Radiation Belt Variability due to Wave-Particle Interactions: A Multiscale Modeling Approach

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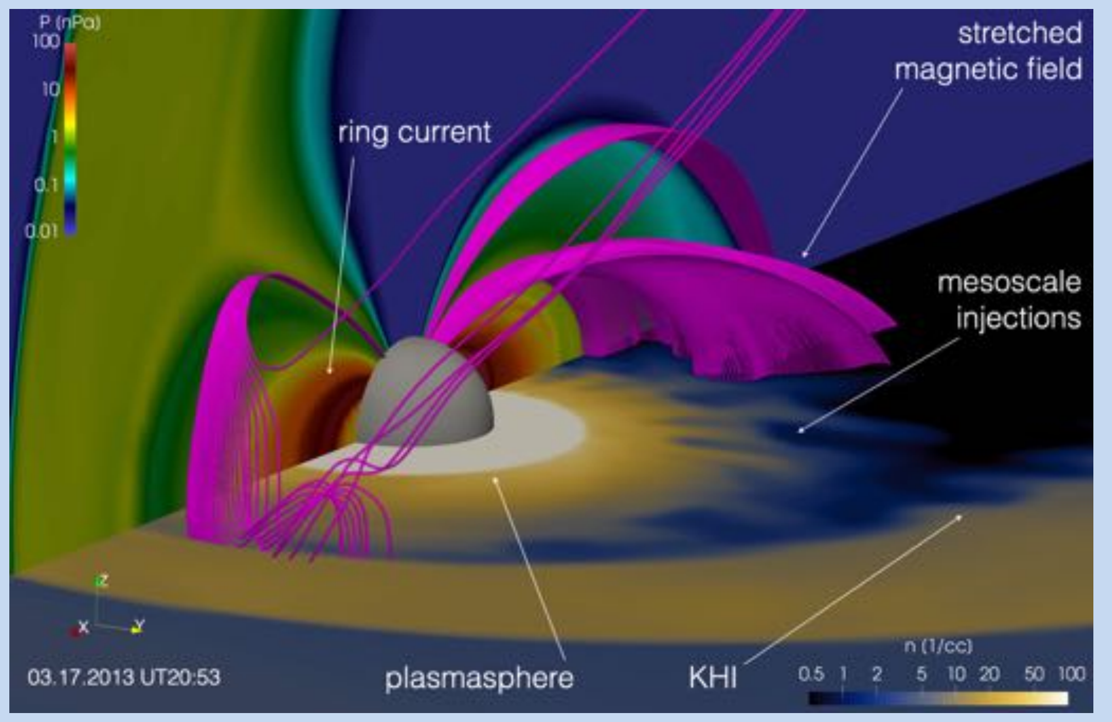
Introduction

Understanding the variability of radiation belt intensities has remained a major challenge due, in part, to local acceleration and loss mechanisms often occurring simultaneously with large-scale convection and discrete, mesoscale (~1 Re) plasma sheet injections.

Global magnetosphere and test particle simulations are capable of capturing evolution through realistic electromagnetic fields, including mesoscale dynamics necessary for radial transport and buildup of the radiation belts; however, until recently, they have lacked microscale energization and scattering processes.

We have incorporated wave-particle interactions into our test particle model to describes all key global-to microscale processes of relativistic electron acceleration and loss

