Numerical Modeling of Radiation Belt Dynamics

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Outline

1. Introduction
2. Fokker-Planck equation
3. From 1D simulation to 3D
4. How can you run diffusion code? (NASA CCMC)
5. 3D simulation on a single grid
6. Practical results
7. 4D simulations

INTRODUCTION

Radiation Belts

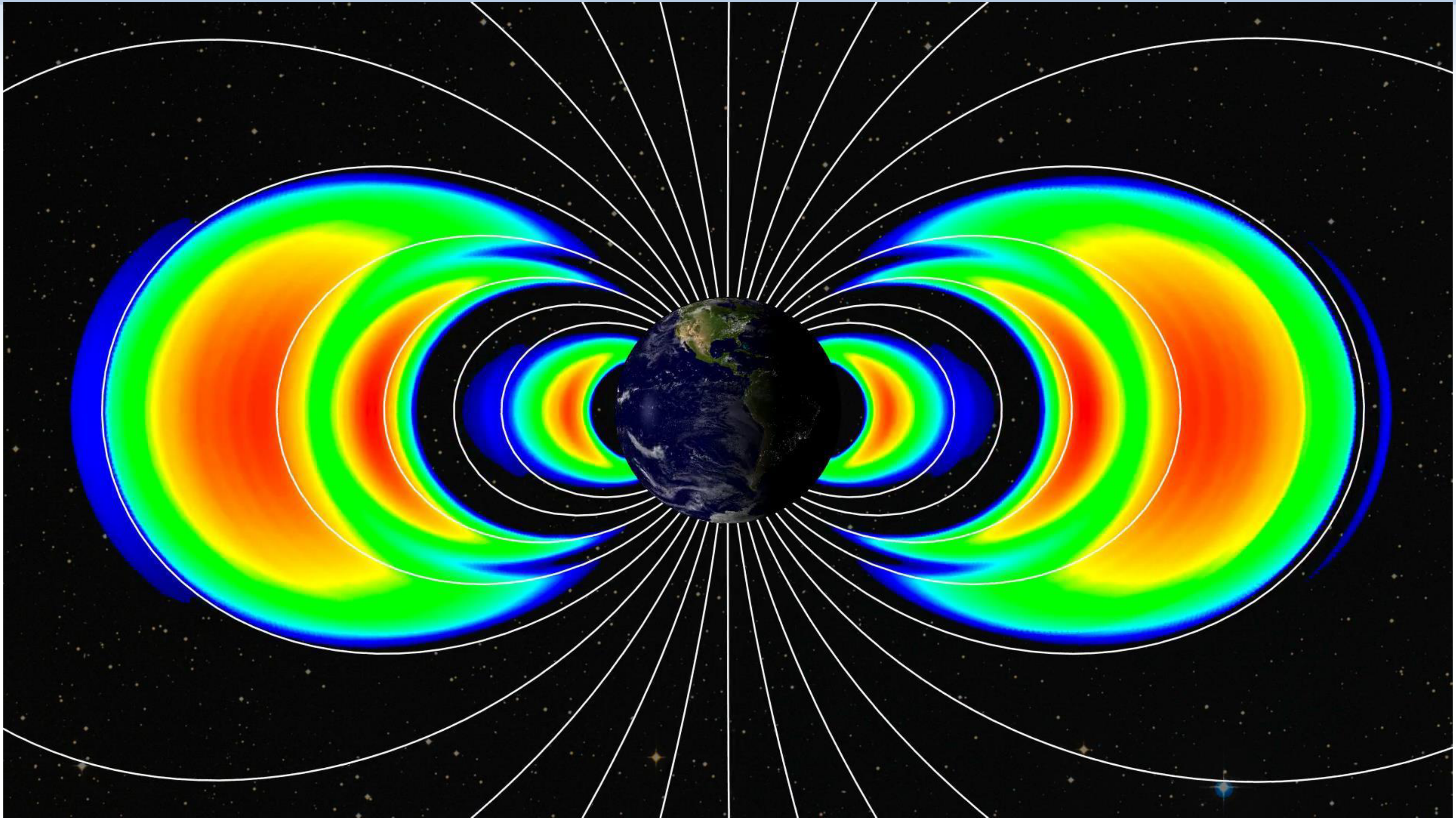
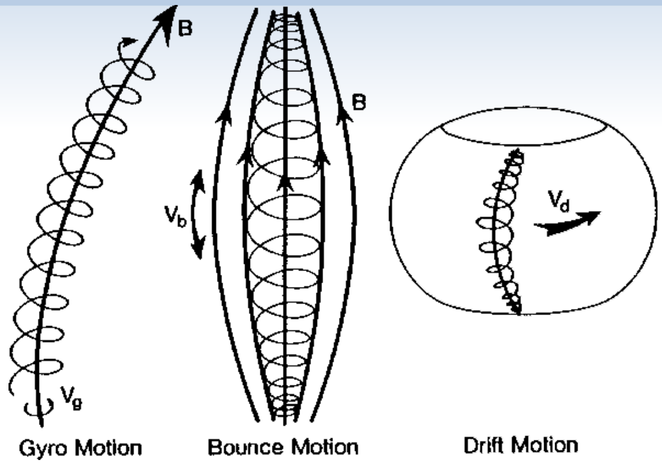


Image Credit: APL, NASA

Adiabatic invariants of the particle motion



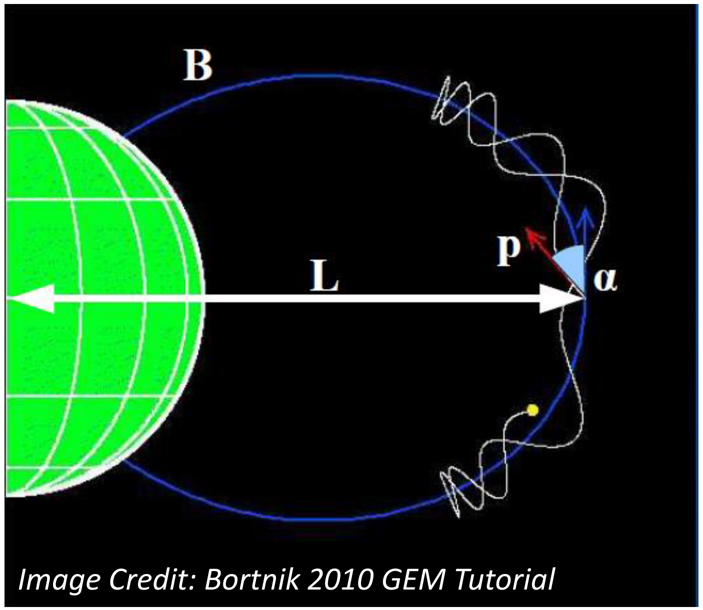


Image Credit: Bortnik 2010 GEM Tutorial

- The gyration around field lines
- The magnetic momentum invariant

$$\mu = \frac{p_\perp^2}{2m_0B} = \frac{p^2\sin^2(\alpha)}{2m_0B}$$

- The bounce motion between magnetic mirror points
- The longitudinal invariant

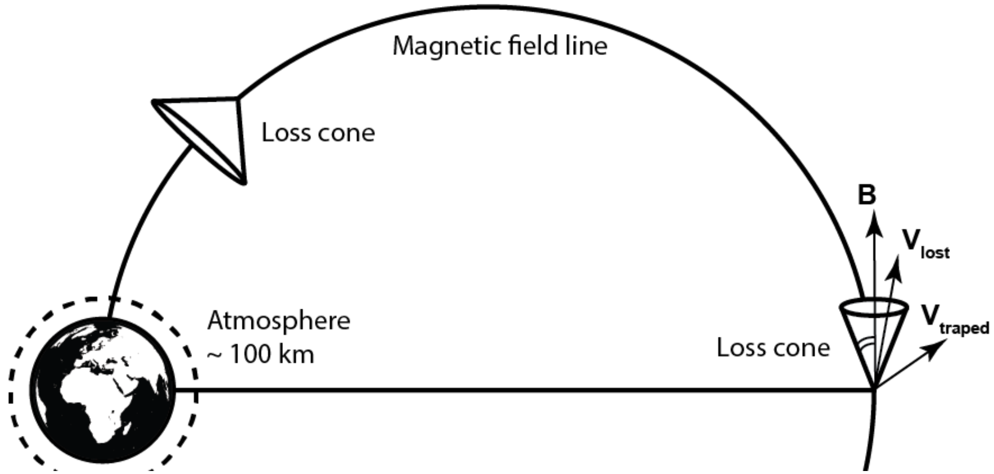
$$J = \oint p_\parallel\, ds = 2\int_{s_s}^{s_n} p_\parallel ds$$

$$K = \frac{J}{\sqrt{8m_0\mu}} = \int_{s_s}^{s_n} \sqrt{B_m - B(s)}ds$$

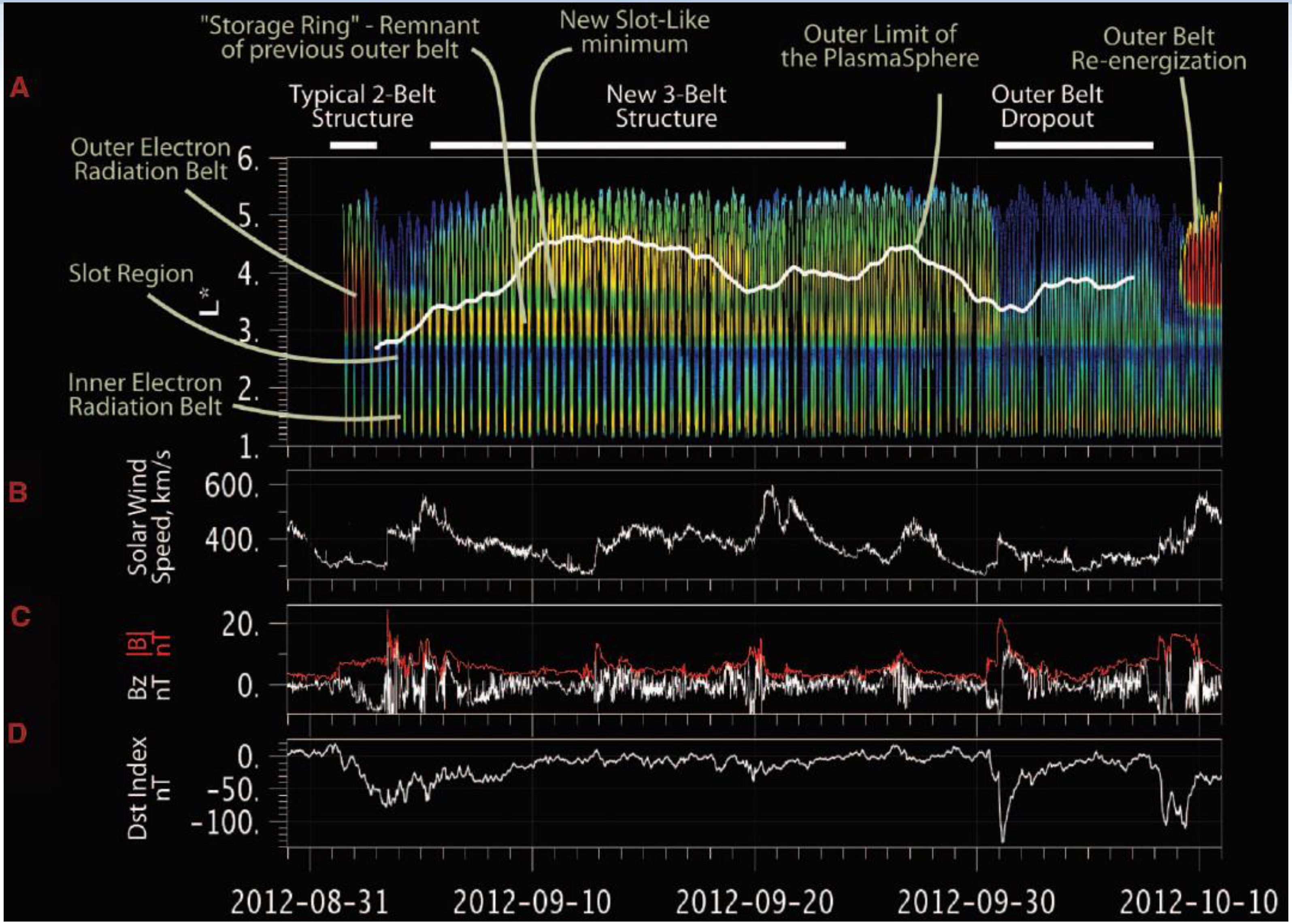
- The periodic azimuthal drift in the non-uniform geomagnetic field
- The flux invariant

$$\Phi = \oint \vec{B} d\vec{A}$$

$$L^* = \frac{2\pi M}{\Phi R_E} \sim \frac{1}{\Phi}$$

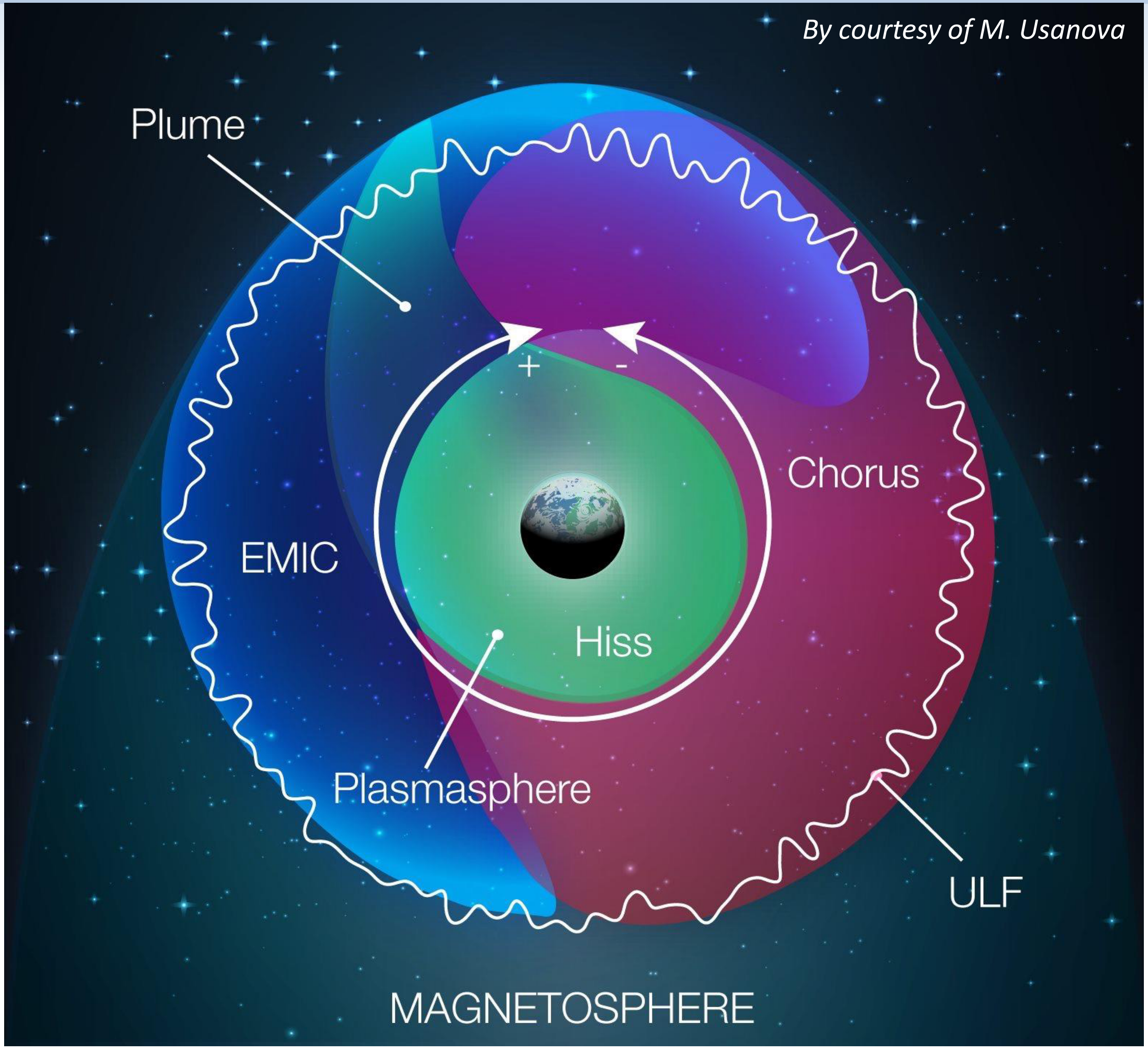


Radiation belts dynamics



Baker et al, 2013, Science

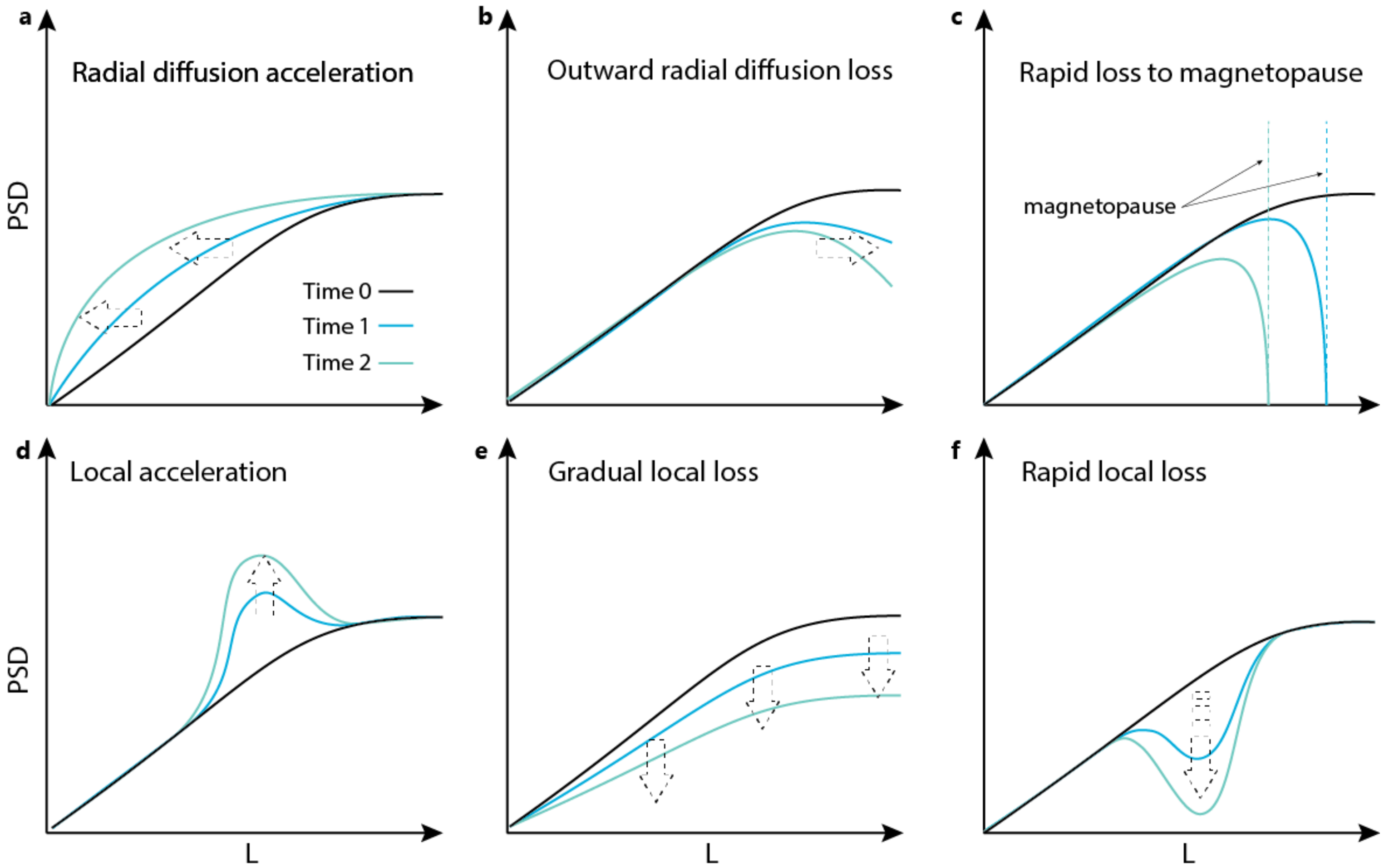
Waves in magnetosphere



Phase Space Density

$$f = \frac{dN}{dx \cdot dy \cdot dz \cdot dp_x \cdot dp_y \cdot dp_z} = \frac{dN}{p^2 \cdot dA \cdot dt \cdot d\Omega \cdot dE} \equiv \frac{j}{p^2}$$

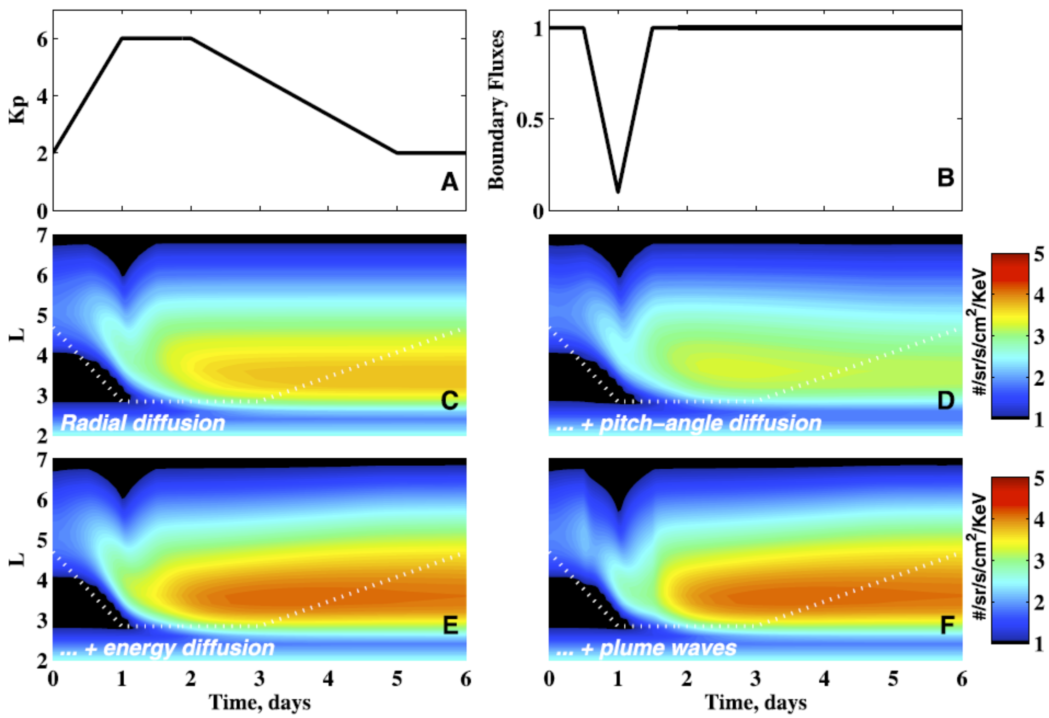
Lyons and Williams, 1983



Flux vs PSD (Idealized geomagnetic storm)

