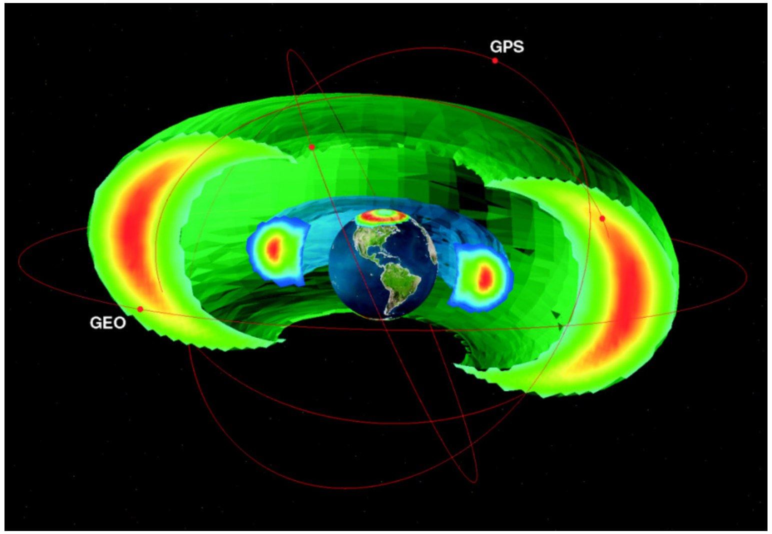
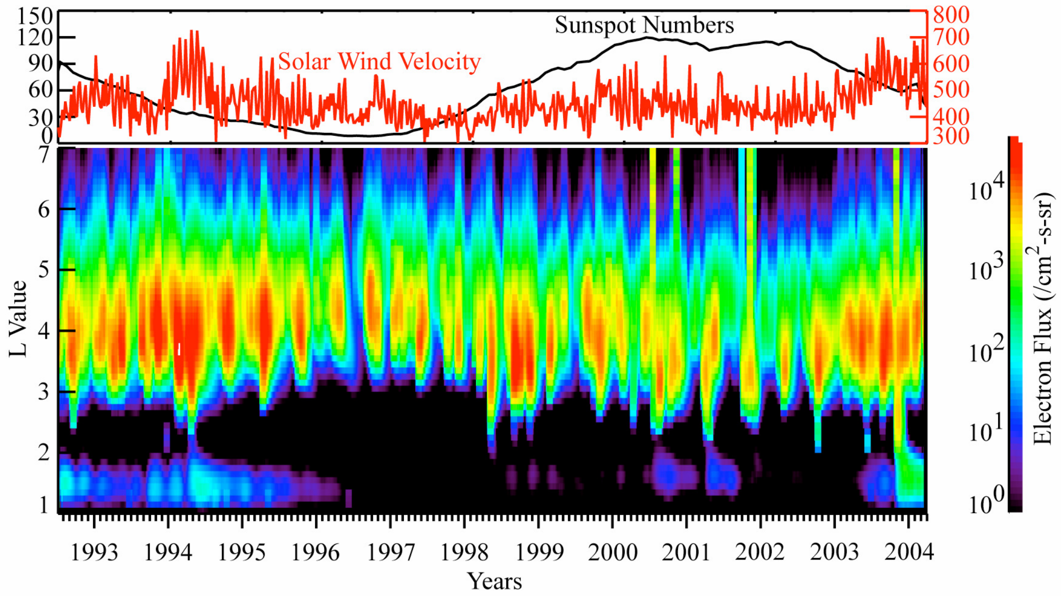
Radiation Belts:

Astrophysical & Planetary Particle Accelerator Ignored by French Scientific Community

- Vladimir Krasnosselskikh
- using materials provided by Richard Horn, Daniel Boscher and Iannis Dandouras

Earth’s Radiation Belts



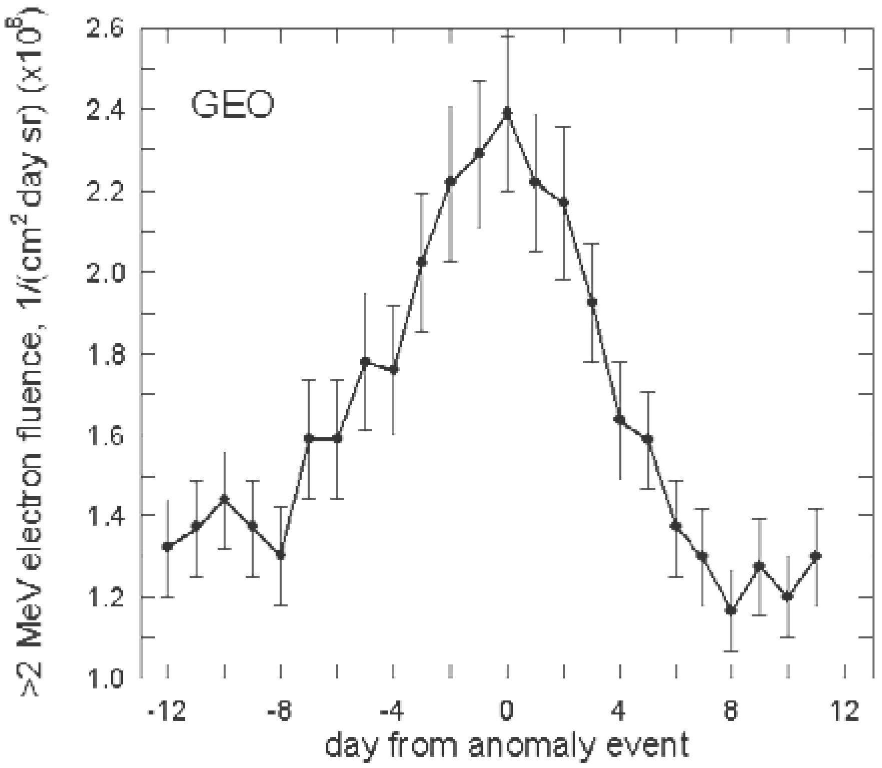


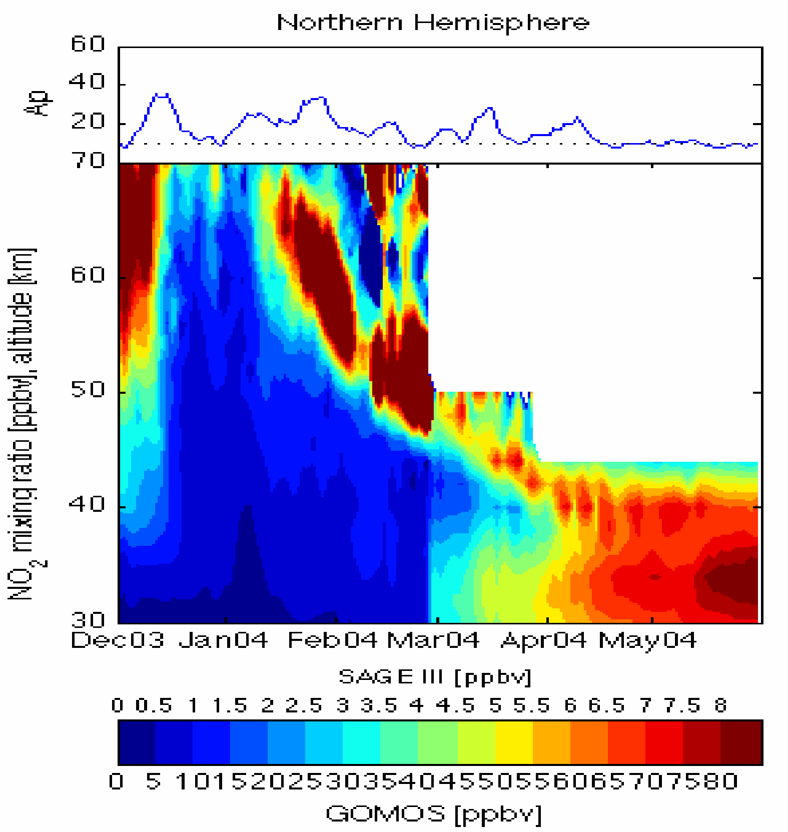
Baker and Kanekal, JASTP, 2007

- One proton belt
- Two electron belts
  - Energies > 1 MeV
  - Peaks near L=1.6 and 4.5

- How do you produce >1 MeV electrons?
- How do we explain the variability?