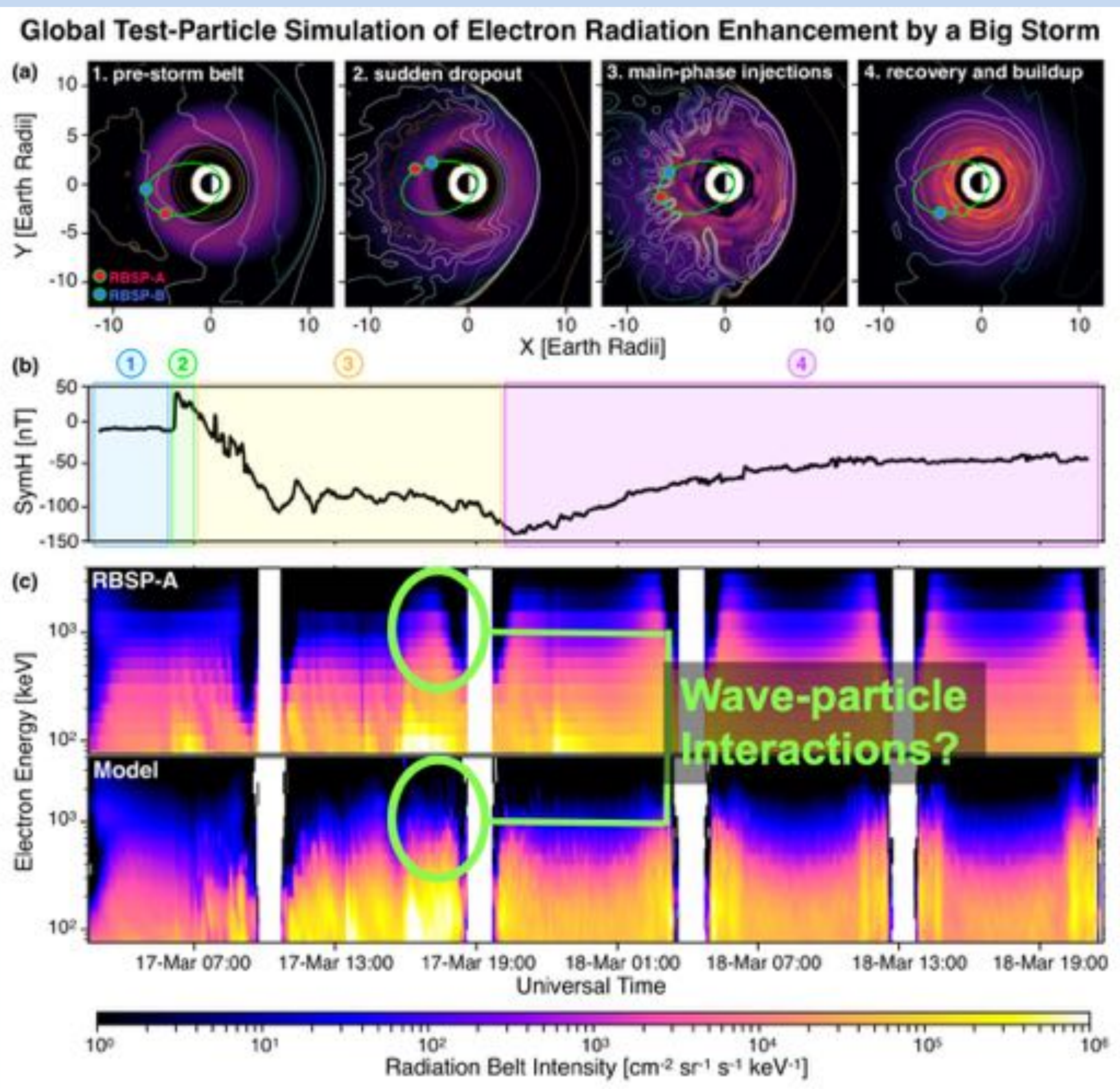
Global MHD simulation from the MAGE model that can capture mesoscale flows, ring current, plasmasphere and accurate stormtime fields through which test particles are evolved



Mesoscale Injections

- We use the test particle model (CHIMP) that evolves particles through accurate, time-varying electromagnetic fields provided by global MHD simulations (GAMERA-RCM). RCM is also used to solve for the plasmaspheric population, producing a dynamic plasmasphere evolving consistently with the global electromagnetic fields.

