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The Earth's Radiation Belts; Highlights from the SPACESTORM project and how SuperDARN could contribute

Richard B. Horne
British Antarctic Survey

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Invited talk, SuperDARN Workshop, Leicester, 2nd June 2015.

Outline

- Goal of the SPACESTORM project
- Modelling of the high energy (>100 keV) electron radiation belts
- Space Weather forecasts for satellite operators
- How SuperDARN could contribute to radiation belt physics and space weather

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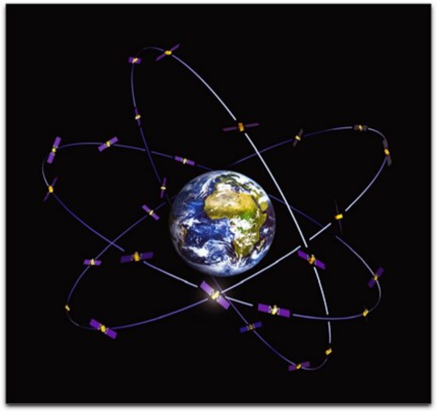
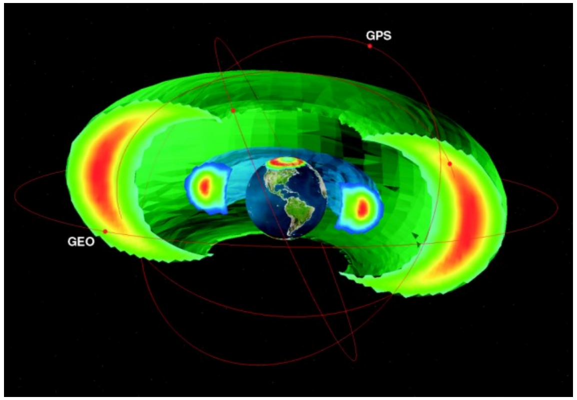
SPACESTORM - The Goal

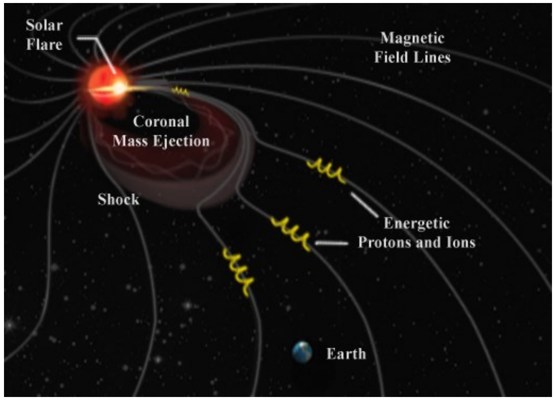
Satellites



Radiation Belts



Solar Energetic Particles



- ***Goal***
  - *To model severe space weather events and mitigate their effects on satellites by developing better mitigation guidelines, forecasting, and by experimental testing of new materials and methodologies to reduce vulnerability.*

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Team Roles

• British Antarctic Survey	Modelling high energy electrons, forecasting
• Finnish Met Institute	Modelling low energy electrons, nowcasting
• DH Consultancy	Data management and real-time displays
• U of Surrey	Lab expts. and mitigation
• French Aerospace Lab	Lab expts. and testing materials

Stakeholder Advisory Committee

• D Pitchford (Luxembourg)	Satellite operations
• J Likar (USA)	Satellite design
• D Wade (London)	Satellite insurance
• C Amiens (Italy)	Space assets
• J Green (USA)	Data analysis
• R Thorne (USA)	Theory

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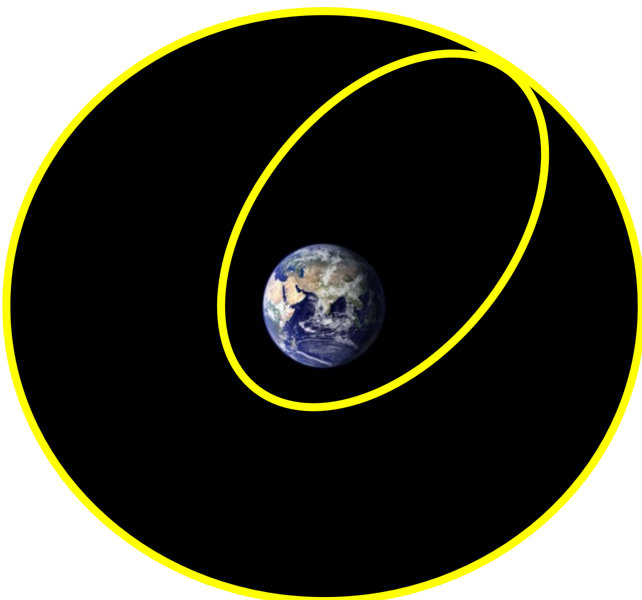
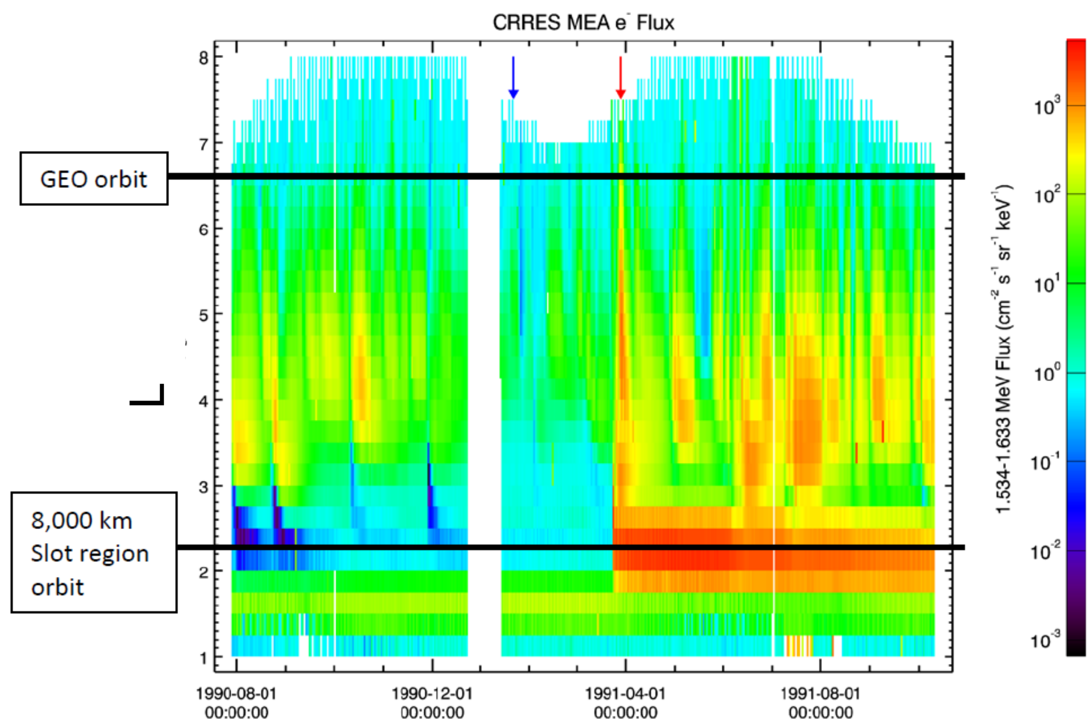
Key New Driver

- Boeing: all-electric satellite propulsion for commercial satellites
- Half the cost of launch to ~ US$ 60m
- But takes 200-300 days to reach geostationary orbit
- Radiation protection for Medium Earth Orbit?

Horne and Pitchford [2015]





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Transport, Acceleration and Loss in the Electron Radiation Belts

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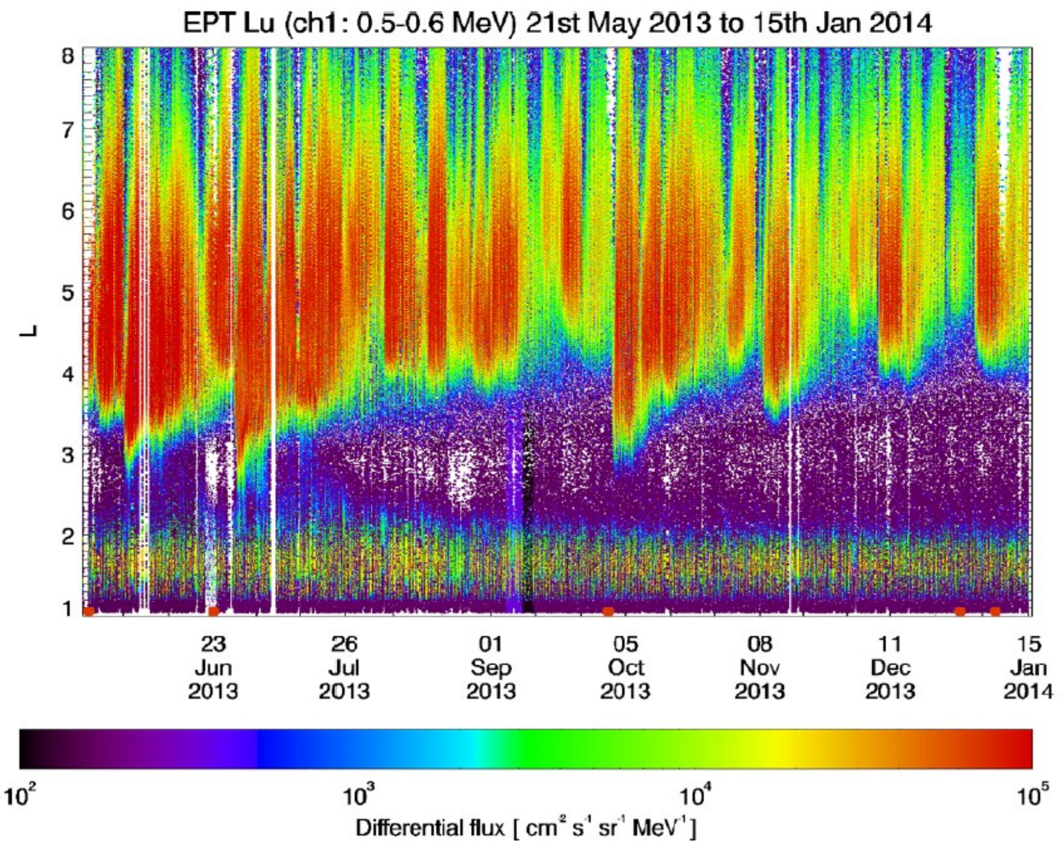
Radiation Belts - The Problem

- 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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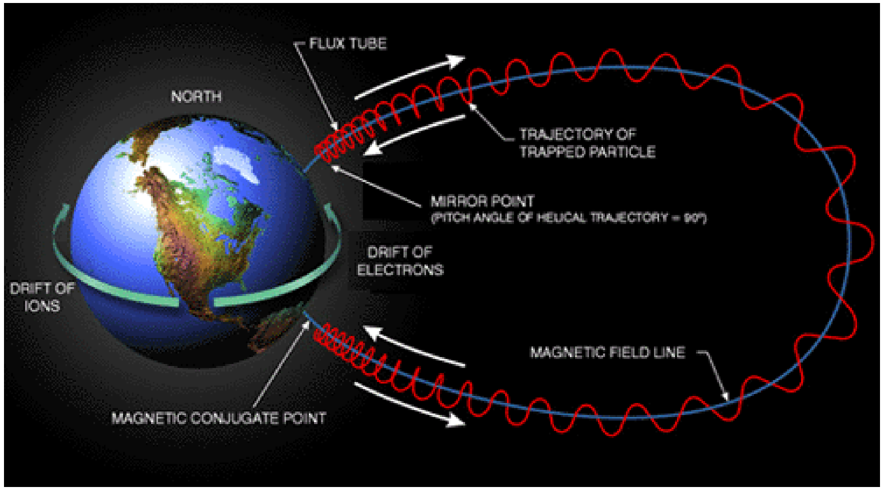
Particle Motion in the Earth's Magnetic Field

For 1 MeV electron ($\alpha = 45^o$) 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



$$\mu = \frac{p_\perp^2}{2mB}$$

$$J = \int_{bounce} p_\parallel ds$$

$$\Phi = \int_{drift} BdS$$

- Acceleration and loss requires breaking 1 or more invariant

- When wave frequency ~ particle frequency

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BAS Radiation Belt model – 3d