Importance





- chemistry (NOx), depletes ozone

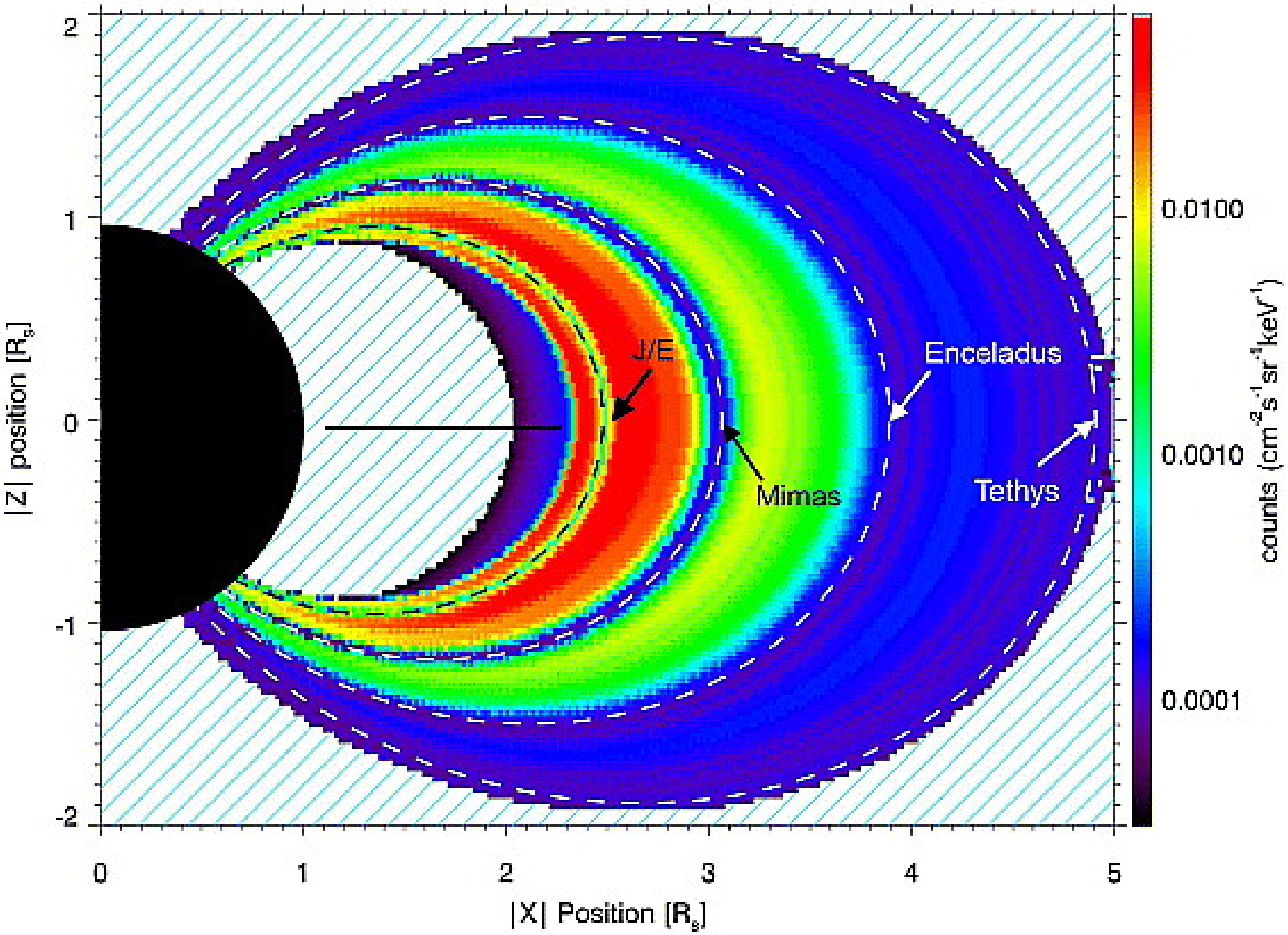
- **MeV electrons cause satellite anomalies**

- **Iucci et al. [2005]**

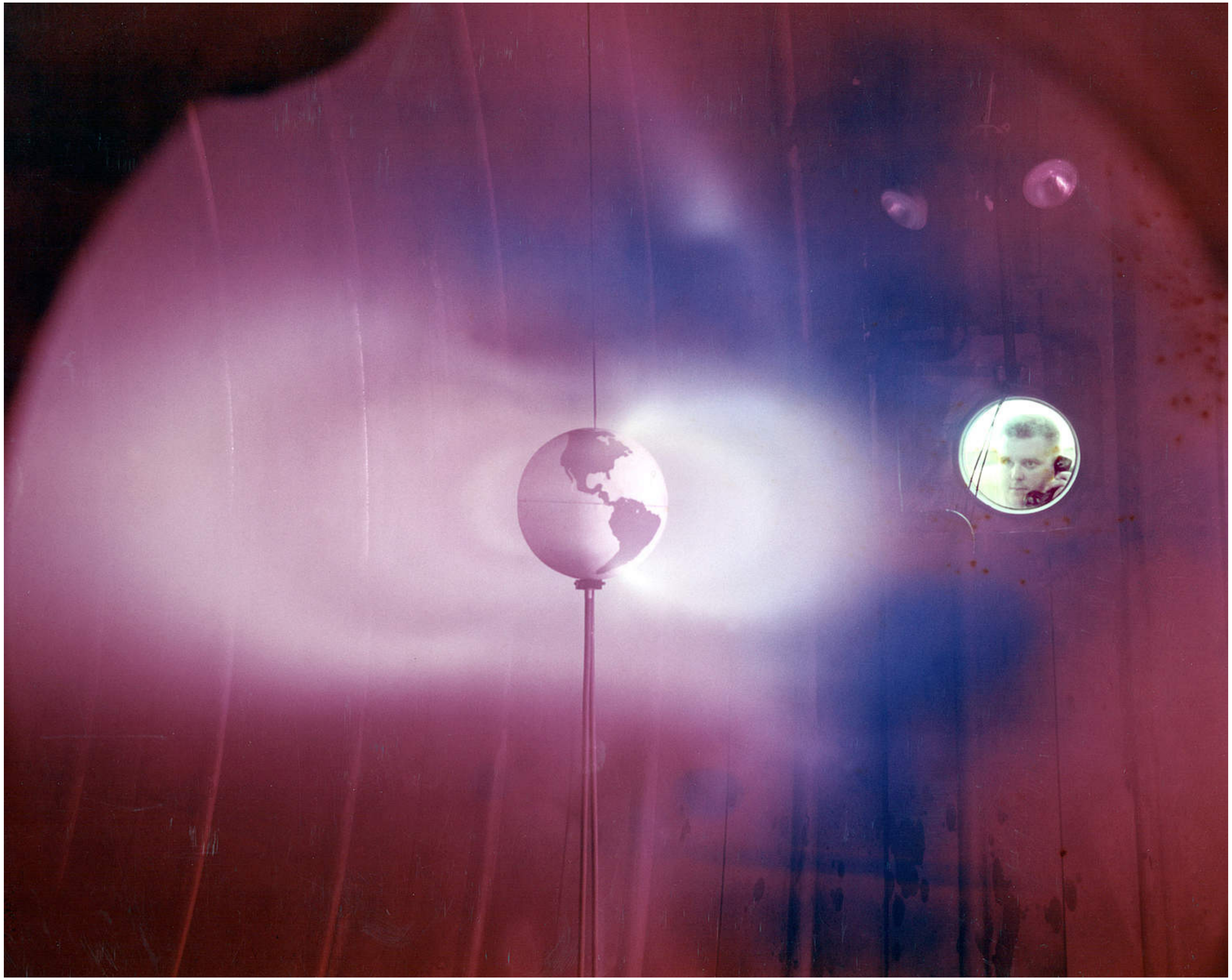
- **Solar activity may affect temperature via particle precipitation, chemistry, and atmospheric coupling**