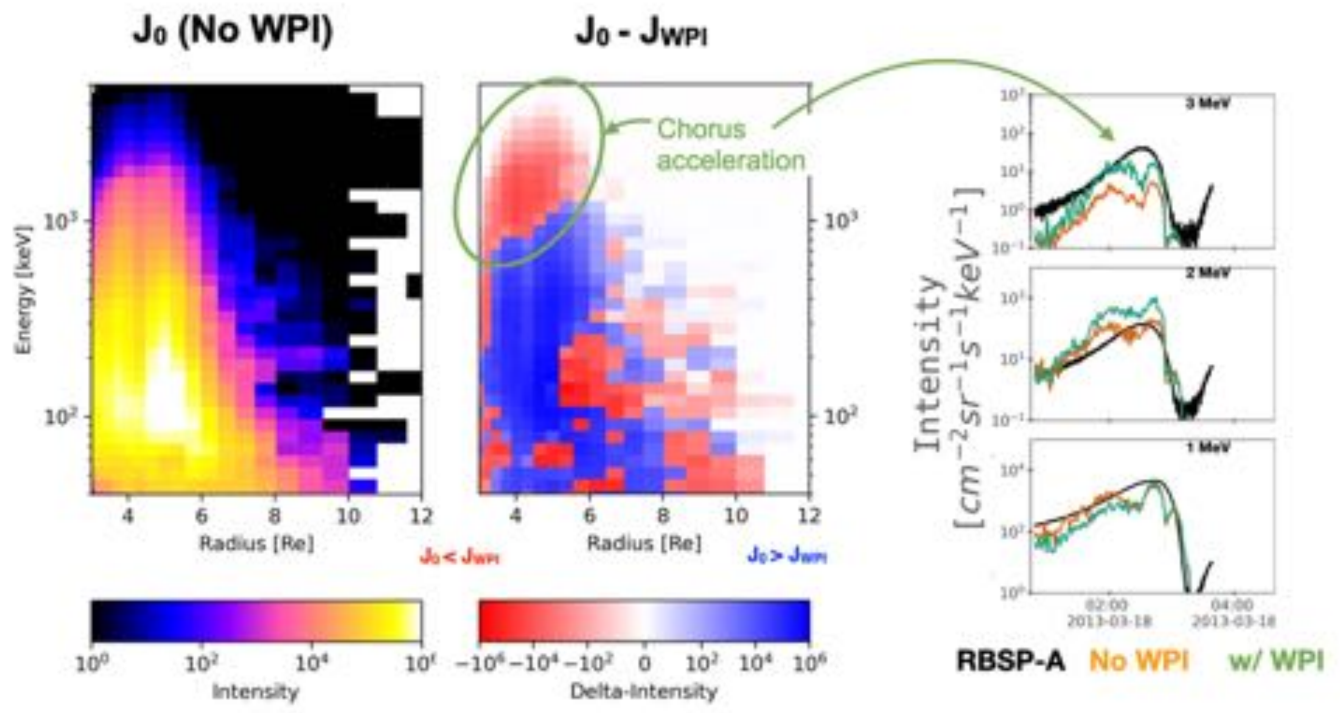
- These simulations can accurately capture:
  - Acceleration and trapping within mesoscale flow injections (Ukhorskiy et al., 2018)
  - Depletion and rapid recovery of the outer belt due to injections and magnetopause losses (Sorathia et a. 2018)



Test-particle simulations of radiation belt dynamics during the March 17, 2013 storm (Sorathia et al.,2018) is shown above. Driven only by the upstream solar wind conditions, CHIMP simulations show a remarkable qualitative agreement with the radiation belt observations from RBSP during all phases of the storm. Larger discrepancies at higher energies are likely attributed to the lack of wave-particle interactions within the model, which we extend to include in this work.