BAS-RBM solves the Fokker-Planck equation for phase-space density (f) in pitch-angle (α), energy (E) and L* (L) coordinates

Radial diffusion

Pitch-angle diffusion

$$\frac{\partial f}{\partial t} = L \quad + \frac{1}{g(\alpha)}\frac{\partial}{\partial \alpha}\left(g(\alpha) \right)_{EL}$$

Mixed pitch-angle/energy diffusion

Losses

$$+ \frac{1}{A(E)}\frac{\partial}{\partial E}\left(A(E) \right)$$

Energy diffusion

$$A(E) = (E + E_0)(E + 2E_0)^{\frac{1}{2}} E^{\frac{1}{2}}$$

$$g(\alpha) = \sin\alpha \cos\alpha (1.30 - 0.56 \sin\alpha)$$

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Glauert et al. JGR [2014]

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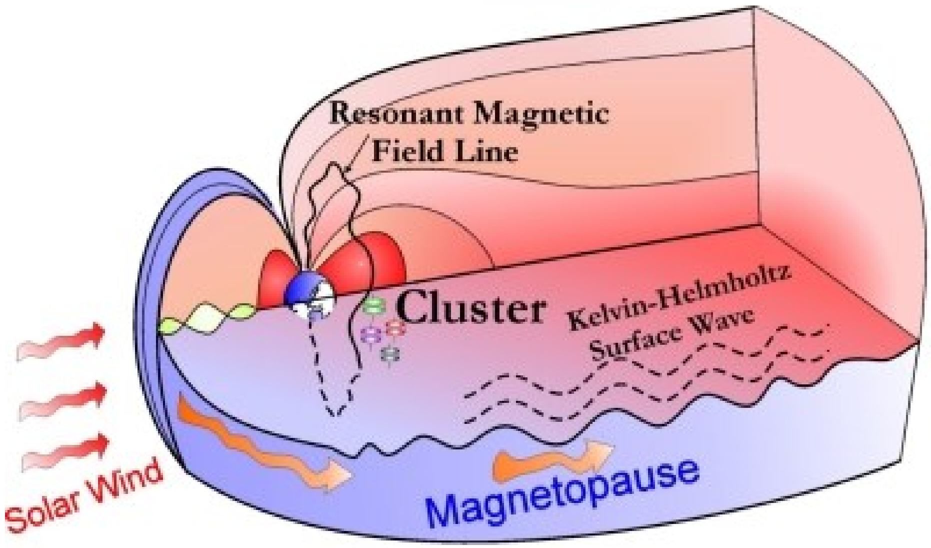
ULF Enhanced Radial Diffusion



- Ultra low frequency (ULF) waves
- Generated by solar wind-magnetosphere interaction - Kelvin Helmholtz instability.
- f ~ mHz
- Breaks 3rd invariant and drives electron transport across the magnetic field

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

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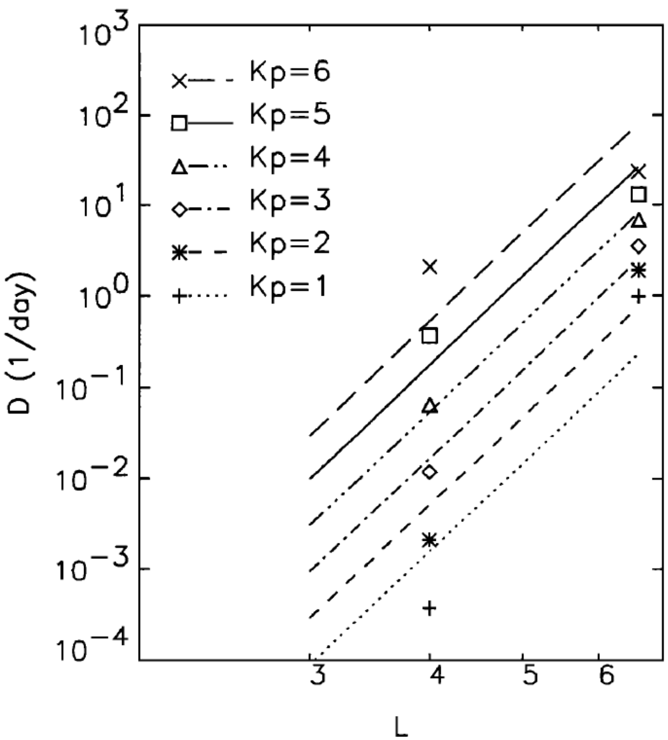
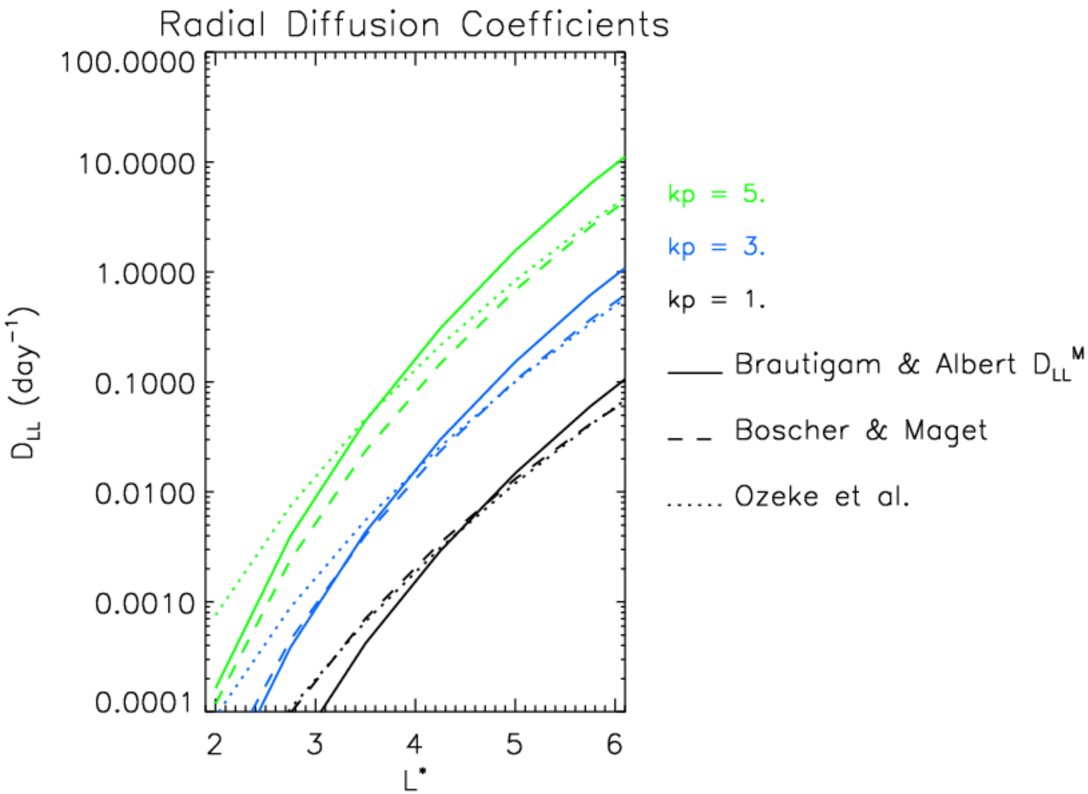
Radial Diffusion Coefficients

Brautigam and Albert [2000] ~L^{10}



B&A, Ozeke et al., Lejosne et al.



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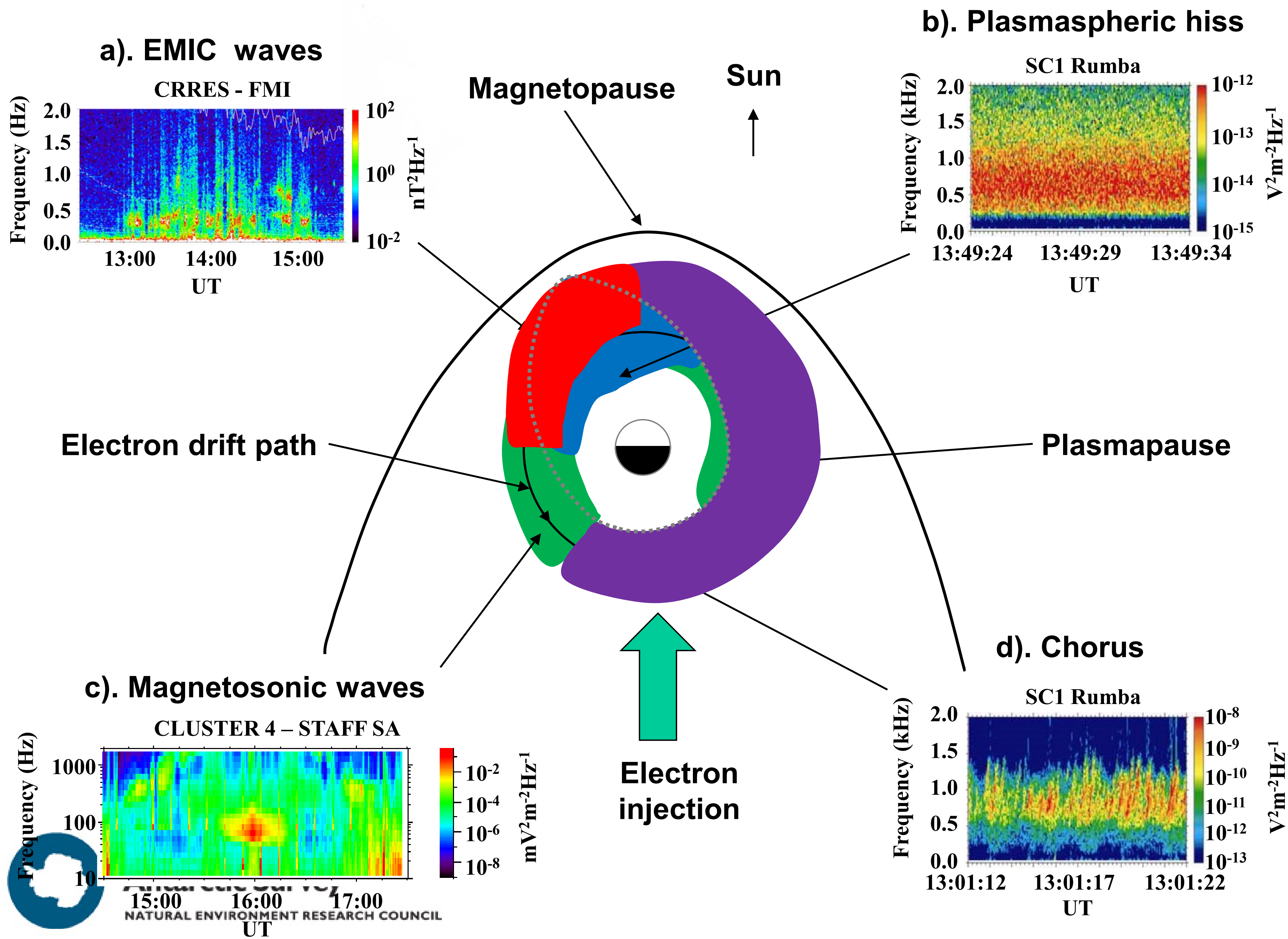