Rozanov et al., GRL, [2005]
Clilverd et al., GRL, [2007]

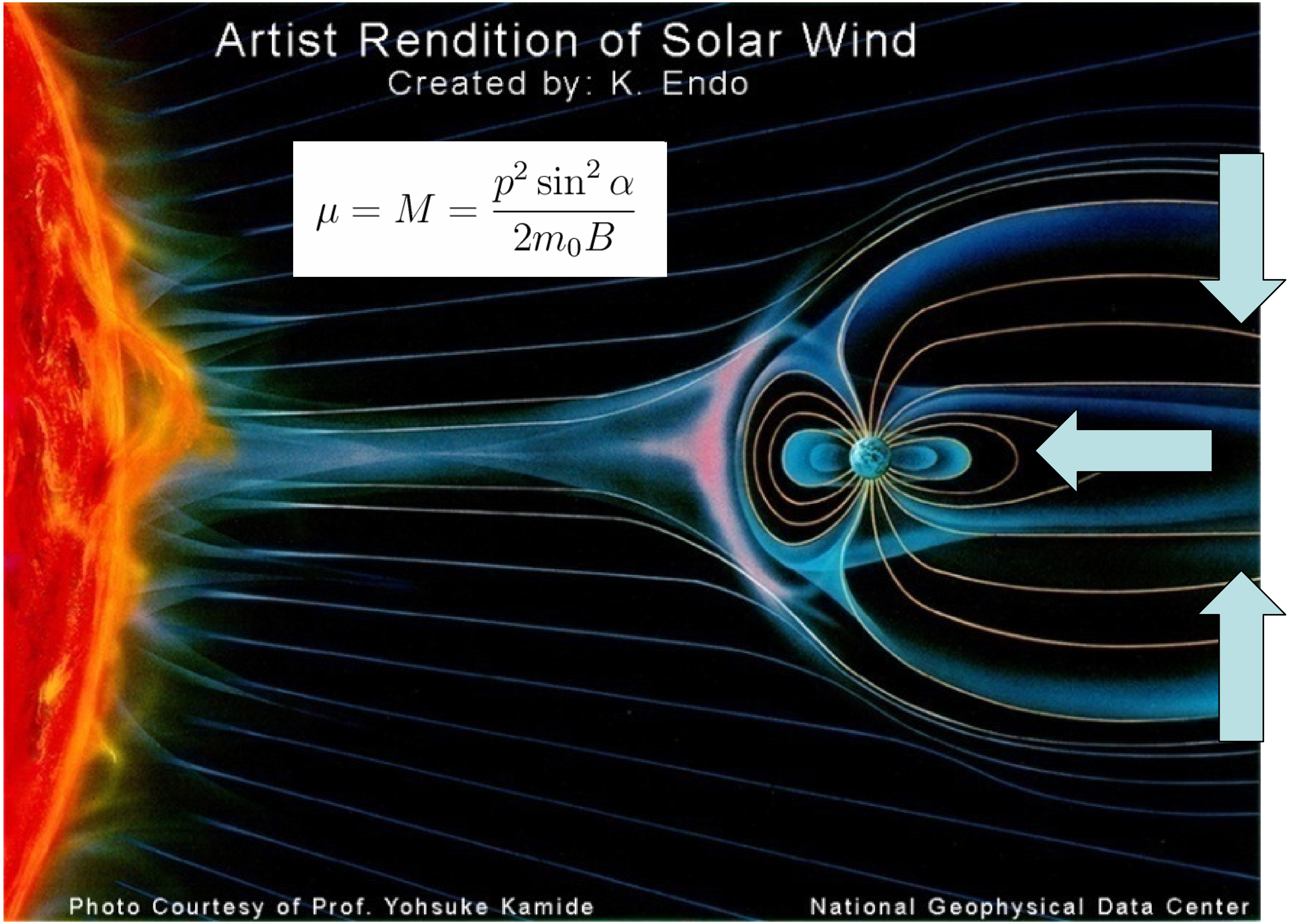
Saturnian Radiation belt



Radiation belt modelling in the plasma tank using plasma thruster



Radiation Belt Formation – Original Idea

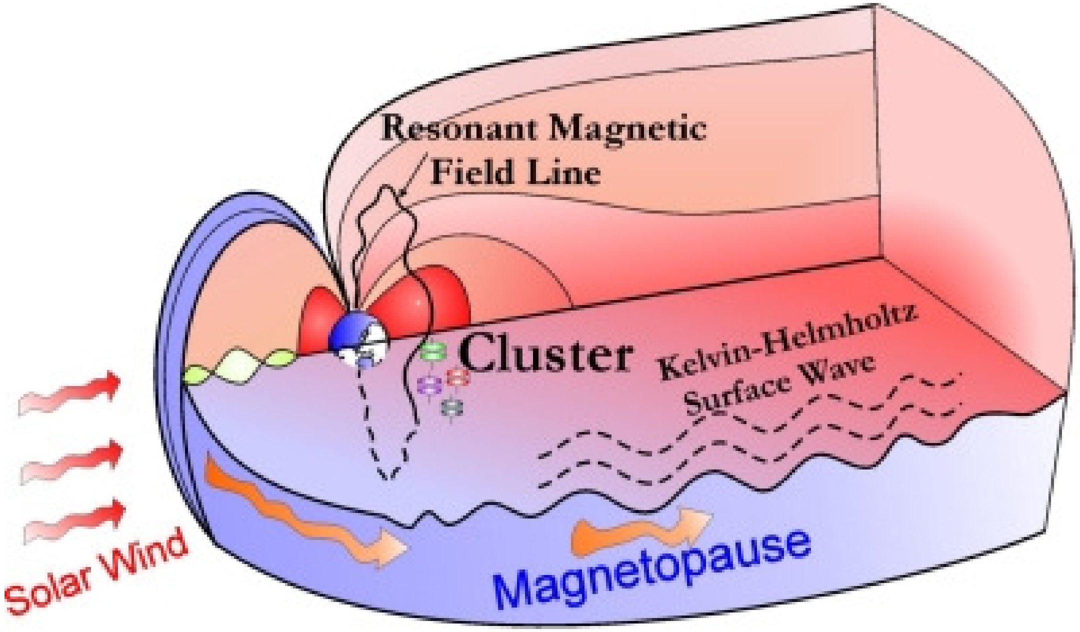


$$\mu = M = \frac{p^2 \sin^2 \alpha}{2 m_0 B}$$

Photo Courtesy of Prof. Yohsuke Kamide

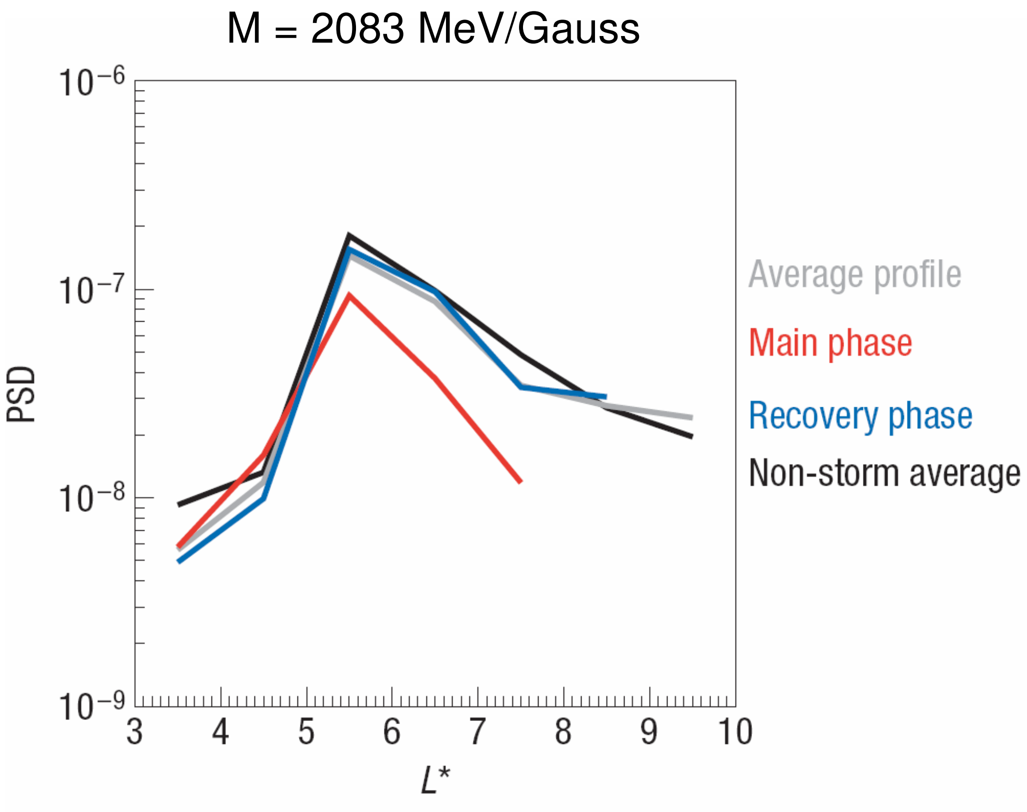
National Geophysical Data Center

ULF Enhanced Radial Diffusion



- Fast solar wind drives ULF waves inside magnetosphere
- ULF wave frequency ~ electron drift frequency