Combined Mutiscale Modeling

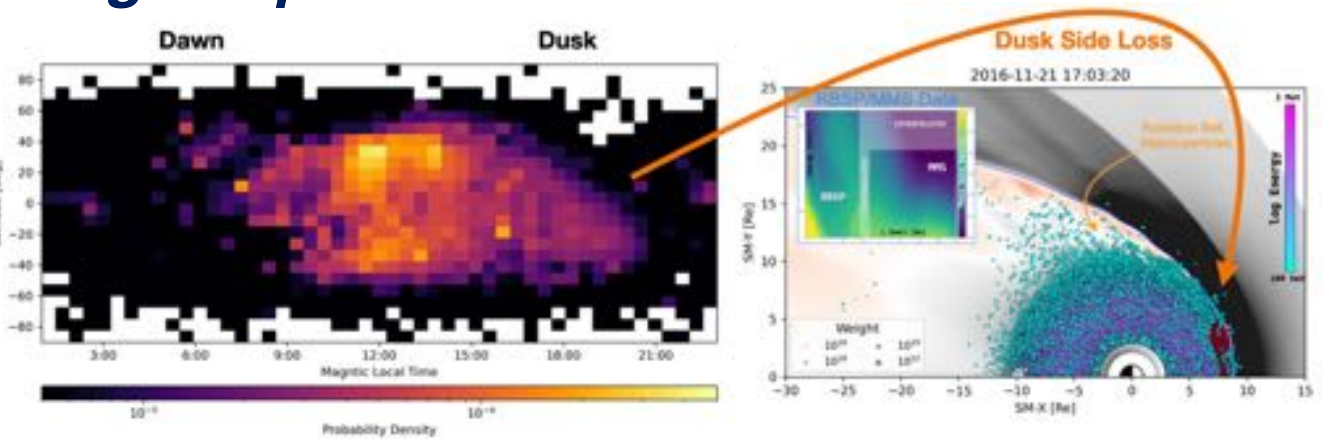
Local Acceleration



Azimuthally averaged intensity as well as the difference in intensities between the runs with and without wave particle interactions, with quantitative comparisons to RBSP-A measurements intensity at selected MeV channels.

- Simulated the evolution of the outer radiation belt from 20 UT Mar. 17, 2013 - 6:00 UT on Mar. 18, 2013.
- Wave-particle interactions with lower band chorus waves show increased enhancement of > 1 MeV intensity between 4 < L < 6.

