Electron Acceleration and Loss in the Earth's Radiation Belts

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Discovery of the Radiation Belts

- Discovered in 1958, by James Van Allen, U. of Iowa
- First US satellite, Explorer I
- Discovered by accident
- Intended to measure cosmic rays
  - but the count rates too high

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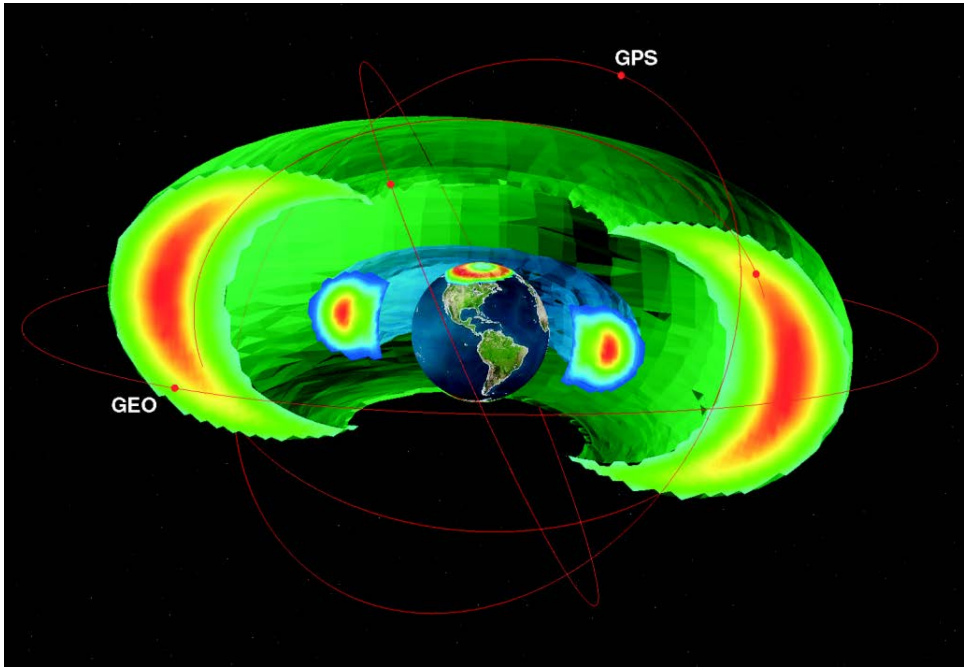
Earth's Radiation Belts

- Electrons and ions trapped inside the magnetic field
- Only one proton belt
- Two electron belts
    - Energies > 1 MeV
    - Peaks near 1.6 and 4.5 Re
- Outer electron belt highly variable
- Hazardous for spacecraft and humans



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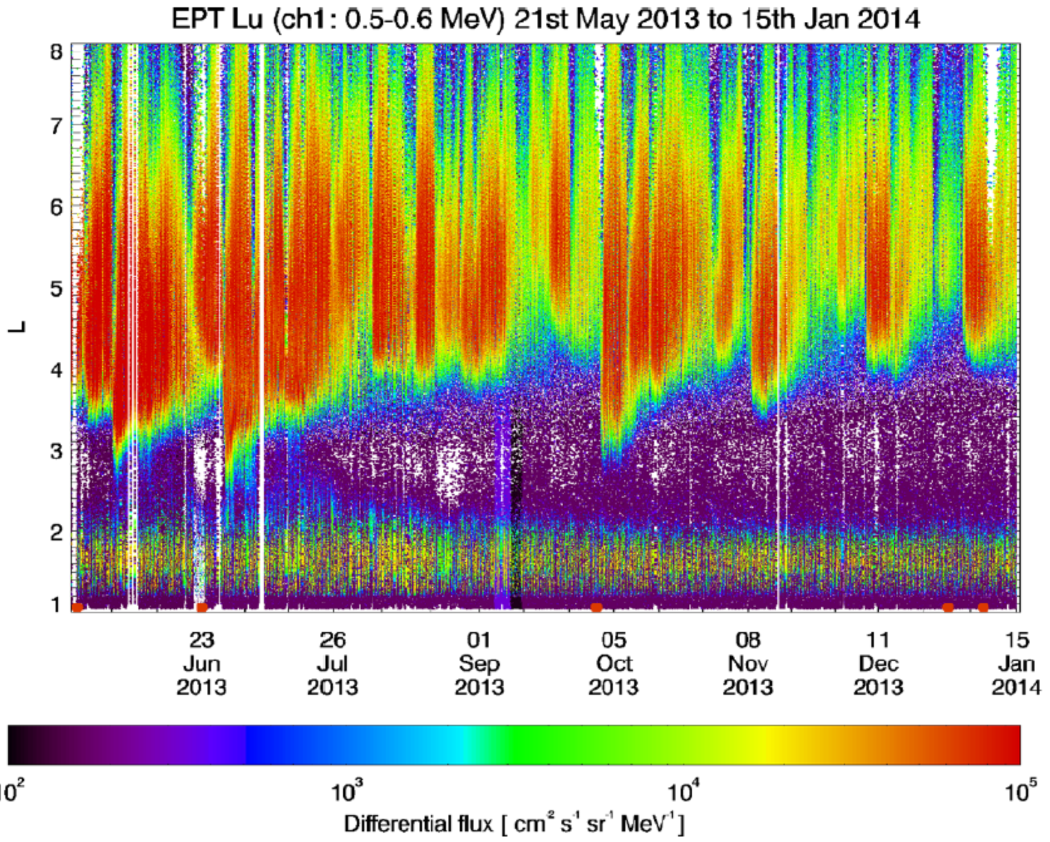
Satellite Anomalies – Related to Space Weather

- 20th Jan 1994
  - Intelsat 4 and Anik E1 - recovered in a few hours
  - Anik E2 - Loss of service for 6 months
- 11th January 1997
  - Telstar 401 - Total loss – Insurance payout $132m
- 19th May 1998
  - Galaxy IV - Total loss – Insurance payout $165m
- 23rd Oct to 6th Nov 2003
  - 47 satellites reported malfunctions – 1 total loss
  - 10 satellites – loss of service for more than 1 day
- 3rd Aug 2004
  - Galaxy 10R – loss of propulsion – Insurance payout $75m
- 5th Apr 2010
  - Galaxy 15 - Loss of service for 8 months - risk of collision
- 7th March 2012,
  - Sky Terra 1 and Spaceway 3 - Safe mode, loss of service for hours – days

- Impact of 1 in 100 year event?
  - Estimates vary widely

Radiation Belts - The Problem

- Proba V EPT data
- Pierrard et al. [2014]



- How do you produce >1 MeV electrons?
- What is responsible for the flux variations?
- The magnetosphere is a giant particle accelerator

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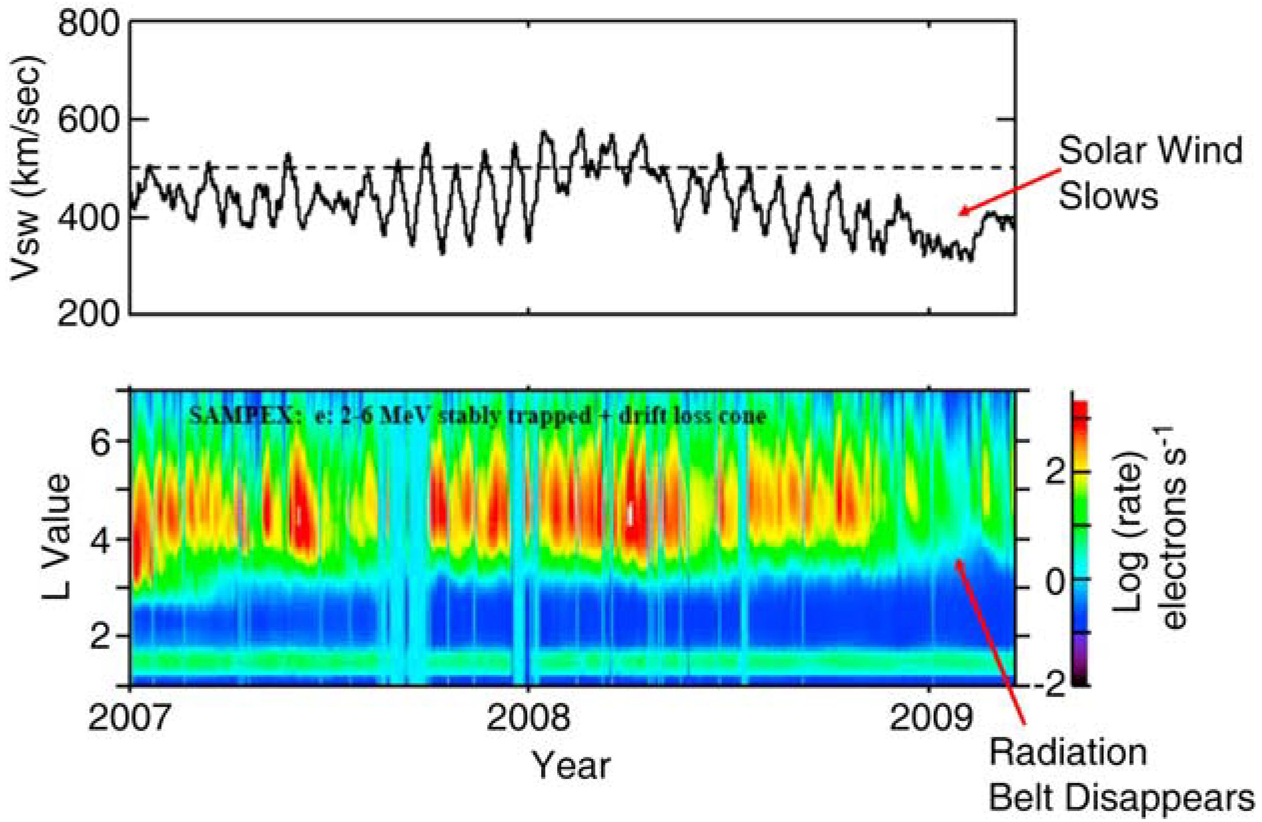
Solar Wind Speed – Electron Radiation Belts

Paulikas and Blake [1979] Russell et al. [2010]



- What causes the variability?
- How is the solar wind coupled to the radiation belts inside the magnetosphere?

