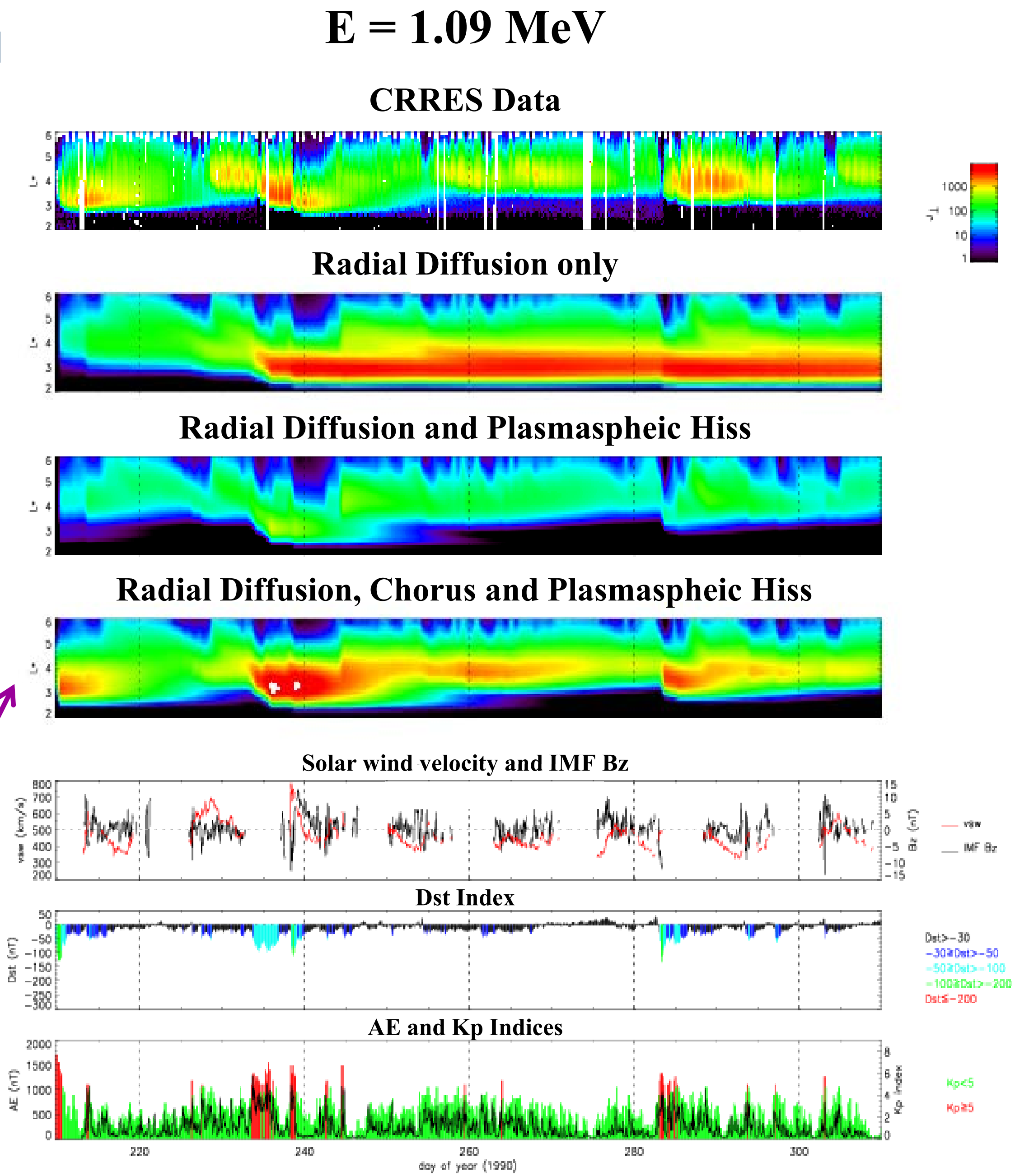
Simulation of a long time period

- Model 100 days during the CRRES mission
- Radial diffusion alone overestimates flux and does not predict the slot
- Radial diffusion and hiss predicts the slot but underestimates flux due to lack of local acceleration
- Radial diffusion, chorus and hiss best reproduce structure of the radiation belts



Glauert *et al*., JGR, in prep

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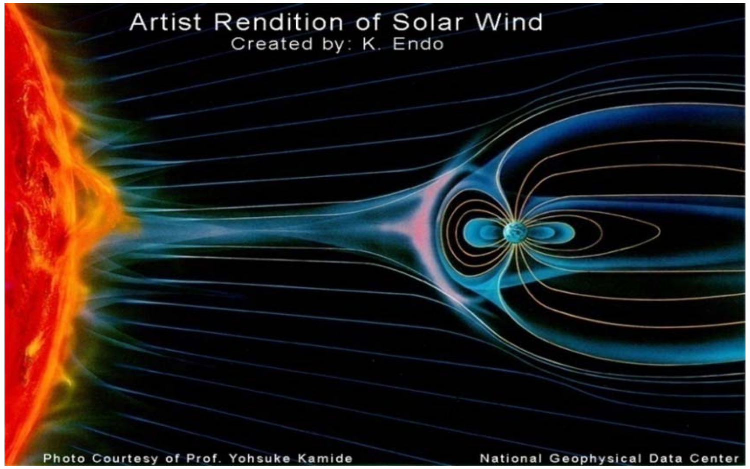
• SPACECAST is an EU-funded project designed to protect space assets from high energy particles by developing European dynamic modelling and forecasting capabilities

