Simulating the Earth's radiation belts with continuous losses to the magnetopause

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COOPERATION

Geospace Revisted, Rhodes, 2014

Outline

- Diversion – Low frequency chorus
  - Diffusion rates
  - Effect in simulations
- Simulations with continuous loses to the magnetopause
  - Background – BAS Radiation Belt Model
  - Boundary conditions
  - Simulations under steady conditions
  - Comparison with data
  - Model location of the last closed drift shell

BAS chorus matrix

- *Horne et al. [JGR, 2013]*
- Data from 7 satellites
- Upper and lower band chorus
- Frequency spectra determined for:
  - 5 levels of activity – AE or Kp
  - All MLT - 3 hour bins
  - $0 \leq |\lambda| \leq 60^o$, 6^o latitude bins
  - $1.5 \leq L^* \leq 10$ in bins of 0.5 L^*
- Wave-normal angle model
  - peak 0^o, spread tan(30^o)
- 10 keV ≤ Energy ≤ 30 MeV
- f_{pe}/f_{ce} from new model based on CRRES and THEMIS

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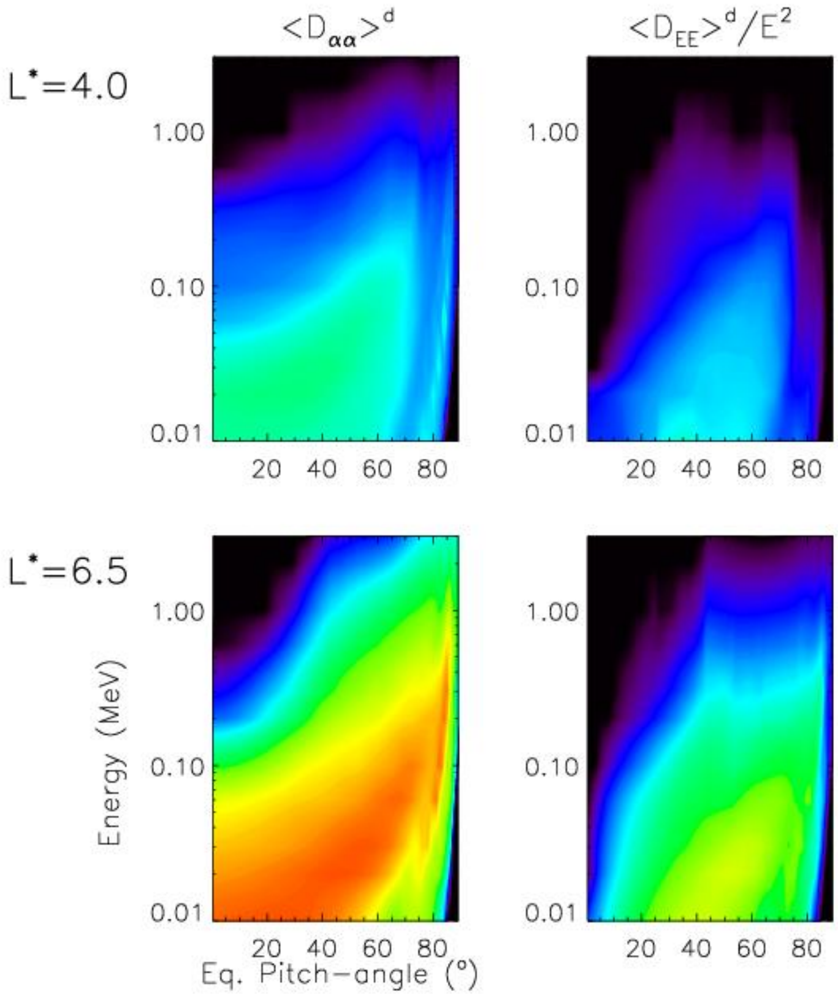
Diffusion rates

