Reanalysis of radiation belt electrons relying on a Kalman filter, four spacecraft, and a diffusion model

Sebastián Cervantes[1,2], Yuri Shprits[1,2,3], Alexander Drozdov[3], Adam Kellerman[3], Nikita Aseev[1,2], Angélica Castillo[1,2]

1: GFZ German Research Centre for Geosciences, Potsdam, Germany
2: Institute of Physics and Astronomy, University of Potsdam, Potsdam, Germany
3: Earth, Planetary, and Space Sciences, University of California, Los Angeles, California, USA

Workshop on Conservation Principles, Data, and Uncertainty in Atmosphere-Ocean Modelling
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Space weather and its effects

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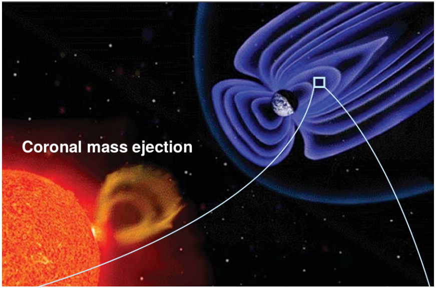
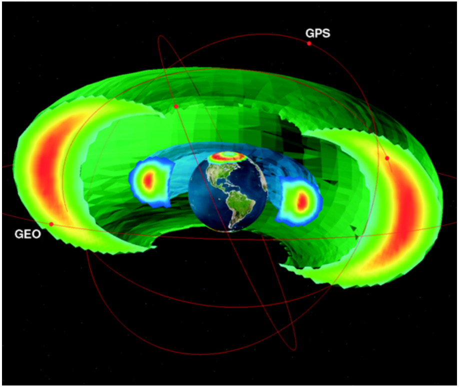
- The **Sun** ejects clouds of ionized gas towards the Earth.
- Some **effects**: aurorae, communication disruptions, radiation hazards to orbiting astronauts and spacecraft, and induced currents in power lines.



[*Baker, 2002*].

Radiation belts: two zone structure

What are the radiation belts?



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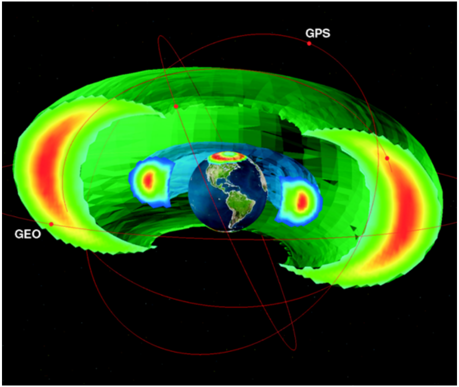

- Radiation belts are two donut shaped regions of **high radiation** encompassing the Earth.
- **Inner belt**: fairly stable.
- **Outer belt**: can change in timescale of an hour.
- **Slot region**: gap of lower fluxes.
- Particles with energies from $\sim$ 100 keV up to tens of MeV.

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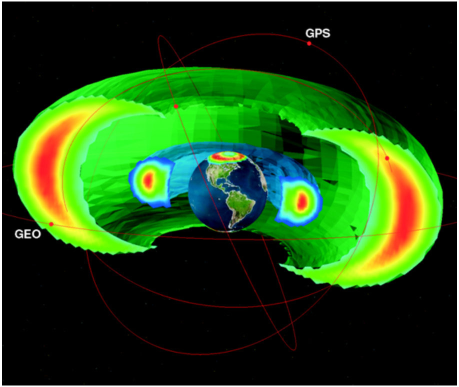

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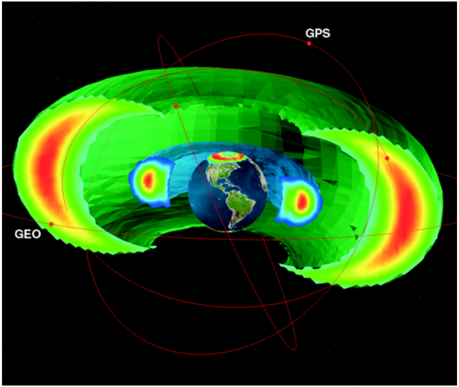
- The outer belt **overlaps many satellite orbits**!

How can data assimilation be applied in radiation belt modeling?



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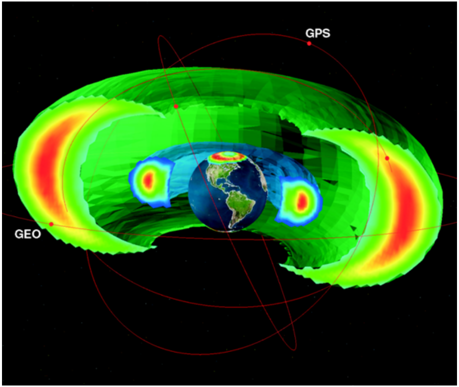

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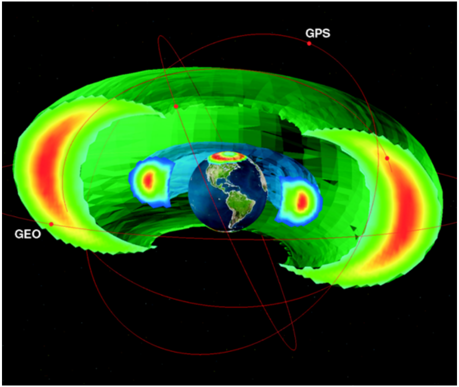

Data assimilation can help with:

- **Understanding** the fundamental physics underlying the radiation belts dynamics.
- **Predicting** radiation in space and the response of radiation belts to geomagnetic disturbances.
- **Increased dependence** on the technology in space causes surge in space weather interest.

