Modelling the diffusion due to wave-particle interactions in the radiation belts

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Background

Diffusion equation for phase-space density (*f*) in pitch-angle (*α*), energy (*E*) and L* (*L*) coordinates

Radial

Pitch-angle

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

Mixed pitch-angle/energy

$$+ \frac{1}{A(E)}\frac{\partial}{\partial E}\left(A(E)\left(D_{E\alpha}\frac{\partial f}{\partial \alpha} + D_{EE}\frac{\partial f}{\partial E}\right)\right)\Bigg|_{\alpha,EL} - \frac{f}{\tau(\alpha,E,L)}$$

Energy

Loss processes

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

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

Background

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

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

$$+ \frac{1}{A(E)}\frac{\partial}{\partial E}\left(A(E)\left(D_{E\alpha}\frac{\partial f}{\partial \alpha} + D_{EE}\frac{\partial f}{\partial E}\right)\right)\Bigg|_{\alpha,EL} - \frac{f}{\tau(\alpha,E,L)}$$

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

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

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How do you calculate the diffusion rates?

Use a code like PADIE [Glauert & Horne, 2005]

- Gyro-resonant wave-particle interactions
- Describe the wave
  - Frequency distribution
  - Wave normal angle distribution
  - Distribution of the waves in space
- Location
  - Plasma frequency
  - Magnetic field
- Particle type (electron or ion) and energy
- Number of resonances

→ local diffusion coefficients $D_{\alpha\alpha}$, $D_{\alpha E}$ and D_{EE}

Drift-averaged diffusion rates

Average the local diffusion coefficients over one bounce
→ Bounce average diffusion coefficients $<D_{\alpha\alpha}>$, $<D_{\alpha E}>$ and $<D_{EE}>$

Average around a drift path
→ drift and bounce averaged coefficients used in the model

$<D_{\alpha\alpha}>^d$, $<D_{\alpha E}>^d$ and $<D_{EE}>^d$

Repeat for

- multiple energies
- multiple L*
- varying geomagnetic conditions
  - Plasma frequency
  - Wave parameters

Chorus diffusion model

Model from EU-FP7 project SPACECAST [Horne et al., 2013]

- Lower ($0.1 f_{ce} \le f < 0.5 f_{ce}$) and upper $0.5 f_{ce} < f \le 0.9 f_{ce}$ band chorus
- Parameterised geomagnetic activity by Kp and AE
- Data from 7 satellites

f_{ce} = local gyro-frequency

- Wave spectra determined for
  - $2 \le L^* \le 10$ in steps of $0.5 R_e$
  - 5 levels geomagnetic activity
  - 3 hour MLT bins
  - 6^o latitude bins $0 \le |\lambda| \le 60^o$
- Wave normal angle distribution - peak at 0^o, width of tan 30^o
- 10 keV ≤ Energy ≤ 30 MeV
- f_{pe}/f_{ce} from new model based on CRRES and THEMIS data

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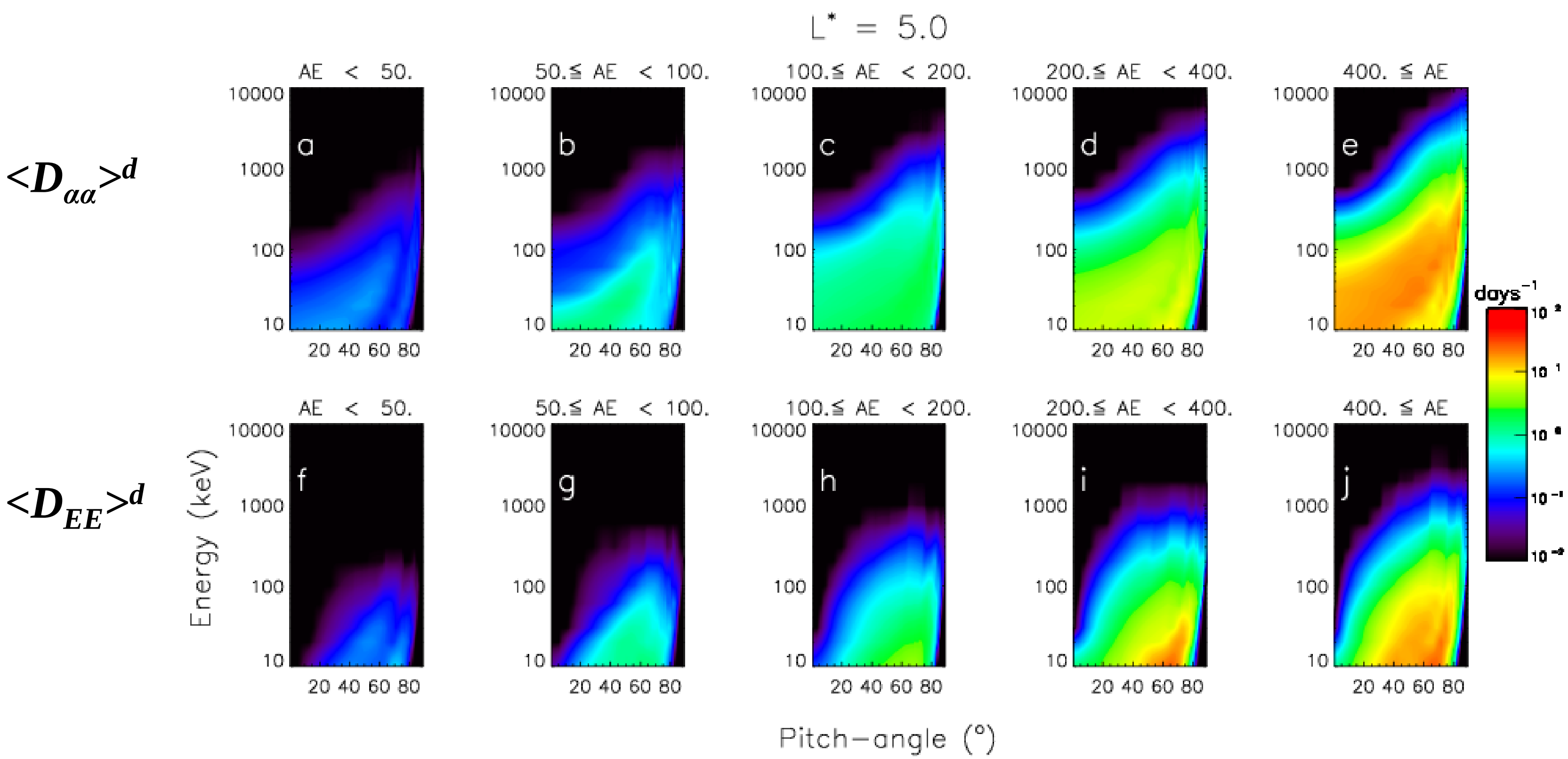
Chorus diffusion model