Upper & lower band chorus

Upper, lower & lf chorus



100 nT ≤ AE < 200nT

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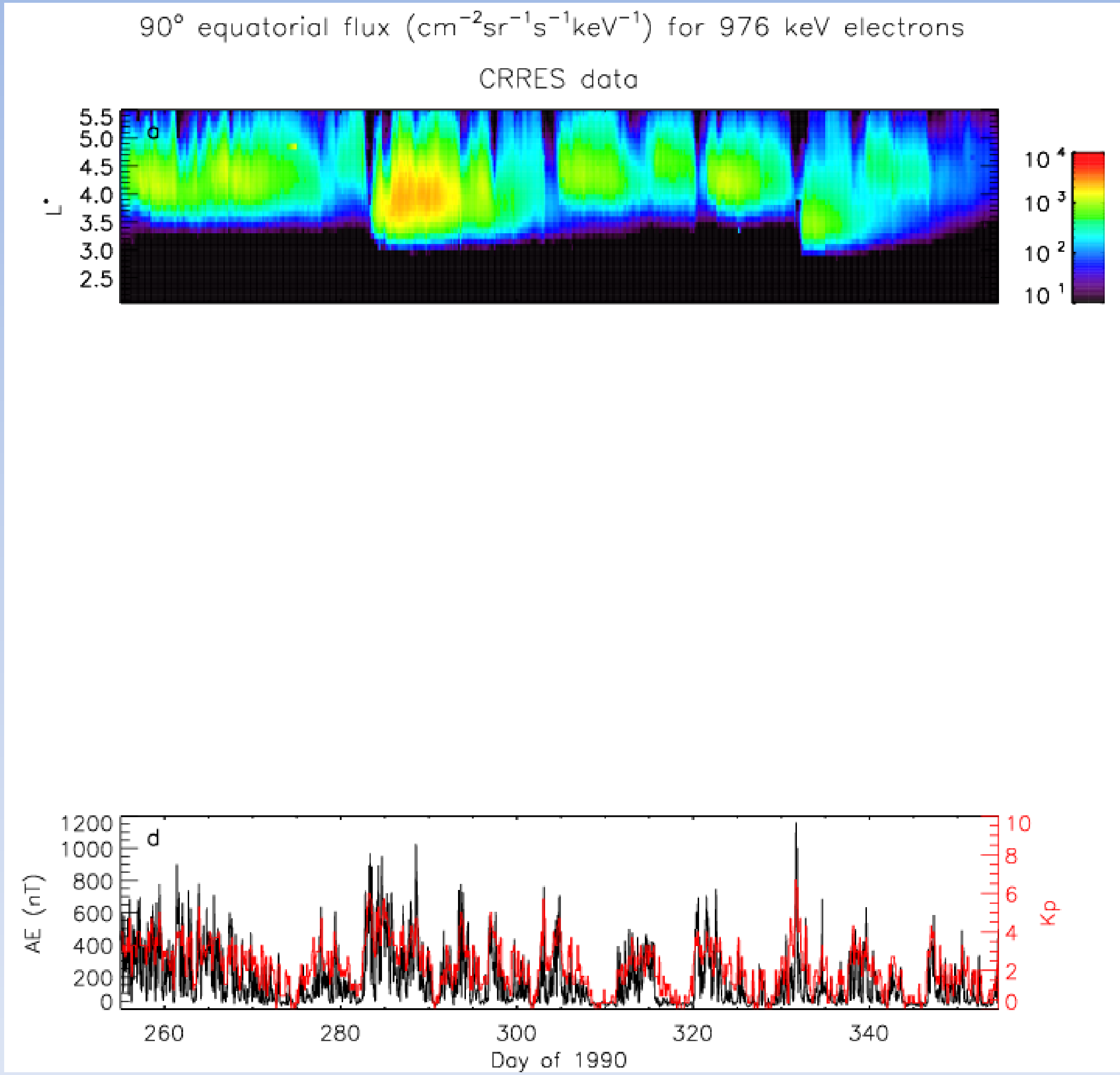
Effect in Simulations

CRRES data

100 days

1 MeV (90°)

Glauert et al. [JGR, 2014]



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Simulating the Earth's radiation belts with continuous losses to the magnetopause

BAS Radiation Belt Model

- Drift averaged, 3d model uses Fokker-Plank equation in α, E, L*

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

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

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

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

- Chorus and hiss diffusion based on wave data
  - Driven by Kp as no AE forecast available
  - Chorus for 1.5 ≤ L* ≤ 10 *Meredith et al. [JGR,2012]*
  - *Horne et al. [JGR, 2013], Glauert et al. [JGR, 2014]*
- Radial diffusion – *Brautigam & Albert [JGR, 2000]*
- Collisions – *Abel & Thorne [JGR, 1997]*
- Plasmapause – *O' Brien & Moldwin [JGR, 2003]*

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Boundaries

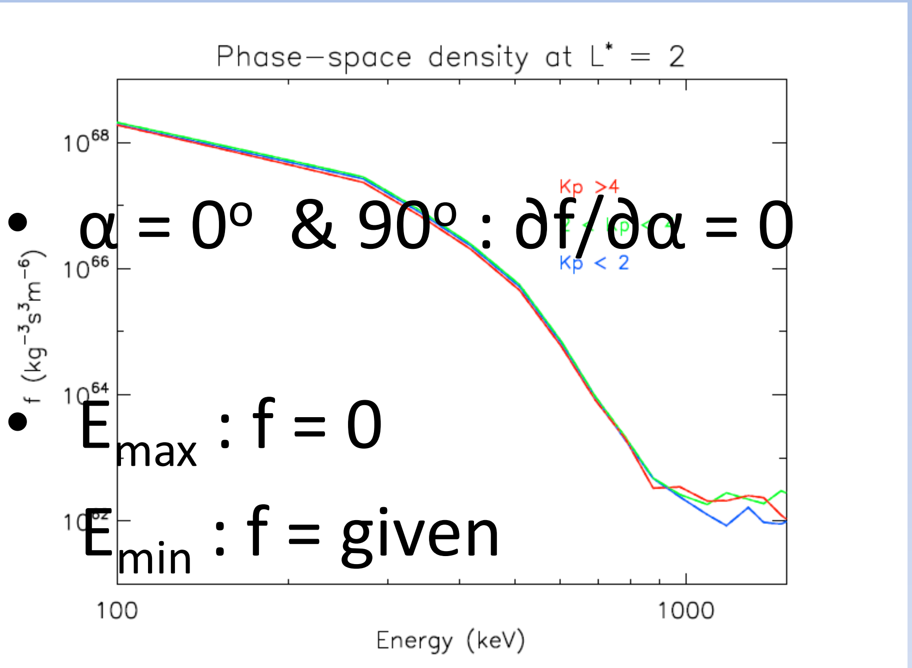
- $L_{min} \le L^* \le L_{max}$
  - $L_{min} = 2$
  - $L_{max} = 10$

- $0 \le \alpha \le 90^o$

- $E_{min}(L^*) \le E \le E_{max}(L^*)$
  - $E_{max}(L^*=10) = 20$ MeV
  - $E_{min}(L^*=10) = 30.3$keV

- L_{min}: f = given

  (average, Kp dependent f from CRRES)



- $\alpha = 0^o$ & 90^o : $\partial f/\partial \alpha = 0$

- E_{max} : f = 0

  E_{min} : f = given

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Location of minimum energy boundary

