Simulations of the inner magnetospheric energetic electrons using the IMPTAM-VERB coupled model

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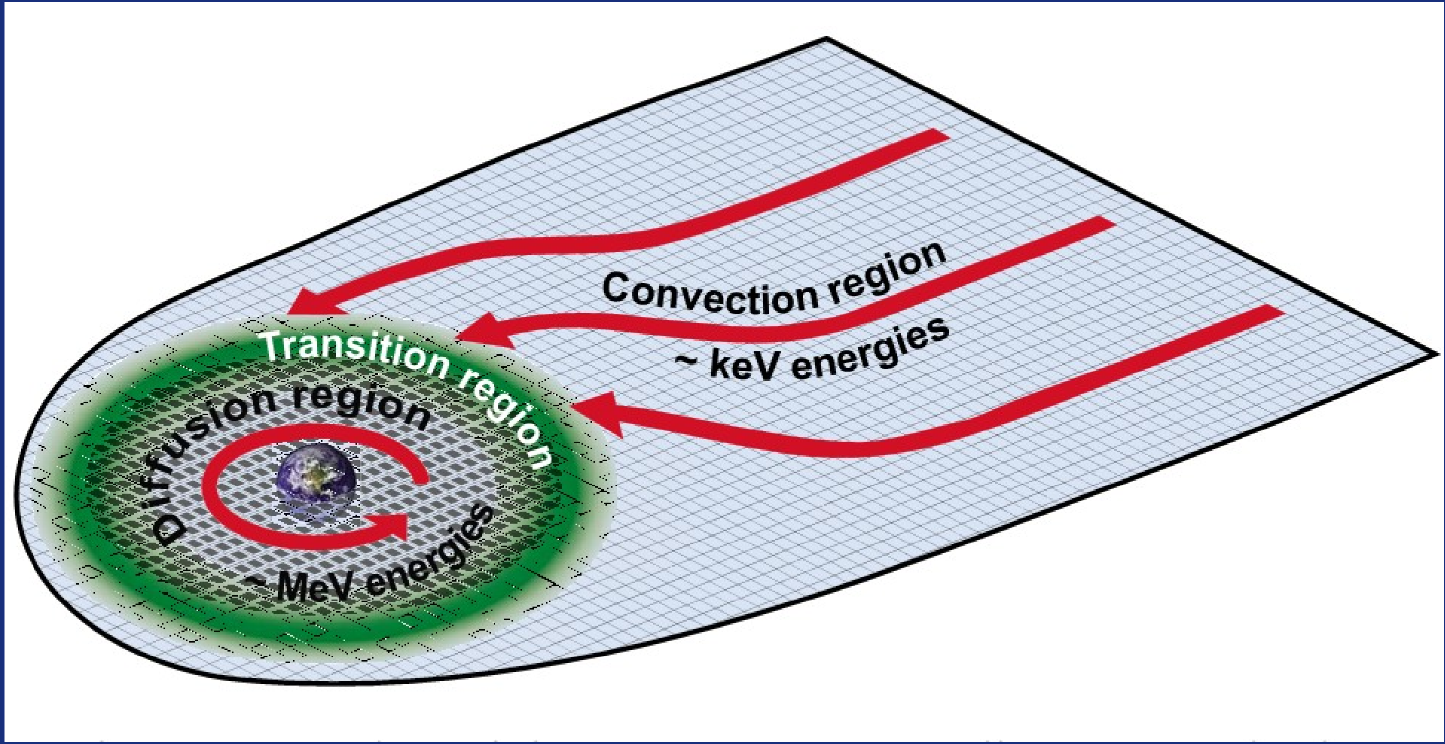
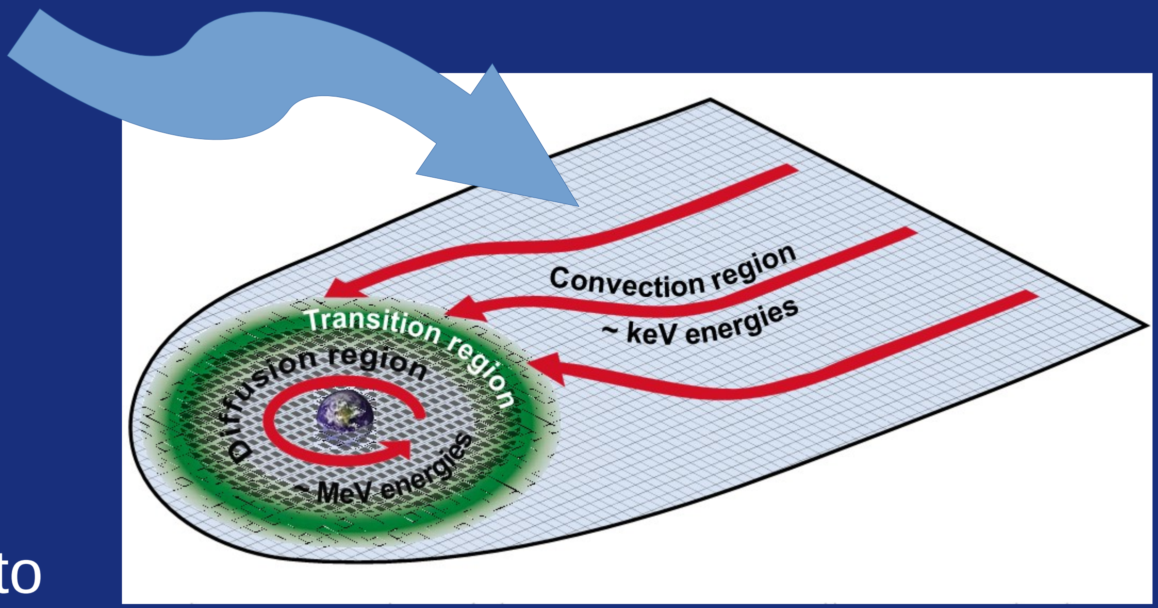
Introduction