a). EMIC waves
CRRES - FMI
Frequency (Hz)
2.0
1.5
1.0
0.5
0.0
13:00
14:00
15:00
UT
10^2
10^0
10^{-2}
nT^2Hz^{-1}
Magnetopause
Sun
b). Plasmaspheric hiss
SC1 Rumba
Frequency (kHz)
2.0
1.5
1.0
0.5
0.0
13:49:24
13:49:29
13:49:34
UT
10^{-12}
10^{-13}
10^{-14}
10^{-15}
$V^2m^{-2}Hz^{-1}$
Electron drift path
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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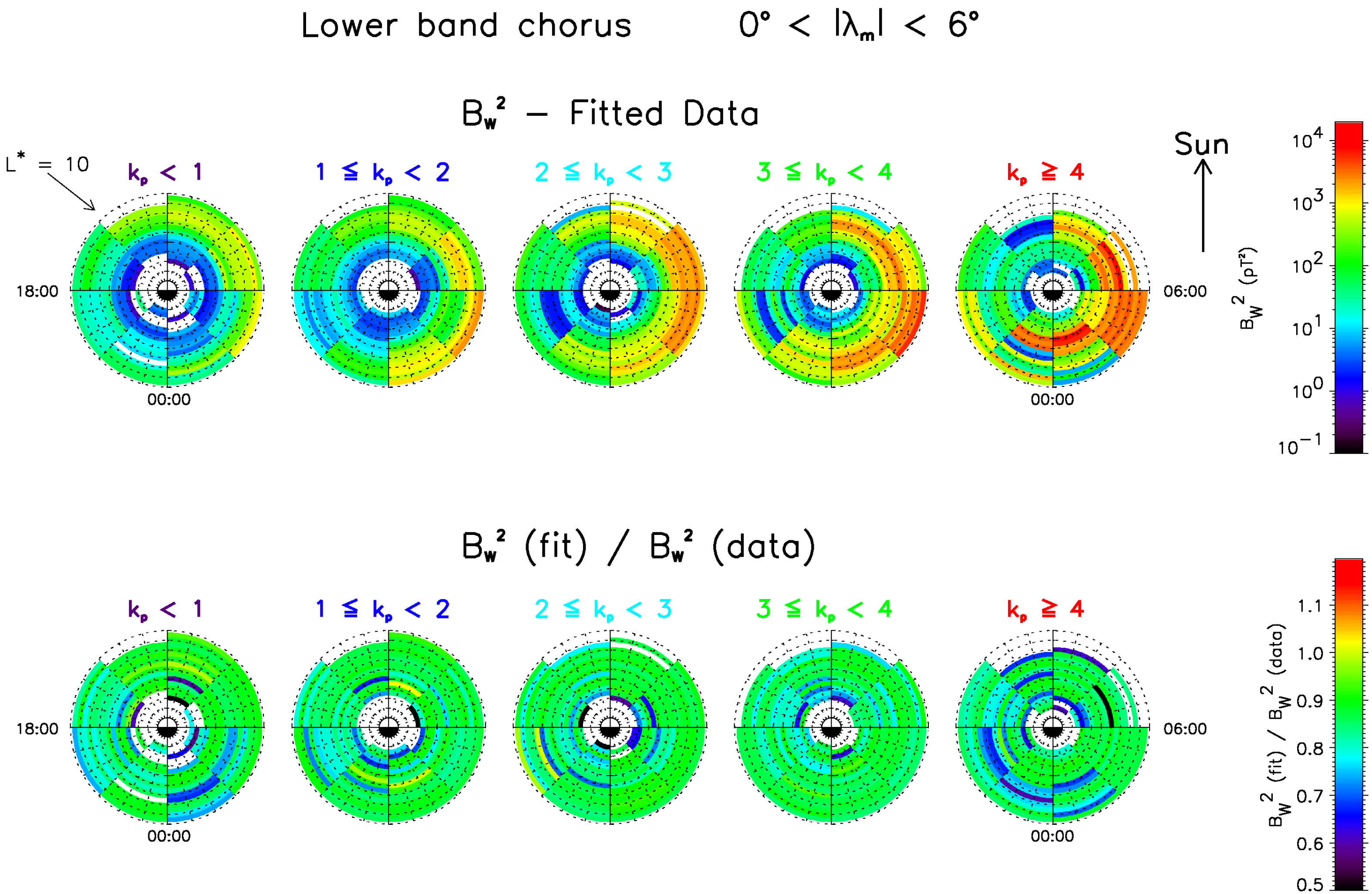
Chorus Wave Data – From 7 Satellites



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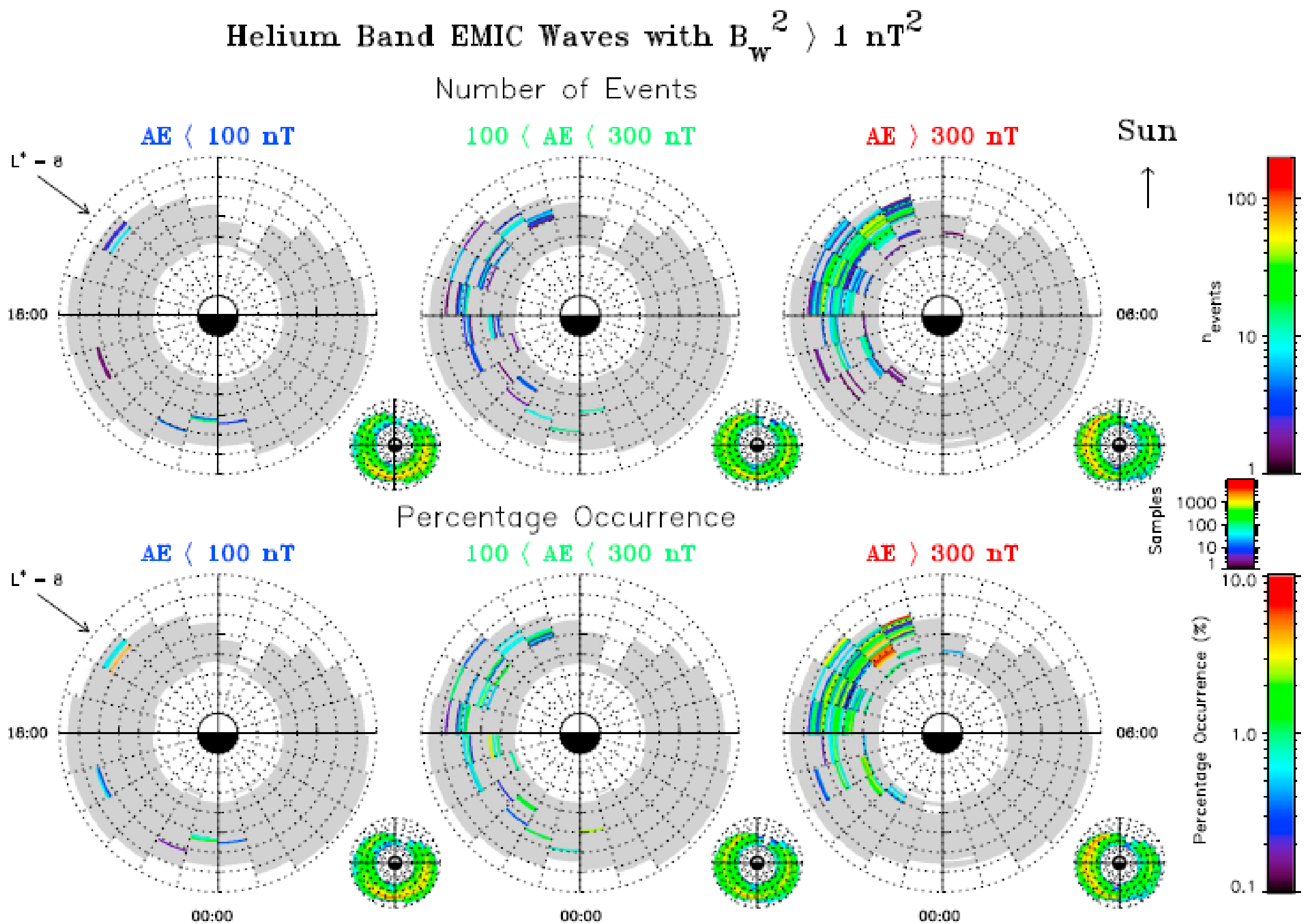
CRRES EMIC Wave Survey



- Meredith et al. JGR, [2014]

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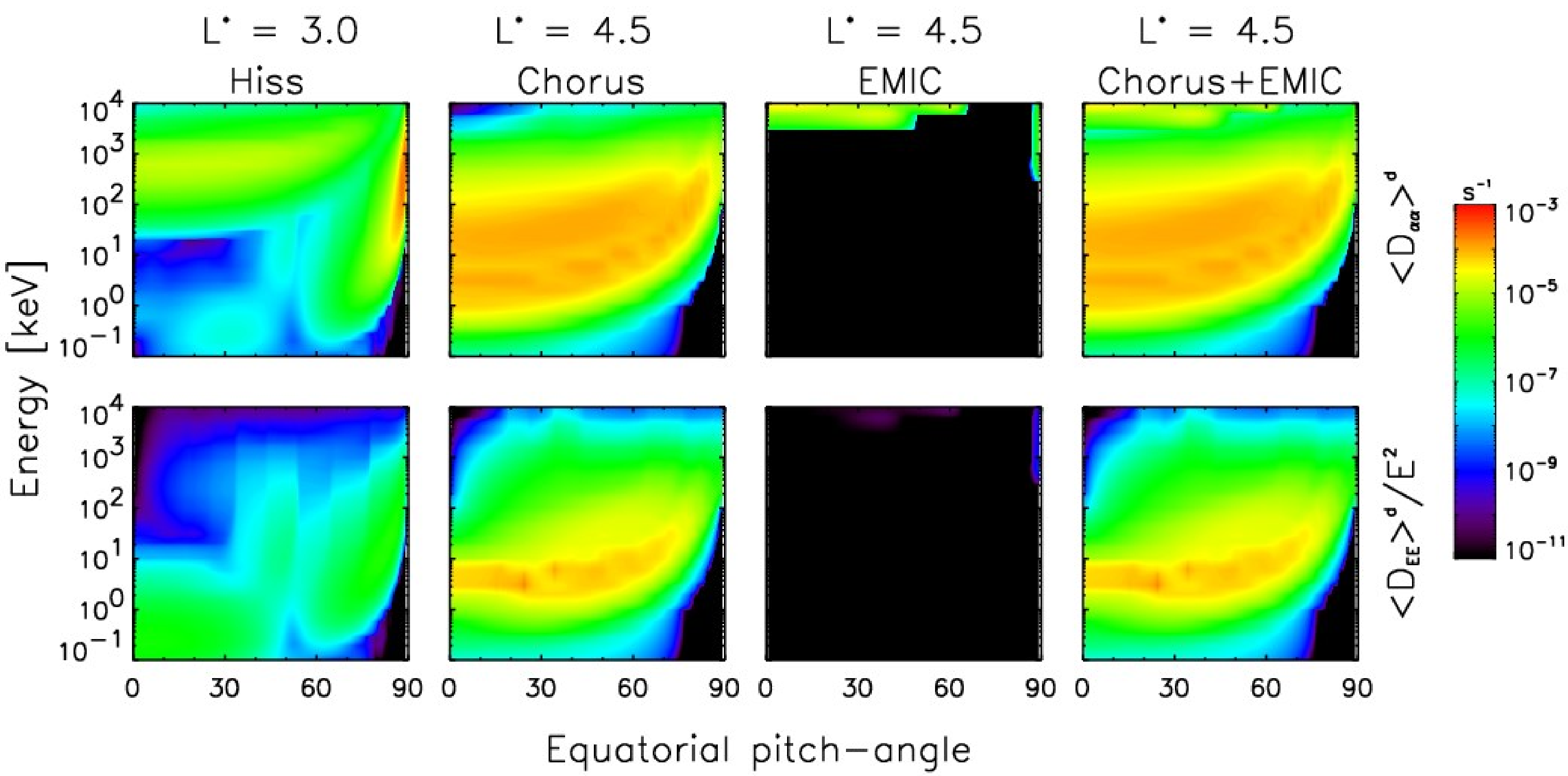
Pitch Angle and Energy Diffusion Rates



- Kersten et al. [2014]

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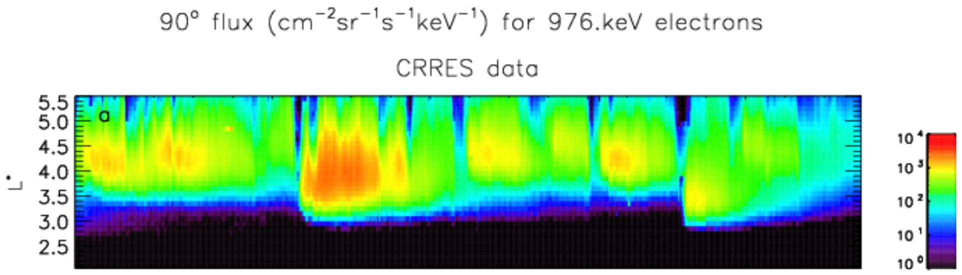
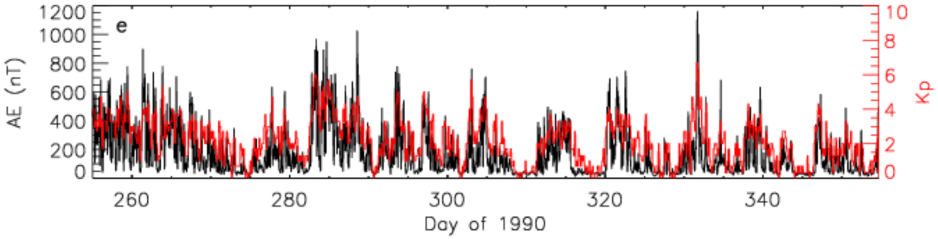
Importance of Wave-Particle Interactions