For μ=100 MeV/G, f = constant for L*>5.5

Brautigam & Albert [JGR, 2000]
CRRES data

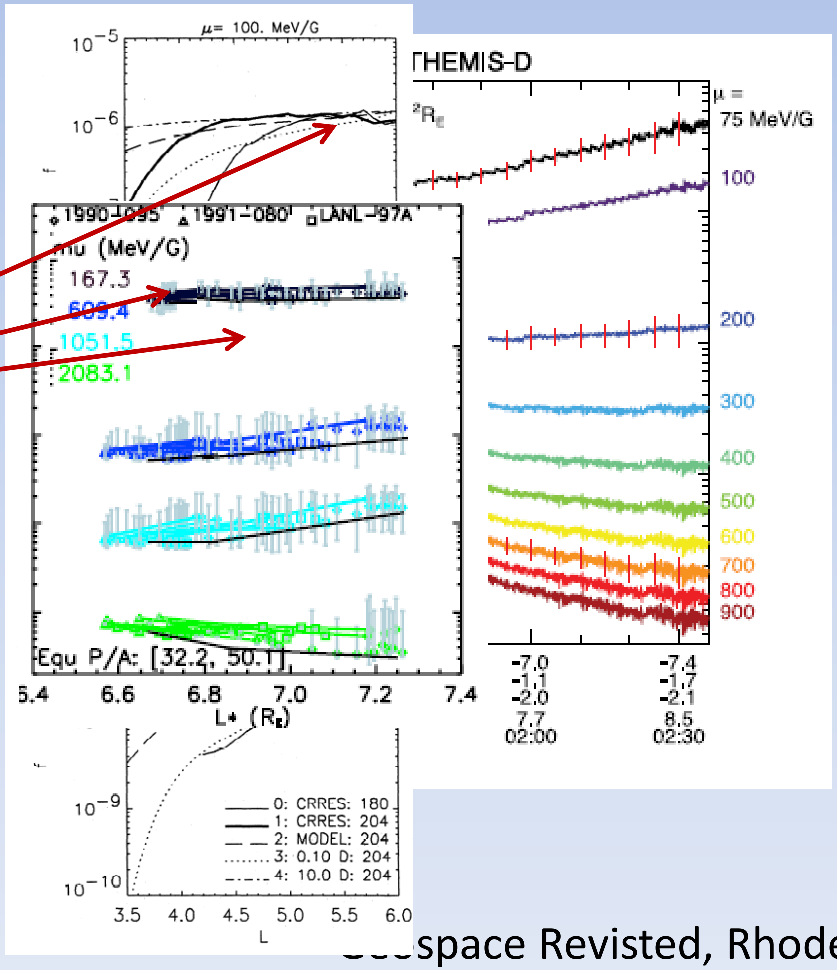
For 5.5 ≤ L* ≤ 6.0
∂f/∂L ≈ 0 for μ = 100 MeV/G

Chen et al. [JGR, 2005]
LANL and GOES

For 6.6 ≤ L* ≤ 7.2
∂f/∂L ≈ 0 for μ = 167 MeV/G

Turner et al. [GRL, 2012]
THEMIS data

∂f/∂L ≈ 0 for μ = 200 MeV/G



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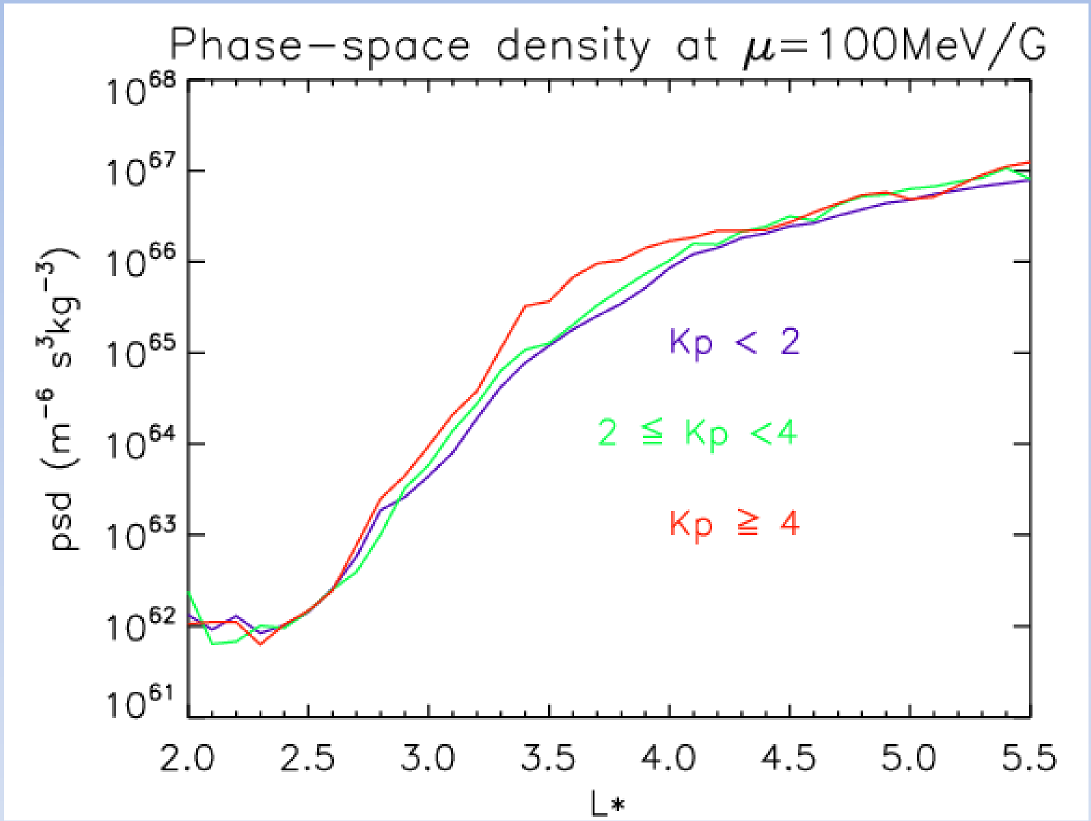
Minimum energy boundary condition