- Low energy electrons in the ring current can be accelerated up to MeV energies during geomagnetic storms and become the drivers of the radiation belt dynamics. In that sense, low energy electrons are the “seed population” of the radiation belts
- Accounting only for the dominant particle transport mechanism at the different regions of the magnetosphere acting on low energy and energetic electrons, it can be divided into 2 dynamic regions:



Introduction

- Convection zone: the dominant transport mechanism of particles is convection.
- Convection is mostly important for low energy particles with energies up to a few 100s of keV.
- ExB drift dominant motion for particles at such energies

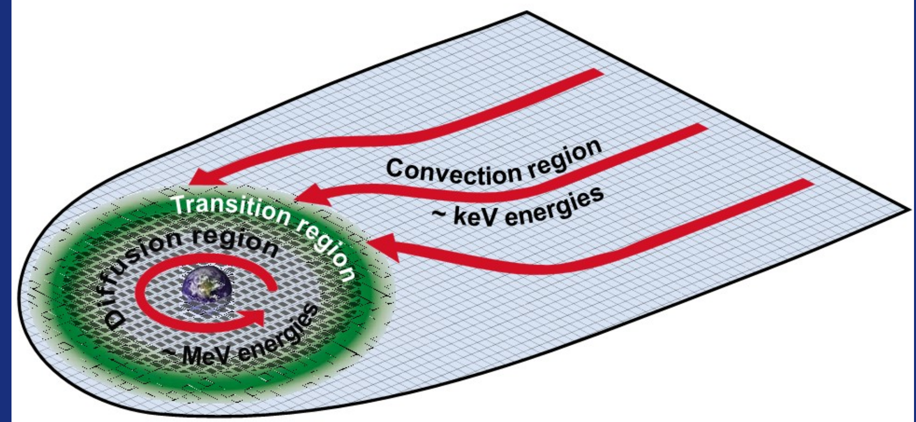


$$\mathbf{v}_E = \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$

where **E** and **B** are the electric and magnetic field vectors

Introduction

- <u>Diffusion zone</u>: dominant transport mechanism is diffusion (radial, energy, pitch angle, mixed energy diffusion)
- Diffusion transport is more effective on energetic particles (several 100s of keV and a few MeV)
- Dominant motion type in this region are the gradient and curvature drifts



Gradient Drift: $$\mathbf{v}_\nabla = \frac{m v_\perp^2}{2q B^3} (\mathbf{B} \times \nabla B)$$

Curvature Drift: $$\mathbf{v}_R = \frac{m v_\parallel^2}{q R_c^2 B^2} (\mathbf{R}_c \times \mathbf{B})$$

radius of curvature $\mathbf{R}_c$ of the magnetic field lines

Coupling strategy

- Model the electrons in the radiation belt region of the Earth by considering the dynamics of the electron seed population
- How to do it?
  - Combine available physics-based models of each dynamic region to compute the dynamics of each electron population.
  - IMPTAM traces low energy electrons from the plasma sheet (~ 9 Re) to geosynchronous orbit (6.6 Re).
  - The electron evolution modeled by IMPTAM is used to drive VERB-3D simulations, which describe the evolution of energetic electrons in the inner magnetosphere.

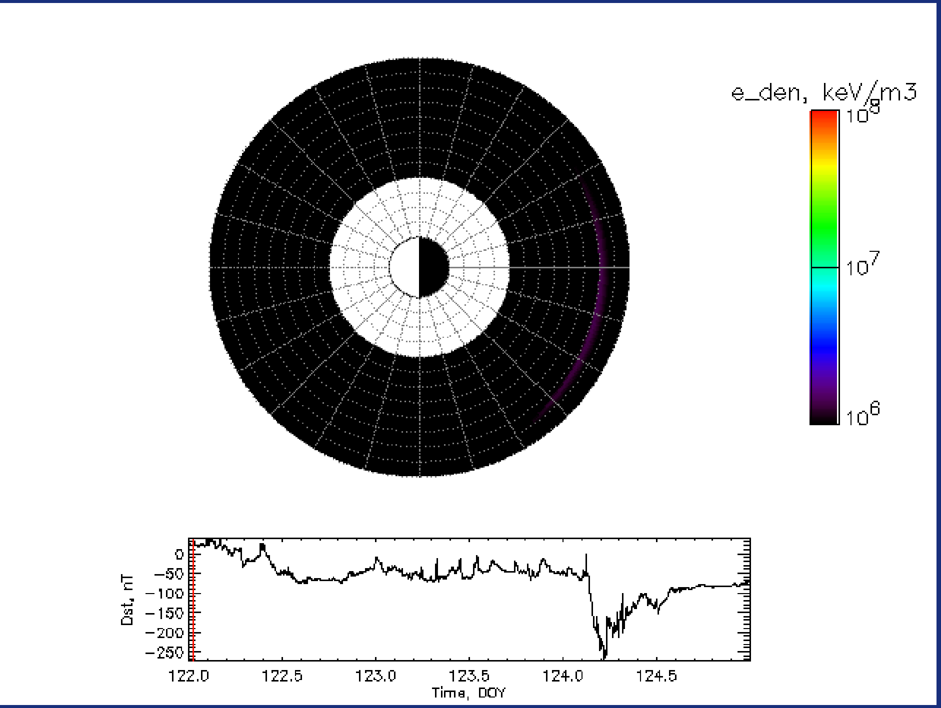
Models: IMPTAM and VERB-3D

Models: IMPTAM

IMPTAM: The Inner Magnetospheric Particle Transport and Acceleration Model

- The model traces ions and electrons with energies up to 100s of keV from the plasma sheet to inner L-shell regions in time-dependent magnetic and electric fields

