Incorporating Wave-Particle Interactions into Global models

Richard B. Horne

British Antarctic Survey

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SHIELDS Workshop, Los Alamos, USA, 23 Feb 2015

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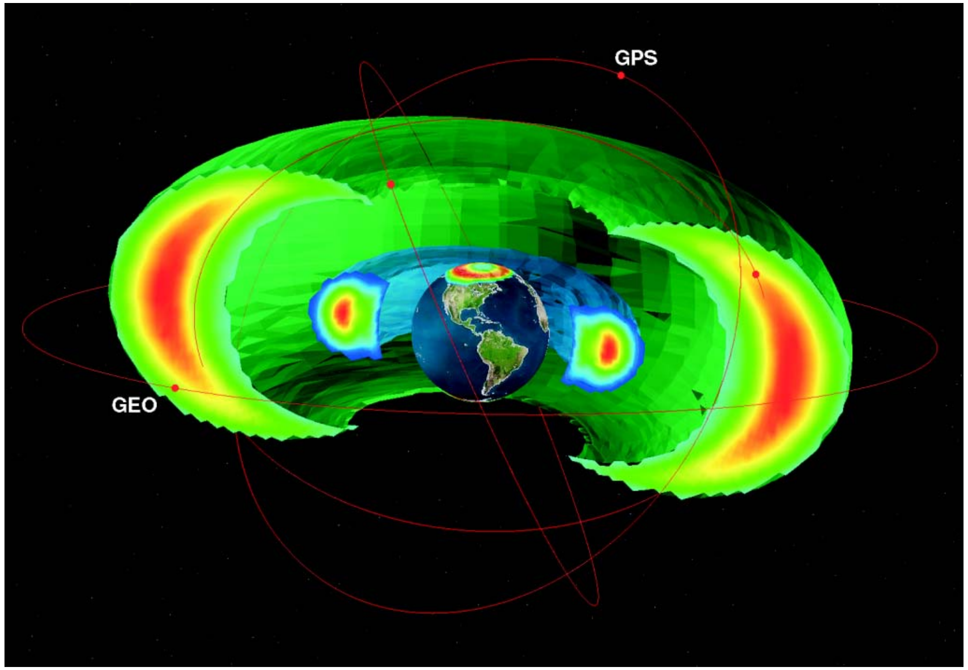

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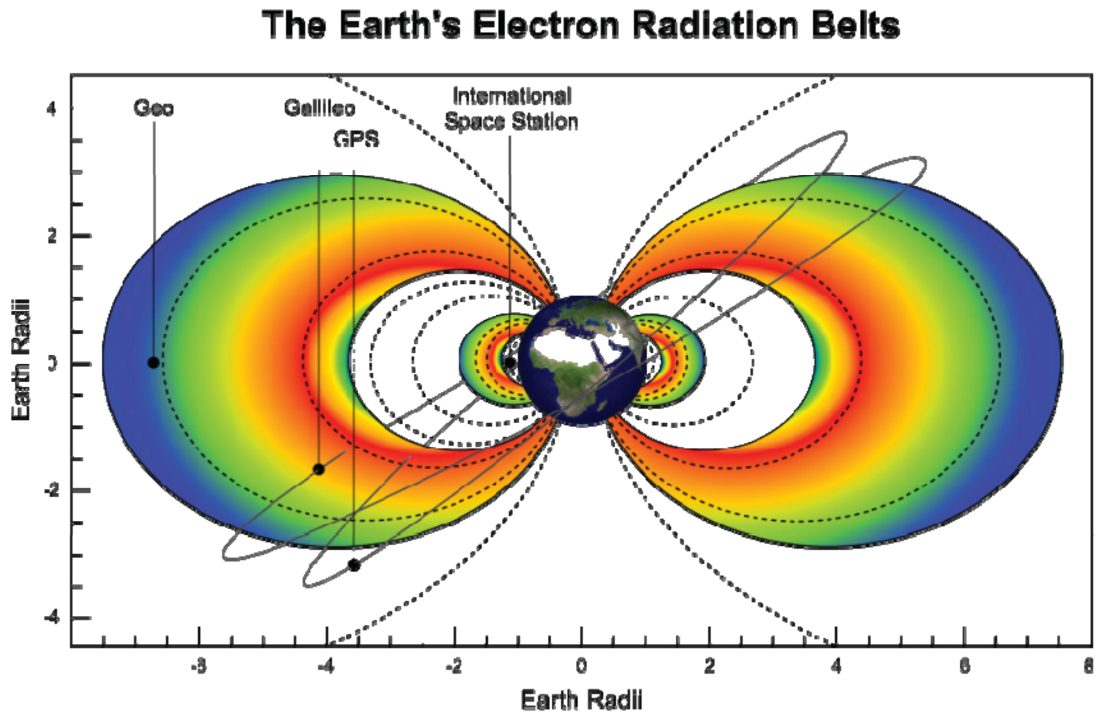
SHIELDS Workshop, Los Alamos, USA, 23 Feb 2015

Satellite Orbits and the Earth's Radiation Belts



- About 1000 satellites in orbit:
    - 420 in geosynchronous orbit GEO
    - 70 in medium Earth orbit MEO
    - 470 in low Earth orbit LEO
    - 35 in highly elliptical orbit HEO

- Earth's radiation belts contain very high energy electrons and ions that damage satellites

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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? - National Risk Register
  - Estimates vary widely (all space weather - US$0.6 – 2.6 trillion)

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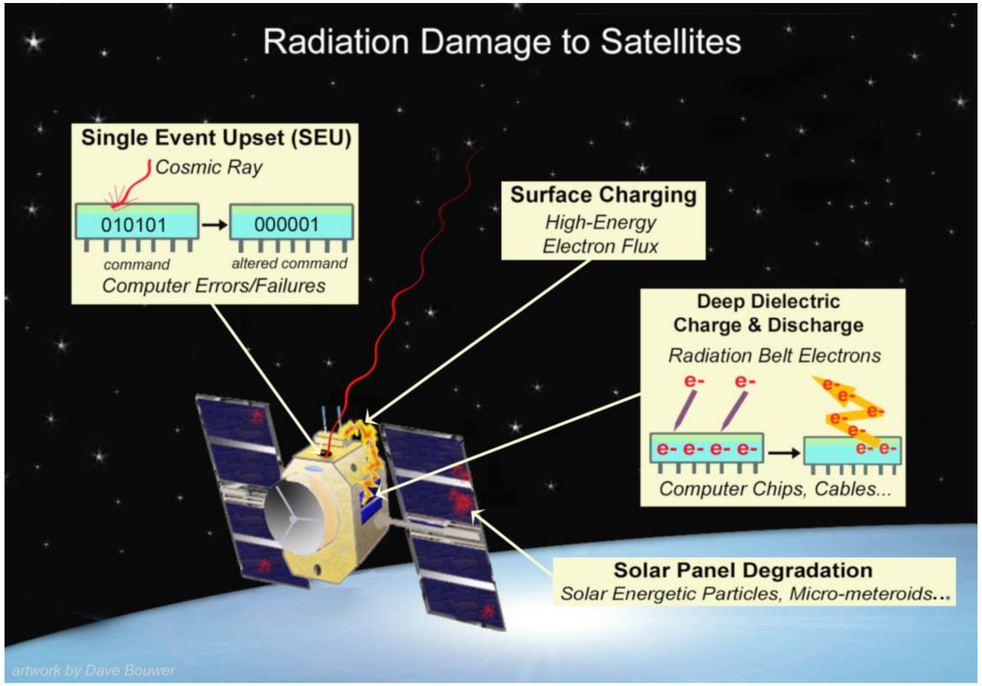
Spacecraft Damage