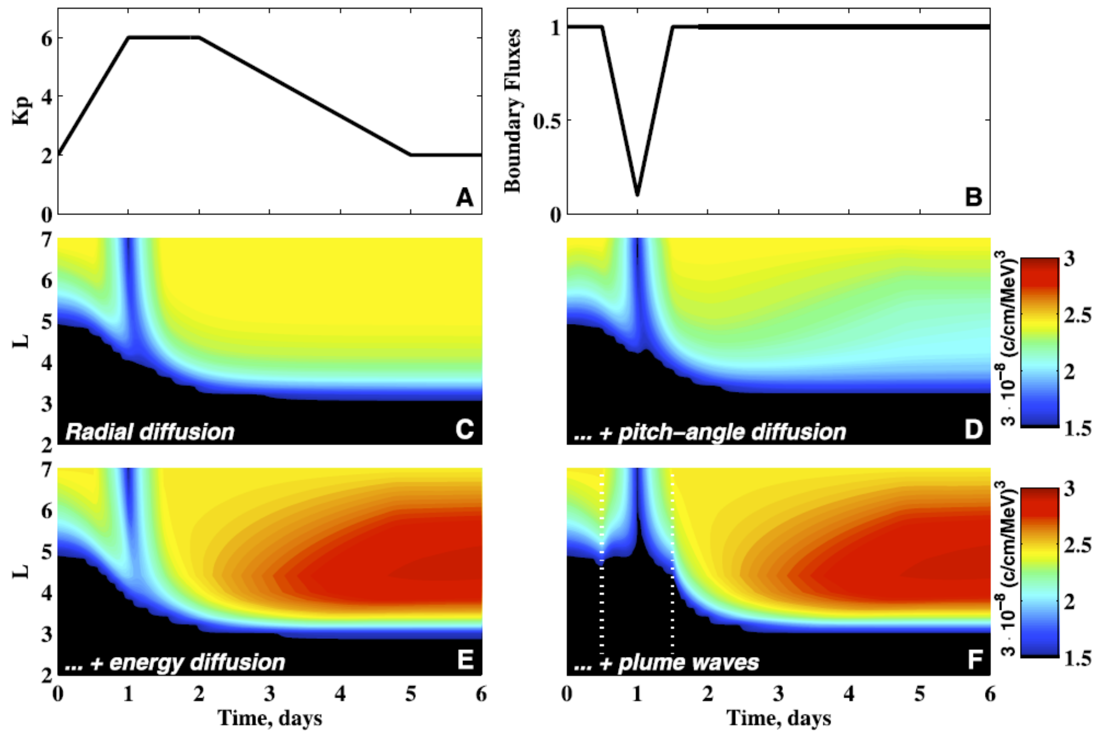
Flux. Fixed Energy (E) and pitch angle (α)

$$J = \frac{dN}{dA \cdot dt \cdot d\Omega \cdot dE}$$



PSD. Fixed adiabatic invariants μ and K

$$f = \frac{j}{p^2}$$



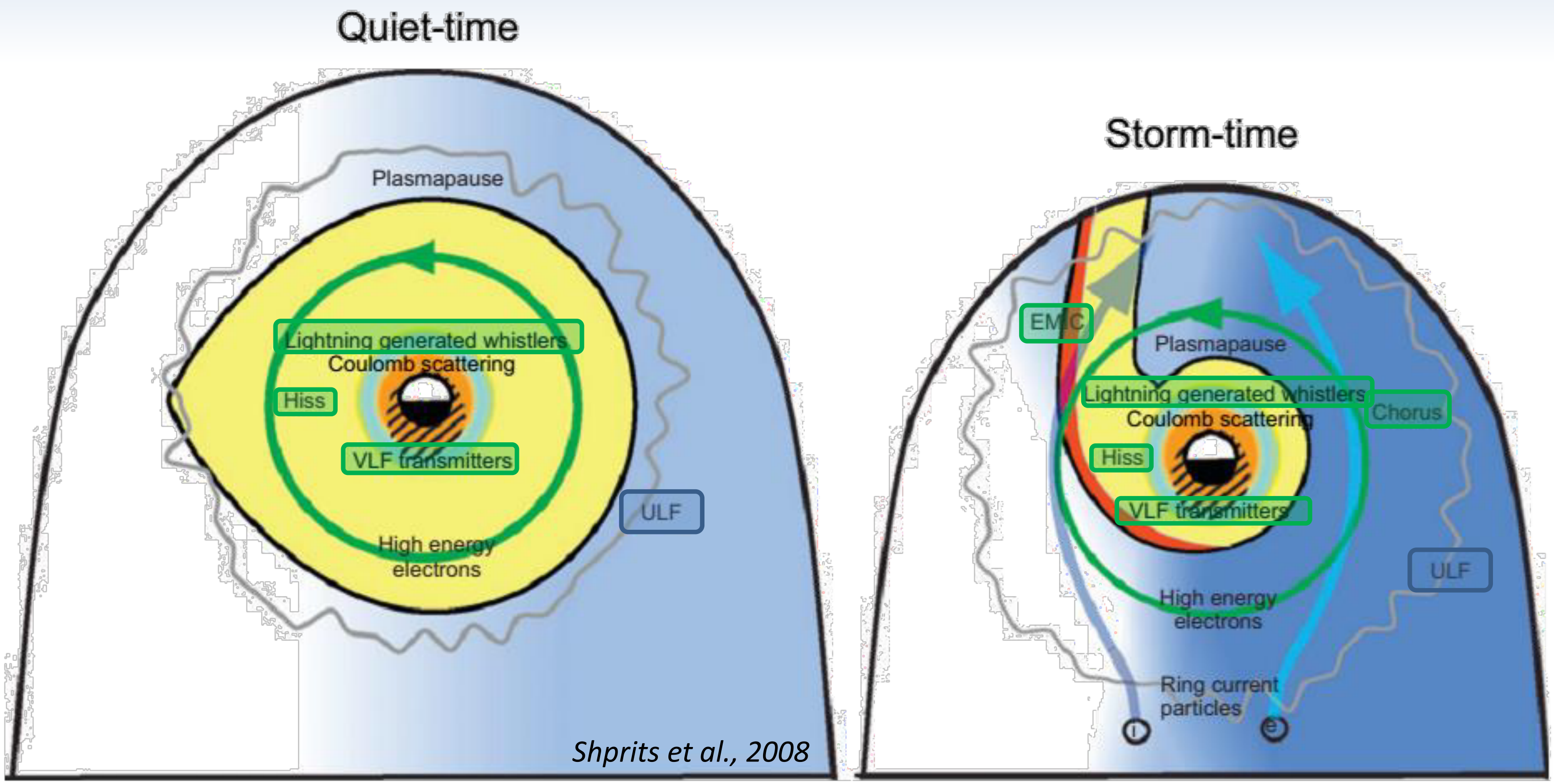
Shprits et al., 2009

FOKKER-PLANCK EQUATION

Diffusion codes that solve Fokker-Planck equation

- **Salammbo**, [*Beutier and Boscher*, 1995]
  - The first radiation belt code capable of solving the 3D Fokker-Planck equation
  - *Varotsou et al*. [2005] and *Horne et al.* [2006] added pitch-angle and energy scattering by equatorial chorus waves
- Pitch Angle and Energy Diffusion of Ions and Electrons (**PADIE**) [Glauert and Horne, 2005] and developed to **BAS-RBM** Radiation Belts Code [Glauert et al., 2014].
  - Includes mixed terms.
- Improved atmosphere interactions (**RAM**) model, [Jordanova and Miyoshi, 2005]
  - Convective model with radial diffusion due to the magnetic component of the ULF waves and parameterized losses
- Multidimensional quasi-linear diffusion code, [Albert, 2004], [Albert and Young, 2005]
  - Cross diffusion term vanishes
- Radiation Belt Environment (**RBE**) model [Fok et al. 2008]
  - Magnetospheric differential convection associated with changes in the electric field, electron loss, and acceleration due to wave-particle resonant interaction with equatorial chorus waves in the *Tsyganenko and Sitnov* [2005] magnetic field model and *Weimer* [2001] electric field model
- Versatile Electron Radiation Belt (**VERB**) code [Shprits et al, 2008, Subbotin and Shprits, 2009]
  - VERB code is a useful tool for space weather forecasting and nowcasting of the relativistic electron environment. The computational efficiency of the code makes it also appropriate for future use with data assimilation tools to specify the state of the radiation environment and correct imperfect models
- Dynamic Radiation Environment Assimilation Model: **DREAM** [Reeves et al, 2012]
  - **DREAM3D** code [*Tu et al*., 2013]
  - includes radial, pitch angle, and momentum diffusion and mixed pitch angle-momentum diffusion, which are driven by dynamic wave databases from the statistical CRRES wave data, including plasmaspheric hiss, lower-band, and upper-band chorus
- Storm-time evolution of electron radiation belt (**STEERB**) [Su et al., 2010]
  - Includes coulomb collisions, radial diffusion due to magnetic and electric field perturbations, and local pitch angle, energy, and cross-pitch angle-energy diffusion due to various wave-particle interactions.
- **Salammbo 3-D**, [Varotsou et al, 2008]
  - 3D diffusion using VERB approach
- **VERB-4D**, *Shprits et al.* [2014]
  - Convection, loss to the asymmetric magnetopause, adiabatic effects, and can use a non-dipole magnetic field.
- Commissariat à l'Energie Atomique **CEVA** code, [Ripoll et al., 2020]

Fokker-Planck Equation



Shprits et al., 2008

- Phase-space density dynamics
- VERB code
- Radial diffusion
- Local diffusion
  - Pitch-angle
  - Energy
  - Mixed-terms
- Loss into atmosphere or magnetopause

Waves:

- ULF

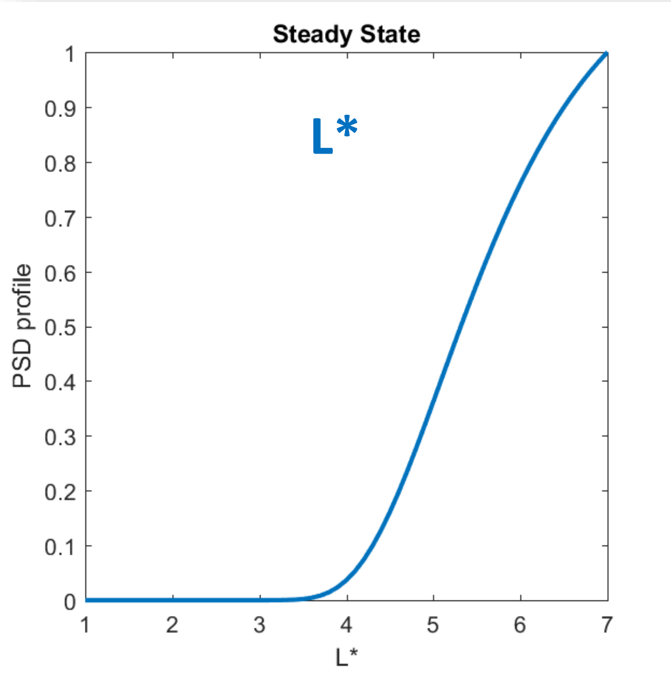
- Hiss
- Chorus
- VLF transmitters
- Lightning whistlers
- EMIC

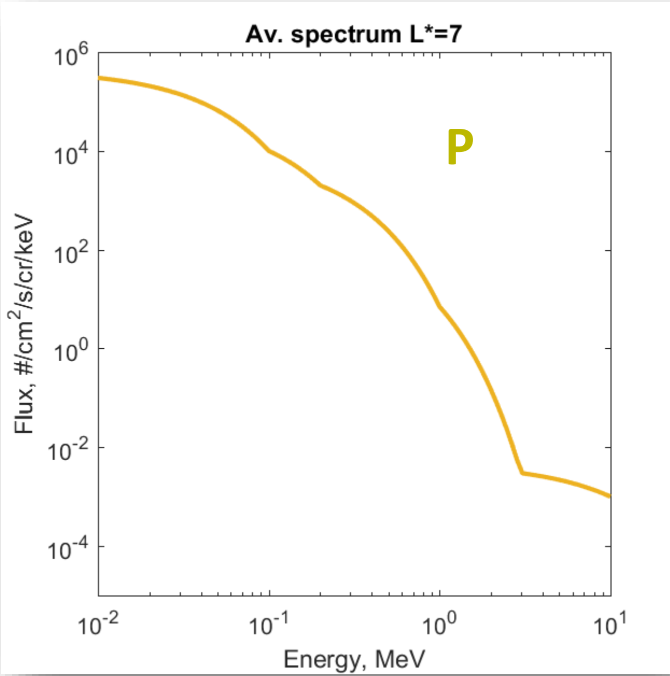
$$\frac{\partial f}{\partial t} = L^{*2}\frac{\partial}{\partial L^*}\Big|_{\mu,J}\frac{1}{L^{*2}}D_{L^*L^*}\frac{\partial f}{\partial L^*}\Big|_{\mu,J} + \frac{1}{p^2}\frac{\partial}{\partial p}\Big|_{\alpha_0,L} p^2\left(D_{pp}\frac{\partial}{\partial p}\Big|_{\alpha_0,L} f + D_{p\alpha_0}\frac{\partial}{\partial \alpha_0}\Big|_{p,L} f\right)$$
$$+\frac{1}{T(\alpha_0)\sin(2\alpha_0)}\frac{\partial}{\partial \alpha_0}\Big|_{p,L} T(\alpha_0)\sin(2\alpha_0)\left(D_{\alpha_0\alpha_0}\frac{\partial}{\partial \alpha_0}\Big|_{p,L} f + D_{\alpha_0 p}\frac{\partial}{\partial p}\Big|_{\alpha_0,L} f\right) - \frac{f}{\tau}$$

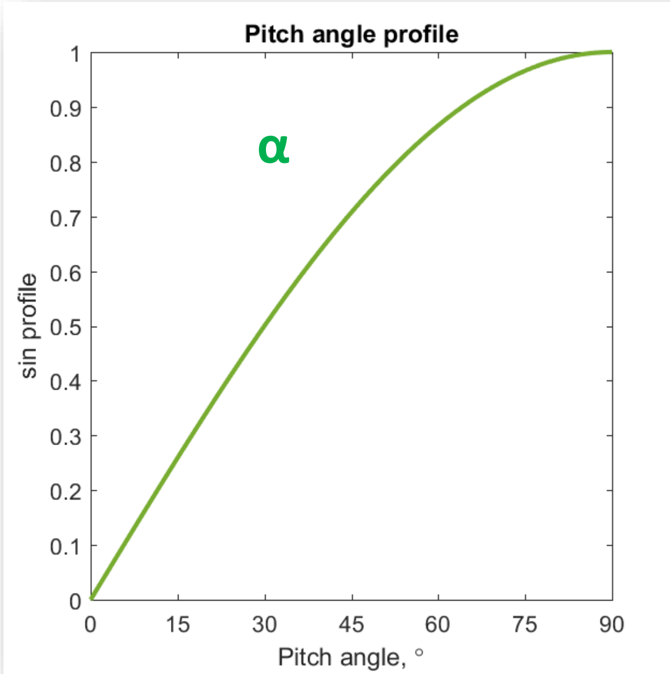
Initial conditions

$$\frac{\partial f}{\partial t} = L^{*2}\frac{\partial}{\partial L^*}\Big|_{\mu,J}\frac{1}{L^{*2}}D_{L^*L^*}\frac{\partial f}{\partial L^*}\Big|_{\mu,J} - \frac{f}{\tau_{param}} = 0$$

τ_{param} is an imitation of local loss processed due to wave-particle interaction with hiss, chorus, etc.







$$\frac{\partial f}{\partial t} = L^{*2}\frac{\partial}{\partial L^*}\Big|_{\mu,J}\frac{1}{L^{*2}}D_{L^*L^*}\frac{\partial f}{\partial L^*}\Big|_{\mu,J} + \frac{1}{p^2}\frac{\partial}{\partial p}\Big|_{\alpha_0,L^*} p^2\left(D_{pp}\frac{\partial}{\partial p}\Big|_{\alpha_0,L^*} f + D_{p\alpha_0}\frac{\partial}{\partial \alpha_0}\Big|_{p,L^*} f\right)$$
$$+\frac{1}{T(\alpha_0)\sin(2\alpha_0)}\frac{\partial}{\partial \alpha_0}\Big|_{p,L^*} T(\alpha_0)\sin(2\alpha_0)\left(D_{\alpha_0\alpha_0}\frac{\partial}{\partial \alpha_0}\Big|_{p,L^*} f + D_{\alpha_0 p}\frac{\partial}{\partial p}\Big|_{\alpha_0,L^*} f\right) - \frac{f}{\tau}$$

Boundary Conditions

L*

- The absence of electrons at the atmospheric level at L = 1
- PSD = const*b(t), for L* upper boundary due to observed variation

P, Energy

- PSD = const, for low-energy electrons to represent a balance between a convective source and losses.
- The absence of very high-energy electrons

α

- Zero gradient at 90° accounts for the flat pitch angle distribution observed at 90°.
- PSD = 0 at 0° simulates the loss at the atmospheric level and surface.

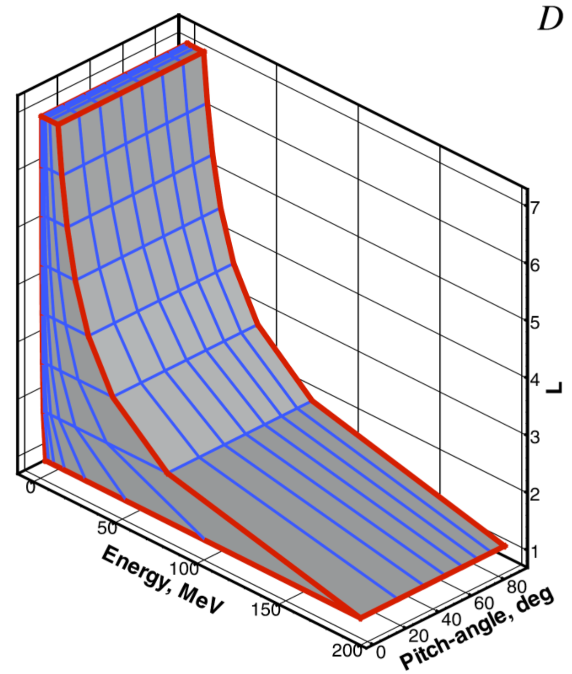
Dirichlet

$$f(q_0) = 0$$

$$f(q_0) = F_0$$

Neumann

$$\frac{\partial f}{\partial q} = 0$$



$$\frac{\partial f}{\partial t} = L^{*2}\frac{\partial}{\partial L^*}\Big|_{\mu,J}\frac{1}{L^{*2}}D_{L^*L^*}\frac{\partial f}{\partial L^*}\Big|_{\mu,J} + \frac{1}{p^2}\frac{\partial}{\partial p}\Big|_{\alpha_0,L^*}p^2\left(D_{pp}\frac{\partial}{\partial p}\Big|_{\alpha_0,L^*}f + D_{p\alpha_0}\frac{\partial}{\partial \alpha_0}\Big|_{p,L^*}f\right)$$
$$+\frac{1}{T(\alpha_0)\sin(2\alpha_0)}\frac{\partial}{\partial \alpha_0}\Big|_{p,L^*}T(\alpha_0)\sin(2\alpha_0)\left(D_{\alpha_0\alpha_0}\frac{\partial}{\partial \alpha_0}\Big|_{p,L^*}f + D_{\alpha_0 p}\frac{\partial}{\partial p}\Big|_{\alpha_0,L^*}f\right) - \frac{f}{\tau}$$

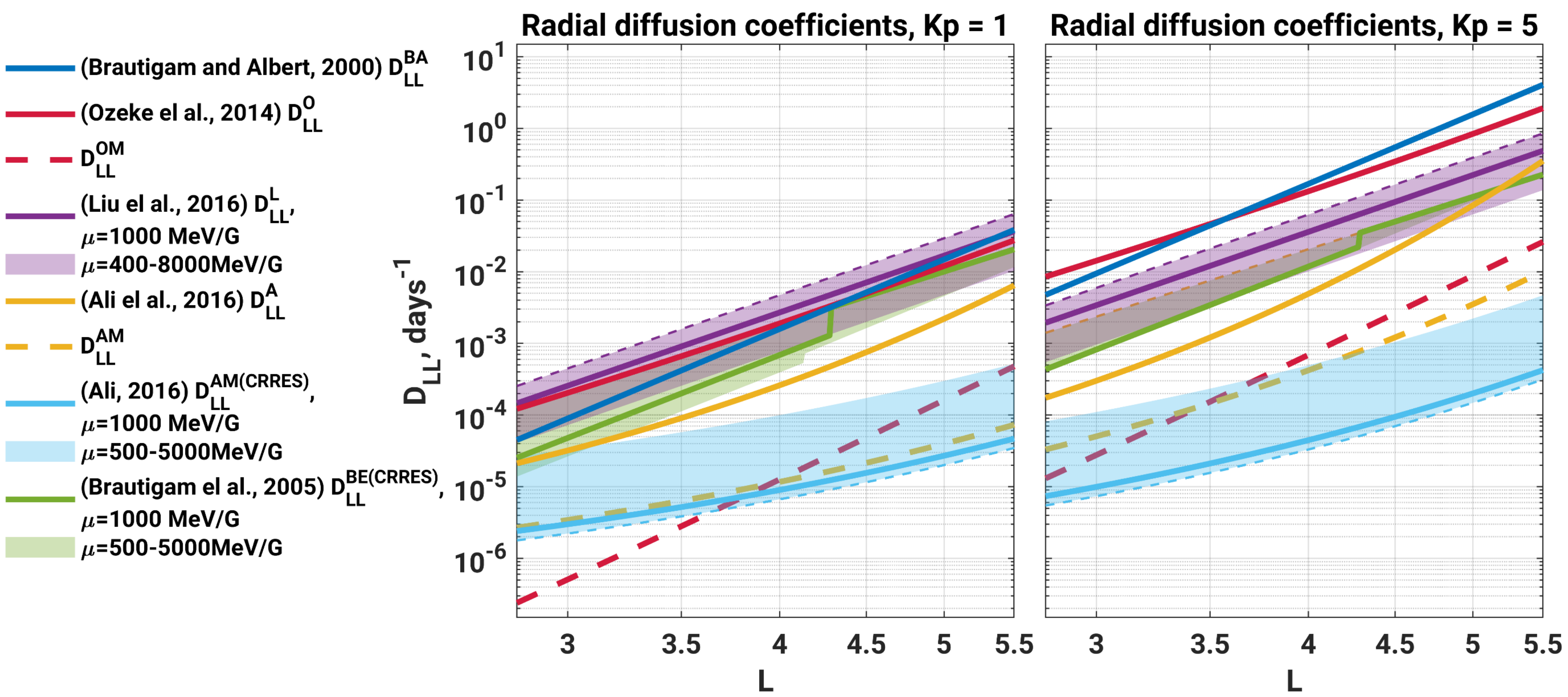
Diffusion Coefficients in Fokker-Plank Equation

- Radial diffusion
- Local pitch-angle scattering
- Local energy diffusion
- Mixed diffusion
- Losses

- Radial diffusion coefficients
  - Brautigam and Albert, 2000
  - Ozeke et al. 2014
  - etc
- Local diffusion coefficients
  - Chorus (day-side, night-side)
  - Hiss,
  - EMIC, etc.
- Loss
  - Loss cone (atmosphere)
  - Magnetopause

