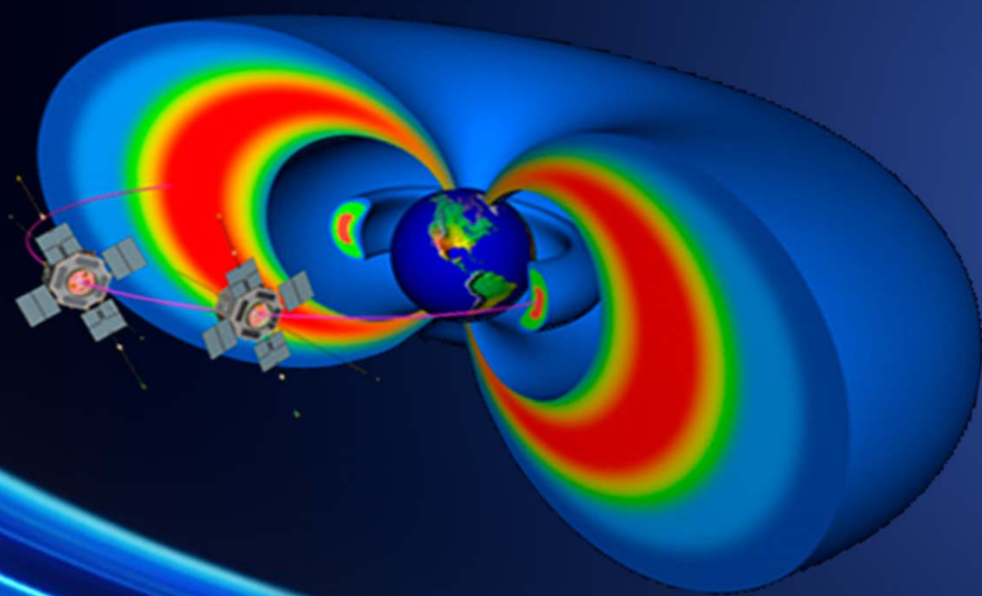
Quantitative Modeling of Radiation Belt Dynamics:
Overview and Challenges



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West Virginia University

2015/06/16

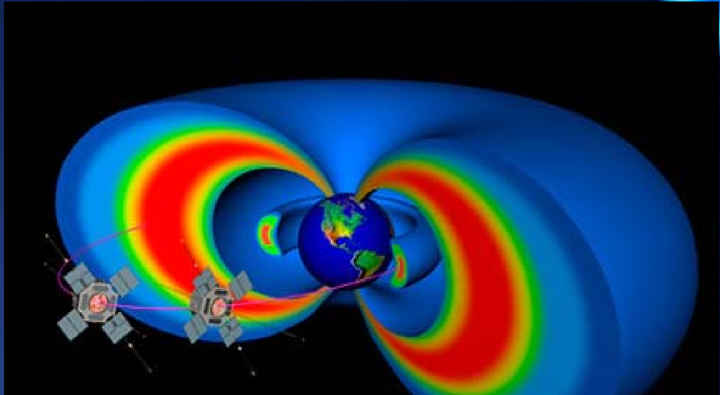
Special Thanks to:
J. M. Albert, W. Li, S. K. Morley, G. S. Cunningham, Y. Chen, R. H. W. Friedel, G. D. Reeves, X. Li

Outline

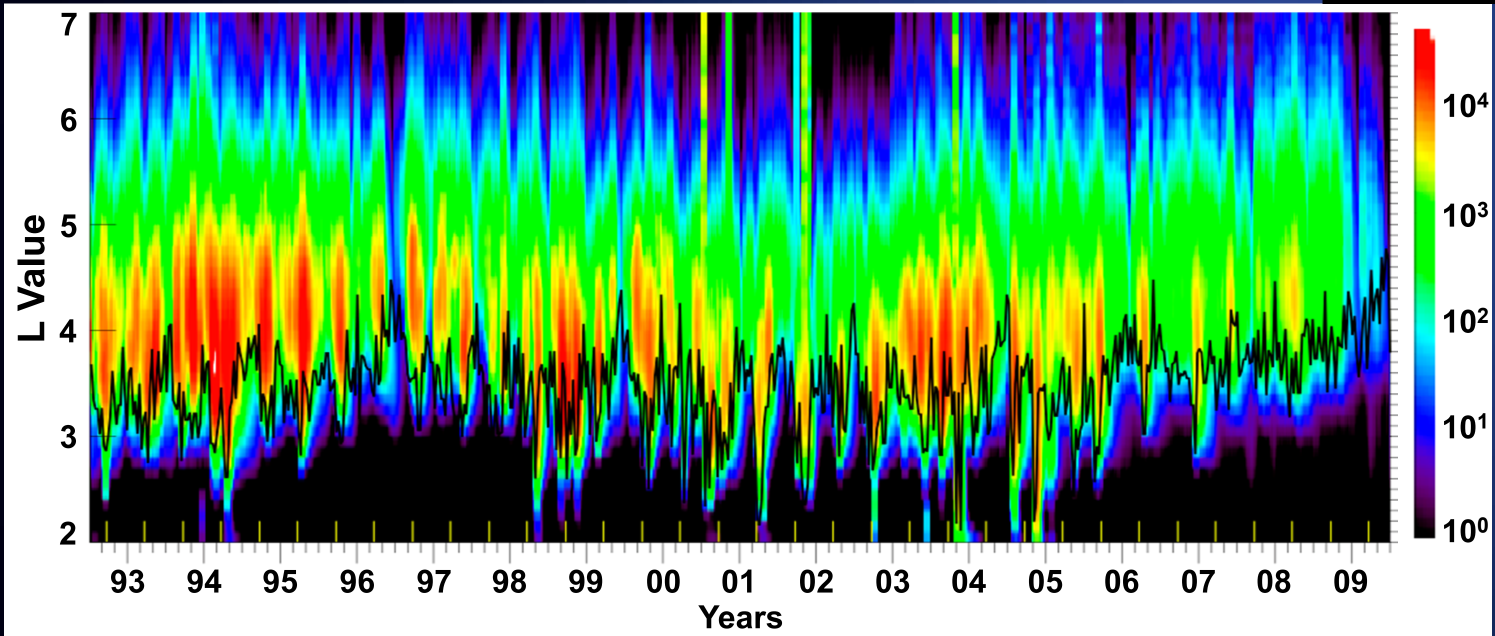
- Introduction of Radiation Belt Dynamics: Sources and Losses
- Advances in Quantitative RB Modeling: Models and Inputs
- Challenges and Opportunities

Radiation Belt Dynamics

- Outer electron belt is very dynamic!
- The complex dynamics is a delicate balance of source, transport, and loss.
- Understanding the dynamics is the No.1 goal of the NASA Van Allen Probes Mission.



Van Allen Probes
(Aug 2012 - present)

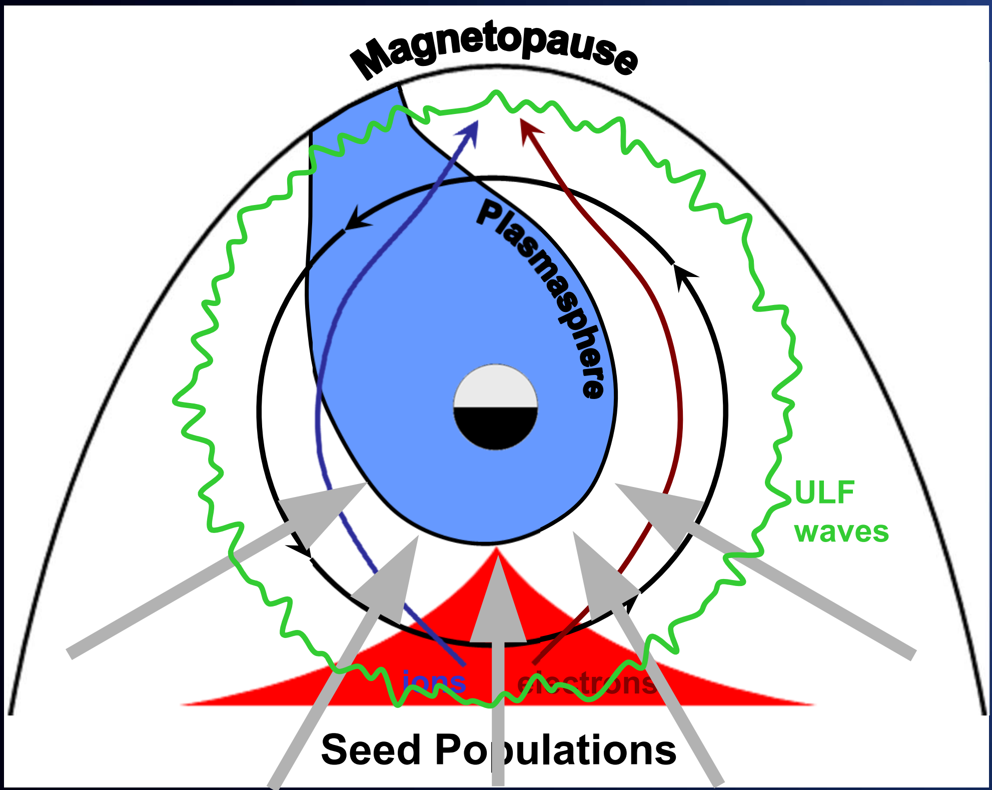


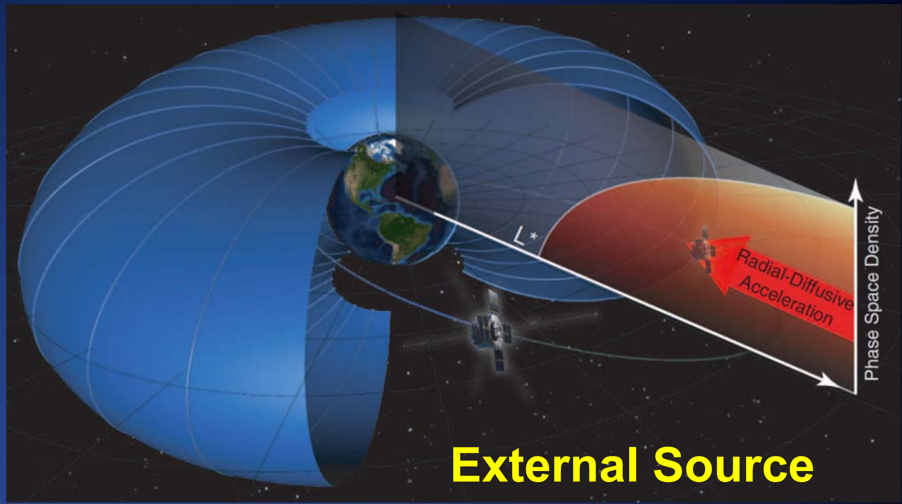
- Color-coded: SAMPEX 2-6 MeV Electron Flux (in log).

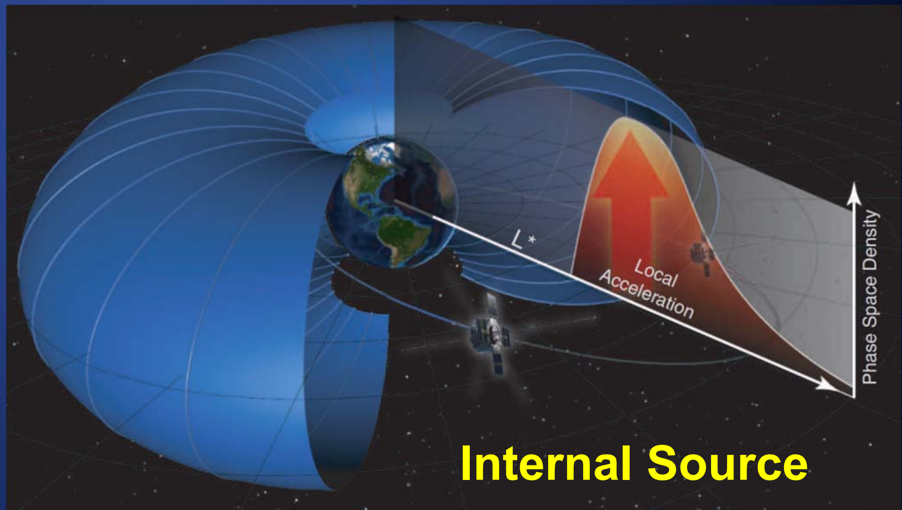
[Courtesy of Xinlin Li]

Radiation Belt Dynamics: Sources

- External source: Inward radial transport due to interaction with ULF waves.



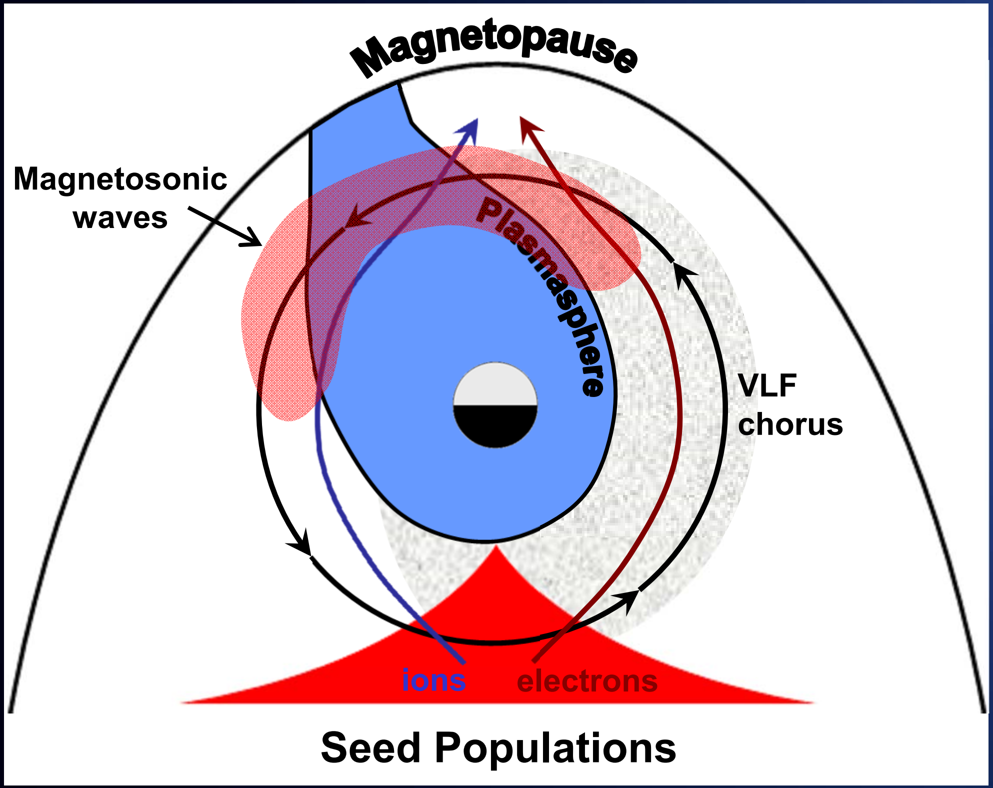


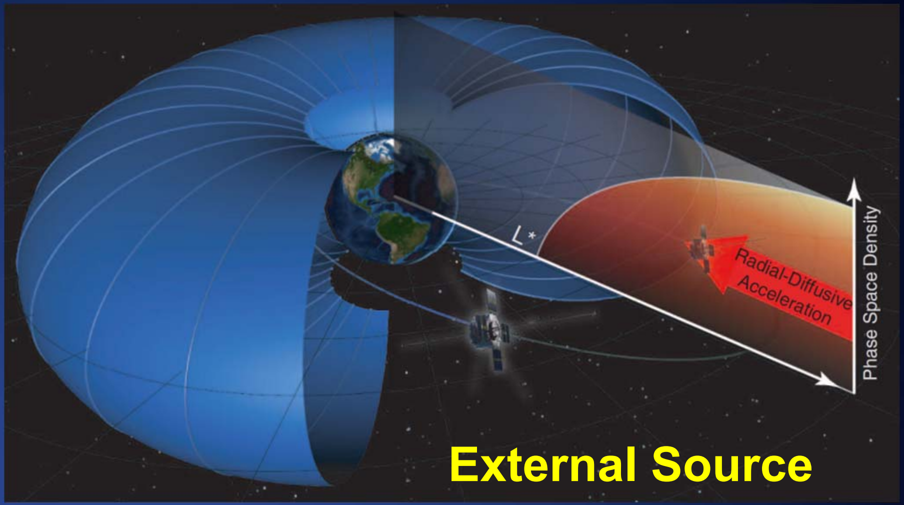


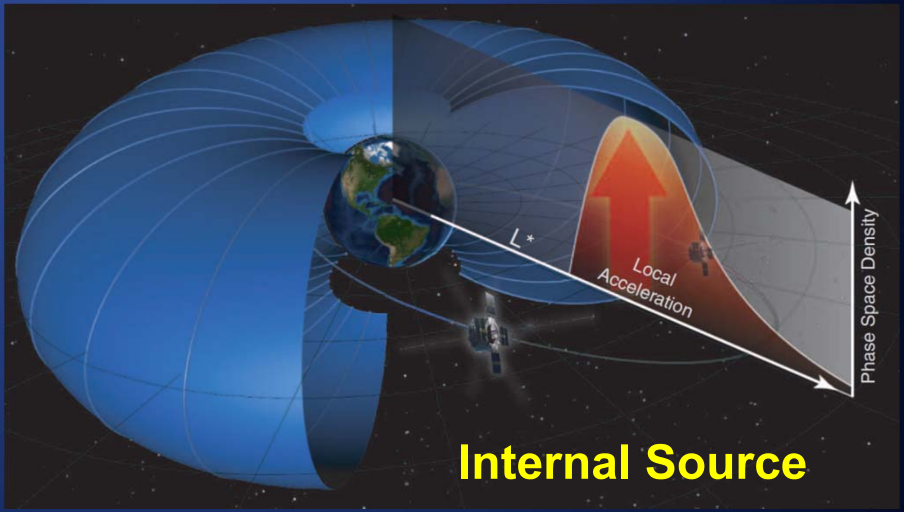
[Reeves et al., Science 2013]

Radiation Belt Dynamics: Sources

- External source: Inward radial transport due to interaction with ULF waves.
- Internal source: Local acceleration due to interaction with VLF waves.