  – 3 year FP7 collaborative project

  – March 2011-March 2014

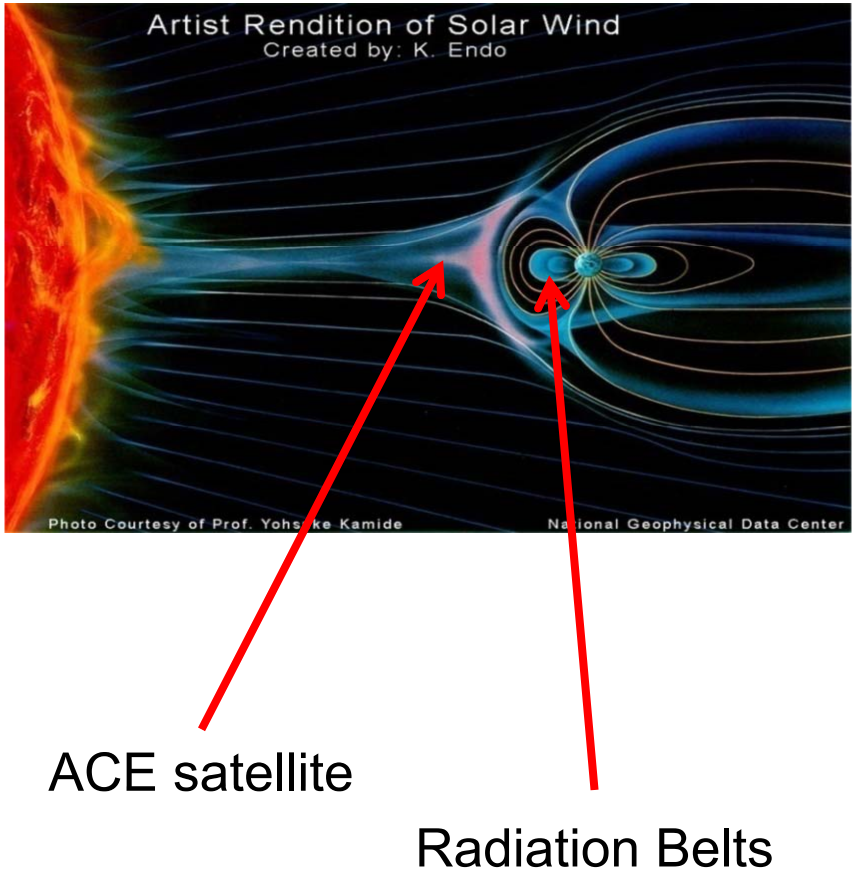
  – led by Professor Richard Horne (BAS)



• A major goal of the SPACECAST project is to forecast the electron flux in the outer radiation belt

Forecasting Concept

- It takes ~ 40-60 minutes for the solar wind to flow from the ACE satellite to the Earth
- The Swedish Inst. Sp. Phys. (Lund) uses the ACE data to forecast the Kp index
- We then use the Kp forecast to drive the BAS radiation belt model