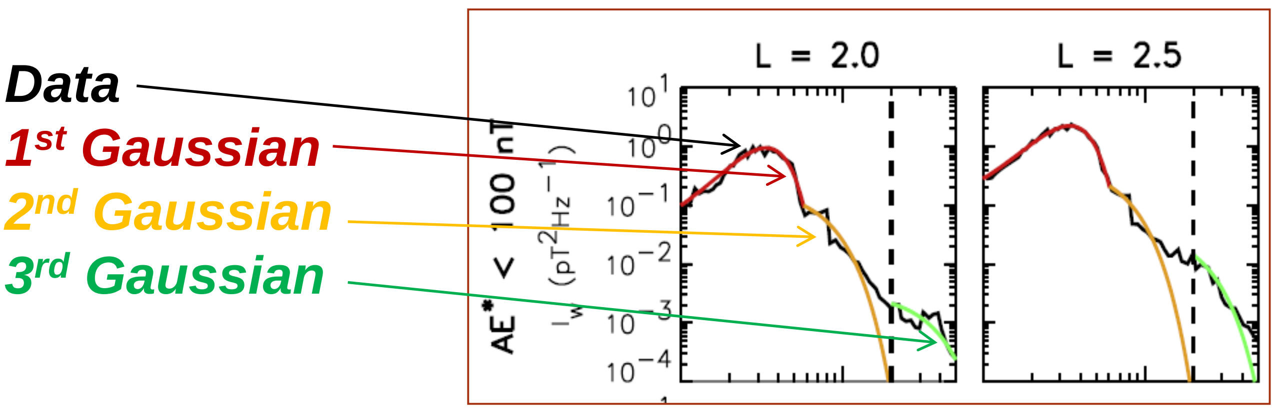
- Diffusion increases with increasing activity
- Significant energy diffusion



Plasmaspheric hiss diffusion model

Hiss model based on CRRES data [Glauert et al., 2014]

- 100 Hz to 5 kHz – includes lightning generated whistlers
- Wave spectra determined for
  - 2 ≤ L*≤ 6.5 in steps of 0.5 R_e
  - 3 levels geomagnetic activity
  - Average spectra over all MLT for each L*
  - Fit 3 Gaussian distributions to cover whole frequency range [Meredith et al., 2007]

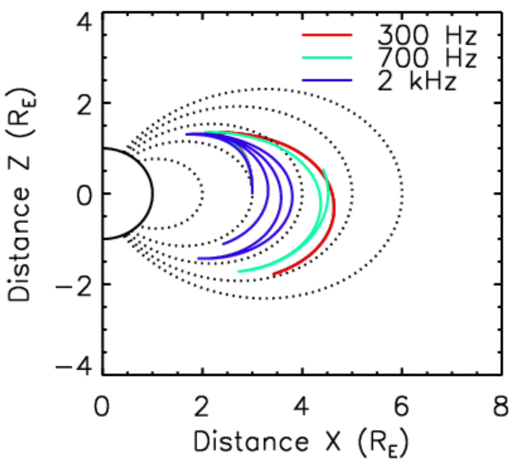


Wave-normal angle model for hiss

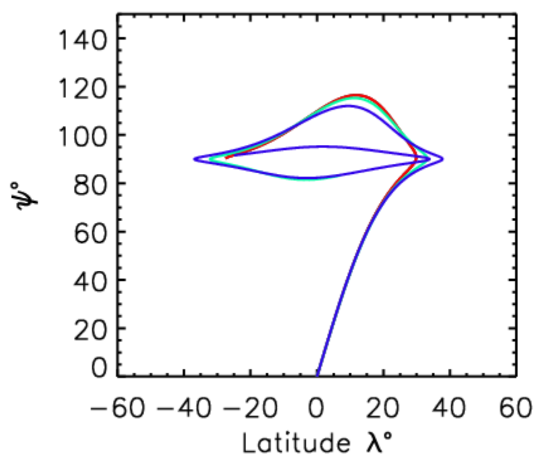
Peak wave-normal angle varies with latitude

- Field aligned near equator, oblique at higher latitudes [*Bortnik et al., 2008*]
- HOTRAY ray tracing code estimates variation with latitude
  - at each L for 3 frequencies, (300Hz, 700Hz and 2kHz)
- Width of the wave-normal angle distribution fixed at tan 80°