- Average L* profile
  - CRRES data
  - Before March 1991 storm
  - Kp dependent (Kp<2, 2≤Kp<4, Kp≥4)
- Assume psd is constant for L*> 5.5



Formation of a radiation belt

- $2 \leq L^* \leq 10$
- Phase space density = 0 at $L^* = 10$
- Start with ‘empty’ radiation belt
- Source on the low energy boundary
- Run model with fixed Kp=2 for 30 days
- If losses to the slot region and magnetopause dominate acceleration then no belt will form

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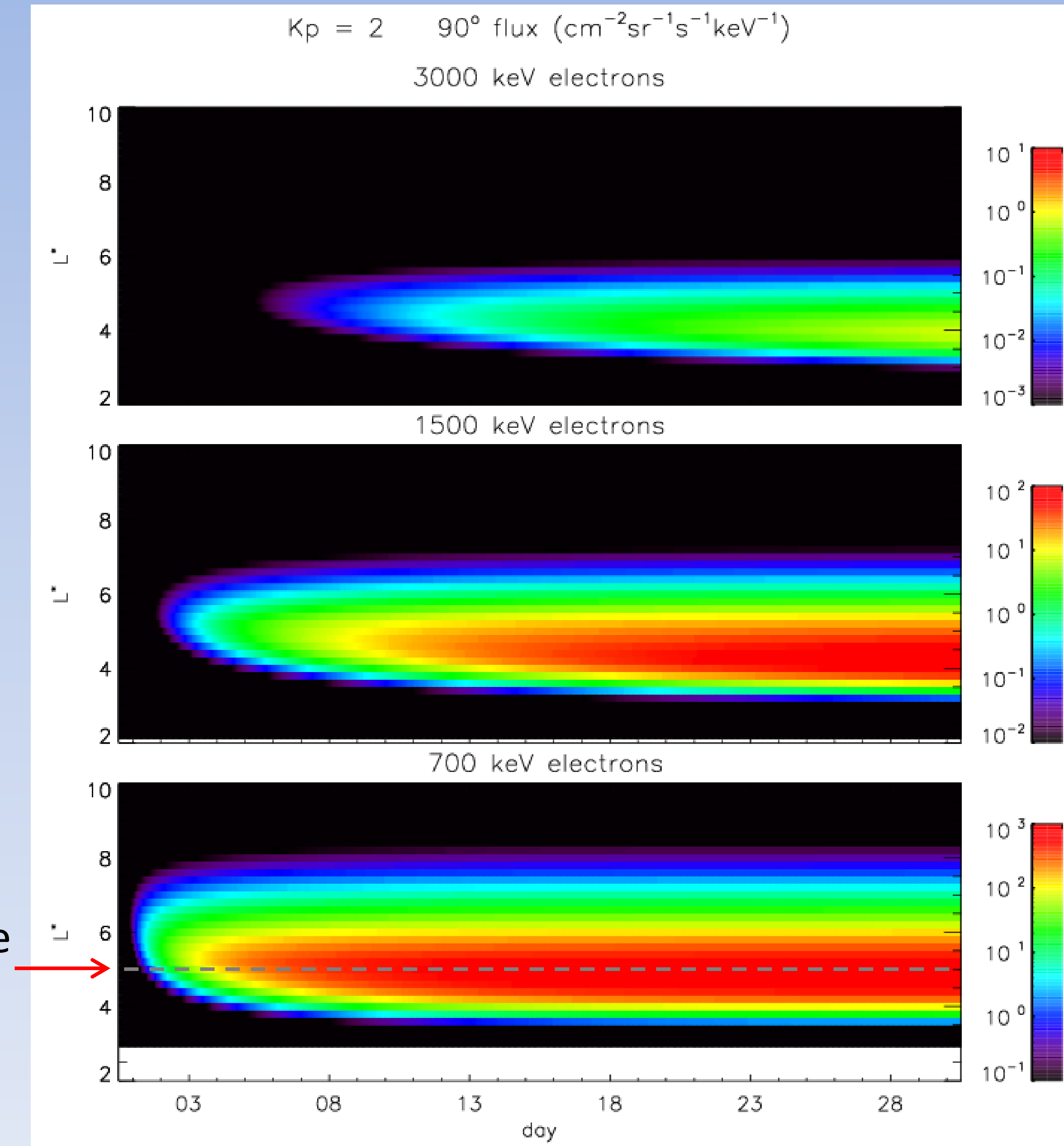
Formation of belt from low energy source

