CRRES Plasma Wave Observations

Nigel P. Meredith
British Antarctic Survey
Plasma waves play a fundamental role in the dynamics of the Earth’s radiation belts and inner magnetosphere.
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.
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.
Energetic electrons \((E > 100 \text{ keV})\) 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
• Fluxes change dramatically on a variety of different time scales.
• Covers a range of over 4 orders of magnitude.

Baker et al., AG, 2008
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
**CRRES Orbit**

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

- Conservation of first invariant implies:
  \[ p_{\perp}^2 = 2m_eB \]

- Inward radial diffusion leads to significant energisation.
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].
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

Hudson et al., AG, 2004
Poloidal Pc 5 ULF Waves Measured by CRRES

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

Hudson et al., AG, 2004
Gyroresonant wave-particle interactions play a key role in the Earth’s radiation belts.

These interactions can occur when the wave frequency, $\omega$, is Doppler-shifted to a multiple of the relativistic electron gyrofrequency, $\Omega_e$.

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

- $k_\parallel$ is the wave number parallel to the magnetic field
- $v_\parallel$ is the electron velocity parallel to the magnetic field
- $\gamma$ is the relativistic factor
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
Plasma waves that can lead to efficient gyroresonant wave particle interactions with relativistic electrons include:

- Whistler mode chorus
- Magnetosonic waves
- Plasmaspheric hiss
- EMIC waves.
Whistler mode chorus is an intense electromagnetic emission observed outside of the plasmapause in the frequency range $0.1f_{ce} < f < 0.8f_{ce}$. 
The waves are generated by plasma sheet electrons injected during substorms and/or enhanced convection.
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].
October 9th 1990 Storm

Recovery phase associated with:

Meredith et al., JGR, 2002
October 9th 1990 Storm

Recovery phase associated with:

- enhanced AE activity

Meredith et al., JGR, 2002
October 9\textsuperscript{th} 1990 Storm

Recovery phase associated with:

- enhanced AE activity
- enhanced levels of whistler mode chorus

Meredith et al., JGR, 2002
October 9\textsuperscript{th} 1990 Storm

Recovery phase associated with:

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

Meredith \textit{et al}., JGR, 2002
Phase Space Density Analysis

- Important information on the nature of the acceleration process can be found through phase space density analysis.
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.
• 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.
Phase Space Density Analysis

\( f(\mu, K, L^*) \) (cm MeV/c)^{-3}

\( \mu = 550 \text{ MeV/G}; K = 0.11 \text{ G}^{1/2}R_E \)

Iles et al., JGR, 2006
Phase Space Density Analysis

- 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.

Iles et al., JGR, 2006
Survey of 26 Geomagnetic Storms

Meredith et al., JGR, 2003
Survey of 26 Geomagnetic Storms

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

Meredith et al., JGR, 2003
Survey of 26 Geomagnetic Storms

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

Meredith et al., JGR, 2003
Survey of 26 Geomagnetic Storms

- 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

Meredith et al., JGR, 2003
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° < λm < 15°)

Equatorial Lower-Band Chorus

- Quiet
- Moderate
- Active

Equatorial fpe/fce

- Quiet
- Moderate
- Active

Meredith et al., GRL, 2003
Equatorial Region (-15° < λ_m < 15°)

Equatorial Lower-Band Chorus

Quiet

Moderate

Active

Equatorial fpe/fce

Quiet

Moderate

Active

active conditions
4 < L < 6
23 – 13 MLT

Meredith et al., GRL, 2003
Mid-Latitude Region (15° < |\(\lambda_m| < 30°\))

Meredith et al., GRL, 2003
Mid-Latitude Region (15° < |λₘ| < 30°)

active conditions
4 < L < 6
06 – 14 MLT

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
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.
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?
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

Cluster 3 - 25 November 2002

- intense electromagnetic emissions, $f_{cp} < f < f_{lhr}$
- compressional waves, propagate across $B_0$
- generated by proton ring distributions [Boardsen et al., JGR, 1992]
Global Distribution of Magnetosonic Waves

Magnetosonic Waves \(0.5f_{\text{LHR}} \leq f < f_{\text{LHR}}; -3^\circ < \lambda_m < 3^\circ\)

Outside the plasmapause

- \(AE^* < 100\) nT
- \(100 \leq AE^* < 300\) nT
- \(AE^* \geq 300\) nT

Inside the Plasmapause

- \(AE^* < 100\) nT
- \(100 \leq AE^* < 300\) nT
- \(AE^* \geq 300\) nT

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

Meredith et al., JGR, 2008
Global Distribution of Magnetosonic Waves

Magnetosonic Waves (0.5f_{LHR} < f < f_{LHR}; -3^0 < \lambda_m < 3^0)

Outside the plasmapause

- AE* < 100 nT
- 100 < AE* < 300 nT
- AE* > 300 nT

Inside the Plasmapause

- AE* < 100 nT
- 100 < AE* < 300 nT
- AE* > 300 nT

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

Meredith et al., JGR, 2008
Global Distribution of Magnetosonic Waves

Magnetosonic Waves \((0.5f_{\text{LHR}} < f < f_{\text{LHR}}; -3^\circ < \lambda_m < 3^\circ)\)