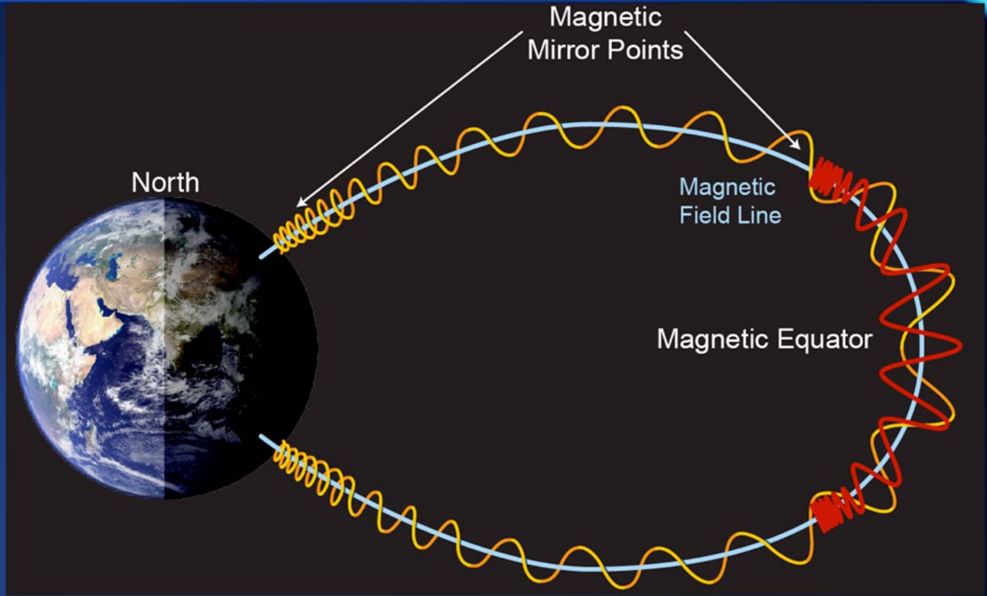


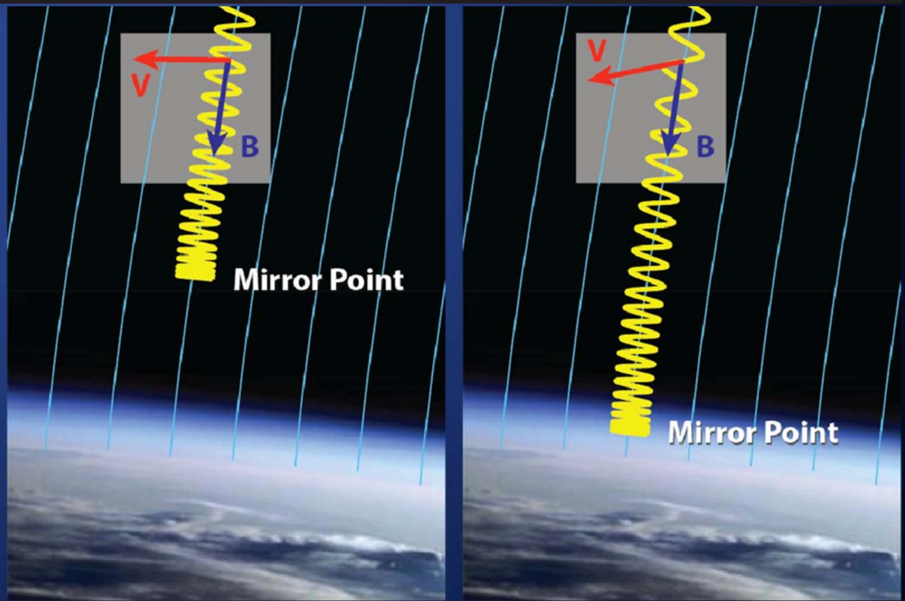


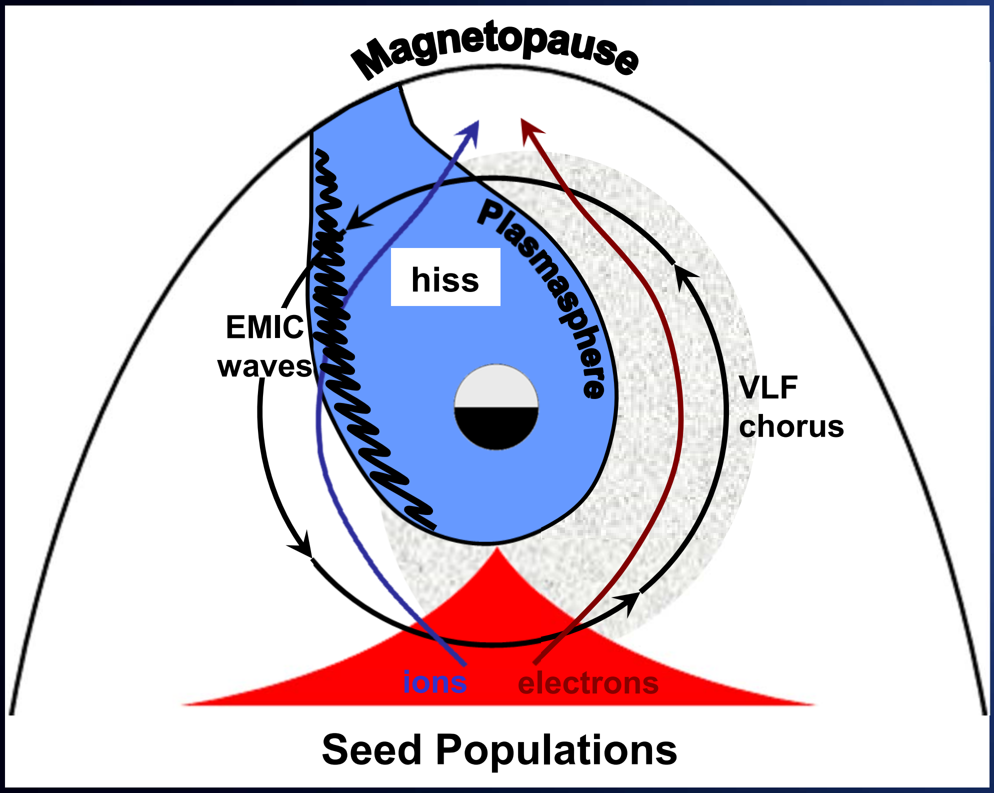
[Reeves et al., Science 2013]

Radiation Belt Dynamics: Losses

- Precipitation loss: pitch angle scattering by, e.g., VLF, EMIC waves.

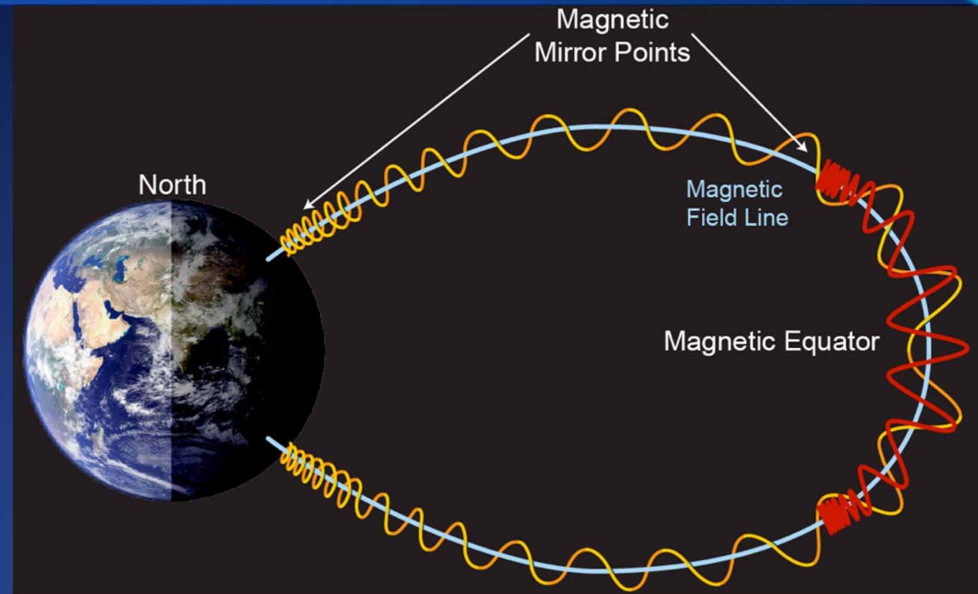


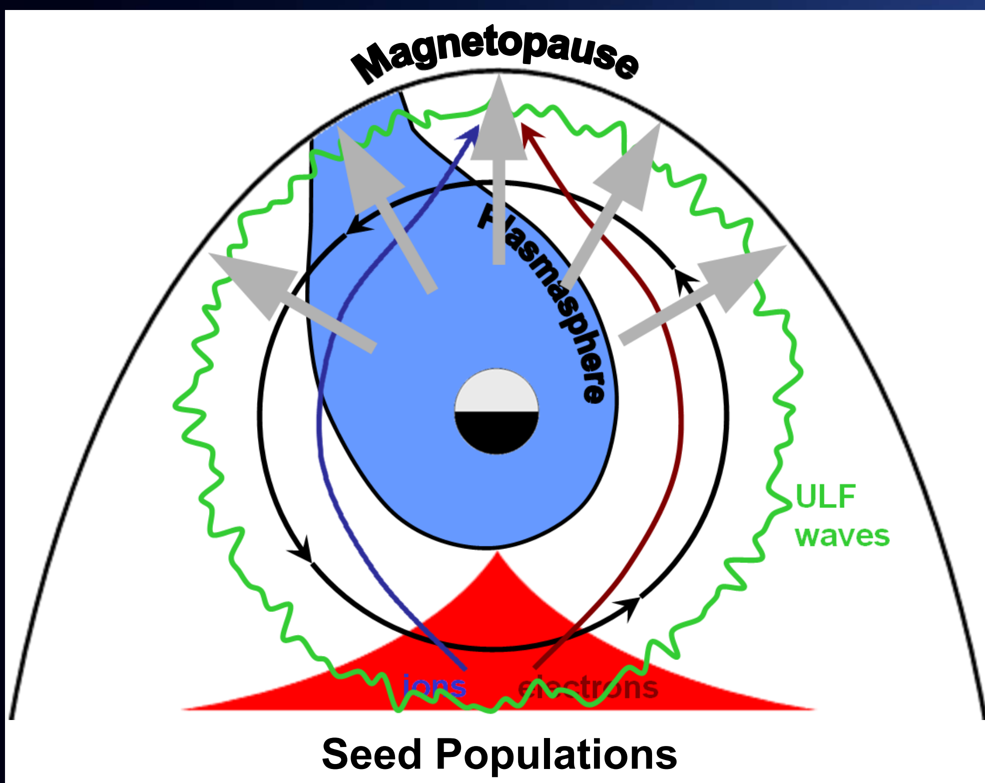


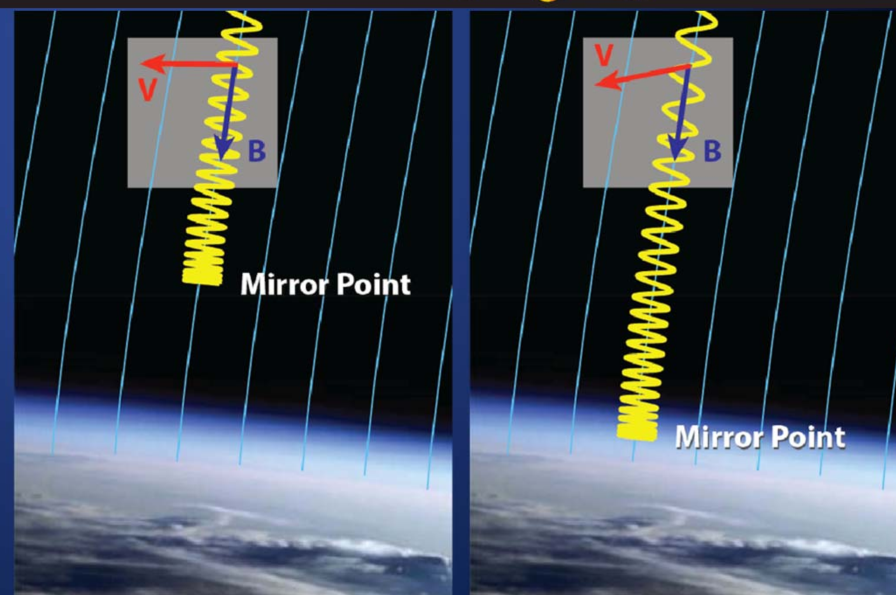


Radiation Belt Dynamics: Losses

- Precipitation loss: pitch angle scattering by, e.g., VLF, EMIC waves.
- Magnetopause shadowing: outward radial transport (ULF waves) or magnetopause compression.