  - diffuse electrons towards the Earth
- Conservation of 1st invariant results in electron acceleration

The Original Idea is not Right



Peak in electron phase space density is near L=5.5

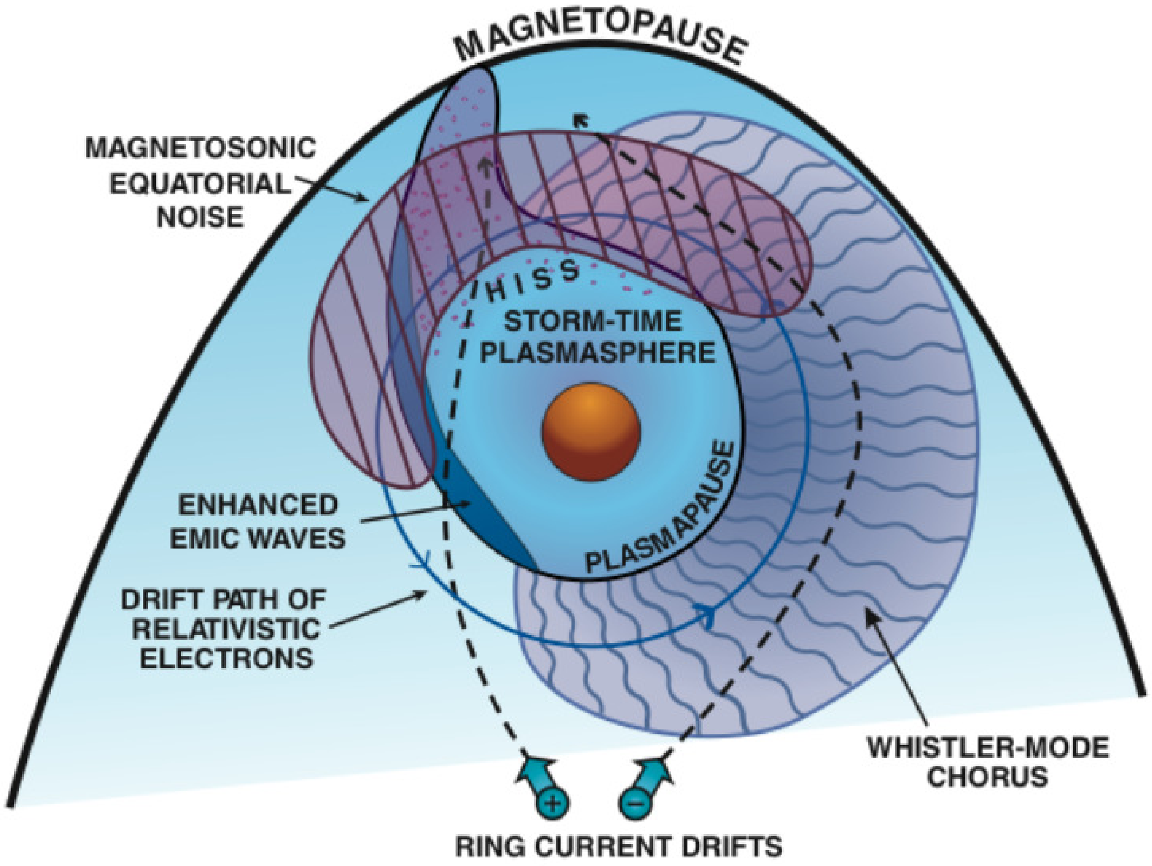
Does not support radial diffusion from a source in the outer magnetosphere

Suggests a new “local” acceleration mechanism

Radial diffusion is still a major transport process

Chen et al., Nature Physics, [2007]

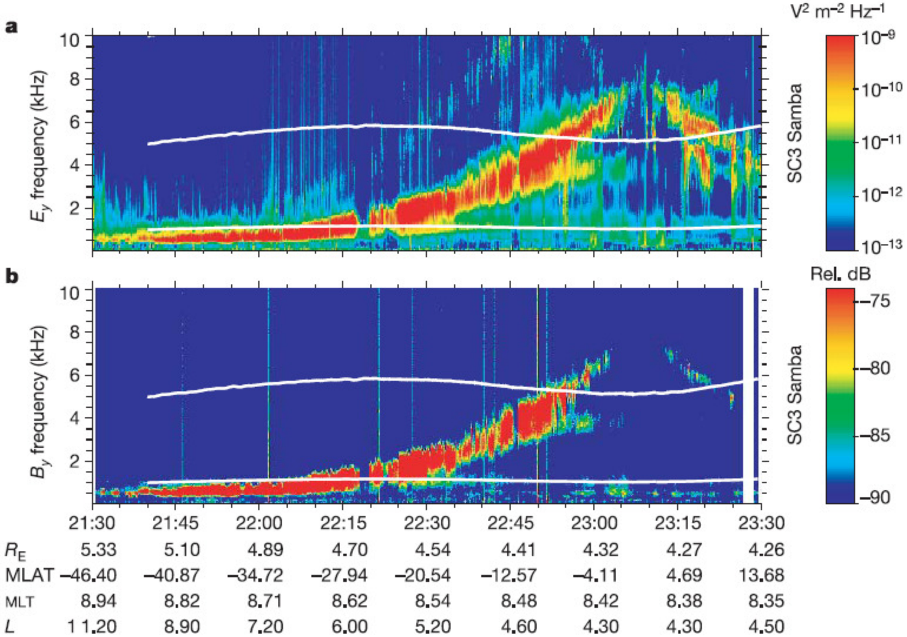
Acceleration and Loss by Wave-Particle Interactions