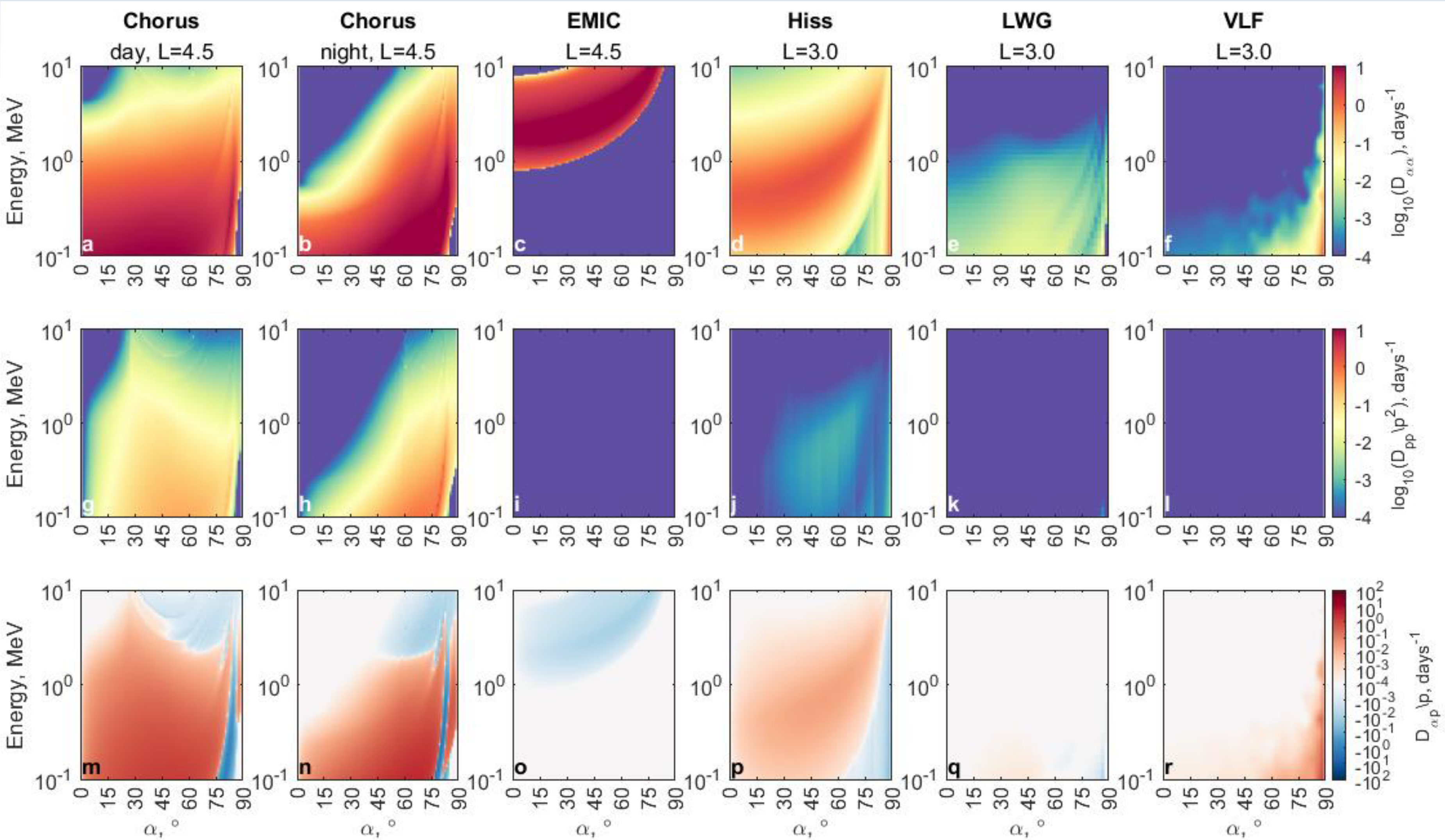
$$\frac{\partial f}{\partial t} = L^{*2} \frac{\partial}{\partial L^*}\Big|_{\mu,J} \frac{1}{L^{*2}} D_{L^*L^*} \frac{\partial f}{\partial L^*}\Big|_{\mu,J} + \frac{1}{p^2}\frac{\partial}{\partial p}\Big|_{\alpha_0,L^*} p^2 \left(D_{pp} \frac{\partial}{\partial p}\Big|_{\alpha_0,L^*} f + D_{p\alpha_0} \frac{\partial}{\partial \alpha_0}\Big|_{p,L^*} f \right)$$
$$+ \frac{1}{T(\alpha_0)\sin(2\alpha_0)} \frac{\partial}{\partial \alpha_0}\Big|_{p,L^*} T(\alpha_0)\sin(2\alpha_0) \left(D_{\alpha_0\alpha_0} \frac{\partial}{\partial \alpha_0}\Big|_{p,L^*} f + D_{\alpha_0 p} \frac{\partial}{\partial p}\Big|_{\alpha_0,L^*} f \right) - \frac{f}{\tau}$$

Radial diffusion coeffects (D_{LL})



Drozdov et al., 2021

Local diffusion coefficients



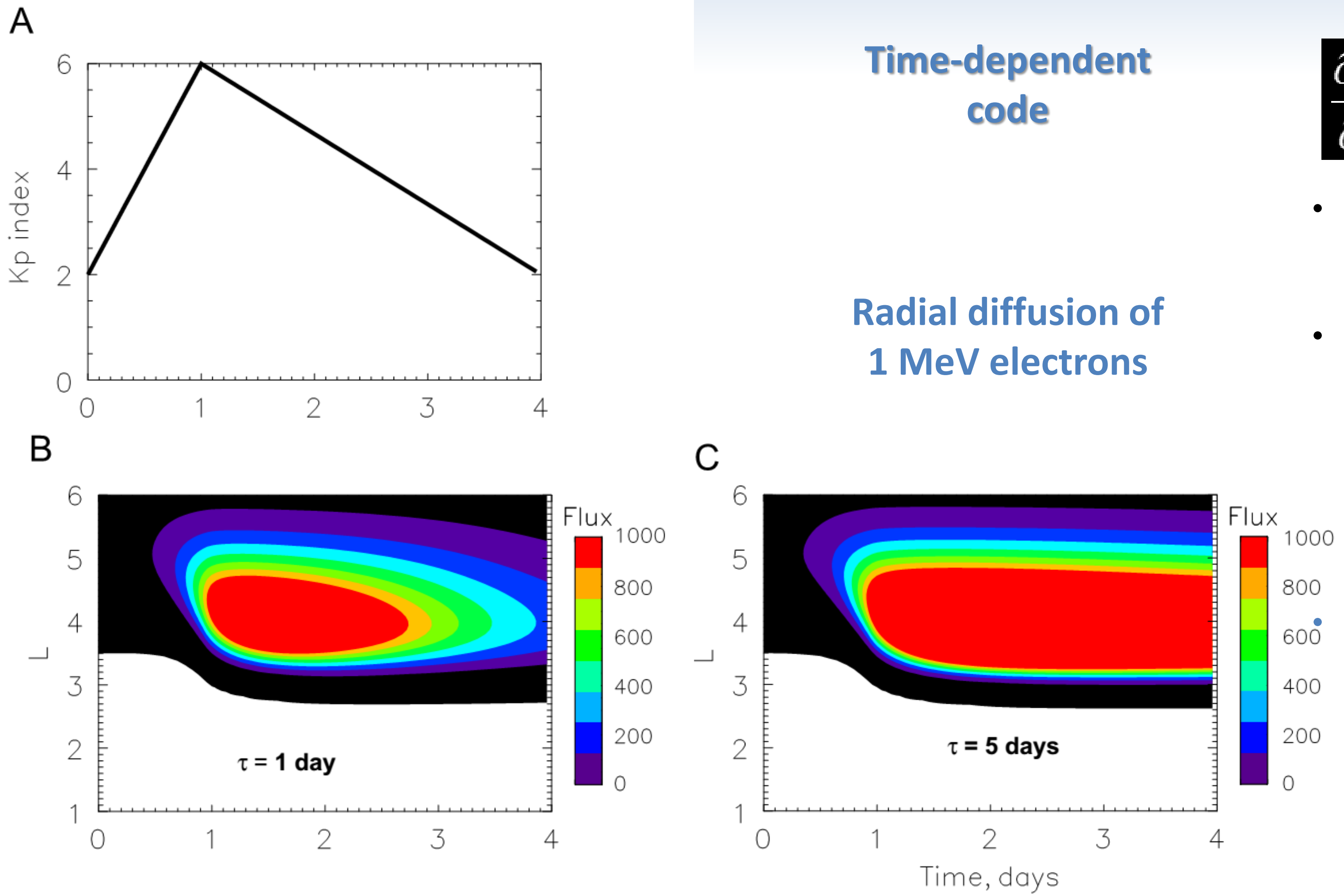
$D_{\alpha_0\alpha_0}$ Log

D_{pp} Log

$D_{\alpha_0 p}$ Linear

1D SIMULATIONS

1D radial diffusion and the loss term (lifetime)



Adopted from Shprits and Thorne, 2004

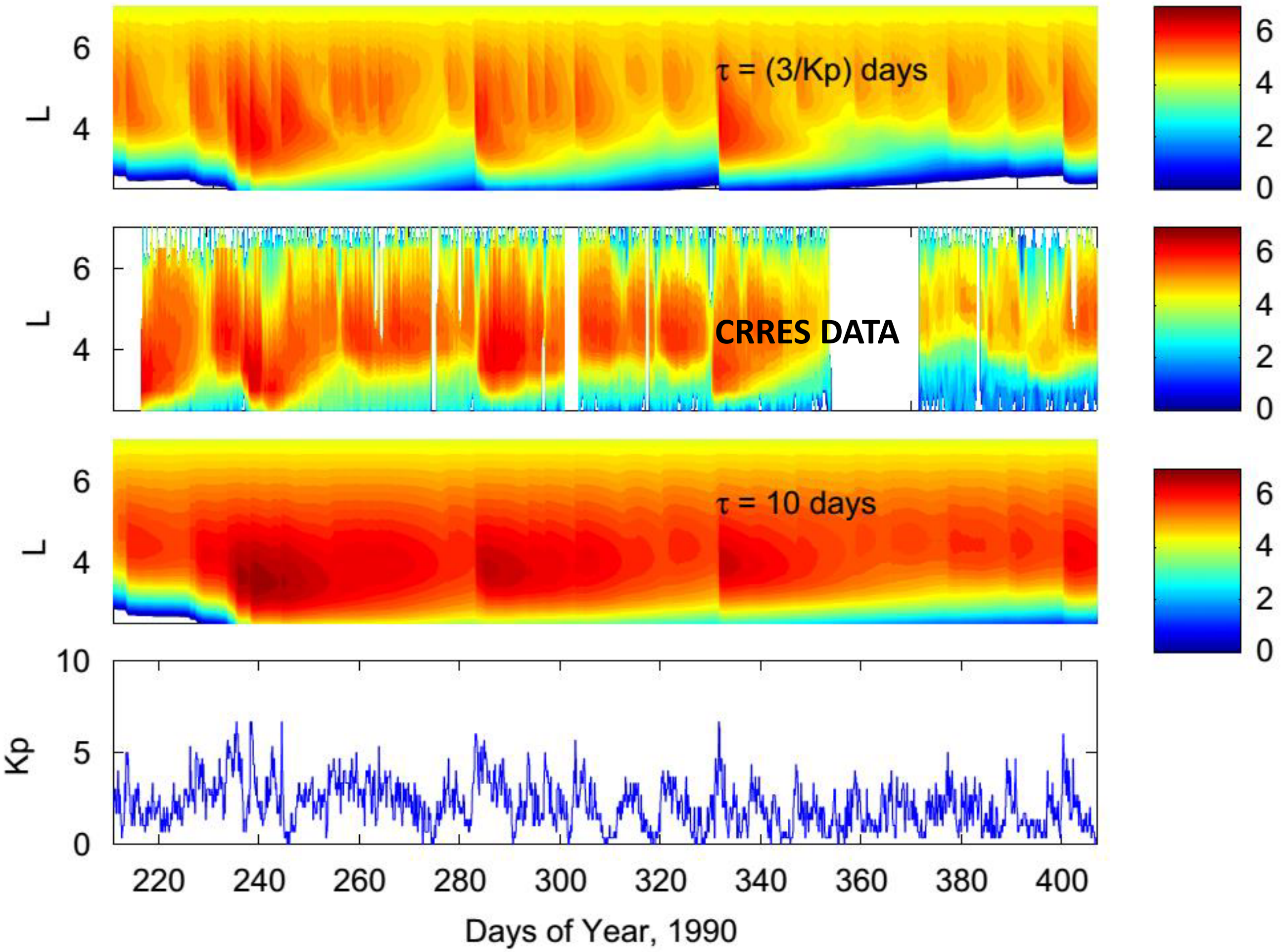
Time-dependent code

Radial diffusion of 1 MeV electrons

$$\frac{\partial f}{\partial t} = L^{*2} \frac{\partial}{\partial L} L^{*-2} D_{L^*L^*} \frac{\partial f}{\partial L^*} - \frac{f}{\tau}$$

- Leading mechanisms for acceleration to relativistic energies include radial diffusion driven by ULF waves.
- Under steady-state conditions the equilibrium structure of the radiation belts is governed by the balance between local acceleration, inward diffusion, and losses due to pitch-angle scattering. The steady-state solution can be used to set up the initial conditions for the modeling.
- **The equilibrium is never attained during the storm, thus the dynamics of electron fluxes during storms must be studied using a time-dependent code.**

1D radial diffusion and empirical lifetime



$$\frac{\partial f}{\partial t} = L^{*2} \frac{\partial}{\partial L} L^{*-2} D_{L^*L^*} \frac{\partial f}{\partial L^*} - \frac{f}{\tau}$$

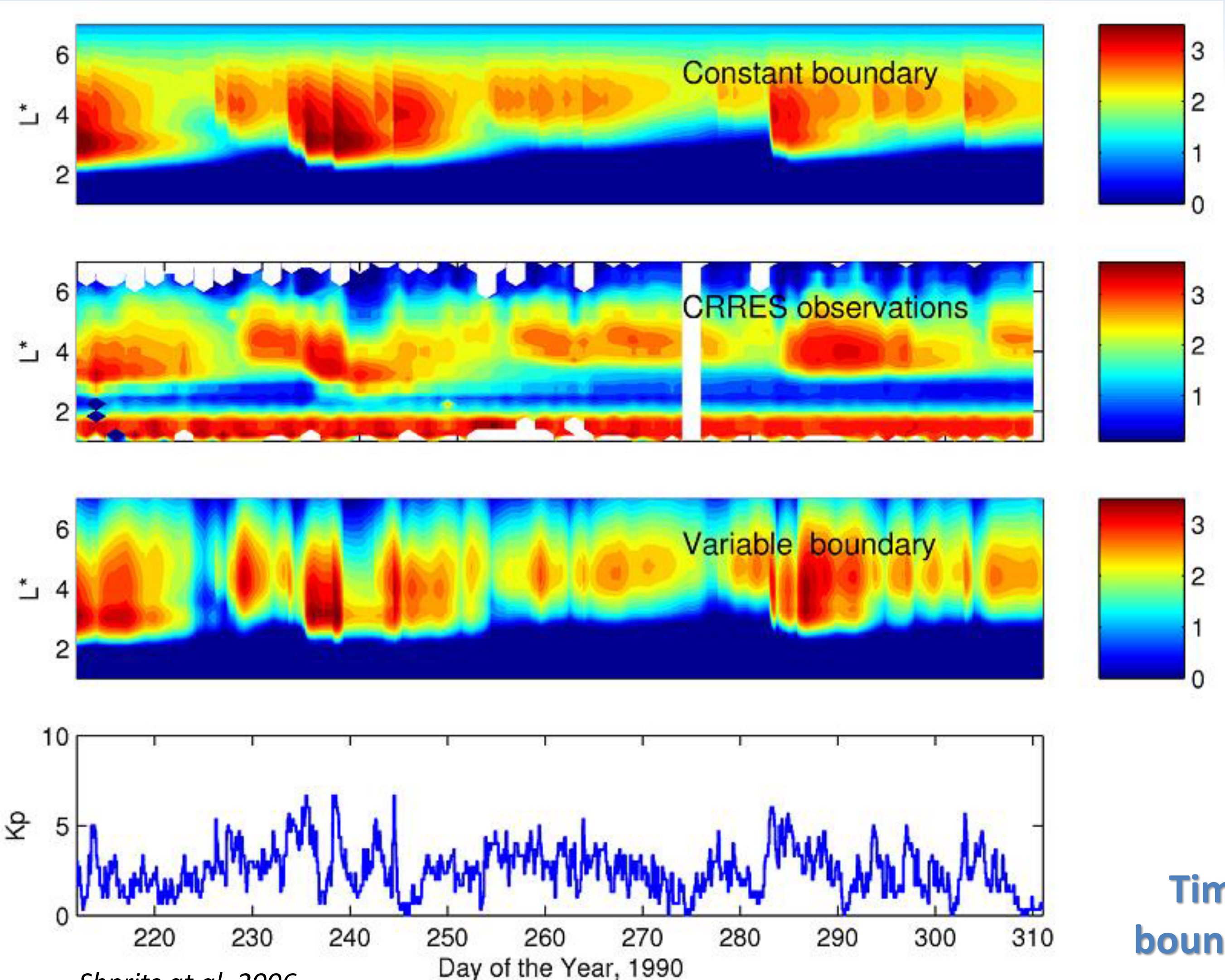
- 500 CRRES orbits starting from 30 July 1990
- Radial diffusion coefficient (D_{LL}) from Brautigam and Albert, 2000
- Simulations with empirical lifetimes parameterized as a function of Kp.
- The radial diffusion model with simplified data-derived lifetimes is capable of predicting the radial extent of high energy fluxes and locations of peak fluxes during storms and predicts MeV fluxes within one order of magnitude accuracy for most of the time of the simulation and most L values.

Time-dependent lifetime

$$\tau = \frac{3}{Kp}, days$$

Shprits at al, 2005

1D radial diffusion and boundary conditions (loss to magnetopause)



Shprits at al, 2006

$$\frac{\partial f}{\partial t} = L^{*2} \frac{\partial}{\partial L} L^{*-2} D_{L^*L^*} \frac{\partial f}{\partial L^*} - \frac{f}{\tau}$$

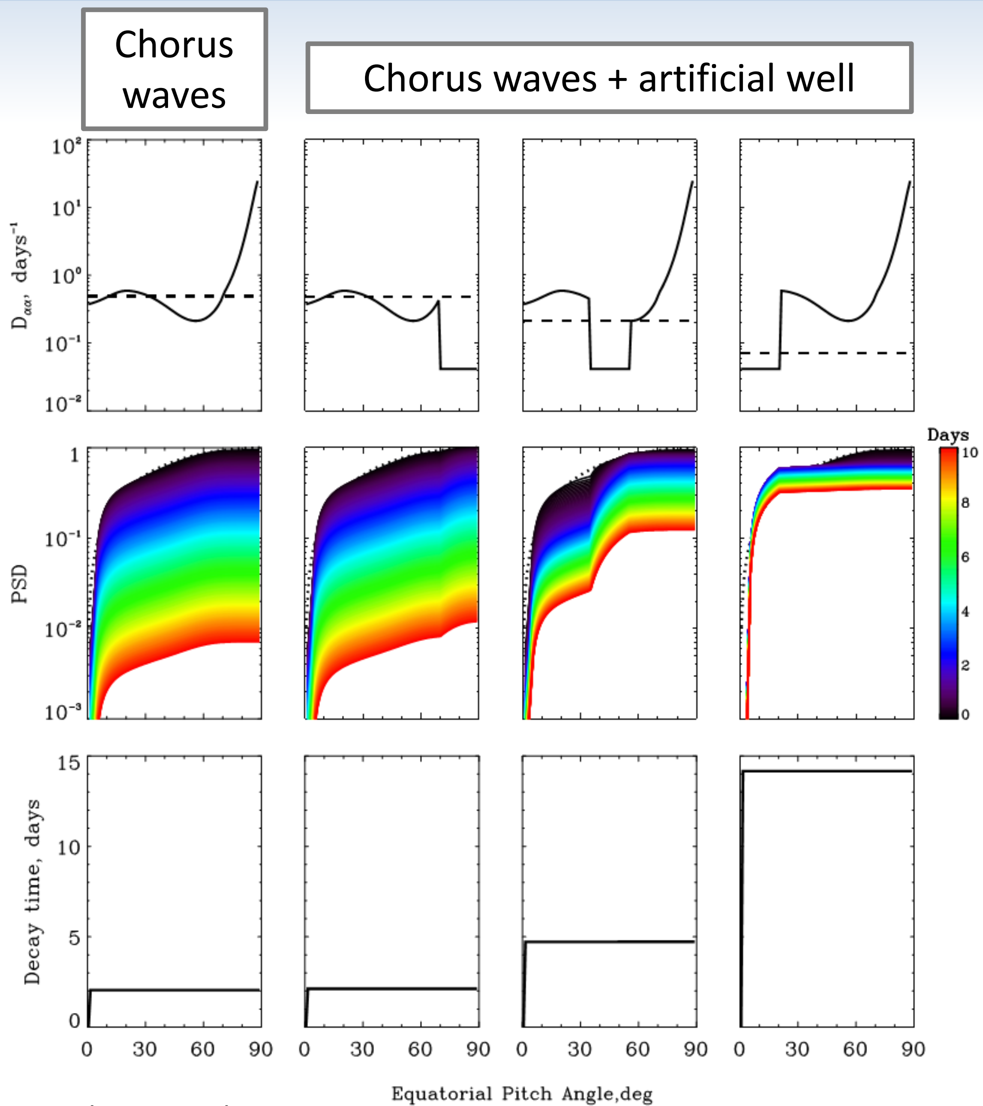
- 19 July - 6 November 1990
- Simulations with both variable and constant outer boundary conditions.
- The results of the simulations indicate that radial diffusion can effectively redistribute outer radiation belt fluxes and smooth PSD gradients, which are produced by losses to magnetopause or by local acceleration and loss.