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1960s - High Altitude Nuclear Detonations

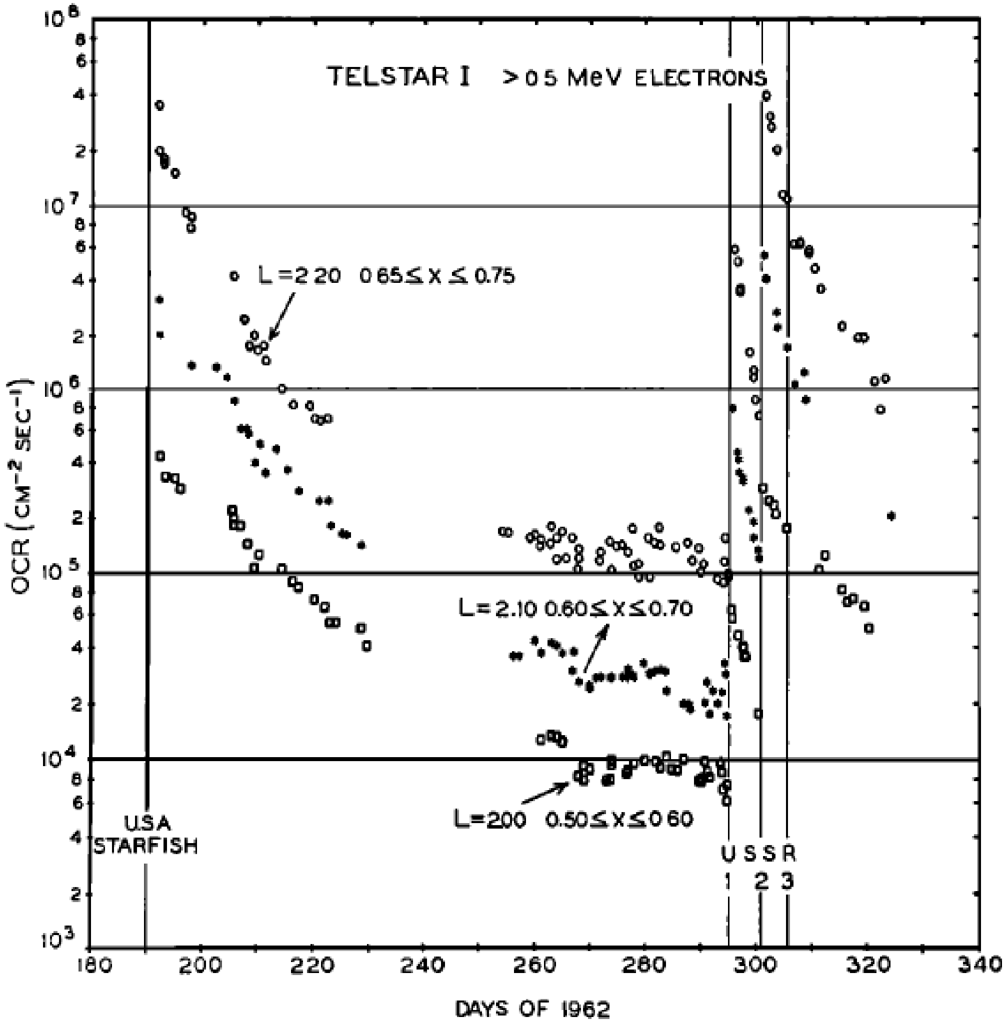

Fig. 8. Decay of >500-kev electrons following the high-altitude nuclear explosions of 1962. The data points for $L = 2.10$ and 2.00 have been displaced downward by one and two decades, respectively. On each L shell, the data are for a range of the coordinate $x = (1 - B_0/B)^{1/2}$.

- Starfish nuclear detonation, July 1962
- 1.4 Megaton at 400 km
- Injection of energetic electrons from beta decay of fission fragments

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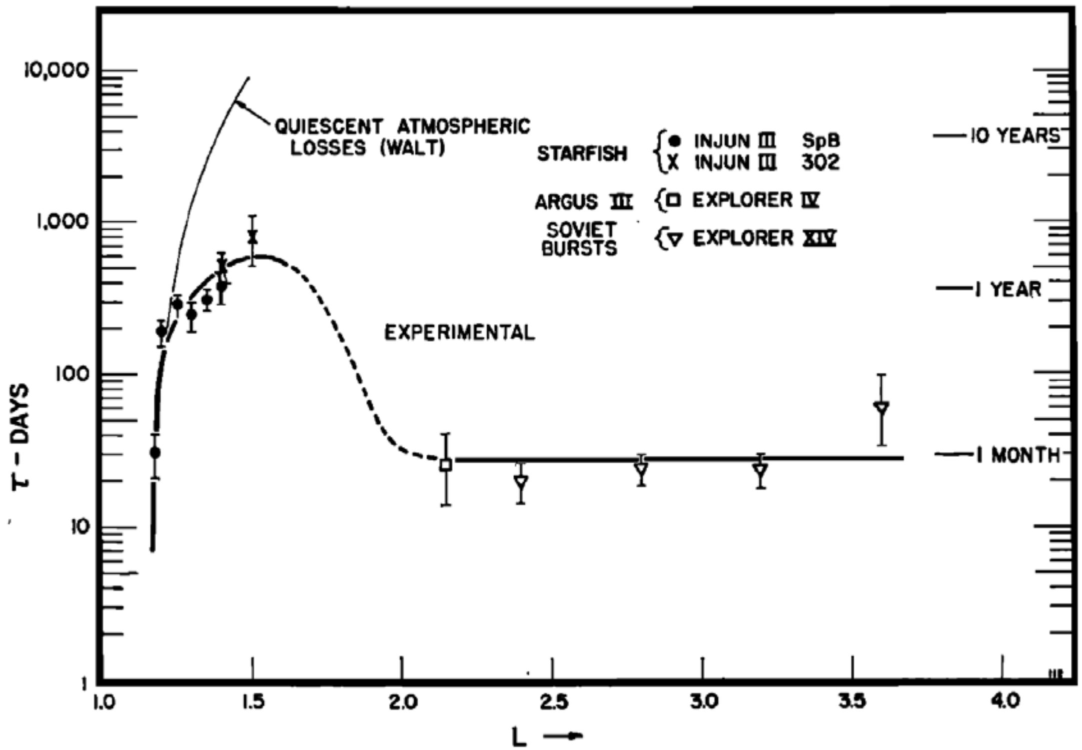
Timescale for Decay

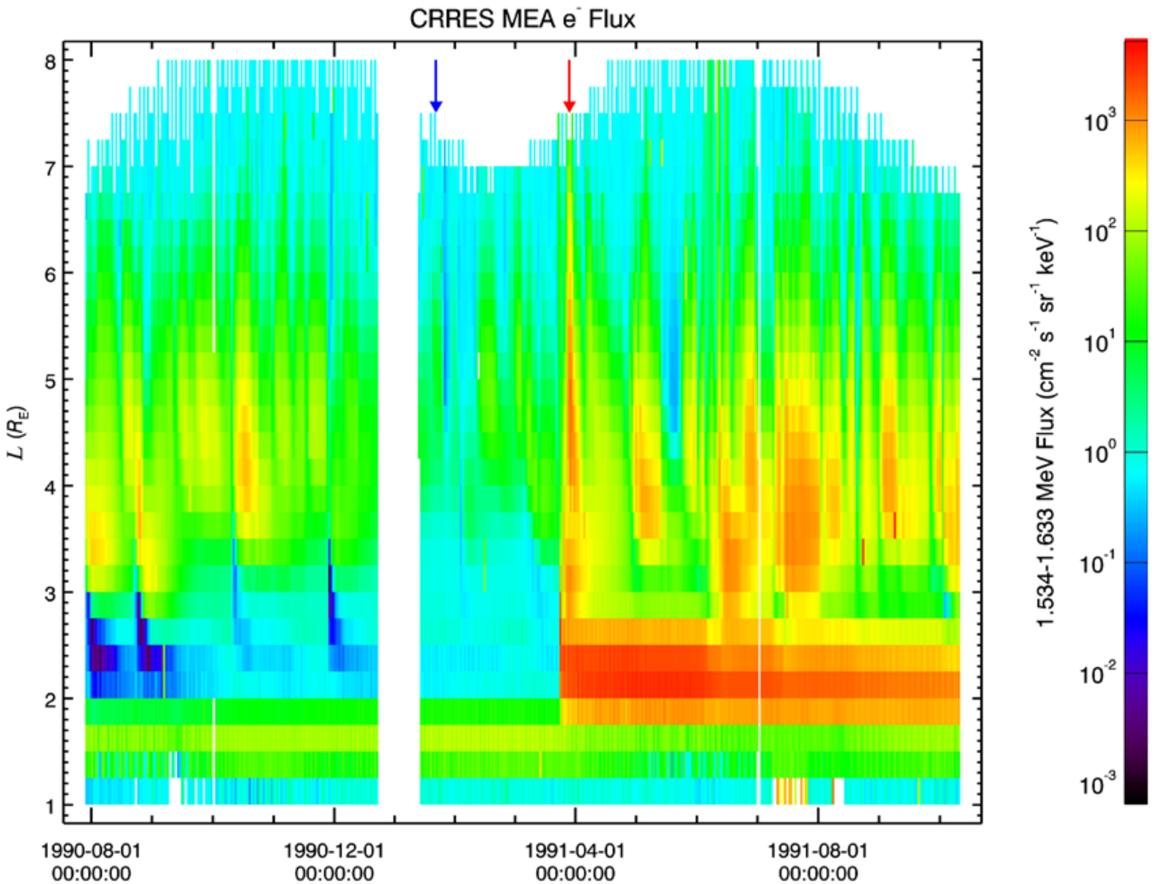


Van Allen [1966]

- Electron flux decays faster than predicted due to collisions
- Dungey, [1963] – suggested losses due to whistlers
- Losses due to wave-particle interactions + outward transport

March 1991 - Largest Injection Event

- Driven by a shock striking the magnetosphere
- Blake et al [1992], Hudson et al, [1995]



Heynderickx [2014]

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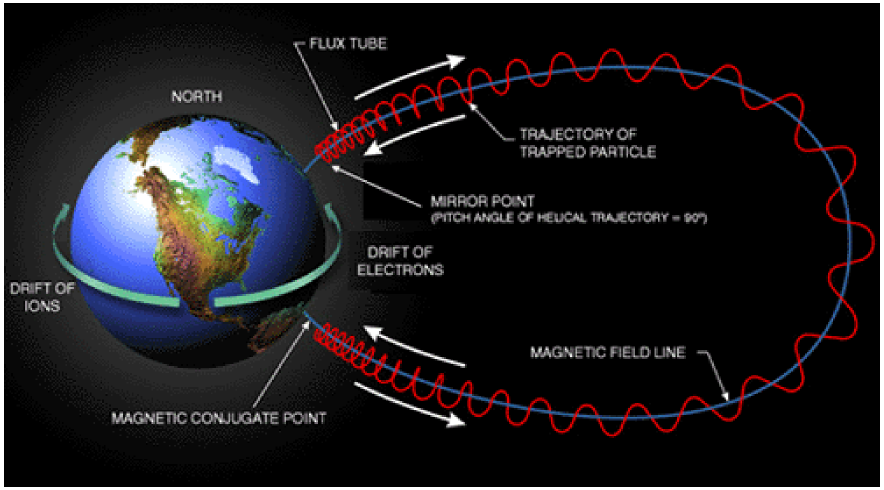
Particle Motion in the Earth's Magnetic Field

- Cyclotron motion around the field
- Bounce motion between mirror points in the north and south
- Drift motion around the Earth