L = 3 Distance Z vs distance X

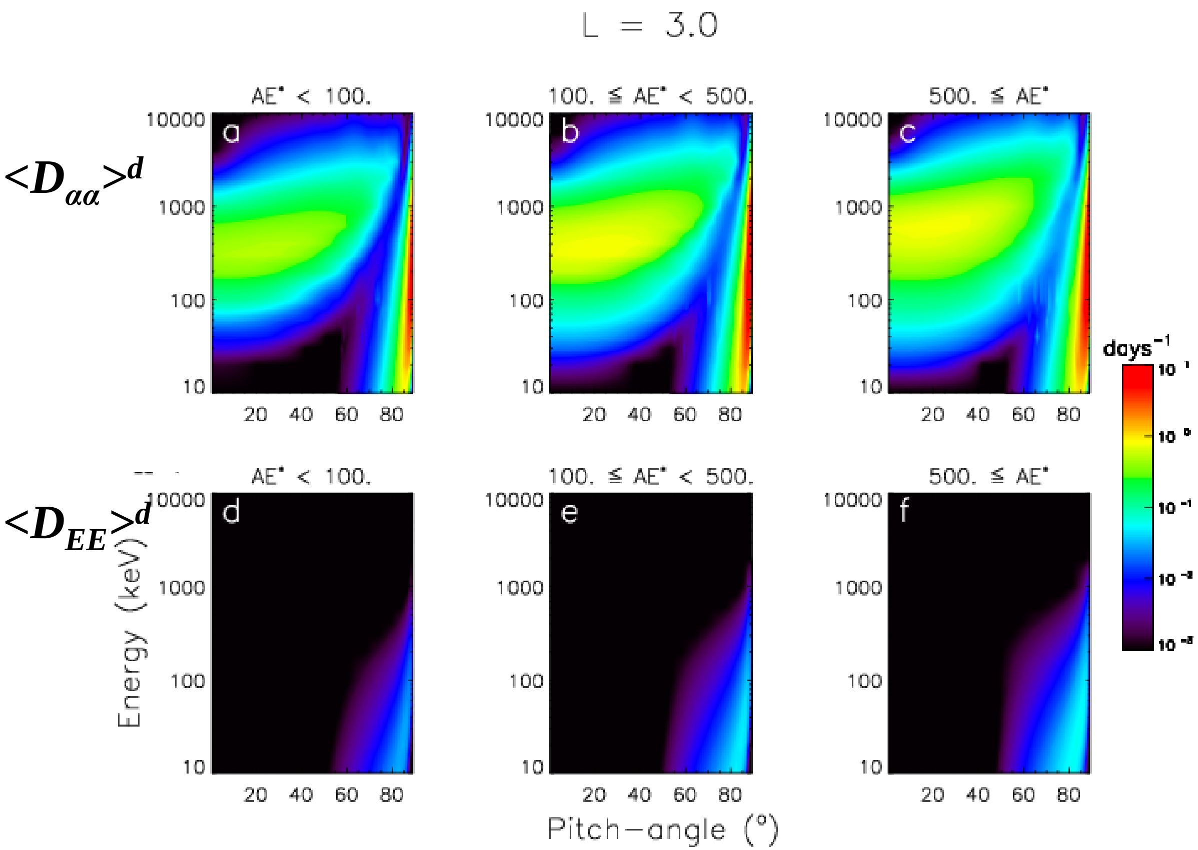


wna vs latitude



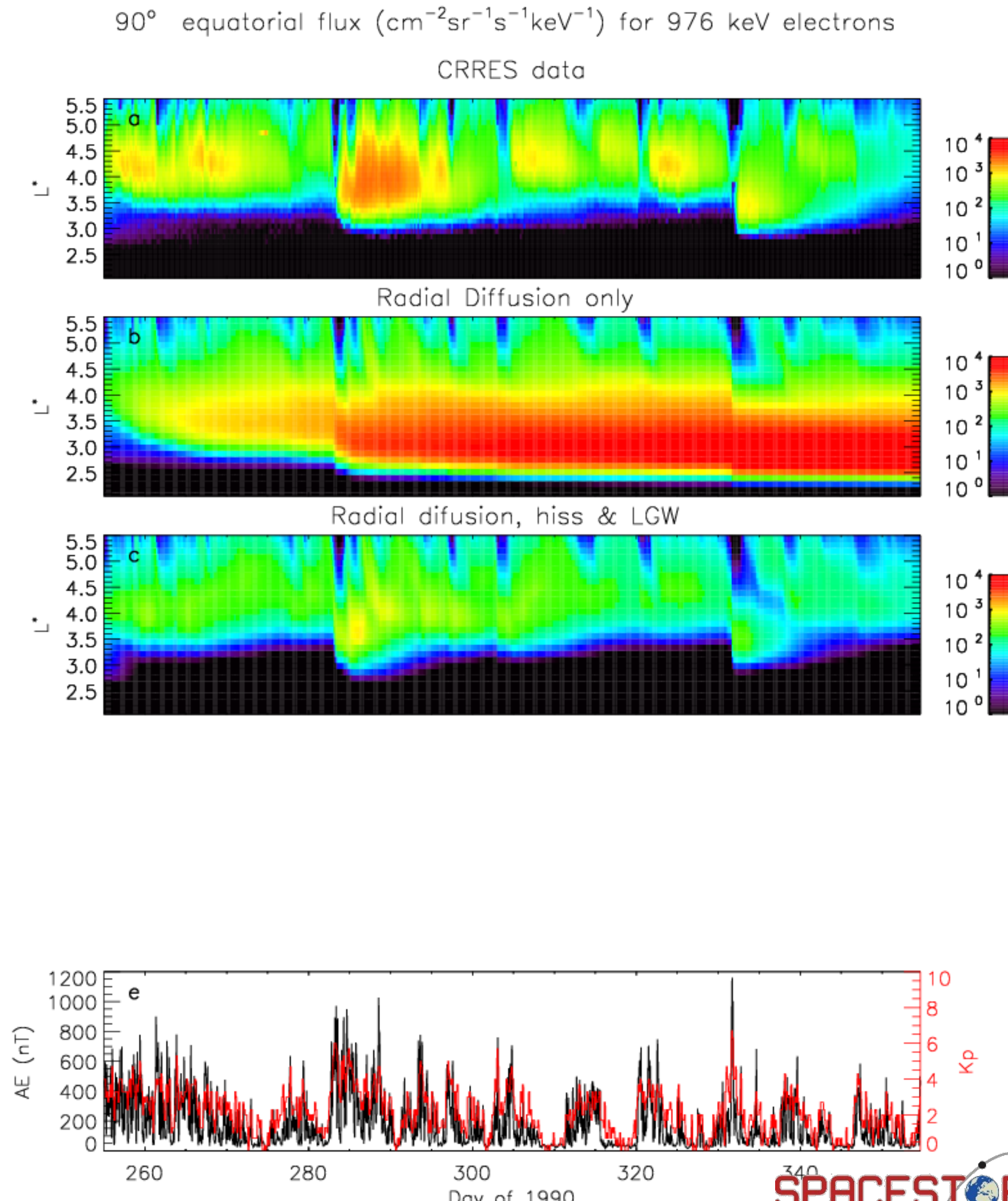
Diffusion due to hiss and LGW

- Losses increase with increasing geomagnetic activity
- Losses peak at ~300 keV at L*=3
- No significant energy diffusion



3d simulations

- Hiss model reproduces inner edge of outer belt
- Chorus provides acceleration



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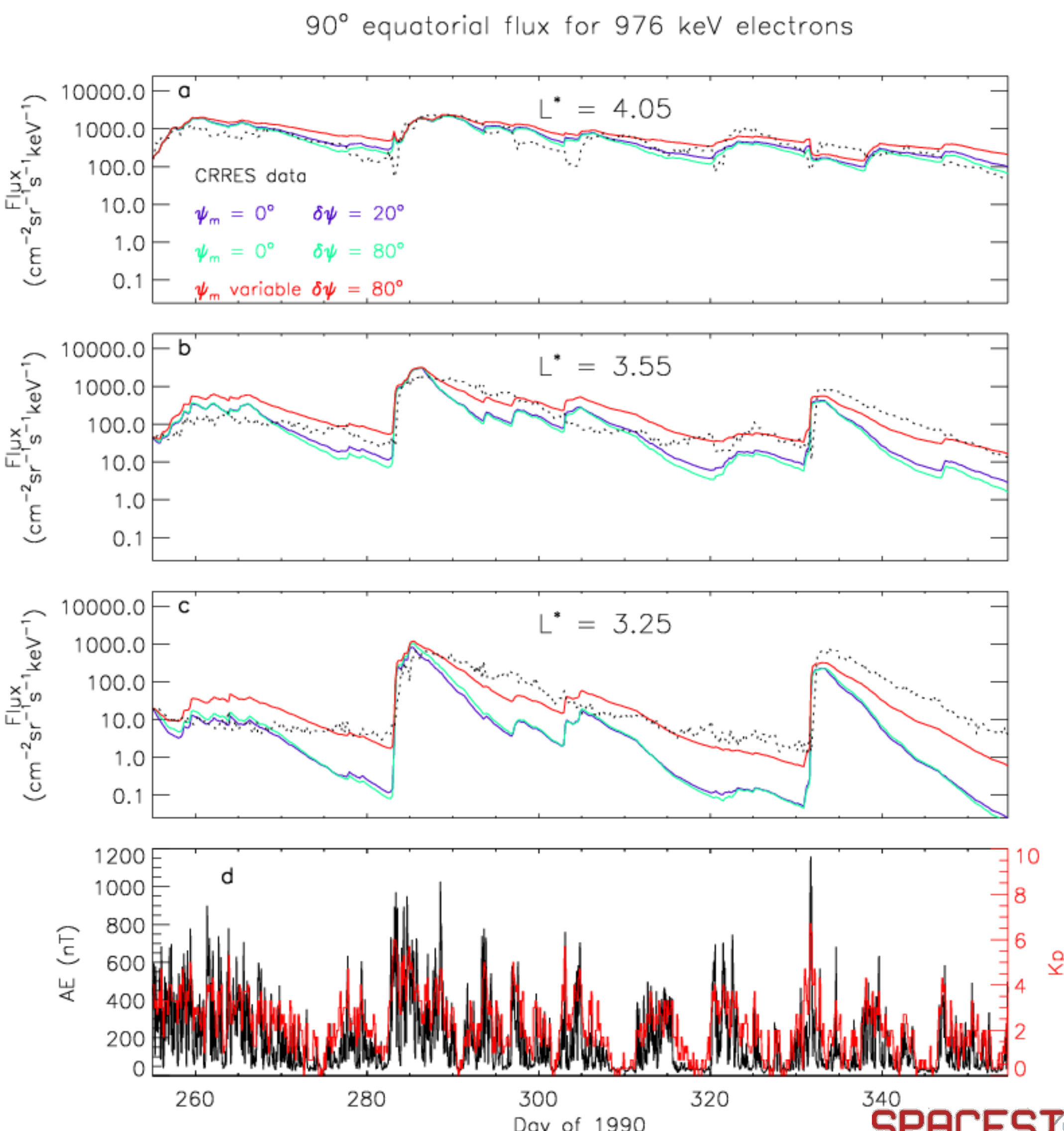
Decay rates

