Versatile Electron Radiation Belt (VERB) code 3D and 4D

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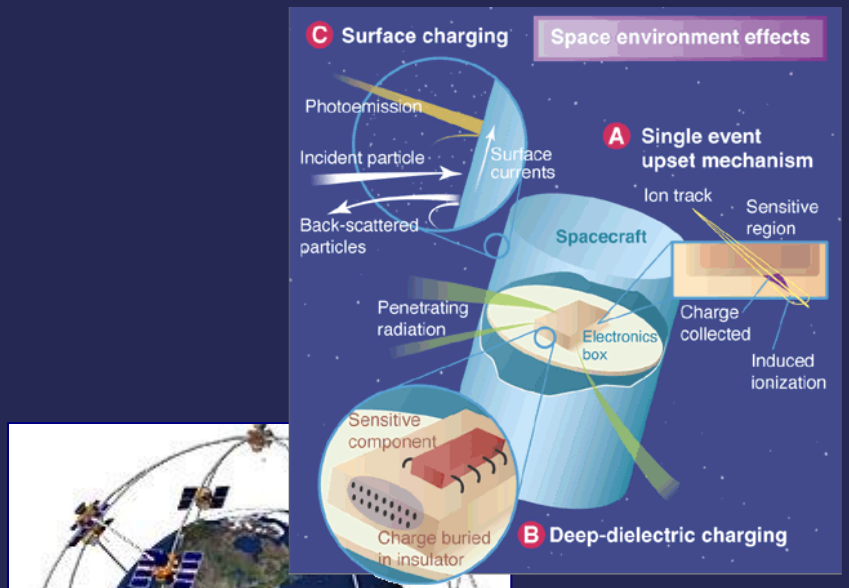
Outline

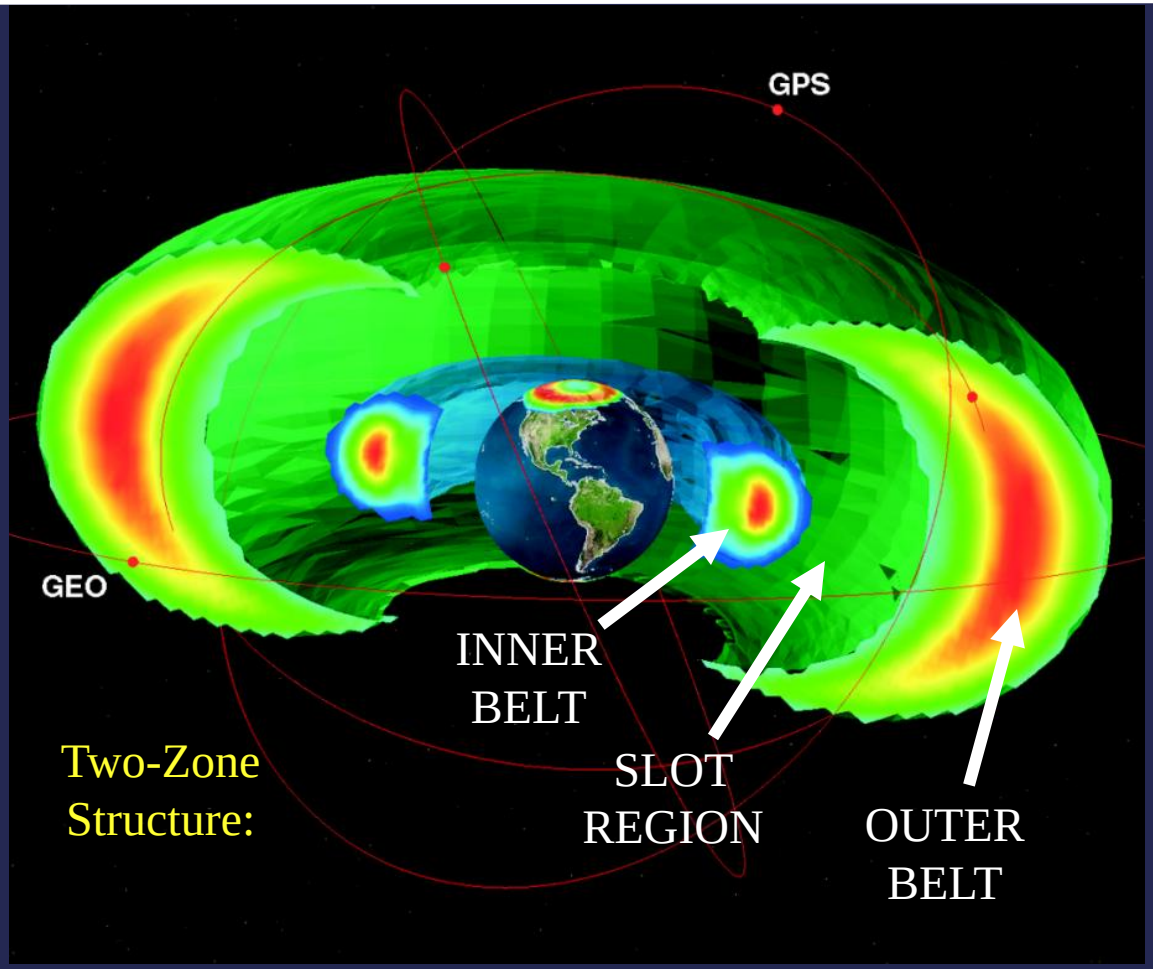
- **VERB 3Dcode (available at CCMC)**
- **VERB 3D with Data assimilation**
- **VERB 4D**
- **VERB coupled to kinetic codes**
- **Summary**

Space Weather Effects of Radiation in Space

- **Radiation is hazardous to satellite electronics & humans in space**
- Over 3,000 satellites; Supporting $25B/yr industry; Replacement cost: $75B; GPS industry is to grow to $1 trillion by 2017
- The effects of radiation include: single event upsets, surface charging, and deep dielectric charging.
- With miniaturization of satellite electronics satellites become more vulnerable to the radiation in space.

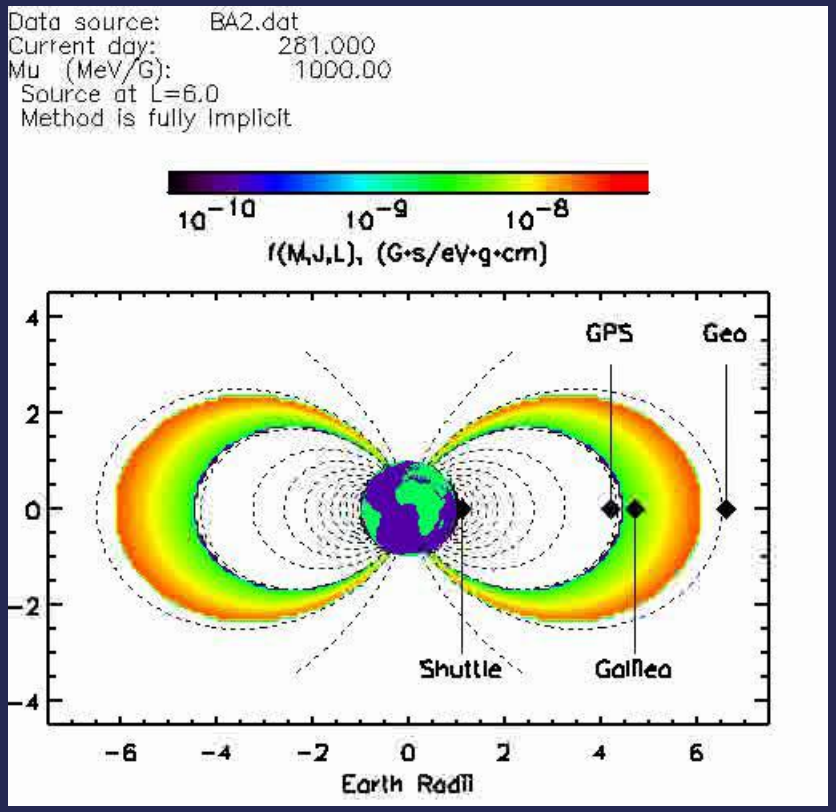


Radiation Belts - Two Zone Structure



- Radiation belts – two donut shaped regions of high radiation encompassing the Earth
  - energies >100 keV
  - two-zone structure
- Inner belt: fairly stable
- Outer belt: can change on the time scale of an hour