Satellite data - Electrons





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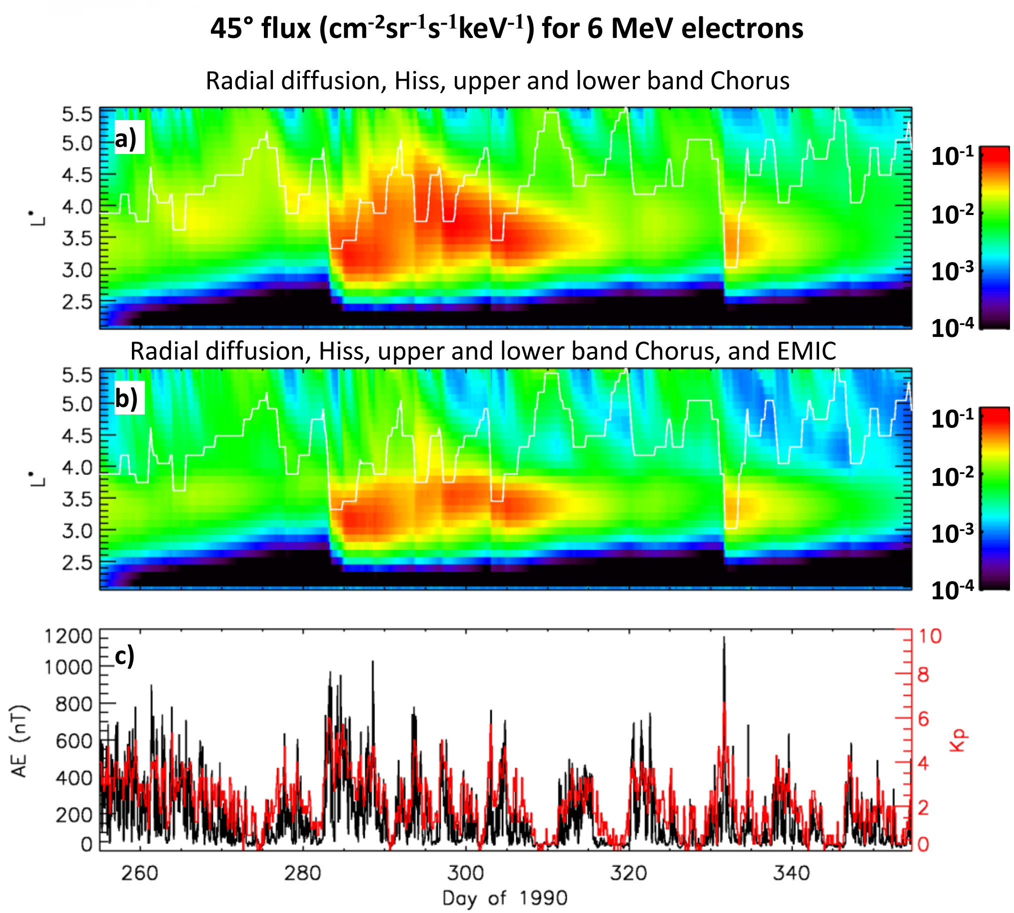
Electron flux: 100 day simulation – 45°

Without EMIC

With EMIC



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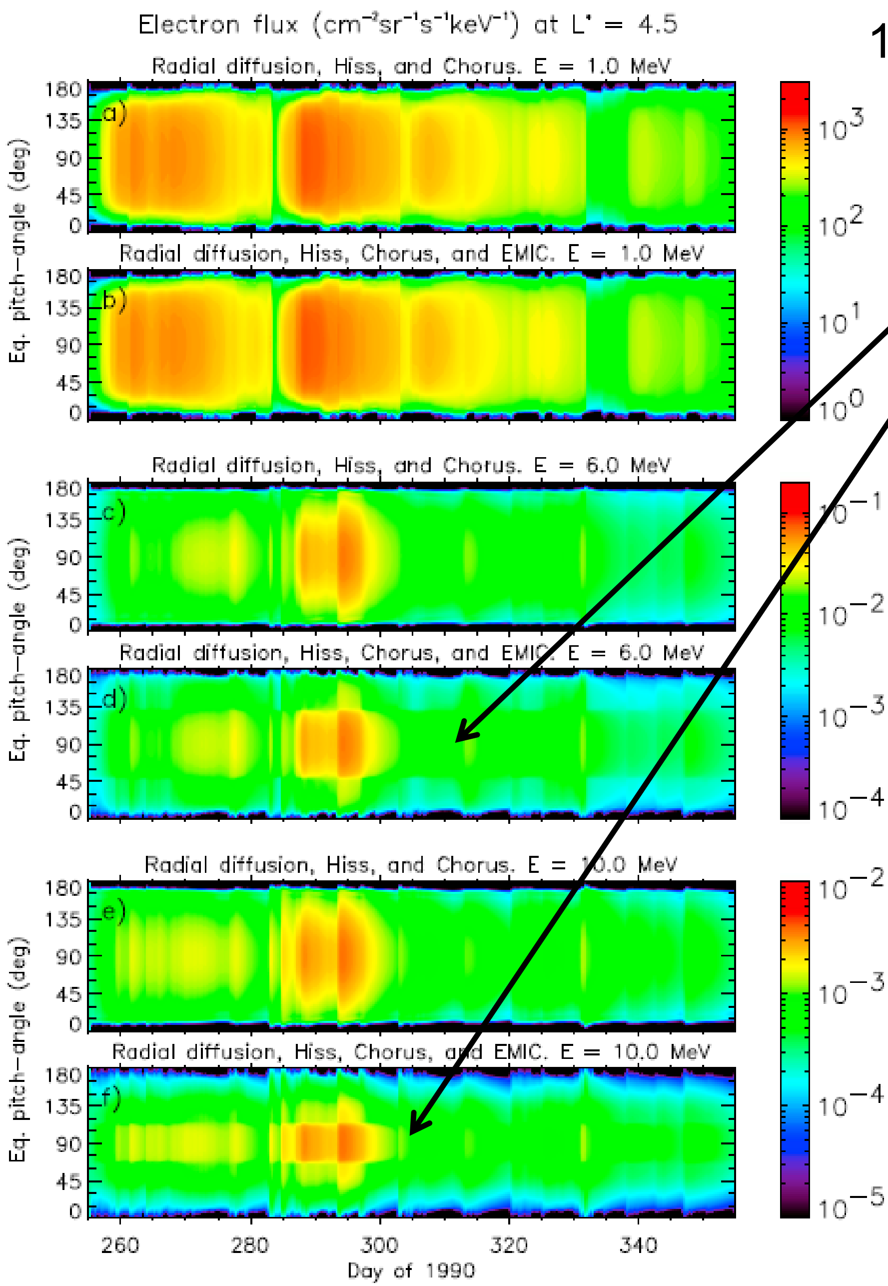
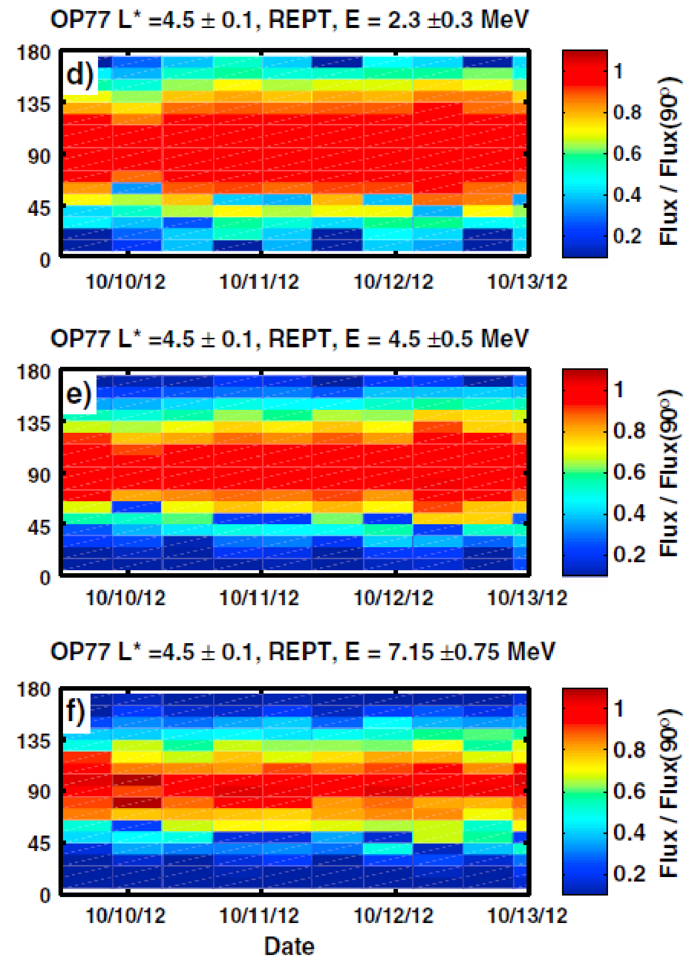
- Electron distribution becomes narrower for higher energies



1 MeV

6 MeV

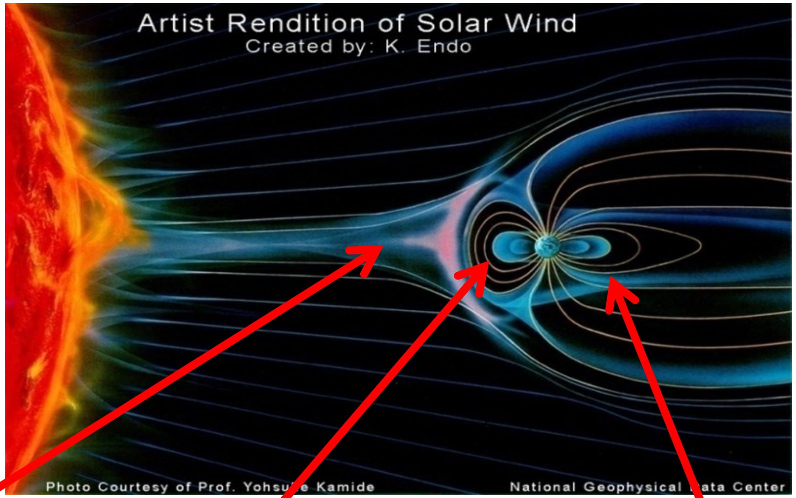
10 MeV



Usanova et al. [2014]