- Satellite charging
  - Internal charging – MeV electrons
  - Surface charging – keV electrons
- Electrostatic discharge
  - Component failure
  - Phantom commands
- Single event effects
  - Corrupt memory circuits
  - Loss of power in solar cells
  - ~ 2% in GaAs/Ge cells – SEP event
  - Parts failure
- Cosmic rays
- Solar energetic particle events (SEPs)



- Cumulative radiation dose limits spacecraft lifetime
  - Aging of surface coatings
  - Erosion
  - Reduced thermal resilience

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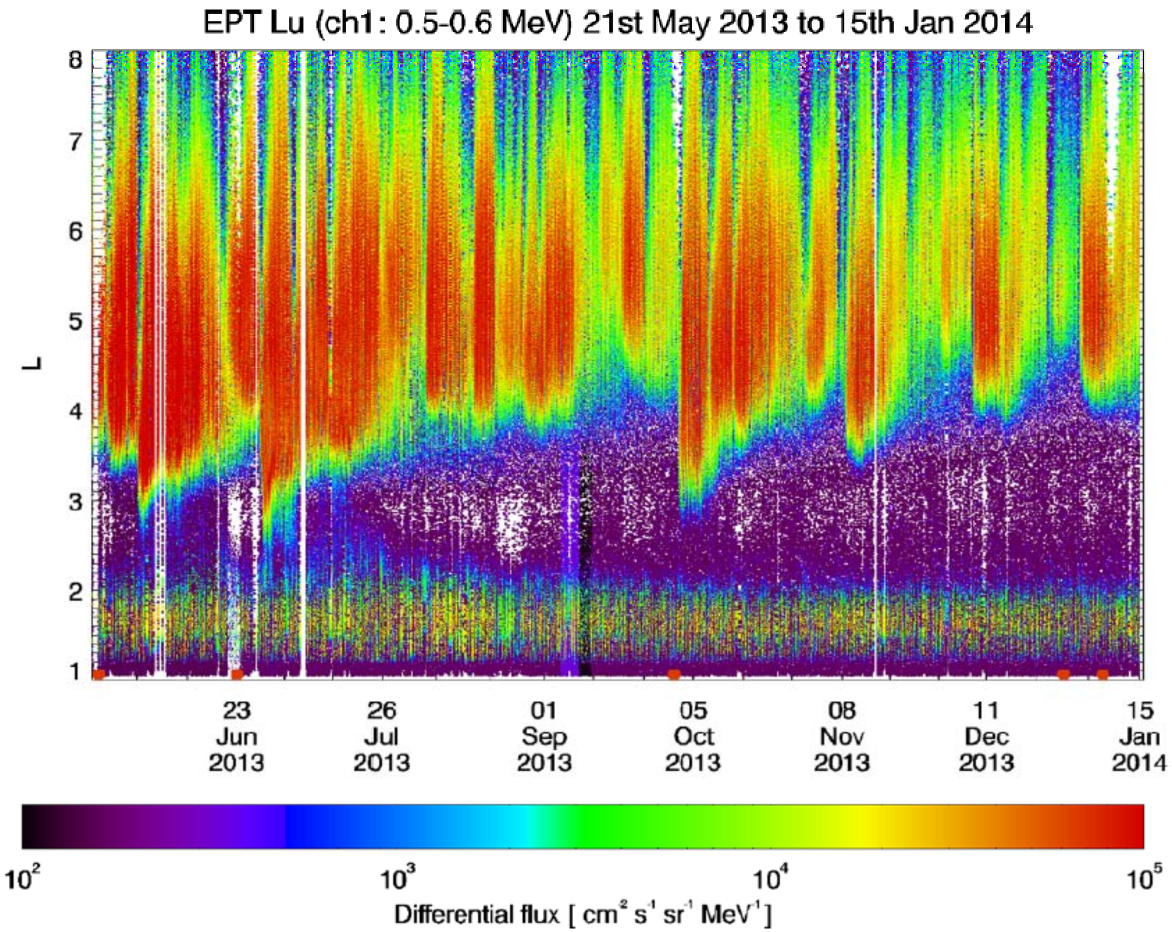
Electron flux variability

- Proba V EPT data



- Pierrard et al. [2014]

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BAS Radiation Belt Model

- Fokker-Planck Equation

$$\frac{\partial f}{\partial t} = \underbrace{L^2 \frac{\partial}{\partial L}\left(\frac{D_{LL}}{L^2}\frac{\partial f}{\partial L}\right)\bigg|_{\mu J}}_{\text{Radial transport}} + \underbrace{\frac{1}{g(\alpha)}\frac{\partial}{\partial \alpha}\left(g(\alpha)D_{\alpha\alpha}\frac{\partial f}{\partial \alpha}\right)\bigg|_{EL}}_{\text{Pitch angle diffusion}} + \underbrace{\frac{1}{A(E)}\frac{\partial}{\partial E}\left(A(E)D_{EE}\frac{\partial f}{\partial E}\right)\bigg|_{\alpha L}}_{\text{Energy diffusion}} \underbrace{- \frac{f}{\tau(\alpha, E)}}_{\text{Losses}}$$

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

- Details in: Glauert et al. [2014a, b]

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Wave-particle Interactions - Challenges

- Wave-particle interactions cause electron acceleration and precipitation (loss)
- Challenges
  - Timescale – milliseconds – but we need to model days
  - Which waves are most important? (Chorus, Hiss, magnetosonic, EMIC, LO, RX, Z mode, lower hybrid, ECH, transmitters, lightning-whistlers...)
  - How do we capture MLT dependence?
  - Latitude dependence
  - Power spectra
  - Plasma density effects
  - Propagation direction – wave normal angle
  - Ion composition effects – polarization and propagation
  - Nonlinear effects!! – and saturation
  - Relate to substorms
  - Relate to CMEs and fast solar wind – magnetopause compressions