Radial Diffusion- Well Established Acceleration Mechanism

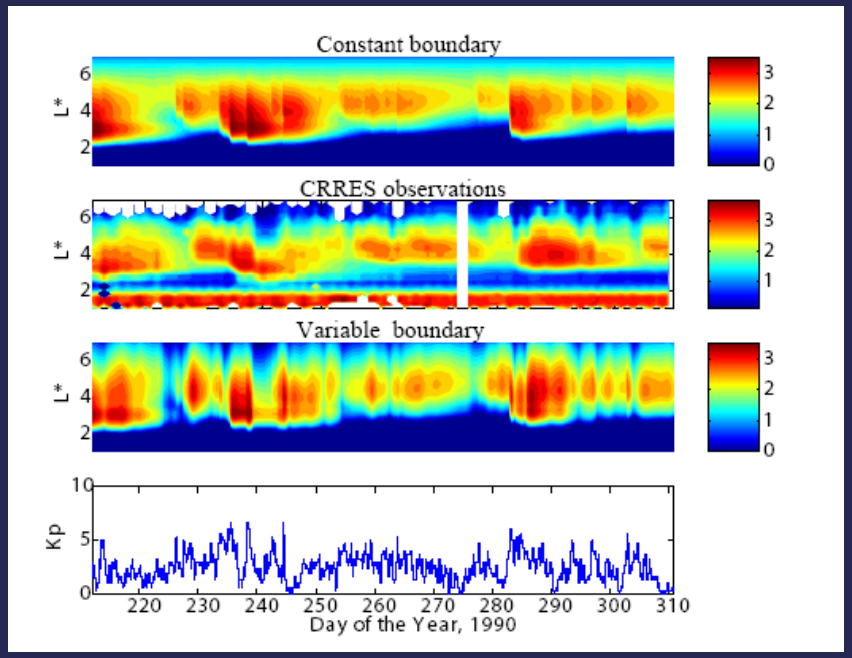


Interactions with Ultra Low Frequency (ULF) waves cause random radial displacements that can result in radial diffusion.

Particles that are diffused into the inner region of strong magnetic field will gain energy.

Animation Courtesy of Richard Horne

Loss of Relativistic electrons in the Radiation Belts



Flux dropouts are correlated with the increases in the solar wind dynamic pressure and enhanced loss to magnetopause.

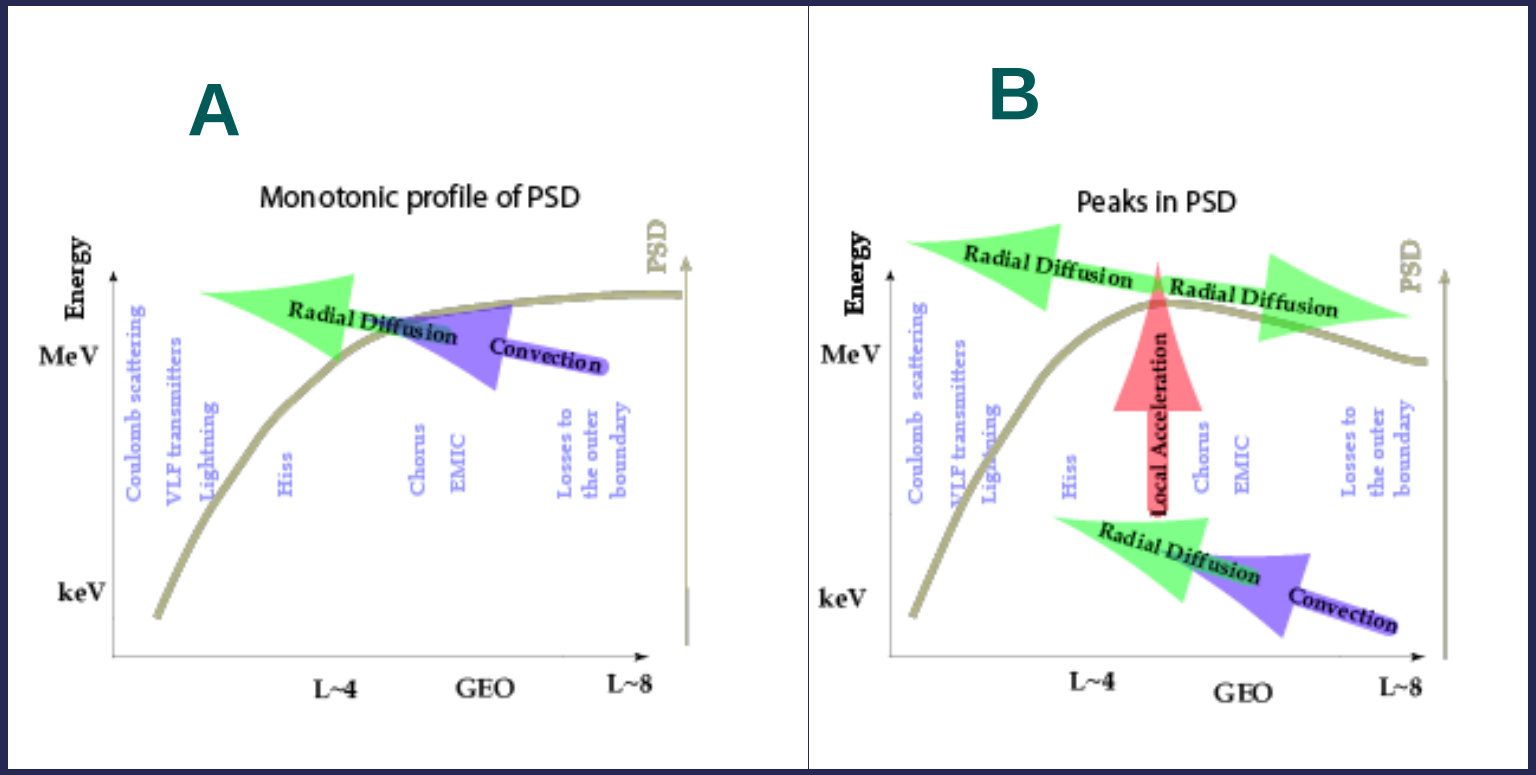
Modeling showed that outward diffusion can explain dropouts