How can the dynamics in the radiation belts be modeled?

- The evolution of relativistic electrons in the radiation belts is modeled by the **Fokker-Planck equation**, in terms of the radial distance L, relativistic momentum p, and pitch angle α as follows:

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

- μ, J, and L^* are the particle adiabatic invariants.
- $D_{L^*L^*}$, D_{pp}, $D_{\alpha\alpha}$, $D_{p\alpha}$, and $D_{\alpha p}$ are diffusion rates, and describe the effect of **wave-particle interactions**.
- Pitch angle (α): angle between the particle's velocity vector and the local magnetic field.
- This equation accounts for **radial**, **energy**, **pitch-angle**, and **mixed pitch angle - energy** diffusion.

Radiation belts and data assimilation

An example of 1D reanalysis (*Shprits et al., 2012*)

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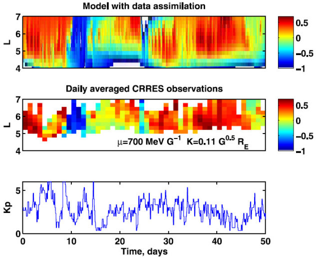
- Top: **Reanalysis**.
- Middle: CRRES **observations**.
- Bottom: Geomagnetic activity index.



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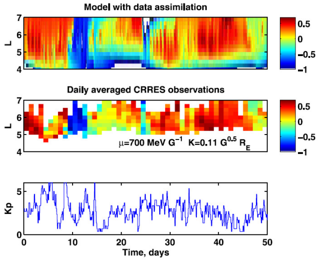

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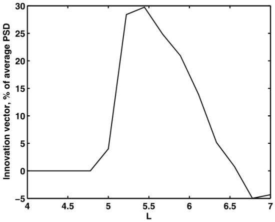
- **Innovation vector** peaks where observations add PSD.
- **Positive innovation**: local acceleration **not accounted** for by the model.
- **Negative innovation**: due to losses to the interplanetary medium.



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- Incorporate the following **loss processes** into the data assimilation code:
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  2. scattering by Electromagnetic Ion Cyclotron (EMIC) waves, and
  3. losses to the interplanetary medium.
- Assess their effect on radiation belt modeling via the **innovation vector**.

Methodology

Model framework: VERB code

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

- The **VERB** (**V**ersatile **E**lectron **R**adiation **B**elt) **code** (*Subbotin and Shprits, 2009*) solves it numerically, by accounting for **radial**, **energy**, **pitch-angle**, and **mixed pitch angle - energy** diffusion.

Spacecraft observations

- NASA's Radiation Belt Storm Probes (**RBSP**), highly elliptical orbit.
- NOAA's Geostationary Operational Environmental Satellites (**GOES**), geostationary orbit.
- Period under study: October 1st, 2012 to March 31st, 2013.

Reconstructing the evolution of the Van Allen belts

- We performed four different simulations, and systematically added **one loss process at a time**:

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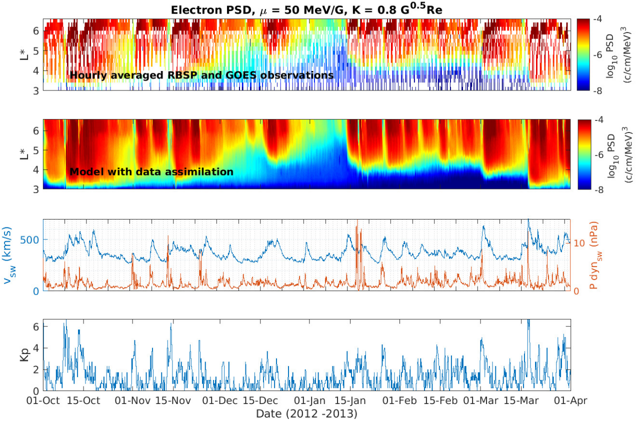
Reconstructing the evolution of the Van Allen belts

Radial profiles of electron PSD



Electron PSD for $\mu = 50$ MeV/G and $K = 0.8$ G$^{0.5}$ Re: (i) spacecraft data, (ii) 3D + mixed diffusion + scattering by EMIC waves + magnetopause shadowing reanalysis; and evolution of (iii) solar wind dynamic pressure and speed, and (iv) geomagnetic Kp index. Time interval: October 1st, 2012 - March 31st, 2013.