- Accounts for: radial and pitch angle diffusion, wave-particle interactions, losses to the atmosphere, coulomb collions, a.o.



Models: VERB-3D

VERB-code: Versatile Electron Radiation Belt code, here only 3D

- Describes the dynamics and evolution of electrons in the radiation belts calculating a numerical solution of the 3D Fokker-Planck equation (Energies: 100s of keV to MeV)

$$\frac{\partial f}{\partial t} = \boxed{L^{*2}\frac{\partial}{\partial L^*}\bigg|_{J_1,J_2} \frac{1}{L^{*2}} D_{L^*L^*}\frac{\partial f}{\partial L^*}\bigg|_{J_1,J_2}} +$$

$$+\boxed{\frac{1}{p^2}\frac{\partial}{\partial p}\bigg|_{L,\alpha_0} p^2\left(D_{pp}\frac{\partial f}{\partial p}\bigg|_{L,\alpha_0} + D_{p\alpha_0}\frac{\partial f}{\partial \alpha_0}\bigg|_{L,p}\right)} +$$

$$+\boxed{\frac{1}{T(\alpha_0)\sin(2\alpha_0)}\frac{\partial}{\partial \alpha_0}\bigg|_{L,p} T(\alpha_0)\sin(2\alpha_0)\left(D_{\alpha_0 p}\frac{\partial f}{\partial p}\bigg|_{L,\alpha_0} + D_{\alpha_0\alpha_0}\frac{\partial f}{\partial \alpha_0}\bigg|_{L,p}\right)} +$$

$$+ Sources - Losses$$

RADIAL DIFFUSION

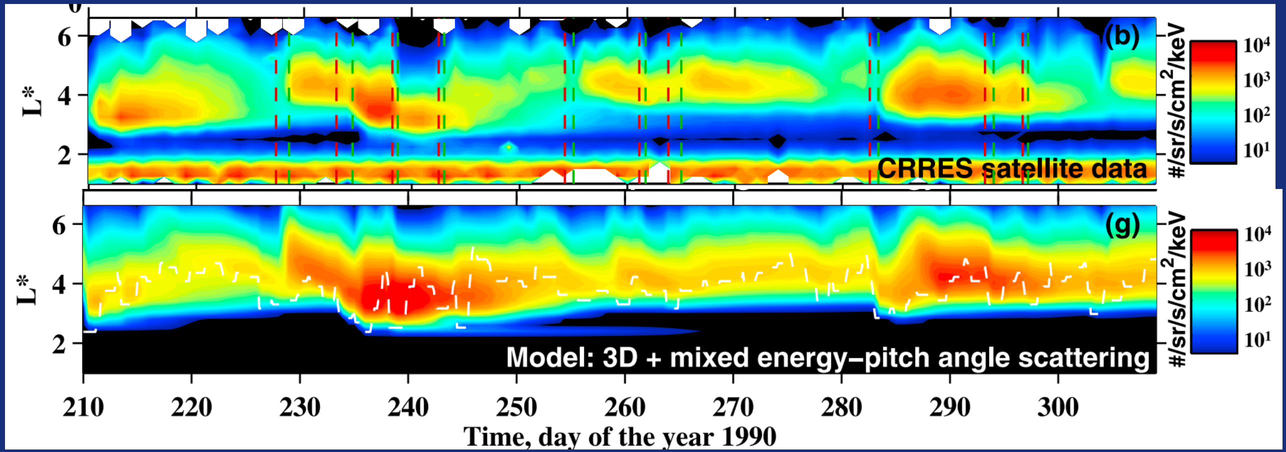
ENERGY DIFFUSION RESULTS IN LOCAL ACCELERATION