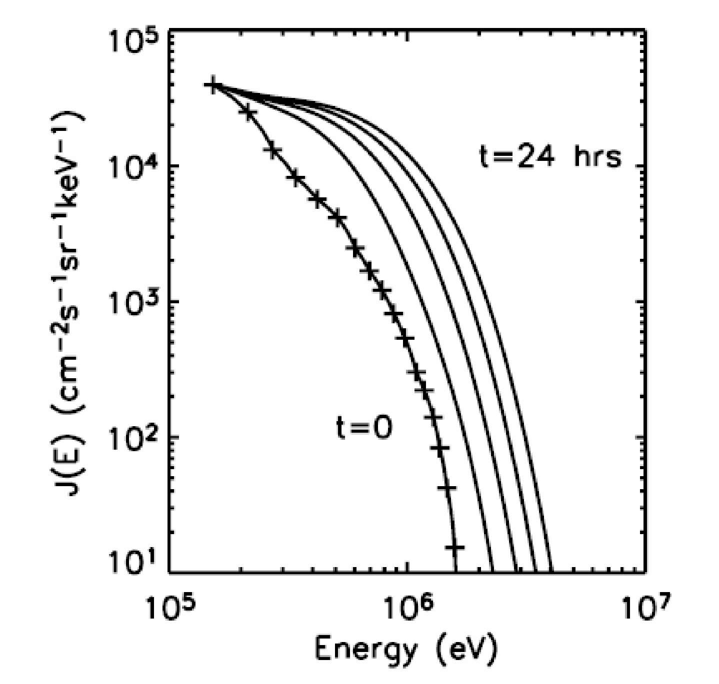


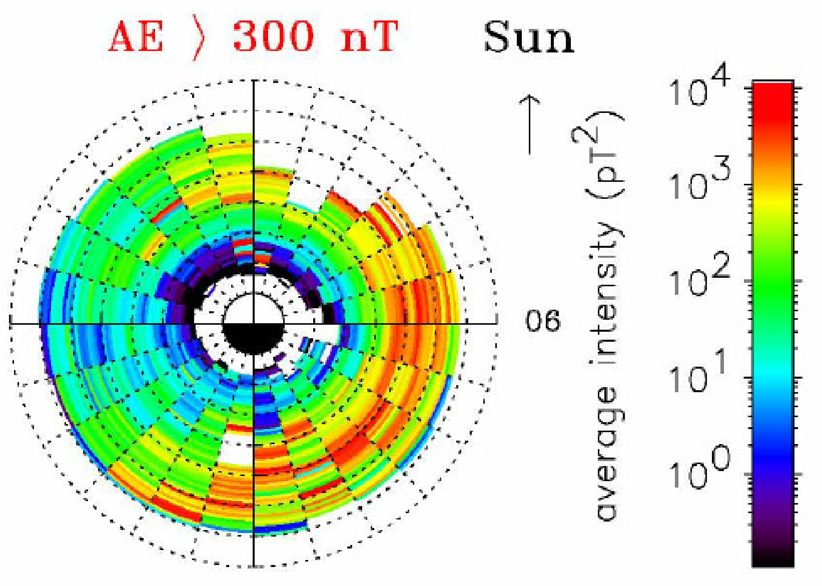
- Particles encounter many types of waves:

- Chorus
- Hiss
- Lightning generated whistlers
- VLF transmitters
- EMIC
- Magnetosonic
- Z mode
- LO and RX modes