For 1 MeV electron (α = 45^{o}) at L = 4.5

	Cyclotron	bounce	drift
Frequency =	10 kHz	3 Hz	1 mHz
Period =	0.1 ms	0.36 s	15 min

- Periodic motion results in conservation laws – the 3 adiabatic invariants



- Acceleration requires breaking 1 or more invariant
- When wave frequency ~ particle frequency

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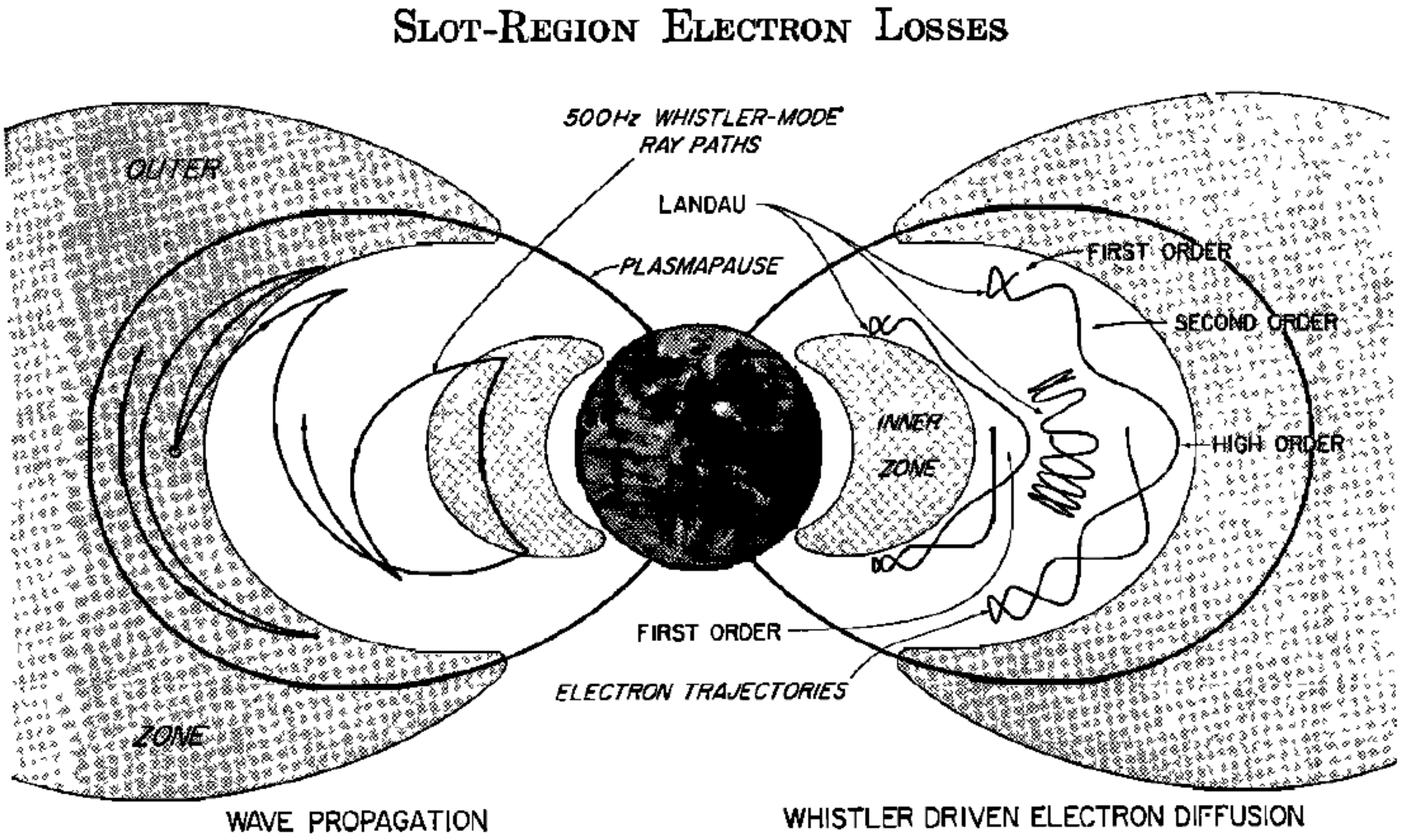
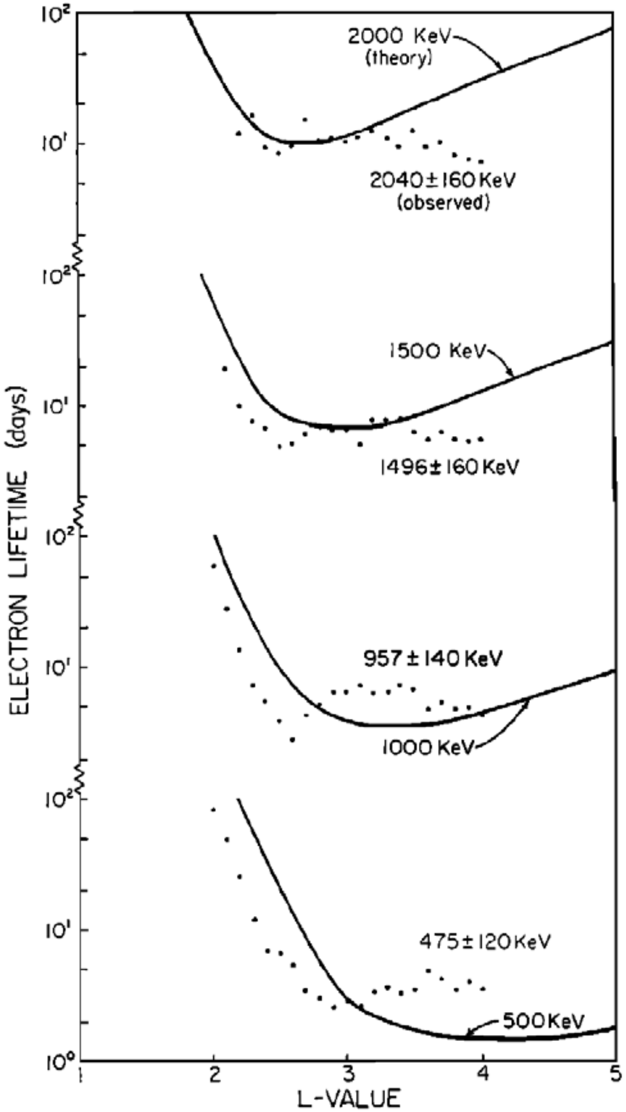
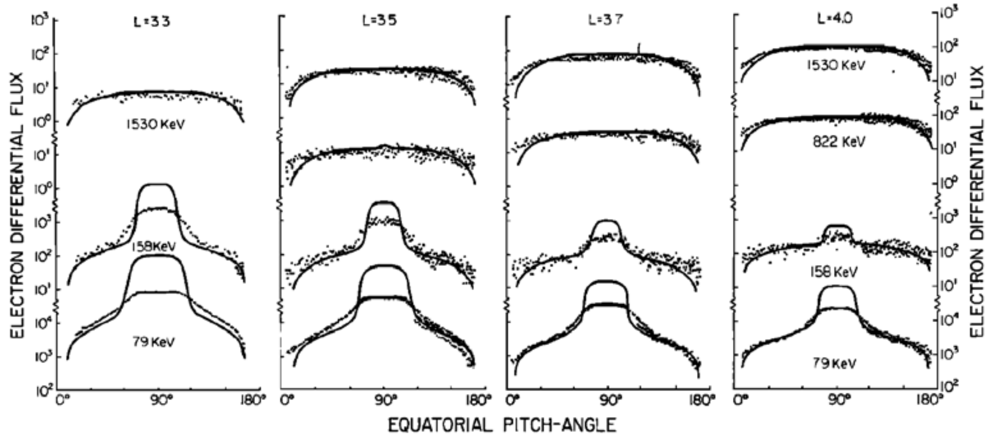
Electron losses due to wave-particle interactions

Lyons et al [1972]



3 Compelling Reasons





- Decay rates agree well with data
- Energy dependence
- Pitch angle distributions agree well

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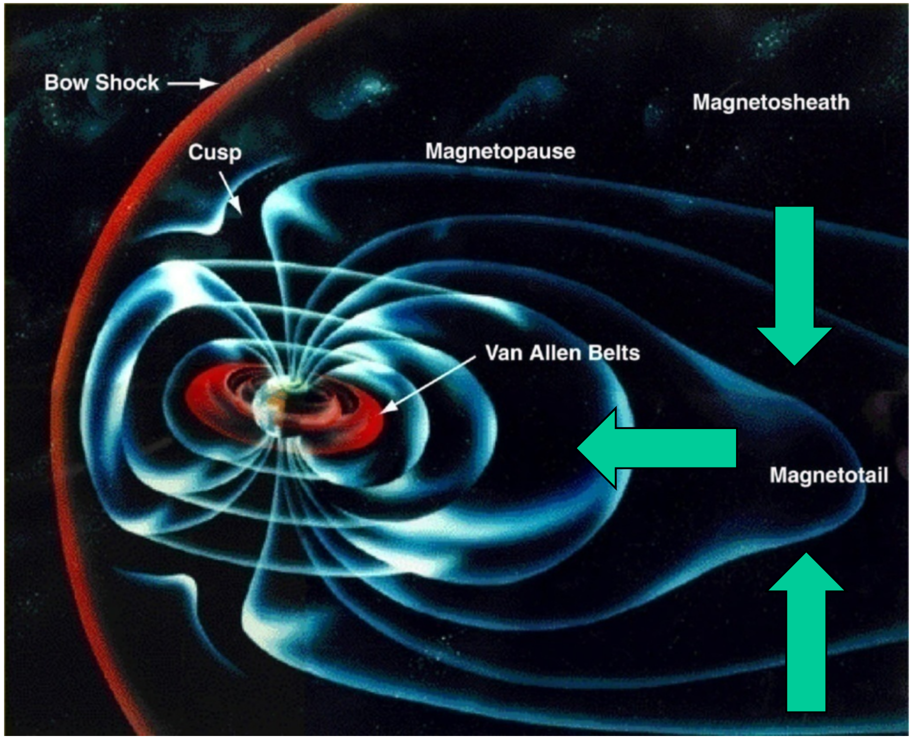
General idea on producing the radiation belts – 1970s



$$\mu = M = \frac{p^2 \sin^2 \alpha}{2 m_0 B}$$

- Electrons originate from the solar wind
  - Diffuse inwards towards the planet and gain energy by conservation of the first 2 invariants
  - Lost by precipitation into the atmosphere
  - Two zone structure