PITCH ANGLE DIFFUSION CAUSES LOSS INTO THE ATMOSPHERE

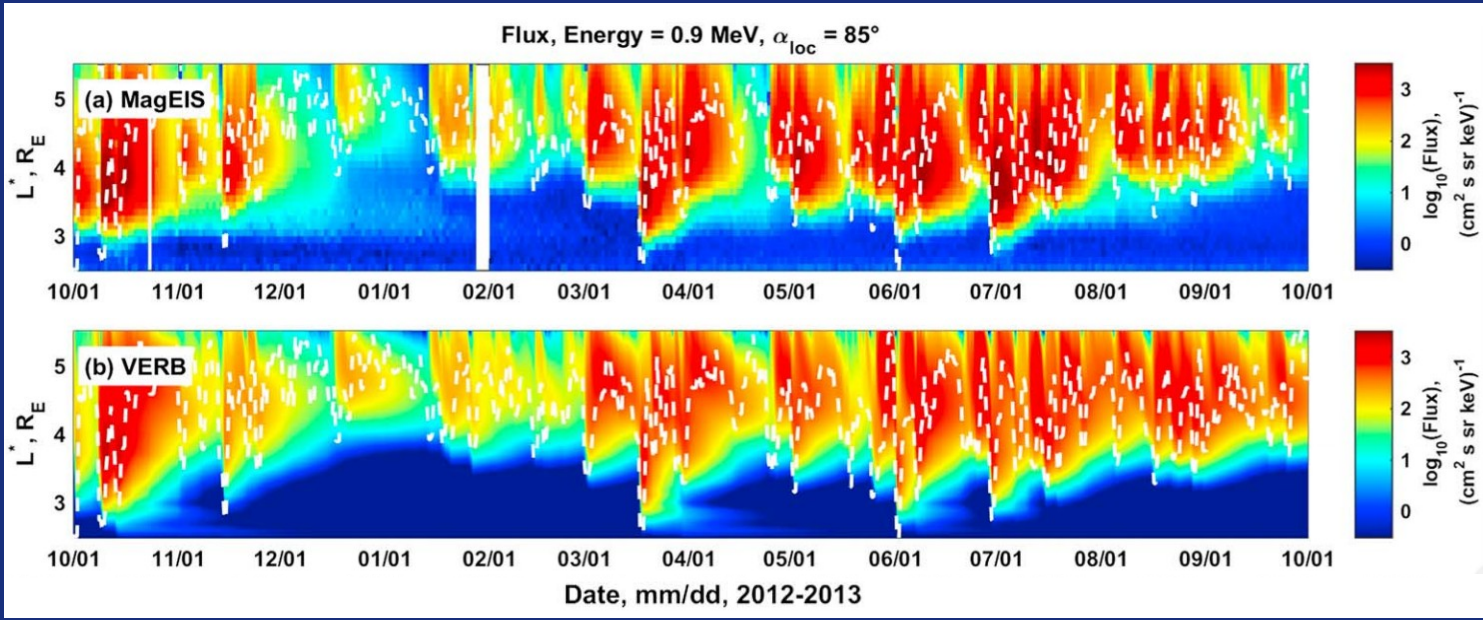
[Haerendel, G. 1968; Schult and Lanzerotti., 1974; Shprits et al., 2008]

Models: VERB-3D

- Wave-particle interactions: chorus (dayside, nightside), hiss, VLF-transmitters, lightning, EMIC
- magnetopause losses



Subbotin et al. 2011



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Models: IMPTAM vs. VERB-3D

IMPTAM

- Ring current model
- MLT - dependent
- Computes particle dynamics due to convective transport
- Tracing of particles from the plasma sheet into inner magnetosphere
- Electrons with energies from 10 keV to a few 100s of keV

VERB-3D

- Model of the radiation belts
- MLT - independent
- Computes particle dynamics due to diffusion processes
- Assumes particles are trapped in the radiation region
- Electrons with energies from some 100s of keV up to a few MeV

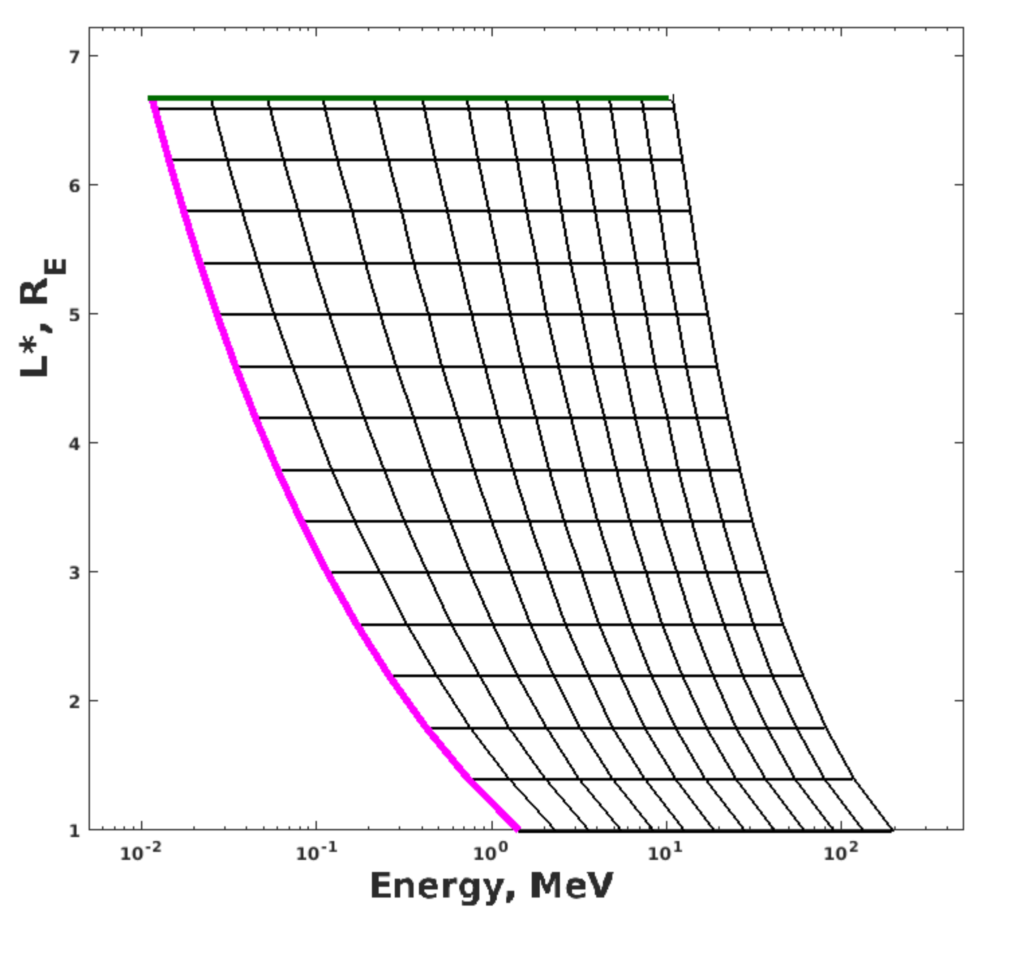
Code Coupling

Coupling of simulation codes:

1) Simulation of time period of interest using the convection code (IMPTAM)
2) The results from this simulation are used as boundary conditions to drive the simulations with the diffusion code (VERB-3D)
3) Electron fluxes modeled by IMPTAM are used as low energy and outer radial boundaries for VERB-3D simulations

The coupled model takes into account magnetospheric convection and diffusion

2D Section of the computational grid of VERB-3D code



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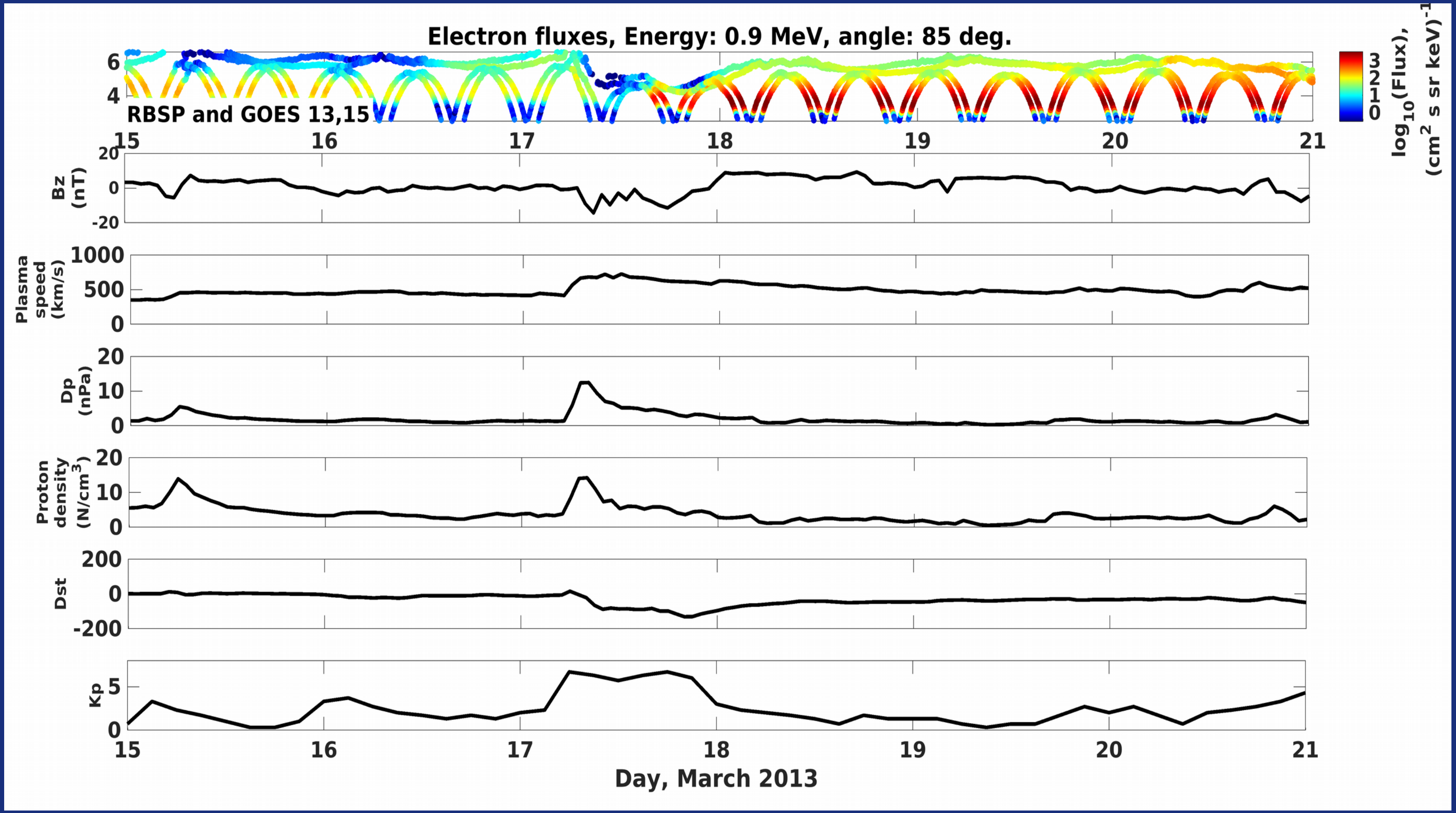
Geomagnetic Event
March 17th, 2013 storm