Outline

- Introduction of Radiation Belt Dynamics: Sources and Losses
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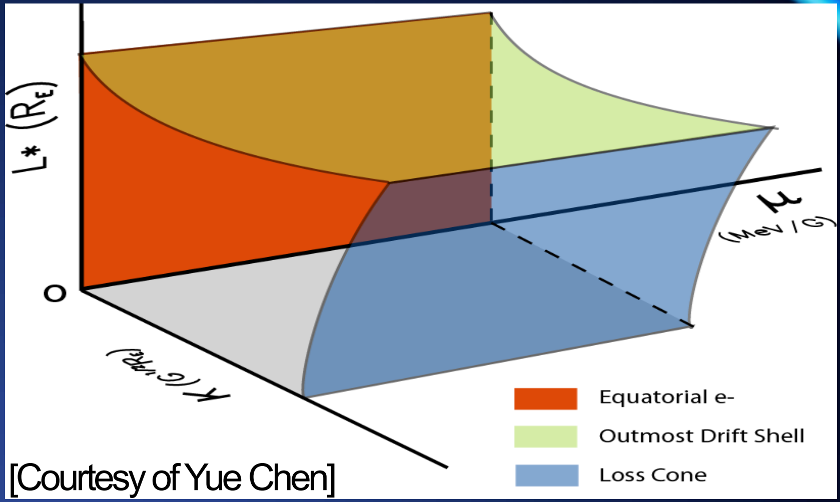
Types of Radiation Belt Models

- Fokker-Planck diffusion models
- Convection-Diffusion models
- Test particle codes
- PIC & Hybrid codes



[Courtesy of Yue Chen]

Inputs

Diffusion coefficients
Boundary conditions

→

Outputs

PSD(μ,K,L,time)

Pros:
- Efficient, useful for global problems

Cons:
- Assumptions of quasi-linear theory and diffusion physics

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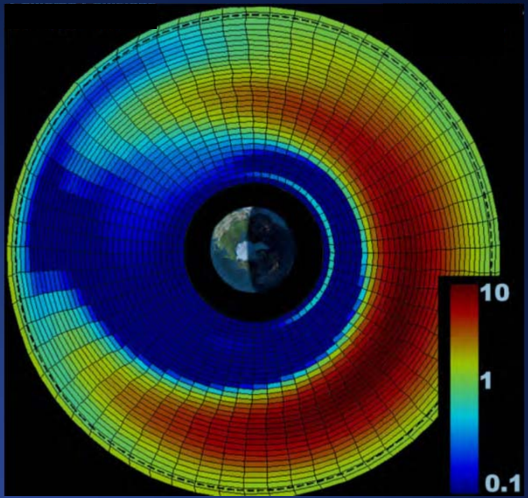

[Courtesy of V. Jordanova]

Inputs

Diffusion coefficients
Global E&B models

→

Outputs

PSD(E, α ,r,Φ,time)

Pros:

- Include drift phase and convection physics, useful for seed population

Cons:

- Assumptions of quasi-linearity and diffusion; performance of the global E&B models

Types of Radiation Belt Models

- Fokker-Planck diffusion models
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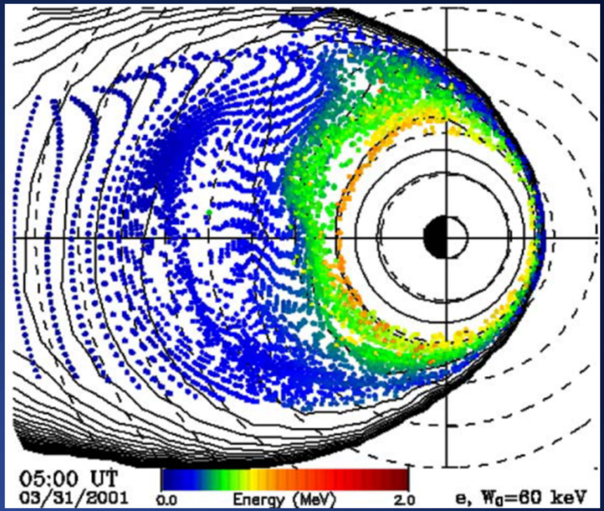


[Elkington et al., JASTP 2004]

Inputs

Global E&B models or Analytical wave models

→

Outputs

flux(E, α, r, Φ, time)

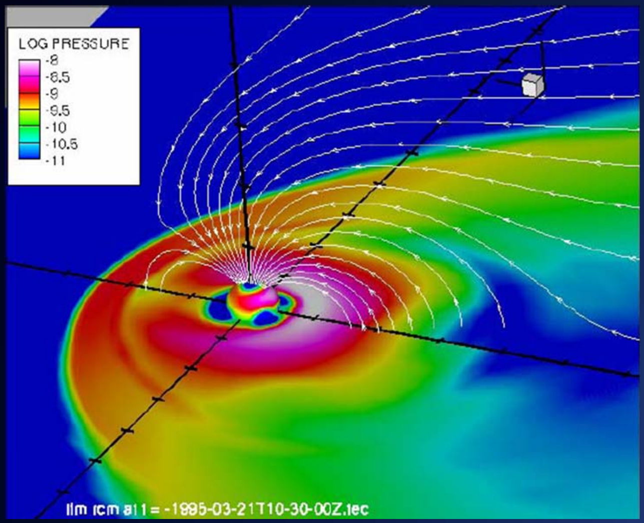
Pros:

- Include convection physics, no diffusion assumption

Cons:

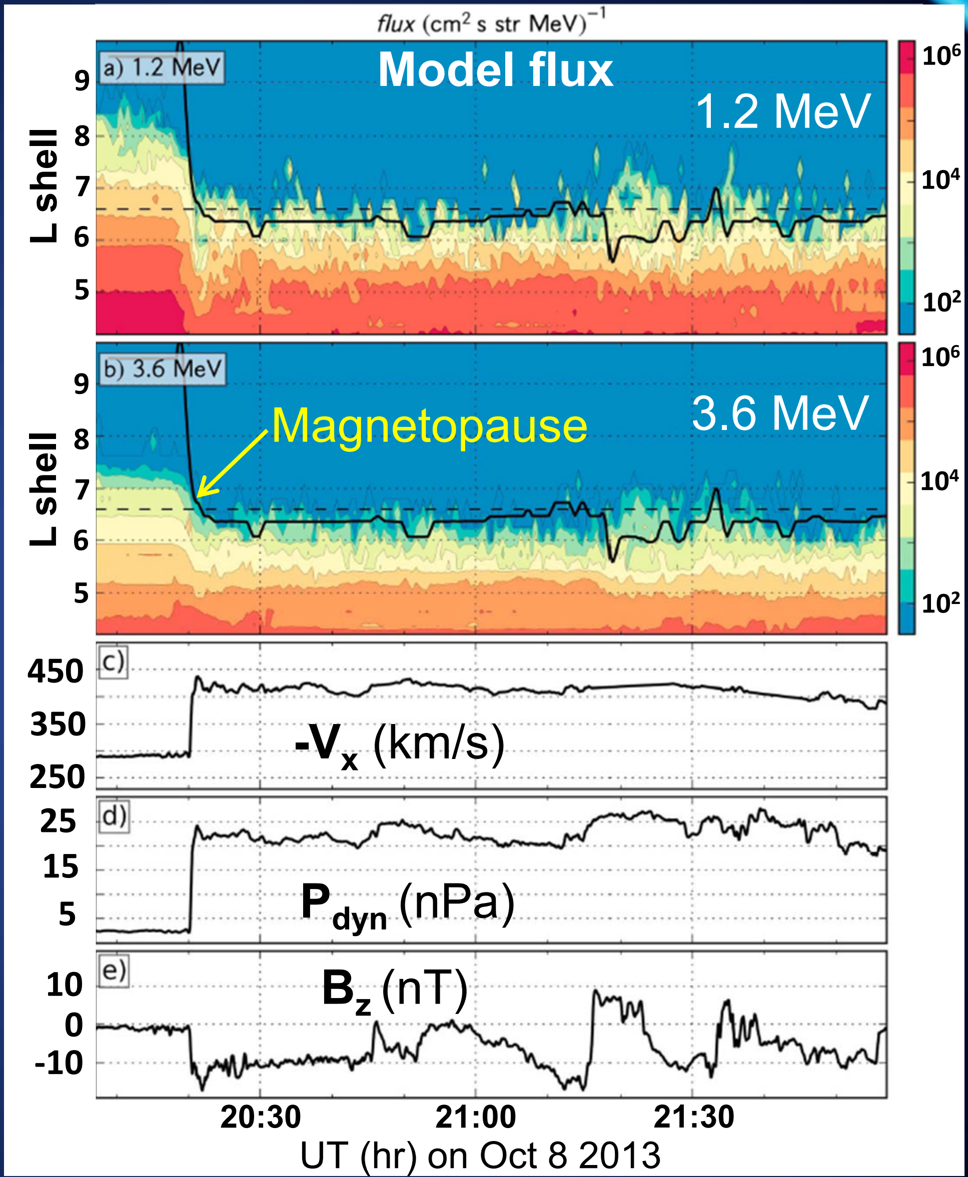
- Performance of the global E&B models (if MHD fields, no VLF waves); computationally expensive.

MHD Test Particle Simulation

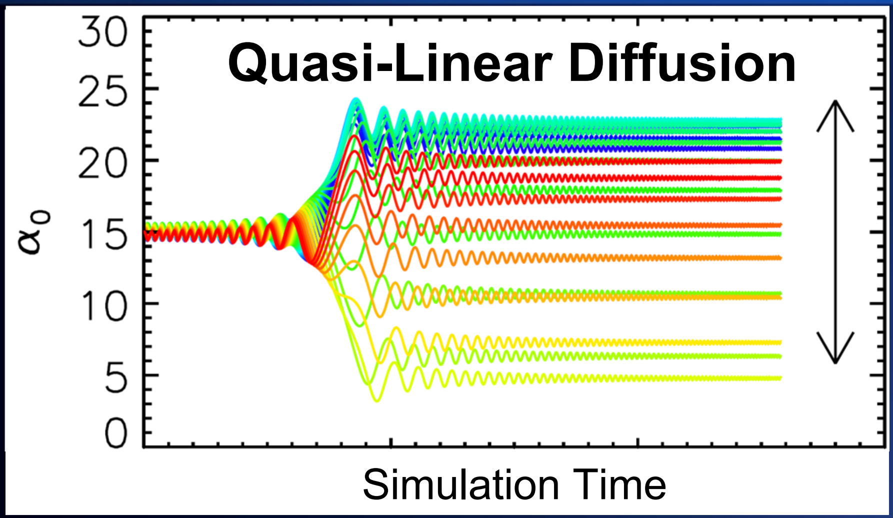


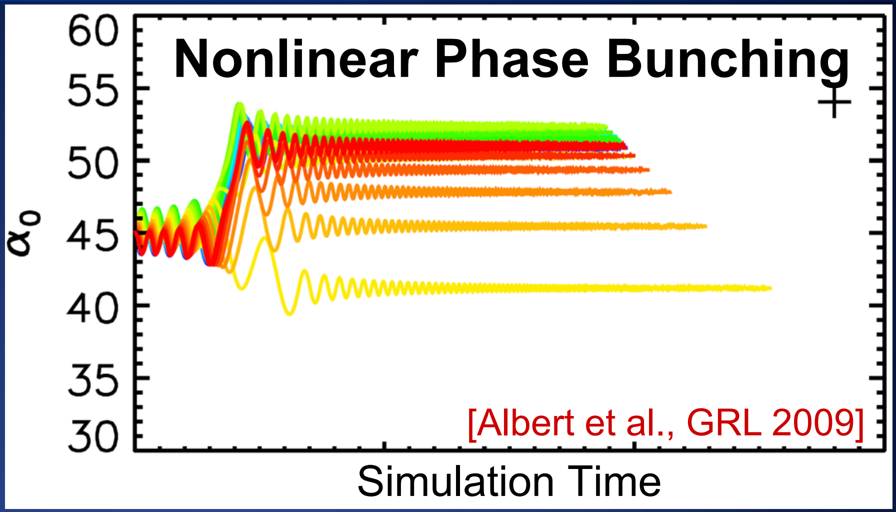
[Courtesy of F. Toffoletto]

- Trace electrons under global LFM-RCM fields [Hudson et al., JGR 2015]
- Loss of MeV electrons by magnetopause shadowing and outward radial transport (enhanced ULF waves)

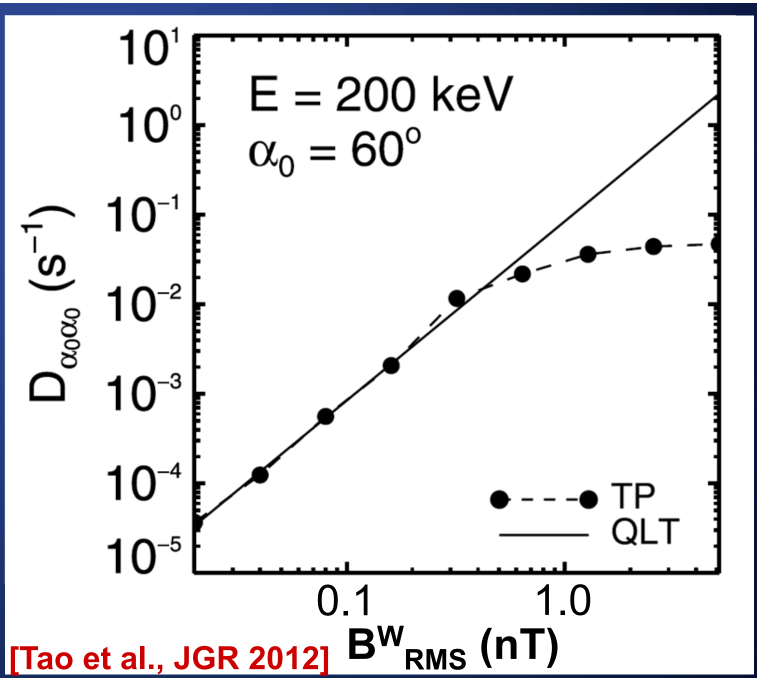


Test Quasi-Linear Theory





- Trace energetic electrons under a given wave model to test quasi-linear theory and its limit.
- E.g., Tao [JGR 2012] found that for parallel propagating whistler waves, quasi-linear theory becomes invalid when the wave amplitude increases.



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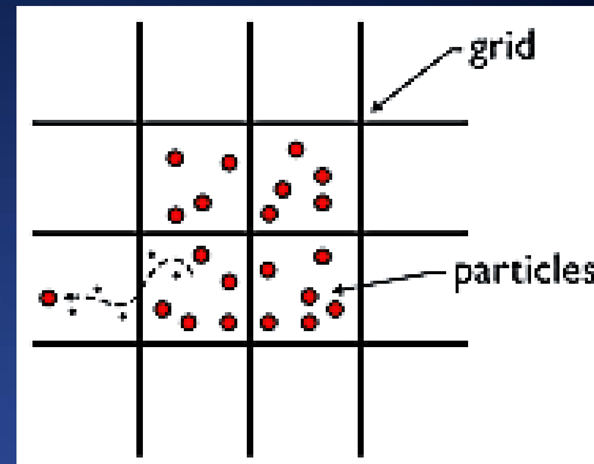

[from LANL website]

Inputs

Initial plasma and field conditions

→

Outputs

Wave growth and interaction

Pros:

- Self-consistent wave particle interactions

Cons:

- Computationally expensive; limited coupling to global codes

Types of Radiation Belt Models

- Fokker-Planck diffusion models
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Self-consistency ↓

Global efficiency ↑

Inputs

Initial plasma and field conditions

→

Outputs

Wave growth and interaction

Pros:

- Self-consistent wave particle interactions

Cons:

- Computationally expensive; limited coupling to global codes

Fokker-Planck Diffusion Models

- 3D Fokker-Planck Equation [Schulz and Lanzerotti, 1974]:

$$\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L}\left(\frac{D_{LL}}{L^2}\frac{\partial f}{\partial L}\right) + \frac{1}{G}\frac{\partial}{\partial K}\left(G D_{KK}\frac{\partial f}{\partial K}\right) + \frac{1}{G}\frac{\partial}{\partial \mu}\left(G D_{\mu\mu}\frac{\partial f}{\partial \mu}\right) + \frac{1}{G}\frac{\partial}{\partial K}\left(G D_{K\mu}\frac{\partial f}{\partial \mu}\right) + \frac{1}{G}\frac{\partial}{\partial \mu}\left(G D_{\mu K}\frac{\partial f}{\partial K}\right)$$

- Simplified to 1D radial diffusion model at fixed μ and K:

$$\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L}\left(\frac{D_{LL}}{L^2}\frac{\partial f}{\partial L}\right) - \frac{f}{\tau} + S$$

τ: electron lifetime from pitch angle diffusion;

S: electron source rate from energy diffusion

  - Useful when radial diffusion is the dominant process.
  - Need reliable inputs for D_{LL}, lifetime and source rate.