- 700 keV ~1 day
- 1.5 MeV ~2 days
- 3 MeV ~6 days



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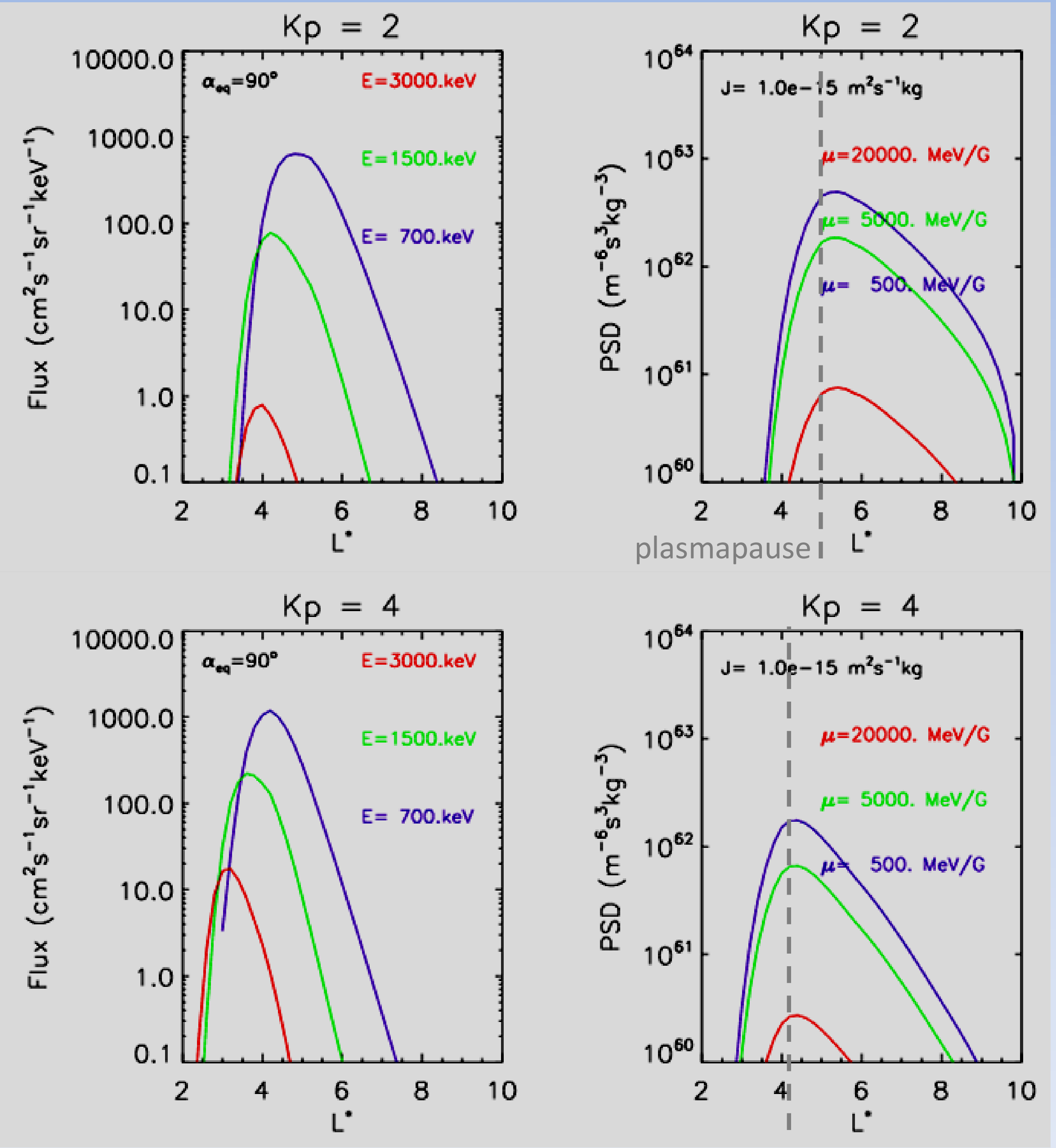
After 30 days

- Peak flux moves inward with increasing energy
  - From psd to flux
  - Hiss is stronger at lower energies
  - Inner side of peak eroded more at low energies
- Peak psd moves inward with increasing Kp
- Consistent with *Walt, Horne et al. [JGR,2003], Subbotin & Shprits [JGR,2012] ...*



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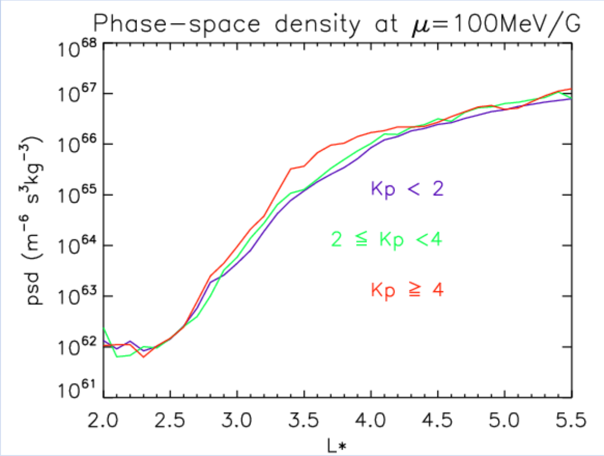
Can we simulate data?

- Radial profile from average CRRES data
  - Assume psd constant for L*>5.5 (μ=100 MeV/G)
  - Scale according to psd for L*>5.5
- How to determine psd for L*>5.5?
  - Need a method that can be used for forecasting