Time-dependent boundary conditions

$$f(L^* = 6) = f_0$$

$$f(L^* = 6) = f_0 \cdot bf(t)$$

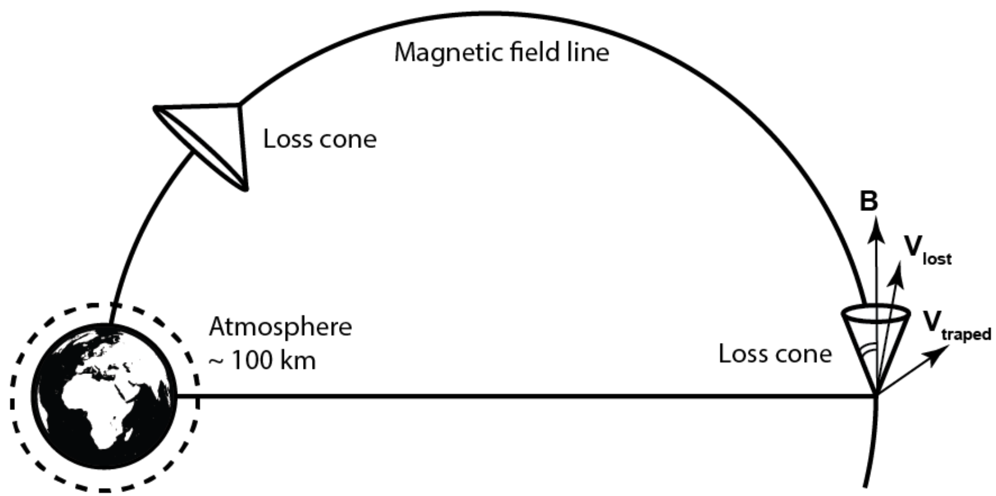
1D pitch-angle diffusion and controlling effect of scattering rates



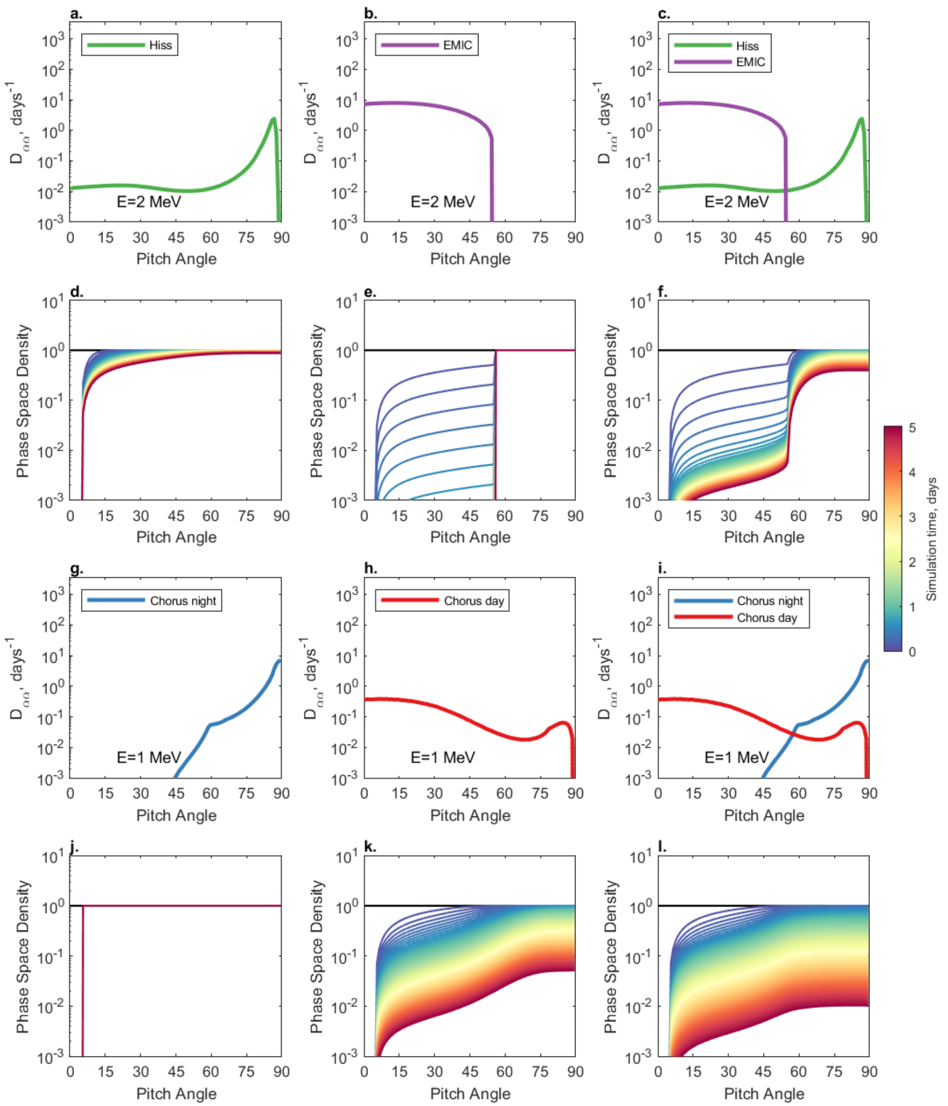
Shprits et al., 2006

$$\frac{\partial f}{\partial t} = \frac{1}{T(y)y}\frac{\partial}{\partial y}\Big|_{p,L} T(y)yD_{yy}\frac{\partial}{\partial y}\Big|_{p,L} f - \frac{f}{\tau_{lc}},$$
$$y = \sin(\alpha_0)$$

If the pitch angle distribution reaches an equilibrium shape the decay of the PSD can be described by a single lifetime parameter, independent of the pitch angle of particles and **lifetimes are primarily controlled by the diffusion rates near the edge of the loss cone**.

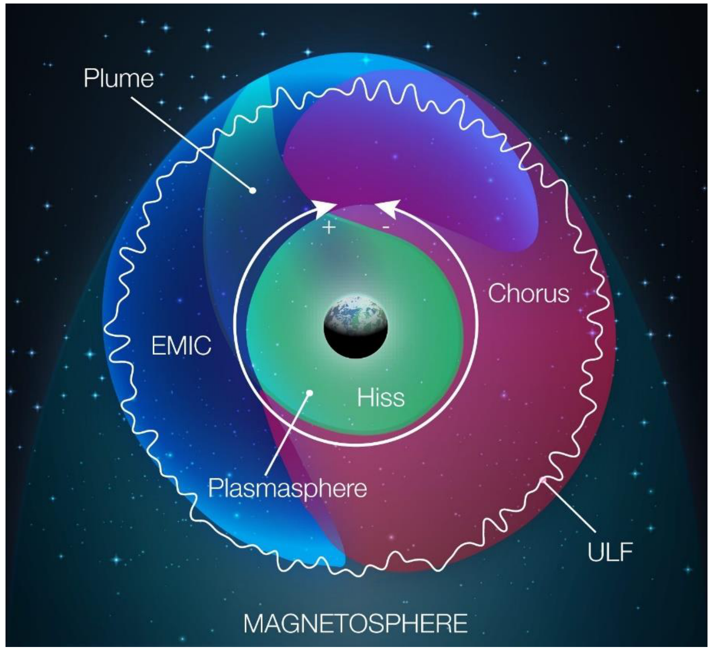


1D pitch-angle diffusion and local waves at different MLT



$$\frac{\partial f}{\partial t} = \frac{1}{T(y)y}\frac{\partial}{\partial y}\Big|_{p,L} T(y)yD_{yy}\frac{\partial}{\partial y}\Big|_{p,L} f - \frac{f}{\tau_{lc}},$$
$$y = \sin(\alpha_0)$$

- Electrons drift around the Earth and interact with different waves along their drift
- Hiss and chorus waves assist EMIC waves in scattering the core population



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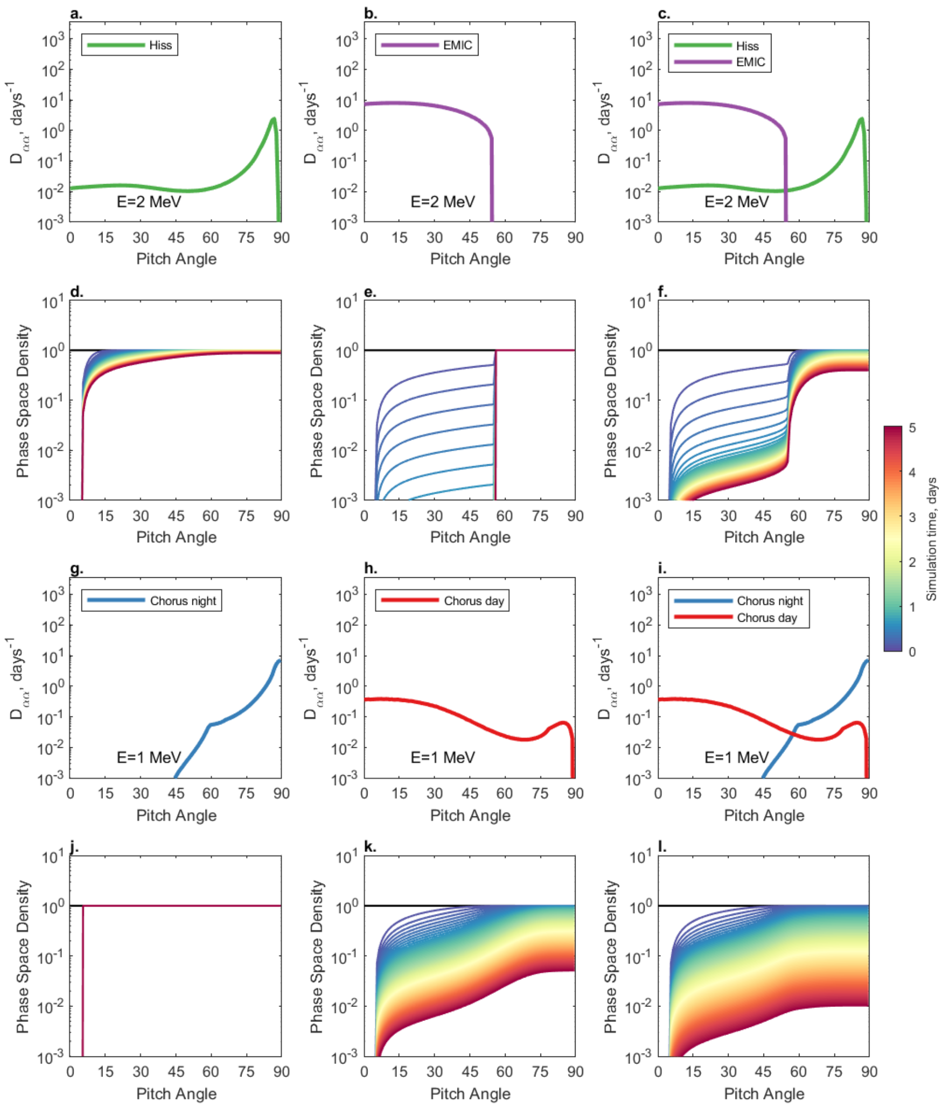

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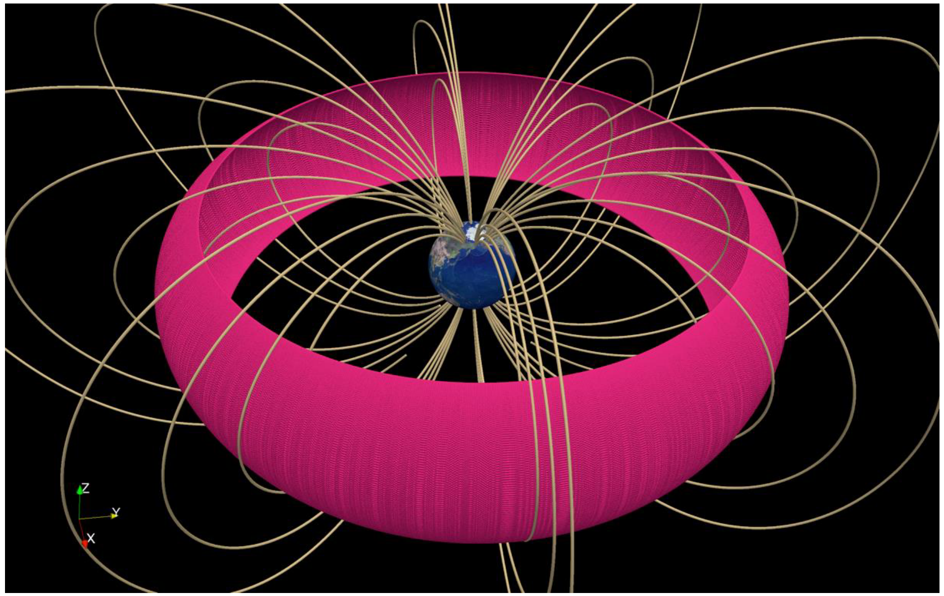
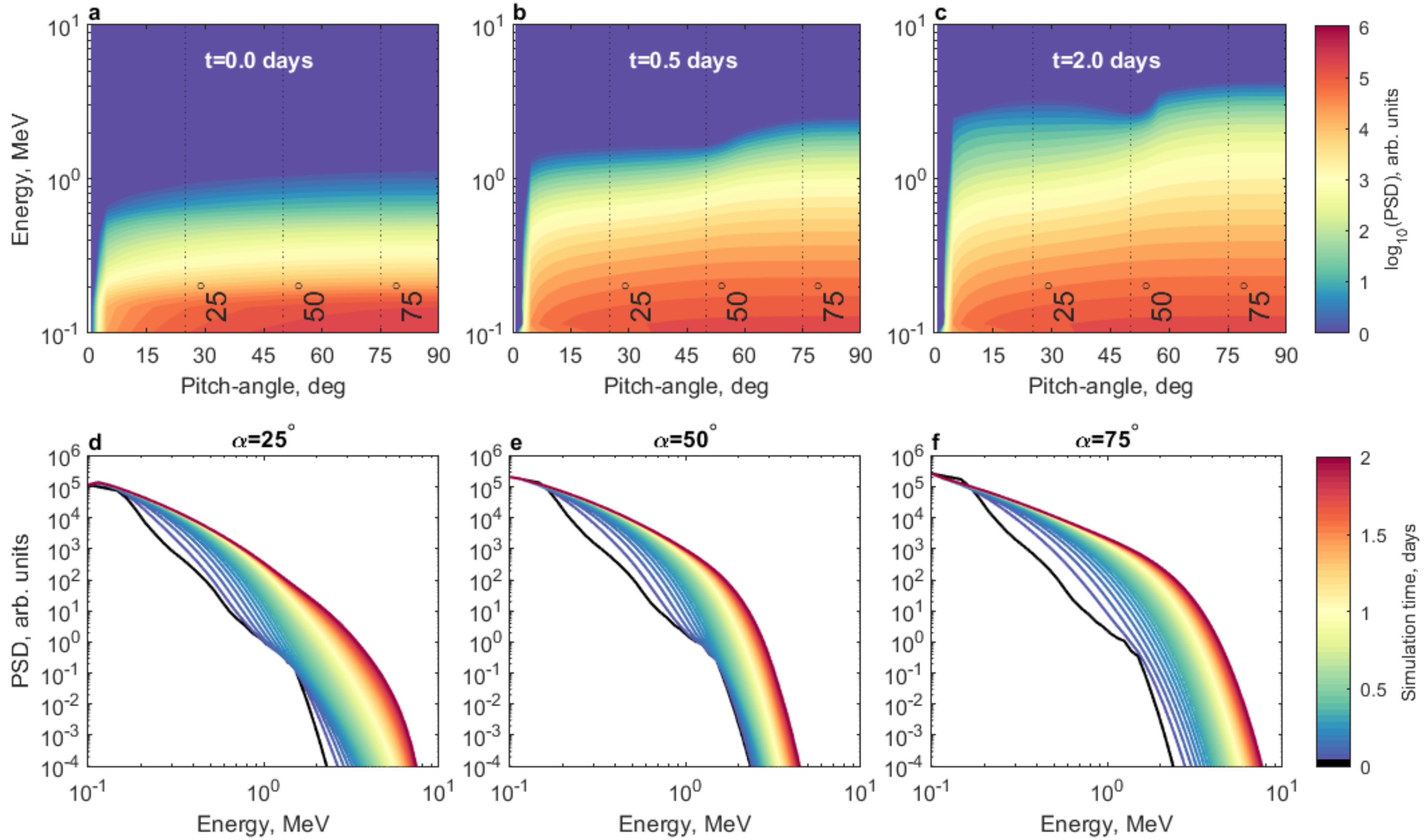


2D SIMULATIONS

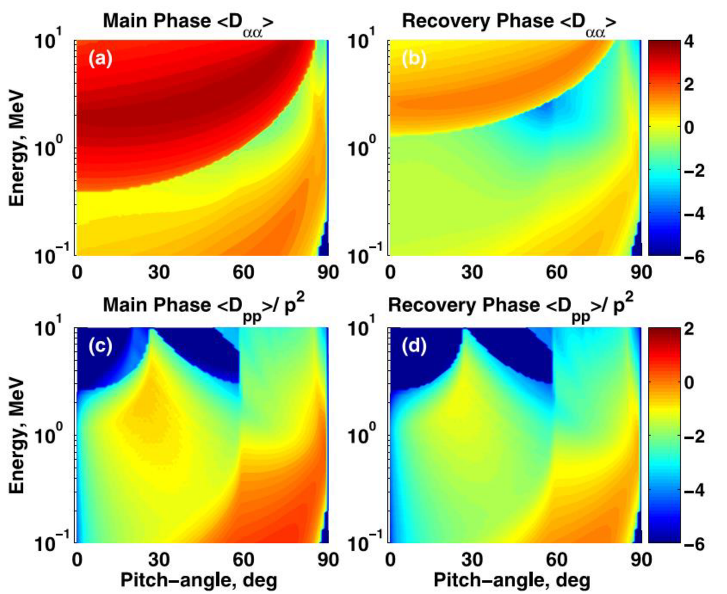
2D simulation of local acceleration

- The wave-particle interactions with whistler mode chorus waves result in a net acceleration

$$\frac{\partial f}{\partial t} = \frac{1}{T(y)y}\frac{\partial}{\partial y}\Big|_{p,L} T(y)yD_{yy}\frac{\partial}{\partial y}\Big|_{p,L} f + \frac{1}{p^2}\frac{\partial}{\partial p}\Big|_{\alpha_0,L} p^2 D_{pp}\frac{\partial}{\partial p}\Big|_{\alpha_0,L} f - \frac{f}{\tau_{lc}},$$
$$y = \sin(\alpha)$$



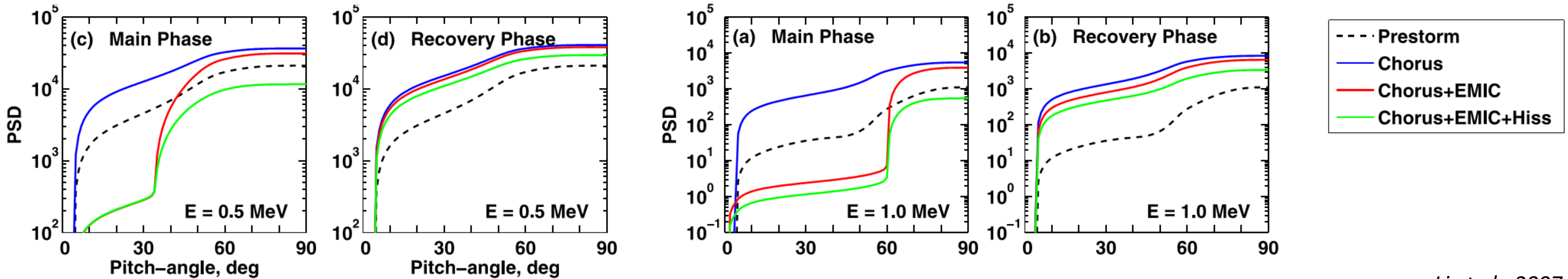
2D simulation of the electron dynamics during storms



Chorus + EMIC + Hiss

$$\frac{\partial f}{\partial t} = \frac{1}{T(y)y}\frac{\partial}{\partial y}\Big|_{p,L} T(y)yD_{yy}\frac{\partial}{\partial y}\Big|_{p,L} f + \frac{1}{p^2}\frac{\partial}{\partial p}\Big|_{\alpha_0,L} p^2 D_{pp}\frac{\partial}{\partial p}\Big|_{\alpha_0,L} f - \frac{f}{\tau_{lc}},$$
$$y = \sin(\alpha)$$

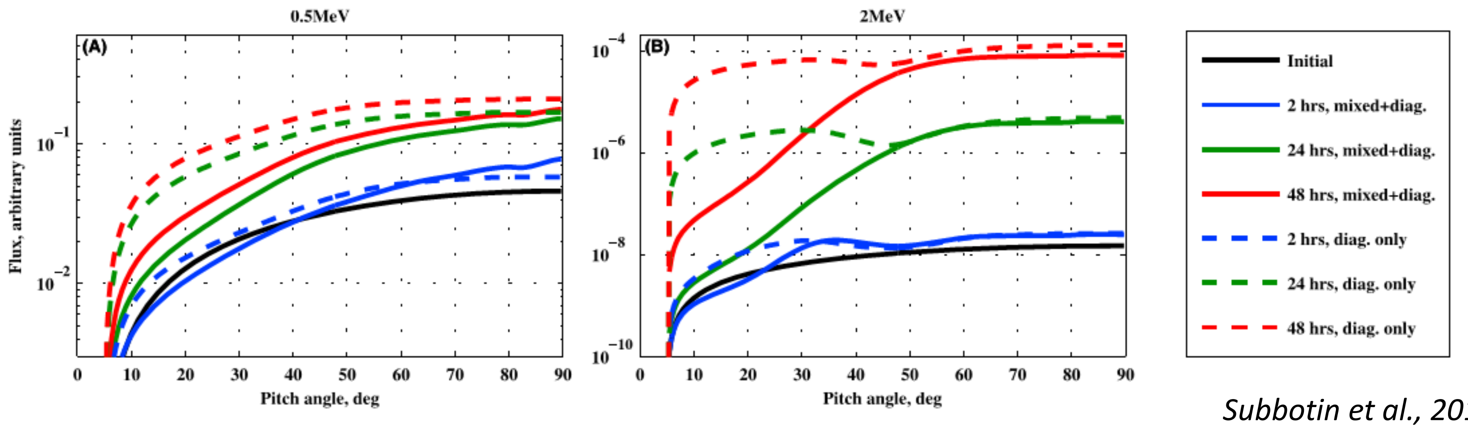
- The wave-particle interactions with whistler mode chorus waves result in a net acceleration of relativistic electrons, while EMIC waves, which provide very fast scattering near the edge of the loss cone, may be a dominant loss mechanism during the main phase of a storm.