1D Radial Diffusion Model

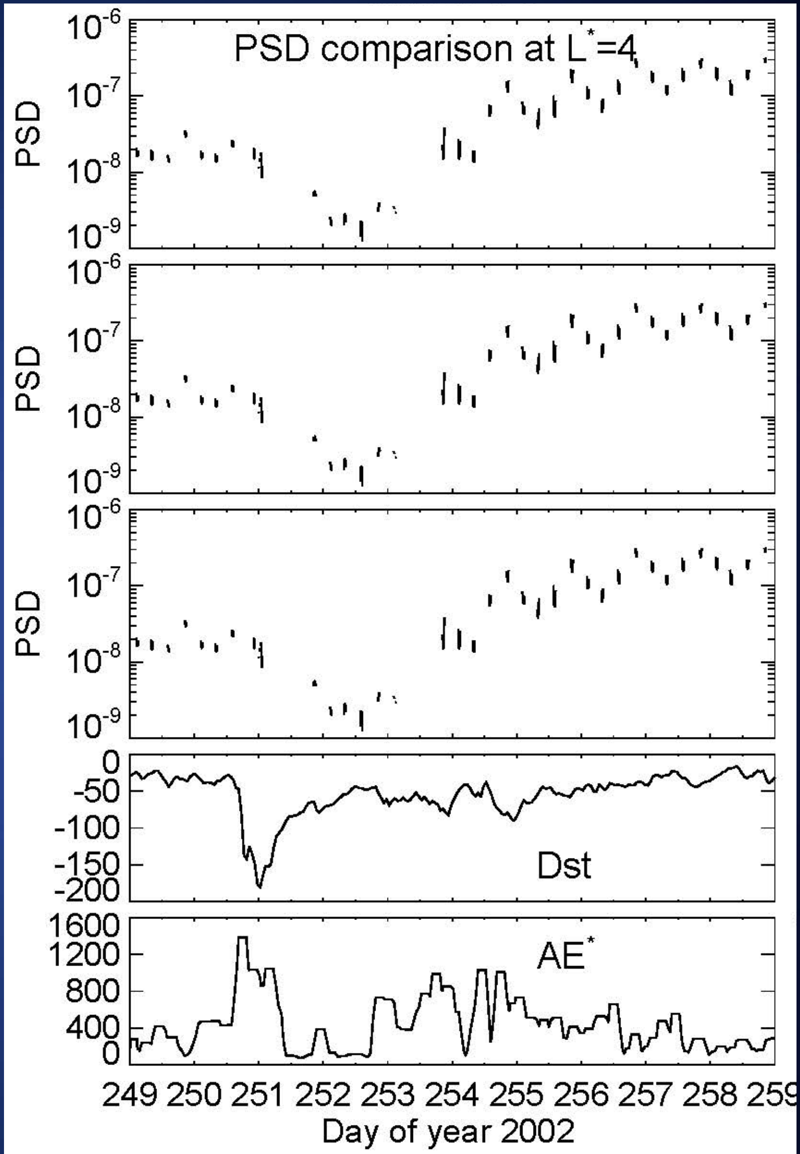
- [Tu et al., JGR 2009]

$$\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L}\left(\frac{D_{LL}}{L^2}\frac{\partial f}{\partial L}\right) - \frac{f}{\tau} + S$$

- Goal: to reproduce the PSD dynamics observed at L=4 (with data-driven outer boundary at L=6)
- Empirical inputs:

$$D_{LL}(Kp, D_0) = D_0 \times 10^{(0.506Kp - 9.325)} L^{10}$$

$S(AE, S_0)$ and $\tau(AE, Dst, \tau_0)$



1D Radial Diffusion Model

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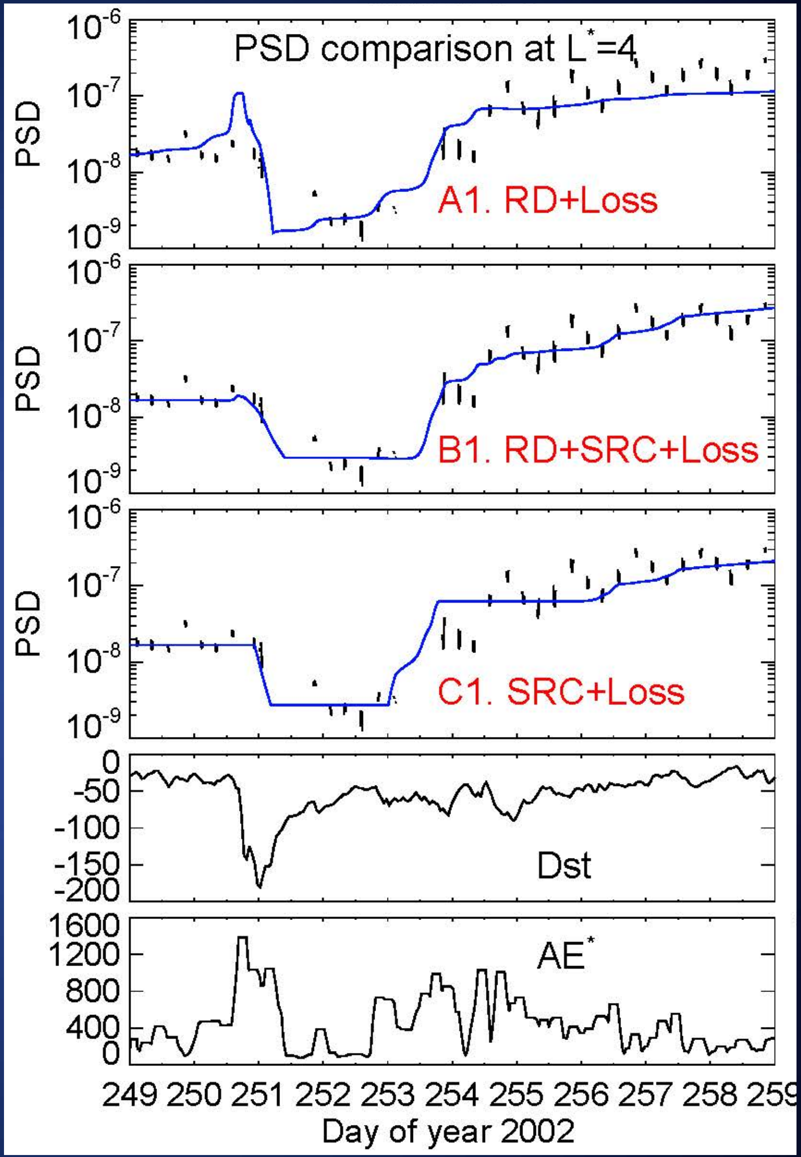
$S(AE, S_0)$ and $\tau(AE, Dst, \tau_0)$

- Model results: well-reproduce the dynamics by all three different runs.
- Uncertainties in the model inputs: D_{LL}, electron lifetime, and source rate

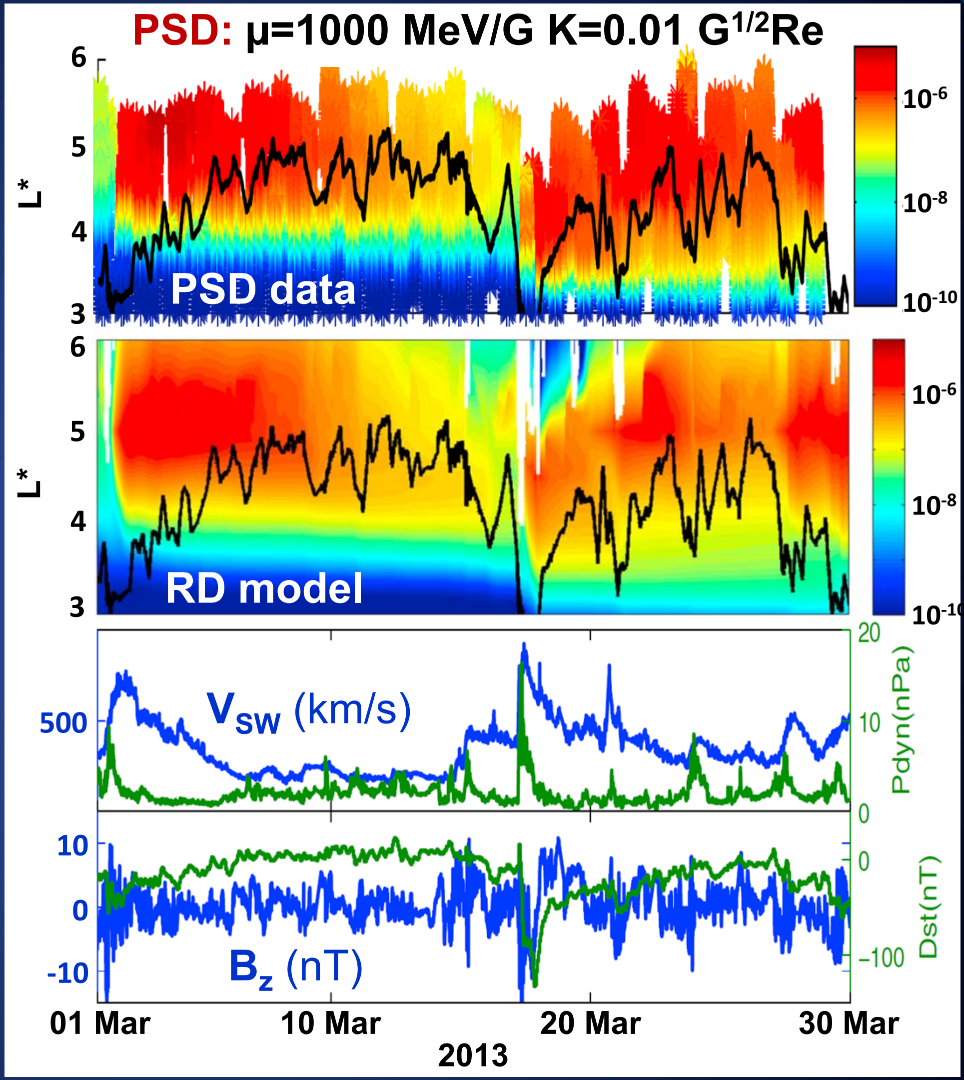


1D Radial Diffusion Model

- Z. Li et al. [JGR 2014] simulated the 1-month Van Allen Probes interval in March 2013.

$$\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L}\left(\frac{D_{LL}}{L^2}\frac{\partial f}{\partial L}\right) - \frac{f}{\tau}$$

- The 1st enhancement at the beginning of March is reproduced by radial diffusion from a source at larger L.
- The Mar 17 storm enhancement is under-reproduced by radial diffusion only.



2D Diffusion Model

- Coordinates

  (μ,K,L)

  ↓

  (p,α,L)

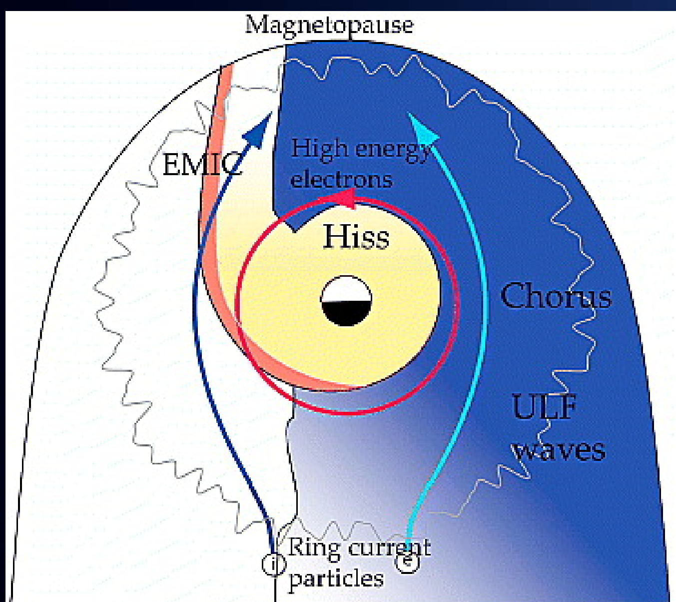
$$\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L}\left(\frac{D_{LL}}{L^2}\frac{\partial f}{\partial L}\right) + \frac{1}{G}\frac{\partial}{\partial K}\left(G D_{KK}\frac{\partial f}{\partial K}\right) + \frac{1}{G}\frac{\partial}{\partial \mu}\left(G D_{\mu\mu}\frac{\partial f}{\partial \mu}\right) + \frac{1}{G}\frac{\partial}{\partial K}\left(G D_{K\mu}\frac{\partial f}{\partial \mu}\right) + \frac{1}{G}\frac{\partial}{\partial \mu}\left(G D_{\mu K}\frac{\partial f}{\partial K}\right)$$

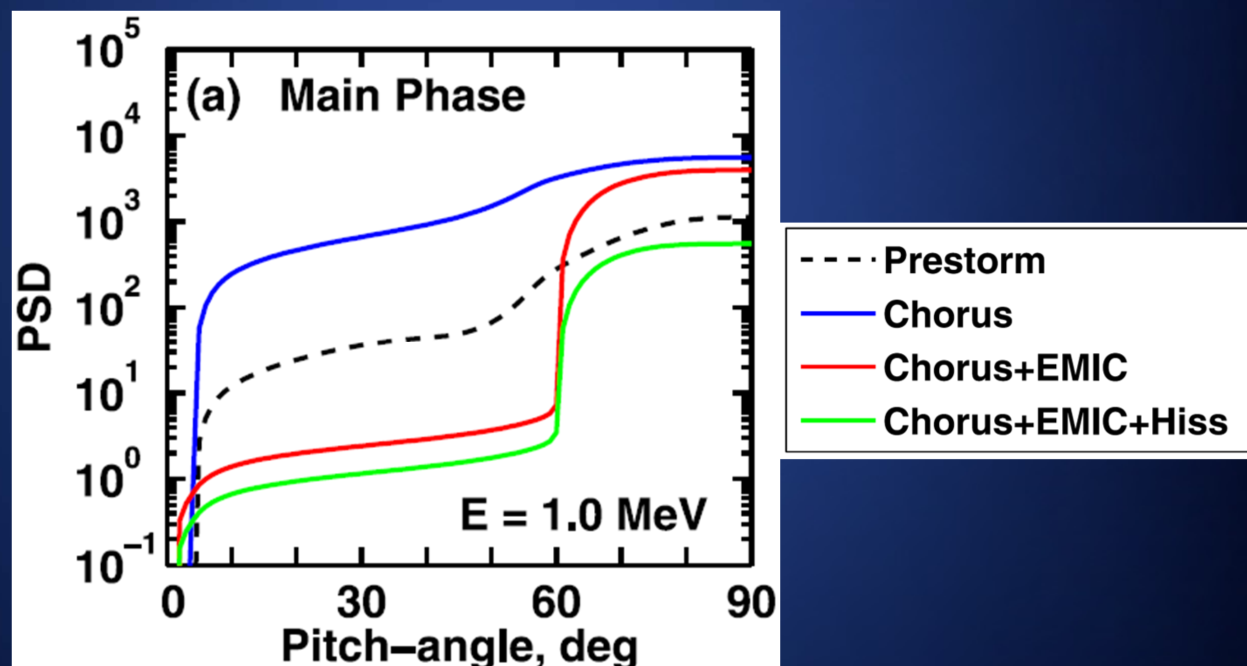
$$\frac{\partial f}{\partial t} = \quad \frac{1}{\Gamma}\frac{\partial}{\partial \alpha}\left(\Gamma D_{\alpha\alpha}\frac{\partial f}{\partial \alpha}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial f}{\partial p}\right) + \frac{1}{\Gamma}\frac{\partial}{\partial \alpha}\left(\Gamma D_{\alpha p}\frac{\partial f}{\partial p}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{p\alpha}\frac{\partial f}{\partial \alpha}\right)$$

- Simplified to 2D momentum-pitch angle diffusion at fixed L
- Useful to model fast local acceleration and losses, when radial diffusion is not dominant.

2D Diffusion Model

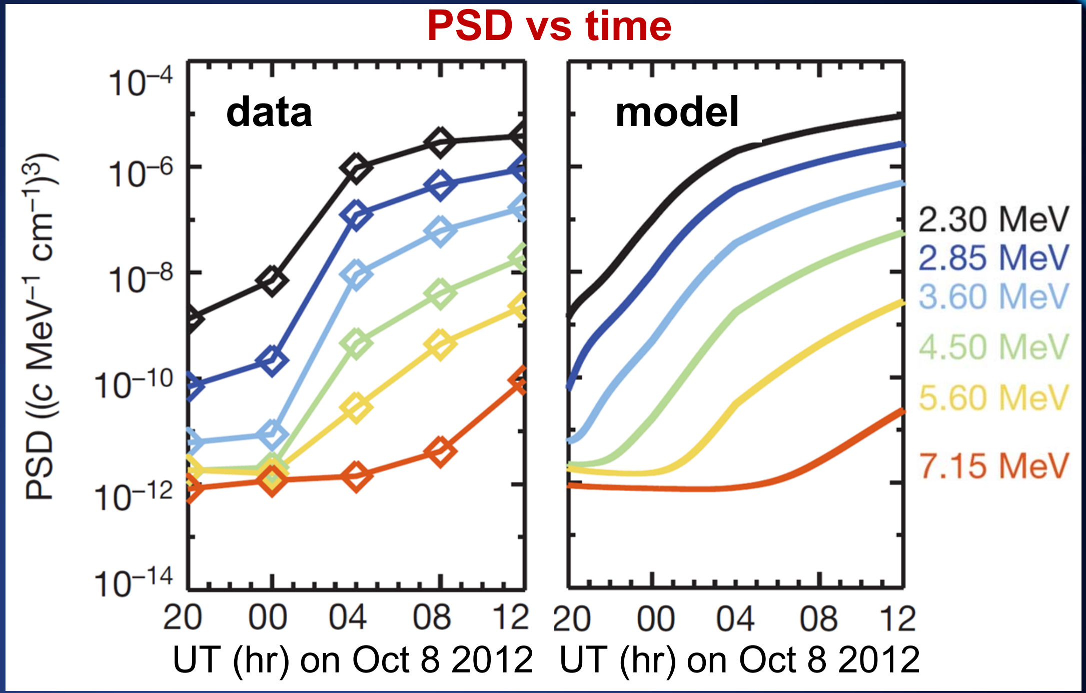
- [W. Li et al., JGR 2007]: Applied a 2D diffusion model to study the acceleration and loss effects from different types of waves, located at different local times.
- Diffusion coefficients are calculated from static wave inputs specified for dayside/nightside chorus, EMIC, and hiss waves.