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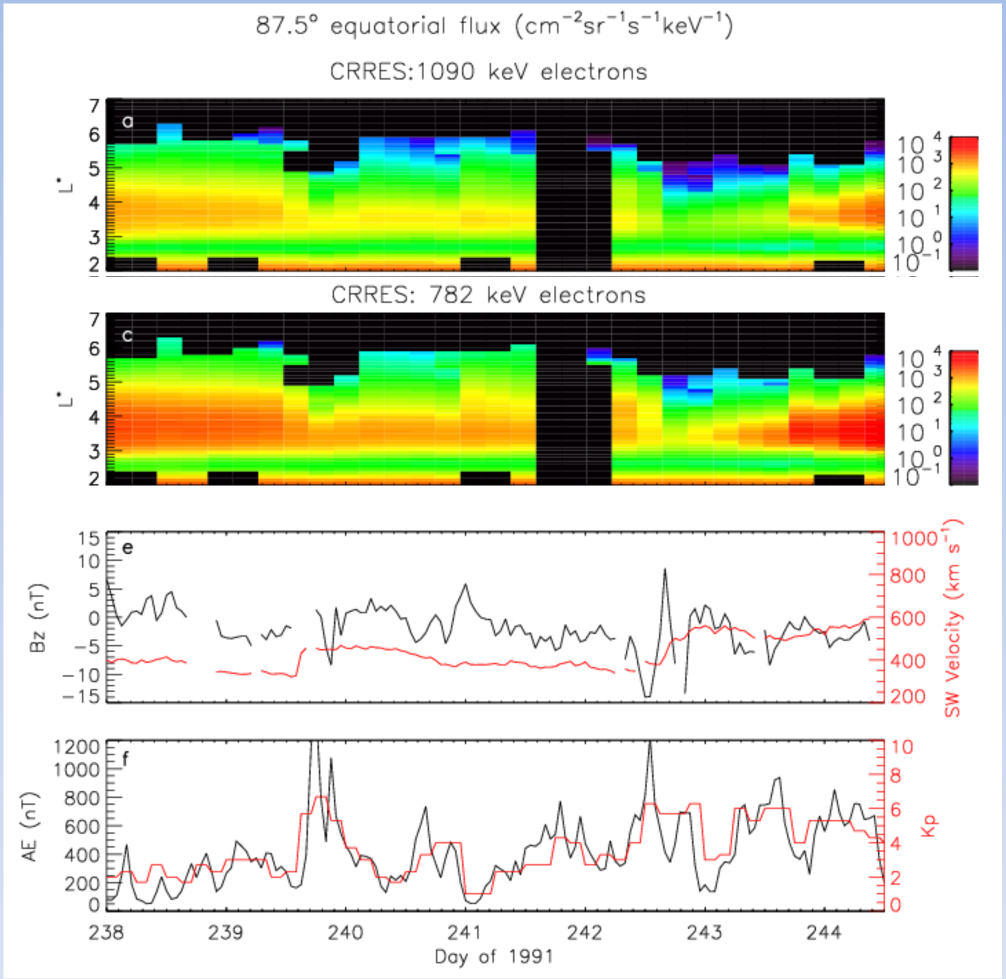
PSD for L*>5.5

- *Shin & Lee [JGR, 2013]*
  - Model for flux on outer L boundary
  - Based on THEMIS data
  - Average for 7Re ≤ r ≤ 8 Re on nightside
  - Driven by SW velocity

- Use this to set psd for L*>5.5
  - Assume model gives flux at 7.5 Re on equator
  - Calculate average L* for nightside (T89)
  - Find energy of boundary at this L*
  - Use Shin & Lee model to get flux for this energy