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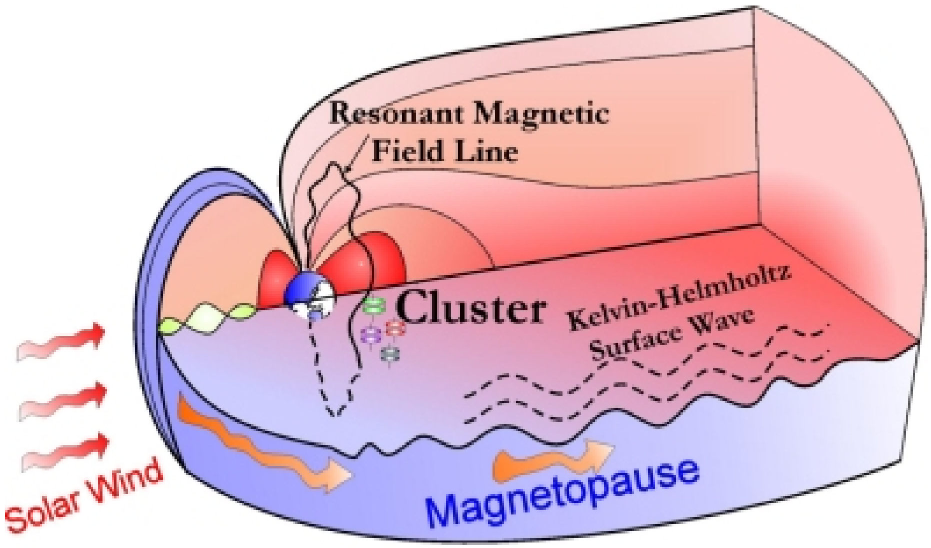
ULF Enhanced Radial Diffusion



- Electron transport across the magnetic field
- Ultra low frequency (ULF) waves
- Generated by solar wind-magnetosphere interaction - Kelvin Helmholtz instability.
- f ~ mHz
- Measured on the ground by magnetometers, and by satellites

Elkington et al., [1999], Mathie and Mann [2000]

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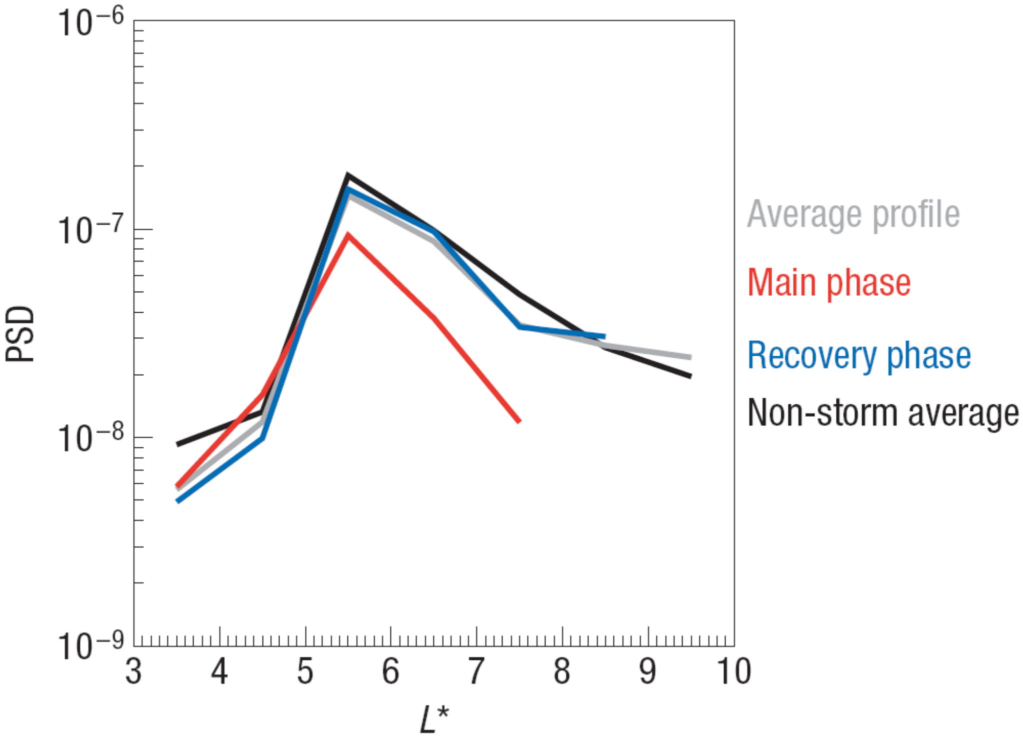
Electron Phase Space Density

M = 2083 MeV/Gauss



- Data shows peak in electron phase space density near 5.5 Re
- Does not support radial diffusion from the outer magnetosphere
- Suggests “local” acceleration

Chen et al., *Nature Physics,* [2007]

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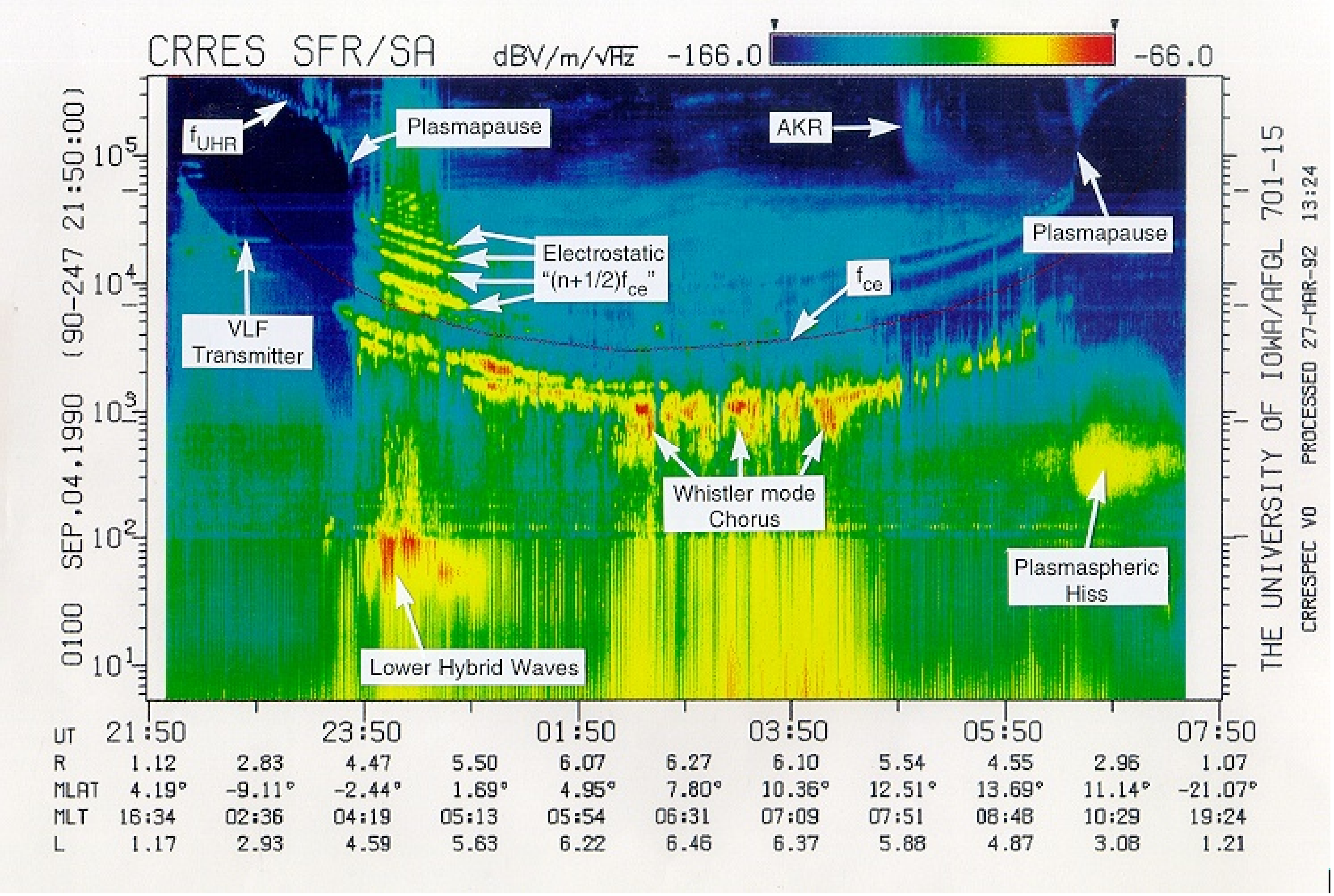
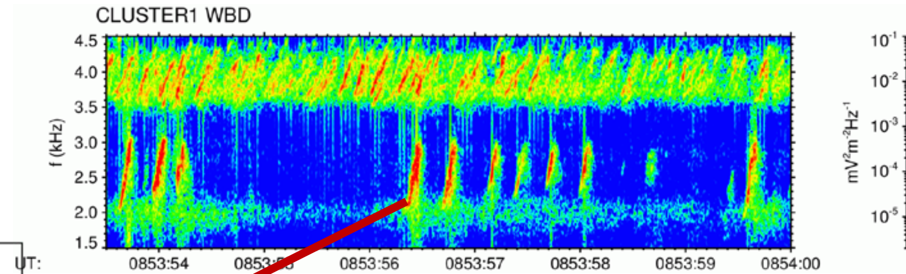
Acceleration by Wave-Particle Interactions: Which Waves?

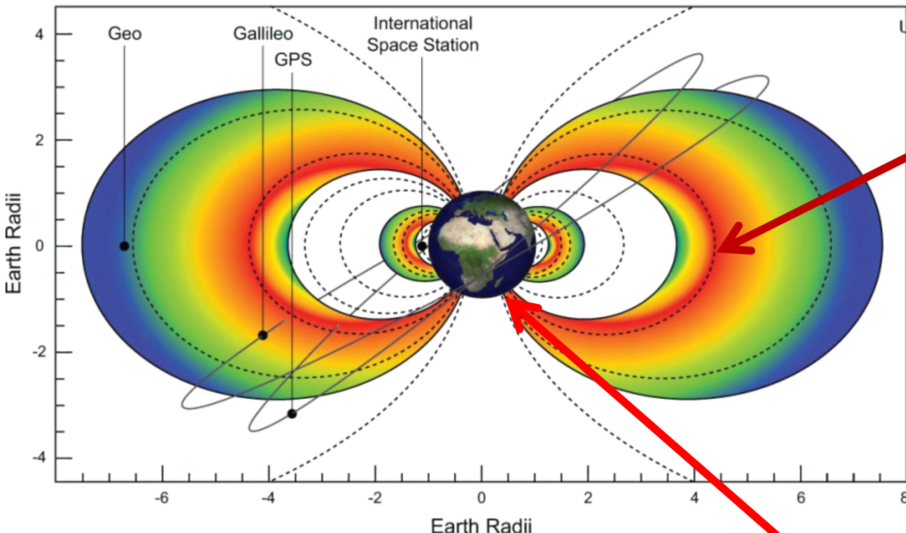


- 5 wave modes can accelerate electrons [Horne and Thorne, 1998]
- Whistler mode chorus can resonate with ~ 1 keV – 10 MeV