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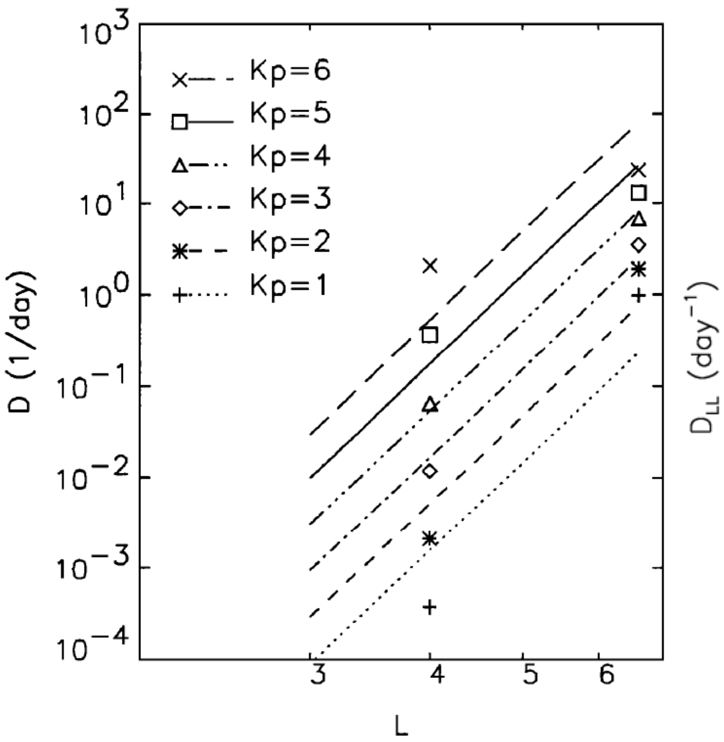
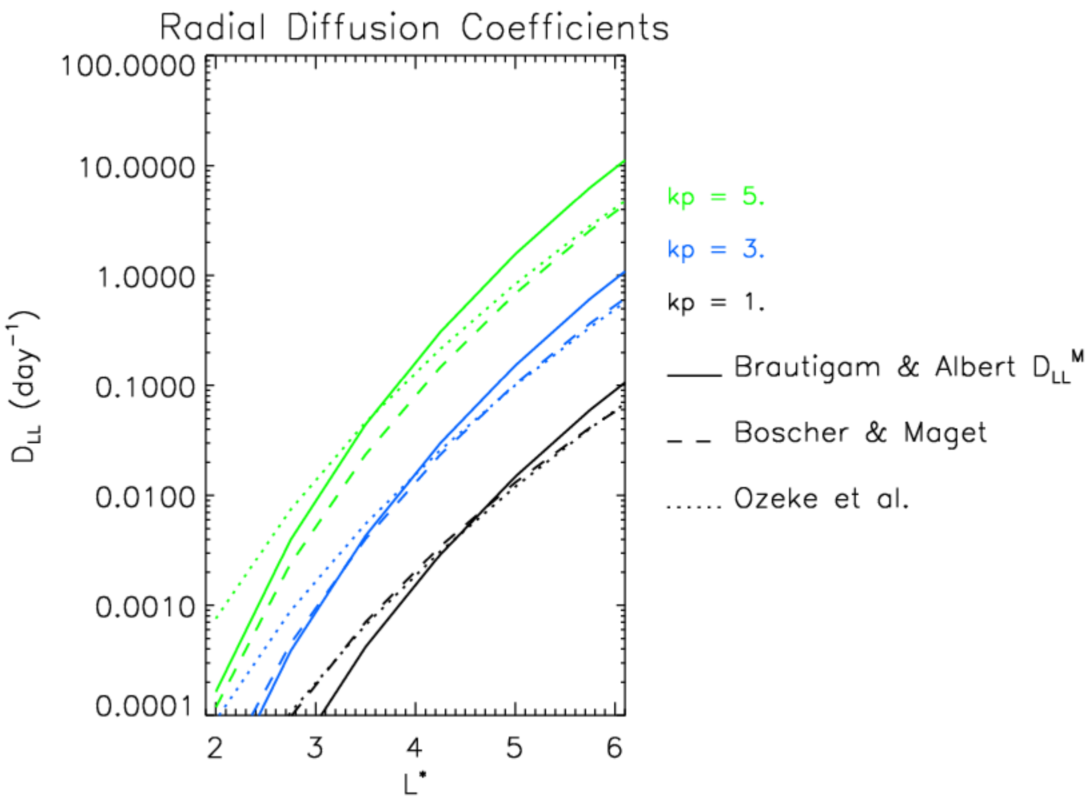
Radial Diffusion Coefficients

Brautigam and Albert [2000]



B&A, Ozeke, Boscher



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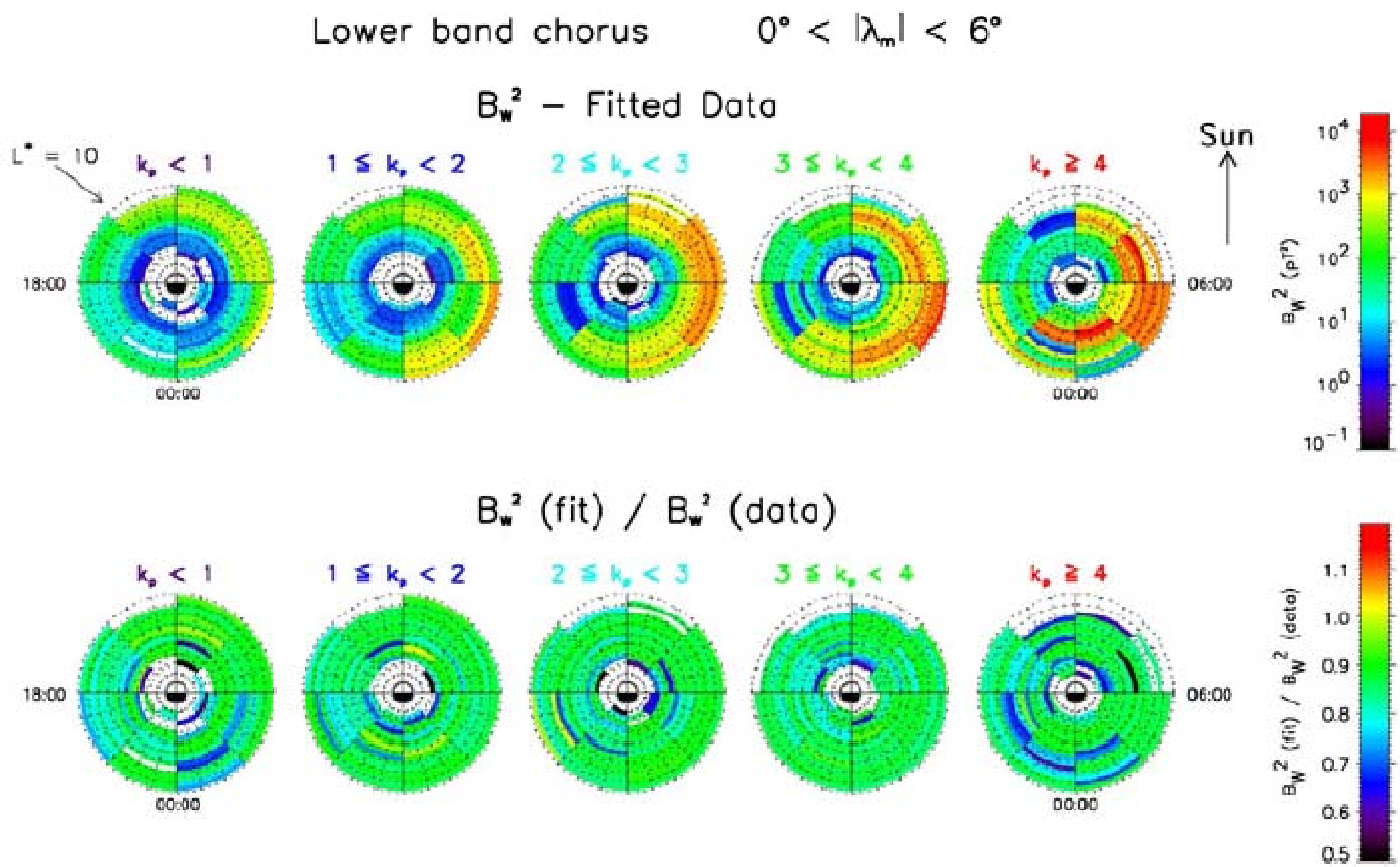
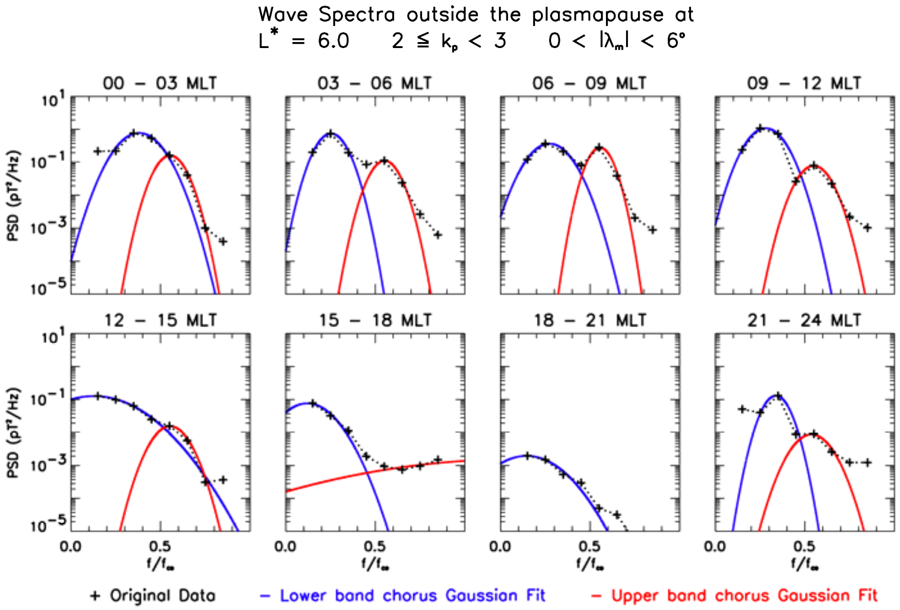
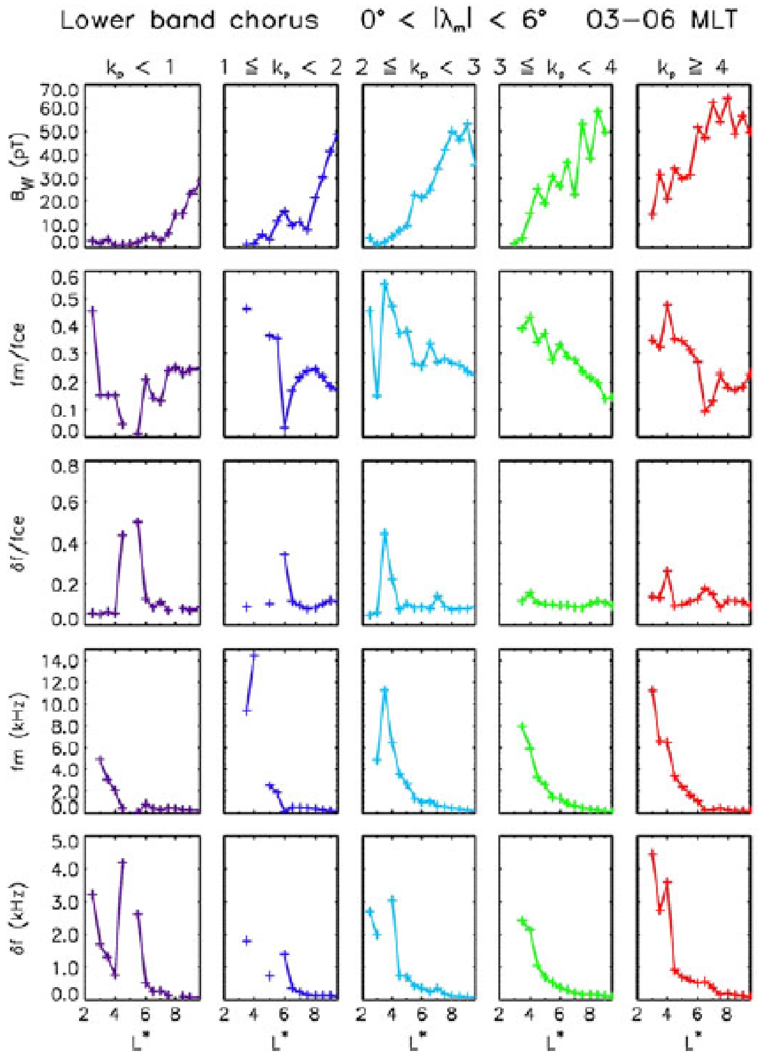
New Chorus Wave Model