Li et al., 2007

2D simulation with mixed terms

$$\frac{\partial f}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\Big|_{\alpha_0,L} p^2 \left(D_{pp}\frac{\partial}{\partial p}\Big|_{\alpha_0,L} f + D_{p\alpha_0}\frac{\partial}{\partial \alpha_0}\Big|_{p,L} f \right) + \\ + \frac{1}{T(\alpha_0)\sin(2\alpha_0)}\frac{\partial}{\partial \alpha_0}\Big|_{p,L} T(\alpha_0)\sin(2\alpha_0)\left(D_{\alpha_0\alpha_0}\frac{\partial}{\partial \alpha_0}\Big|_{p,L} f + D_{\alpha_0 p}\frac{\partial}{\partial p}\Big|_{\alpha_0,L} f \right) - \frac{f}{\tau_{lc}}$$



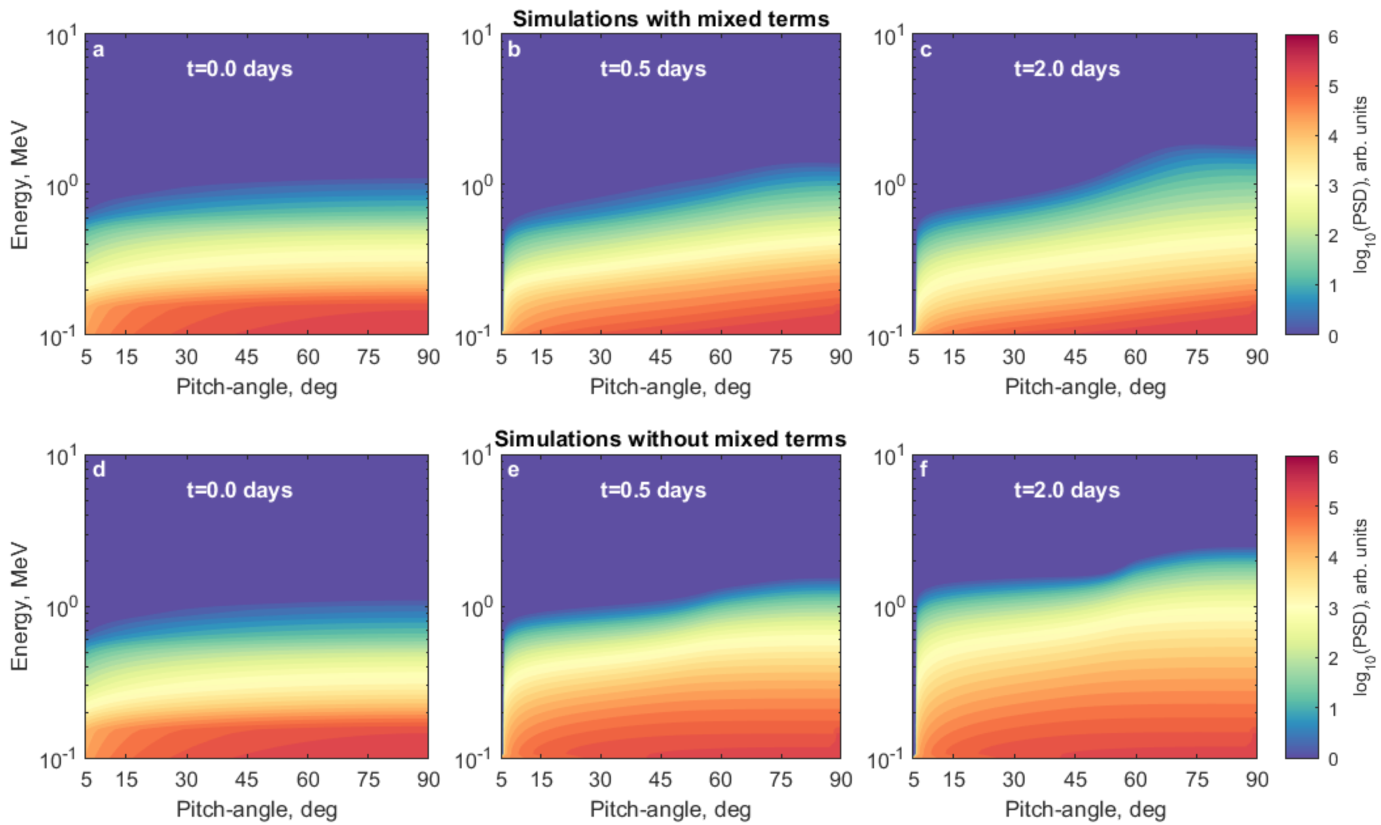
Subbotin et al., 2010

- The mixed diffusion terms **act to decrease the enhancement** of relativistic electron flux by chorus waves
- The effect of the mixed diffusion terms is most significant at small pitch angles

Albert and Young, 2005

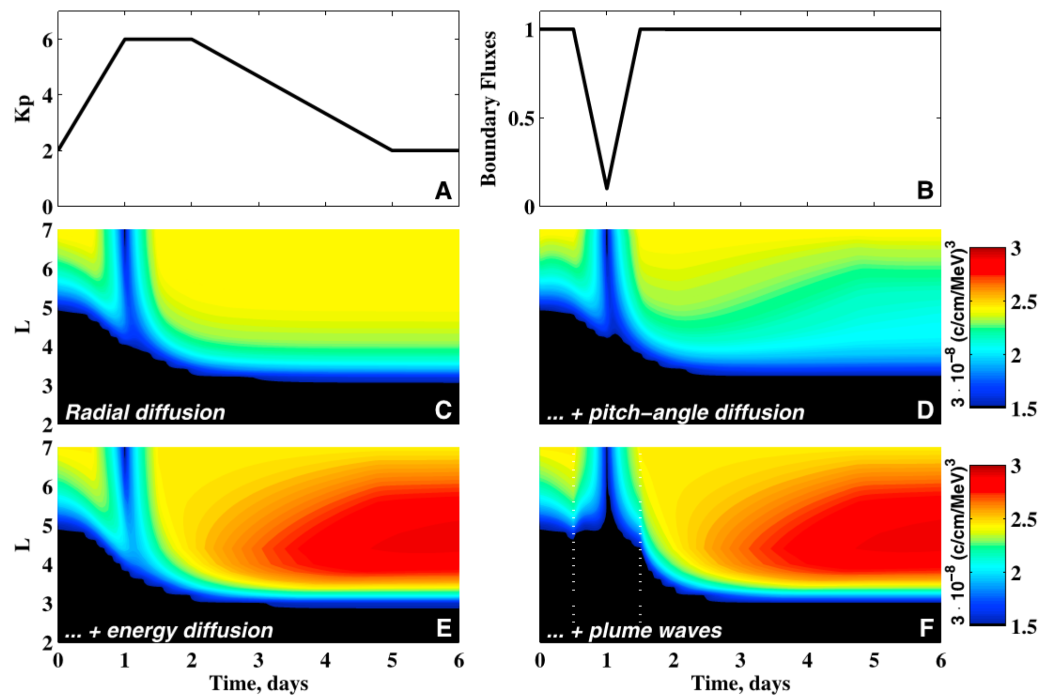
2D simulation with mixed terms

$$\frac{\partial f}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\Big|_{\alpha_0,L} p^2 \left(D_{pp} \frac{\partial}{\partial p}\Big|_{\alpha_0,L} f + D_{p\alpha_0} \frac{\partial}{\partial \alpha_0}\Big|_{p,L} f \right) + \\ + \frac{1}{T(\alpha_0)\sin(2\alpha_0)} \frac{\partial}{\partial \alpha_0}\Big|_{p,L} T(\alpha_0)\sin(2\alpha_0) \left(D_{\alpha_0\alpha_0} \frac{\partial}{\partial \alpha_0}\Big|_{p,L} f + D_{\alpha_0 p} \frac{\partial}{\partial p}\Big|_{\alpha_0,L} f \right) - \frac{f}{\tau_{lc}}$$



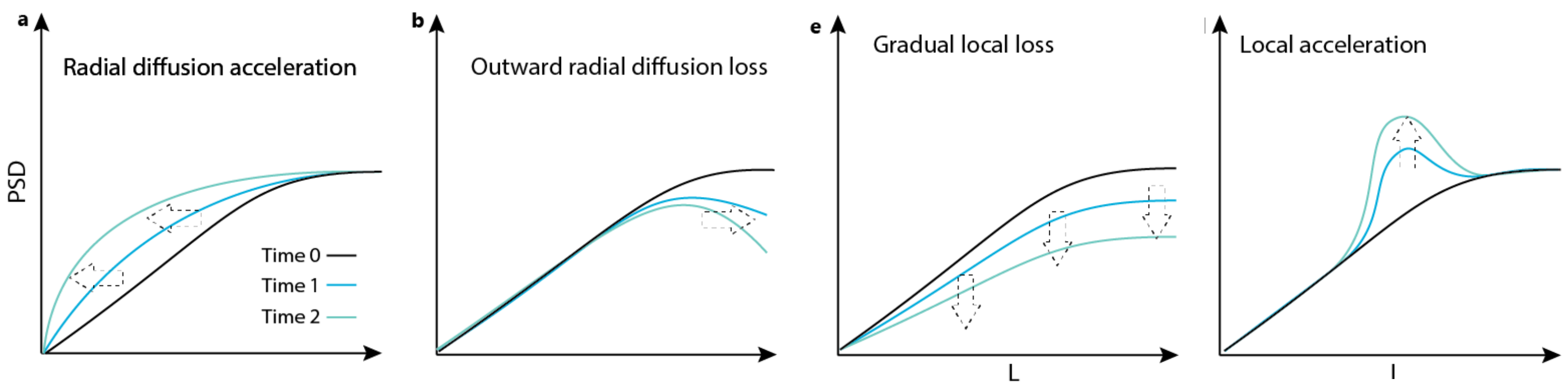
3D SIMULATIONS

3D simulations of an Idealized Storm



$$\frac{\partial f}{\partial t} = L^{*2}\frac{\partial}{\partial L^*}\Big|_{\mu,J}\frac{1}{L^{*2}}D_{L^*L^*}\frac{\partial f}{\partial L^*}\Big|_{\mu,J} + \frac{1}{T(\alpha_0)\sin(2\alpha_0)}\frac{\partial}{\partial \alpha_0}\Big|_{p,L} T(\alpha_0)\sin(2\alpha_0)\left(D_{\alpha_0\alpha_0}\frac{\partial}{\partial\alpha_0}\Big|_{p,L} f\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\Big|_{\alpha_0,L} p^2\left(D_{pp}\frac{\partial}{\partial p}\Big|_{\alpha_0,L} f\right) - \frac{f}{\tau}$$

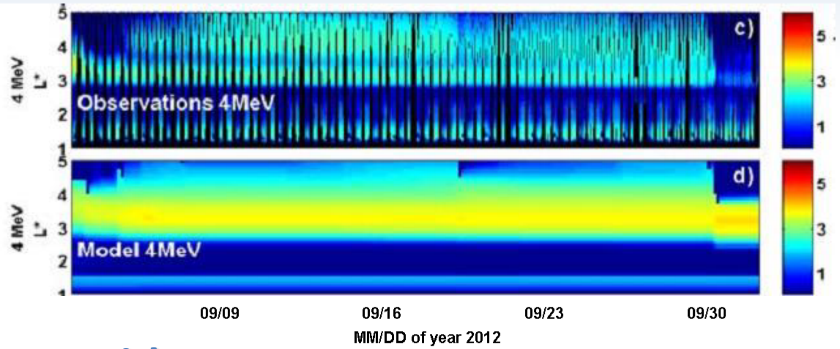
- Radial diffusion can transport electrons inward and accelerate them. Outward – loss to the magnetopause.
- Pitch-angle diffusion produces loss to the atmosphere
- Energy diffusion accelerates particles and creates peaks in phase space density.



Shprits at al, 2009

Modeling of the 3rd radiation belt

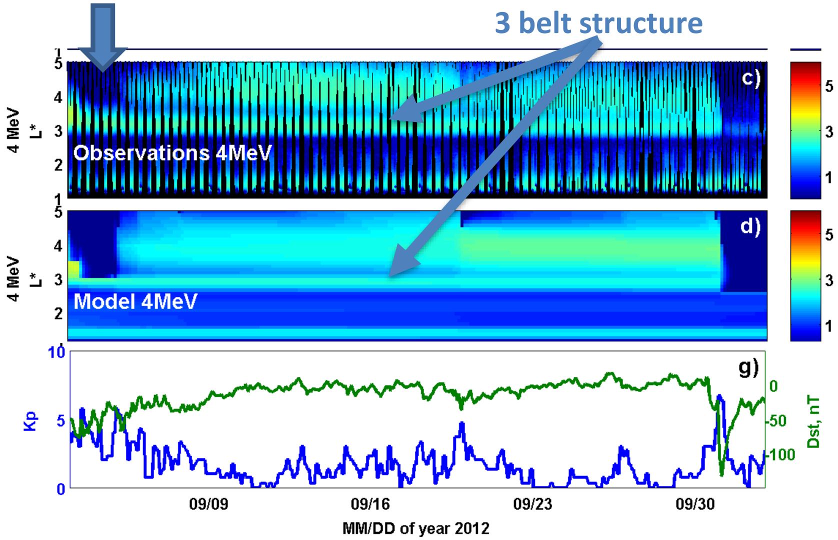
Without EMIC waves



Observations REPT 4.2 MeV

VERB simulation

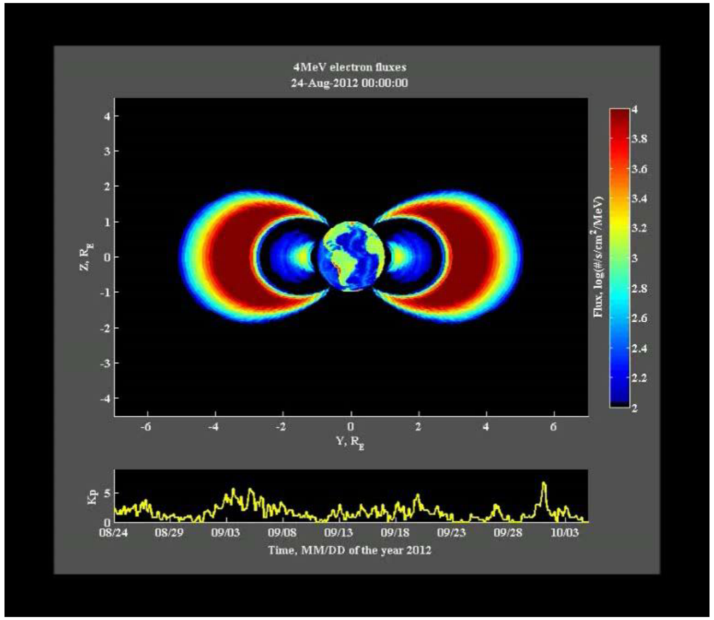
With EMIC waves

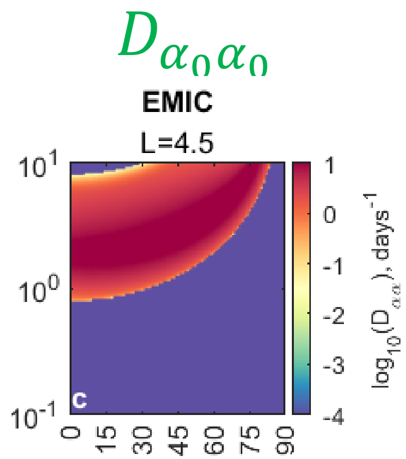


Observations REPT 4.2 MeV

VERB simulation

$$\frac{\partial f}{\partial t} = L^{*2}\frac{\partial}{\partial L^*}\bigg|_{\mu,J}\frac{1}{L^{*2}}D_{L^*L^*}\frac{\partial f}{\partial L^*}\bigg|_{\mu,J} + \frac{1}{T(\alpha_0)\sin(2\alpha_0)}\frac{\partial}{\partial\alpha_0}\bigg|_{p,L}T(\alpha_0)\sin(2\alpha_0)\left(D_{\alpha_0\alpha_0}\frac{\partial}{\partial\alpha_0}\bigg|_{p,L}f + D_{\alpha_0 p}\frac{\partial}{\partial p}\bigg|_{\alpha_0,L}f\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\bigg|_{\alpha_0,L}p^2\left(D_{pp}\frac{\partial}{\partial p}\bigg|_{\alpha_0,L}f + D_{p\alpha_0}\frac{\partial}{\partial\alpha_0}\bigg|_{p,L}f\right) - \frac{f}{\tau}$$





The VERB code simulation with EMIC waves reproduces the third belt structure during September 2012.

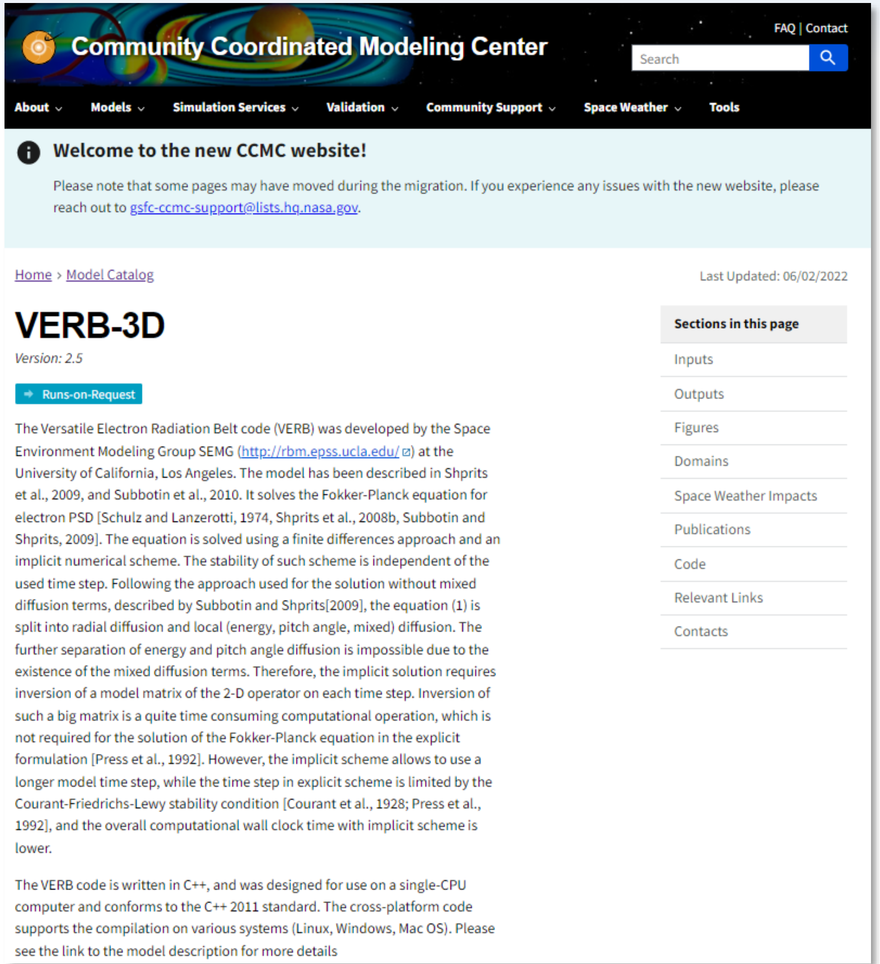
Shprits et al., 2014, Nature Physics

Community Coordinated Modeling Center

NASA CCMC

VERB code at CCMC

https://ccmc.gsfc.nasa.gov/models/VERB-3D~2.5



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Home › Model Catalog

Last Updated: 06/02/2022

VERB-3D

Version: 2.5

Runs-on-Request

The Versatile Electron Radiation Belt code (VERB) was developed by the Space Environment Modeling Group SEMG (http://rbm.epss.ucla.edu/) at the University of California, Los Angeles. The model has been described in Shprits et al., 2009, and Subbotin et al., 2010. It solves the Fokker-Planck equation for electron PSD [Schulz and Lanzerotti, 1974, Shprits et al., 2008b, Subbotin and Shprits, 2009]. The equation is solved using a finite differences approach and an implicit numerical scheme. The stability of such scheme is independent of the used time step. Following the approach used for the solution without mixed diffusion terms, described by Subbotin and Shprits[2009], the equation (1) is split into radial diffusion and local (energy, pitch angle, mixed) diffusion. The further separation of energy and pitch angle diffusion is impossible due to the existence of the mixed diffusion terms. Therefore, the implicit solution requires inversion of a model matrix of the 2-D operator on each time step. Inversion of such a big matrix is a quite time consuming computational operation, which is not required for the solution of the Fokker-Planck equation in the explicit formulation [Press et al., 1992]. However, the implicit scheme allows to use a longer model time step, while the time step in explicit scheme is limited by the Courant-Friedrichs-Lewy stability condition [Courant et al., 1928; Press et al., 1992], and the overall computational wall clock time with implicit scheme is lower.

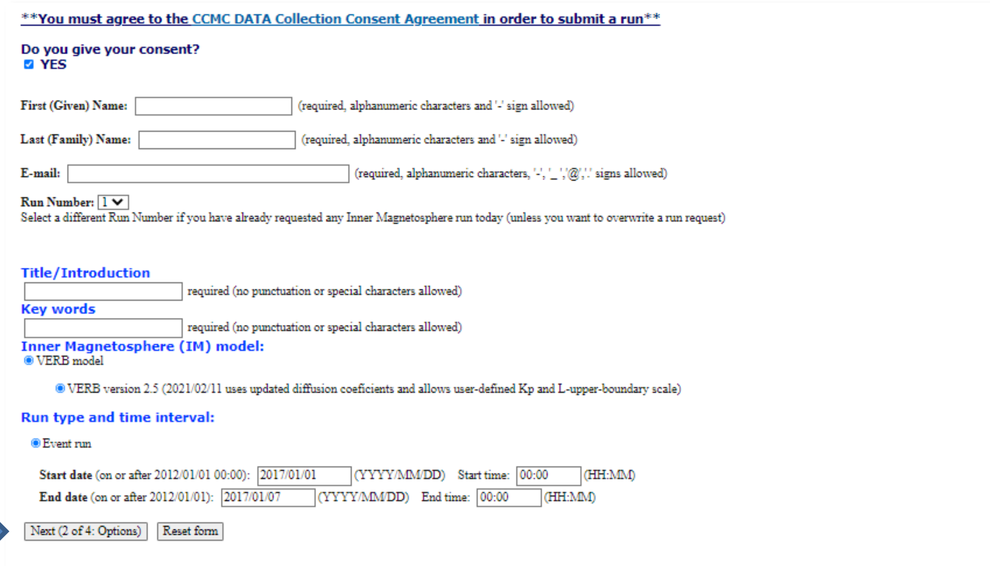
The VERB code is written in C++, and was designed for use on a single-CPU computer and conforms to the C++ 2011 standard. The cross-platform code supports the compilation on various systems (Linux, Windows, Mac OS). Please see the link to the model description for more details

Sections in this page

- Inputs
- Outputs
- Figures
- Domains
- Space Weather Impacts
- Publications
- Code
- Relevant Links
- Contacts

Creating a simulation request:

- Credentials
- Name of the simulation
- Simulation period



You must agree to the CCMC DATA Collection Consent Agreement in order to submit a run

Do you give your consent?
☑ YES

First (Given) Name: (required, alphanumeric characters and '-' sign allowed)

Last (Family) Name: (required, alphanumeric characters and '-' sign allowed)

E-mail: (required, alphanumeric characters, '-', '_', '@', '.' signs allowed)

Run Number: 1
Select a different Run Number if you have already requested any Inner Magnetosphere run today (unless you want to overwrite a run request)

Title/Introduction
required (no punctuation or special characters allowed)

Key words
required (no punctuation or special characters allowed)