Wave-Particle Interactions

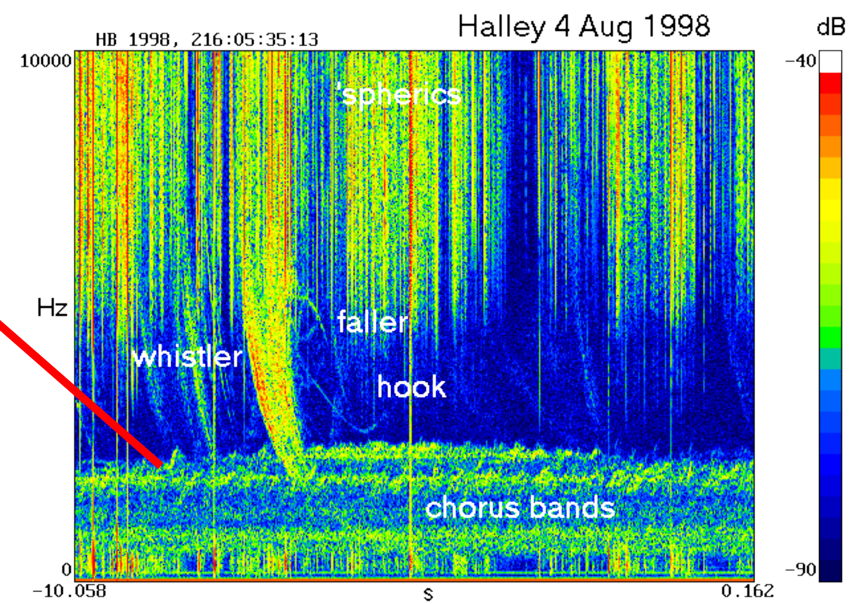
- Chorus waves detected on the ground and in space





Satellite observations

Antarctic observations



- Wave-particle interactions break 1st and 2nd invariants
- Cause electron acceleration as well as loss

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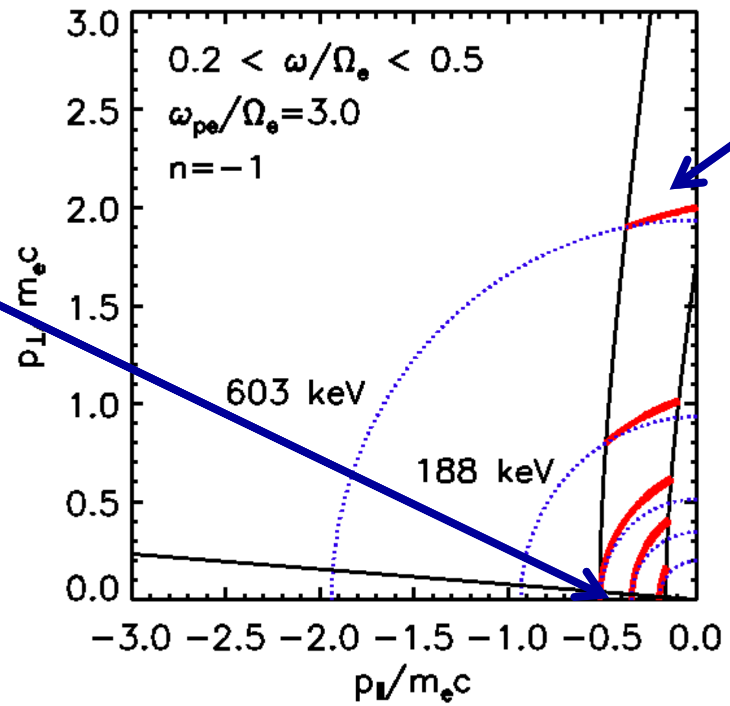
Acceleration by Whistler Mode Waves – QL Theory

Horne and Thorne, [1998]

Horne et al., [2003, 2005a,b]

Plasma instability

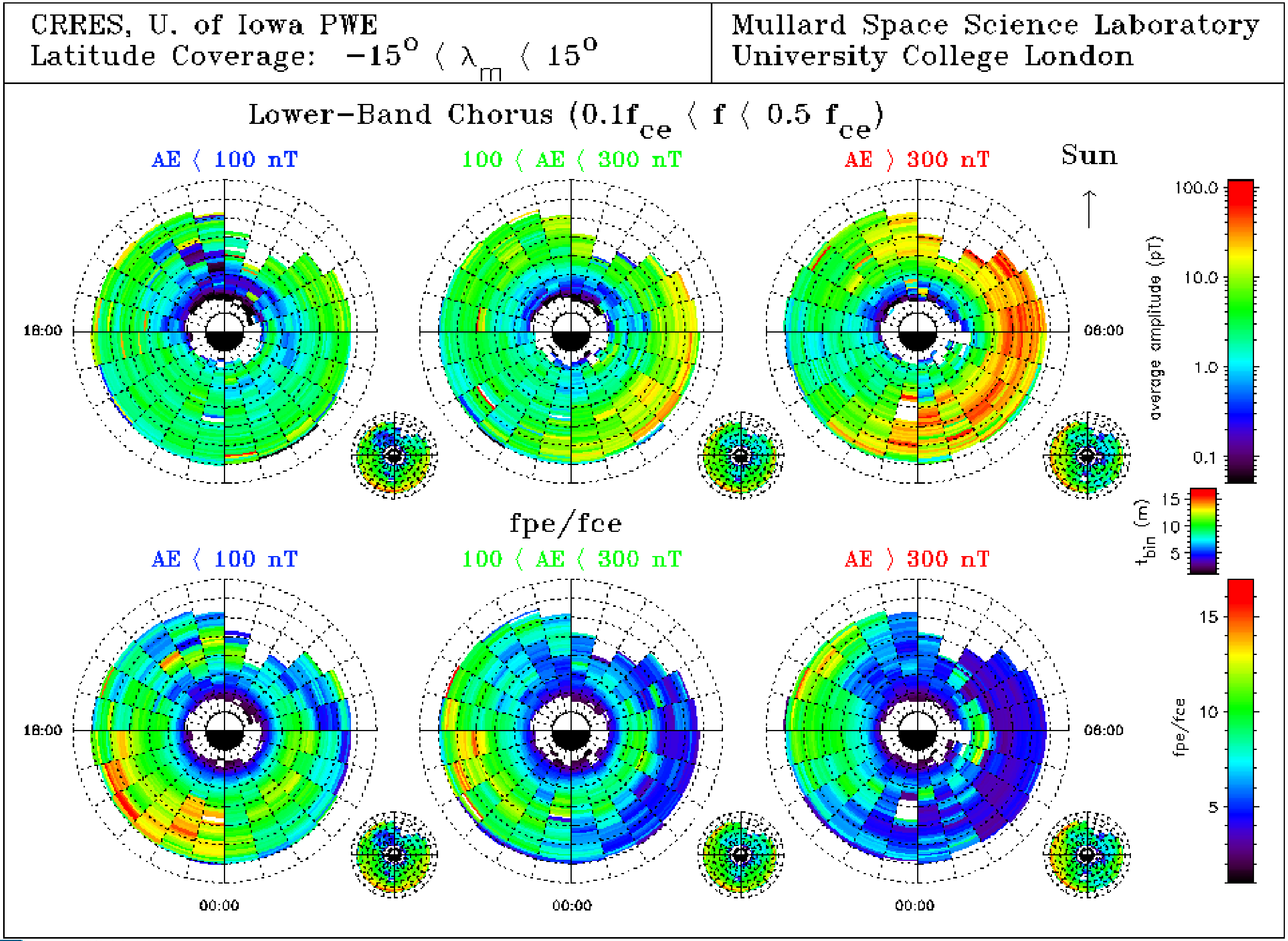
As wave grow electrons lose energy and are diffused into the loss cone at low energies



Since f(p) drops with energy - waves diffuse electrons to higher energy

Waves enable energy transfer

Quasi-linear - average
Nonlinear – bursty



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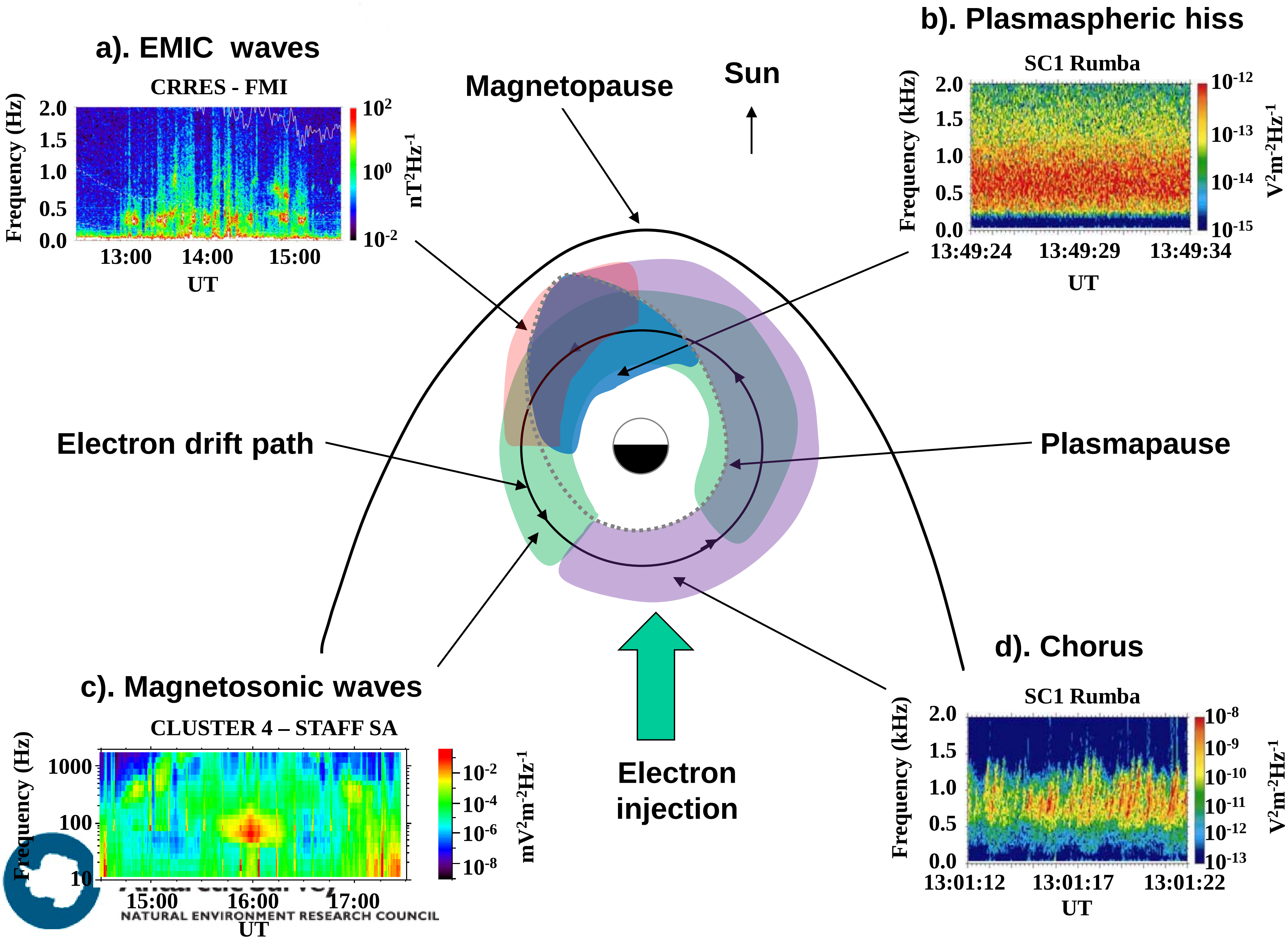
Meredith et al. [2002]



a). EMIC waves
CRRES - FMI
Frequency (Hz)
2.0
1.5
1.0
0.5
0.0
13:00
14:00
15:00
UT
10^2
10^0
10^{-2}
nT^2Hz^{-1}
Magnetopause
Sun
b). Plasmaspheric hiss
SC1 Rumba
Frequency (kHz)
2.0
1.5
1.0
0.5
0.0
13:49:24
13:49:29
13:49:34
UT
10^{-12}
10^{-13}
10^{-14}
10^{-15}
$V^2m^{-2}Hz^{-1}$
Electron drift path
Plasmapause
c). Magnetosonic waves
CLUSTER 4 – STAFF SA
Frequency (Hz)
1000
100
10
15:00
16:00
17:00
UT
10^{-2}
10^{-4}
10^{-6}
10^{-8}
$mV^2m^{-2}Hz^{-1}$
Electron injection
d). Chorus
SC1 Rumba
Frequency (kHz)
2.0
1.5
1.0
0.5
0.0
13:01:12
13:01:17
13:01:22
UT
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
$V^2m^{-2}Hz^{-1}$
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BAS Radiation Belt Model