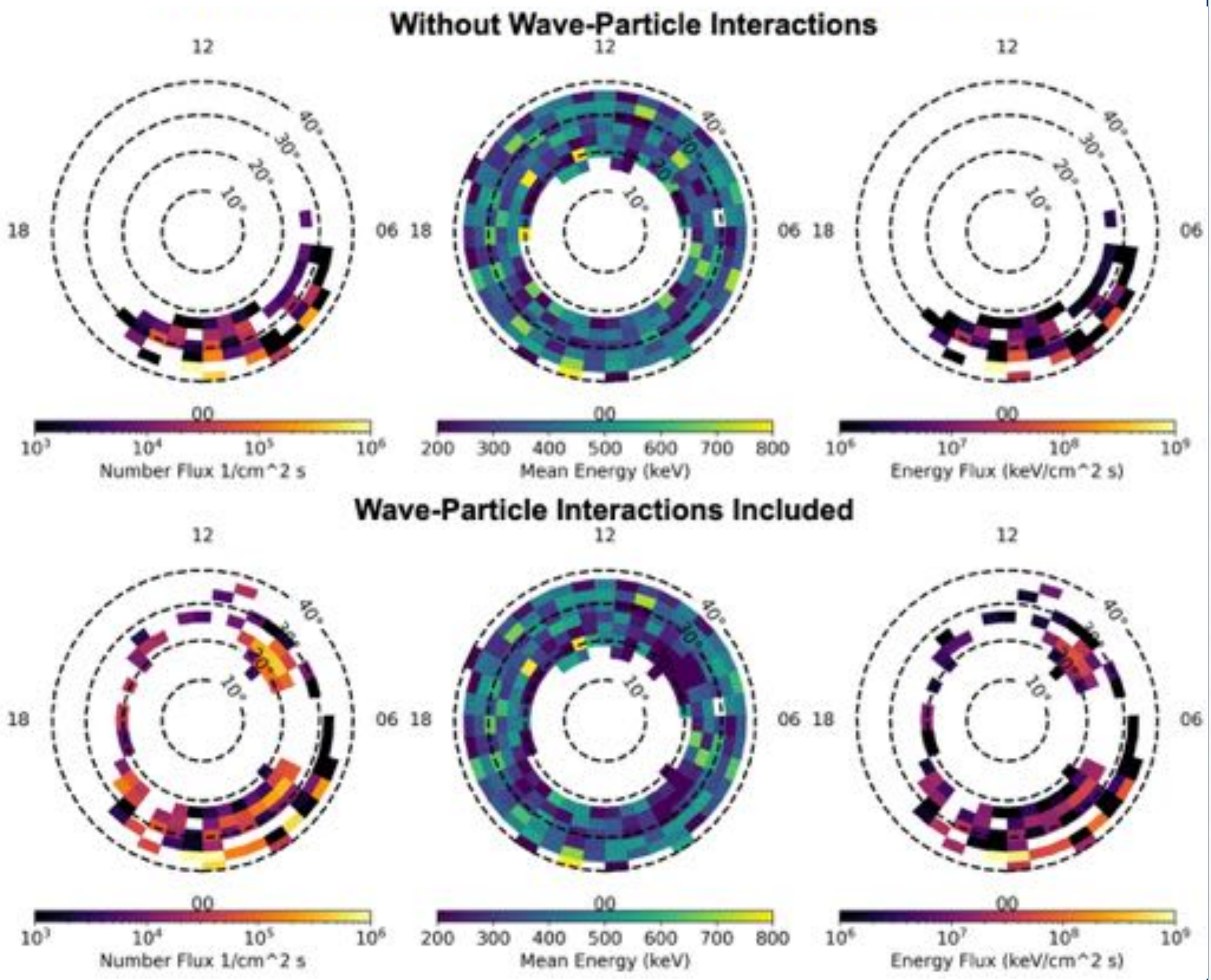
Magnetopause Losses



Left: 2D histogram of the probability density of electrons that have escaped through the magnetopause. Right: Snapshot of the simulation in the equatorial plane with the pre-event phase space density derived from RBSP and MMS data used to weight the test particles (see Cohen et al. 2021)

- Simulated the evolution of the outer radiation belt from 16 - 18:30 UT on Nov. 21, 2016.
- Captures dusk side loss and retains better latitudinal loss variation.
- Over 2.5 hours, 9% of the initial radiation belt is lost through the magnetopause

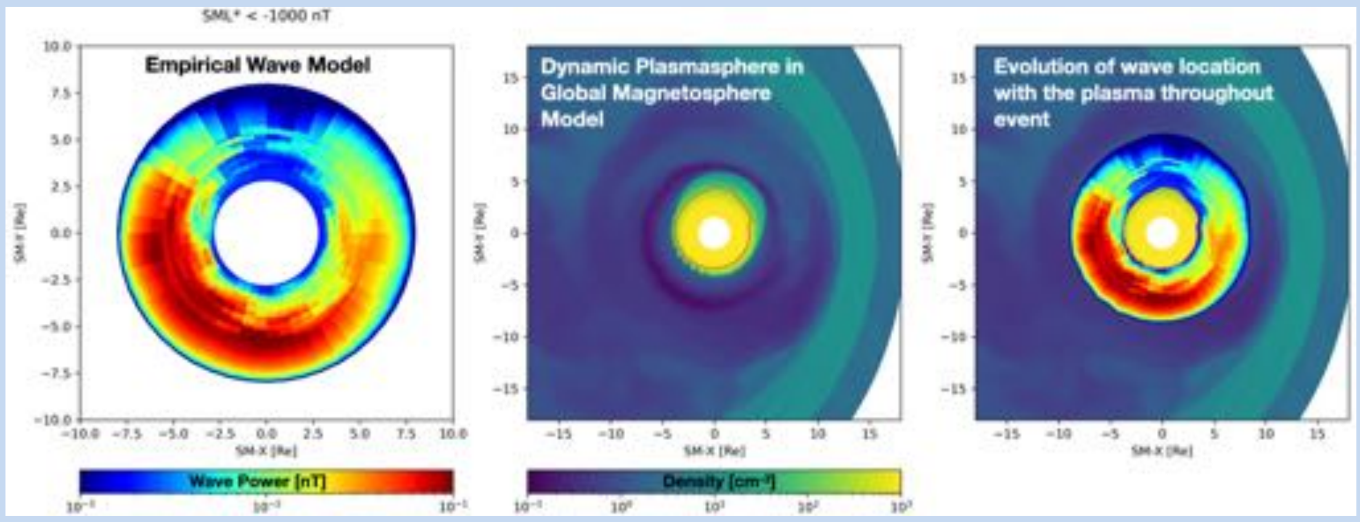
Wave Induced Precipitation



Precipitation, defined as electrons lost to the inner boundary and mapped along dipole field lines to 100 km, in the northern hemisphere in both models (courtesy of K. Pham)