Shprits, Thorne et al., 2006, *JGR*

Turner , Shprits, et al., 2012, *Nature Physics*

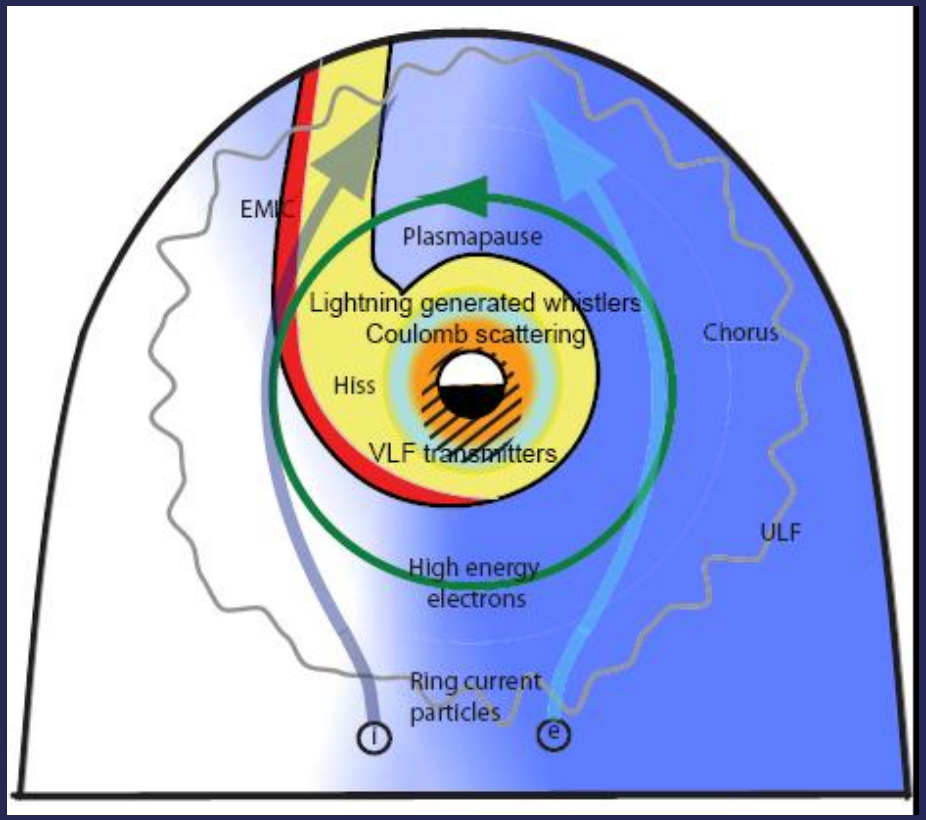
Multi energy observations show that dropouts occur when magnetosphere is compresses and occur at low energy. The low energy dropouts cannot be explained by EMIC waves scattering

Acceleration of electrons to relativistic energies



[Shprits et al., 2009]

Competition Between Acceleration and Loss



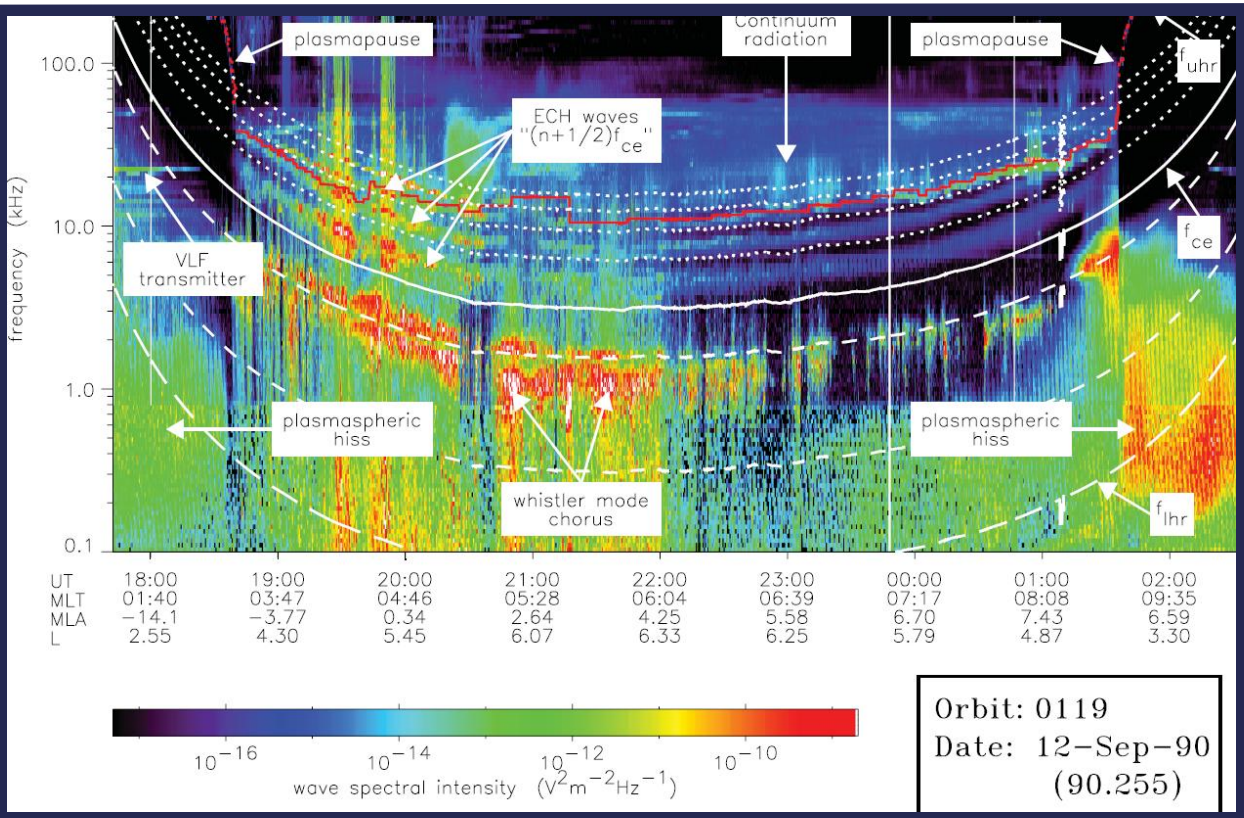
Inward radial diffusion driven by the ULF magnetic fluctuations.

Energy and pitch angle scattering due to resonance interactions with different waves.

Combined effect of losses to magnetopause and outward radial diffusion.

[Shprits et al., 2008; Review JASTP]

Dynamical Spectrogram of ELF/ VLF Waves

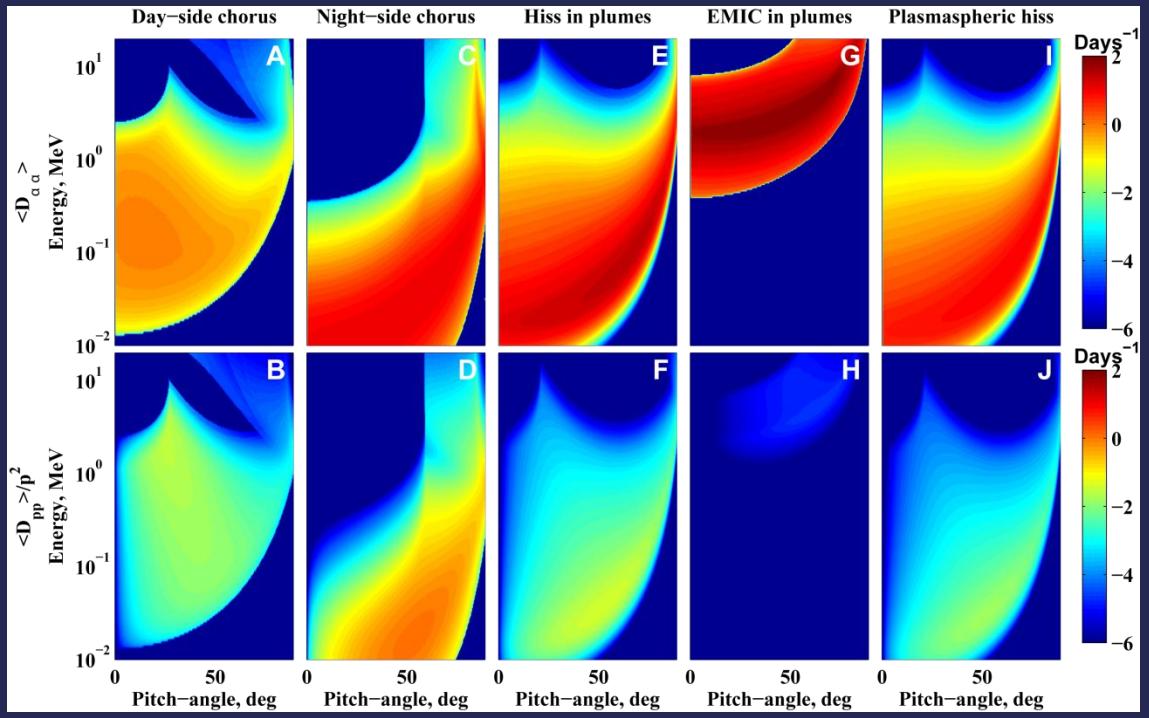


Need a model of waves including latitudinal distribution of waves, frequency distribution of waves, wave-normal distributions of waves and amplitude as a function of geomagnetic activity.