- Fokker-Planck Equation

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

Radial transport | Pitch angle diffusion | Energy diffusion | Losses

- Drift & bounce averaged diffusion coefficients $D_{LL}, D_{\alpha\alpha}, D_{EE}$ are activity, location and energy dependent

- Details in: Glauert et al. [2014]

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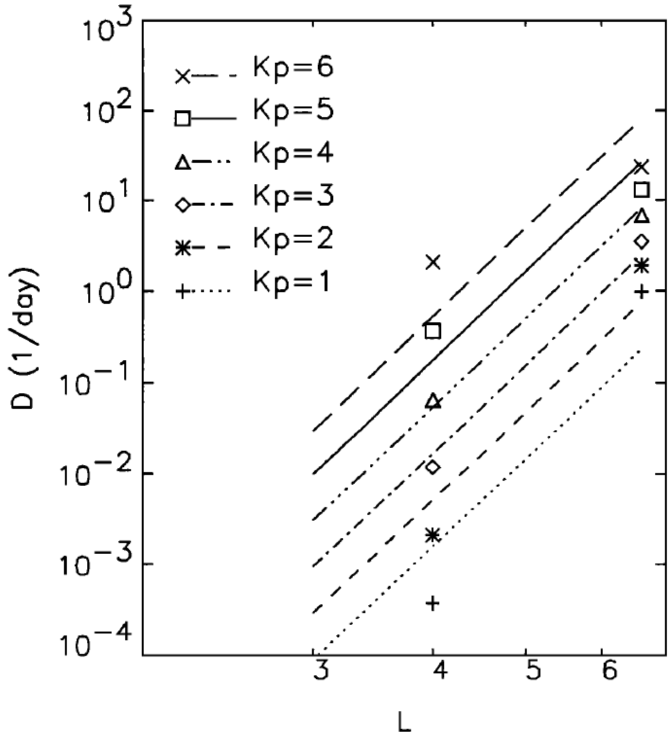
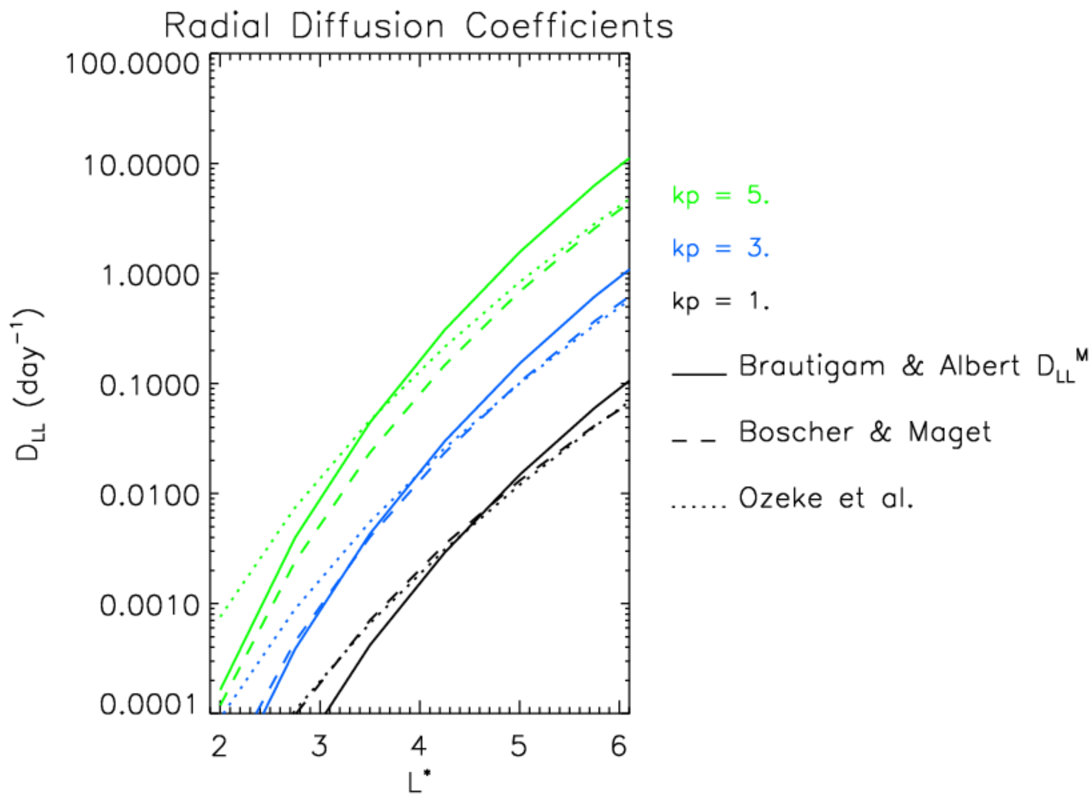
Radial Diffusion Coefficients

Brautigam and Albert [2000]



B&A, Ozeke, Boscher



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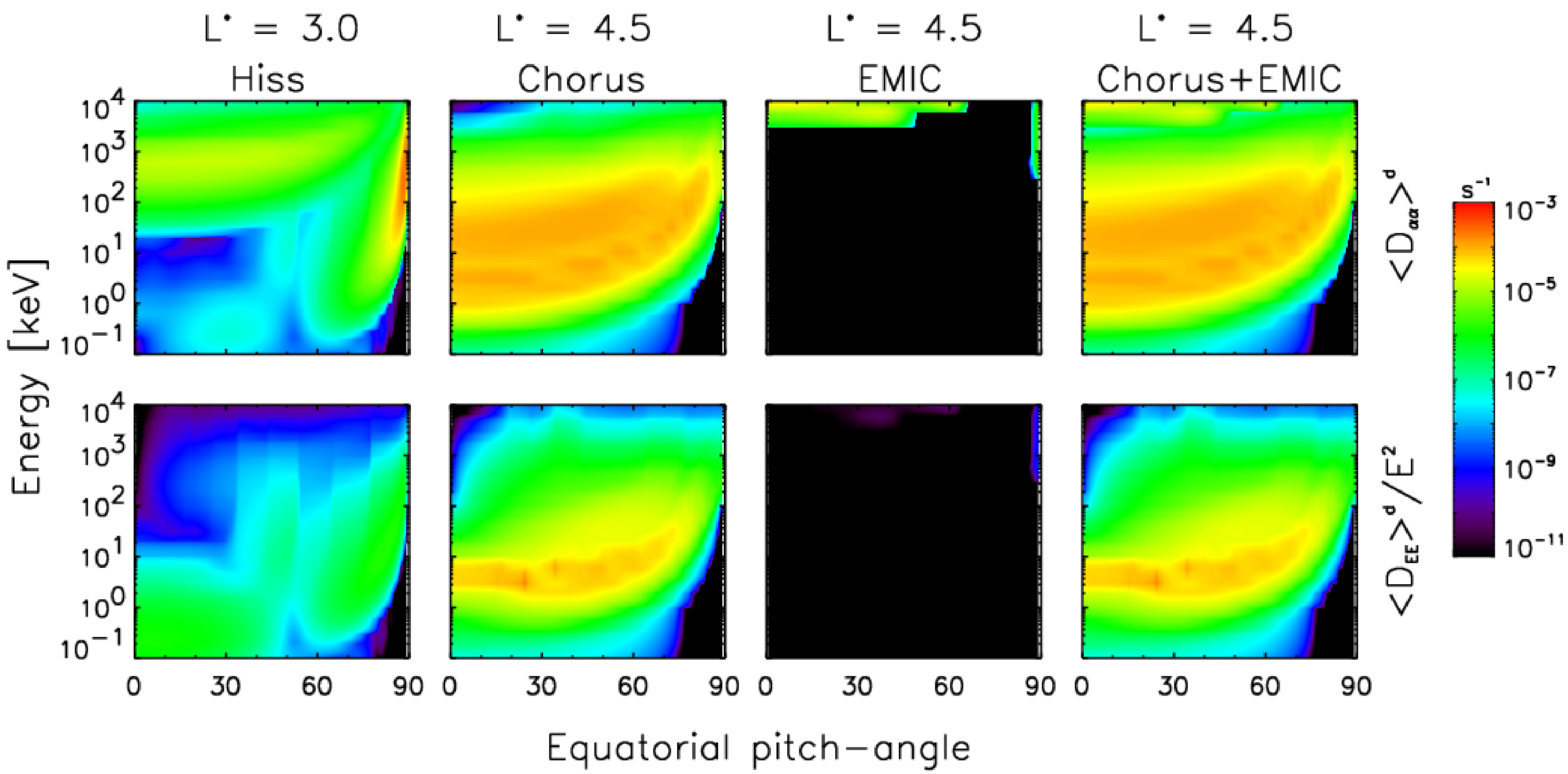
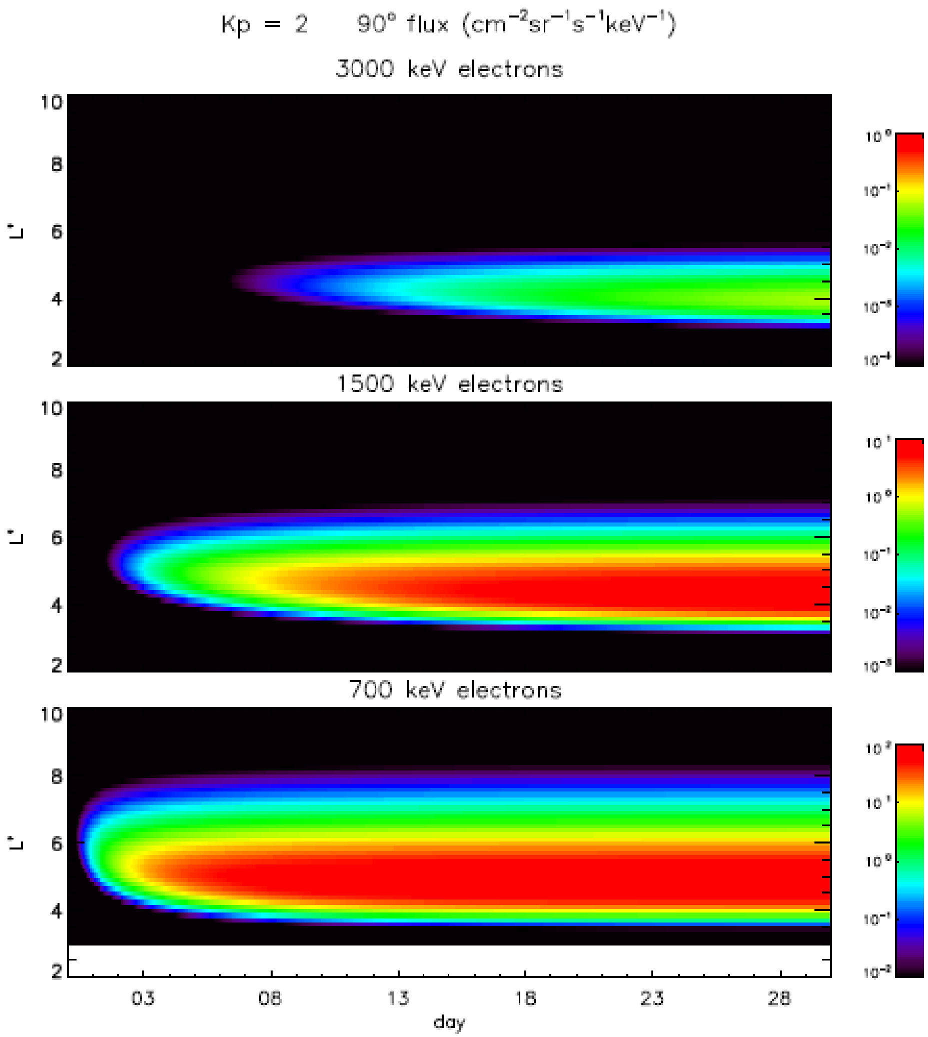
Pitch Angle and Energy Diffusion Rates