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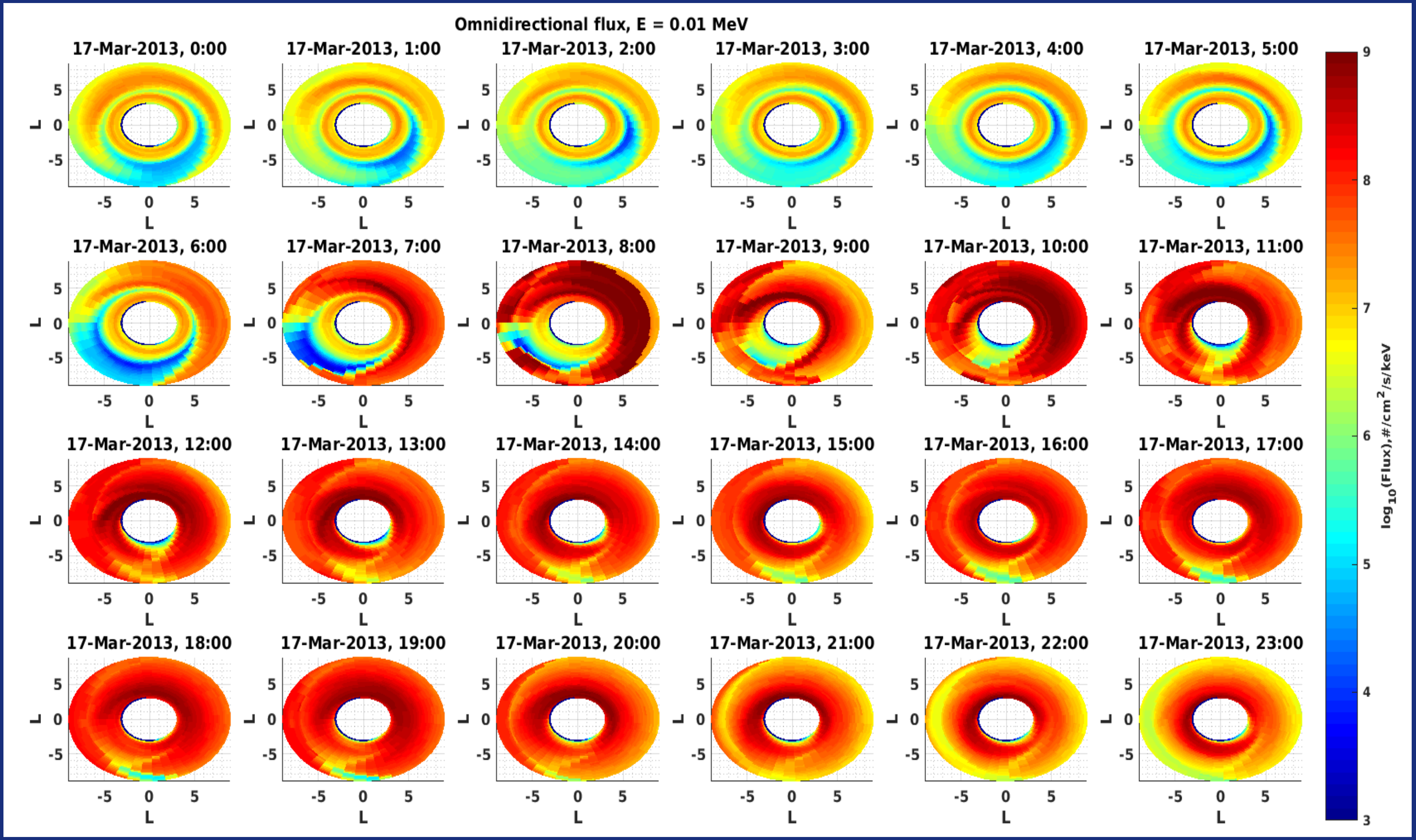
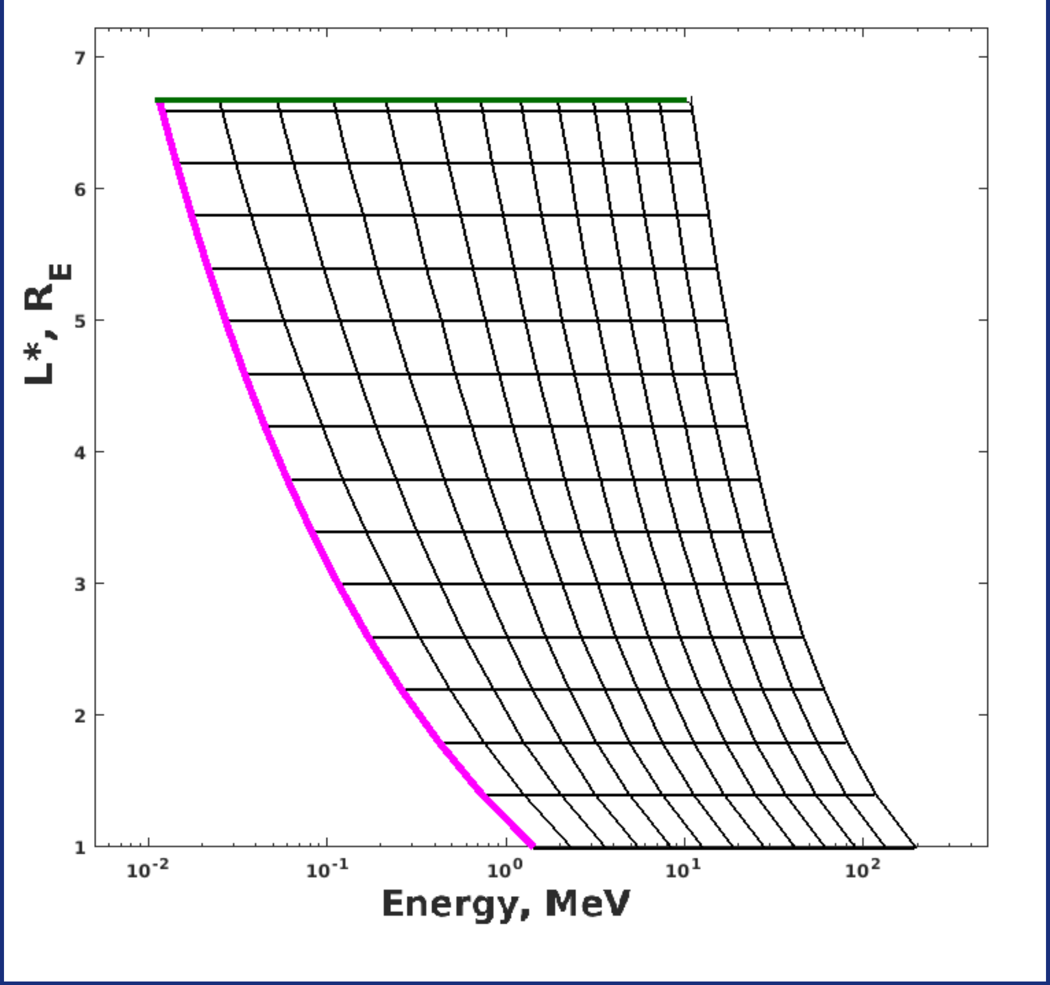
IMPTAM model, 10 keV Electrons