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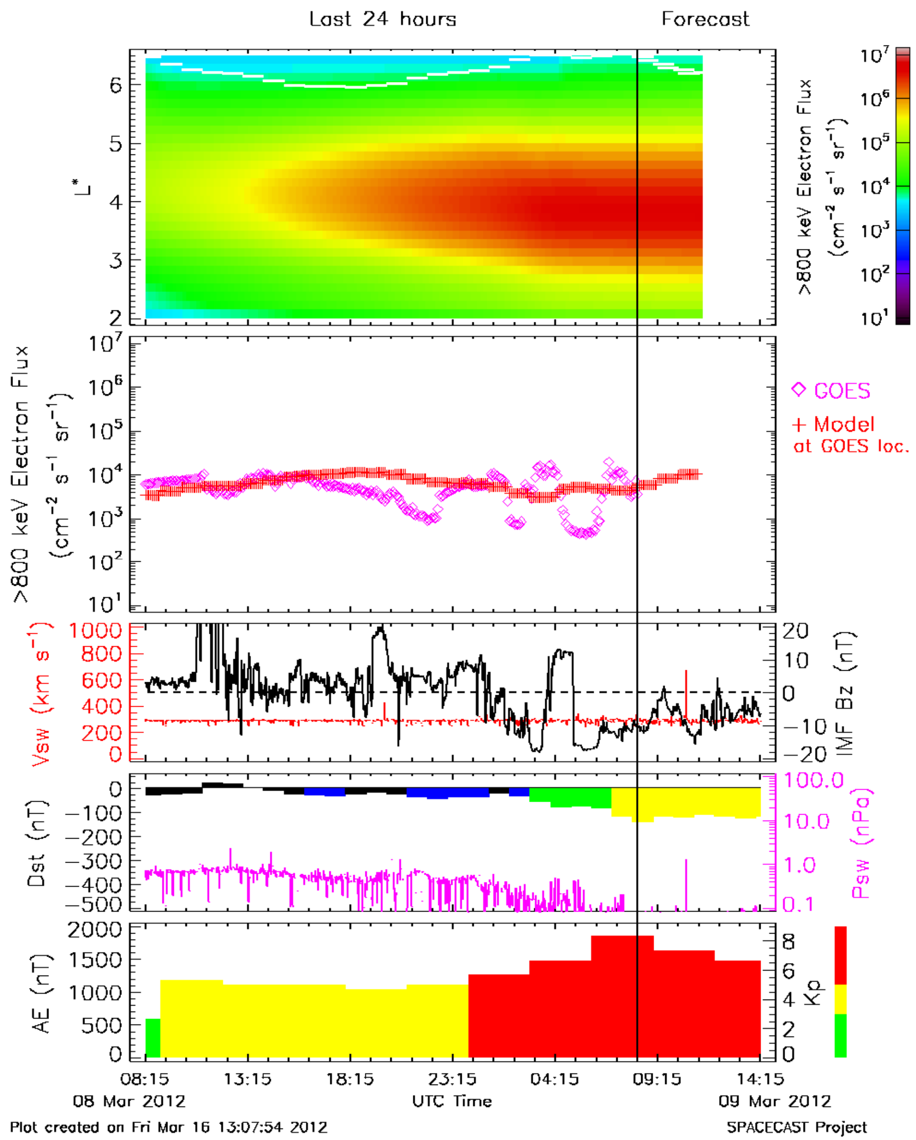
Electron Radiation Belt Forecasts

- Model
  - operates 24 hours a day in near real time and is updated every hour
  - provides 3 hourly forecasts using the Kp forecast from Lund
  - provides a risk index for GEO, MEO and the slot region
- The forecast is freely available on-line: http://www.fp7-spacecast.eu



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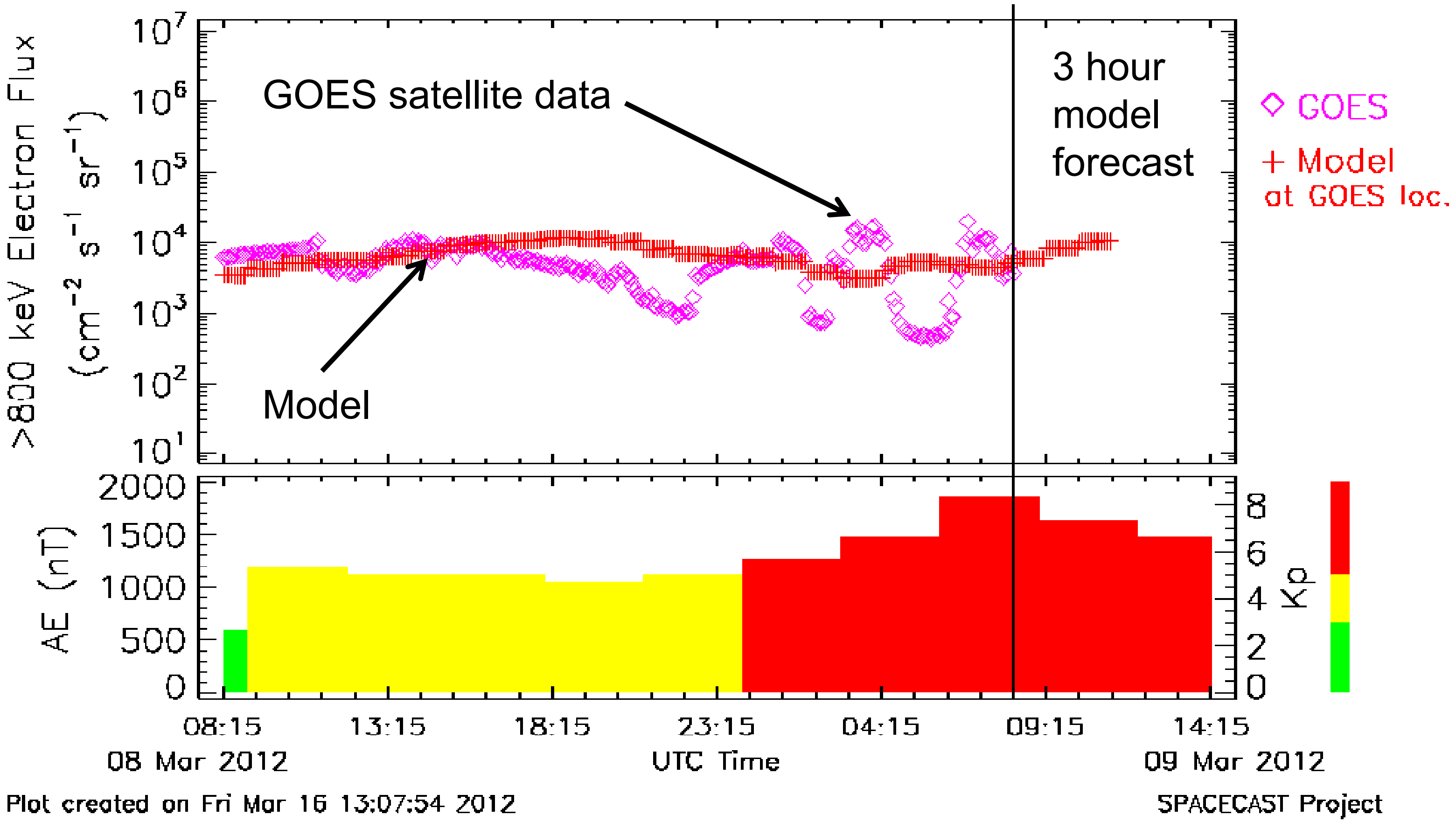
SPACECAST – Forecast >800 keV electrons