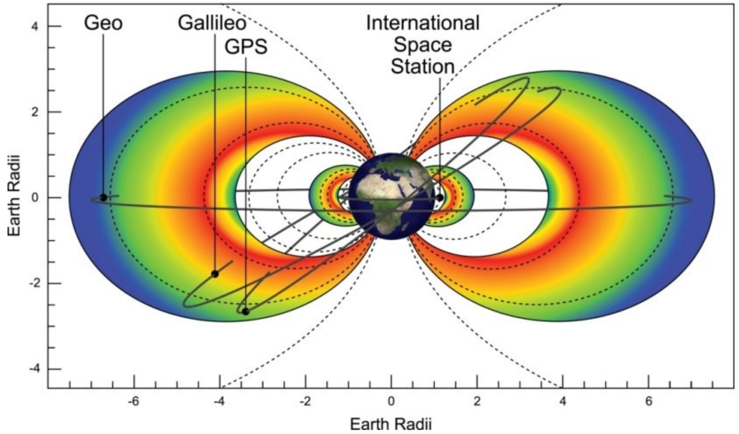
Space Weather - Forecasting Concept

- 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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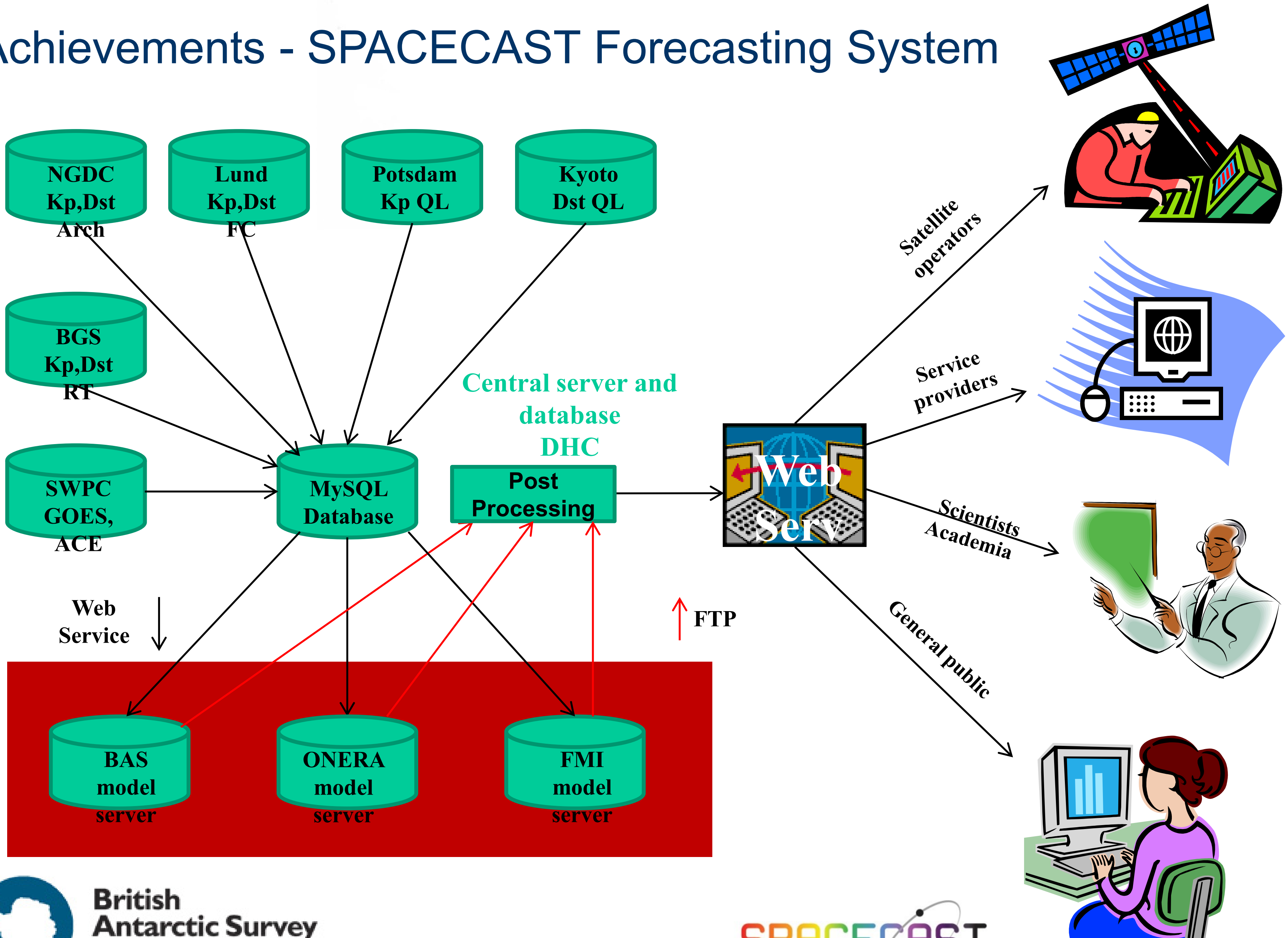
Achievements - SPACECAST Forecasting System



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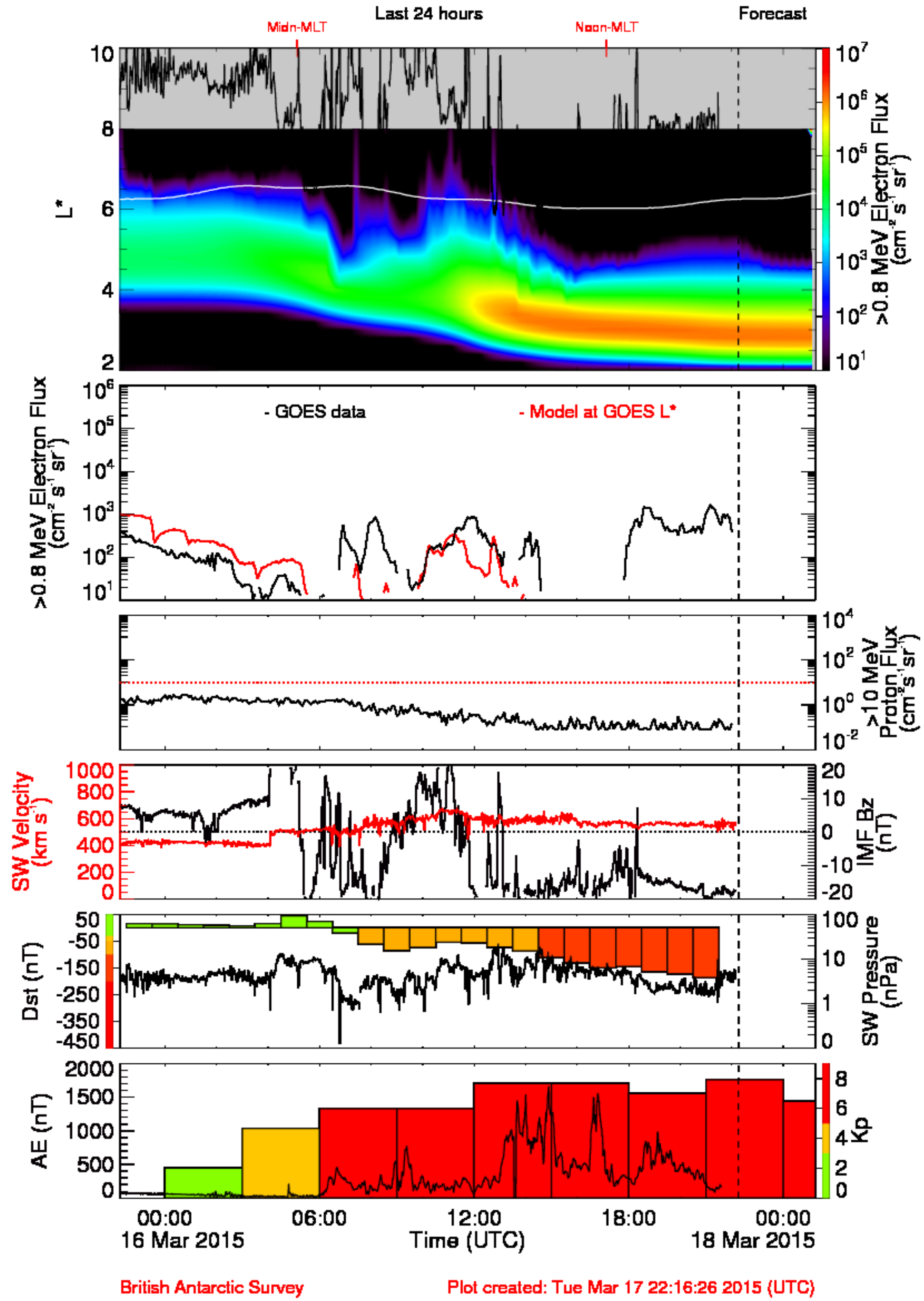
Space Weather

- Forecast the radiation belt electron flux
- Including 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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How Can SuperDARN Contribute to Radiation Belt Research?

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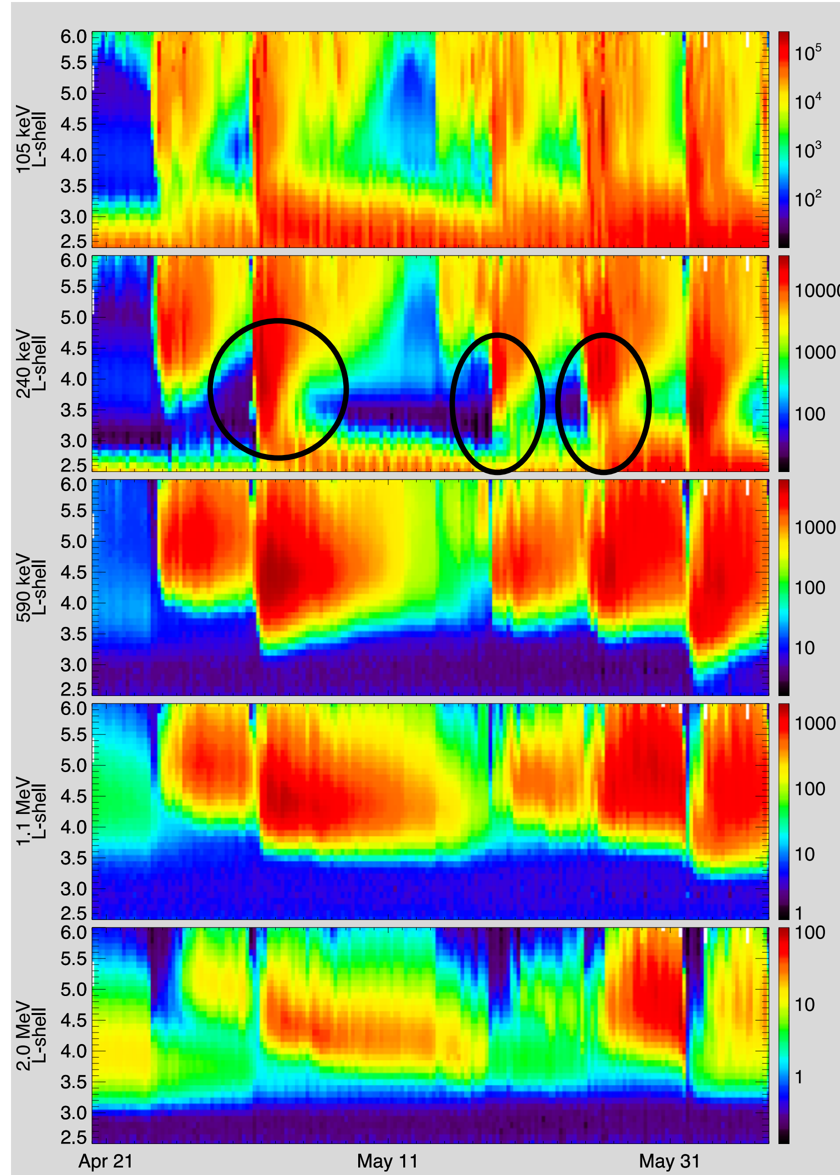
RBSP electron data



- Energetic electrons can penetrate to low L
- Energy seems limited to < 300 keV for L<4

- Source of inner belt electrons?
- Evidence of inward diffusion at low L after injections

- How are electrons transported into the slot region and inner belt?
- Are they related to substorms?
- Is transport diffusive or non-diffusive?