Processing IMPTAM output

- IMPTAM and VERB-3D operate in different computational grids
- IMPTAM is MLT dependent, while VERB-3D is not
- MLT average of the IMPTAM output necessary
- Further adaptation of the output due to resolution of the 3D grid
- Once this is done, we can extract the boundary conditions we want to use and set up the VERB-3D simulations



Setup for VERB simulations

- Grid size: 49x101x91 (L*,Energy,alpha)
- Six boundary conditions
- Initial conditions are the solution of the steady state radial diffusion equation

Table 2. Boundary Conditions Used for the VERB Code Simulations

Boundary	Condition	Underlying Physical Processes
$\alpha_0 = 0°$	$\partial\,(PSD)/\partial\alpha_0 = 0$	strong and weak diffusion regimes
$\alpha_0 = 90°$	$\partial\,(PSD)/\partial\alpha_0 = 0$	flat pitch angle distribution
$L^* = 1$	$PSD = 0$	losses to the atmosphere
$L^* = 6.6$	$PSD\ (time)$	coupling with IMPTAM
$E = E_{\mathrm{min}}$	$PSD\ (time)$	coupling with IMPTAM
$E = E_{\mathrm{max}}$	$PSD = 0$	absence of multi-MeV energy electrons

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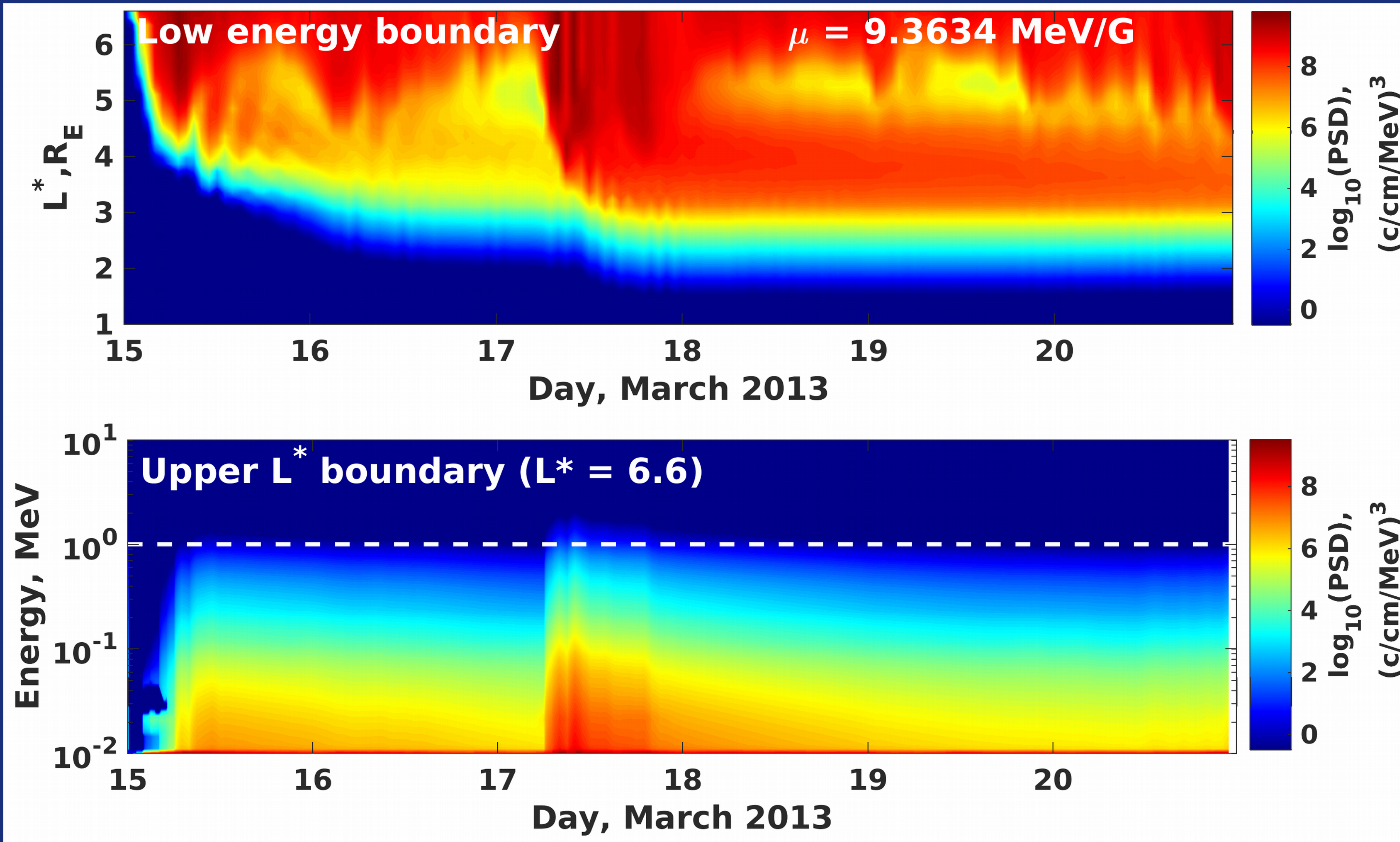
Low-energy and outer L* boundaries from IMPTAM