[e.g. Spasojevic and Shprits., 2013, Orlova et al., 2014]

[Meredith et al., 2003]

Pitch-angle and energy diffusion coefficients due to resonant wave-particle interactions

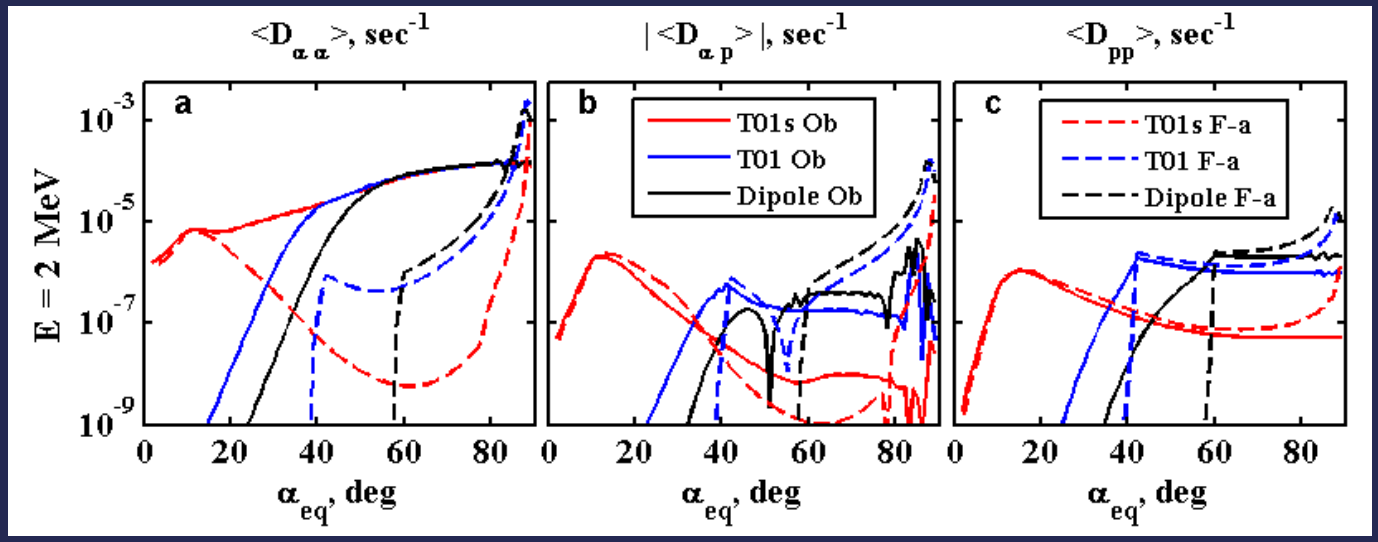


Pitch-angle diffusion results in a loss to the atmosphere

Energy diffusion can locally accelerate electrons

Diffusion rates due to resonance wave particle interactions with various plasma waves using the FDC code [Shprits and Ni, 2009]. We calculate diffusion coefficients using developed models of waves as a function of radial distance, energy, and geomagnetic activity.

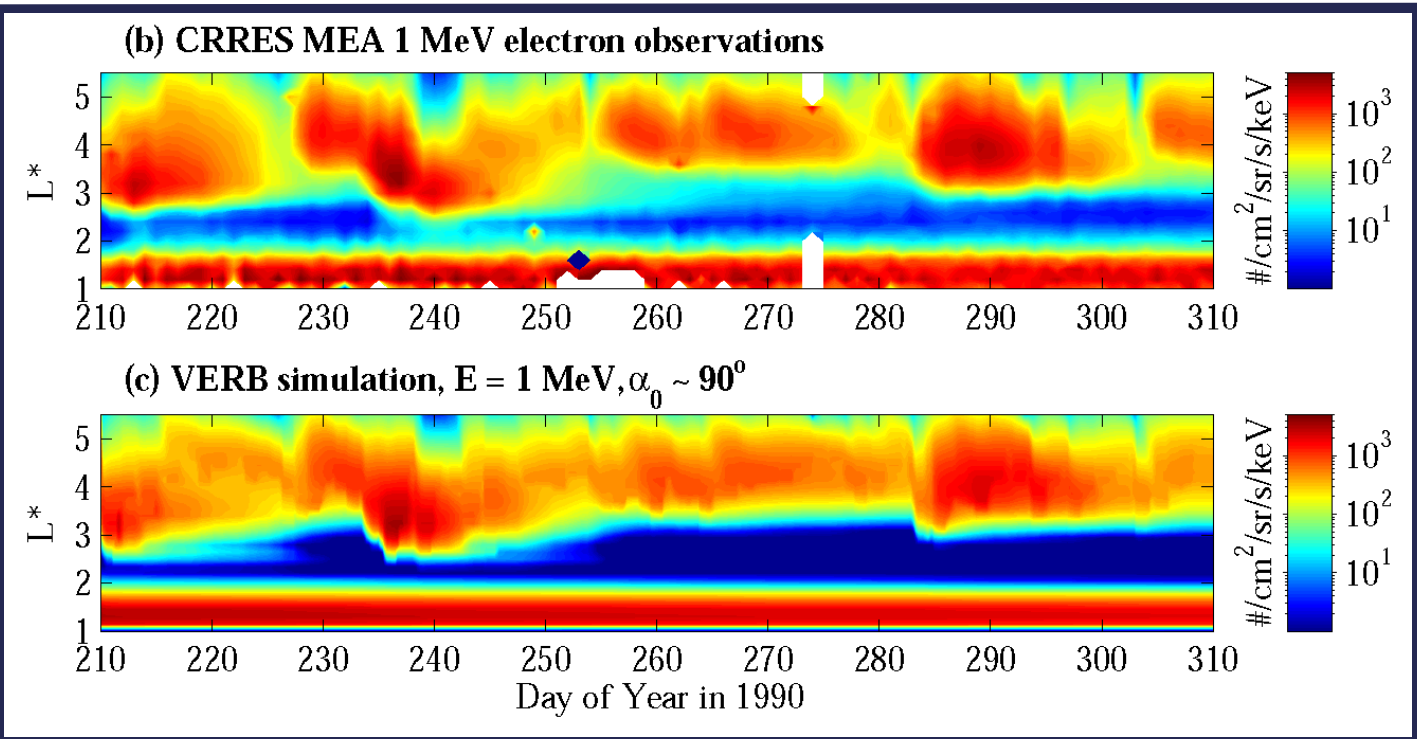
Calculations in a Non-dipole Field



[Orlova et al., 2012]

(a) Pitch angle, (b) absolute value of mixed and (c) energy diffusion coefficients for disturbed (T01s) and quiet (T01) conditions and for the dipole magnetic fields accounting for Oblique waves (solid lines) and using the field-aligned approximation (dashed lines) for radial distance of 7 R_E at midnight.