- Horne et al. JGR [2013]

New Chorus Wave Model





- Fitted 3536 power spectra, L* = 1.5 – 10, lat = 0 – 60, MLT = 0 – 24, 5 activity levels
- Similar fitting of wave data for plasmaspheric hiss

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- Horne et al. JGR [2013]

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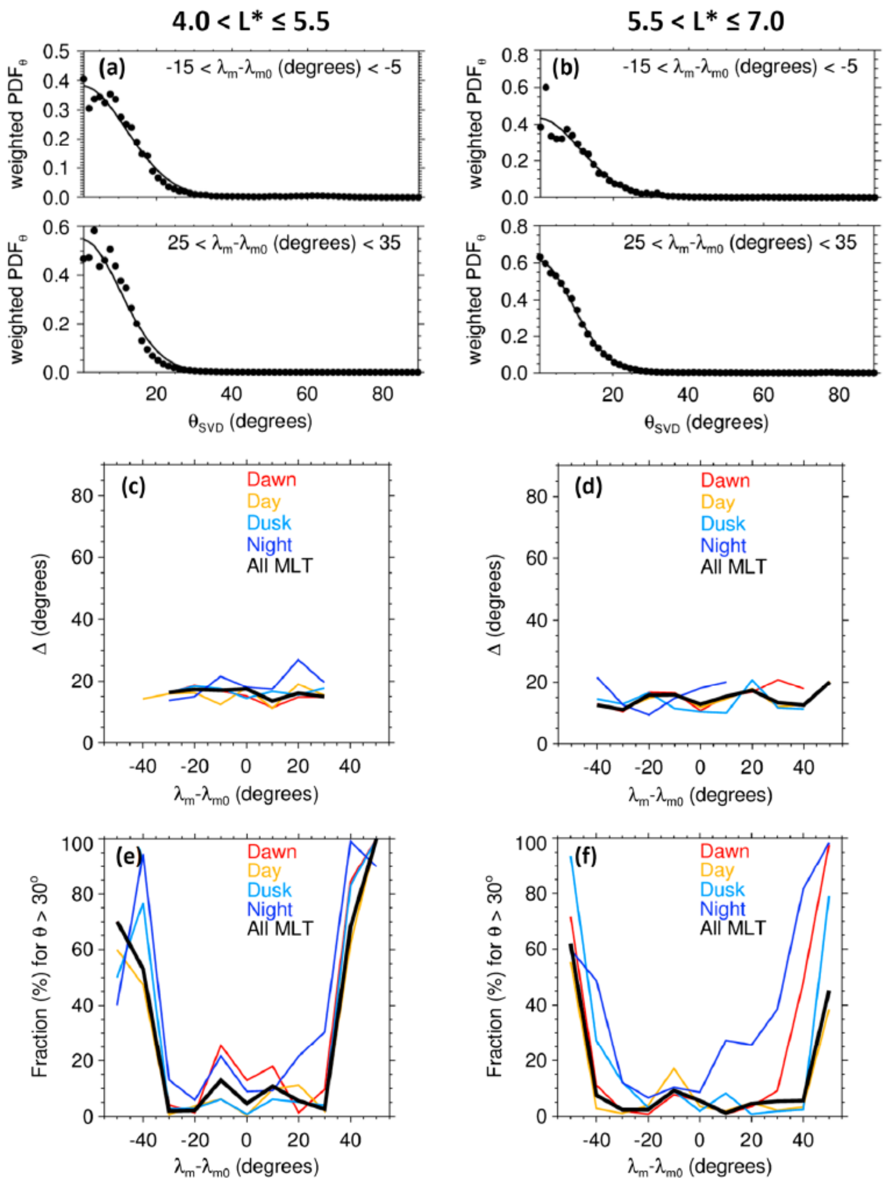
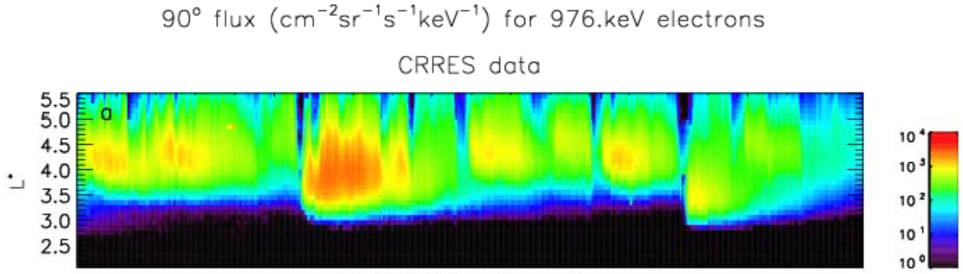
Chorus Wave Normal Angle