Cyclotron Resonant Electron Acceleration: Chorus





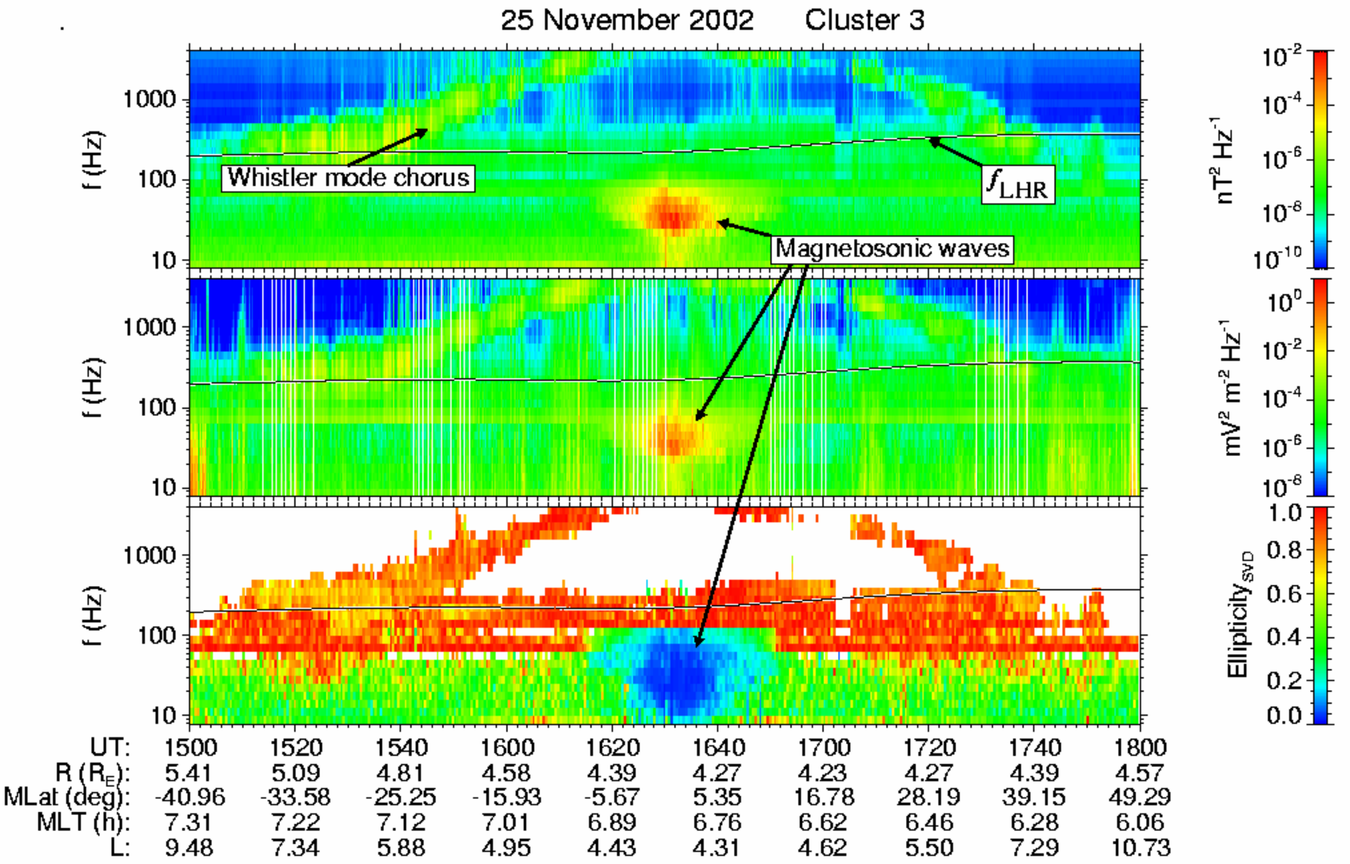


- **Whistler mode waves excited by ~1-50 keV electrons**

- **Waves accelerate a fraction of the population up to MeV energies**

  - **Horne et al., Nature [2005]**

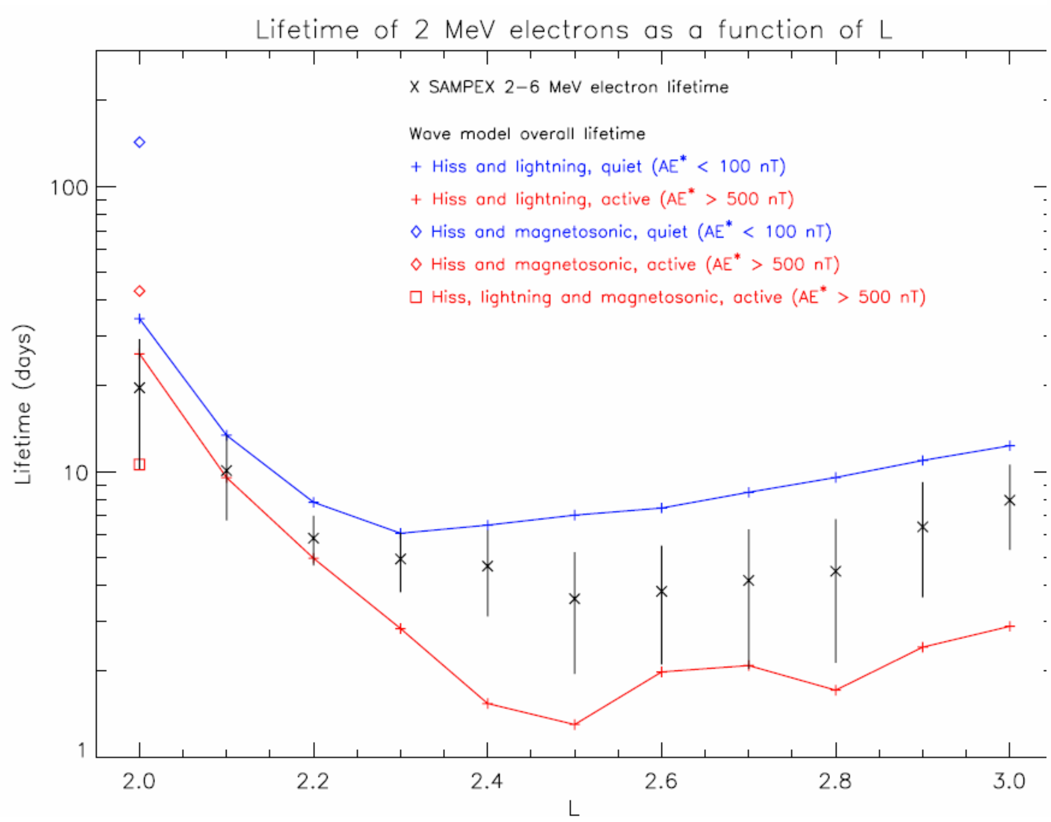
Magnetosonic Waves

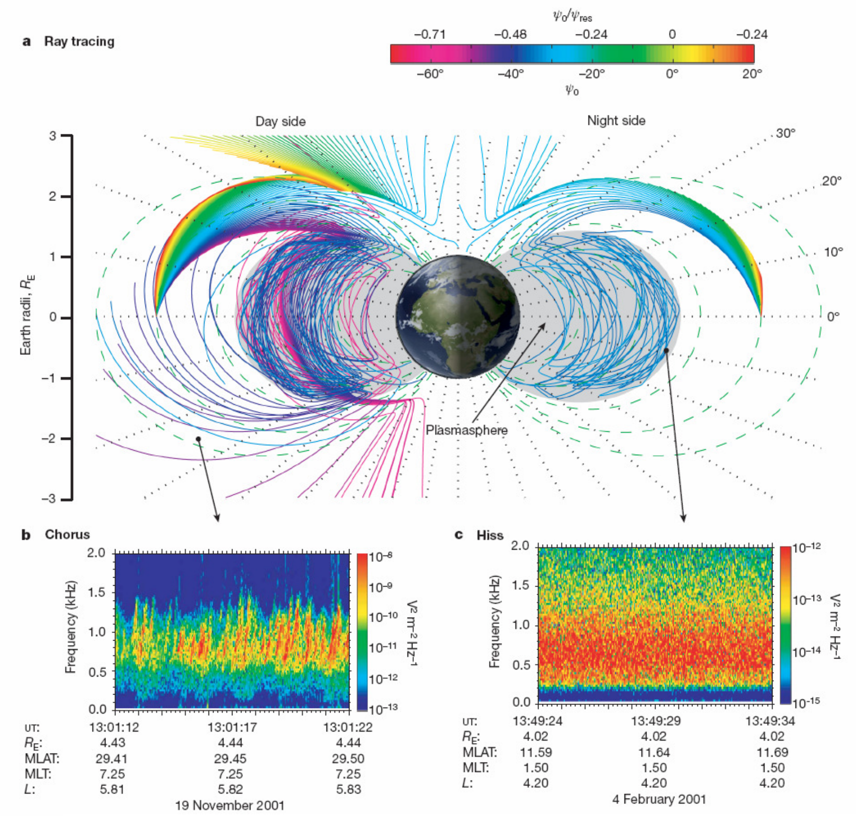


Horne et al., GRL [2007]

- **Magnetosonic waves propagate across Bo, fcH < f < fLHR**
- **Can cause electron acceleration up to MeV energies**
- **How important on a global scale?**

Electron Loss due to Lightning Generated Whistlers and Hiss

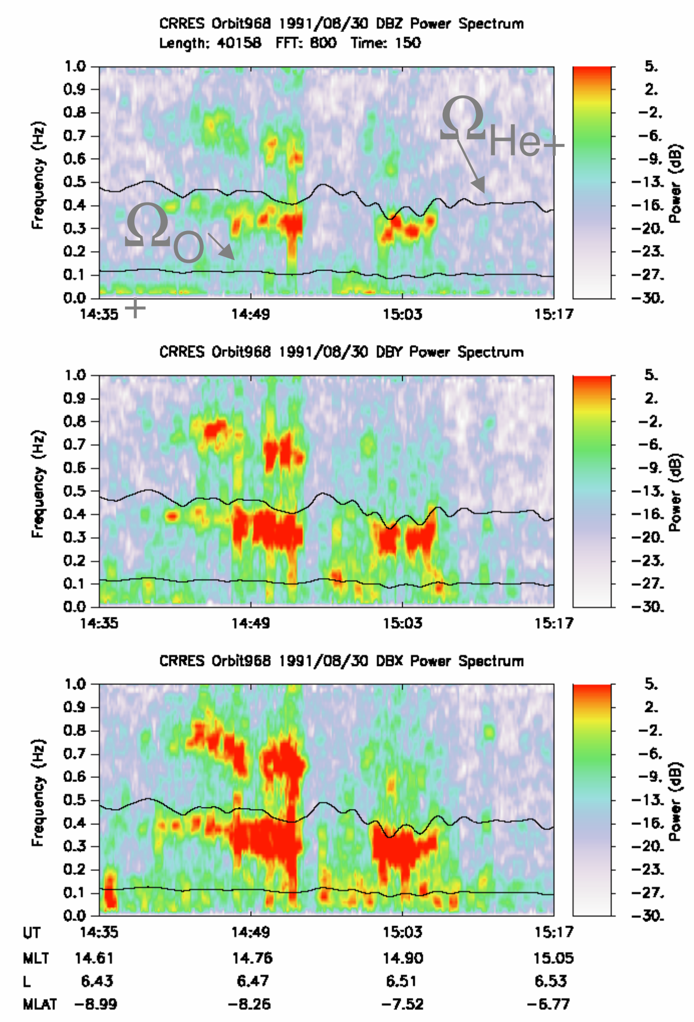


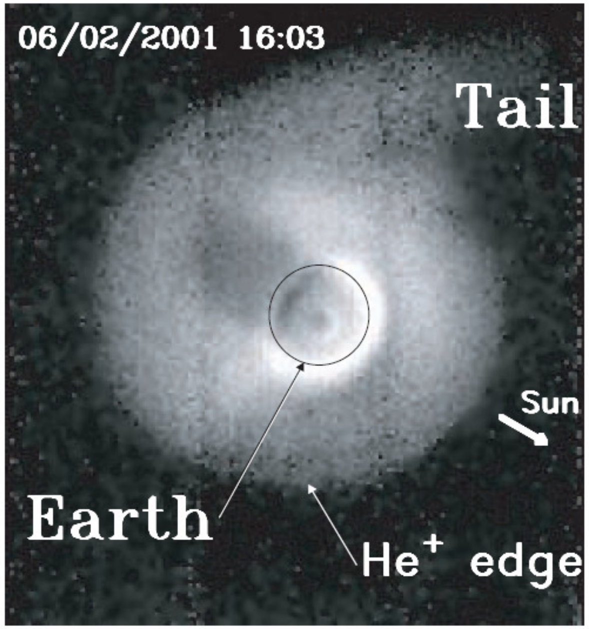


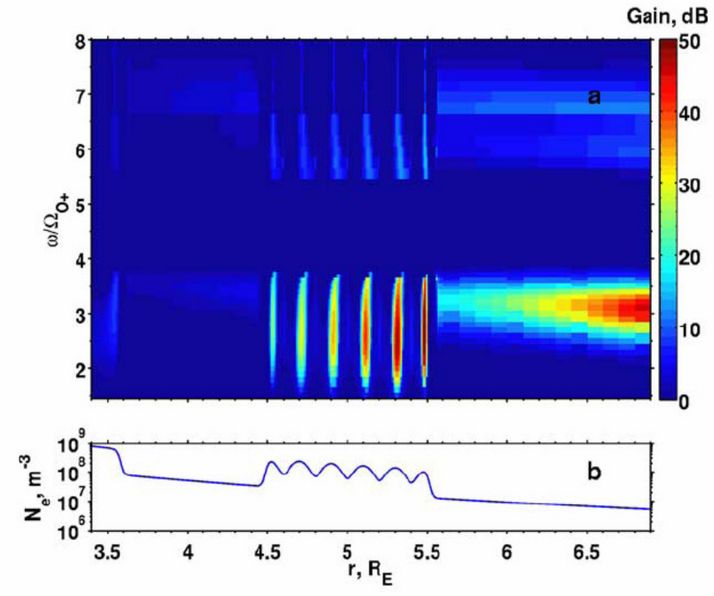
Bortnik et al., Nature [2008]