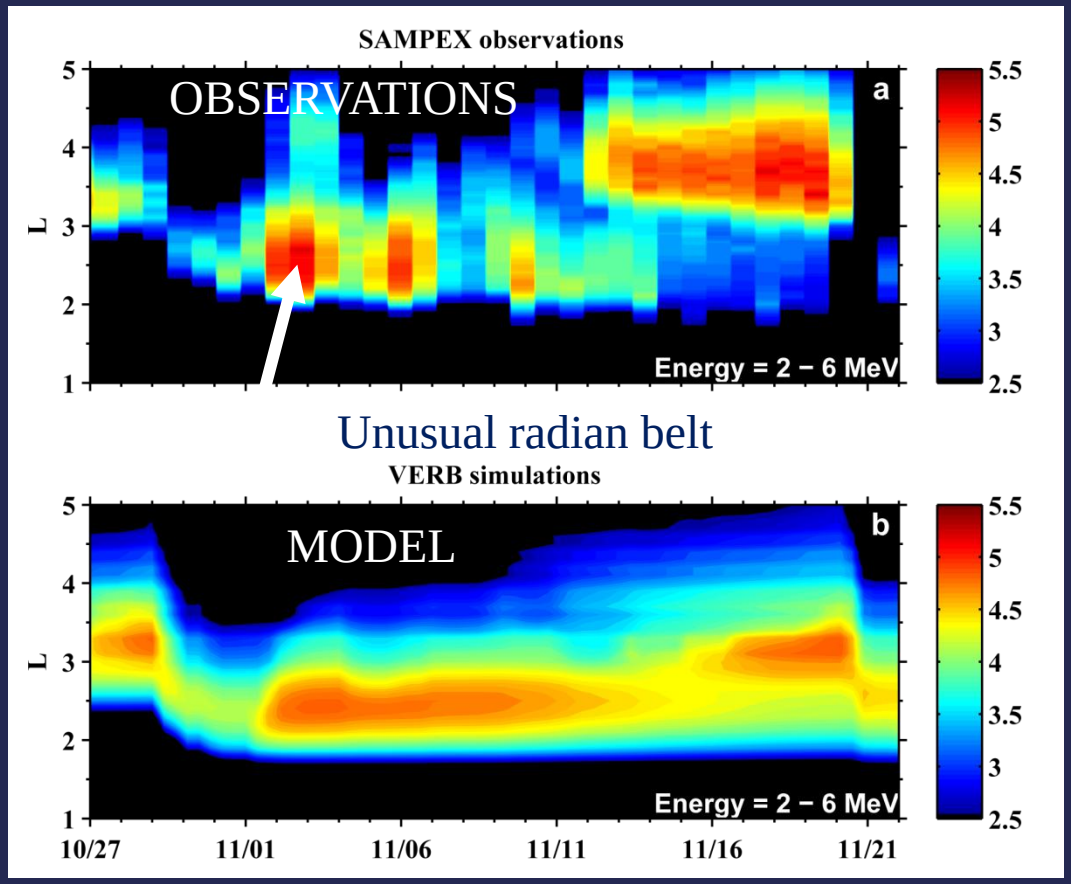
Validation of the Versatile Electron Radiation Belt (VERB) Code for Over 100 Days in 1990



- VERB predicts the instantaneous location of the upper boundary

of the slot region, the empty slot region, the stable inner belt, the location of the peak of fluxes and the amplitude of fluxes.

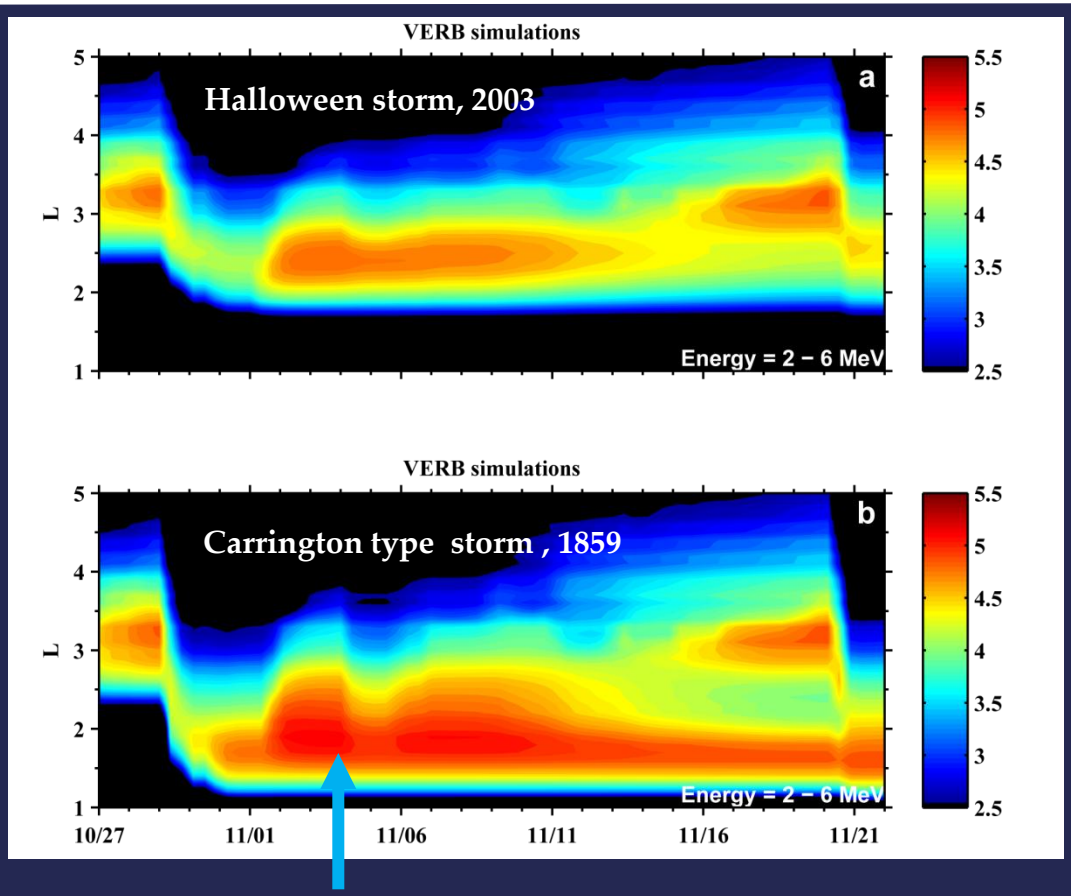
Observations (a) and Modeling (b) of the 2003 Halloween Storms



VERB code which now includes radial transport, pitch-angle scattering, and mixed diffusion scattering can reproduce the formation of the unusual radiation belt. The new belt is formed in the slot region which is usually devoid of killer electrons.