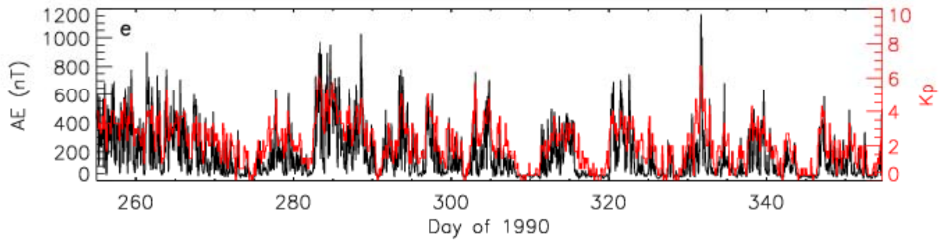


- Santolik et al., [2014]
- Angular width ~ 15^{o}

Importance of Wave-Particle Interactions

Satellite data - Electrons





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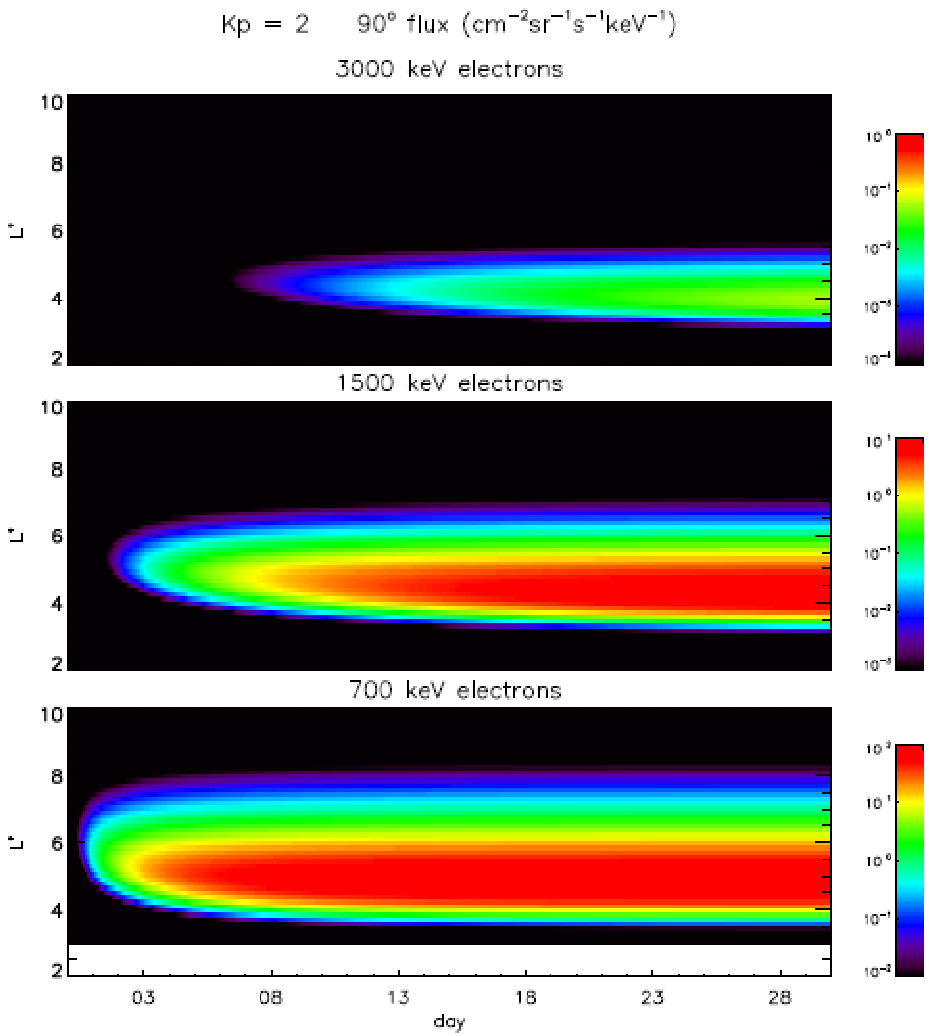
Radiation Belt from Chorus Alone



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

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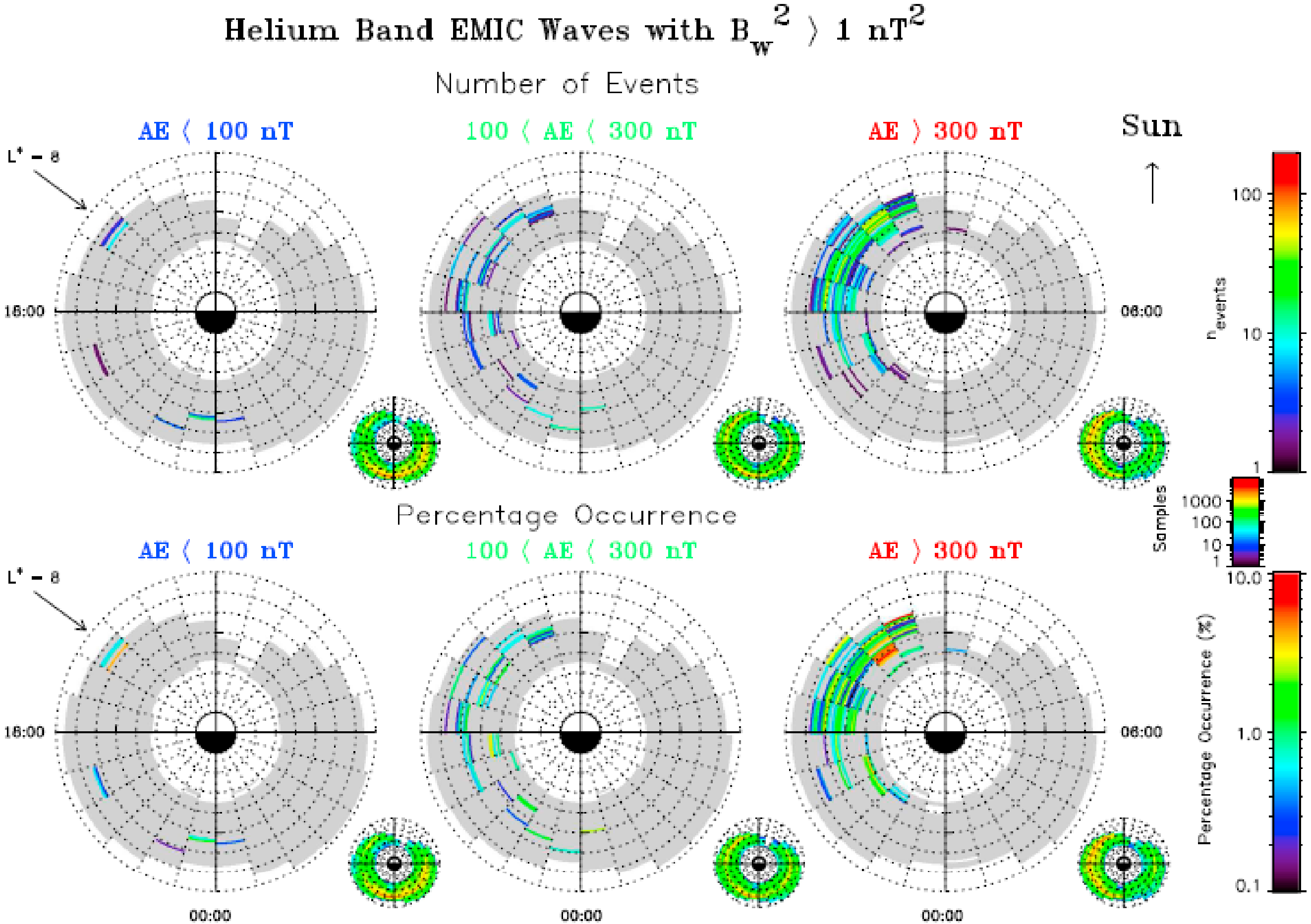
CRRES EMIC Wave Survey