- Hiss model (red line) reproduces decay rates



Red -Hiss model

Black - data

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Improvements to the chorus model

Two recent results:

1. Significant wave power below 0.1 f_{ce} at higher latitudes [Meredith et al., 2014]
   - Not included in previous chorus models

2. Wave normal angle distribution width $\delta X \sim \tan 15^o$ [Santolik et al., 2014]

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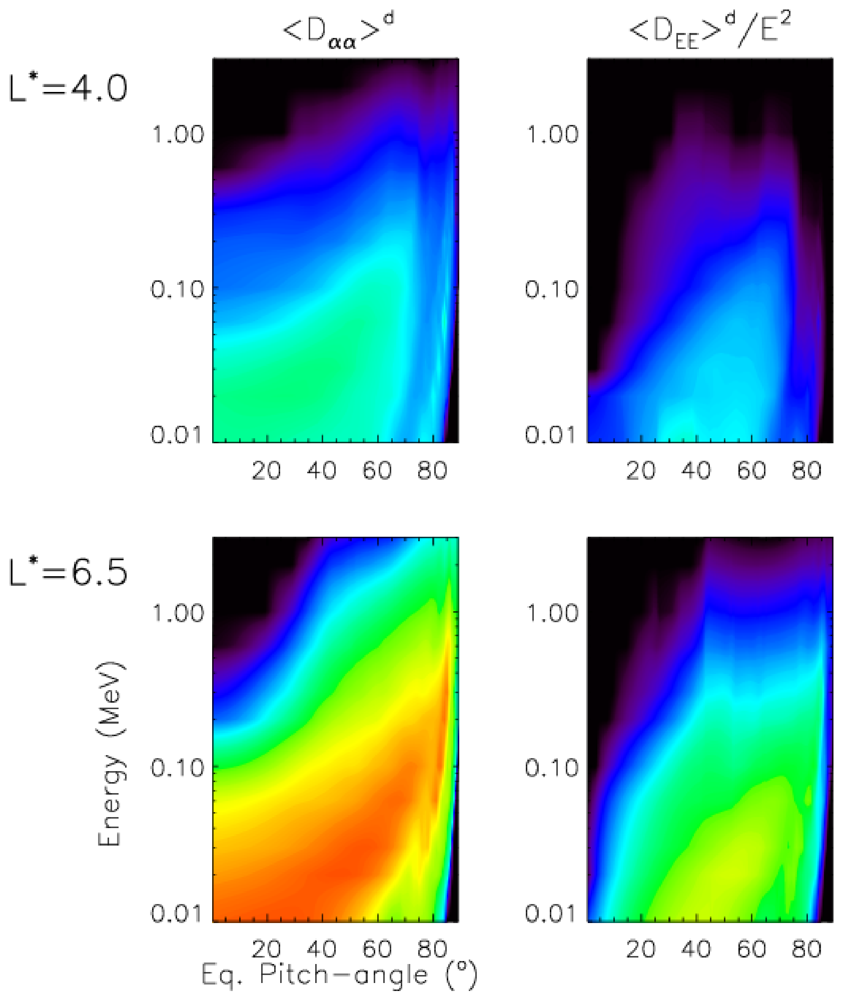
Low frequency chorus

Upper & lower band chorus



100 nT ≤ AE < 200nT

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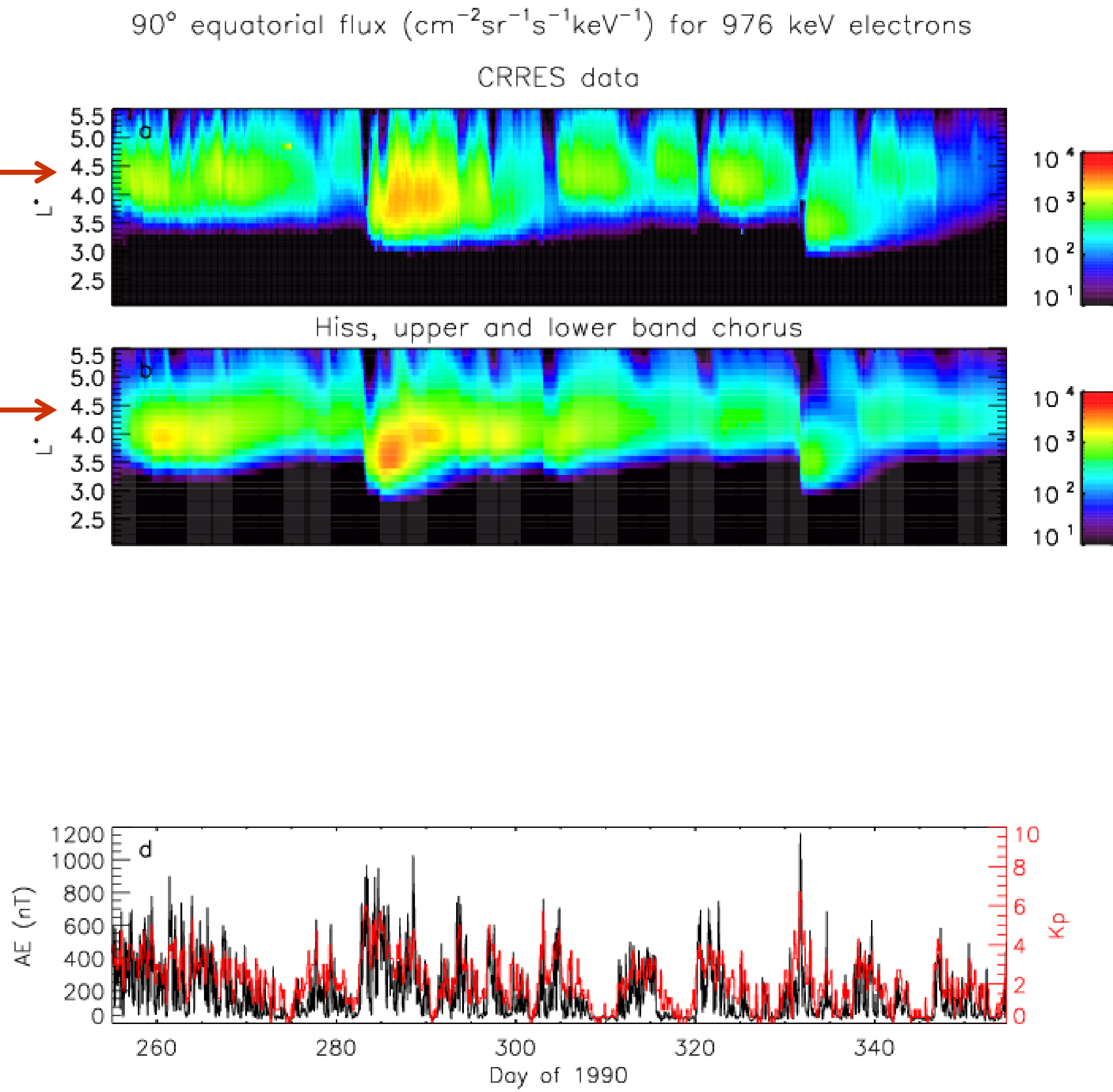
Simulation with low frequency chorus