- Kersten et al. [2014]

Radiation Belt from Chorus Alone



- Initial soft electron spectrum (~ 10 keV) along the low energy boundary
- Chorus wave diffusion only
- Kp = 2
- Time delay for higher energies
- Glauert et al., JGR [2014]

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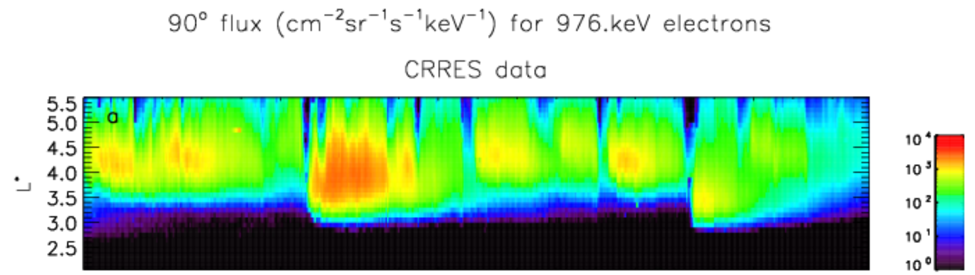
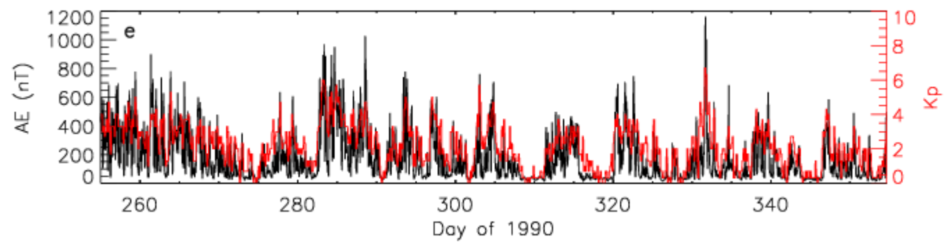
Importance of Wave-Particle Interactions

Satellite data - Electrons





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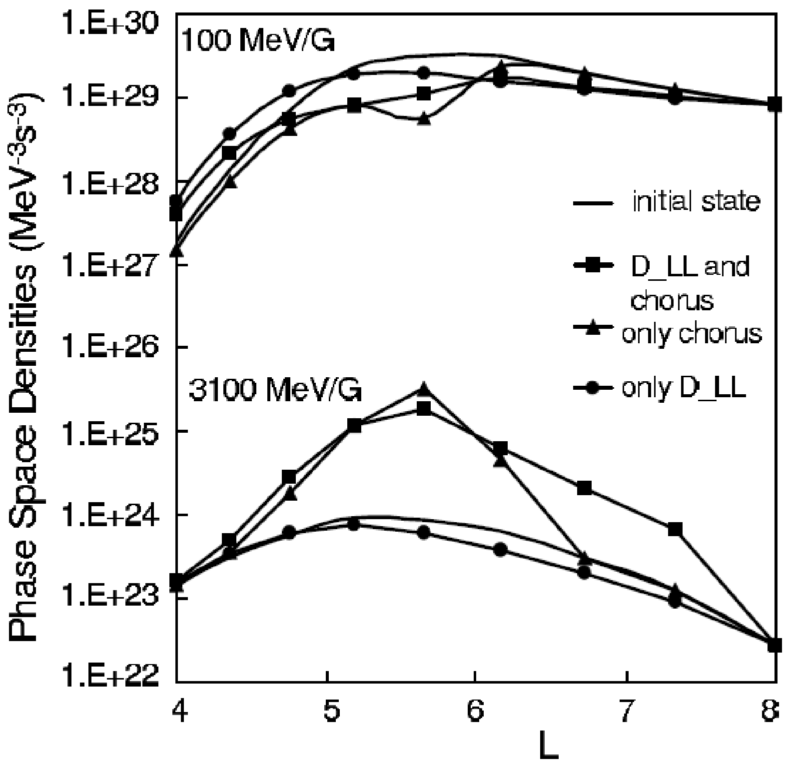
Independent Models Confirm Wave Acceleration



- Salammbô
- Varotsou et al., [2005]

- 3d models with wave-particle interactions

- Varotsou et al. [2005]

- Fok et al. [2008]
- Jordanova et al. [2008]
- Albert et al., [2009]
- Subbotin and Shprits [2009]
- Su et al. [2010]
- Tu et al [2012]
- Glauert et al. [2014]

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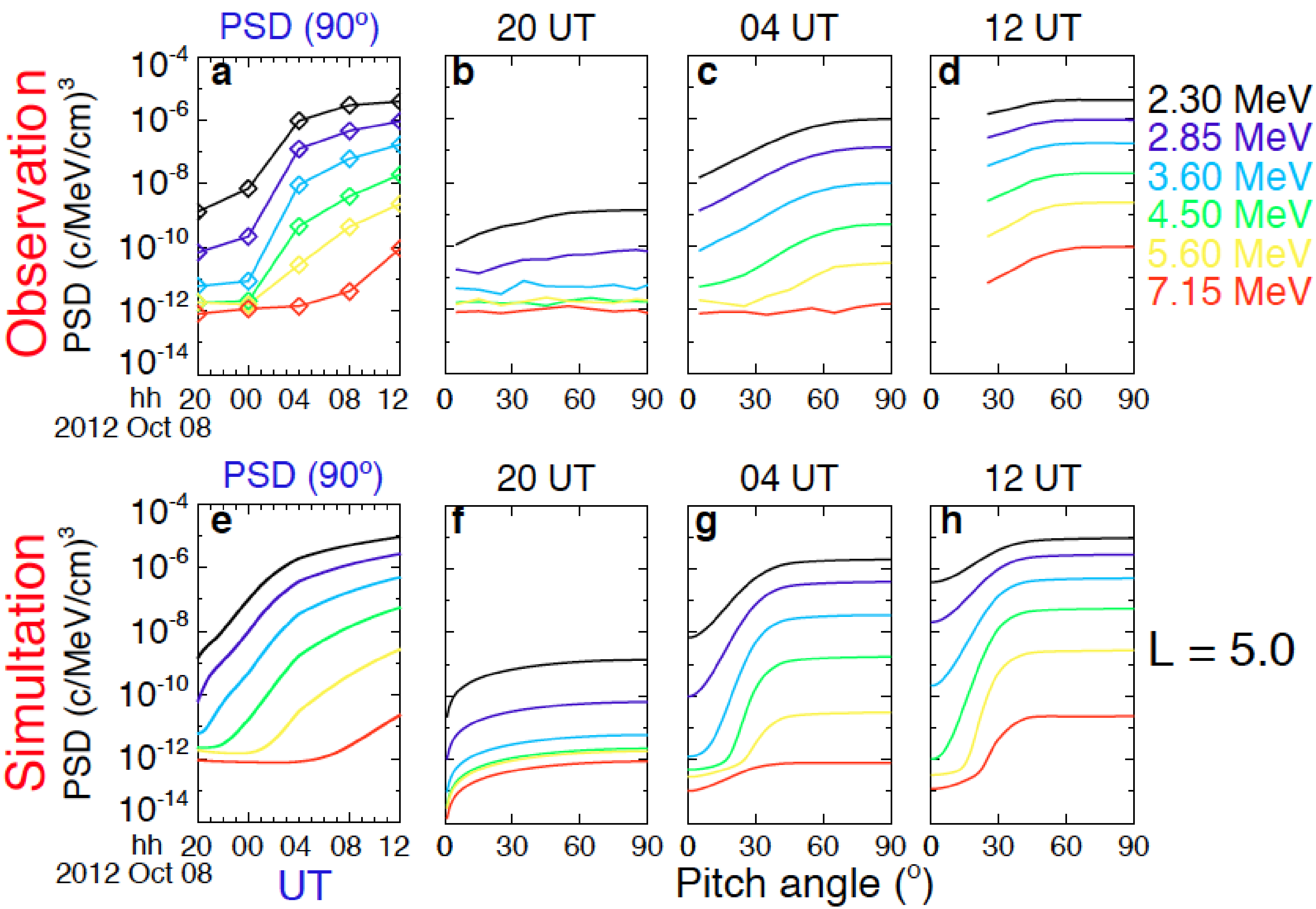
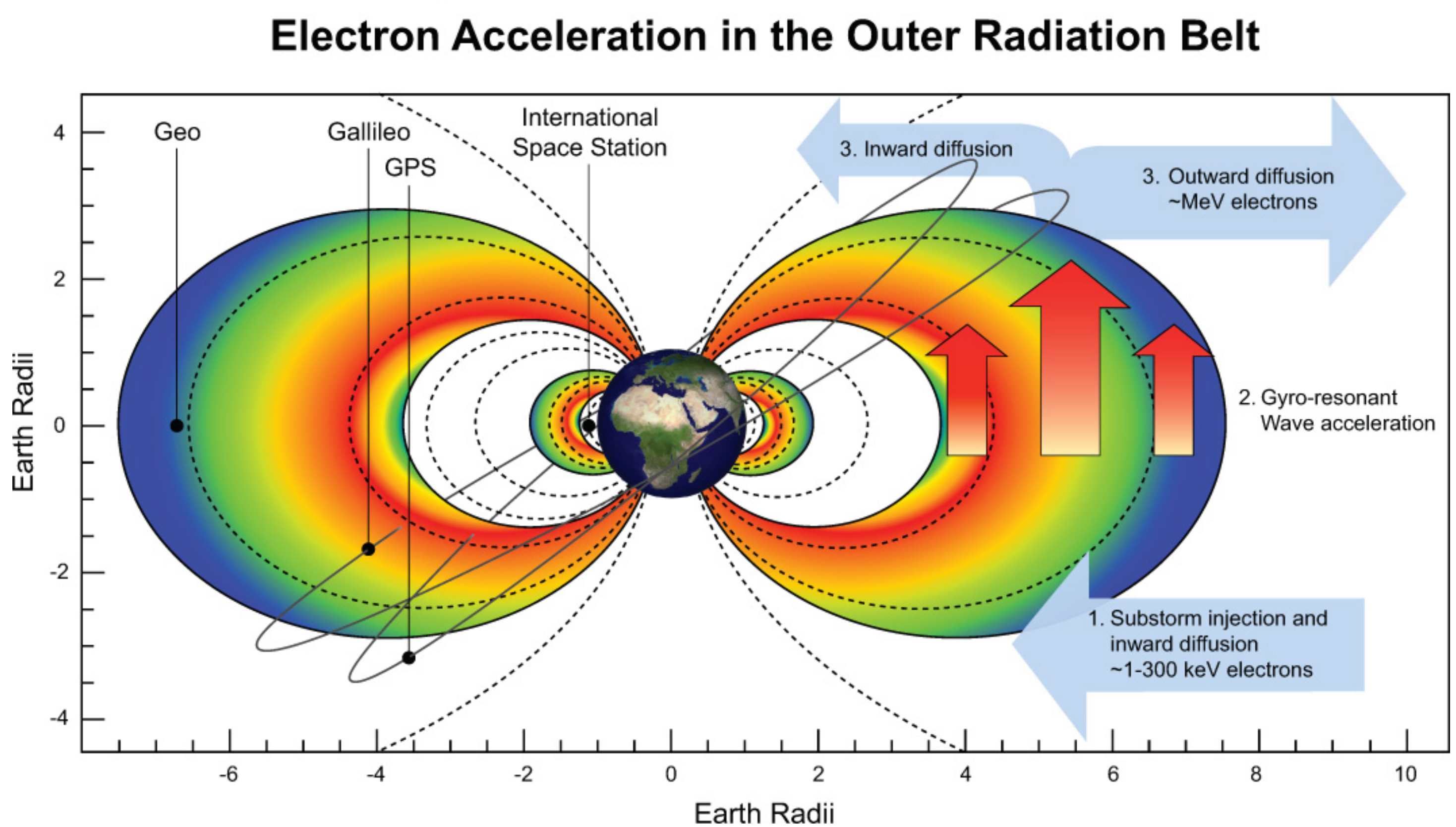
Chorus-driven electron acceleration, Oct 8-9 2012