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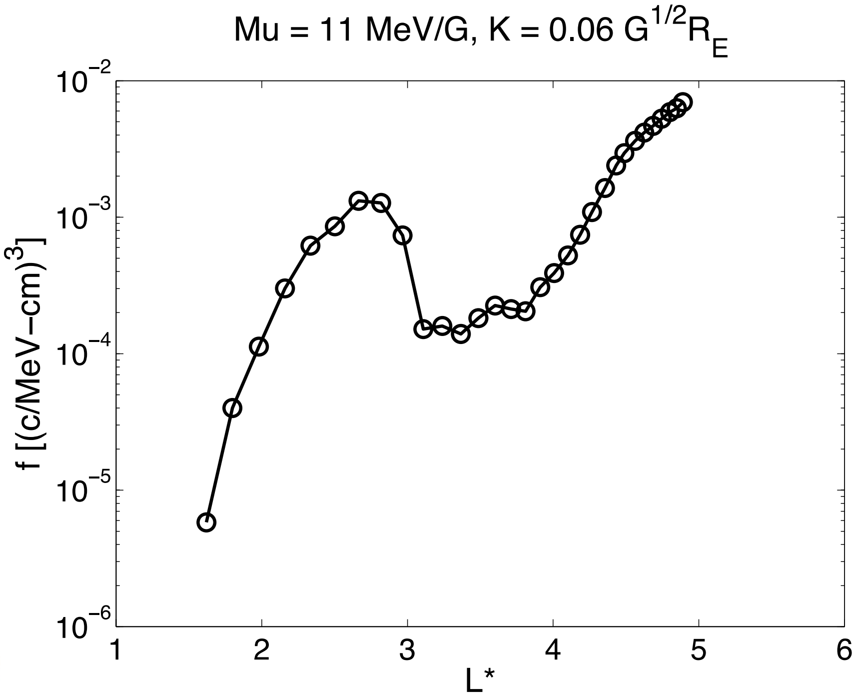
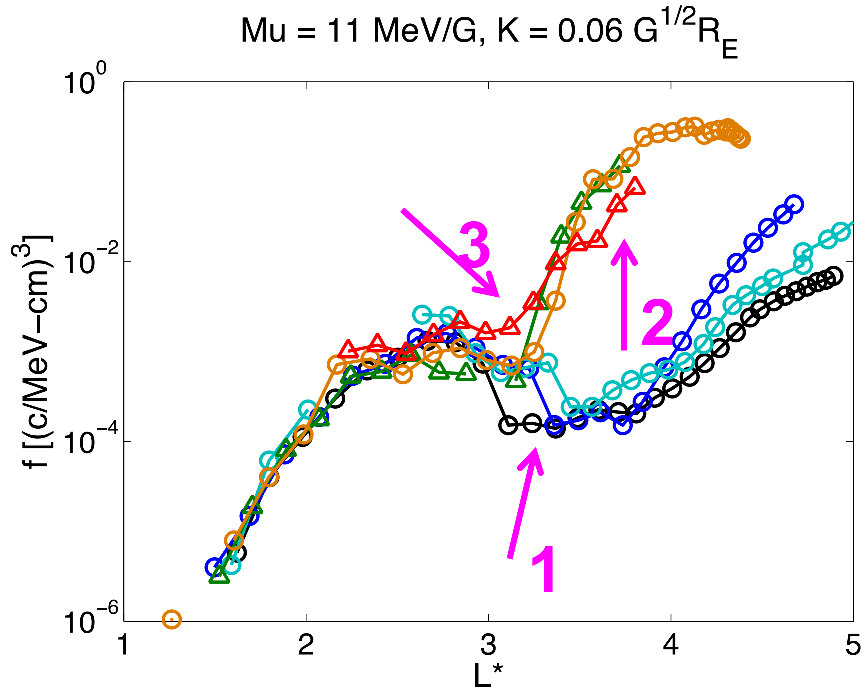
Injections to Low-L

- PSD profiles: evolution and evidence of radial transport at very low L-shells in only ~12 hours

1: Outward diffusion from inner zone peak
2: Sudden injection at 06:30UT on 08 Jun
3: Inward diffusion from injected source

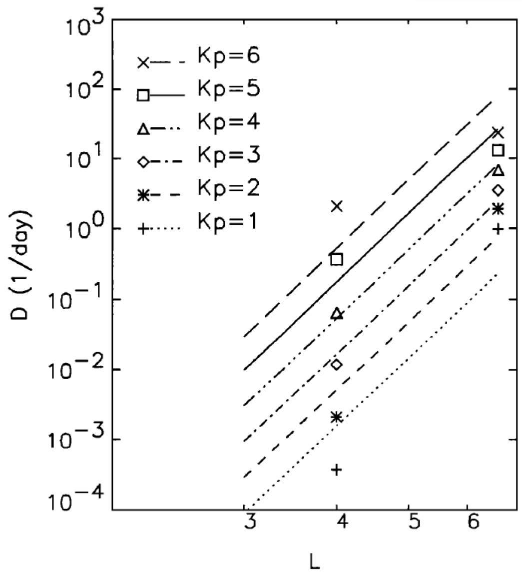
07 Jun 2014 Event: Initial Distribution



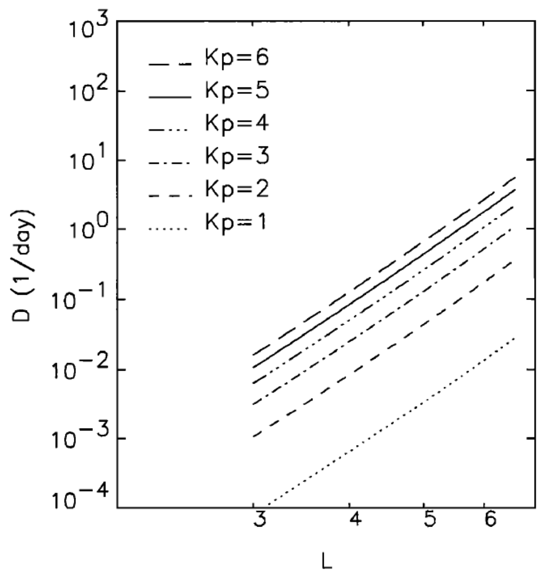


Radial Diffusion Coefficients

Electromagnetic as ~L^{10}



Electrostatic as ~L^{6}



$$D^{M}{}_{LL}(Kp,L) = 10^{(0.506Kp-9.325)}\, L^{10}\ ,\ Kp=1 \text{ to } 6,$$

$$D_{LL}^{E} = \frac{1}{4}\left(\frac{cE_{rms}}{B_o}\right)^2 \left[\frac{T}{1+(\omega_D T/2)^2}\right] L^6\ ,$$

$$\omega_D = \left(\frac{3Mc}{eL^2 R_E^2}\right)\left(1+\frac{2MB}{E_o}\right)^{-1/2},$$

$$E_{rms}(Kp) = 0.26(Kp-1) + 0.1 \text{ mV/m},\ Kp=1 \text{ to } 6.$$

- Fluctuations in convection electric fields – break 3rd invariant. Diffusion.
- Theory says that E field driven diffusion should dominate B field driven diffusion for L < 3
- Assumes a substorm E field modelled as an impulse followed by exponential decay
- Measurements

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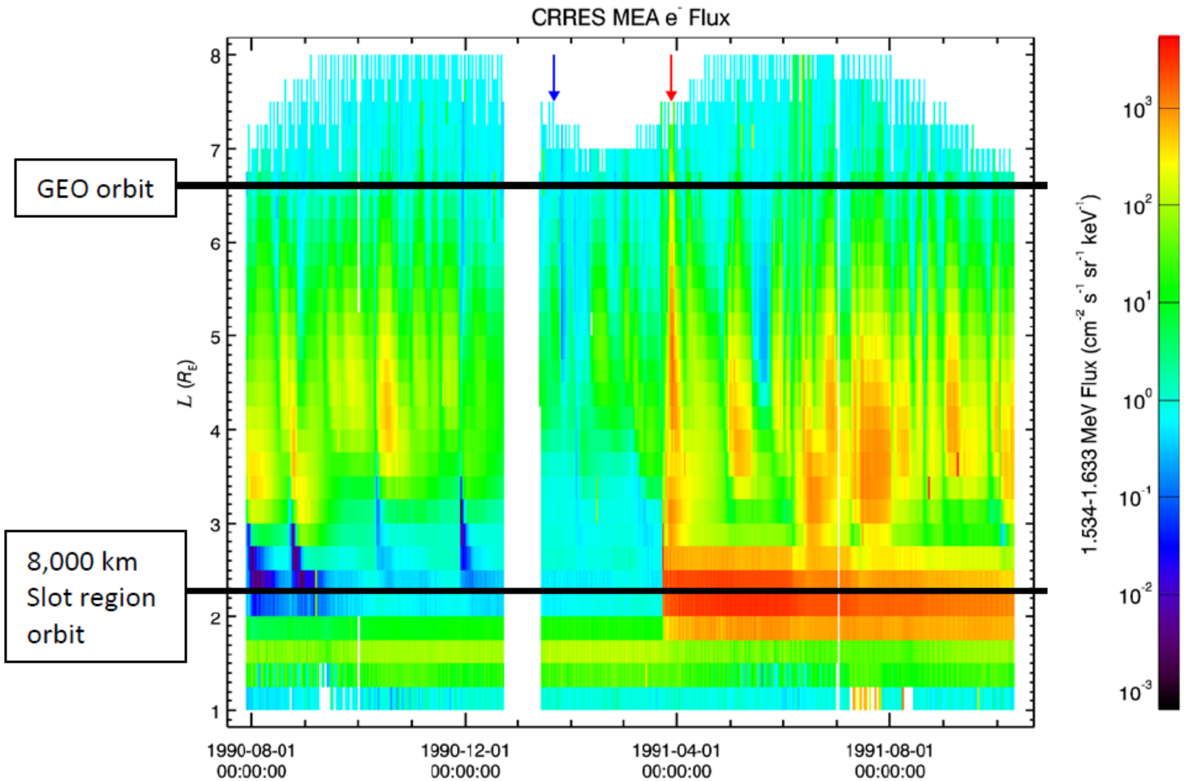
How Can SuperDARN Contribute to Radiation Belt Research?

- Diffusive transport
  - Diffusion should act on electrons at all energies >~100 keV
  - But – injections seem restricted to E < ~ 300 keV
  - But - there are no inner belt electrons (L=1.7) > 800 keV – RBSP result
  - So what is the range of validity in L?
  - How important are magnetic local time variations in E?
  - Test the timescale for diffusion to be valid – much longer than the drift period
  - Uncertainty over separating Electrostatic from Electromagnetic components experimentally – is this the right approach?
- Need to measure the E fields – and work out diffusion rates - and test against observations of radiation belt transport

March 1991 - Largest Injection Event

- Driven by a shock striking the magnetosphere
- Electrons transported by the induced E field – on 1 drift orbit
- Blake et al [1992], Hudson et al, [1995]



Horne and Pitchford [2015]

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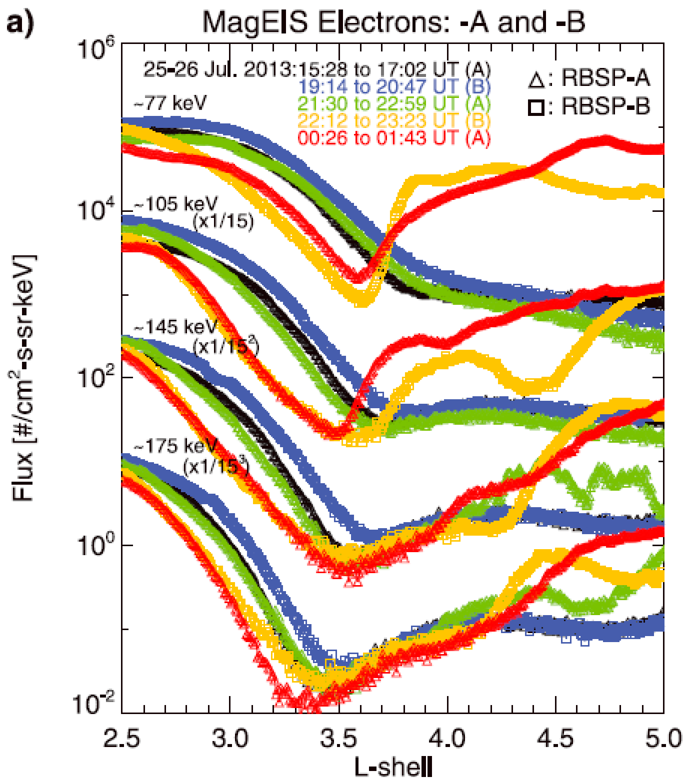
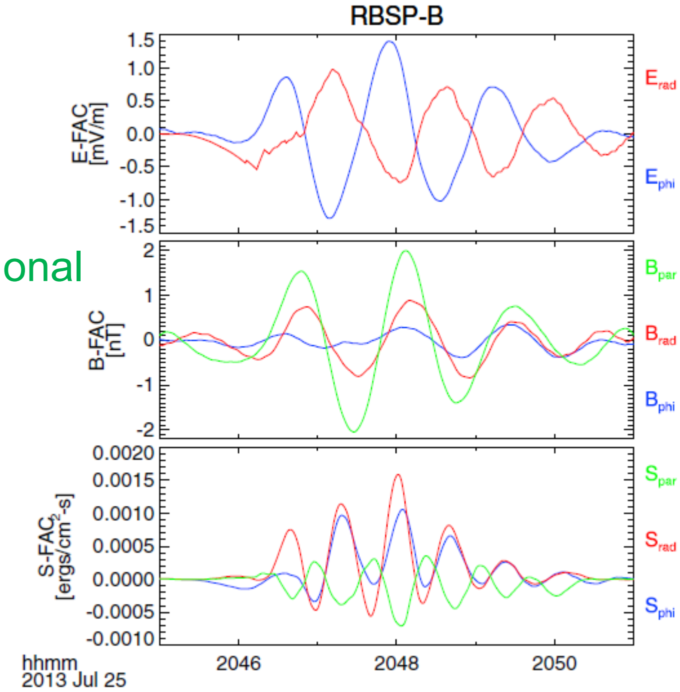
Transport to Low L [Turner et al., GRL 2015]



B Compressional
B radial
B phi



- Injections limited to < 145 keV at L<4
- Peaks (gold-red) suggest drift-bunched echoes and hence localised injection
- Unlikely to be an injection boundary as injections are inside the plasmapause and the Alfven layer is outside, and not a plasma bubble - entropy L<4 is too low

- Suggest fast magnetosonic wave is launched as depolarisation front comes to a stop
- Cavity mode resonance at pi2

How Can SuperDARN Contribute to Radiation Belt Research?