Data

Without lfc



Increased loss

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Wave normal angle distribution

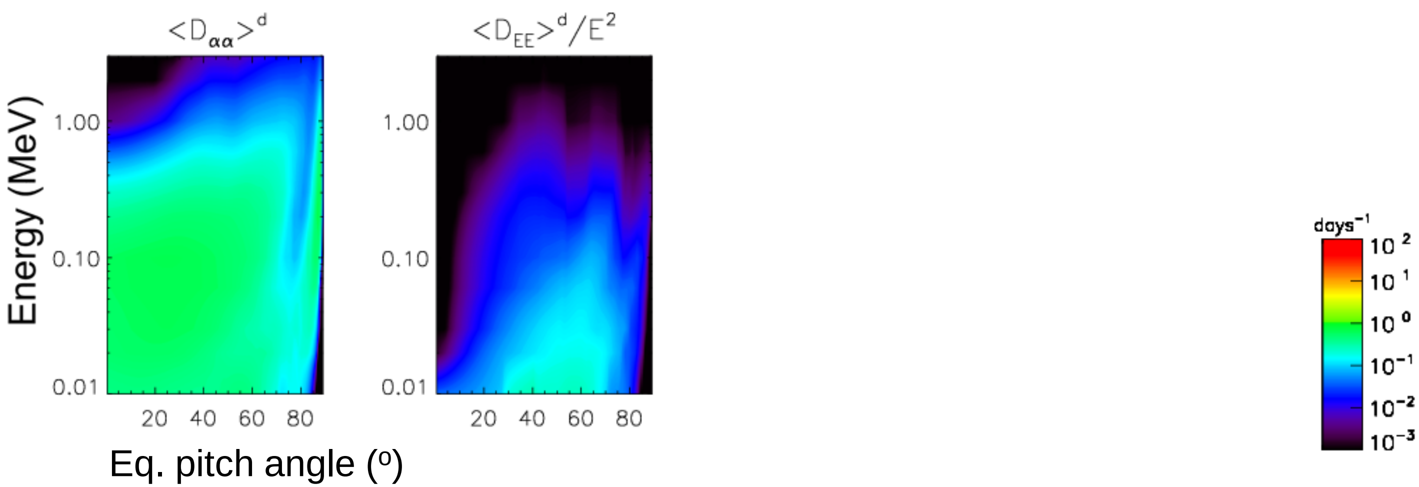
Recalculated chorus diffusion matrix (again)

- Width - tan 15°

L* = 4

2 ≤ Kp < 3

30°



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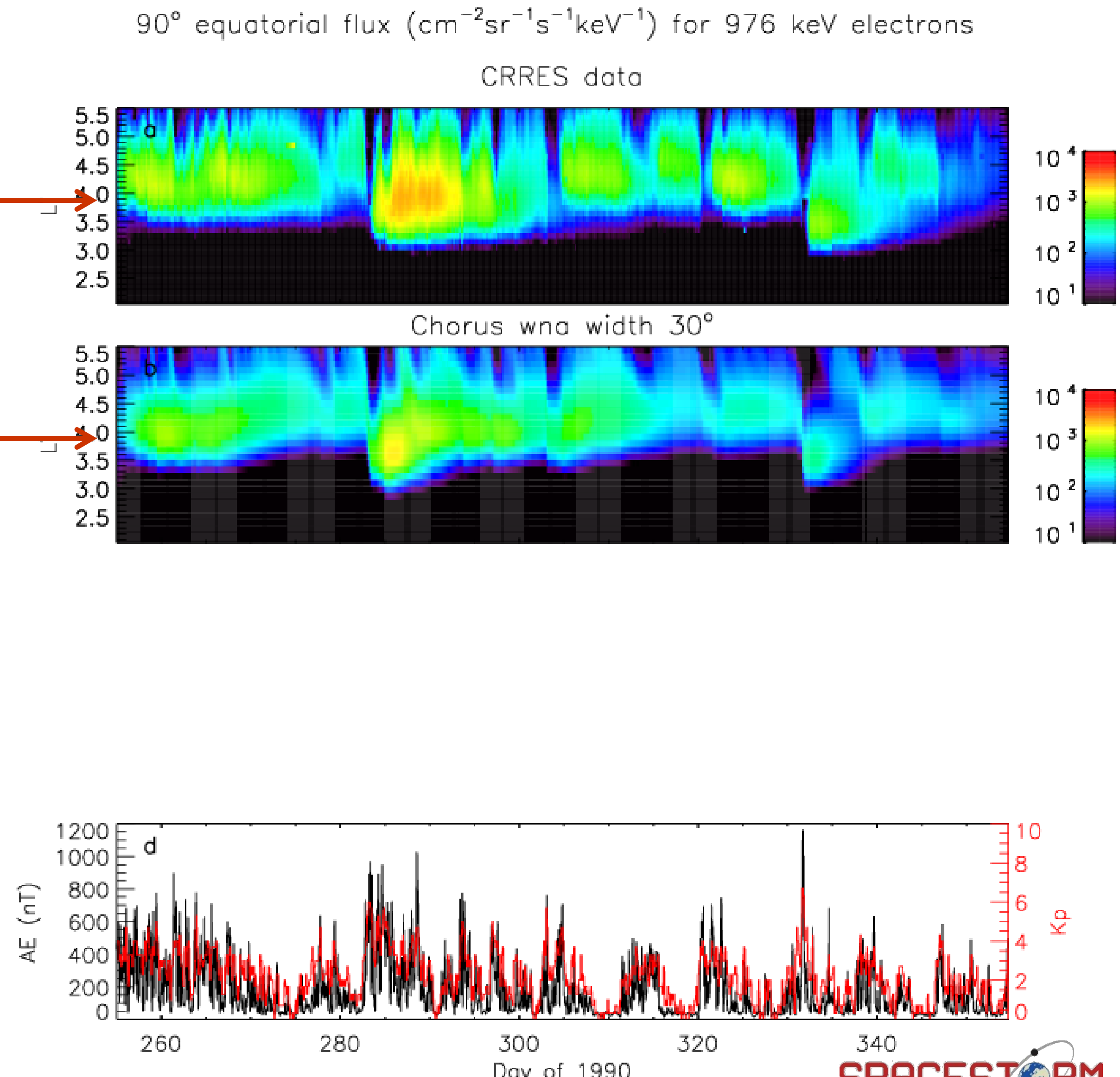
Simulation with wna width 15º

Data

30º



Small increase in acceleration

Increase is more significant at higher energies ~4 MeV

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Improvements to the hiss model

- Have to include a plasmapause model
- Have one spectra for all MLT, scaled by wave power
- Agapitov et al. [2013] suggest $\delta X \sim \tan 20^o$
    - Our model has $\delta X \sim \tan 80^o$

Toby is working on a new model ...