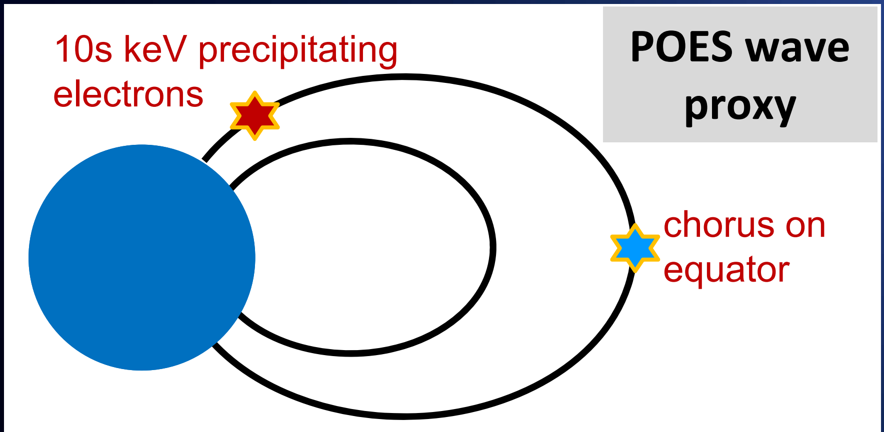




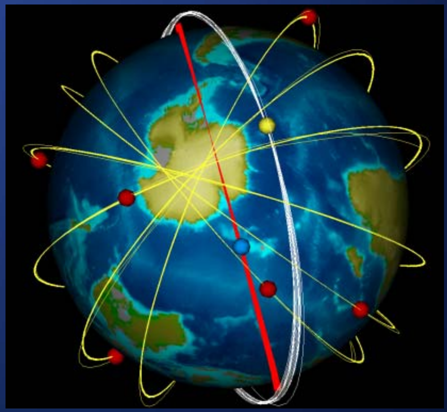
2D Diffusion Model

- Advance in model inputs:
  - [Thorne et al., Nature 2013]
  - Event-specific and global chorus wave model derived from POES proxy
  - Ambient plasma density derived from in situ data
- Model well-reproduced the strong RB enhancement up to 7.2 MeV





6 NOAA/POES



3D Diffusion Model

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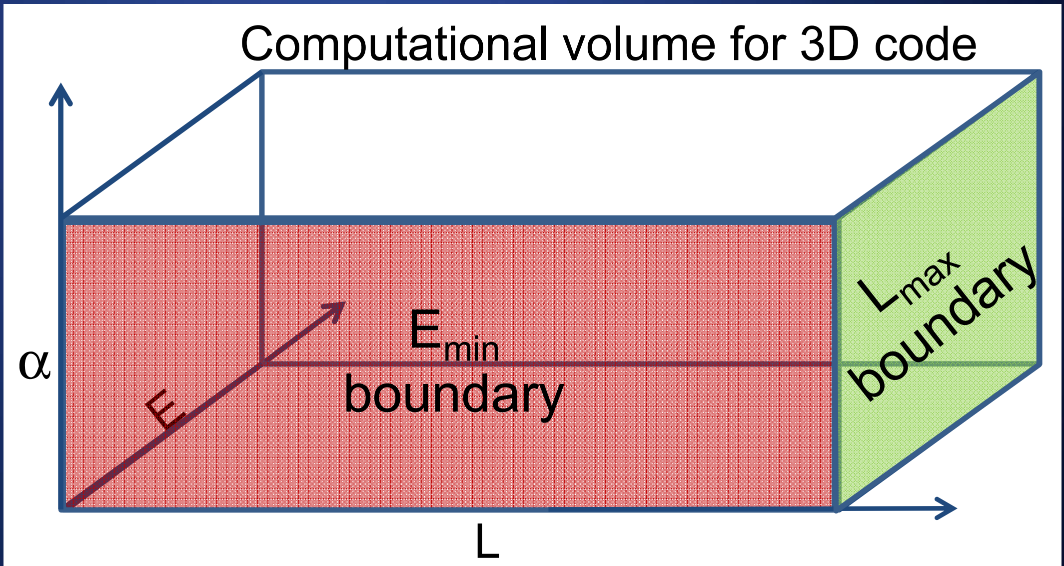
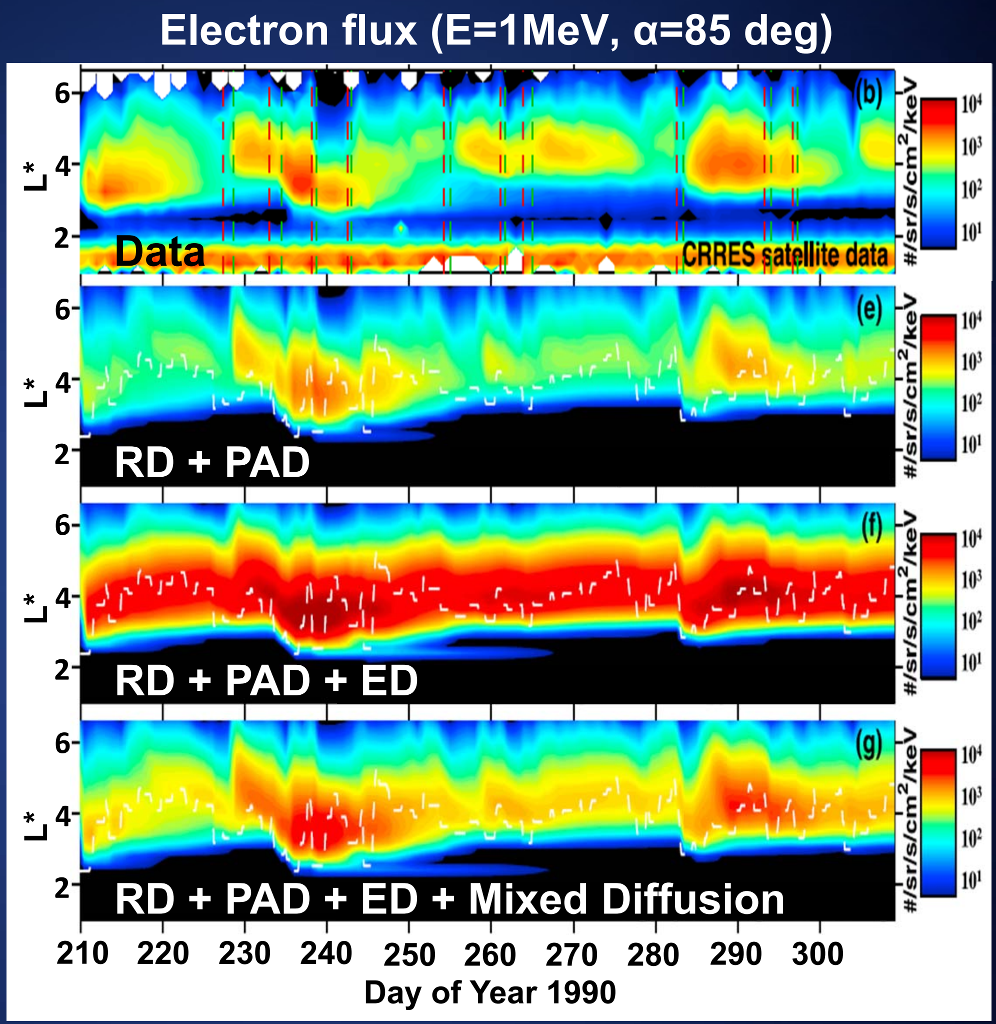
- Many different versions have been developed in the past 10 years:
  - VERB (UCLA), DREAM3D (LANL), Dilbert? (Albert), REM (Rice), BAS model, Salammbô (French), STEERB (China) …
- Inputs: Diffusion Coefficients
- Boundary Conditions:

α=0	PSD=0 (atmosphere)
α=π/2	dPSD/dα=0
L=1	PSD=0 (atmosphere)
$L=L_{max}$	outer boundary
$E=E_{max}$	PSD=0
$E=E_{min}$	seed population (100 KeV)



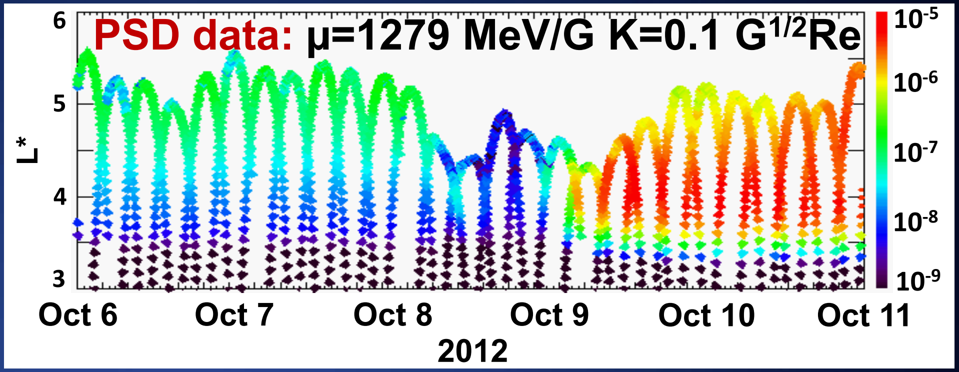
3D Diffusion Model

- VERB results from Subbotin et al. [JGR 2011]
- Long-term simulation of the CRRES interval to model the effects from different diffusion processes.
  - Best reproduce the observations by including all the diffusion processes
- Wave and plasma inputs: dynamic but still empirical (as a function of Kp).

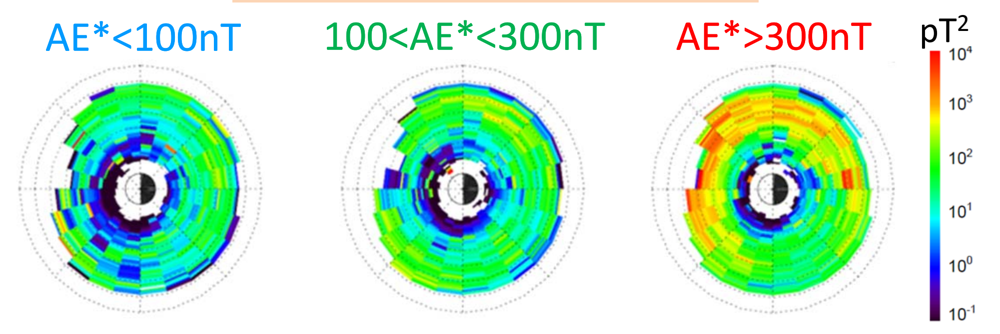


3D Diffusion Model

- Need event-specific inputs for very strong events.
- [Tu et al., GRL 2014]: DREAM3D
  - Model the strong enhancement during the Oct 2012 storm.



Statistical chorus model



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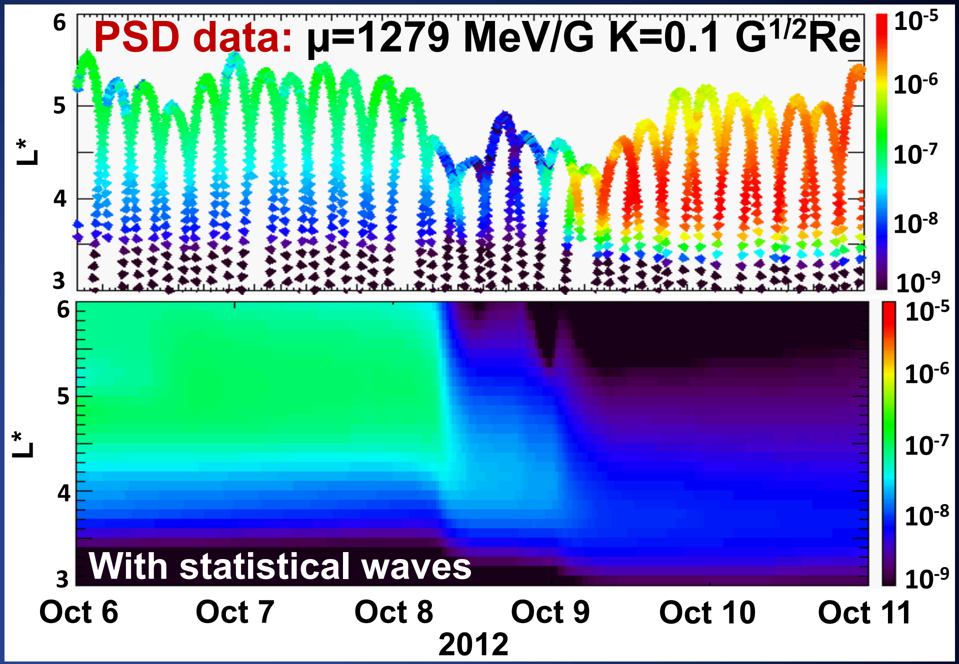