- Non-diffusive transport
  - Low energy < 300 keV electron injection into the slot region and inner belt suggests convection E field transport
  - Higher energy electrons drift according to gradient and curvature drift
  - But the low energy ions are not always observed at low L
  - Drift echoes - Some localised structure in E?   Dipolarisation front?
  - Drift bounce resonance to select and transport electrons?
  - E field penetration into plasmasphere?
  - Excitation of magnetosonic waves and cavity mode waves inside plasmasphere [Turner et al., 2015]?

- Need to measure the E fields and relate to electron transport events

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Summary

- Our understanding of the radiation belts 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
- SuperDARN can play an important role in determining electron transport into the slot region and inner belt; diffusive and non diffusive processes
- SuperDARN could provide important inputs to Space Weather modelling for satellite risk

The End

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Extra Slides

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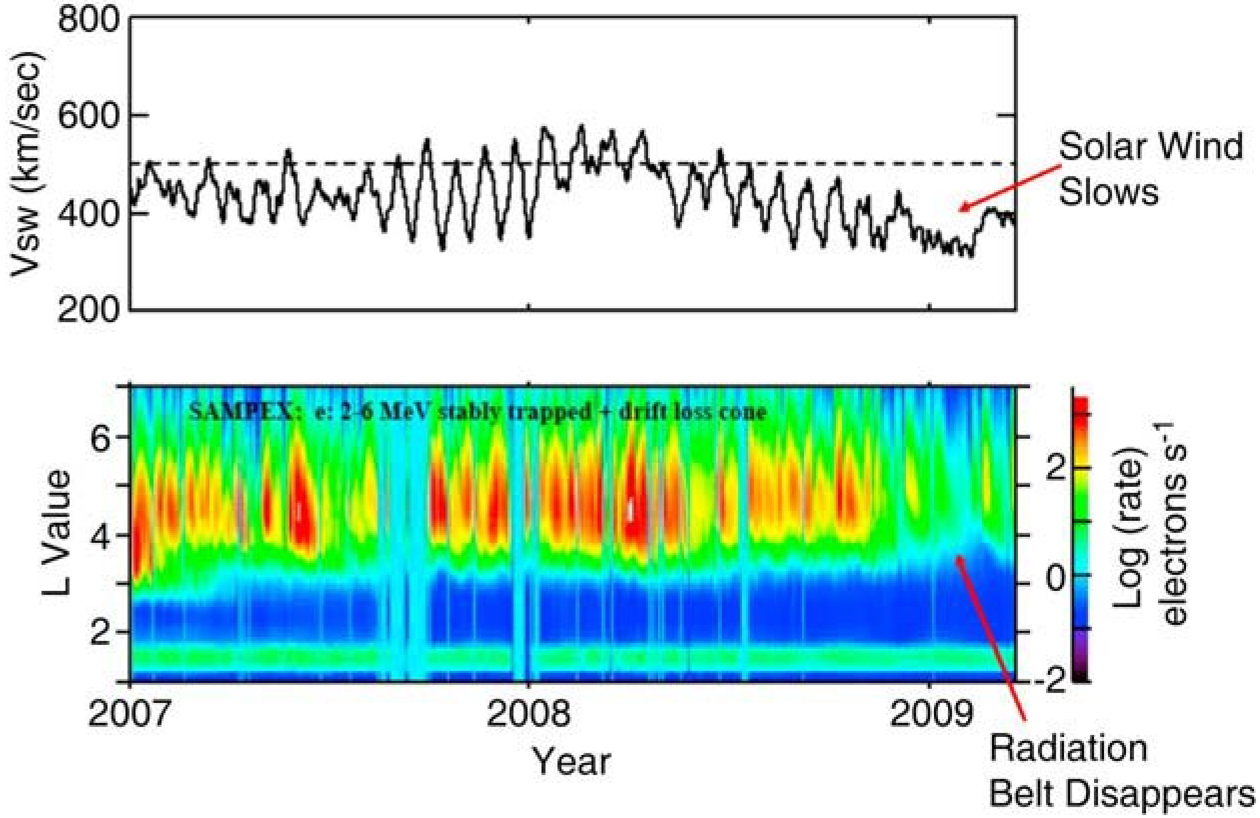
Satellite Anomalies – Related to Space Weather

- 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

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?

BAS Radiation Belt Model 3d

- 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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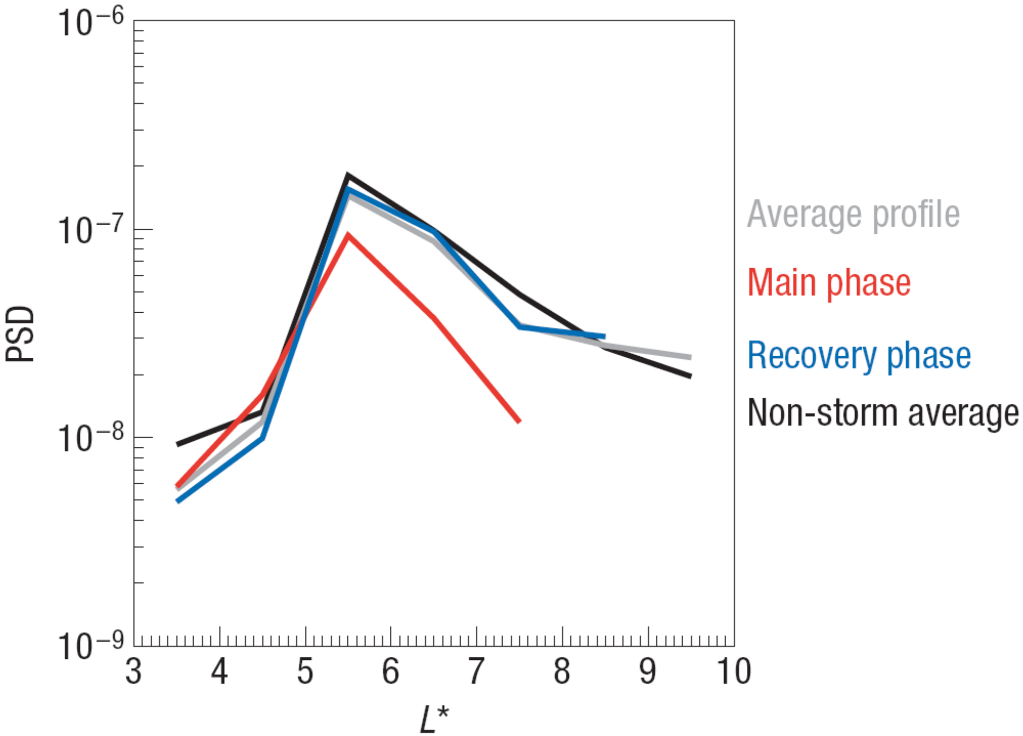
Electron Phase Space Density

M = 2083 MeV/Gauss



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

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

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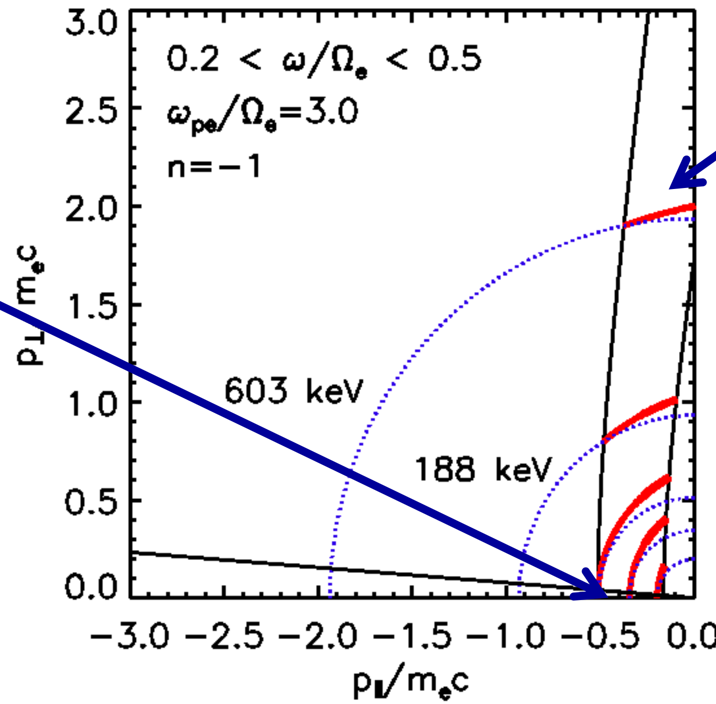
Acceleration by Whistler Mode Waves – QL Theory

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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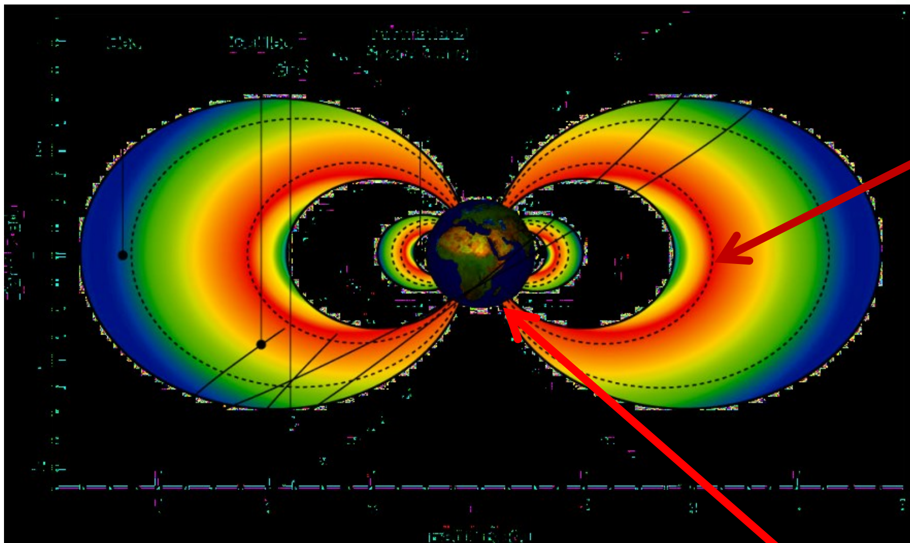
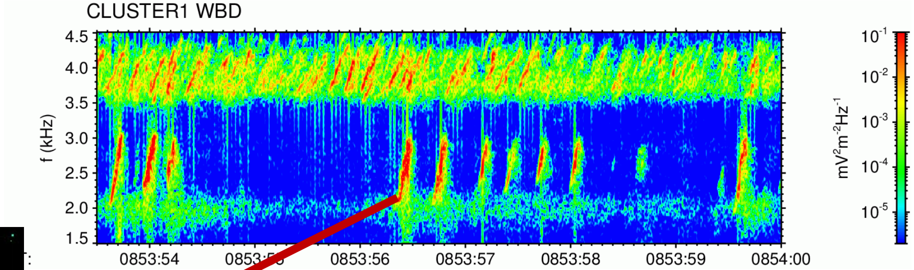
Wave-Particle Interactions