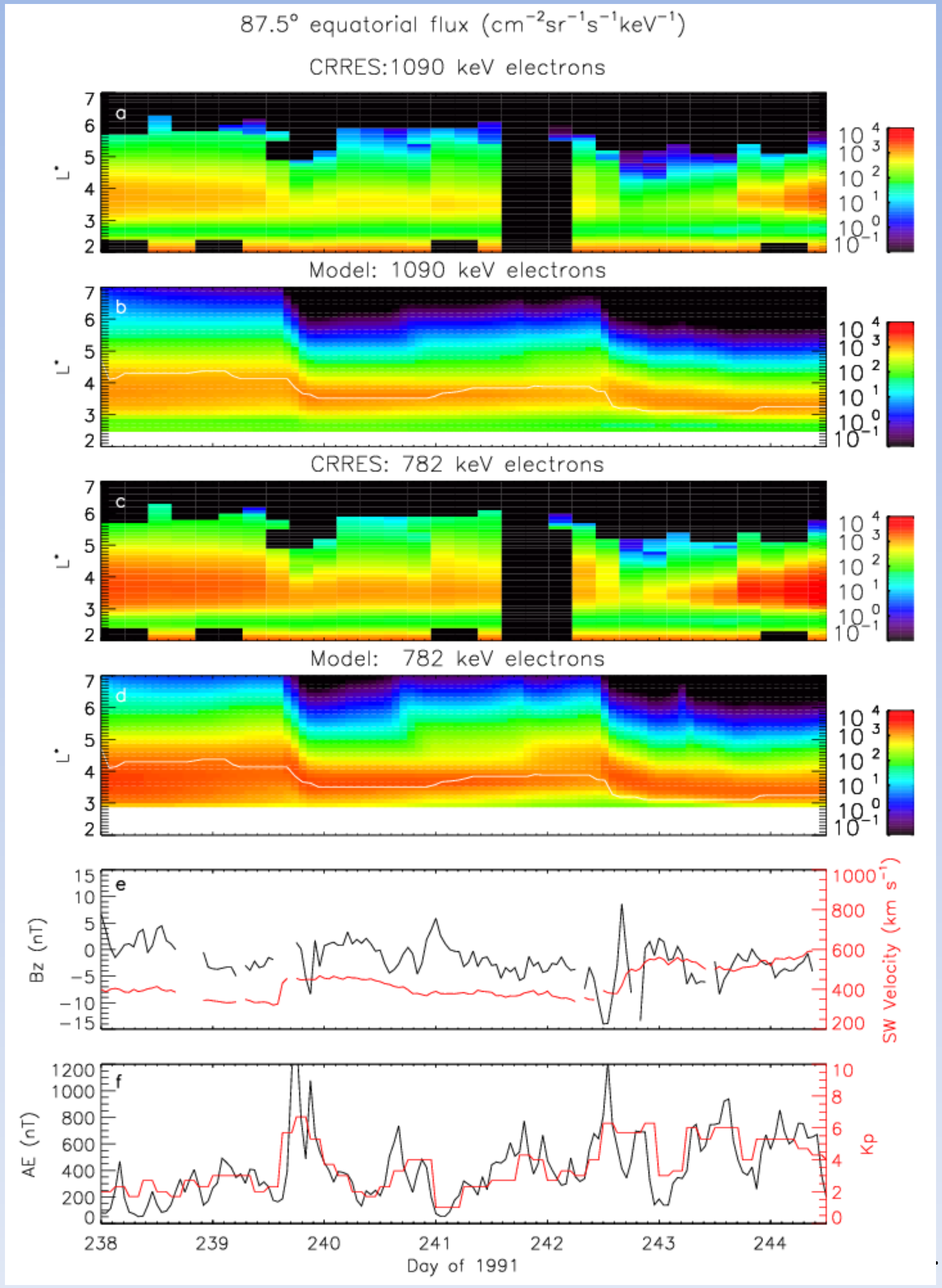
CRRES data

- 26 August 1991 (day 238)
- 6.5 days
- Good solar wind data
- Two storms:
  - Days 239 and 242
  - Both have flux dropout
- Dropouts
  - Day 239 L*~3.5
  - Day 242 L*~3



Model results

- Initial condition- data
- White line - plasmapause
- ‘Dropout’ at each storm
  - Increased outward radial diffusion
- Dropout doesn’t penetrate as far as in the data



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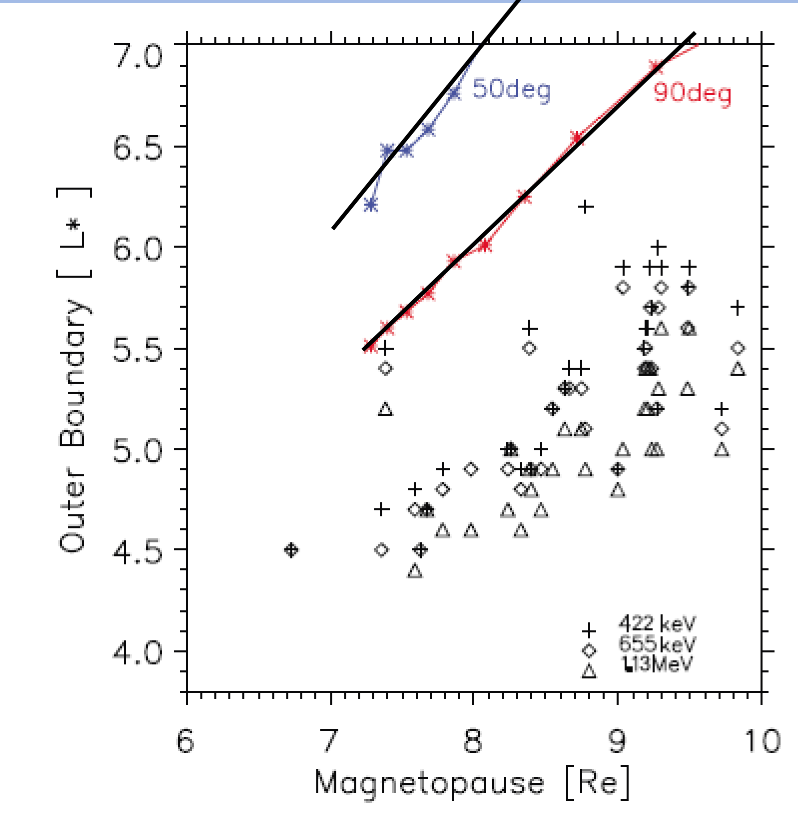
Model for last closed drift shell

- *Shue et al. [JGR, 1998]*
  - Magnetopause location
- *Case and Wild [JGR, 2013]*
  - Shue model overestimates by 1 Re
- *Matsumura et al. [JGR, 2011]*
  - LCDS vs. magnetopause location
  - Includes pitch-angle dependence



→Pitch-angle dependent model for LCDS

- Uses solar wind pressure and IMF Bz
- Extra loss term outside LCDS : τ_{loss} = drift time/2

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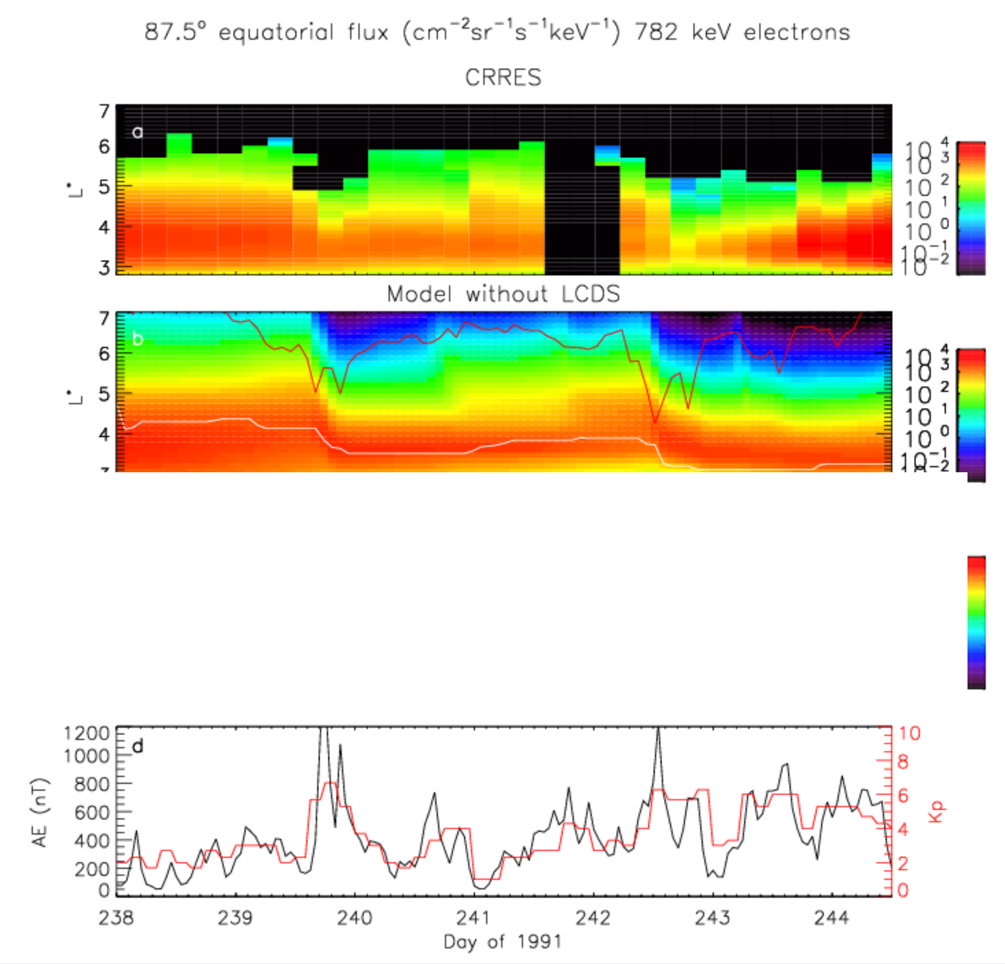
LCDS in model