- Data from 7 satellites
- New method of distinguishing hiss from chorus
- 1 hour resolution in MLT
- Calculate wave spectra for each MLT and L*
- Update wave-normal angle model
- 6 levels of geomagnetic activity

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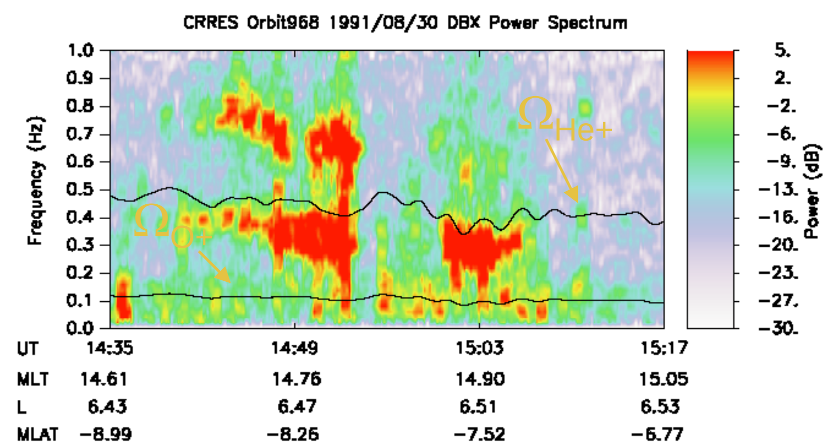
Electromagnetic ion cyclotron (EMIC) waves

Diffusion matrix for EMIC waves

- SPACECAST and MAARBLE projects [Kersten et al., 2014]
- Averaged properties of the waves
- CRRES data
- Hydrogen and helium band waves



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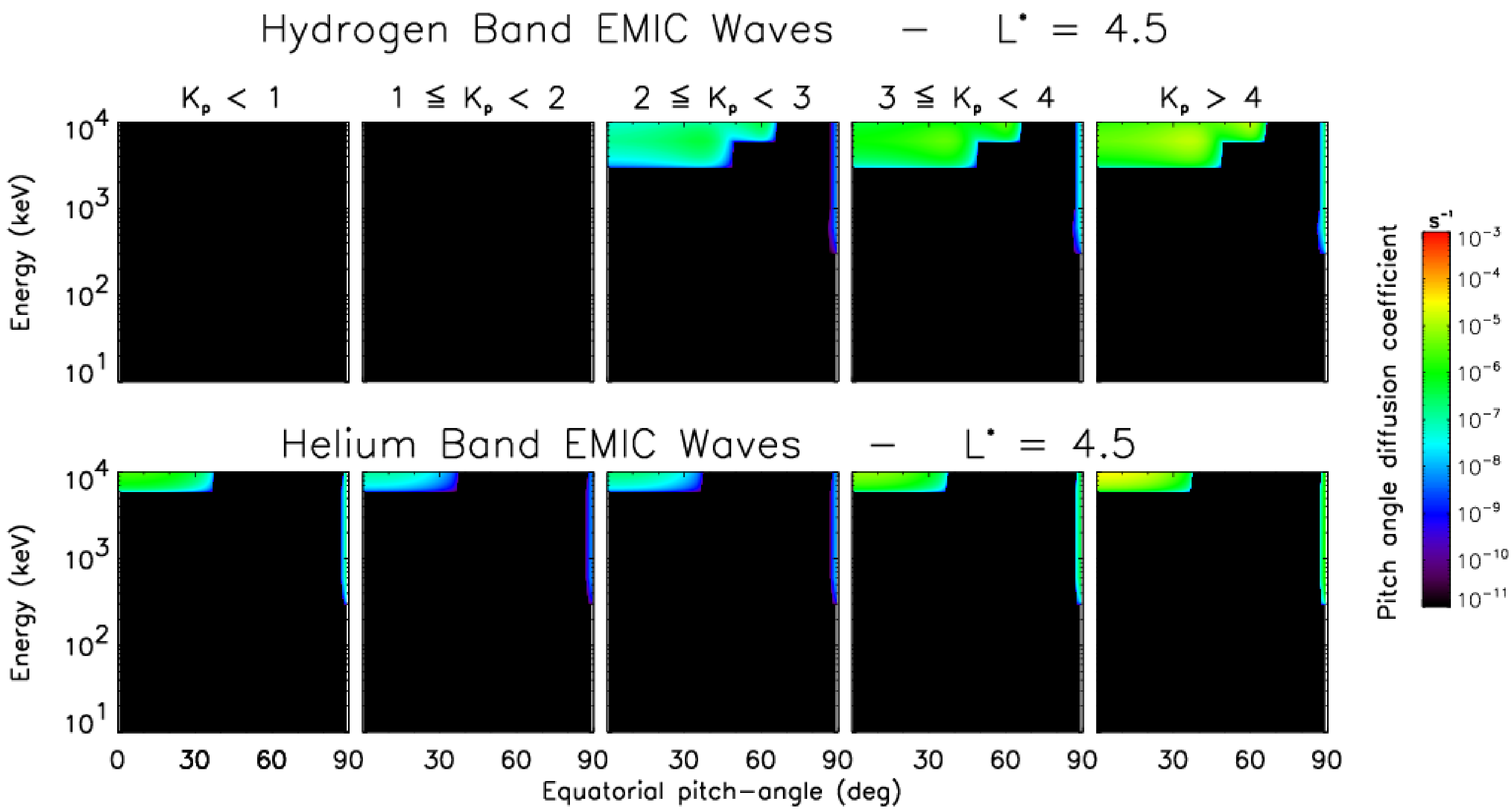
Pitch-angle diffusion rates for EMIC waves