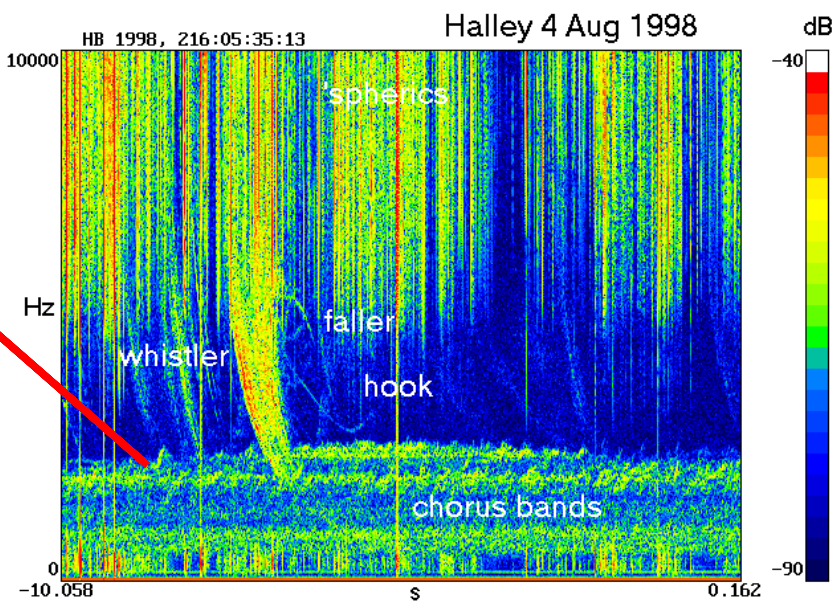
- Chorus waves detected on the ground and in space





Satellite observations

Antarctic observations



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

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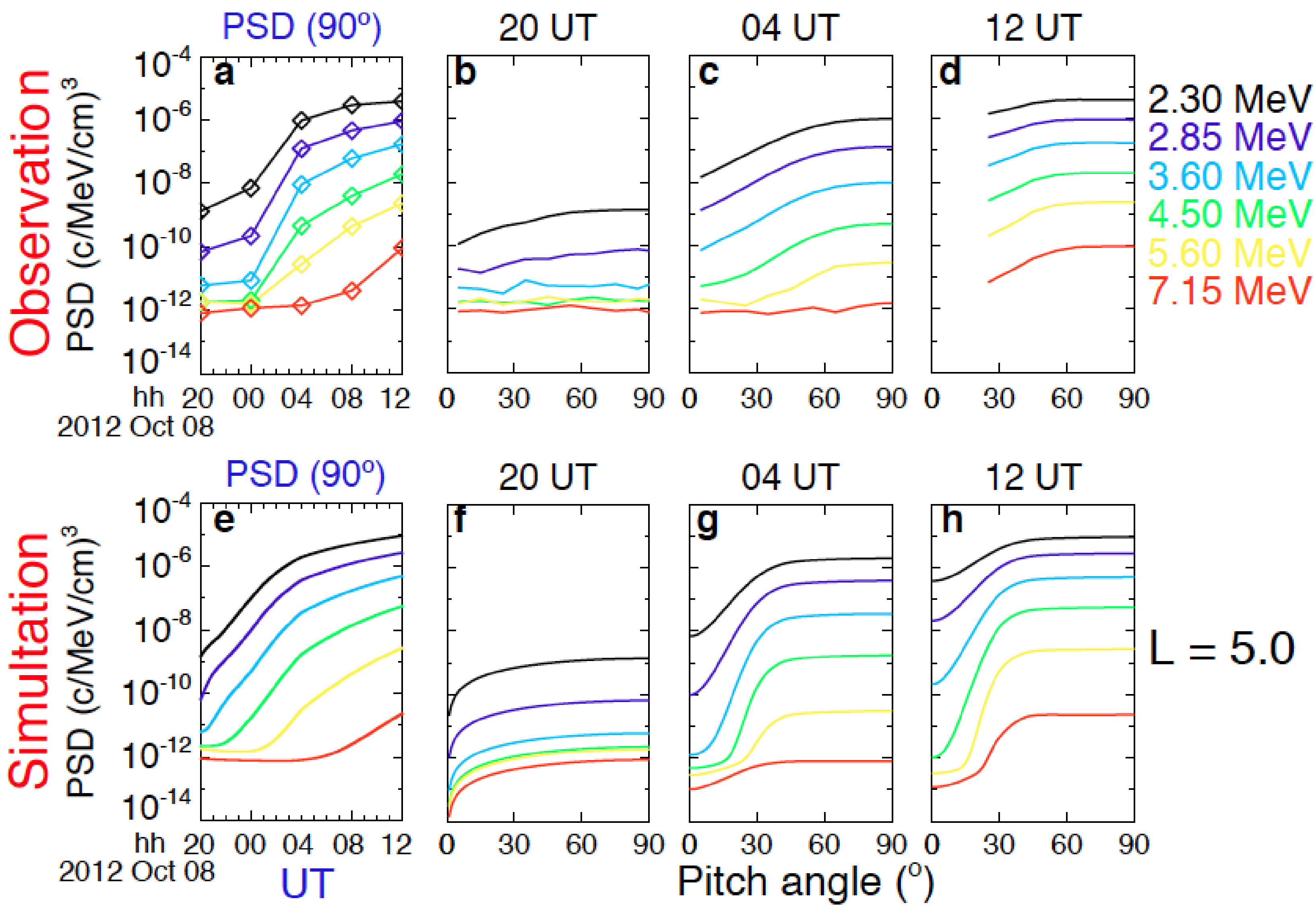
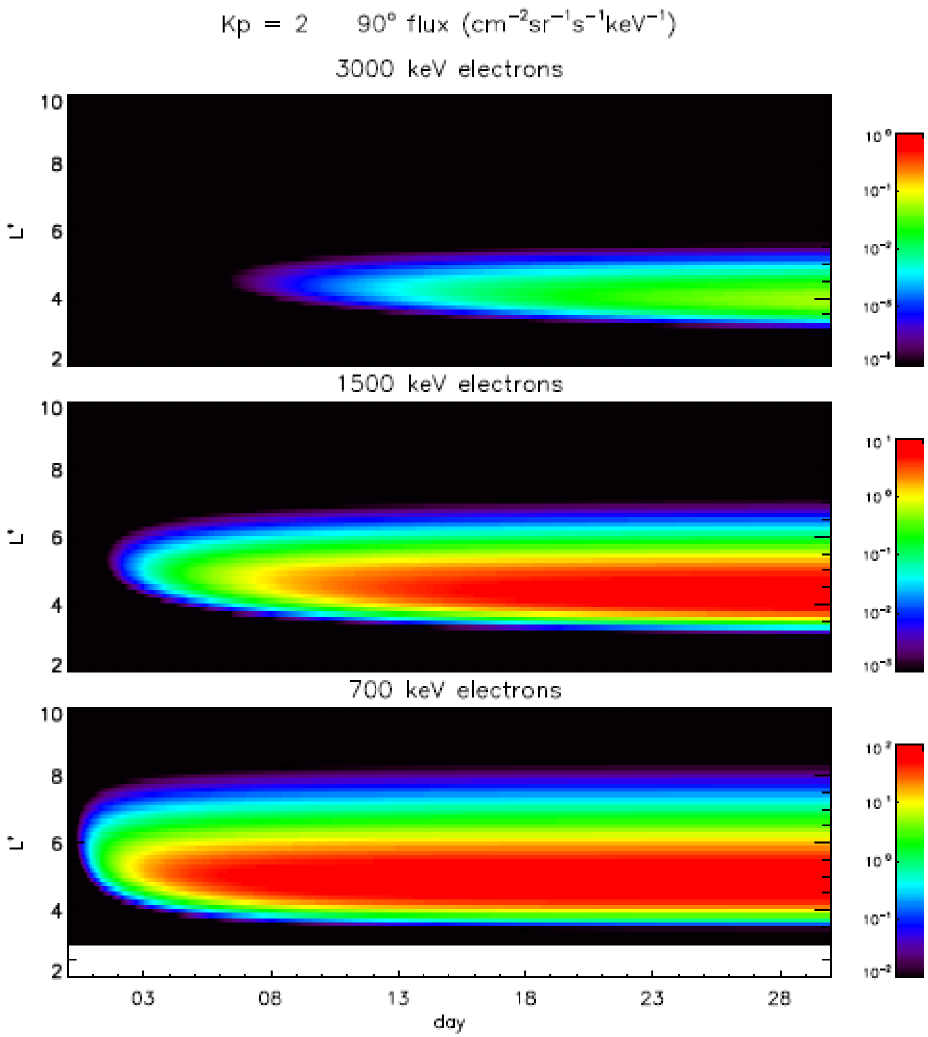
Chorus-driven electron acceleration, Oct 8-9 2012

Thorne et al., *Nature* [2013]



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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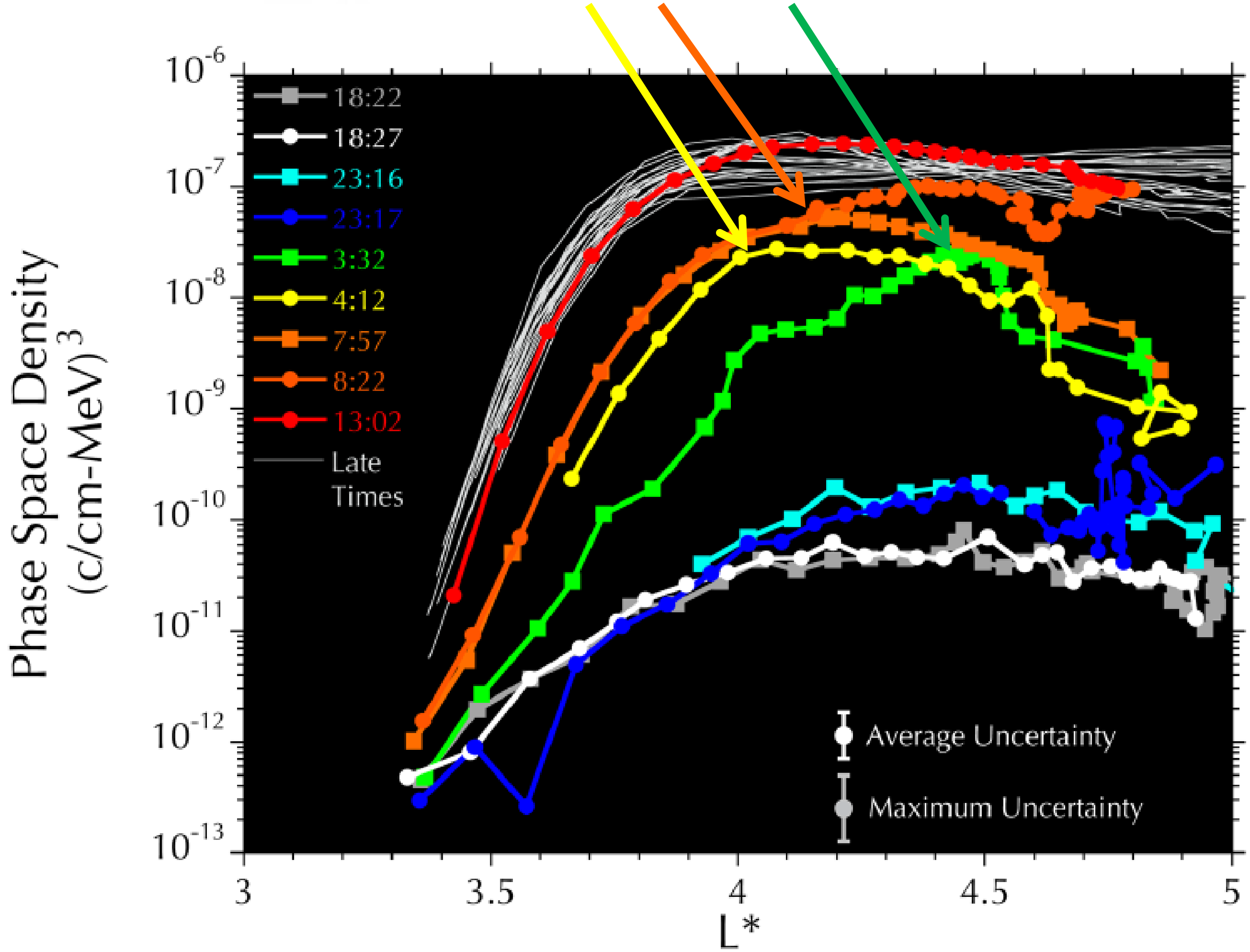
SPACESTORM

Evidence for Local Acceleration - RBSP



- Reeves et al., Science [2013]

Objectives

- To model space weather events using dynamic models
- To construct 30 year dataset for MEO and GEO
- To determine the space radiation environment for extreme SW events
- To determine the impact on satellites
- To develop better mitigation guidelines
- To provide mitigation by monitoring, forecasting and warning
- To test new experimental methods of reducing satellite charging