- 782 keV electrons
- LCDS for α=90º – red

L_{LCDS} = 10

- Dropout is enhanced
- Still does not penetrate to low enough L*
- Don't reproduce acceleration following second storm



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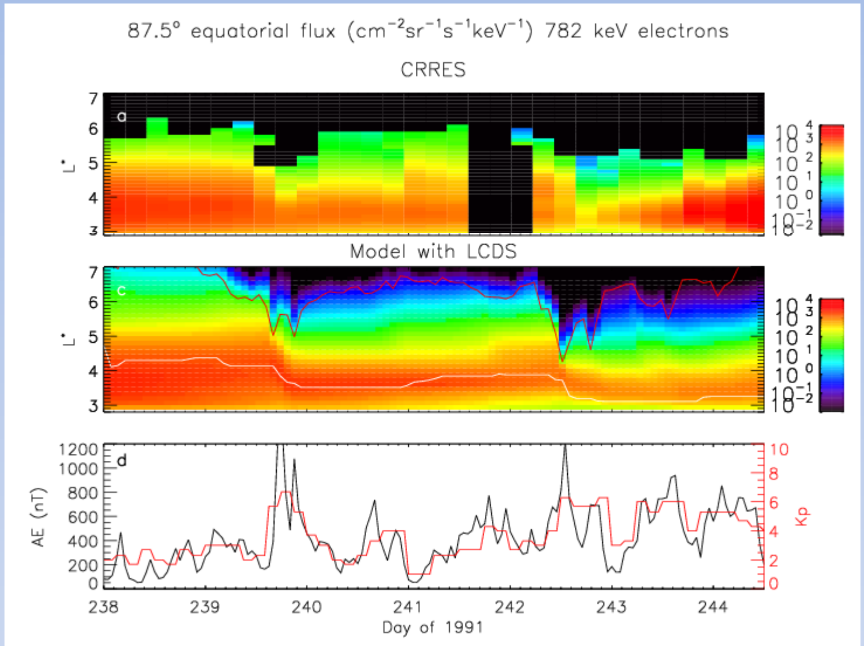
Penetration of dropout

- May over estimate LCDS
- Radial diffusion may be underestimated *Zhao & Li [JGR,2013]*
- *Yu et al. [JGR, 2013]* Magnetopause losses account for dropout for L*>5
- Other processes
  - Low frequency chorus
  - Hiss in plumes



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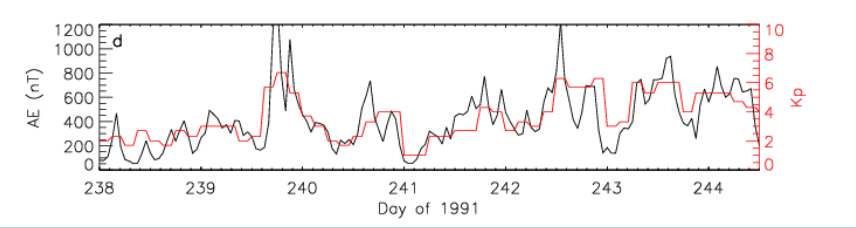
Lack of acceleration after second storm

- Driving chorus by Kp rather than AE
  - AE is better driver (*Glauert et al. [JGR, 2014]*)
  - No forecast of AE available
  - AE ~1200nT on day 242



- Most active level in chorus model is Kp>4
  - Lack of data to fully define model for higher Kp
  - Kp = 6 for most of the period following second storm

- Model of low energy boundary
  - Current model won't capture dynamics of injection events
  - AE is high, so multiple injections are likely

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Next steps

- Use data for the low energy boundary
- Better methods for low energy boundary condition
- Extend comparison with data
  - Van Allen Probes
  - THEMIS

Conclusions

- Existence and location of the outer radiation belt can be reproduced without the need for a source at the outer boundary.
  - Low energy electrons are accelerated by chorus waves to form the outer belt
  - Electrons are then transported inwards and outwards by radial diffusion
- Increased radial diffusion during active conditions results in features that resemble flux dropouts
  - Always have an outward gradient near the outer boundary
  - In active conditions there is increased acceleration due to chorus waves, but increased radial diffusion dominates resulting in loss to outer boundary
- Location of the last closed drift shell has been included in the model
  - results in increased dropouts during storms
- Low frequency chorus needs to be included in future models
  - Increases losses at high energies