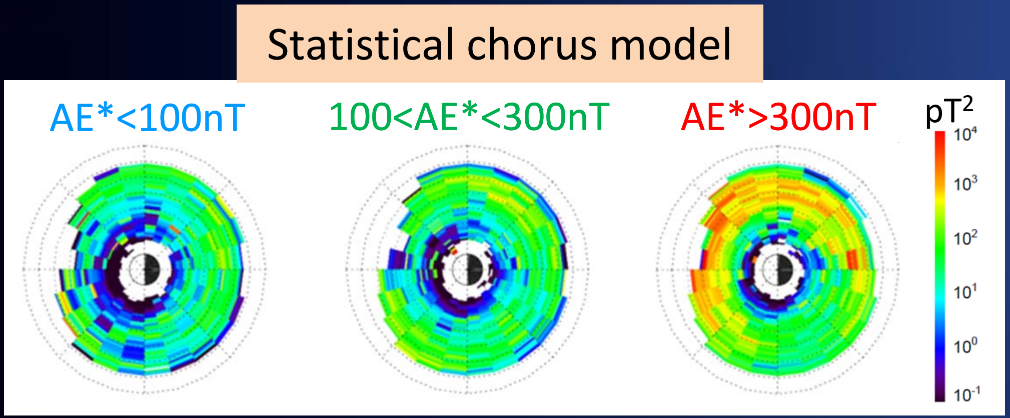

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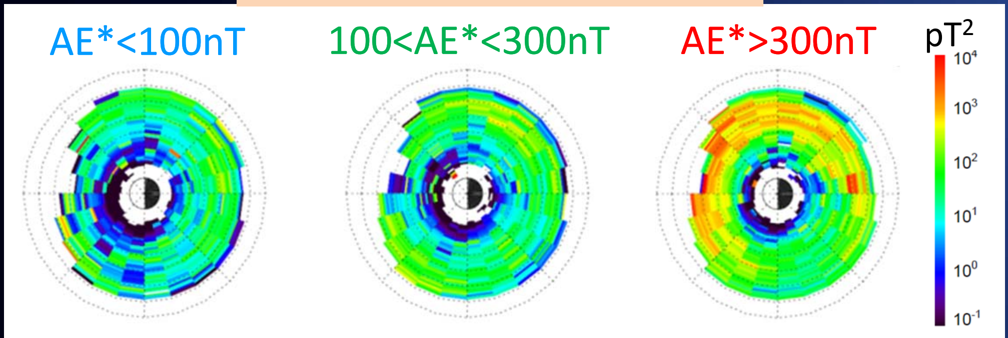
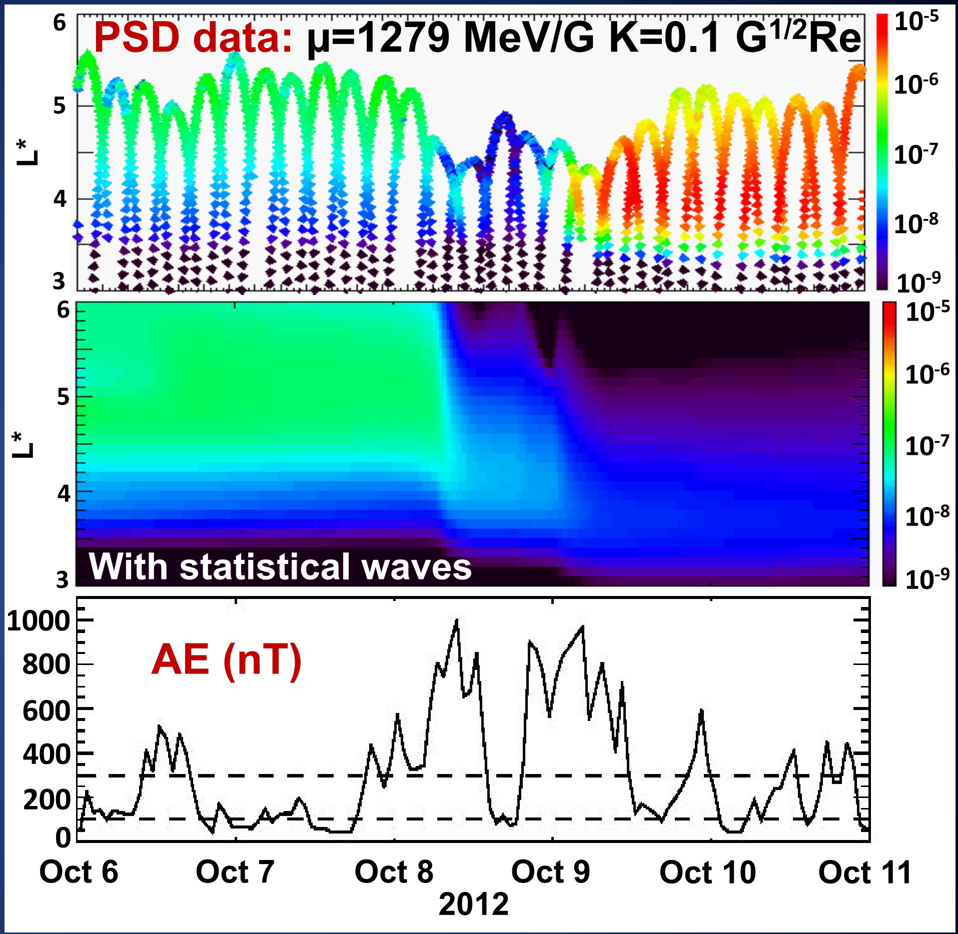
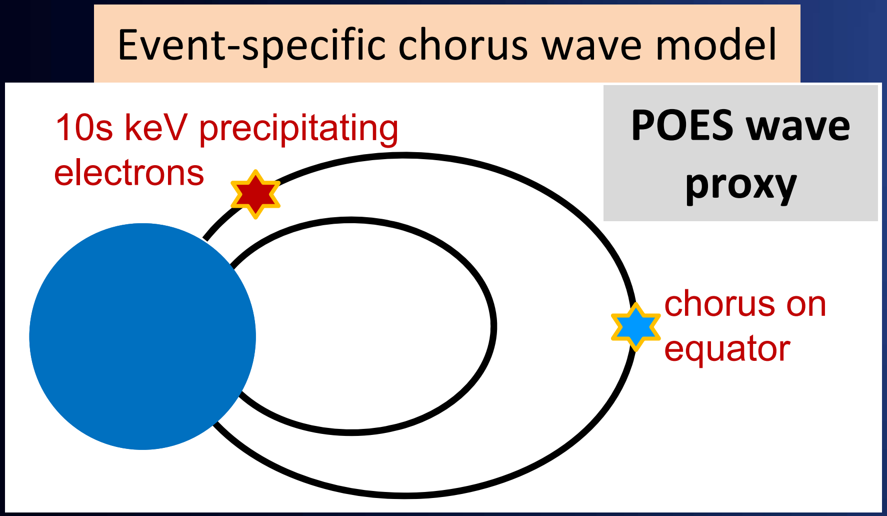
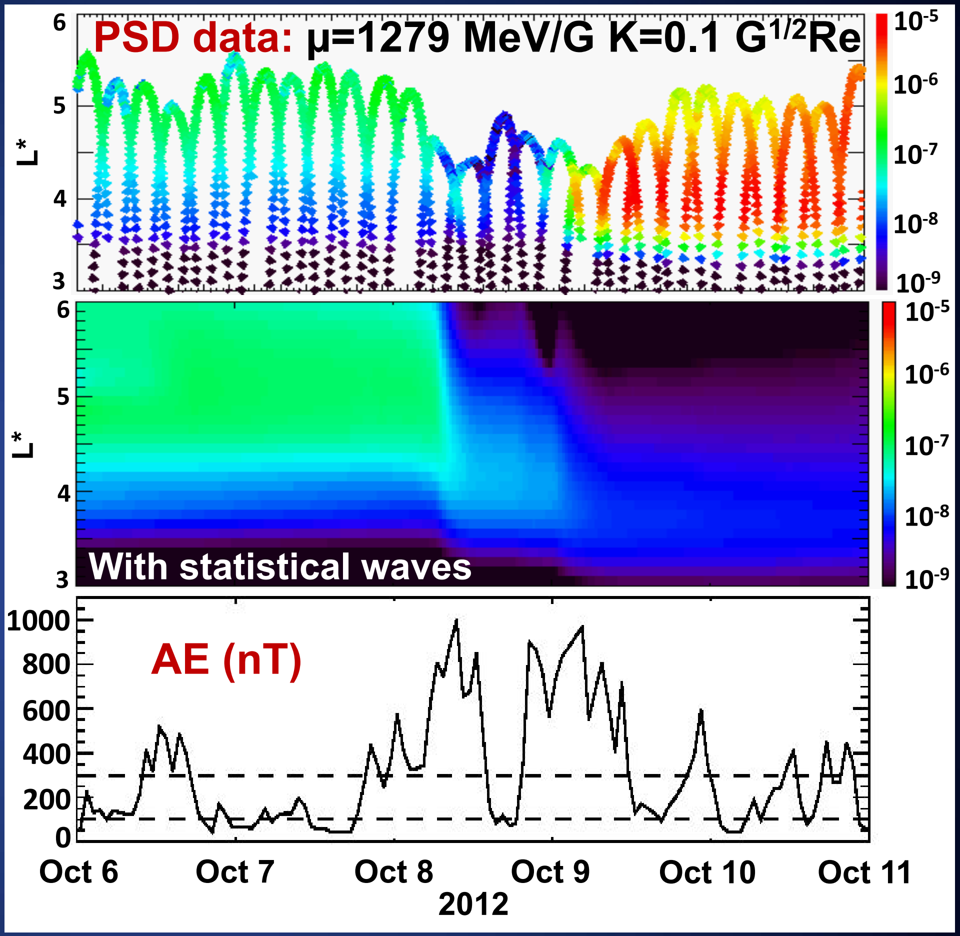




3D Diffusion Model

- Need event-specific inputs for very strong events.
- [Tu et al., GRL 2014]: DREAM3D
  - Model the strong enhancement during the Oct 2012 storm.
  - Event-specific chorus waves





3D Diffusion Model

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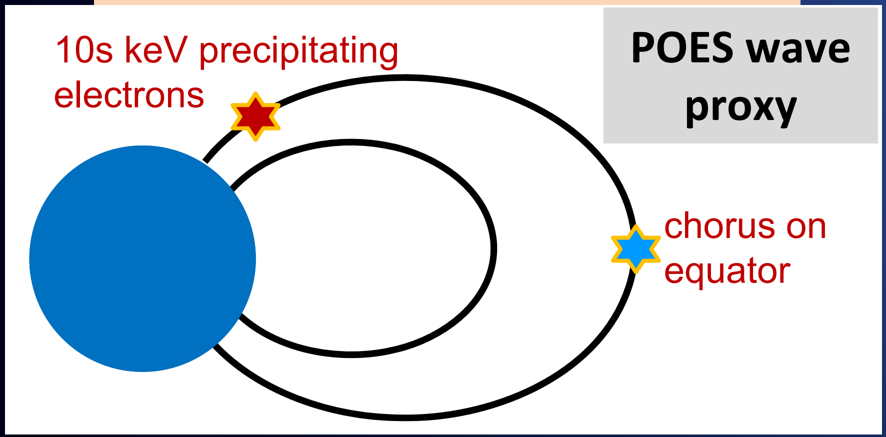
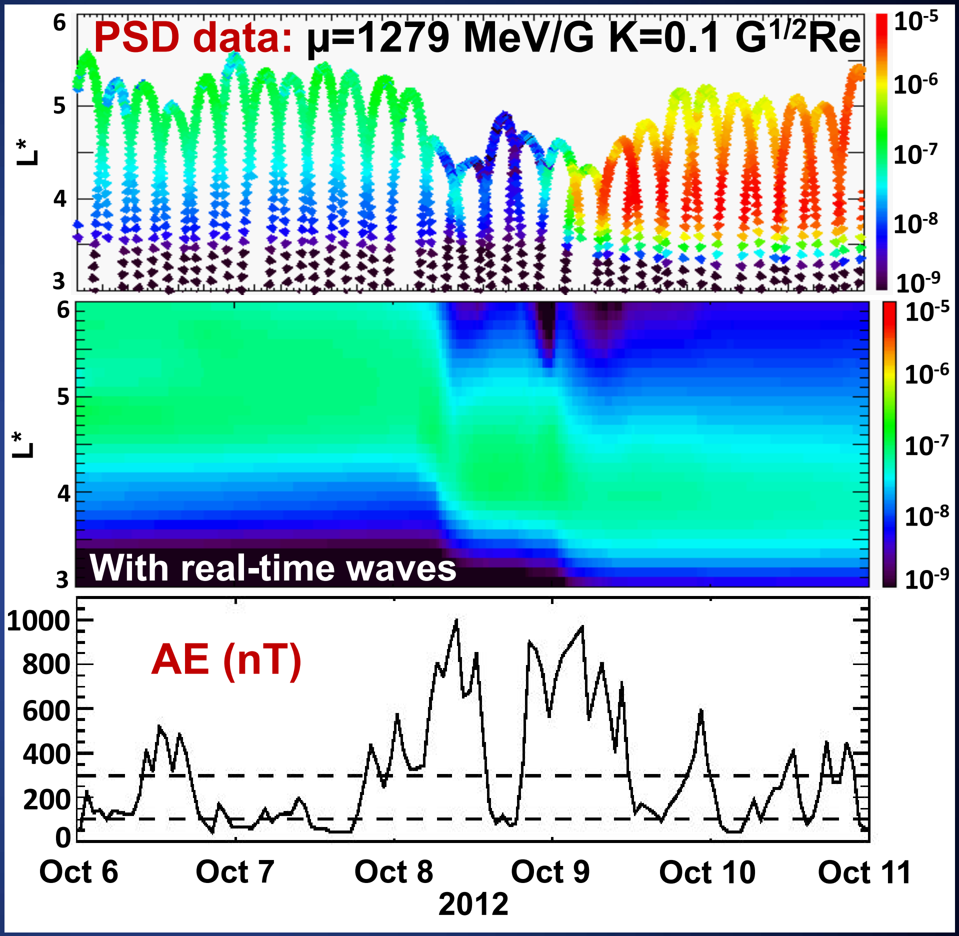
  - Event-specific chorus waves

Event-specific chorus wave model

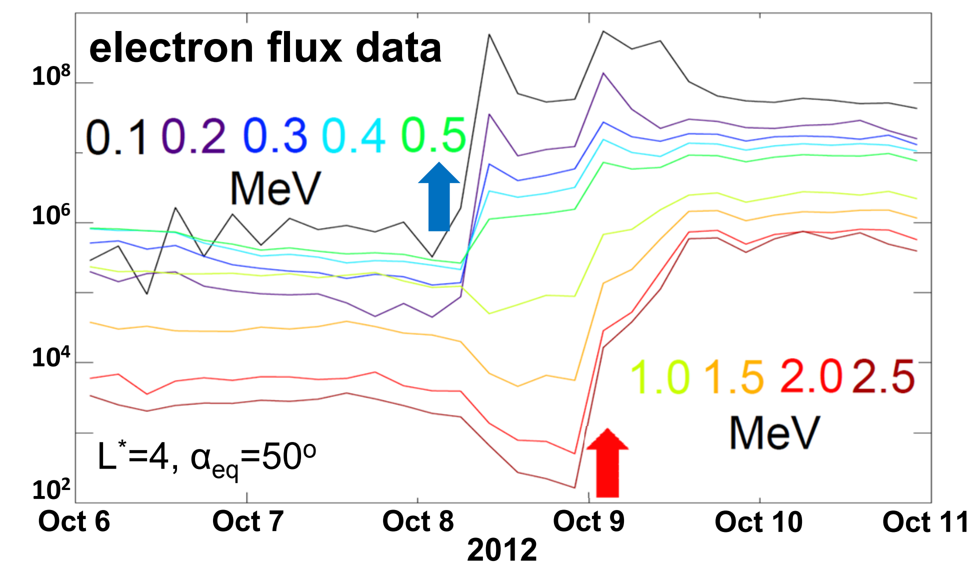


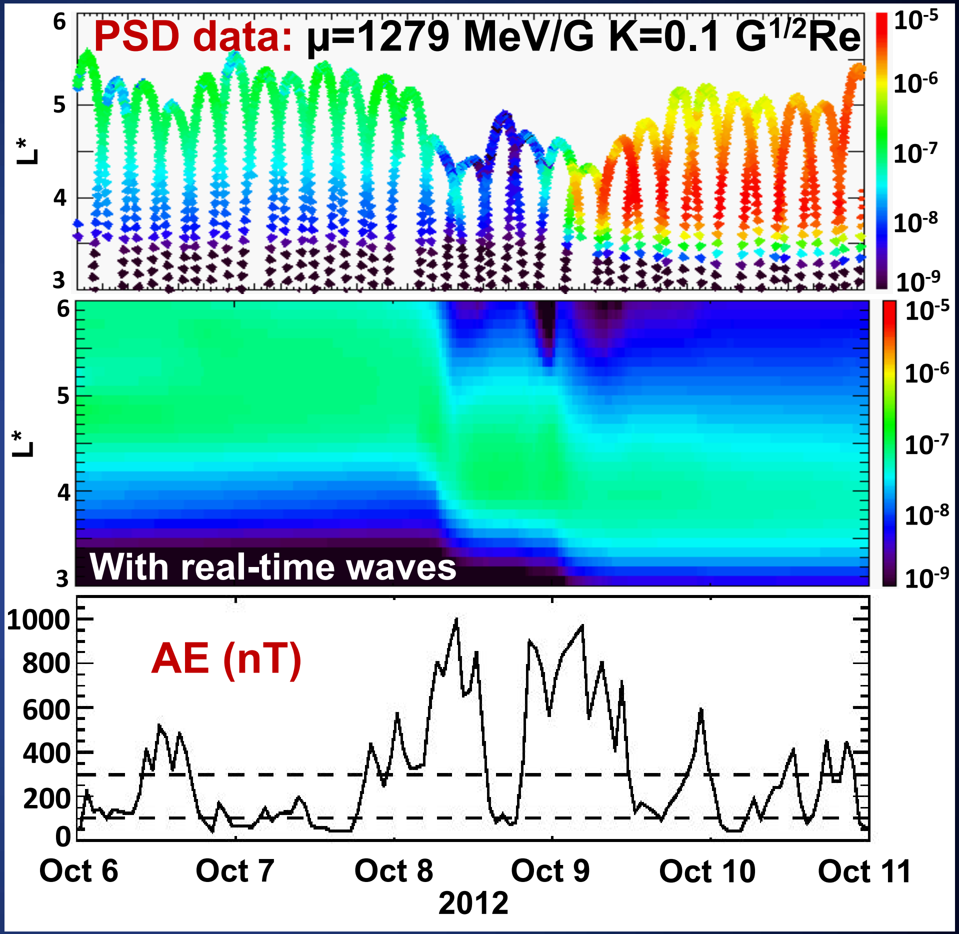


3D Diffusion Model

- Need event-specific inputs for very strong events.
- [Tu et al., GRL 2014]: DREAM3D
  - Model the strong enhancement during the Oct 2012 storm.
  - Event-specific chorus waves
  - Event-specific seed electrons