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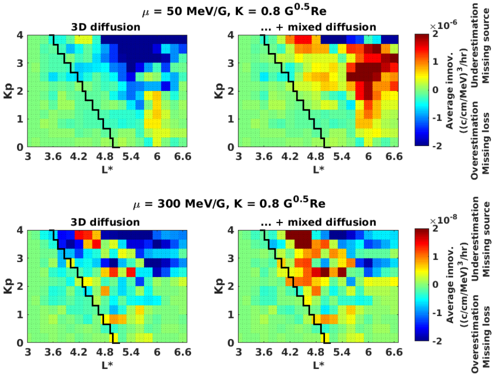
- **Positive** innovation → model underestimates data → observations add PSD → missing source of electrons in the model.
- **Negative** innovation → model overestimates data → observations remove PSD → missing loss of electrons in the model.

Innovation vector: 3D + mixed diffusion

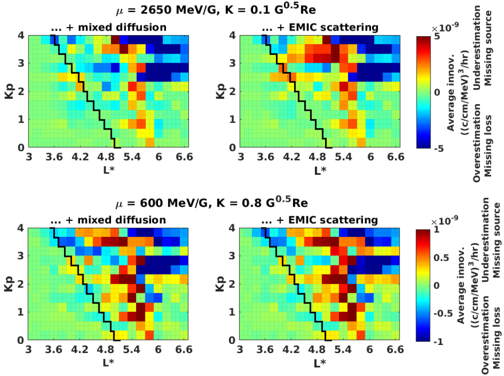
- Mixed diffusion removes the **overestimation** of PSD, particularly at low pitch angles.
- Left column: 3D diffusion.
- Right column: 3D + mixed diffusion.



Innovation vector as a function of L^* and Kp for electron PSD for the indicated pairs of μ and K.

Innovation vector: 3D + mixed diffusion + EMIC scattering

- EMIC scattering reduces the electron PSD **overestimation**, especially at energies greater than 2 MeV.
- Left column: 3D + mixed diffusion.
- Right column: 3D + mixed diffusion + scattering by EMIC waves.



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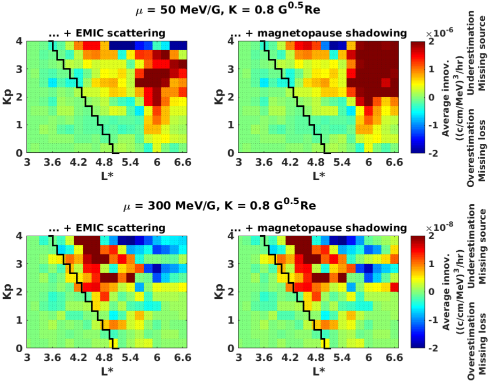

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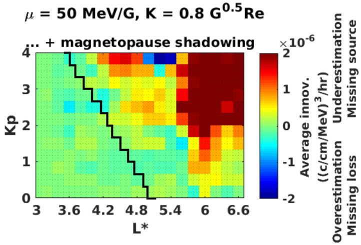

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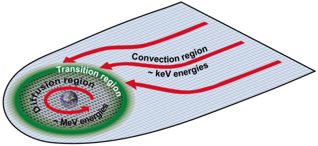
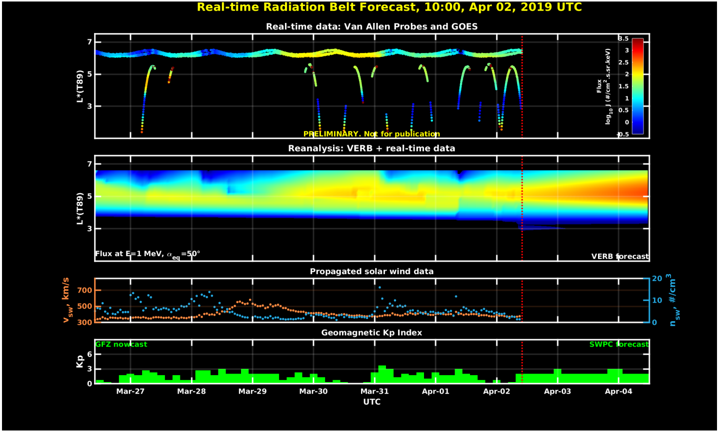


Schematic representation of magnetospheric convection-dominated region in the tail and diffusion-dominated region close to the Earth [*Subbotin et al., 2011*].

- **Underestimation** at high radial distances and low energies due to absence of **magnetospheric convection** in the model.
- Convection brings particles from the **tail** region to the **inner magnetosphere** and can energize electrons by **hundreds of keV** ('seed population' for radiation belts).

Reconstructing the evolution of the Van Allen belts

Real-time Radiation Belt Forecast



Forecast available at *https://www.gfz-potsdam.de/en/section/magnetospheric-physics/data-products-and-services/*.

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  - identified physical mechanisms missing in the model by means of the **innovation vector**, and
  - developed an early warning system for prediction and mitigation of natural hazards related to **space weather**.
- We plan to:
  - validate our DA performance by comparison with independent datasets, and
  - compile a database of spacecraft anomalies and determine failures related to increases in radiation.