Thorne et al., *Nature* [2013]



New Wave Acceleration Concept



Horne, *Nature Physics* [2007]

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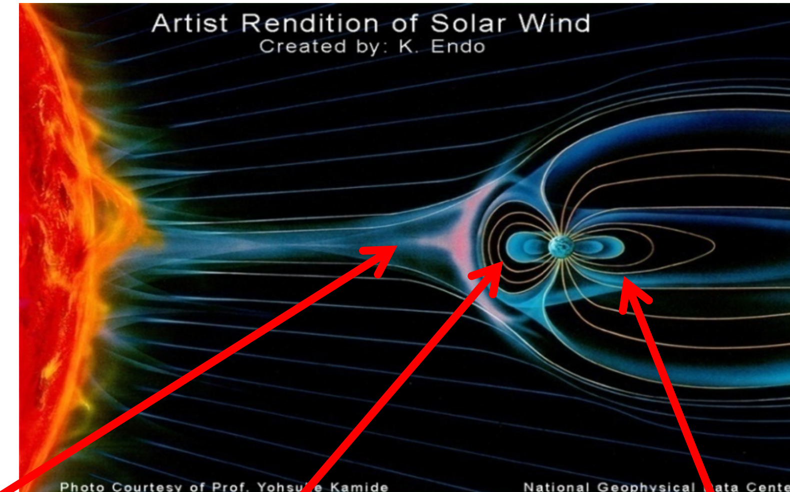
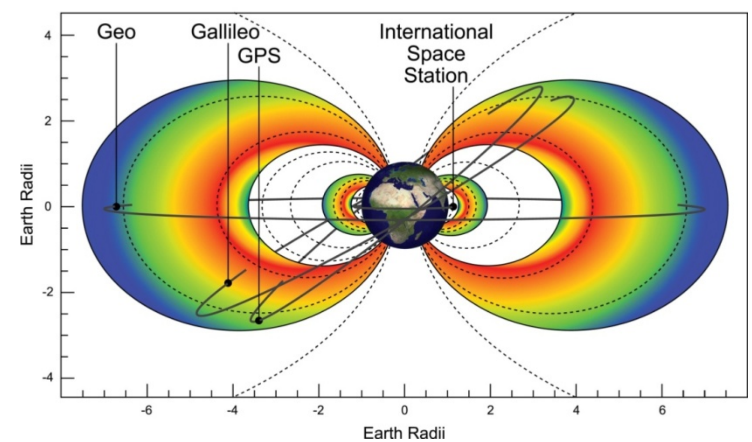
Space Weather - Forecasting Concept

- It takes ~ 40-60 minutes for the solar wind to flow from the ACE satellite to the Earth
- Access ACE satellite data in real time and use it to drive our forecasting models



ACE satellite

Satellite orbits and the van Allen radiation belts



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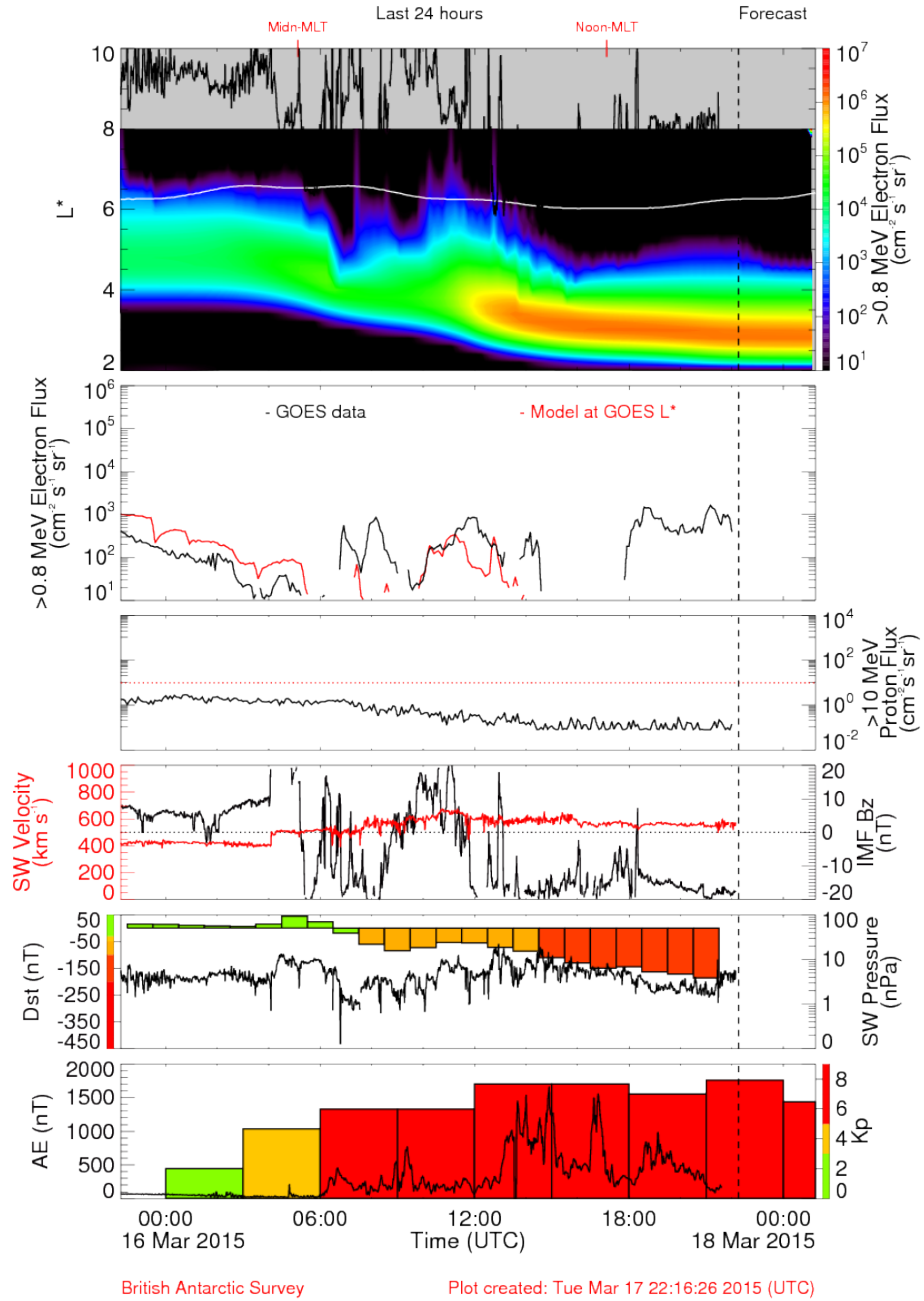
Space Weather

- Forecast the radiation belt electron flux
- Wave-particle interactions give better forecasts and situation awareness [Horne et al., 2013]
- Risk of satellite internal charging
- www.spaceweather.ac.uk



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Summary

- The radiation belts are exciting - Our understanding has changed radically
- Wave-particle interactions play a major role in radiation belt variability
  - Acceleration by chorus, magnetosonic and other waves
  - Loss into the atmosphere by chorus, hiss, EMIC and other waves
  - Combined transport, acceleration and loss are key
- Wave-particle interactions enable better Space Weather forecasting and situation awareness
- Many new results from Van Allen Probes – Sasha – and many unresolved problems
- Do the same processes apply at Jupiter, Saturn, Astrophysics.... ?

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The End

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