- Meredith et al. JGR, [2014]

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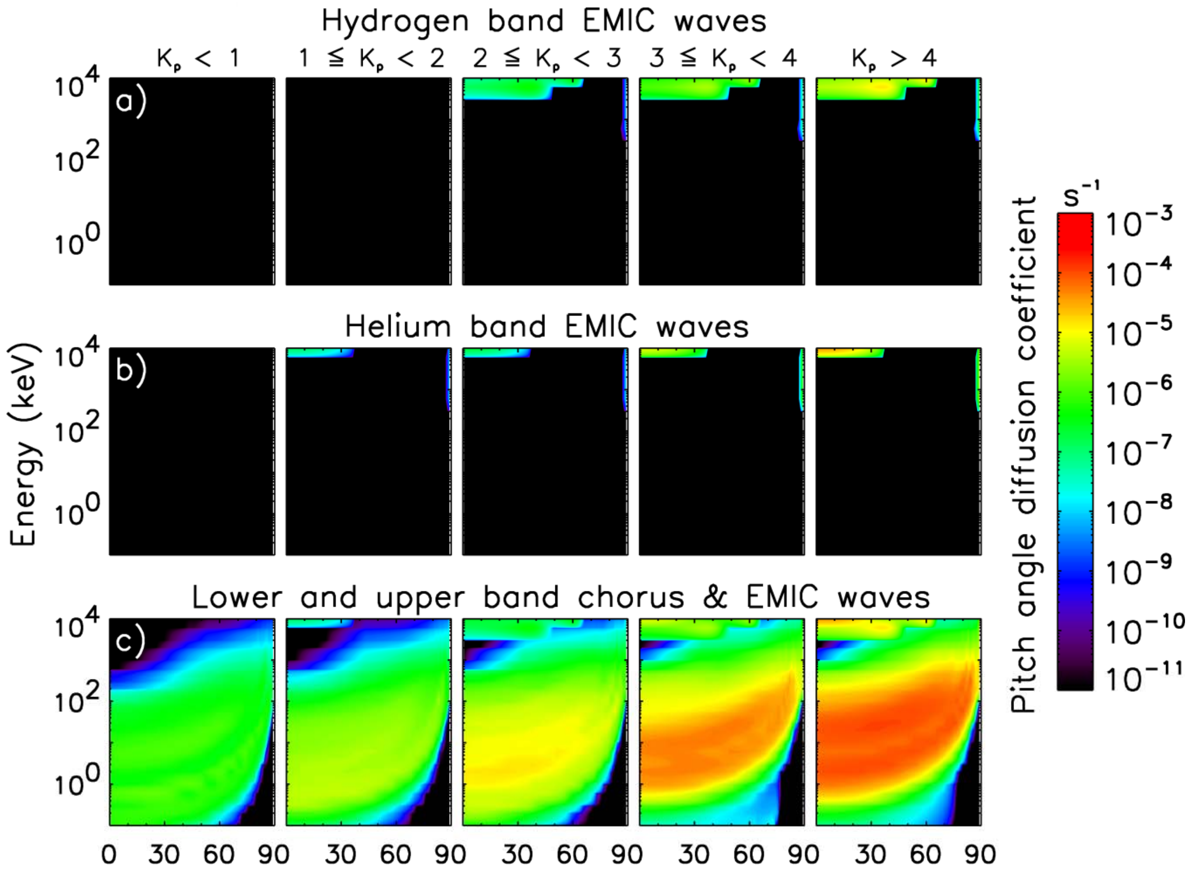
EMIC diffusion rates L* = 4.5

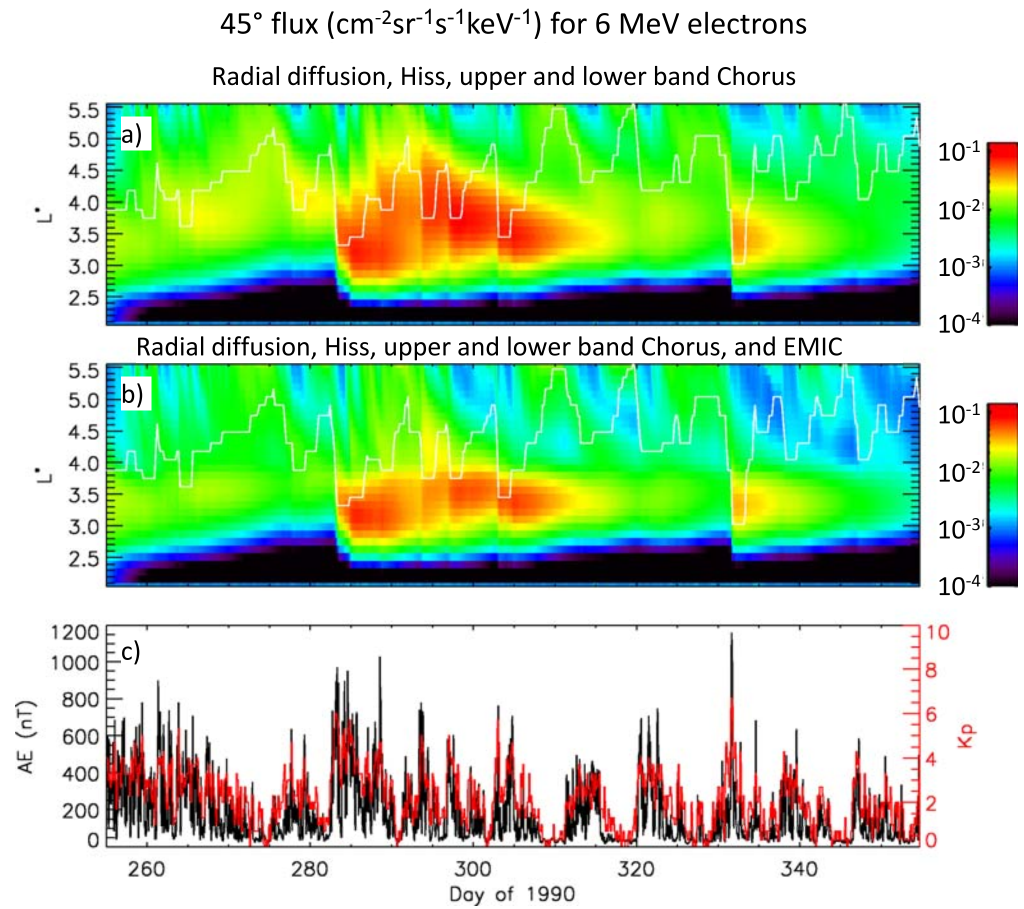


- Pitch angle diffusion becomes significant only at high energies (E > 3 MeV) and low pitch angles (α < ~60°)
- Energy diffusion is insignificant at all energies and pitch angles