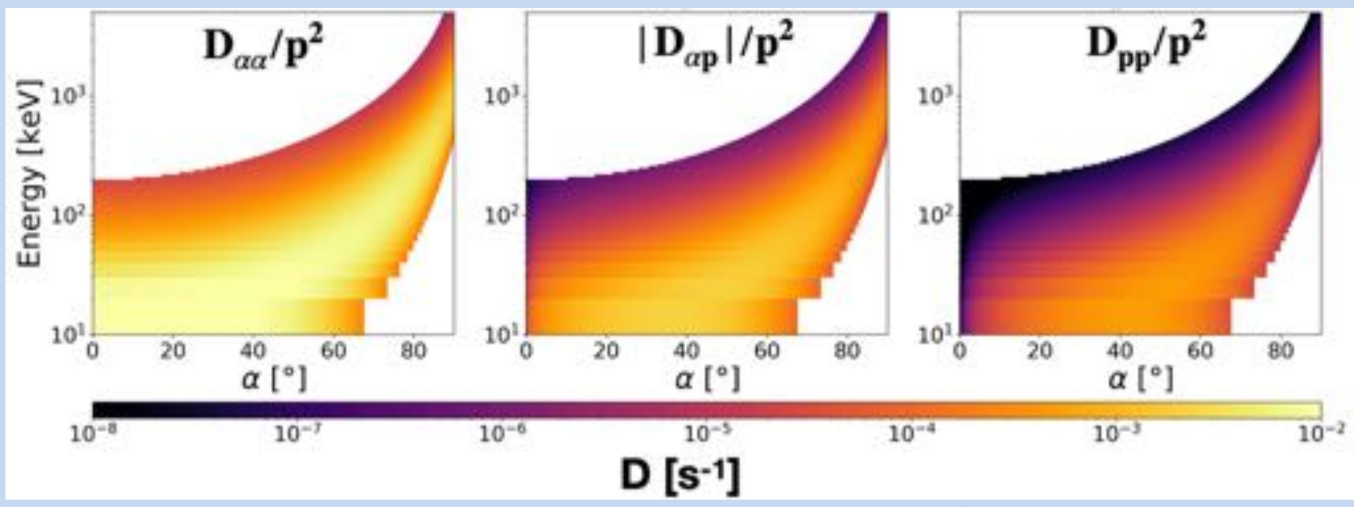
- Over the 2.5 hour period, wave-particle interactions with lower band chorus modes increased atmospheric loss of electrons by 7%, extending over a broader range in MLT

"Grey Box" Wave Model



- Grey box framework combines the dynamic magnetic field and plasma conditions from the global geospace model with an empirical wave power model.
- Lower band chorus waves (see Shen et al. (2019):
  - $B_w(L, MLT, \lambda_{MLAT}, SML^*)$
  - $\Delta L = 0.2$ RE, MLT= 1 hour resolution, $|\lambda_{MLAT}| < 20°$
  - We further assume field aligned with a gaussian spectrum
- Cold plasma density controls chorus wave location, typically generated outside of the plasmasphere.
- Reparametrized the wave model by ΔL_{pp} and dynamically evolve the wave locations based on L_{pp} in the simulation
  - L_{pp} = 5x decrease over 0.5 RE (Malaspina et al. 2016)

Microscale Interactions



Local diffusion coefficients in the equator at L = 4.5, n = 20 cm^{-3}, B_w = 100 pT for parallel propagating waves with a Gaussian distribution between 0.05 - 0.55 f_{ce}

- Test particles are evolved through the electromagnetic fields from the MHD solution and the waves from the wave model
- Use a time-forward stochastic differential equation of the Fokker-Plank formalism (Tao et al. 2008) to determine itch-angle scattering and momentum diffusion from resonant wave-particle interactions

$$\Delta\alpha = a_\alpha \Delta t + b_{\alpha\alpha}\sqrt{2\Delta t}\eta_\alpha$$

$$\Delta p = a_p \Delta t + b_{p\alpha}\sqrt{2\Delta t}\eta_\alpha + b_{pp}\sqrt{2\Delta t}\eta_p$$

- Where $a_\alpha, a_p, b_{\alpha\alpha}, b_{p\alpha}$, and b_{pp} are functions of $D_{\alpha\alpha}, D_{\alpha p}, \& D_{pp}$
- Use an analytic expression of the ***local*** quasi-linear diffusion coefficients, $D_{\alpha\alpha}, D_{\alpha p}, D_{pp}$, derived by Summers (2005)

$$D_{\alpha\alpha} = \frac{\pi}{2}\frac{\Omega^2}{W_0}\left(1 - \frac{\omega_j \cos\alpha}{k_j v}\right)^2 \frac{W_s(k_j)}{|v\cos\alpha - d\omega_j/d k_j|}$$

- Depends on:
  - Local wave intensity and resonant wave
  - Background magnetic field and plasma density
  - Particle energy and pitch-angle
- Dynamically calculate $D_{\alpha\alpha}$, $D_{\alpha p}, D_{pp}$ for each resonant interaction