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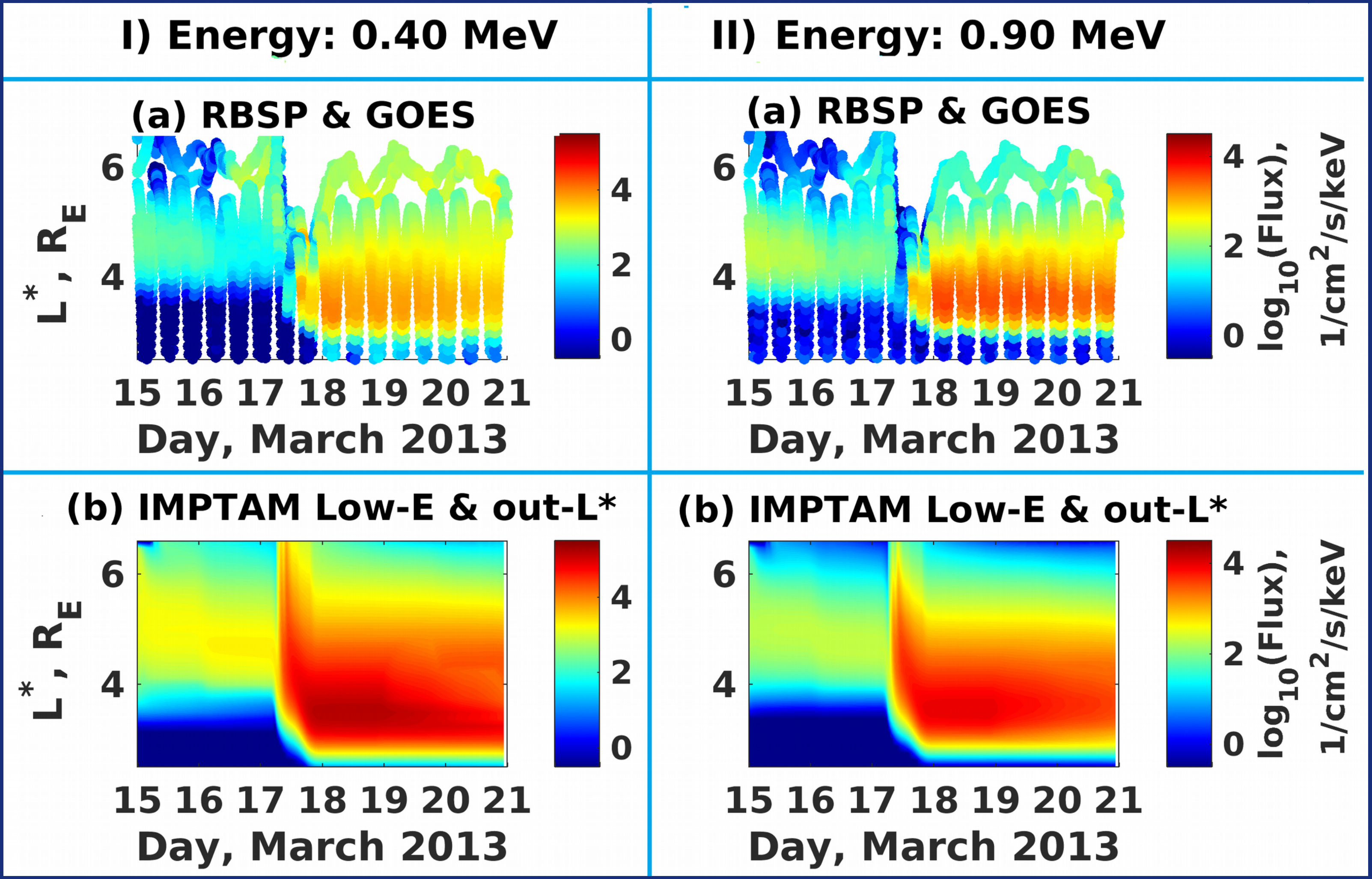
Simulations IMPTAM-VERB



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Summary

- Our simulation with the coupled model has proven to be successful
- General intensification of electron fluxes in the ring current and in the radiation belts is well reproduced by the coupled model
- Improvement could be achieved by including more accurate loss rates in the IMPTAM model and magnetopause losses in the VERB-code