Significant pitch angle diffusion for E> ~2 MeV, pitch angles < 60^o

Effect of EMIC waves

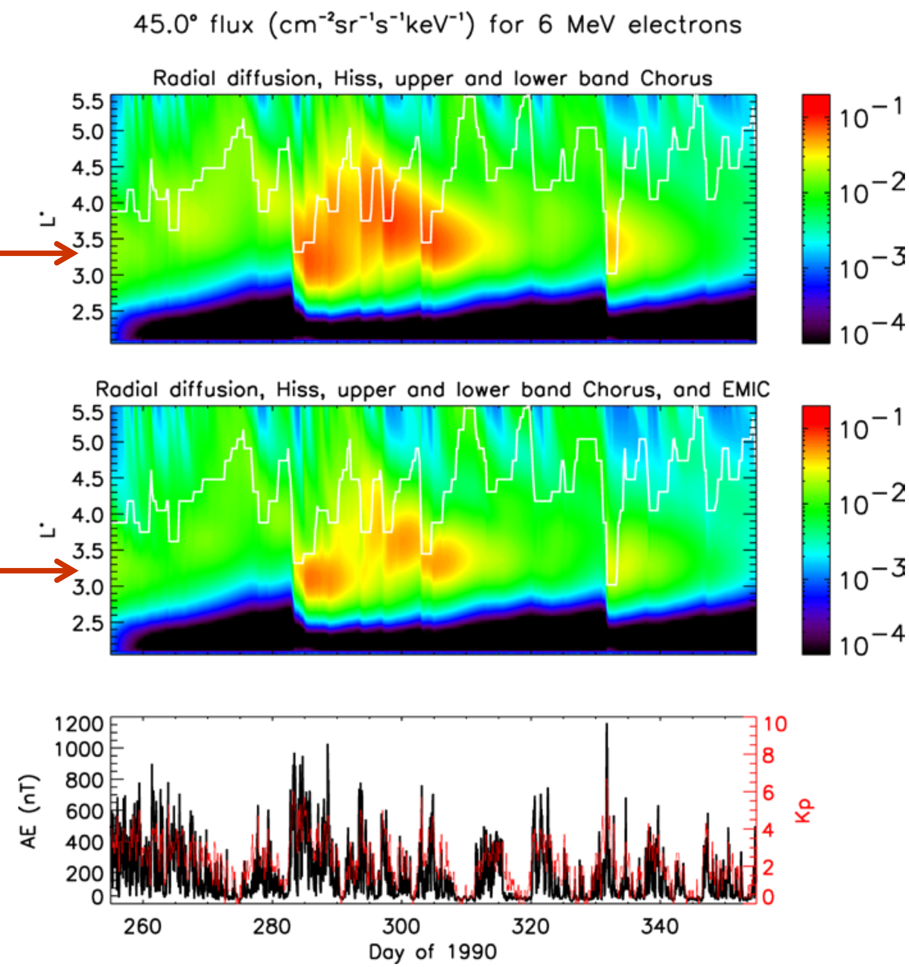
Same 100 days

45°, 6 MeV electrons

No EMIC waves

Including EMIC waves

- Increased losses



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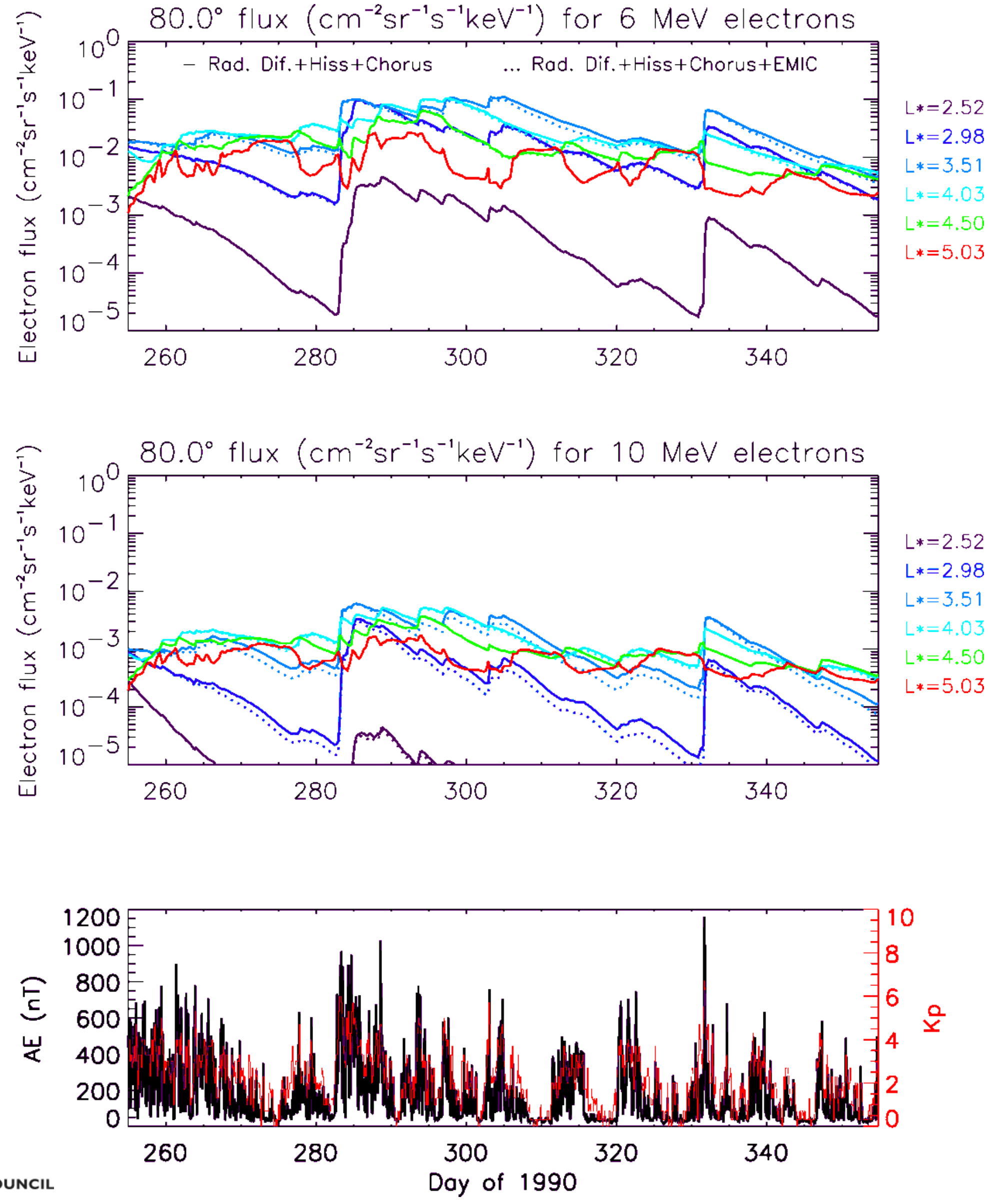
Do you lose electrons near 90º ?