[Shprits et al., 2011]

Simulations of the 2003 Halloween Storm and the 1859 Carrington Superstorm



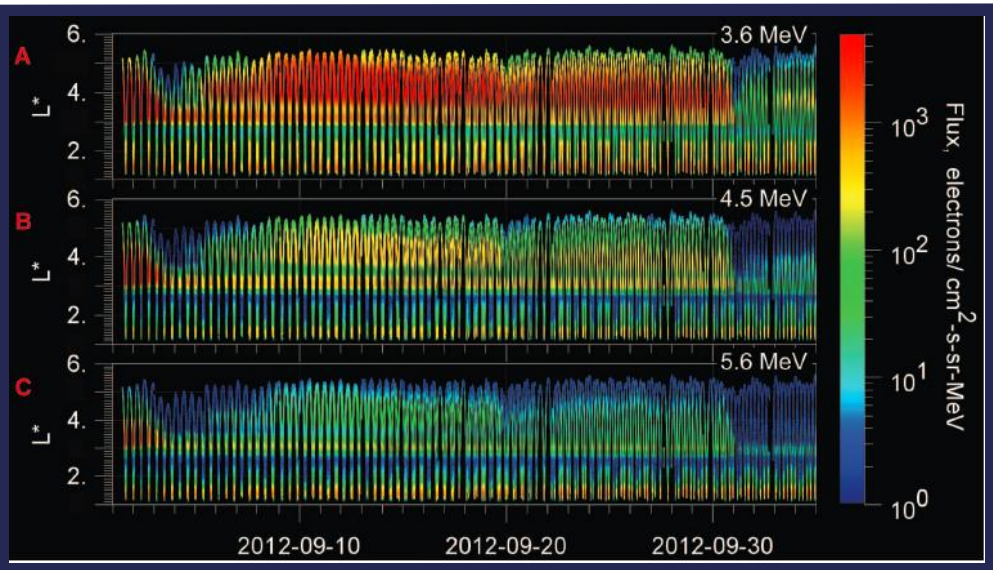
FILLING OF THE INNER ZONE

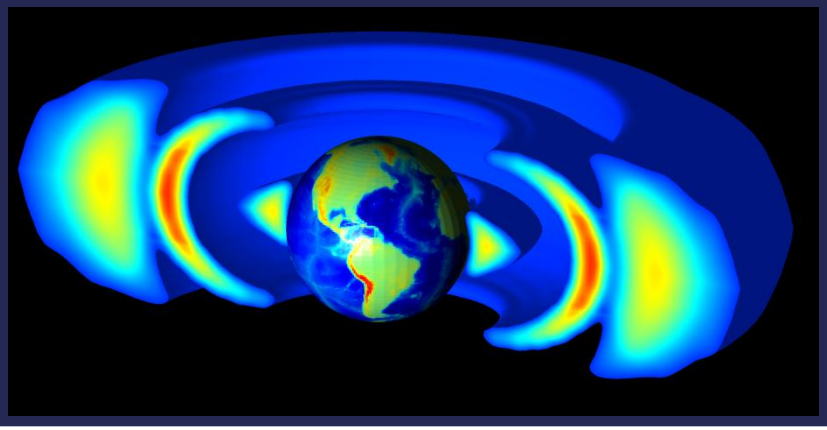
(a) During 2003 Halloween storm slot region between 2 and 3 R_E is filled.

(b) During Carrington storm in 1859 electrons are accelerated in the inner zone (below 2 R_E) where they can persist for up to a decade.

[Shprits et al, 2011] Highlighted in *National Geographic, Forbes magazine*

Observations of the Unusual Storage Ring

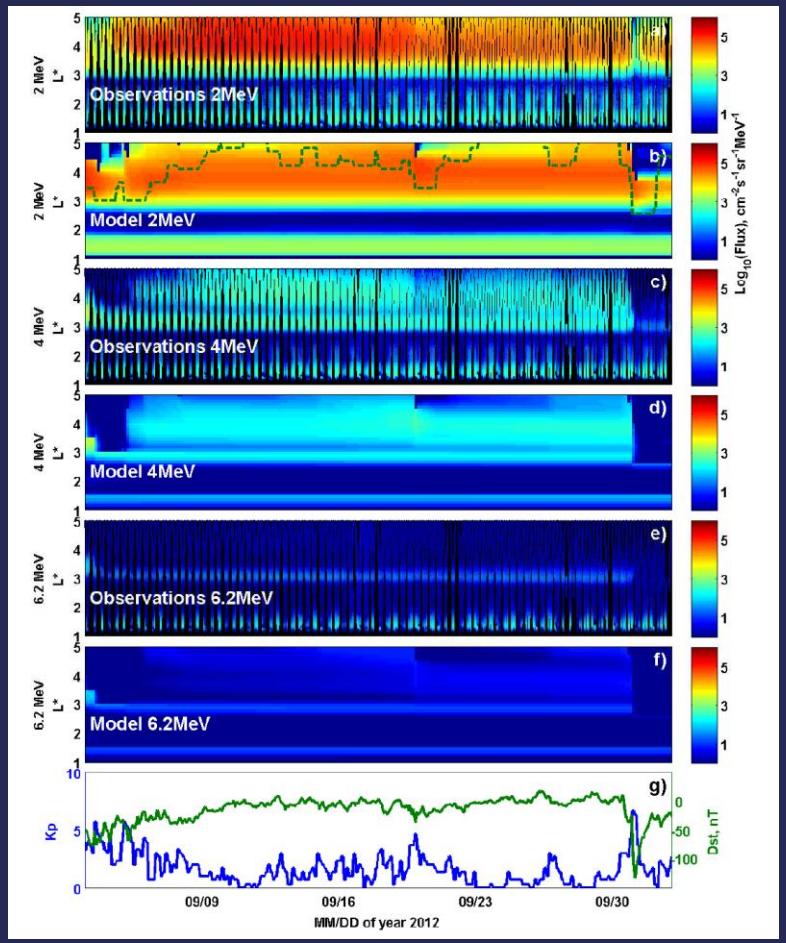




- Third narrow ring was formed on Sept 1st-3rd.
- The structure was very narrow (fraction of Earth radii)
- The ring lived for approximately 1 month until the arrival of the next CME.