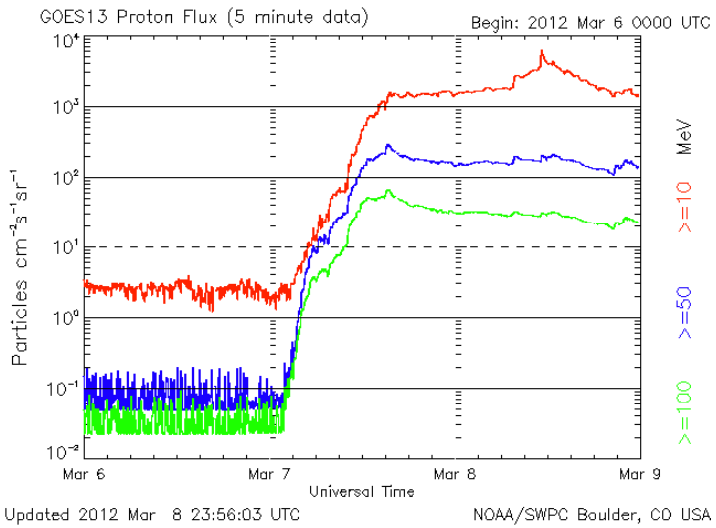


Horne *et al.*, JSW, in press

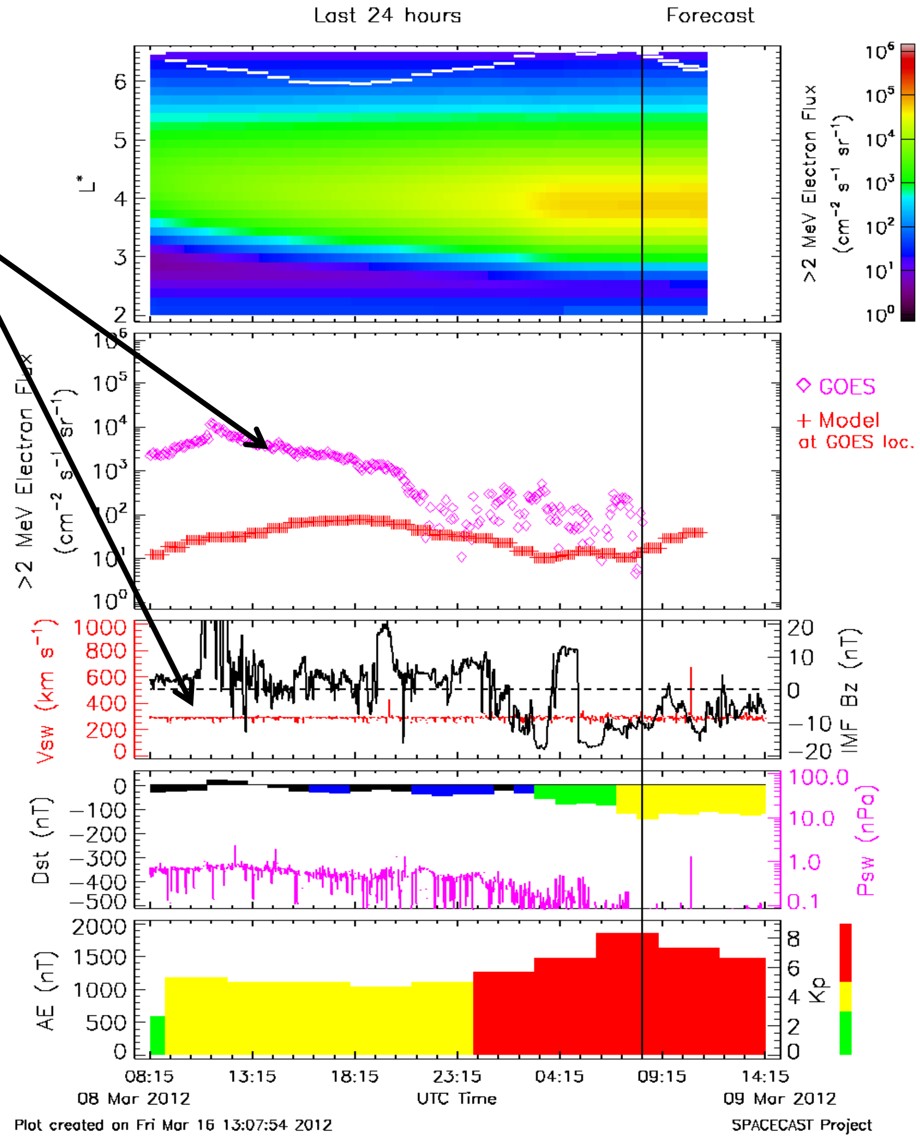
- During the 9 March 2012 magnetic storm the model forecast the E > 800 keV flux at GOES 13 to within a factor of two and later in the event to within a factor of ten