Electron flux: 100 day simulation – 45°

Without EMIC

With EMIC



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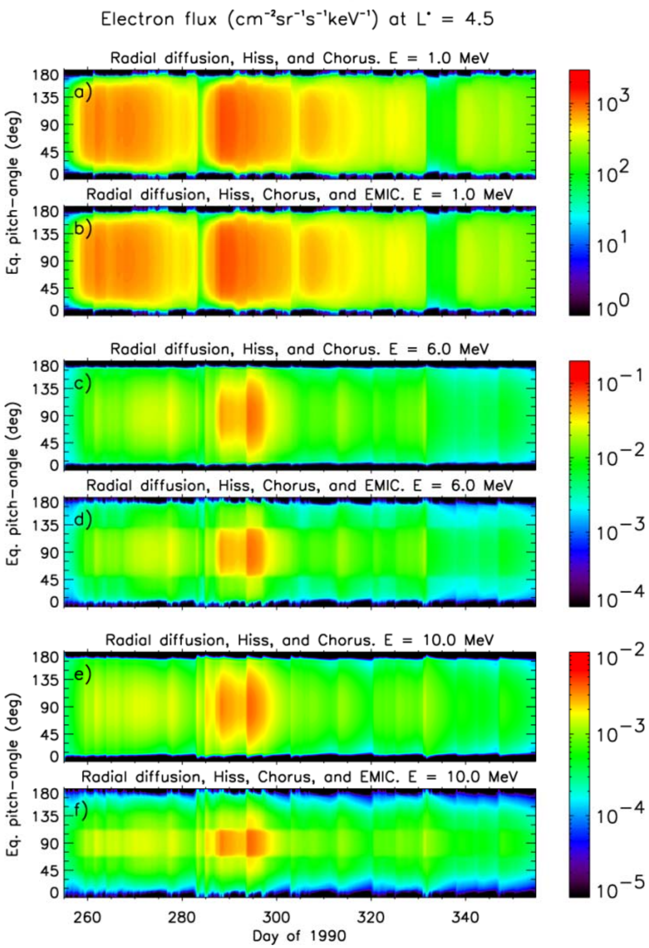
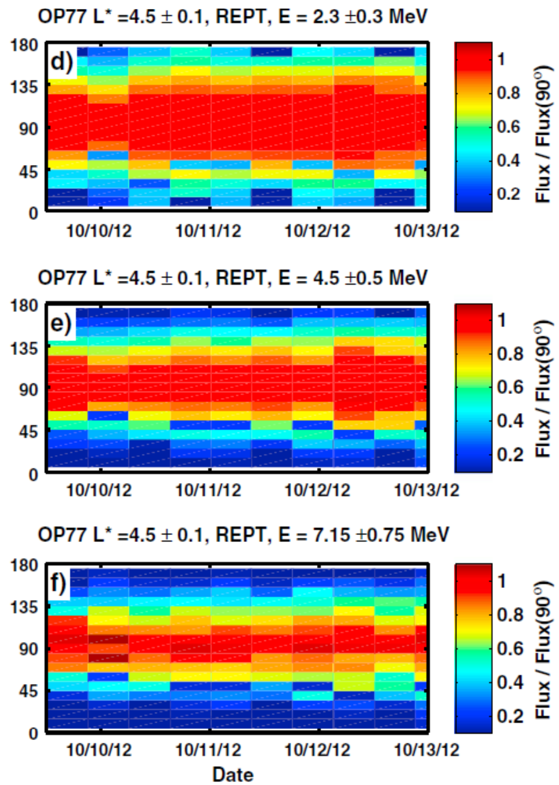
Electron Pitch Angle Distribution

Kersten et al., [2014]



Usanova et al., JGR, [2014]



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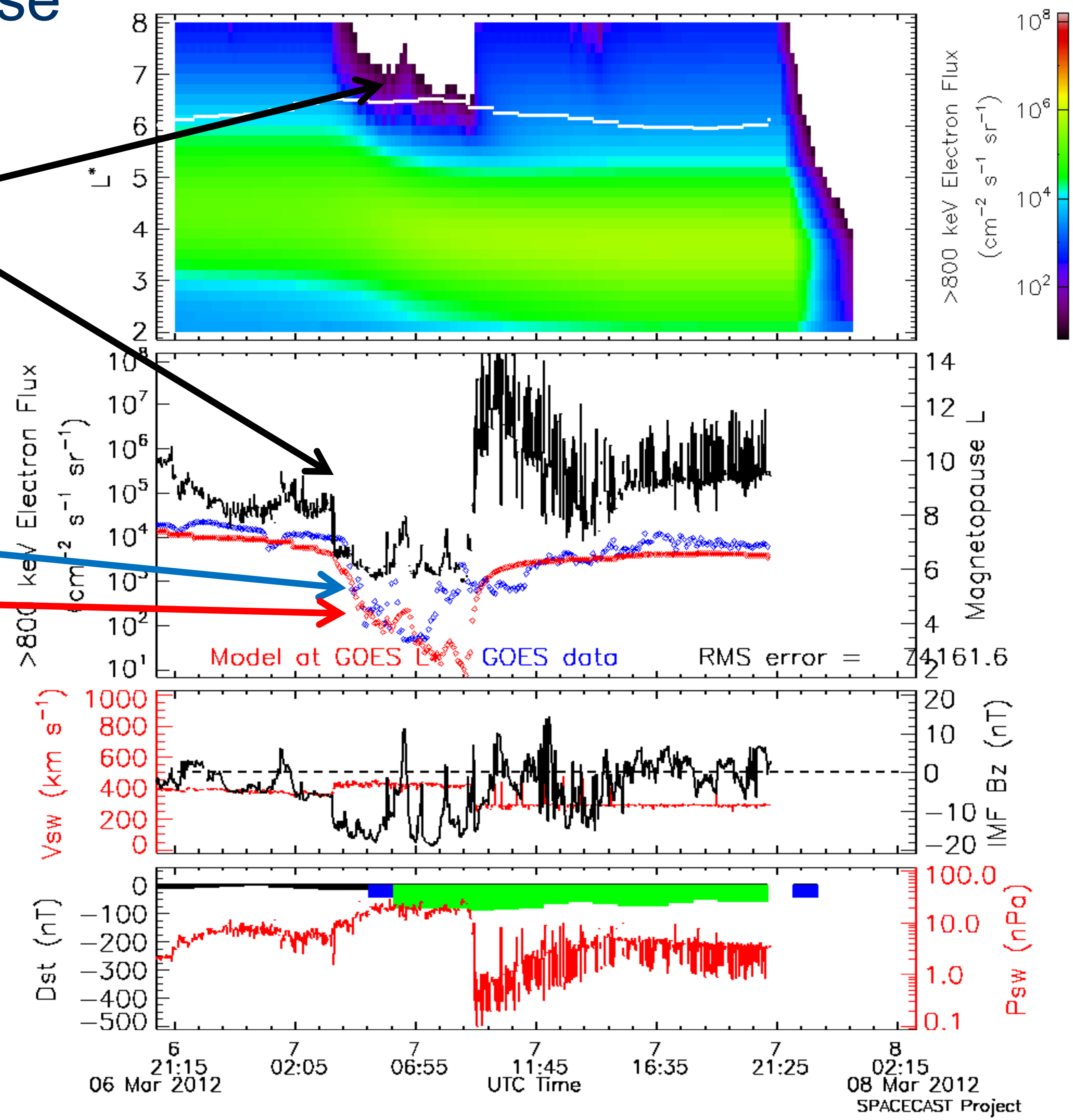
Magnetopause Losses