Baker et al., 2013 , *Science*

Chorus, hiss, EMIC, radial diffusion, 30 days spin up

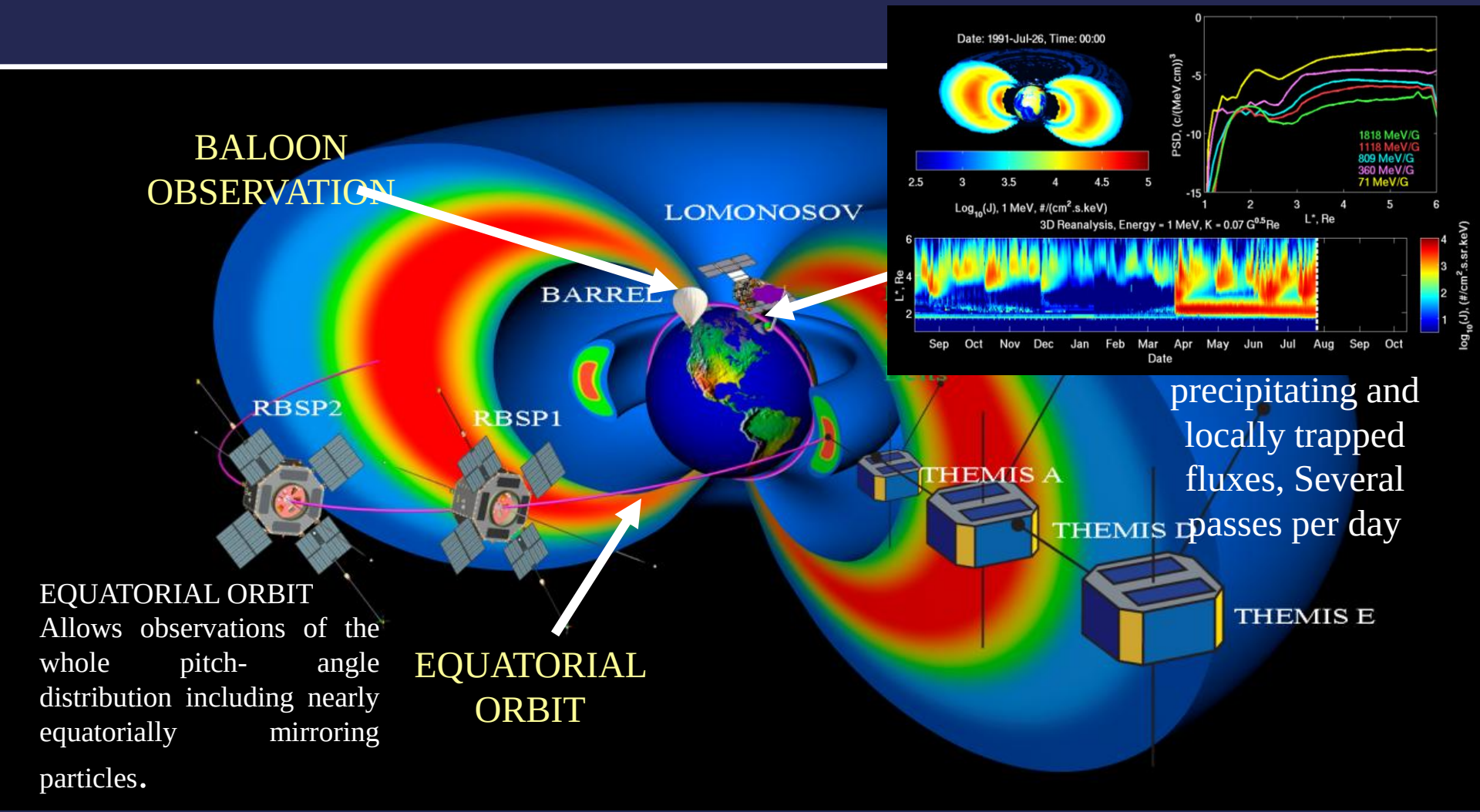


Depletion occurs down to the outer boundary of the plasmapause.

Narrow ring persists until the arrival of the next CME.

Shprits et al., 2013 *Nature Physics*

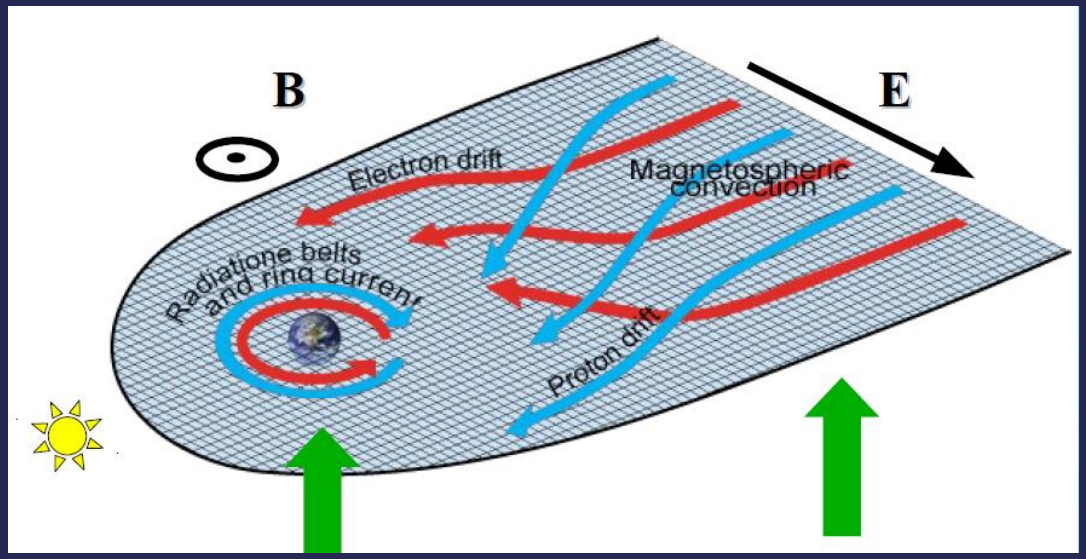
Multi Point Observations; 3D Data Assimilation



precipitating and locally trapped fluxes, Several passes per day

EQUATORIAL ORBIT
Allows observations of the whole pitch- angle distribution including nearly equatorially mirroring particles.

Particle Trajectories of Ring Current and Radiation Belt Particles



Stably trapped particles

Convection of the seed population of energetic electrons

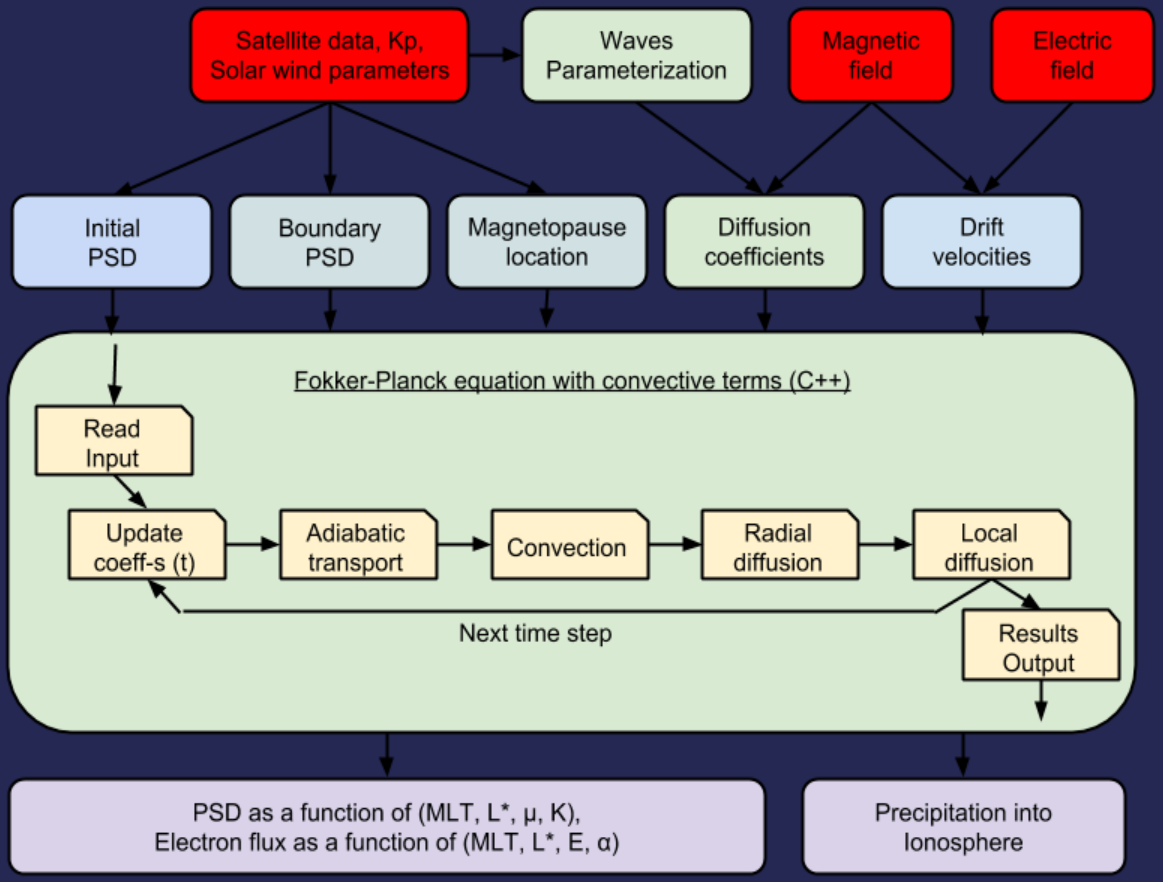
Drift of lower energy particles is dominated by ExB drift.

Radiation Belt particles are subject to the gradient and curvature drifts and will drift around the Earth.

Electrons –eastward,

Ions-westward.