SPACECAST > 2 MeV Electrons

- ACE solar wind velocity data from and GOES E > 2 MeV flux became unreliable due to the solar proton event



- SPACECAST model switched to use a nowcast of the Kp index from BGS and continued to forecast without interruption



Horne *et al*., JSW, in press

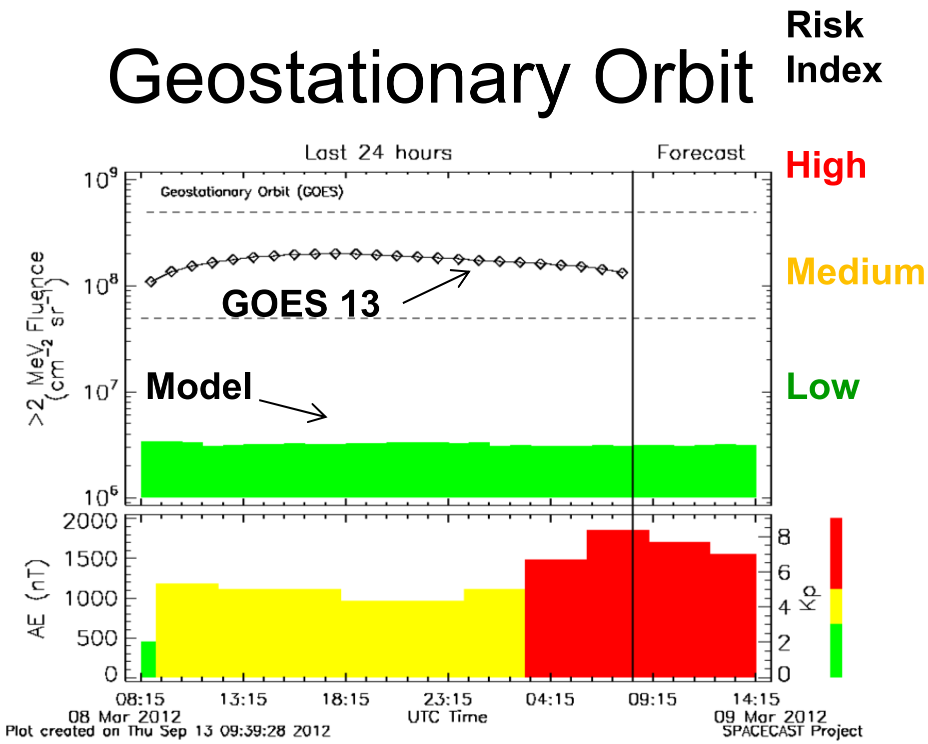
Risk of Satellite Charging - ESD

- Model results converted into a risk index based on previous satellite anomalies at geostationary orbit

- High Risk
  - fluence > 5×10^8 cm^{-2} sr^{-1}
- Medium Risk
  - 5×10^7 < fluence < 5×10^8 $cm^{-2} sr^{-1}$
- Low Risk
  - fluence < 5×10^7 cm^{-2} sr^{-1}

- Note: GOES electron daily fluence too high during this event due to contamination by > 10 MeV protons

Geostationary Orbit



Horne *et al*., JSW, in press

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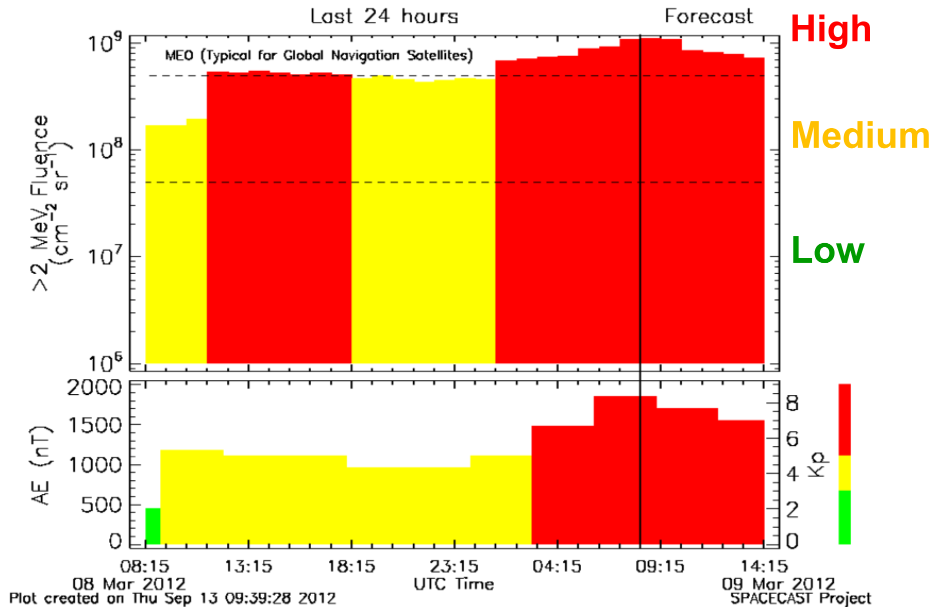
Risk of Satellite Charging - ESD