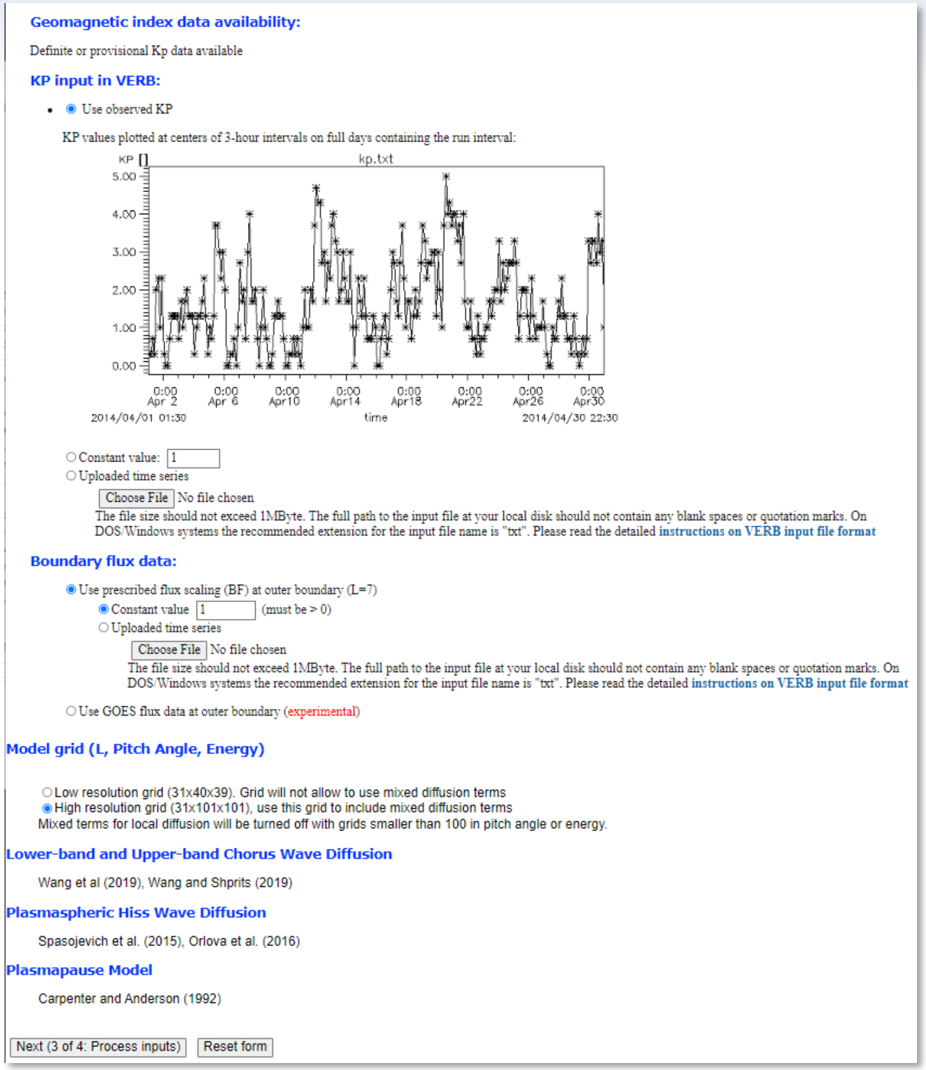
Inner Magnetosphere (IM) model:
◉ VERB model
◉ VERB version 2.5 (2021/02/11 uses updated diffusion coeficients and allows user-defined Kp and L-upper-boundary scale)

Run type and time interval:
◉ Event run

Start date (on or after 2012/01/01 00:00): 2017/01/01 (YYYY/MM/DD) Start time: 00:00 (HH:MM)
End date (on or after 2012/01/01): 2017/01/07 (YYYY/MM/DD) End time: 00:00 (HH:MM)

Next (2 of 4: Options) Reset form

Setup simulation parameters



Setup Kp-index:

- **Default Kp from the World Data Center for Geomagnetism, Kyoto.**
- **Fixed Kp value, e.g., Kp = 1**
- **Kp form the data file**

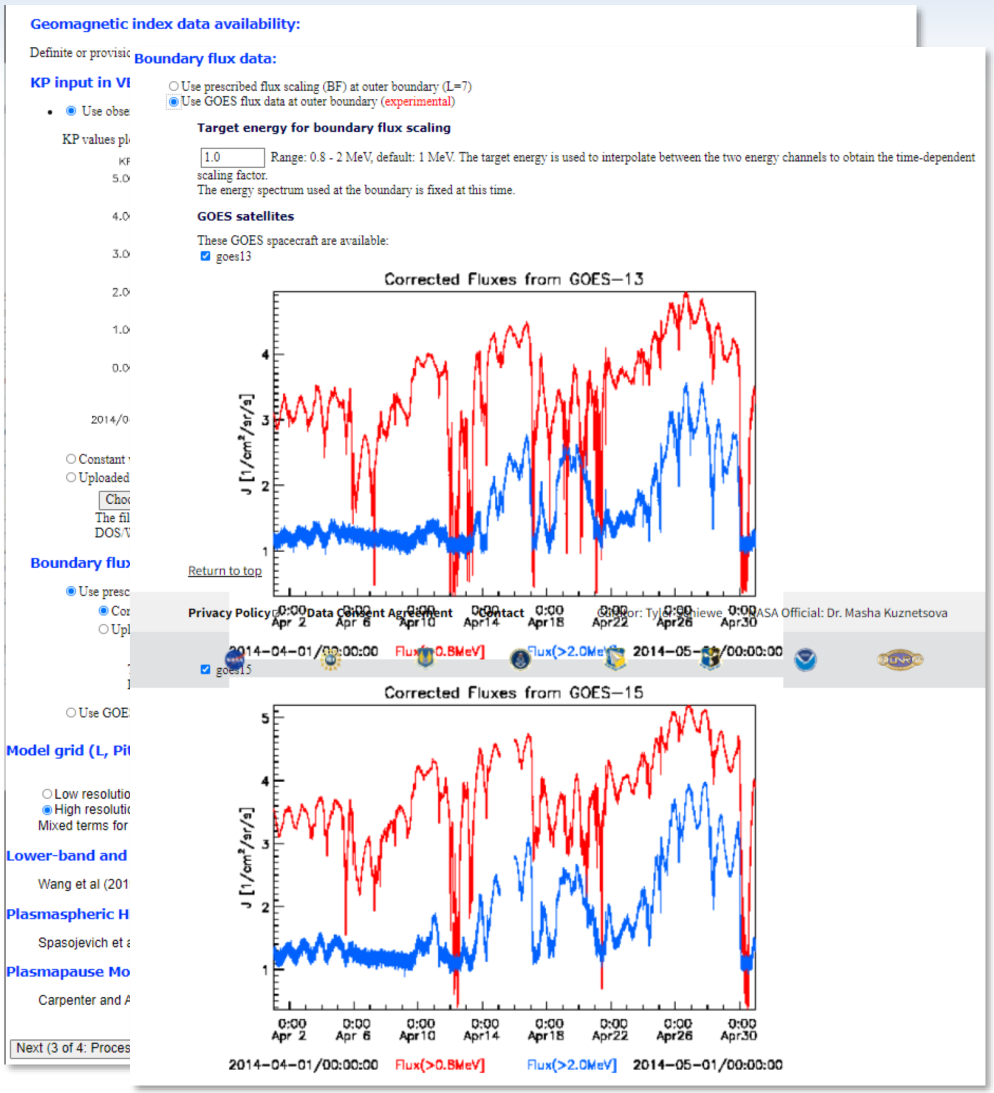
Setup L upper boundary or boundary flux (bf) scaling:

- **Default Fixed Dirichlet boundary condition (e.g., =1)**
- **Bf scaling from data files**
- **Bf scaling from observations (experimental feature)**
  - **GOES 13**
  - **GOES 15**

- **Setup grid size**
  - **Low resolution (no mixed terms)**
  - **High resolution (with mixed terms)**

- **Radial diffusion, chorus and hiss waves are scaled by Kp.**

Setup simulation parameters



Setup Kp-index:

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- **Fixed Kp value, e.g., Kp = 1**
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  - **GOES 13**
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- **Setup grid size**
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  - **High resolution (with mixed terms)**

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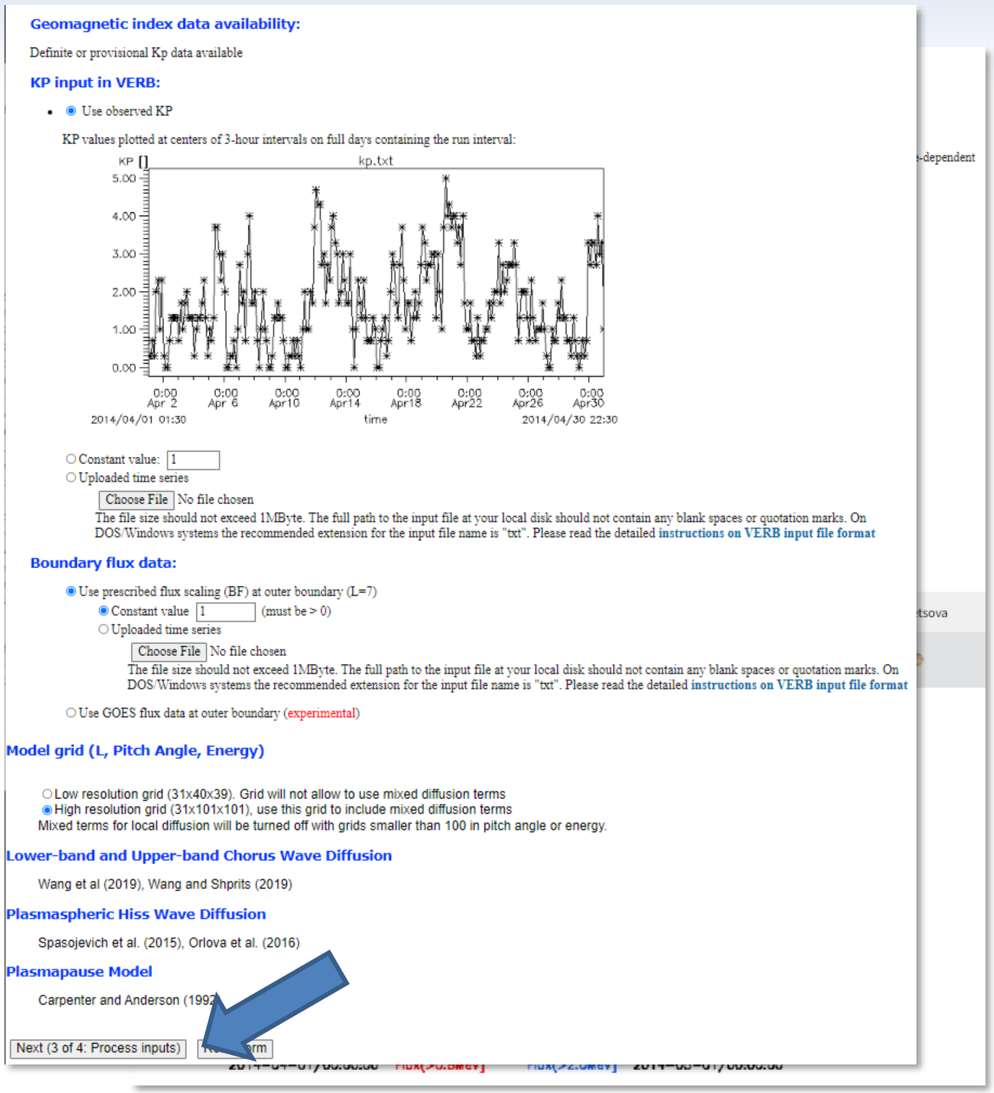
Setup simulation parameters



Setup Kp-index:

- Default Kp from the World Data Center for Geomagnetism, Kyoto.
- Fixed Kp value, e.g., Kp = 1
- Kp form the data file

Setup L upper boundary or boundary flux (bf) scaling:

- Default Fixed Dirichlet boundary condition (e.g., =1)
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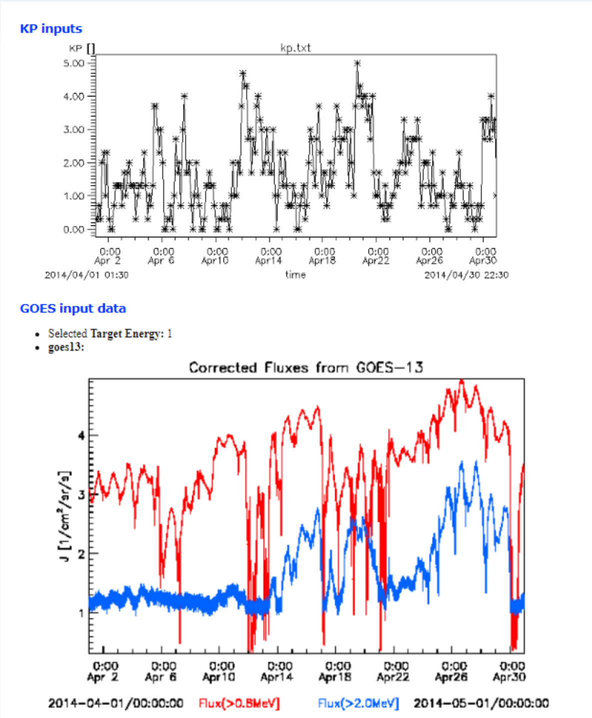
- Bf scaling from observations (experimental feature)
  - GOES 13
  - GOES 15

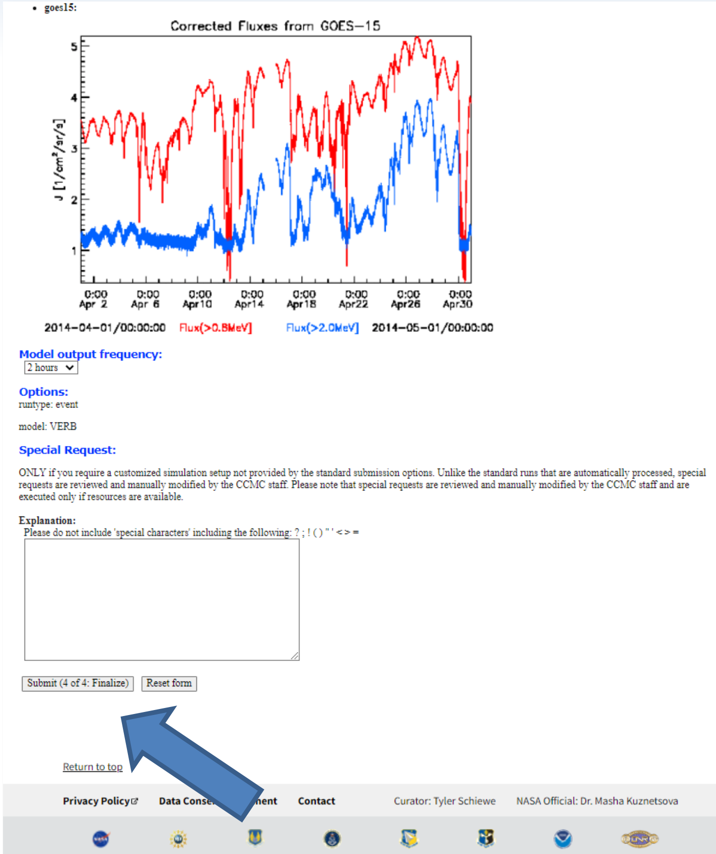
- Setup grid size
  - Low resolution (no mixed terms)
  - High resolution (with mixed terms)

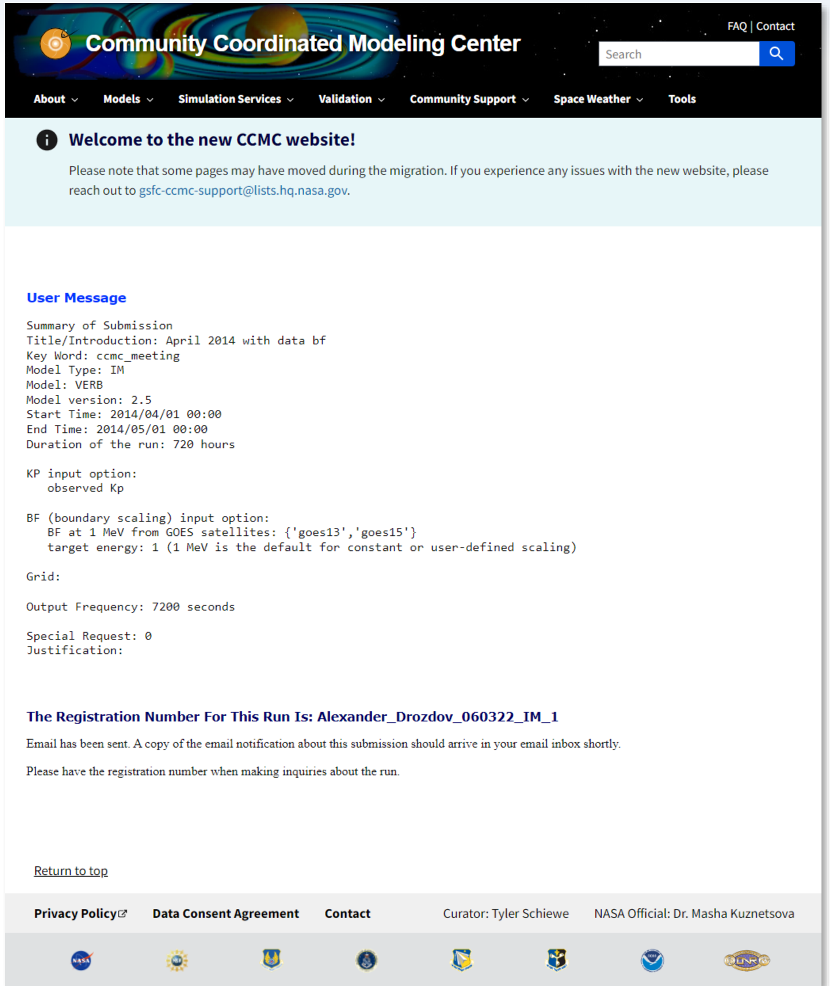
- Radial diffusion, chorus and hiss waves are scaled by Kp.

Review input and submit

Confirmation page



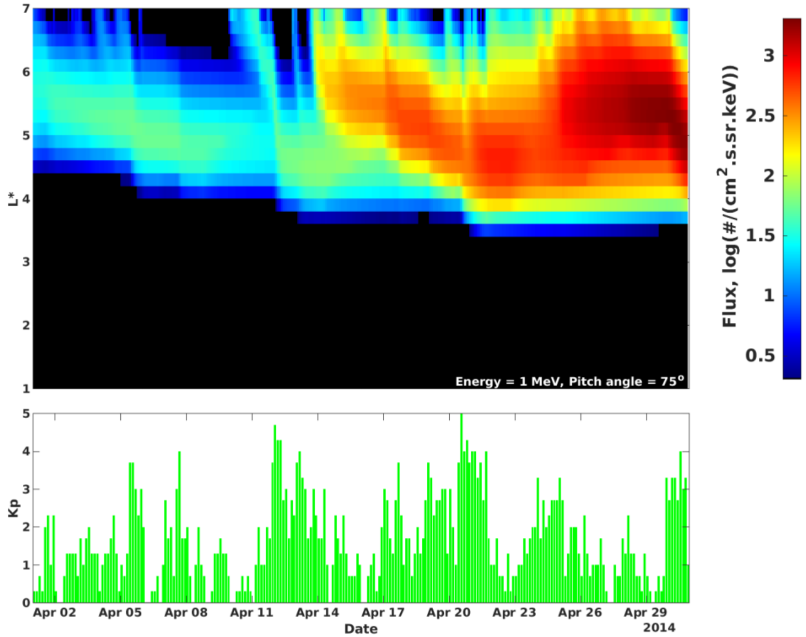




VERB code simulation results at CCMC

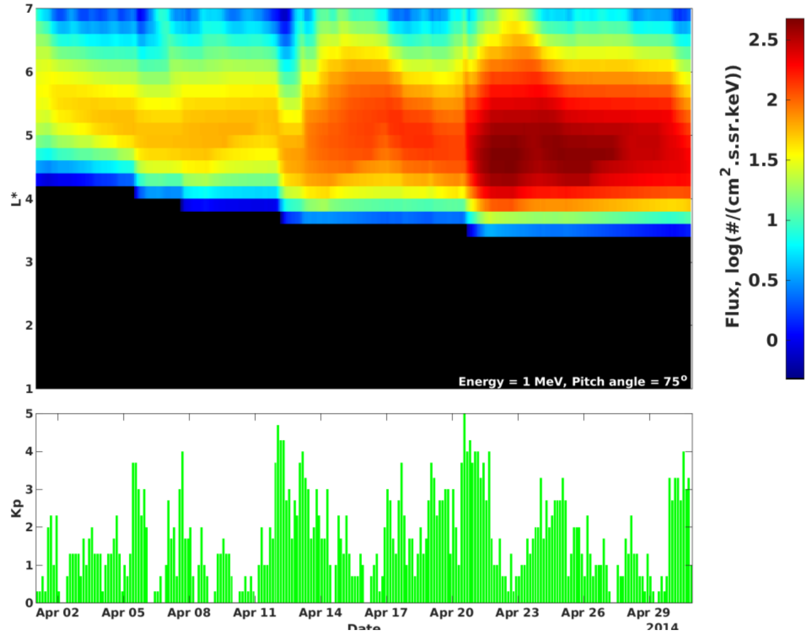
Flux 1 MeV eq. pitch angle 75°

- **Default Kp from the World Data Center from Geomagnetism, Kyoto.**
- **Bf scaling from observations (GOES 13 and 15)**



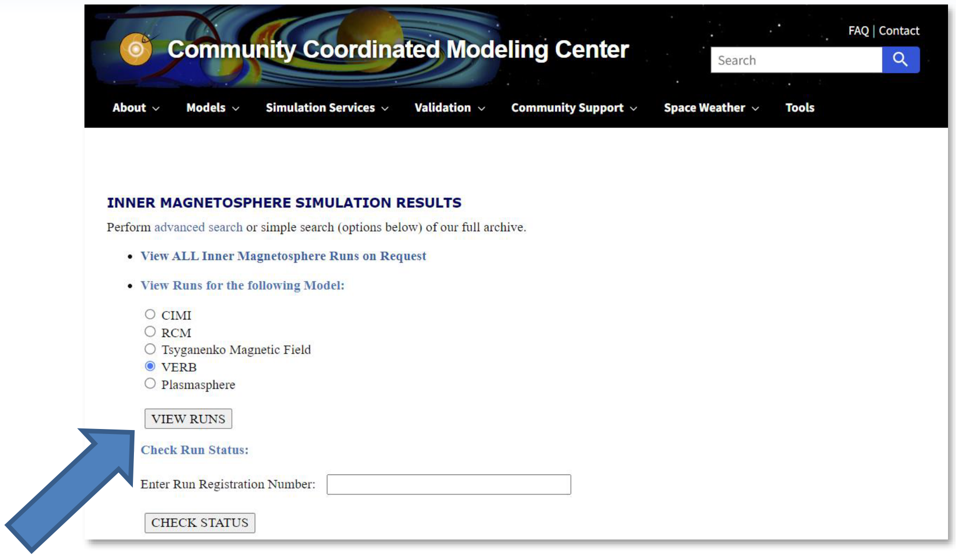
Flux 1 MeV eq. pitch angle 75°

- **Default Kp from the World Data Center from Geomagnetism, Kyoto.**
- **Bf scaling from uploaded file**
  - **Bf reconstructed by neural network**
    - *Landis, D. A., Saikin, A. A., Zhelavskaya, I., Drozdov, A. Y., Aseev, N., Shprits, Y. Y., et al. (2022). Title: NARX neural network derivations of the outer boundary radiation belt electron flux. Space Weather. https://doi.org/10.1029/2021sw002774*