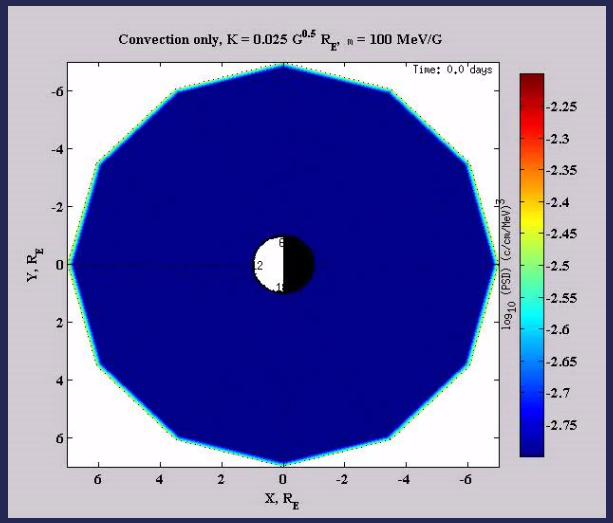
Block diagram showing data exchange between the modules of the VERB 4D code.



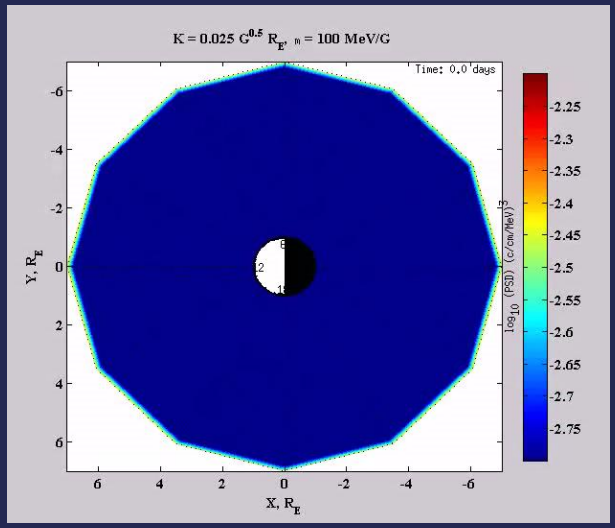
MLT-distribution of electrons

Starting from an empty magnitosphere, we run simulation for 1 day with Kp=6 to demonstrate the difference between convection only, convection and radial diffusion, and convection, radial, and local diffusion. PSD of μ=100 MeV/G, K=0.025 $G^{0.5}$ R_E electrons is plotted.

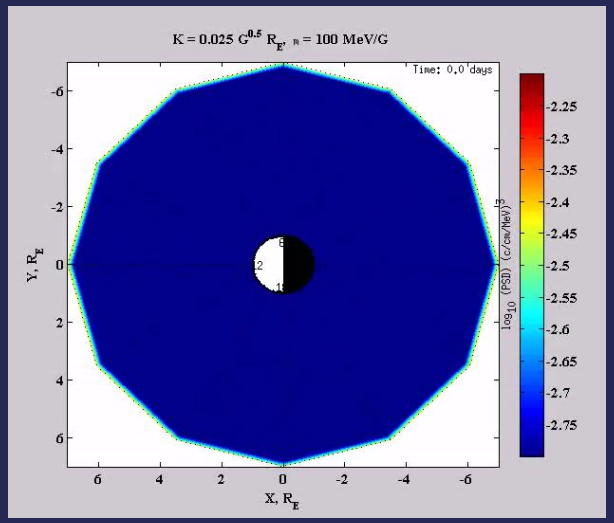
Convection only



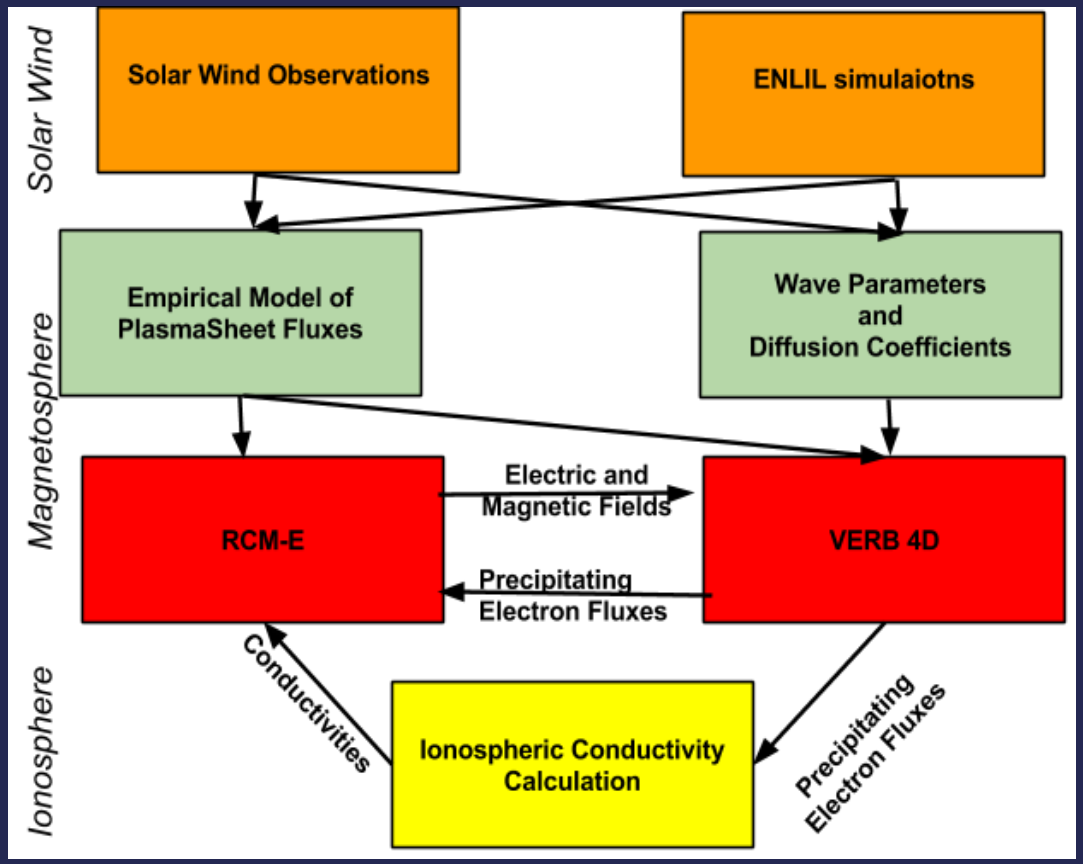
Convection and radial diffusion



Convection, radial, and local diffusion



Code Coupling Framework



Summary I (Submitted to CCMC)

- Dynamics of the radiation belts is driven by the radial, pitch-angle, energy, and mixed diffusion due to various ULF, VLF, and ELF waves.
- Both radial diffusion and energy diffusion are responsible for acceleration of electrons to relativistic energies.
- Modeling which now includes radial, pitch-angle, energy, and mixed diffusion can reproduce the general dynamics of the CME and CIR driven storms.
- VERB 3D can capture the dynamics of the relativistic electrons during long term simulations as well as observations of the unusual behavior of the radiation belts during Halloween storms.
- VERB 3D is available on CCMC

Summary II (New Codes)

- Data assimilative code allows to combine different observations with the 3D code, weight observations and models according to their underling error structure and to utilize a vast amount of observations.
- VERB 4D can model dynamics starting from the plasma sheet and accounts for adiabatic changes, MP loss, radial diffusion pitch-angle, energy and mixed diffusion by chorus, hiss, hiss in plumes, lightning generated whistlers, coulomb scattering, VLF transmitters etc.
- Future versions of VERB 4D will be coupled to kinetic codes like RCM, RCM-E,CRCM and will use self consistently calculated electric and magnetic fields while providing loss for the kinetic codes and loss for the estimation of ionospheric conductivities.

Thank You