Magnetopause

Losses outside last closed drift shell

GOES data

BAS model



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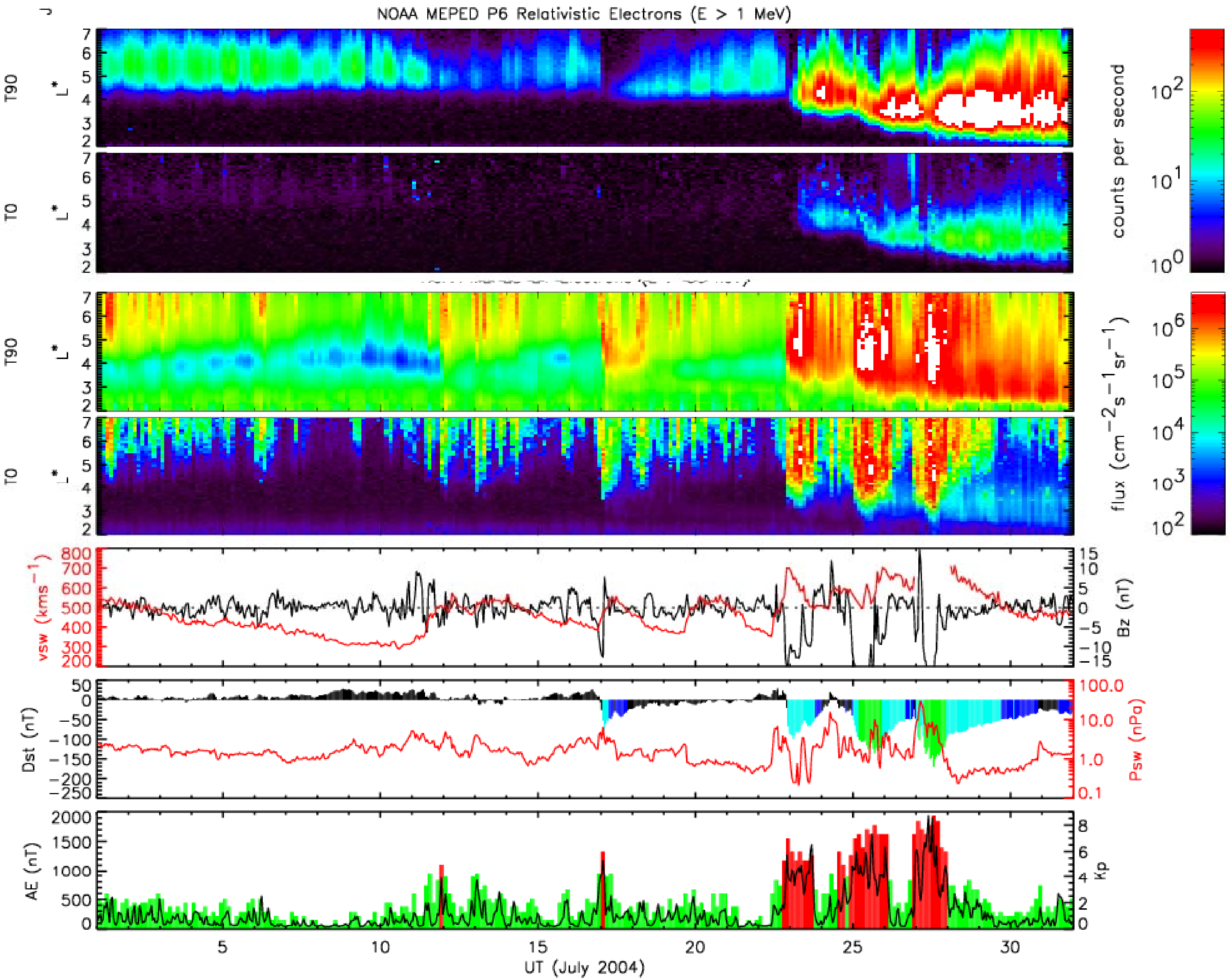
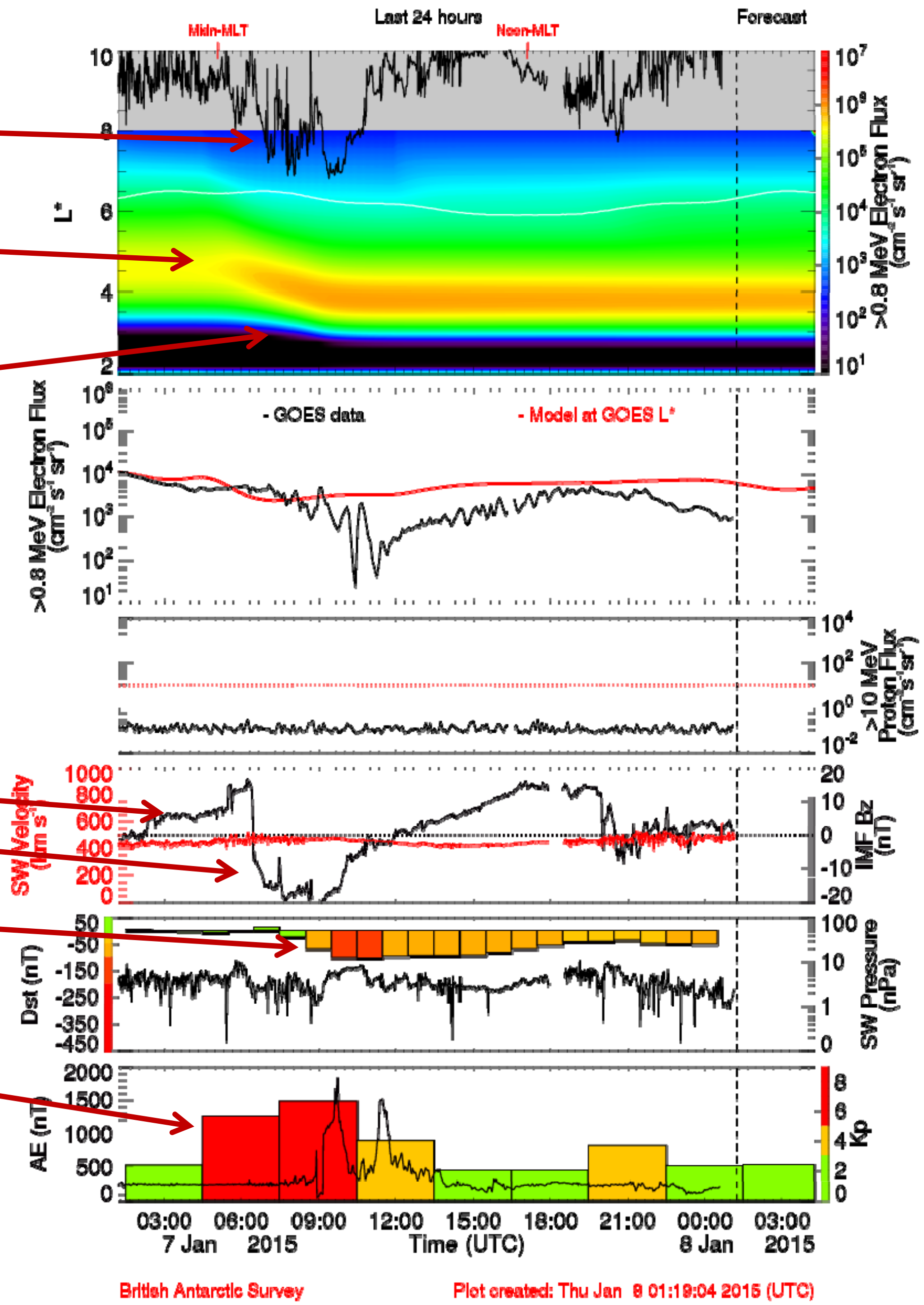

NOAA MEPED P6 Relativistic Electrons (E > 1 MeV)
J
T90
T0
L*
counts per second
flux (cm^-2 s^-1 sr^-1)
vsw (kms^-1)
Bz (nT)
Dst (nT)
Psw (nPa)
AE (nT)
Kp
UT (July 2004)

SW Forecasting - BAS

- Magnetopause compression
- Electrons accelerated to MeV energies by very low frequency waves (kHz)
- Transport towards the Earth by ultra-low frequency waves (mHz)



- IMF Bz ramps up
- IMF Bz turns southward
- Reconnection takes place
- Ring current develops – Dst < 0
- Magnetic activity increases – Kp index

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Conclusions

- Chorus wave acceleration now established – but need to consider severe events carefully – fpe/fce
- EMIC waves – effective loss for E > 2 MeV – and signatures in pitch angle distributions
- Magnetopause – effective loss in the outer region – but how far in?
- Other areas
  - Other waves – magnetosonic, - nonlinear cf quasilinear
  - Plasmapause and plumes – local time dependence on waves
  - Low energy electrons – effects on acceleration to higher energies
  - Mag field models
- Space weather forecasting – the ultimate test