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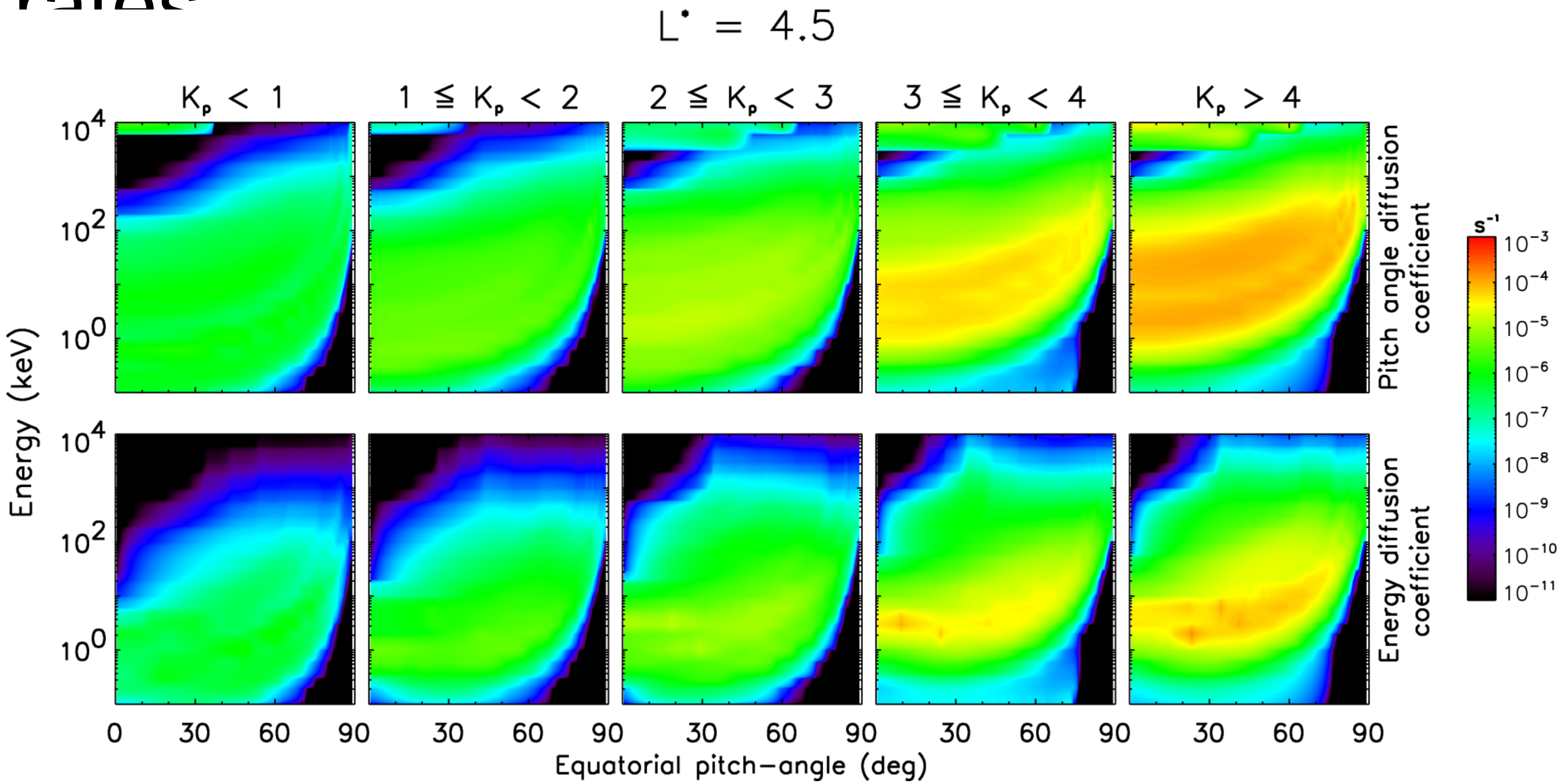
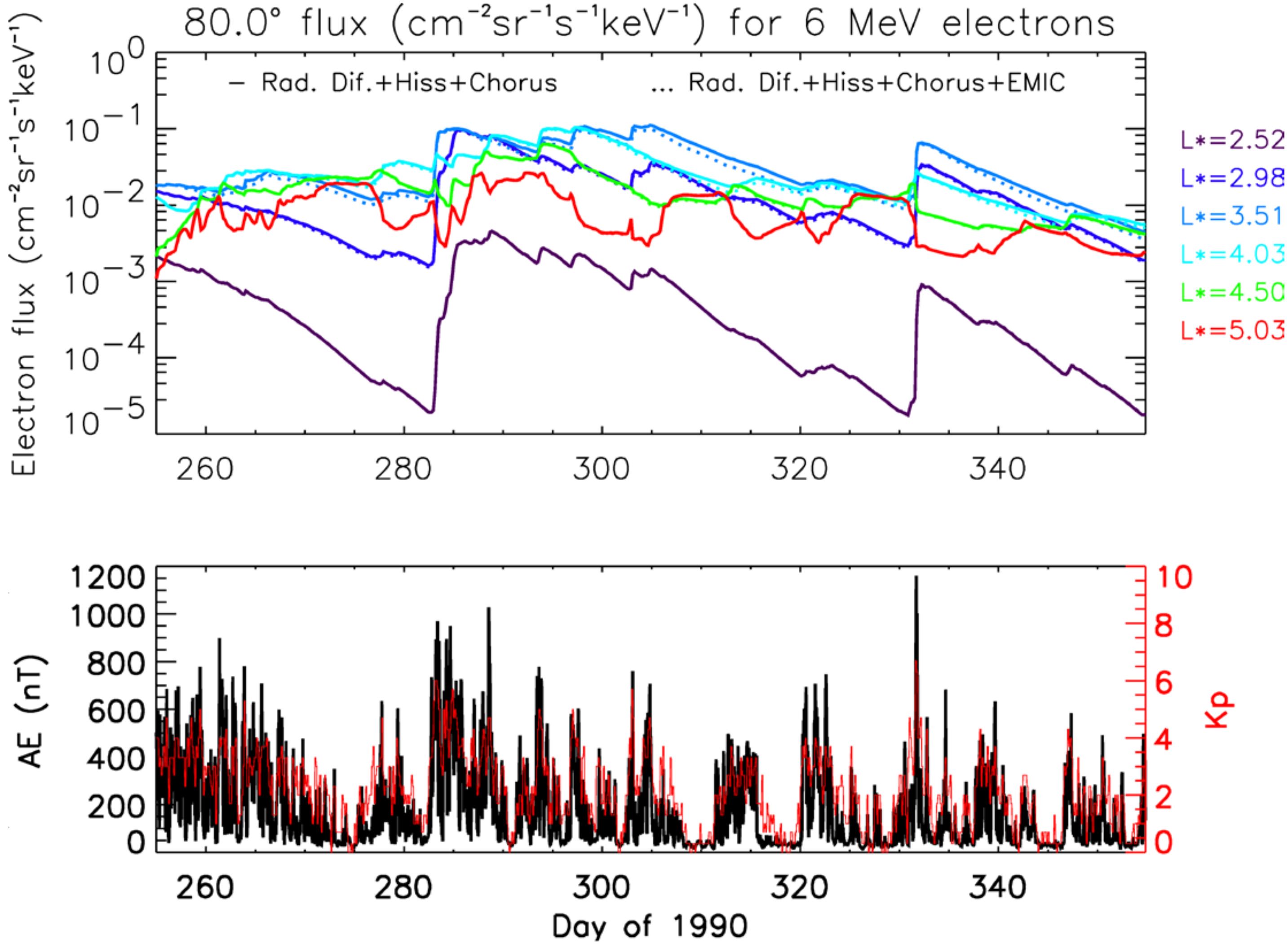
Combined EMIC and Chorus diffusion rates





80.0° flux (cm⁻²sr⁻¹s⁻¹keV⁻¹) for 6 MeV electrons
– Rad. Dif.+Hiss+Chorus
... Rad. Dif.+Hiss+Chorus+EMIC
Electron flux (cm⁻²sr⁻¹s⁻¹keV⁻¹)
L*=2.52
L*=2.98
L*=3.51
L*=4.03
L*=4.50
L*=5.03
AE (nT)
Kp
Day of 1990