- We also calculate a risk index for MEO and the slot region
- Risk depends on satellite design
- Needs close collaboration with satellite operators and designers

GPS/Galileo Orbit

Risk Index



Horne *et al*., JSW, in press

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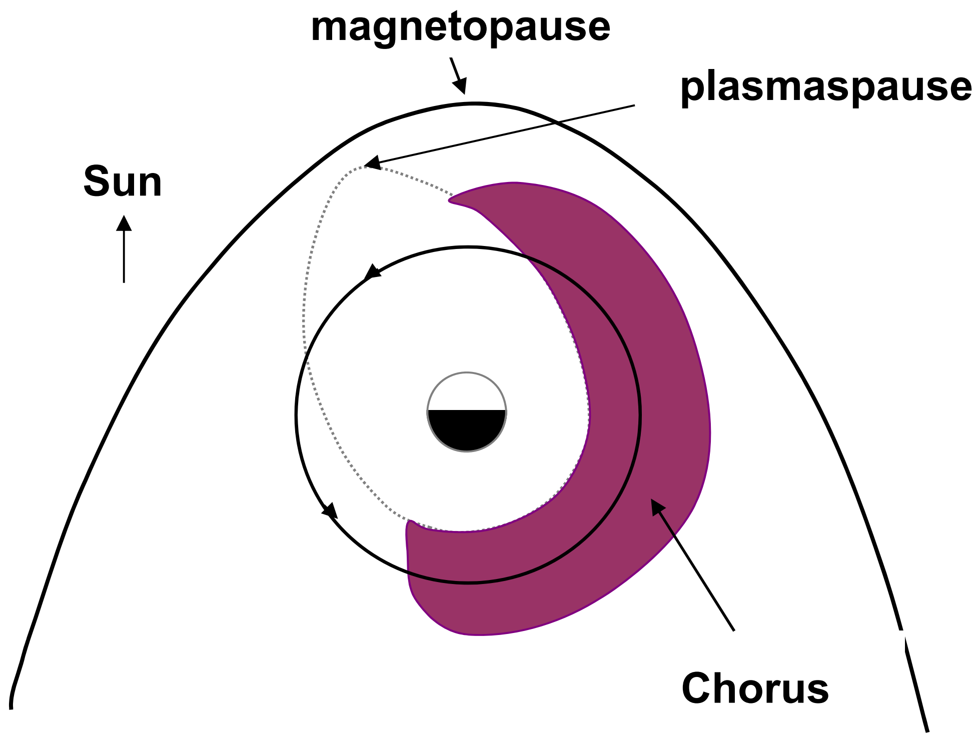
Next Steps

- Current work is focussed on developing the underlying models. Key next steps include:
  - Better treatment of the outer boundary
  - Improved diffusion coefficients for hiss and chorus
  - Improved radial diffusion coefficients
  - Better low energy boundary condition
  - Model validation
- Improvements to the SPACECAST forecasts will be introduced on 1st March 2013
- Future work will include an assessment of the role of magnetosonic waves and EMIC waves in radiation belt dynamics

Conclusions

• ***Chorus waves*** are an important acceleration and loss mechanism for electrons with energies from 0.1 to a few MeV