- **Lightning and transmitters are important for L < ~2.4**
- **Plasmaspheric hiss is important for L > ~2.4**

EMIC waves and Plasmaspheric Dynamics







Dynamic Radiation Belt Models

- Simple physical
  - 1d radial diffusion

- Complex physical
  - MHD/field model + gyro-kinetic
  - Diffusion – 2d, 3d and 4d
    - Radial diffusion
    - Pitch angle diffusion
    - Energy diffusion

- Data assimilation
  - Needs physical model

Modelling Approach

Observations

Transform to a dipole field (L*)

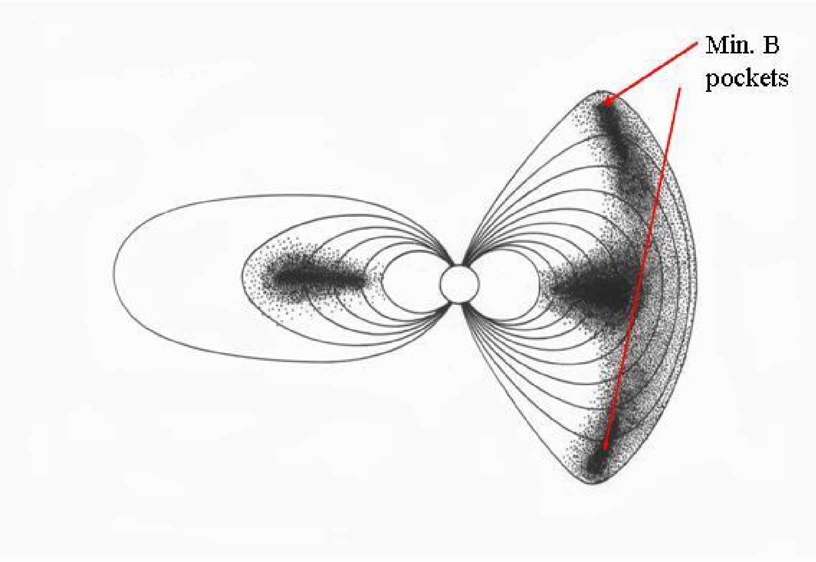
Diffusion Calculations

Observations

Use realistic magnetic field model

Gyro-kinetic Calculations

- Both need good magnetic field models
- Diffusion - complexity in transformations
- Gyro-kinetic - complexity in wave diffusion

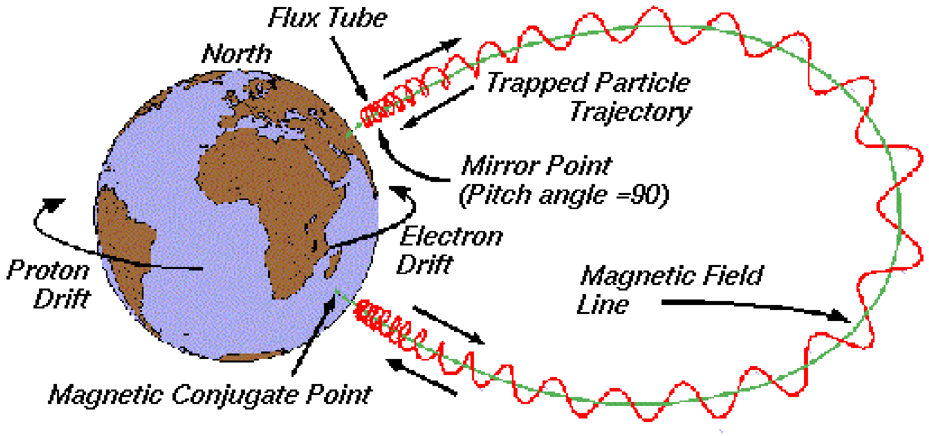


3d Global Modelling: Basic Equations

- **Electron motion has 3 components**
  - **drift, bounce, gyration**
- **Each motion has an associated adiabatic invariant**
- **Use this fact to describe radiation belt variations by a diffusion equation**

$$\frac{\partial f}{\partial t} = \sum_{i,j=1}^{3} \frac{\partial}{\partial J_i} D_{J_i J_j} \frac{\partial f}{\partial J_j}$$

- **f is the phase space density**
- **J_i are the 3 adiabatic invariants**
- **D_{JJ} are diffusion coefficients**



- **Difficult to specify boundary conditions in terms of J_i**
- **Electron flux is usually measured in energy, pitch angle, position**
- **Diffusion coefficients are calculated in terms of energy, pitch angle, not J_i and therefore must be transformed**

3d Global Modelling

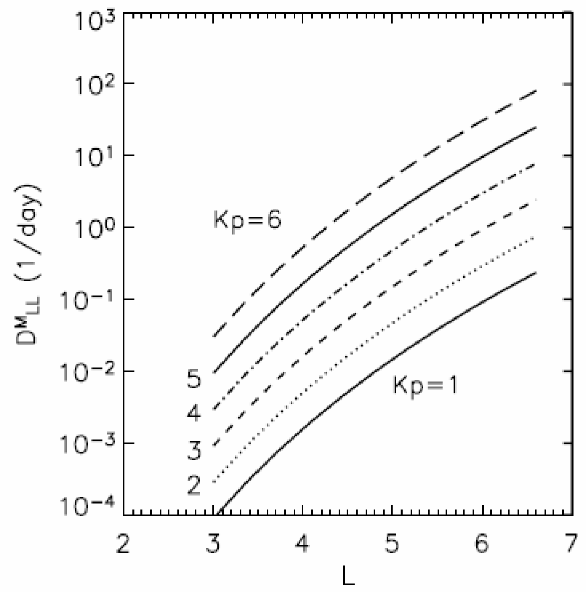
- Transform from invariants (J_1, J_2, J_3) to (α , E, L*) or (y, p, L*) e.g.

$$\begin{aligned}\frac{\partial f}{\partial t} &= L^2 \frac{\partial}{\partial L}\left(D_{LL} L^{-2} \frac{\partial f}{\partial L}\right) \\ &+ \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 \langle D_{pp}\rangle \frac{\partial f}{\partial p} + p^2 \langle D_{py}\rangle \frac{\partial f}{\partial y}\right) \\ &+ \frac{1}{T(y)y}\frac{\partial}{\partial y}\left(T(y)y\langle D_{yy}\rangle \frac{\partial f}{\partial y} + T(y)y\langle D_{yp}\rangle \frac{\partial f}{\partial p}\right) - \frac{f}{\tau}\end{aligned}$$

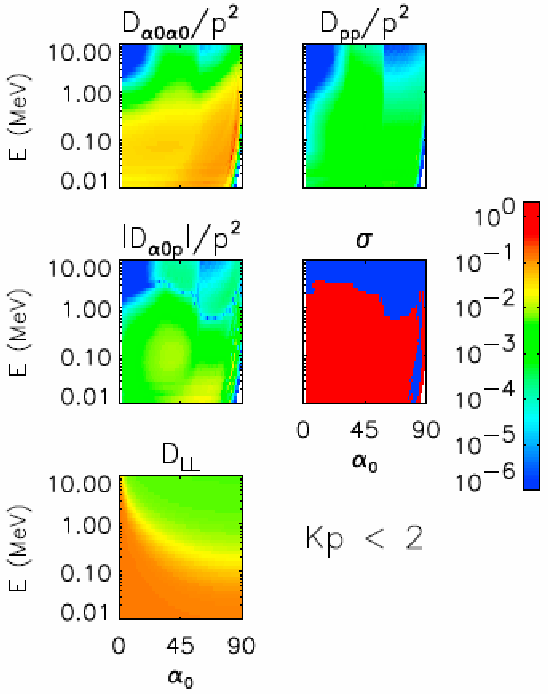
- But now we must include cross diffusion terms – added complexity
- Radial diffusion is for constant J_1 and J_2, - OK on a (J_1,J_2,L*) grid
- However
    - Momentum diffusion is for constant (L*,y)
    - Pitch angle diffusion (y) is for constant (L*,p)
    - Requires complex differential operators
- Solution - use 2 grids – and transform between them