Outside the plasmapause

- \(\text{AE}^* < 100 \text{ nT}\)
- \(100 < \text{AE}^* < 300 \text{ nT}\)
- \(\text{AE}^* > 300 \text{ nT}\)

Inside the Plasmapause

- \(\text{AE}^* < 100 \text{ nT}\)
- \(100 < \text{AE}^* < 300 \text{ nT}\)
- \(\text{AE}^* > 300 \text{ nT}\)

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

- Strongest waves: active conditions
- Strongest waves: most local times
- Strongest waves: dusk side

Meredith et al., JGR, 2008
Global Distribution of Magnetosonic Waves

Magnetosonic Waves ($0.5f_{LHR} < f < f_{LHR}$; $-3^\circ < \lambda_m < 3^\circ$)

Outside the plasmapause

- $\text{AE}^* (100 \text{ nT})$
- $100 < \text{AE}^* < 300 \text{ nT}$
- $\text{AE}^* > 300 \text{ nT}$

Inside the Plasmapause

- $\text{AE}^* (100 \text{ nT})$
- $100 < \text{AE}^* < 300 \text{ nT}$
- $\text{AE}^* > 300 \text{ nT}$

Strongest waves:
- active conditions
- most local times

Strongest waves:
- active conditions
- dusk side

- 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.

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.
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 is a broadband, structureless, ELF emission that occurs in the frequency range from 100 Hz to several kHz.
This whistler mode emission is confined to the higher density regions associated with the plasmasphere or plasmaspheric plumes.
Global Distribution of Plasmaspheric Hiss

Equatorial Plasmaspheric Hiss

- Quiet
- Moderate
- Active

Mid-Latitude Plasmaspheric Hiss

- Quiet
- Moderate
- Active

Meredith et al., JGR, 2004
Global Distribution of Plasmaspheric Hiss

Equatorial Plasmaspheric Hiss
- quiet
- moderate
- active

Mid-Latitude Plasmaspheric Hiss
- quiet
- moderate
- active

active
$2 < L < 4$
06 – 21 MLT

Meredith et al., JGR, 2004
Global Distribution of Plasmaspheric Hiss

Equatorial Plasmaspheric Hiss

- quiet
- moderate
- active

Sun

active
$2 < L < 4$
06 – 21 MLT

Mid-Latitude Plasmaspheric Hiss

- quiet
- moderate
- active

active
$2 < L < 4$
09 – 18 MLT

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.
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
Broadband Plasmaspheric Emissions

- Broadband plasmaspheric emissions can be split into two categories [Meredith et al., 2006]:
  - Plasmaspheric hiss
    - $100 \text{ Hz} < f < 2 \text{ kHz}$
    - generated by whistler mode chorus
  - MR whistlers
    - $2 \text{ kHz} < f < 5 \text{ kHz}$
    - 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.

Meredith et al., JGR, 2007
Slot Region Loss Timescales

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

Hiss \( (\psi_m = 80^\circ) \)

\[
\tau (\text{days})
\]

\[
\begin{array}{c}
\text{Energy (keV)} \\
100 \quad 1000
\end{array}
\]

Quiet Conditions \( (AE^* < 100 \text{ nT}) \)
Active Conditions \( (AE^* > 500 \text{ nT}) \)

Meredith et al., JGR, 2007
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.

Meredith et al., JGR, 2007

Hiss ($\psi_m = 52^\circ$)

Quiet Conditions ($\text{AE}^* < 100$ nT)
Active Conditions ($\text{AE}^* > 500$ nT)

Meredith et al., JGR, 2007
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.
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 $5.7 \pm 0.6$ days

Meredith et al., JGR, 2006
Quiet-time Decay in the Outer Radiation Belt

Experimental loss timescale is $2.0 \pm 0.1$ days
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

*Meredith et al., JGR, 2006*
Quiet Time Loss Timescales

- Quiet-time decay associated with:
  - Large values of $f_{pe}/f_{ce} (> 7)$
  - $<K_p> < 3^{-}$

Meredith et al., JGR, 2006
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 $K_p < 3^-$. 

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
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
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
Hiss in Plasmaspheric Plumes

- Plasmaspheric hiss is also observed in plasmaspheric plumes

Summers et al., JGR, 2008

Orbit: 0869
Date: 18-Jul-91 (91.199)
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
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
• 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
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

- **Whistler 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
Location of Events

• EMIC waves are primarily observed between 13:00 and 19:00 MLT over a range of L shells $>$ 3.
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
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
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
For lower concentrations of heavy ions the lower energy events can also occur over a range of frequencies below the hydrogen ion gyrofrequency.
Dependence on Dst Index

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

- Loss timescale near equatorial loss cone:
  - \( \sim 1 \) hour for 2 MeV electrons.
  - several hours for 1 MeV electrons.

\[
D_{\alpha\alpha} \quad \text{(s}^{-1})
\]

\( \alpha \) = 0.001

\( B_w = 1 \text{ nT} \)

1% drift averaging

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:

  – $E_{\text{min}}$ falls in the 1-2 MeV range

  – $D_{\alpha\alpha}$ is comparable to SD limit

  – suggesting enhanced MeV precipitation.

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
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.
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 $\lambda_m = 30^\circ$
  - 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.
Conclusions

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

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

• *Magnetosonic waves* may be an important acceleration mechanism.
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.
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 $> \sim 1$ MeV.
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*)