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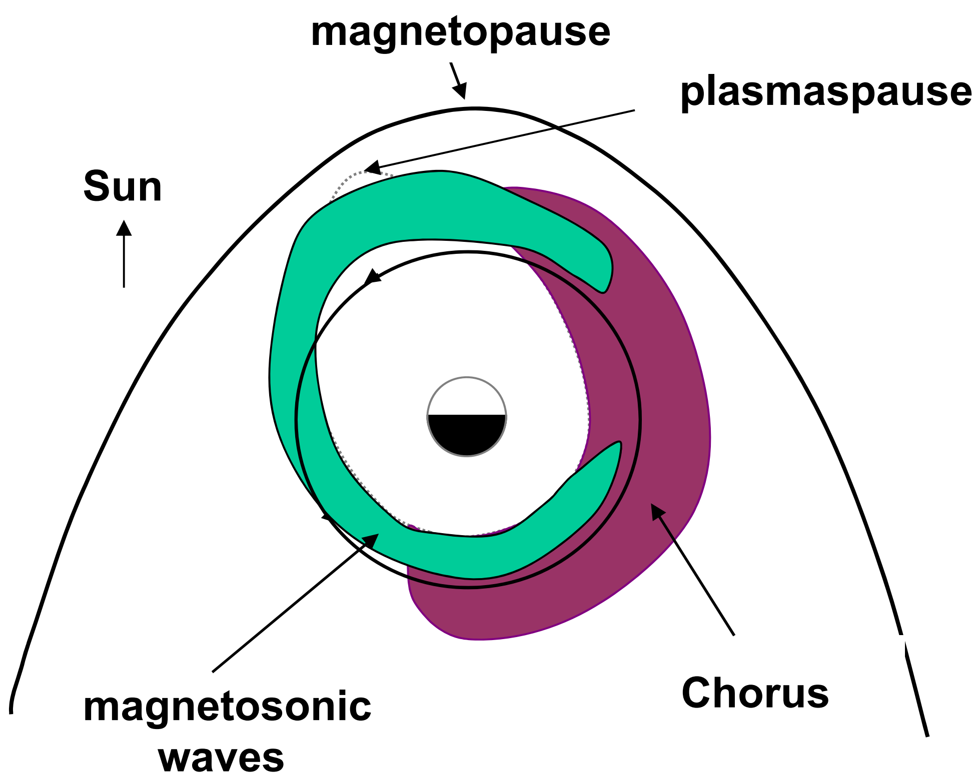
Conclusions

• ***Chorus waves*** are an important acceleration and loss mechanism for electrons with energies from 0.1 to a few MeV

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



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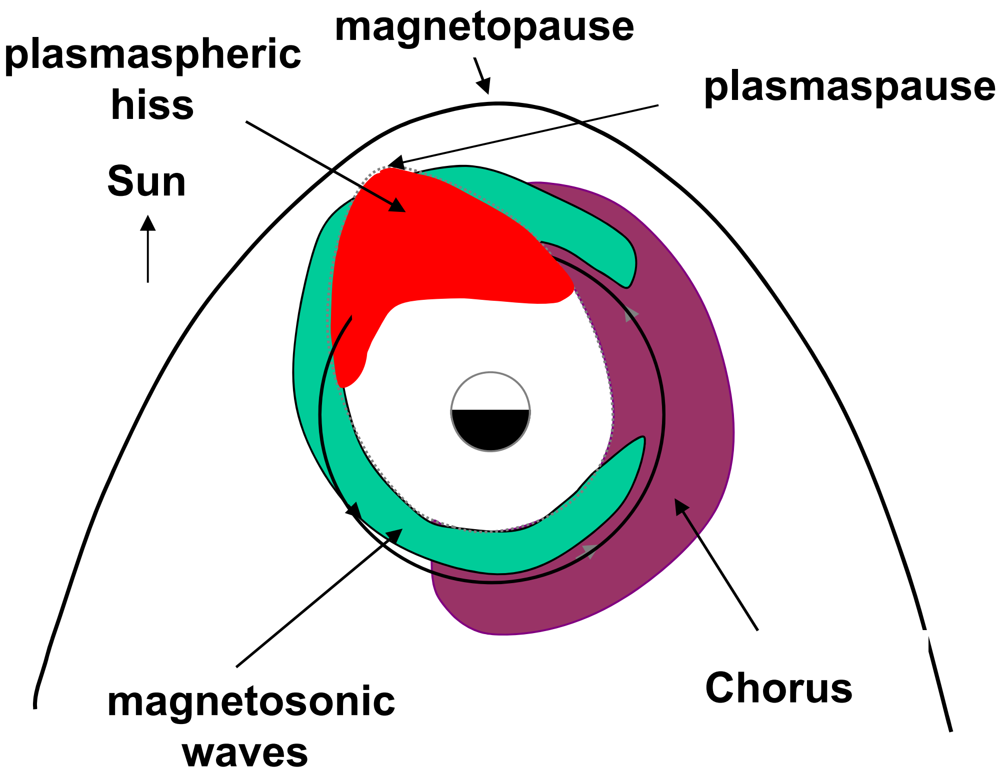
Conclusions

• ***Chorus waves*** are an important acceleration and loss mechanism for electrons with energies from 0.1 to a few MeV

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

• ***Plasmaspheric hiss*** is a major loss process for electron energies from 0.1 to a few MeV