Event-specific seed population

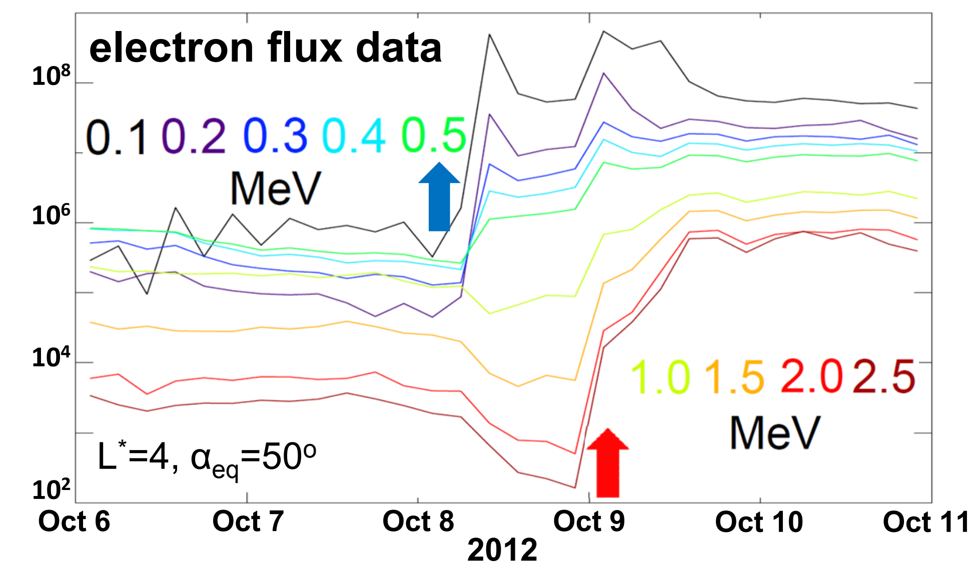


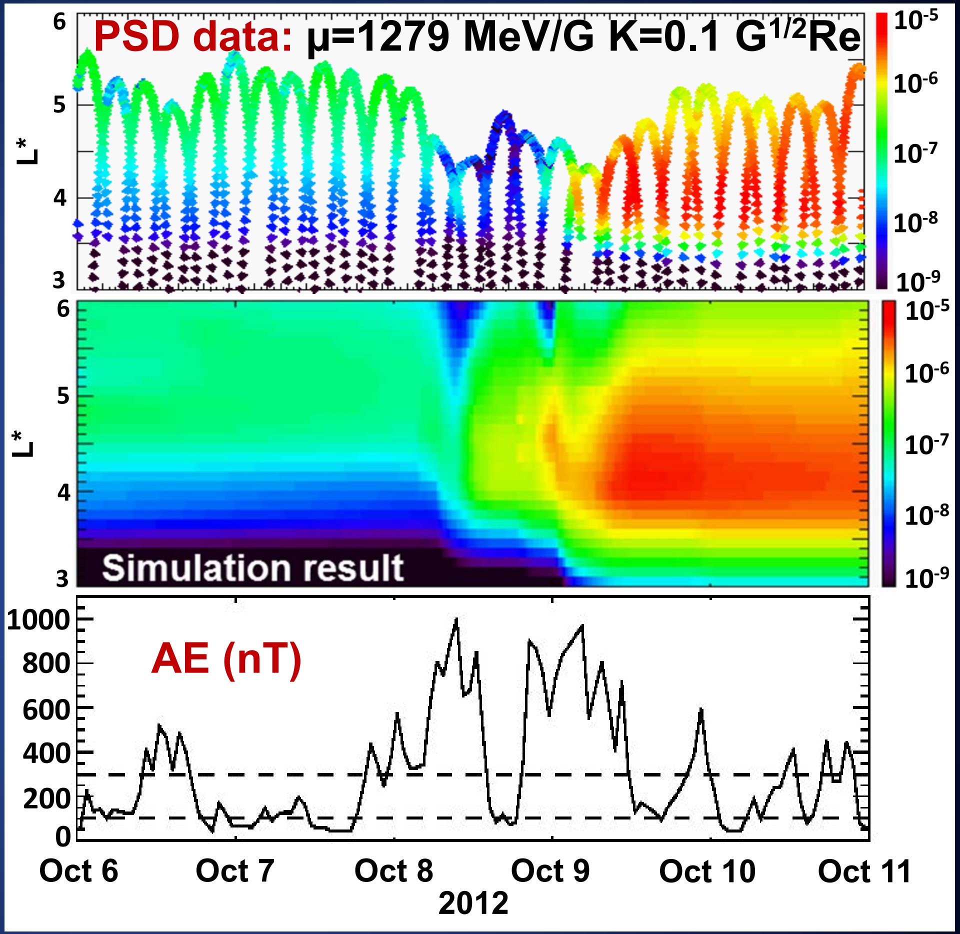


3D Diffusion Model

- Need event-specific inputs for very strong events.
- [Tu et al., GRL 2014]: DREAM3D
  - Model the strong enhancement during the Oct 2012 storm.
  - Event-specific chorus waves
  - Event-specific seed electrons

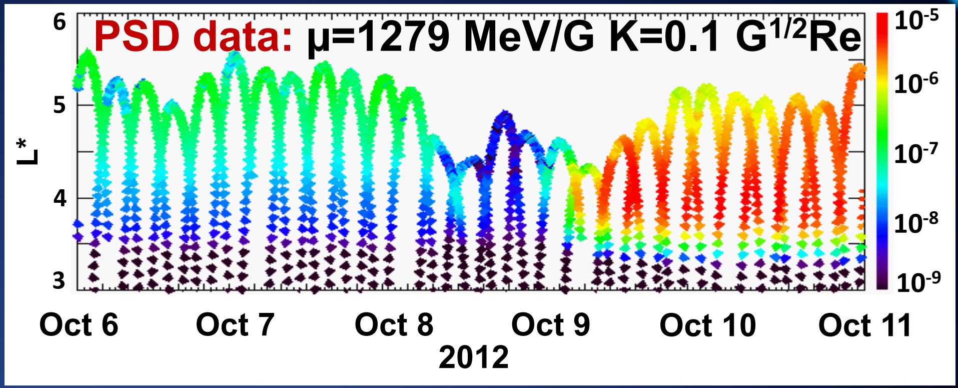
Event-specific seed population





3D Model: Co-operative Physics

- Old: Is radial diffusion the dominant acceleration mechanism or local acceleration?
- New: How do RD, local heating, pitch angle scattering work together to produce the observed acceleration and loss of RB electrons?



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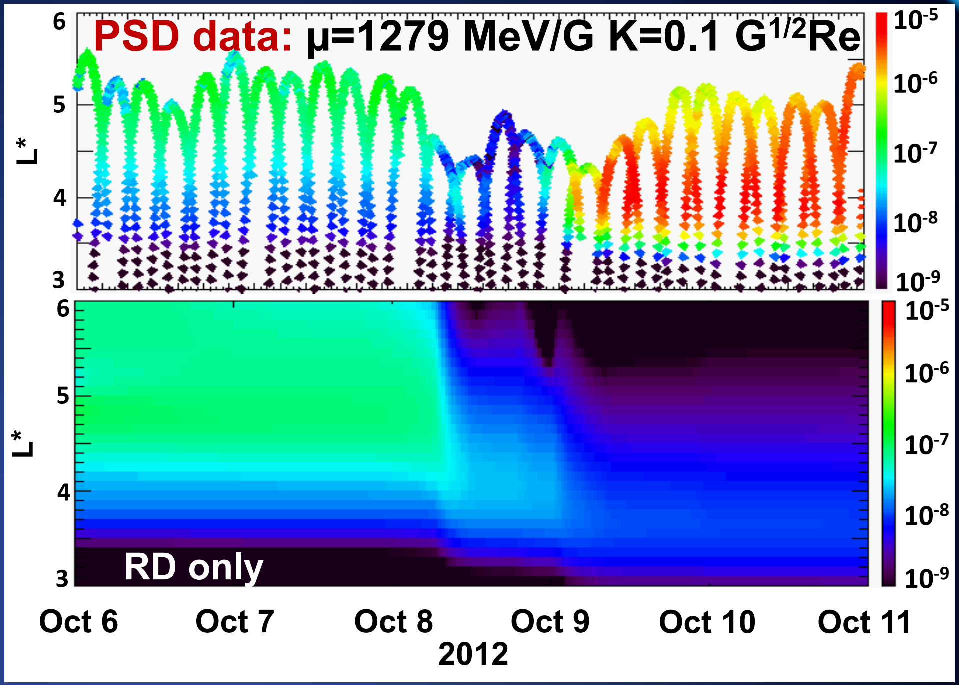

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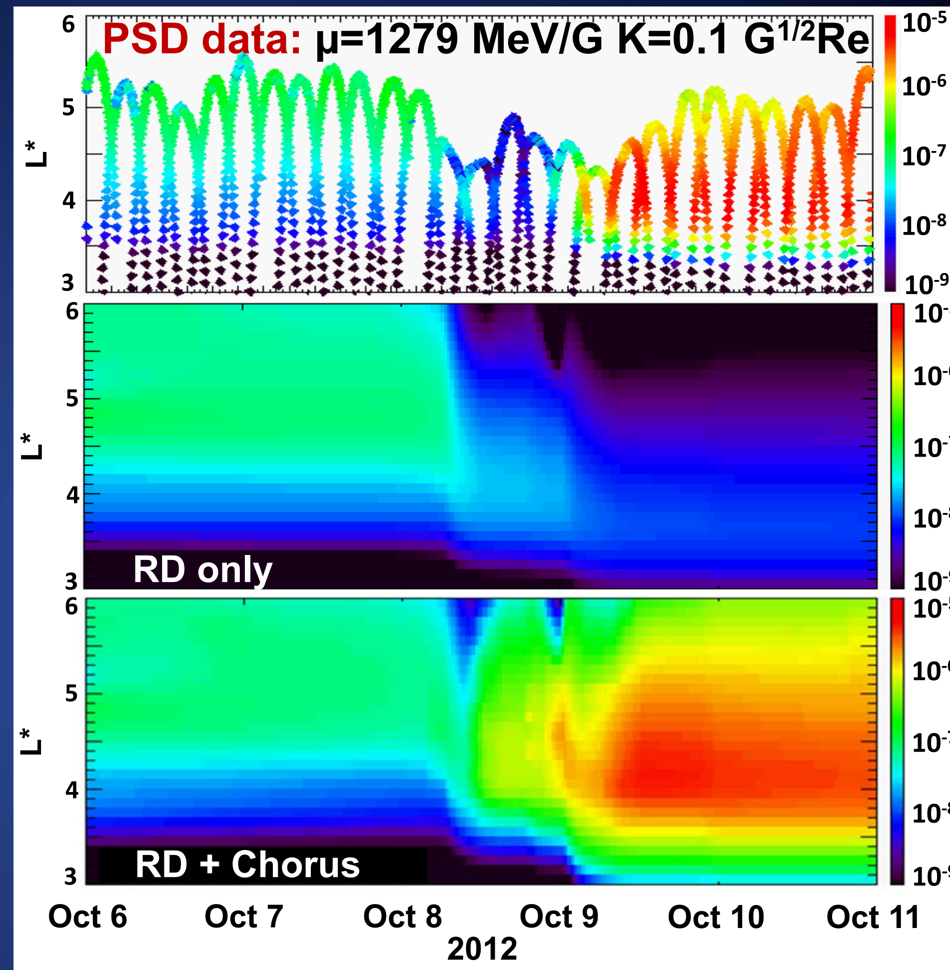


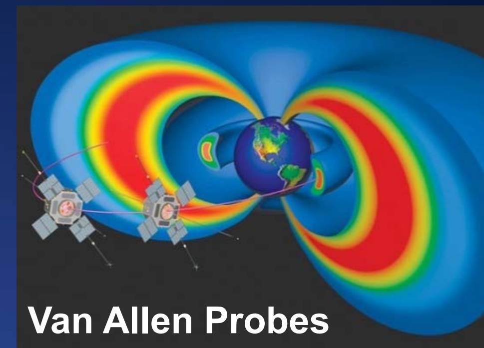
- 3D model implies loss mechanisms: outward RD + precipitation

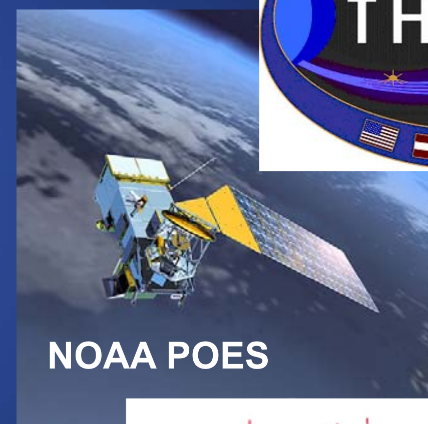
Advance in RB Models

- Great variety!
  - Fokker-Planck diffusion models
  - Convection-Diffusion models
  - Test particles codes
  - PIC & Hybrid codes
- Advances in modeling techniques
  - E.g., 1D diffusion → 2D diffusion → 3D → 4D
- Advances in model inputs:
  - E.g., chorus wave model:

  Static → Dynamic but empirical → Event-specific

  - Made possible by the extensive measurements from multiple missions!



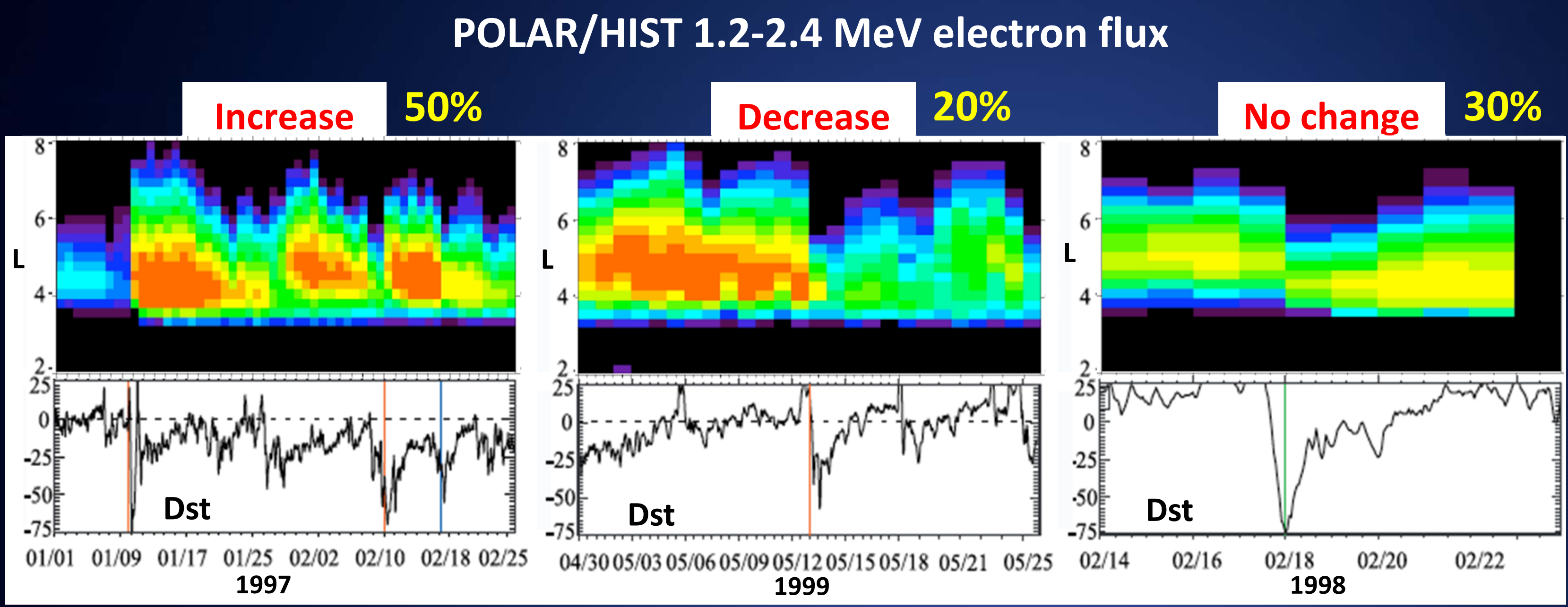


Outline

- Introduction of Radiation Belt Dynamics: Sources and Losses
- Advances in Quantitative RB Modeling: Models and Inputs
- Challenges and Opportunities

Reproduce the Storm Responses

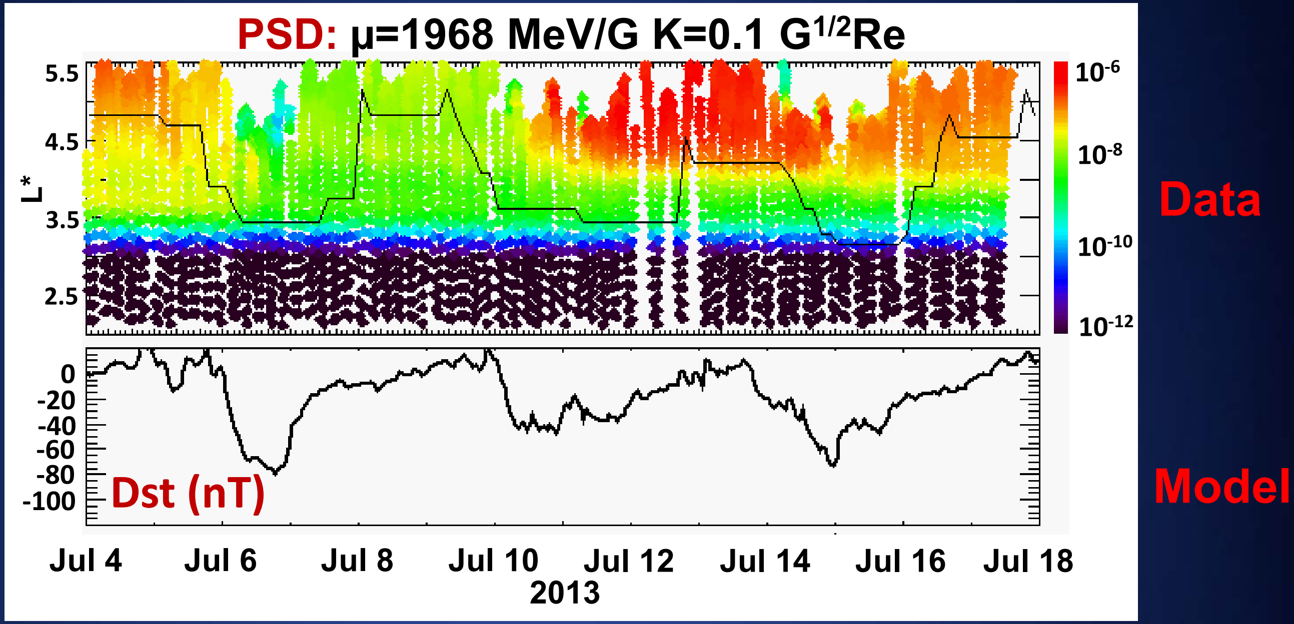
- Complex storm responses of RB electrons:



[Reeves et al., GRL 2003]

Reproduce the Storm Responses

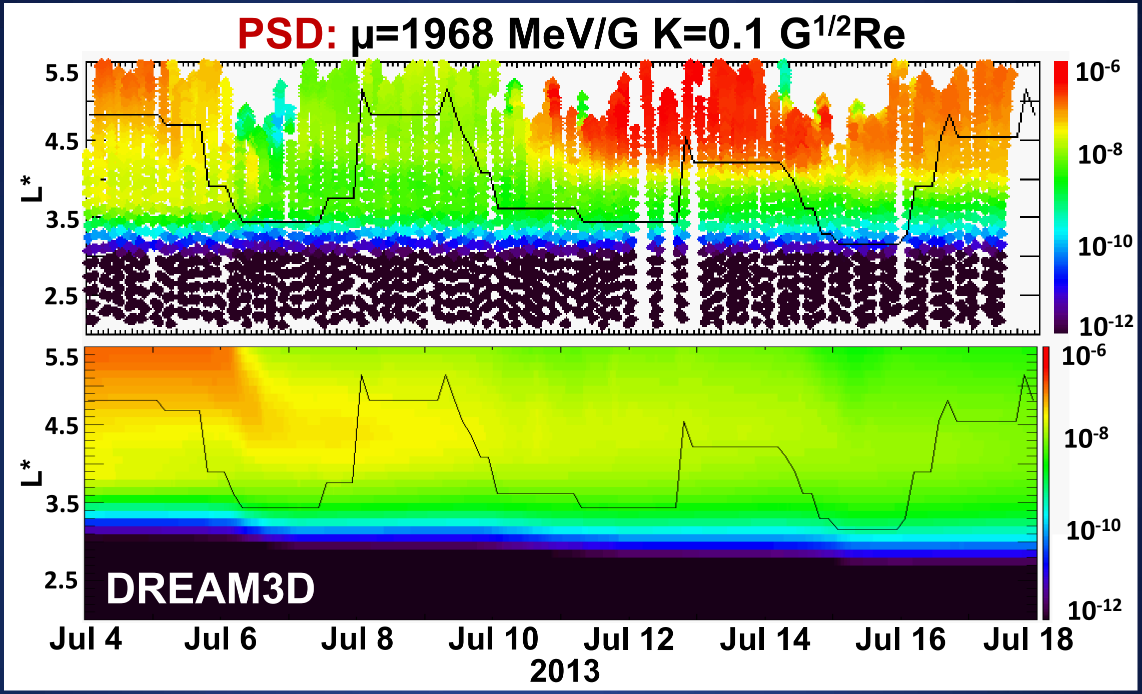
- Complex storm responses of RB electrons:



Reproduce the Storm Responses

- Complex storm responses of RB electrons:

"You have modeled one storm, you have modeled one storm"?

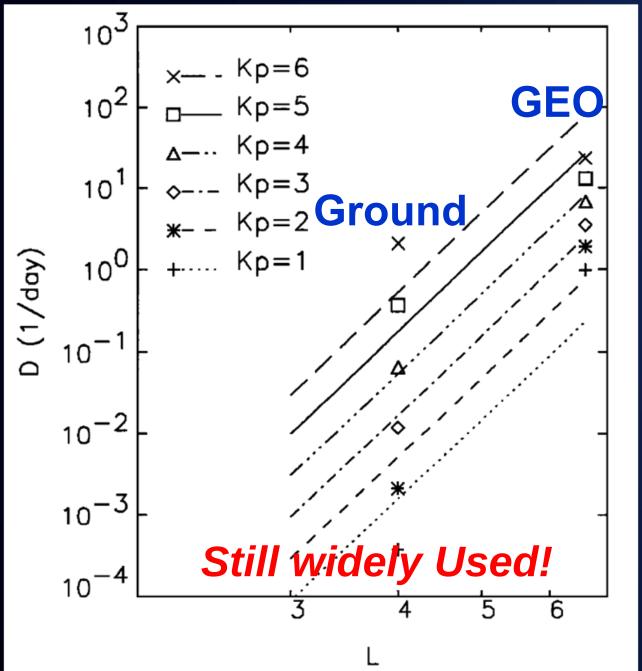


- Challenge: Can we model the complex storm variability and, more importantly, predict the various storm responses?
- Opportunities: Improve the model inputs & Include new physics.

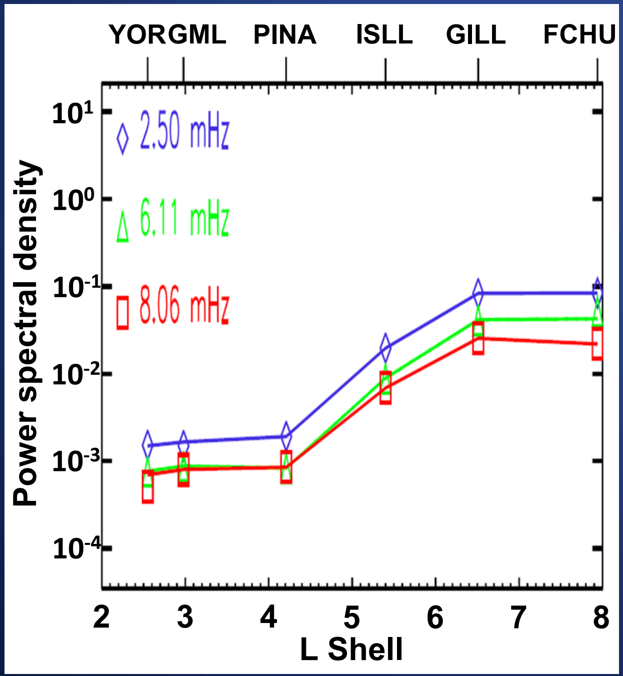
Better Model Inputs

- Current RB models are mature enough, but need better and more accurate model inputs.
- E.g., for diffusion-type models:
  - Radial diffusion coefficient D_{LL}

D_{LL}(Kp): 2 points
[Brautigam and Albert, JGR 2000]

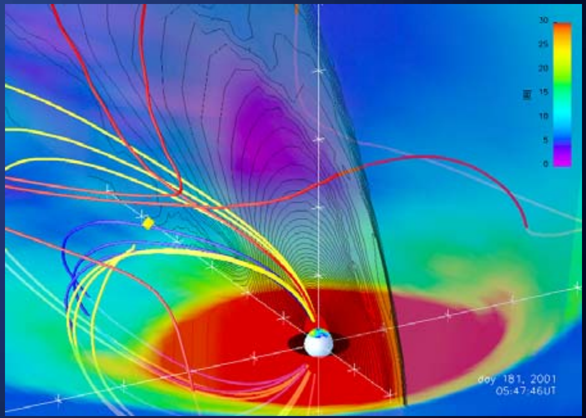


D_{LL}(Kp) [Ozeke et al., JGR 2012]
Multiple ground magnetometers



Event-specific D_{LL}
Global ULF waves from:

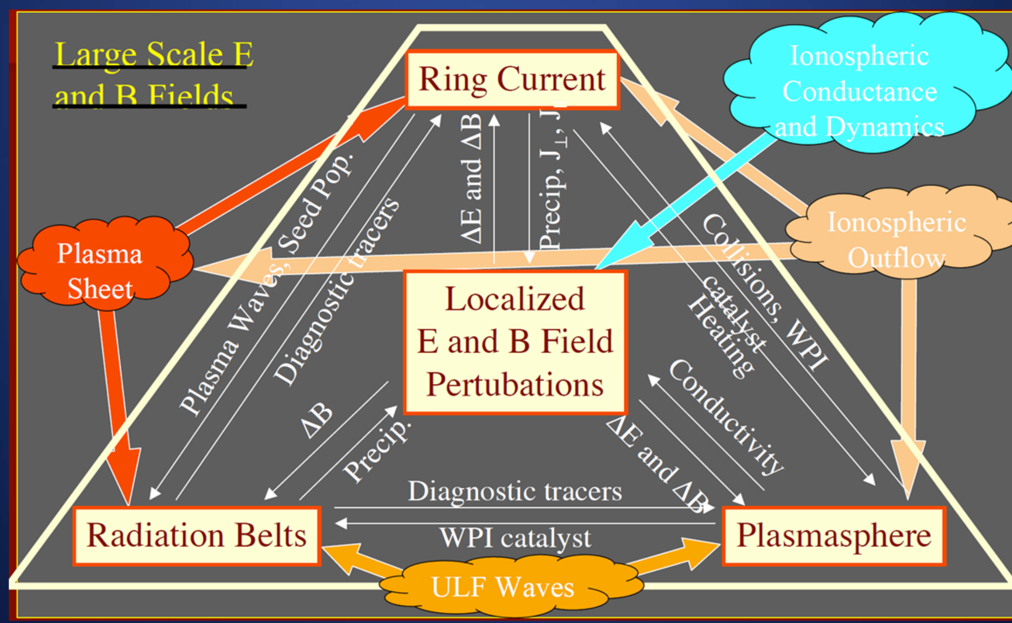
Van Allen Probes
+
Ground magnetometers
+
Global MHD fields



Better Model Inputs

- Current RB models are mature enough, but need better and more accurate model inputs.
- E.g., for diffusion-type models:
  - Radial diffusion coefficient D_{LL}
  - Event-specific and global distribution of various waves
  - Better plasma density and plasmapause models
  - Reliable magnetic field models

Coupling between RB, Ring Current, and Plasmasphere

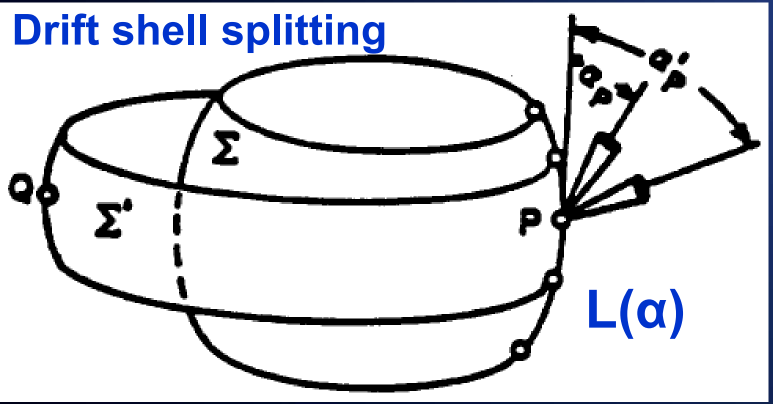


Explore New Physics

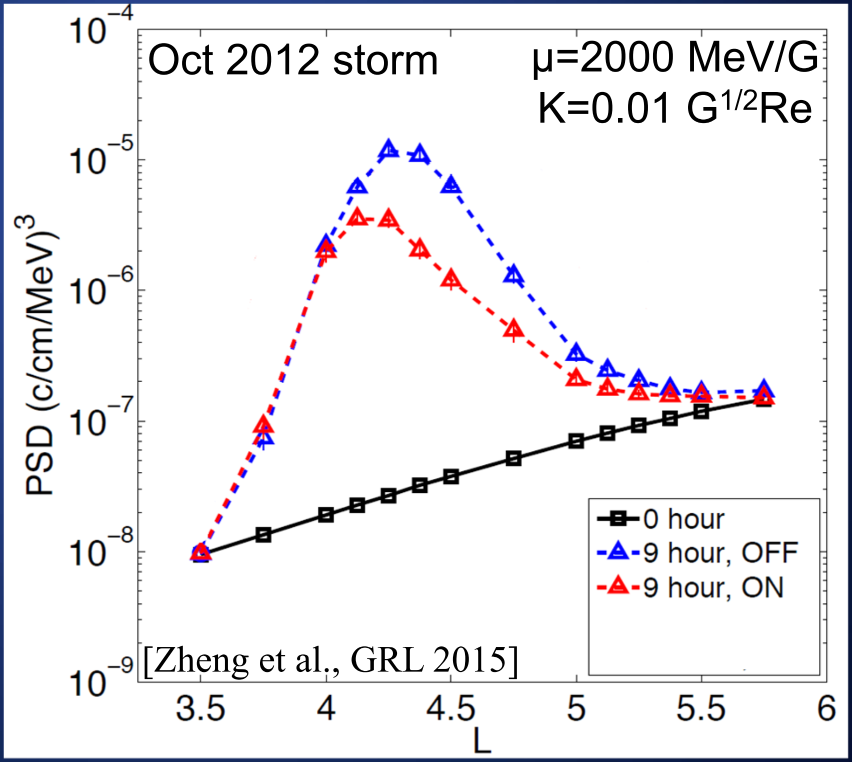
- Important to study new physics and quantify its importance.
- E.g., drift shell splitting → anomalous diffusion [O'Brien, GRL 2014]
- Effects of drift shell bifurcation
- Nonlinear, non-resonant wave particle interactions

Full diffusion tensor

$$\begin{pmatrix} D_{\mu\mu} & D_{\mu K} & D_{\mu L} \\ D_{K\mu} & D_{KK} & D_{KL} \\ D_{L\mu} & D_{LK} & D_{LL} \end{pmatrix}$$



Effects on RB electrons from REM model

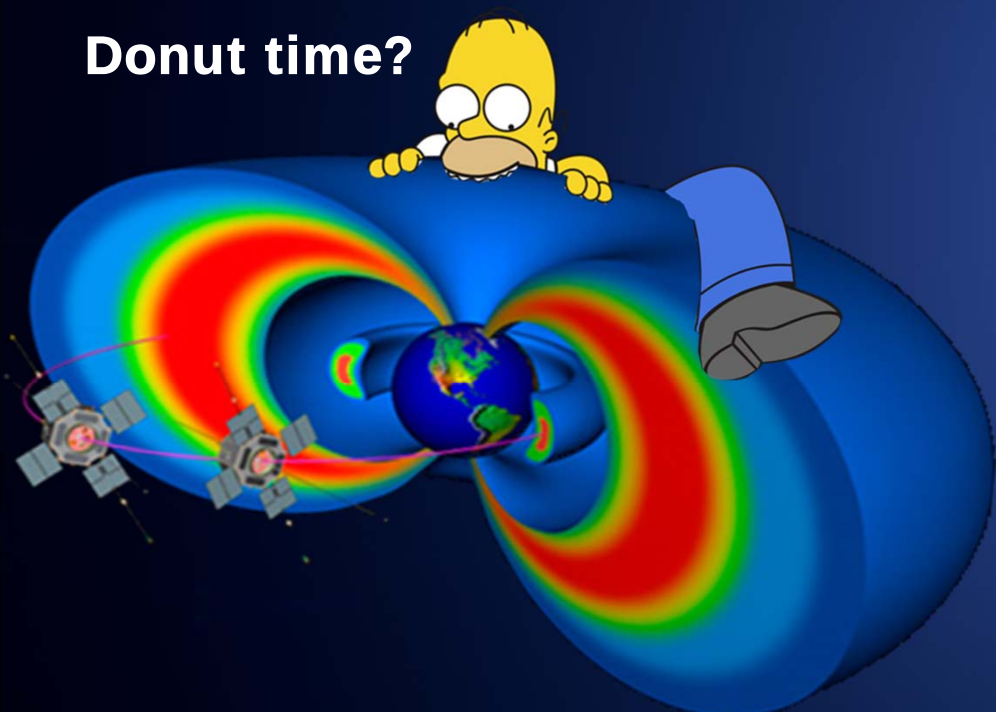


GEM FG: QARBM (Pronounce: “CHARM”)

- Focus Group of “Quantitative Assessment of Radiation Belt Modeling” (2014-2018)
- Co-chairs: Jay Albert, Wen Li, Steve Morley, Weichao Tu
- Goals:
  - Bring together the current state-of-the-art RB models and new physics.
  - Develop event-specific and global RB model inputs (waves, plasma, seed population, magnetic fields).
  - Combine all these components to achieve a quantitative assessment of the RB modeling by validating against real-time measurements.
- Activities:
  - A review of current RB models and required inputs (last year).
  - “RB buildup” and “RB dropout” Challenges (starting this year).
  - Joint activities with other FGs.

Summary and Conclusions

Thank you!



- Radiation belt is a very dynamic and complicated system due to the delicate balance between source, transport, and loss.
- Great progress has been made in quantitative modeling of radiation belt dynamics:
  - Advances in state-of-the-art models
  - Advances in model inputs
- Challenges on reproducing the complex storm responses, improving model inputs, and exploring new physics.