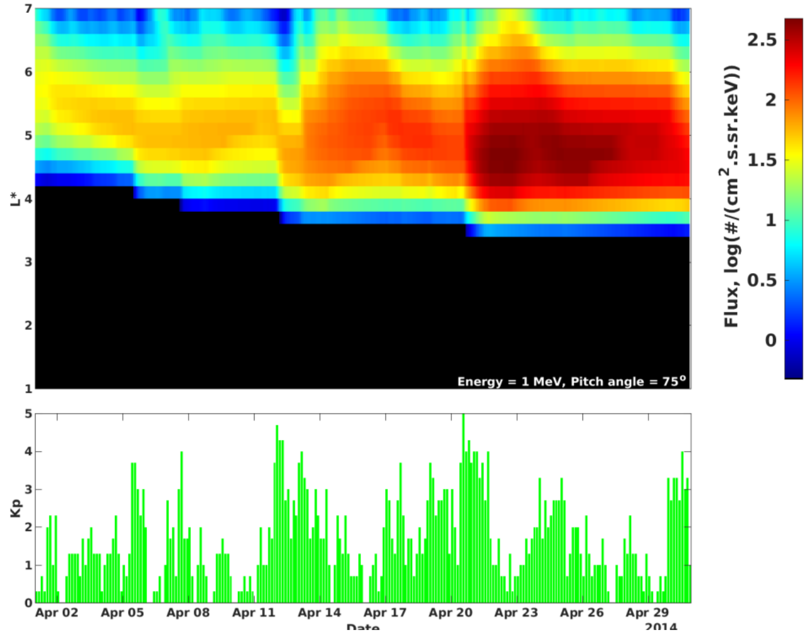


Find VERB code results at CCMC

https://ccmc.gsfc.nasa.gov/results

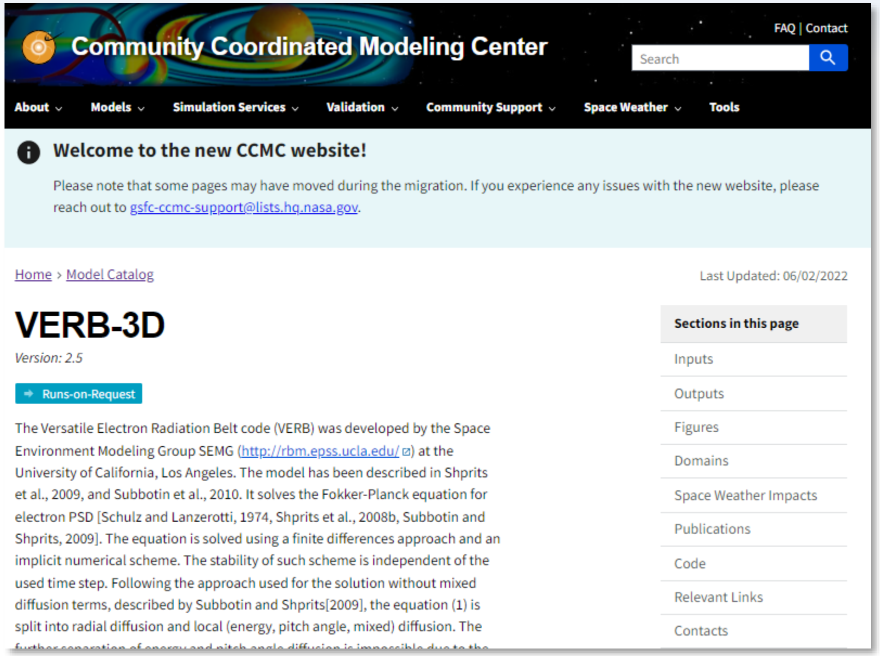


1. Find results of any VERB code simulations
   -Bf reconstructed by neural network



VERB code at CCMC (**Unfair competition**)

https://ccmc.gsfc.nasa.gov/models/VERB-3D~2.5



adrozdov@ucla.edu

1. **Find results of any VERB code simulations**
2. **Reproduce results from Shprits et al., 2009**

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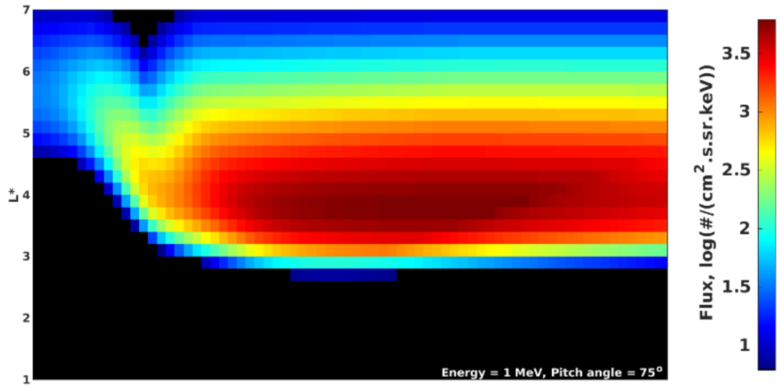
Evolution of electron fluxes in the outer radiation belt computed with the VERB code

Yuri Y. Shprits, Dmitri Subbotin, Binbin Ni

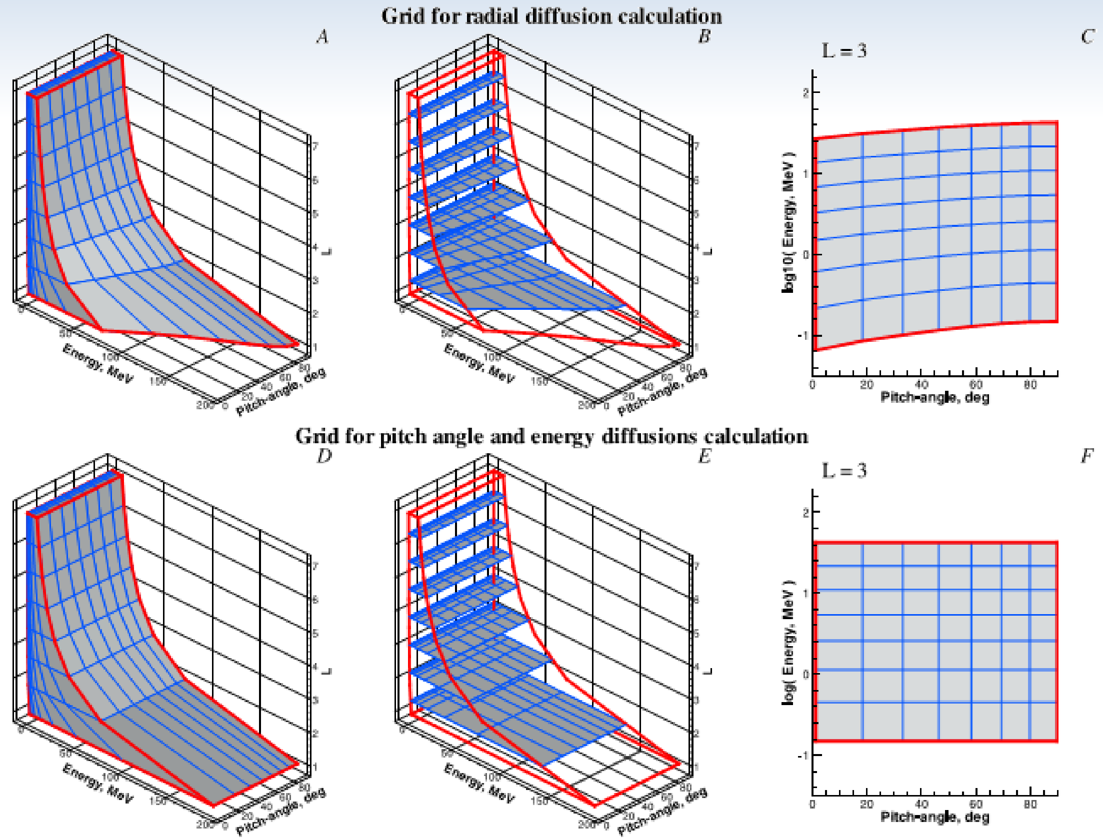
First published: 21 November 2009 | https://doi.org/10.1029/2008JA013784 | Citations: 166

Flux 1 MeV eq. pitch angle 75°

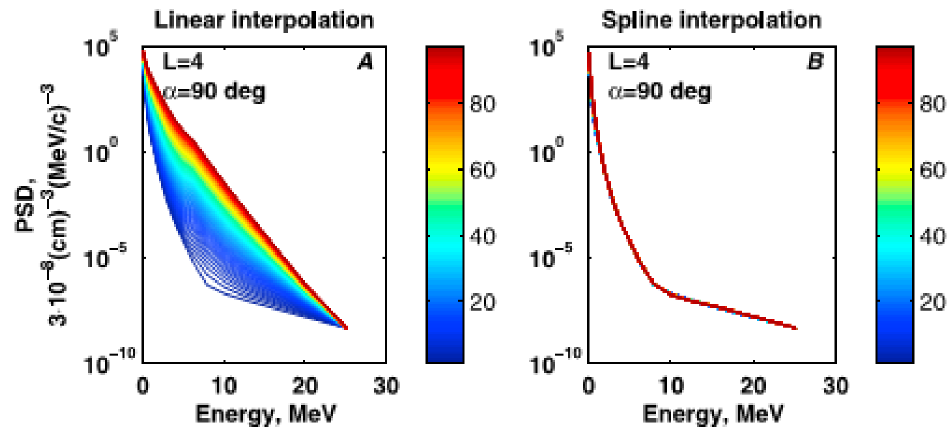


LVK GRID

Three-dimensional grids in the VERB code



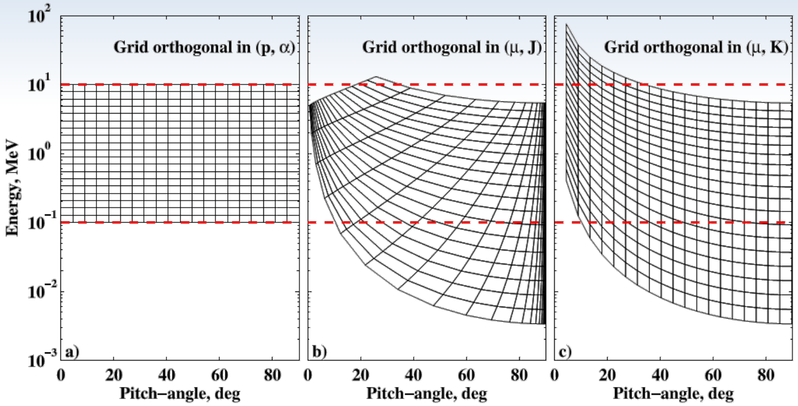
- The radial diffusion term should be solved on the (μ, J, L)
- The pitch angle and energy operators are written on the (p, α_0, L) grid. We can set the boundary conditions.
- Spline interpolation is used.



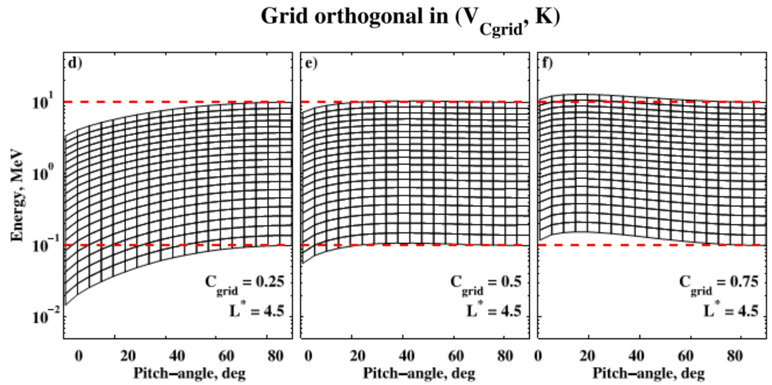
$$\frac{\partial f}{\partial t} = L^{*2}\frac{\partial}{\partial L^*}\Big|_{\mu,J}\frac{1}{L^{*2}}D_{L^*L^*}\frac{\partial f}{\partial L^*}\Big|_{\mu,J} + \frac{1}{p^2}\frac{\partial}{\partial p}\Big|_{\alpha_0,L^*}p^2\left(D_{pp}\frac{\partial}{\partial p}\Big|_{\alpha_0,L^*}f + D_{p\alpha_0}\frac{\partial}{\partial \alpha_0}\Big|_{p,L^*}f\right)$$
$$+\frac{1}{T(\alpha_0)\sin(2\alpha_0)}\frac{\partial}{\partial \alpha_0}\Big|_{p,L^*}T(\alpha_0)\sin(2\alpha_0)\left(D_{\alpha_0\alpha_0}\frac{\partial}{\partial \alpha_0}\Big|_{p,L^*}f + D_{\alpha_0 p}\frac{\partial}{\partial p}\Big|_{\alpha_0,L^*}f\right) - \frac{f}{\tau}$$

Subbotin et al, 2009

Fokker-Planck equation in the VERB code using the new invariant grid (L*,V,K)



$$V_{C_{grid}} \equiv \mu \cdot (K + C_{grid})^2$$



$$\frac{\partial f}{\partial t} = L^{*2}\frac{\partial}{\partial L^*}\Big|_{\mu,J}\frac{1}{L^{*2}}D_{L^*L^*}\frac{\partial f}{\partial L^*}\Big|_{\mu,J} + \frac{1}{p^2}\frac{\partial}{\partial p}\Big|_{\alpha_0,L^*}p^2\left(D_{pp}\frac{\partial}{\partial p}\Big|_{\alpha_0,L^*}f + D_{\alpha_0 p}\frac{\partial}{\partial \alpha_0}\Big|_{p,L^*}f\right)$$
$$+\frac{1}{T(\alpha_0)\sin(2\alpha_0)}\frac{\partial}{\partial \alpha_0}\Big|_{p,L^*}T(\alpha_0)\sin(2\alpha_0)\left(D_{\alpha_0\alpha_0}\frac{\partial}{\partial \alpha_0}\Big|_{p,L^*}f + D_{\alpha_0 p}\frac{\partial}{\partial p}\Big|_{\alpha_0,L^*}f\right) - \frac{f}{\tau}$$

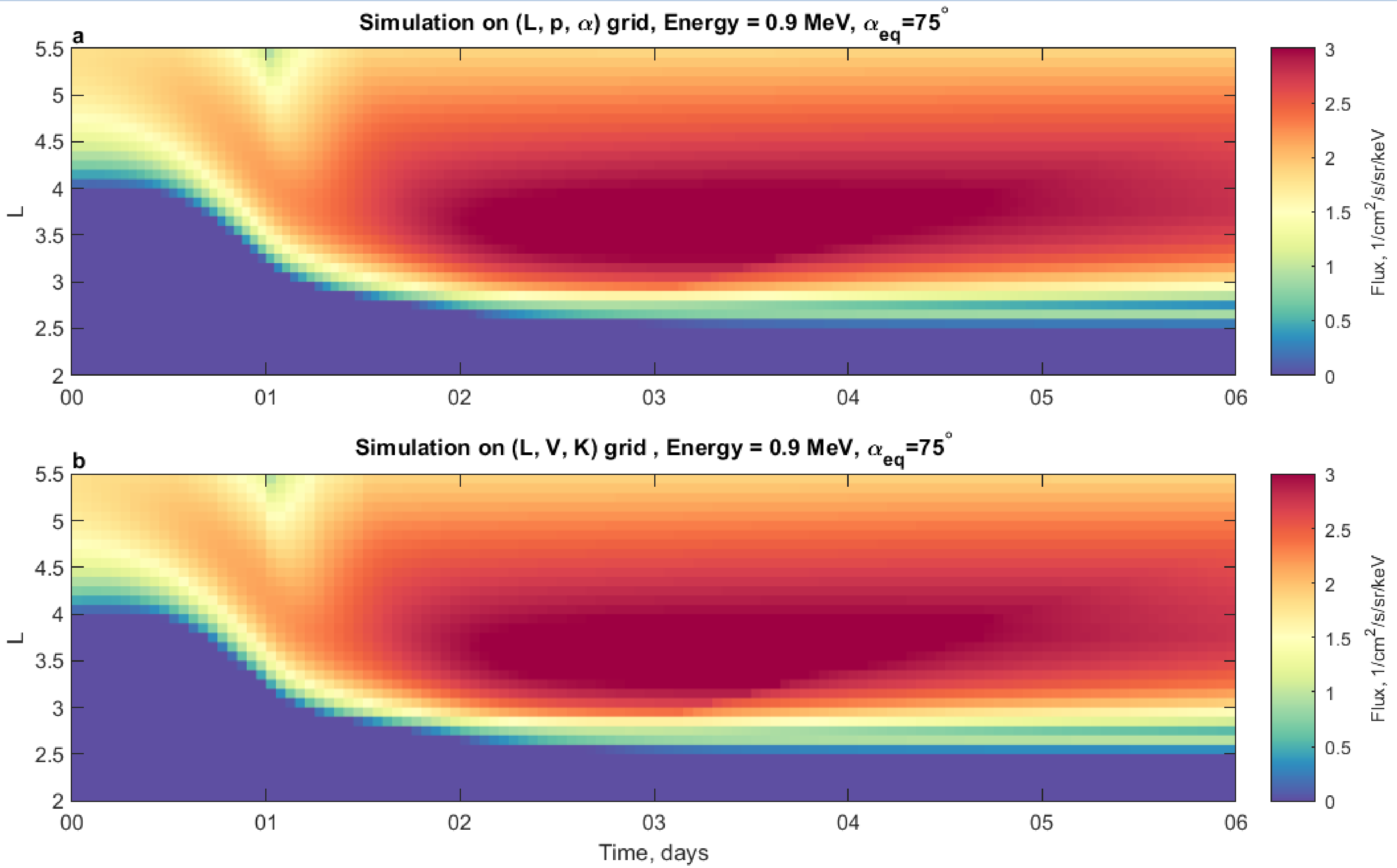
$$\frac{\partial f}{\partial t} = \frac{1}{G}\frac{\partial}{\partial L^*}G D_{L^*L^*}\frac{\partial f}{\partial L^*}$$
$$+\frac{1}{G}\frac{\partial}{\partial V}G\left(D_{VV}\frac{\partial f}{\partial V} + D_{VK}\frac{\partial f}{\partial K}\right)$$
$$+\frac{1}{G}\frac{\partial}{\partial K}G\left(D_{KK}\frac{\partial f}{\partial K} + D_{VK}\frac{\partial f}{\partial V}\right) - \frac{f}{\tau}$$

- Radial diffusion
- Local diffusion (hiss, chorus, EMIC)
- Loss term

- The (L*,V,K) grid can be used for the computation of radial and local energy and pitch angle diffusion.
- Since the lines of constant $V_{0.5}$ are almost parallel to the lines of constant energy, while K grid lines are parallel to the lines of constant pitch angle, the same boundary conditions can be imposed on the (V, K, L*) grid as on the (p, α_0, L*) grid

Subbotin and Shprits., 2012

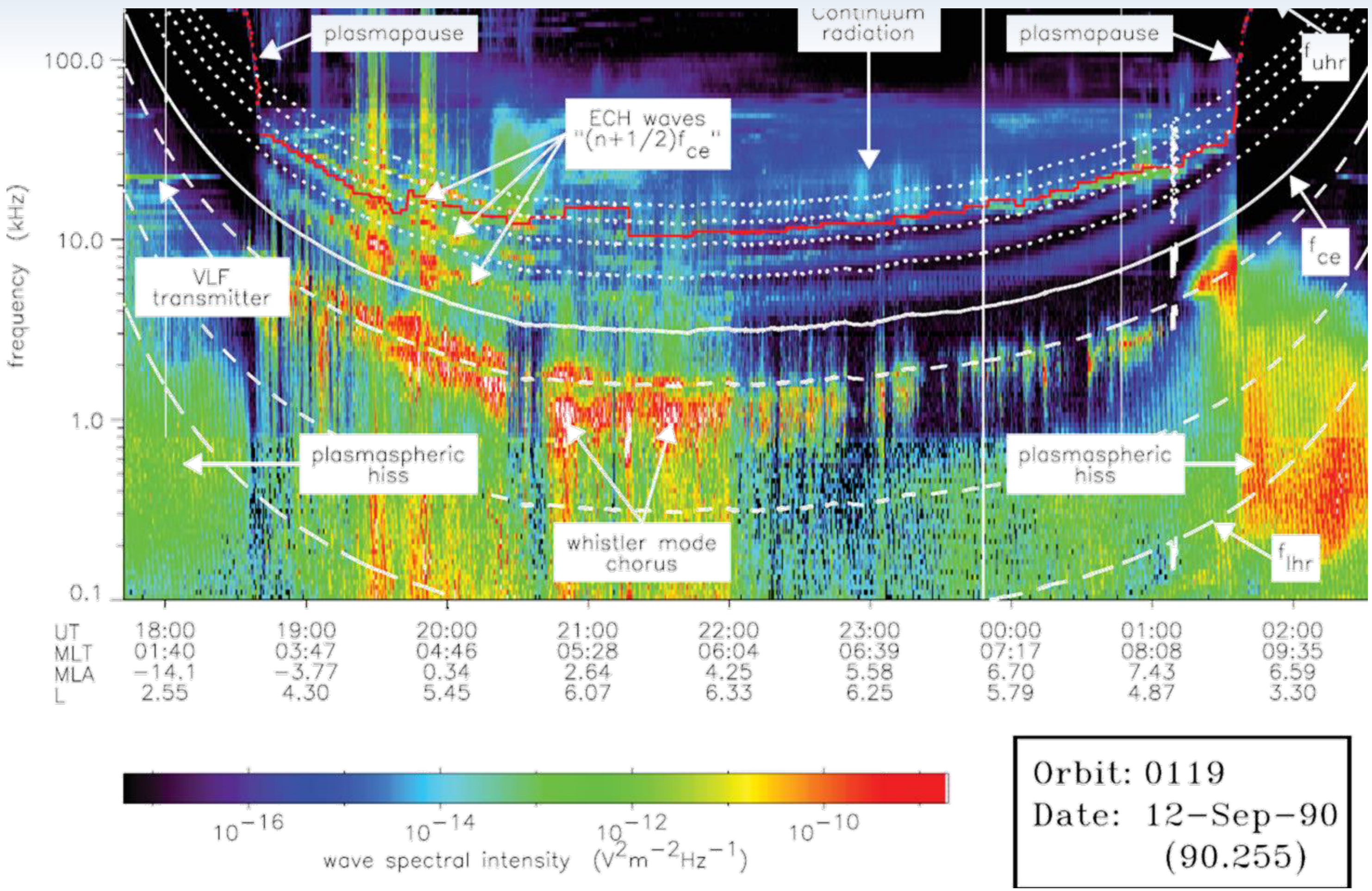
Simulations on different grids



The VERB code

MORE PRACTICAL RESULTS

Waves inside the magnetosphere



Meredith at al, 2003

Comparison between observations and model

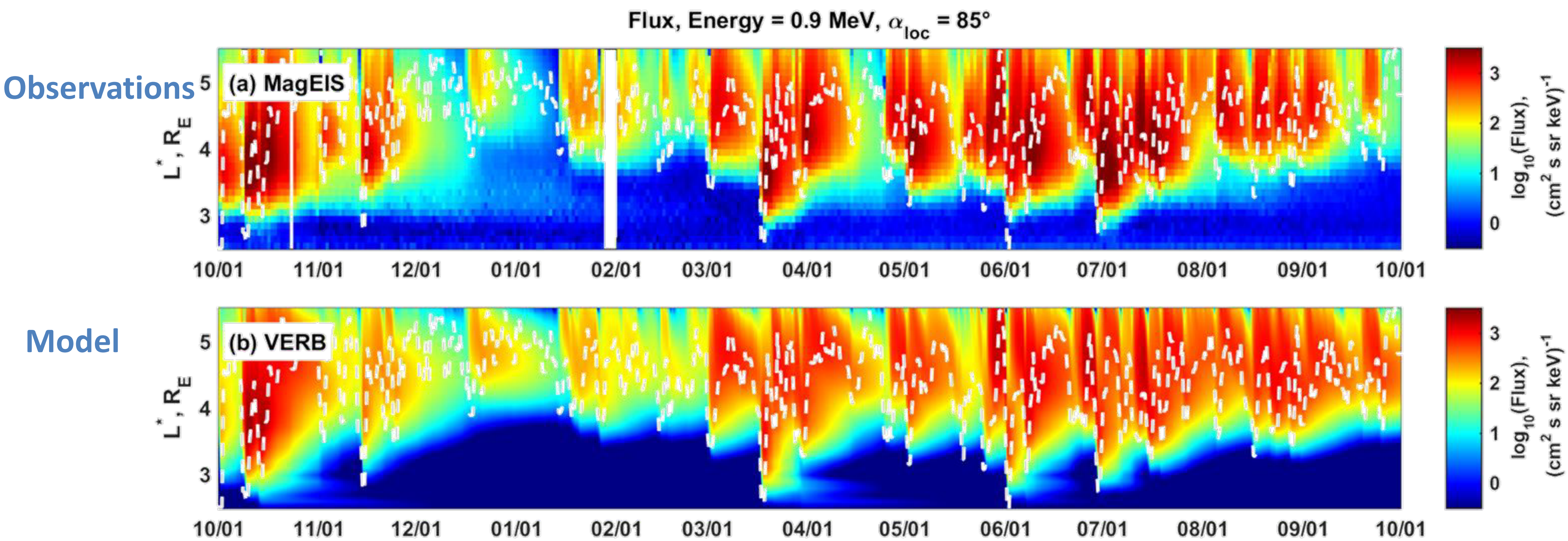
Observations

vs

Model

Comparison between observations and model

We reproduce the dynamics of relativistic electrons (~1 MeV)