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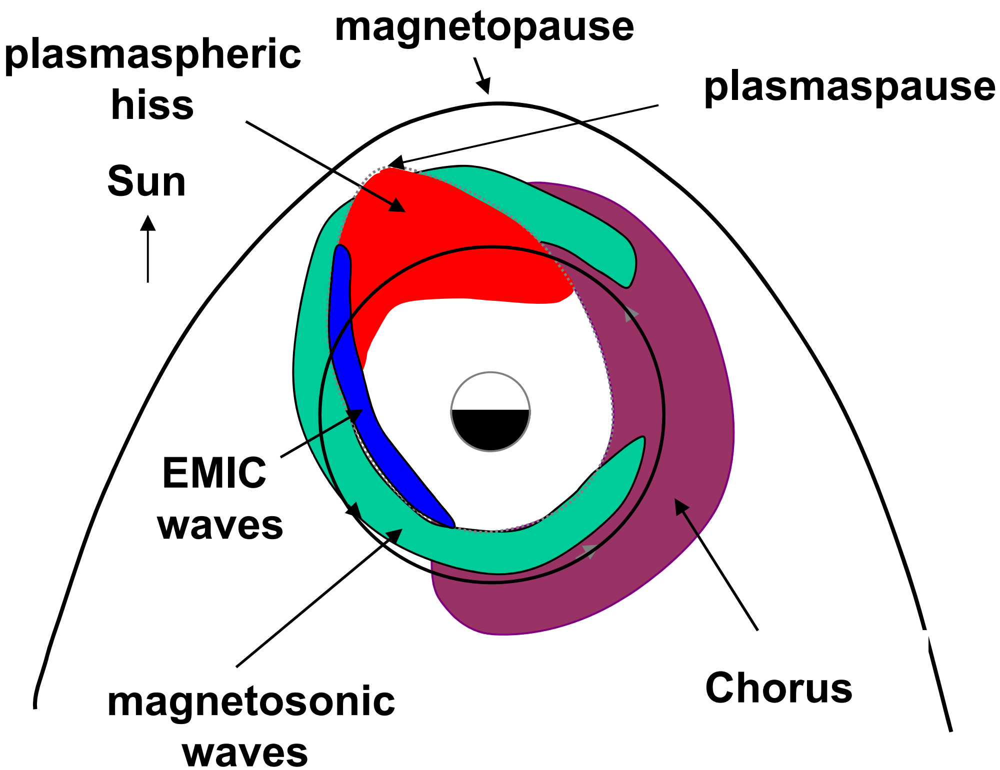
Conclusions

- ***Chorus waves*** are an important acceleration and loss mechanism for electrons with energies from 0.1 to a few MeV

- ***Magnetosonic waves*** may be an important acceleration mechanism

- ***Plasmaspheric hiss*** is a major loss process for electron energies from 0.1 to a few MeV

- ***EMIC waves*** may be an important loss mechanism for MeV electrons



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Conclusions

- SPACECAST is a new European system that includes real time forecasts of the radiation belts for satellite operators
- The forecasts use a physics based model that includes radial diffusion and wave-particle interactions. The model
    - operates 24 hours a day in near real time and is updated every hour
    - provides 3 hourly forecasts using the Kp forecast from Lund
    - provides a risk index for GEO, MEO and the slot region
- Improvements to the SPACECAST forecasts will be introduced on 1st March 2013

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SPACECAST

Acknowledgement

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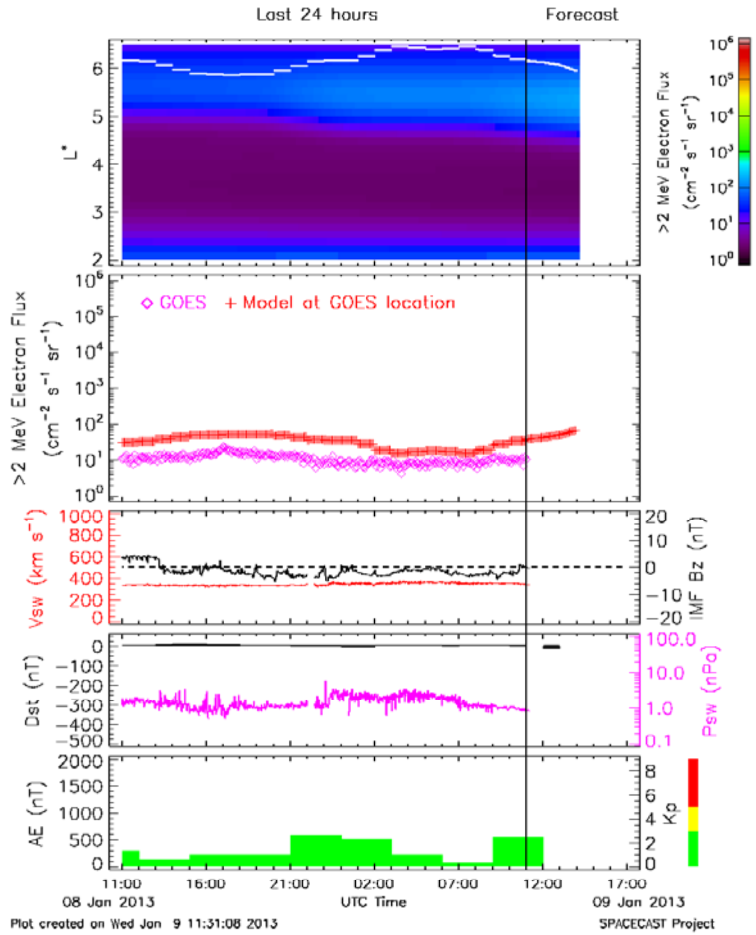
E > 2 MeV Electrons



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http://www.fp7-spacecast.eu