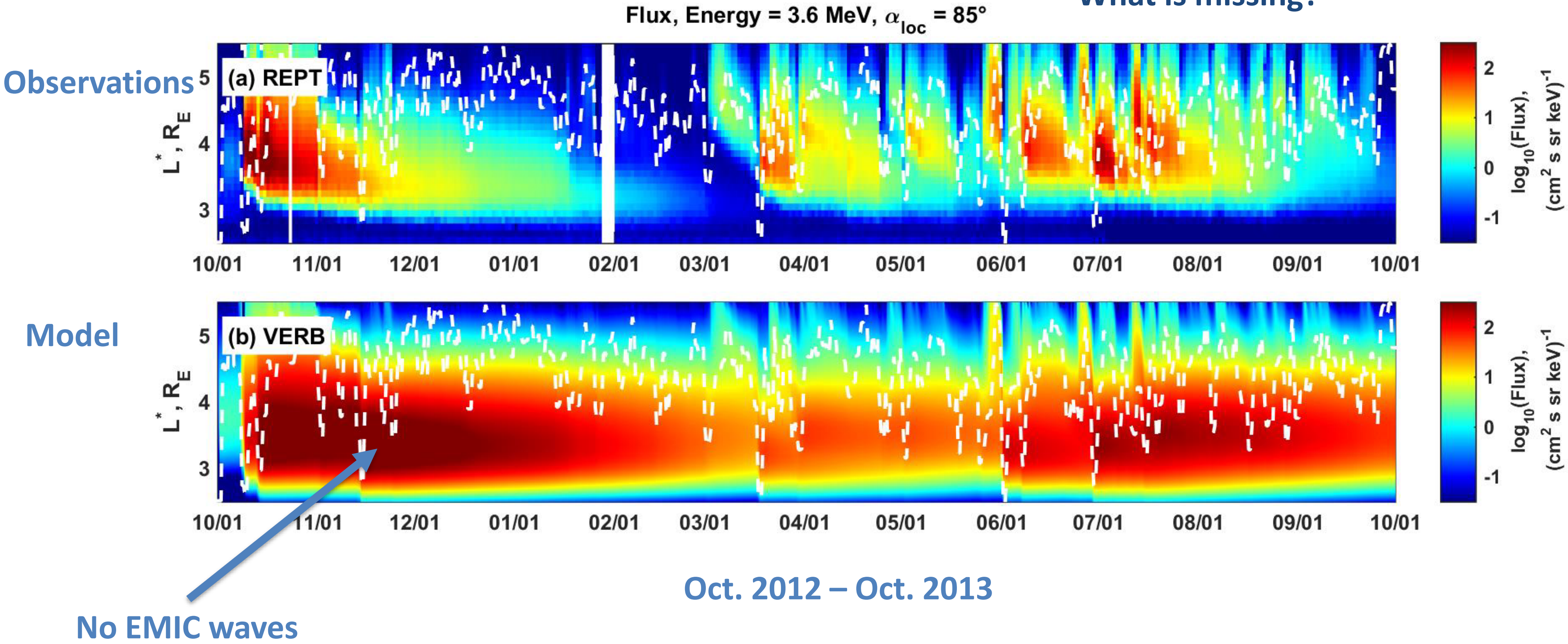
Oct. 2012 – Oct. 2013

Drozdov et al., 2015

Comparison between observations and model

We reproduce the dynamics of relativistic electrons (~1 MeV), but not for the ultra-relativistic energies (> ~2 MeV)

What is missing?



Oct. 2012 – Oct. 2013

Drozdov et al., 2015

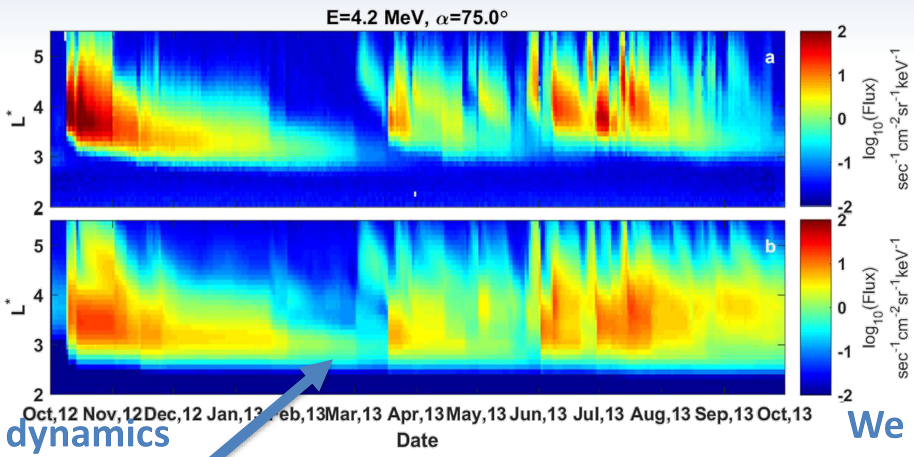
Some VERB code simulation results

Drozdov et al. 2017

Oct. 2012 – Oct. 2013

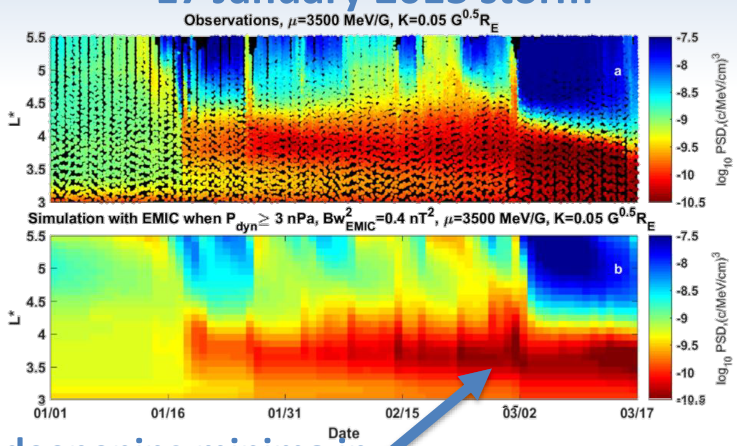
Observations
REPT 4.2 MeV

Model
with 0.4 nT² EMIC
parameterized with
$P_{dyn} \geq 3$ nPa

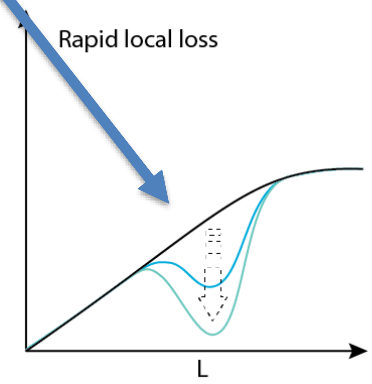


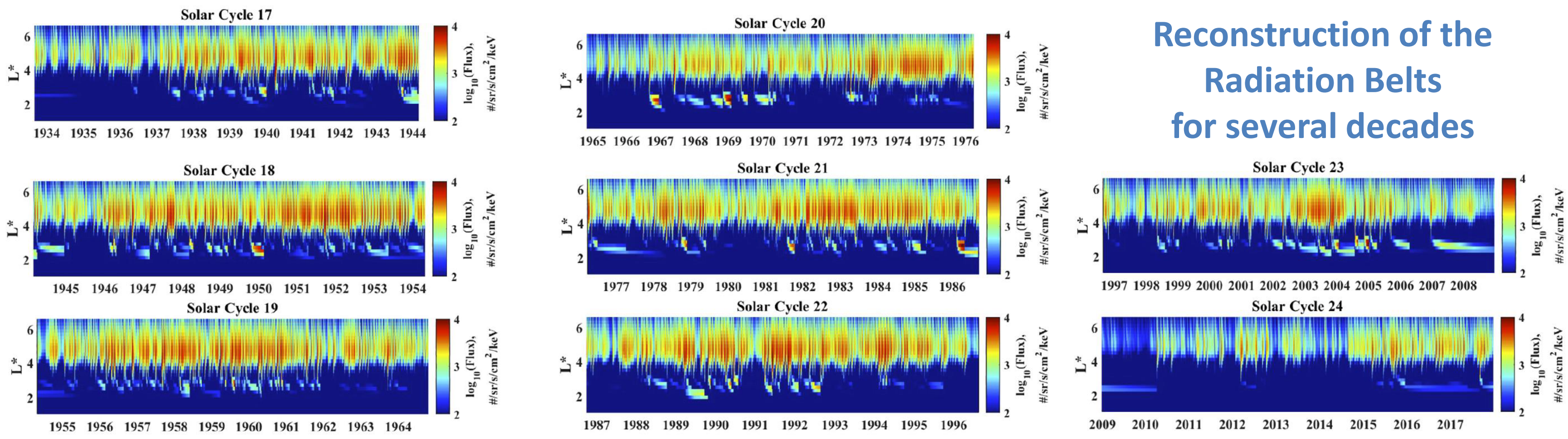
We reproduce the dynamics of multi-MeV electrons

17 January 2013 storm



We reproduce deepening minima in PSD (the colorbar is inverted)



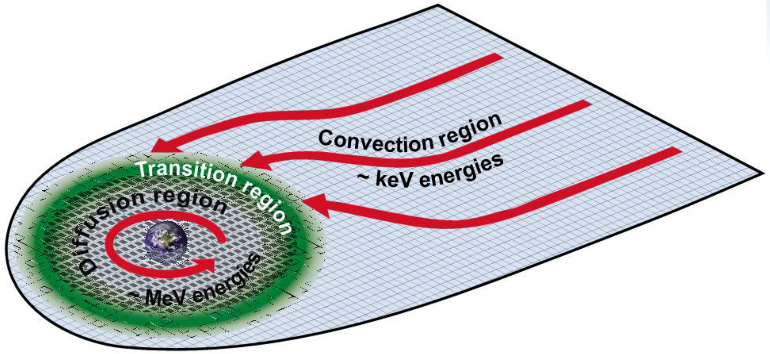


Reconstruction of the Radiation Belts for several decades

Saikin et al. 2021

4D SIMULATIONS

4D simulations



The IRBEM library can be used to calculate to calculate E × B and gradient-curvature **drift velocities** (with electric field model, e.g. Weimer (2005).

$$< \boldsymbol{V}_0 > = < \boldsymbol{V_F} > + < \boldsymbol{V_{GC}} >$$

$$\boldsymbol{V_F} = \frac{\boldsymbol{E} \times \boldsymbol{B_0}}{{B_0}^2}$$

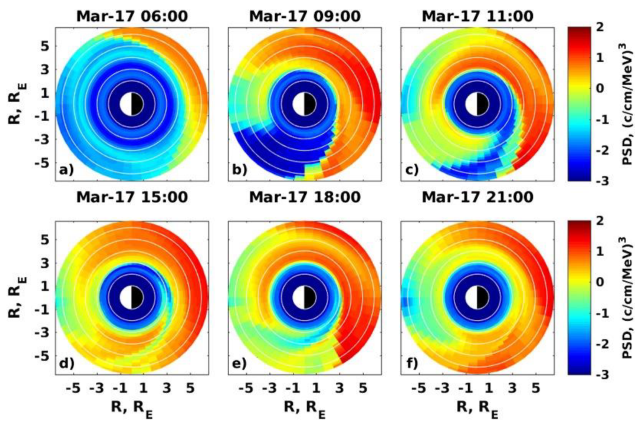
$$\boldsymbol{V_{GC}} = \frac{\sqrt{8 m_0 \mu}}{q \tau_B B_0^2} \boldsymbol{\nabla_0 K} \times \boldsymbol{B_0}$$

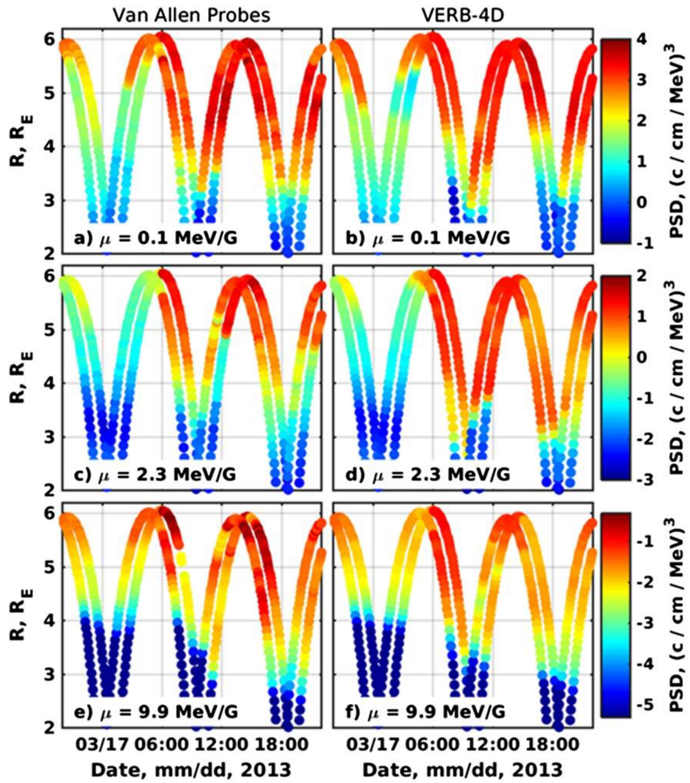
LGPL v3 **IRBEM library** COSPAR

Equation of the 4D simulation in the VERB code

$$\frac{\partial f}{\partial t} = -\langle v_\phi \rangle \frac{\partial f}{\partial \phi} - \langle v_R \rangle \frac{\partial f}{\partial R} + \frac{1}{G} \frac{\partial}{\partial L^*} G D_{L^*L^*} \frac{\partial f}{\partial L^*} + \frac{1}{G} \frac{\partial}{\partial V} G \left(D_{VV} \frac{\partial f}{\partial V} + D_{VK} \frac{\partial f}{\partial K} \right) + \frac{1}{G} \frac{\partial}{\partial K} G \left(D_{KK} \frac{\partial f}{\partial K} + D_{VK} \frac{\partial f}{\partial V} \right) - \frac{f}{\tau}$$

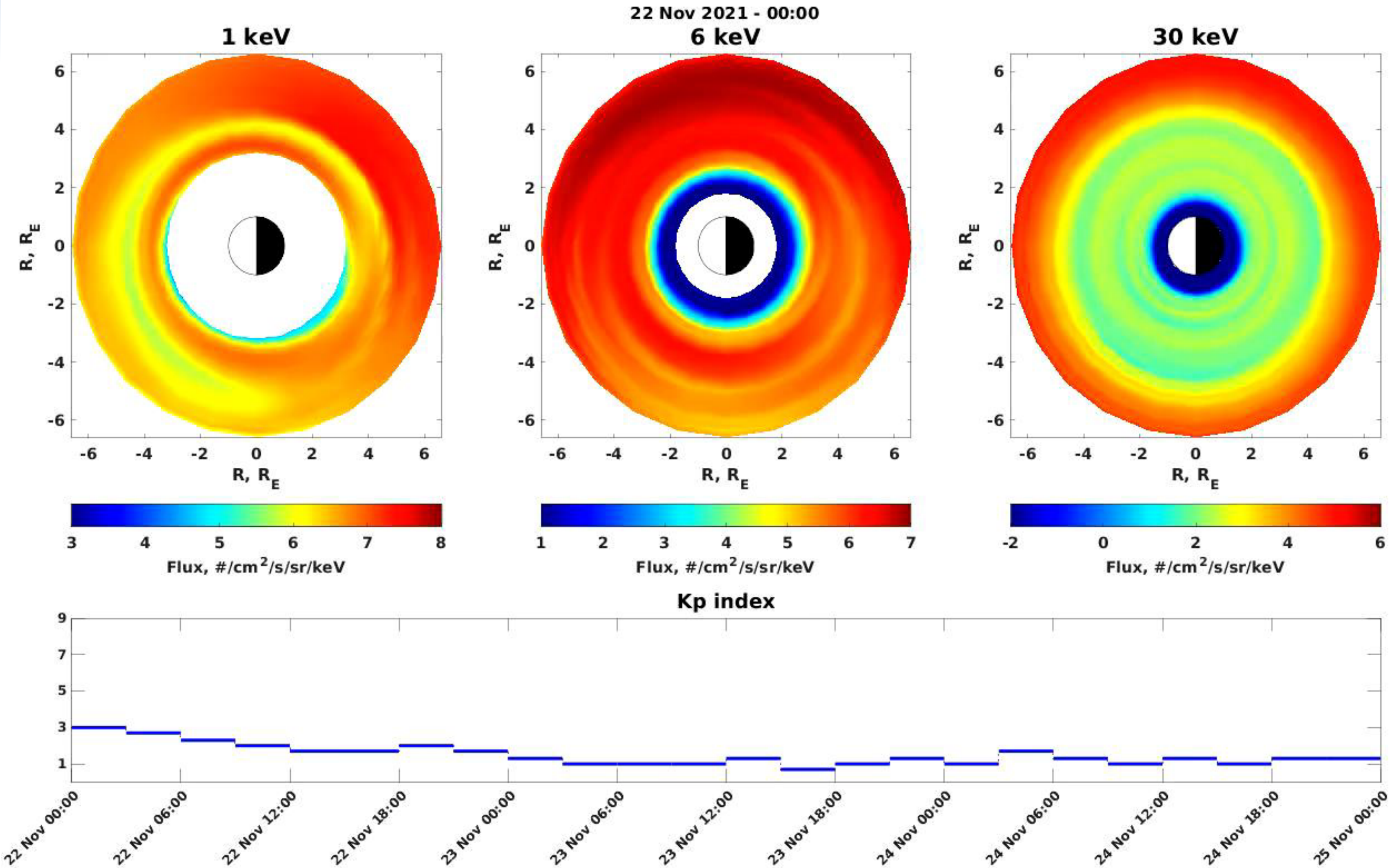
The storm time dynamics of the low energy electrons is reproduced relatively well by the VERB-4D code.



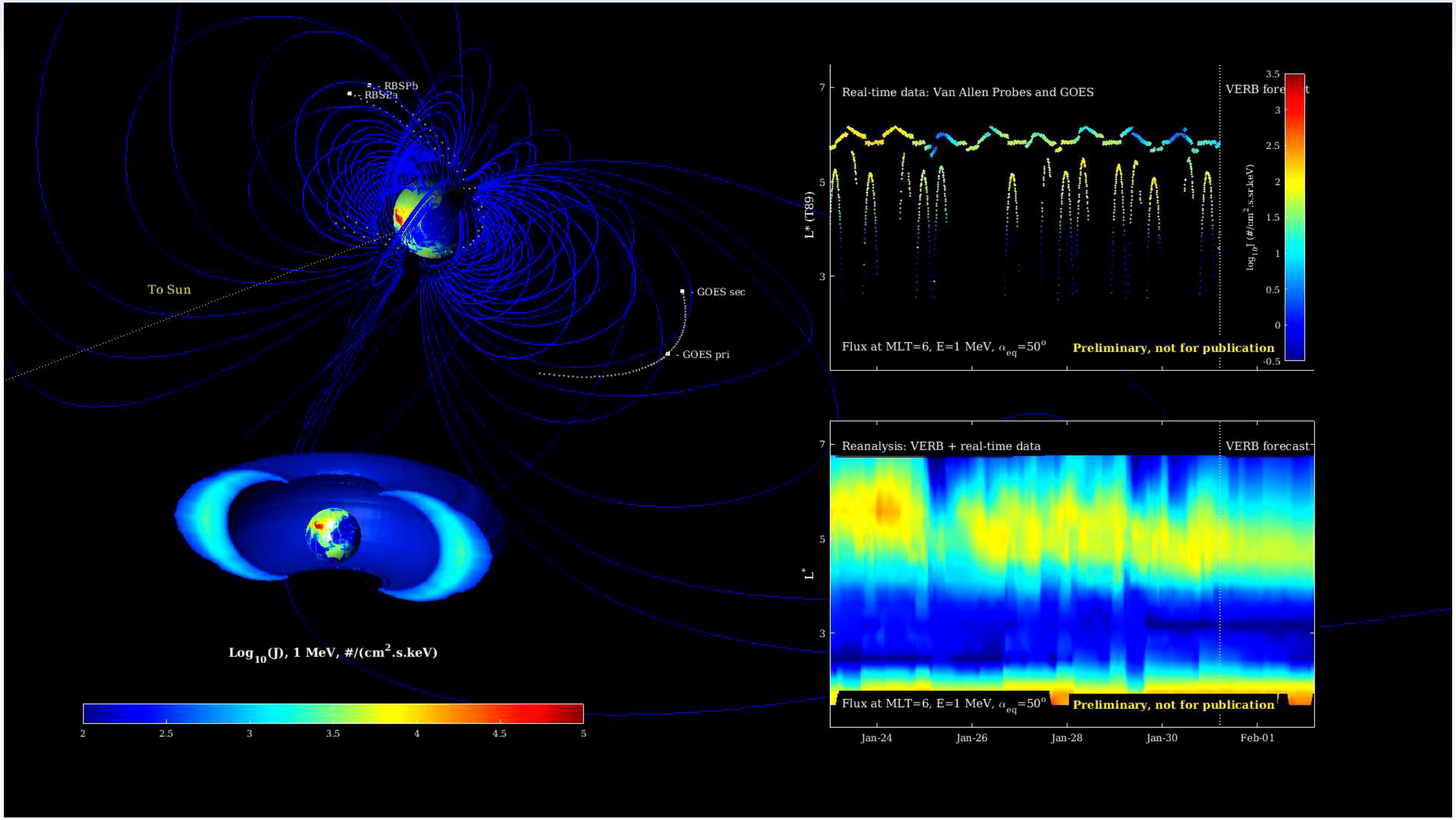


Aseev et al., 2019

Electron ring current dynamics



Radiation belts



THANK YOU