Diffusion Coefficients

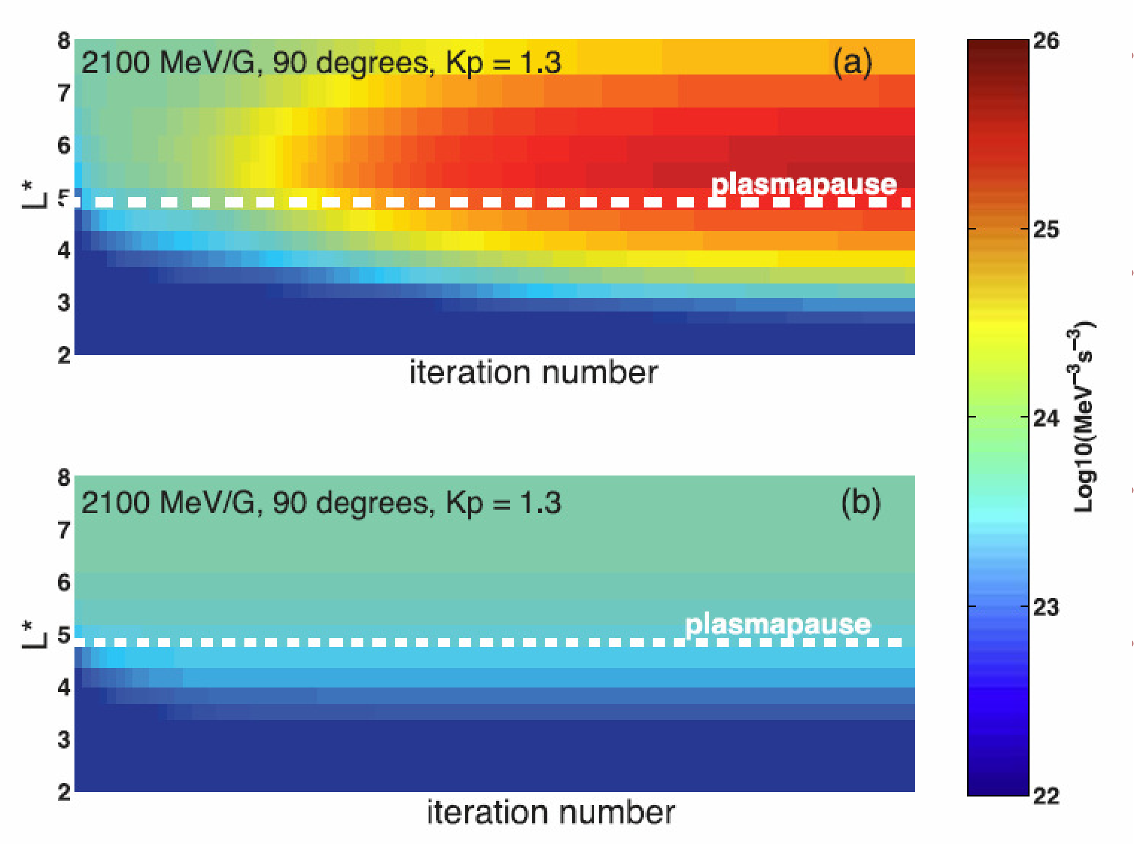
- D_{LL}
- Driven by ULF waves
- Drives radial diffusion (transport) across the magnetic field
- Function of magnetic activity (Kp), pitch-angle, energy and L shell
- From [Brautigam & Albert, JGR ,2000]



- $D_{\alpha\alpha}$ and D_{EE}
- Driven by wave-particle interactions
- Drive acceleration and loss
- Function of wave power pitch-angle, energy and L shell
- Chorus and hiss wave power scaled to AE (or Kp)

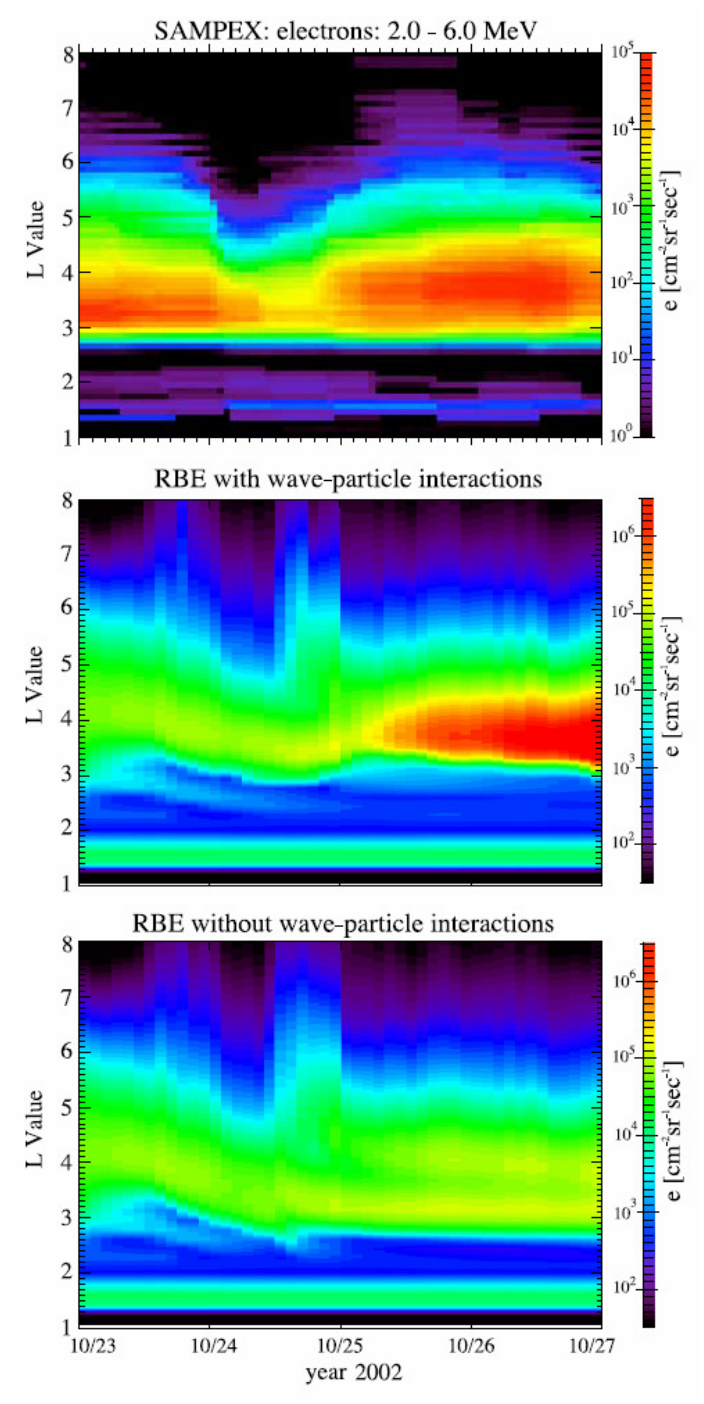


Salammbo Model



- [Varotsou et al. 2005, 2008; Horne et al., 2006]
- Radial diffusion + wpi due to chorus – steady state
- No cross terms
- Significant increase in electron flux due to chorus acceleration

$$\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L}\left(\frac{D_{LL}}{L^2}\frac{\partial f}{\partial L}\right) + \frac{1}{yT}\frac{\partial}{\partial y}\left(yTD_{yy}\frac{\partial f}{\partial y}\right) + \frac{1}{a}\frac{\partial}{\partial E}\left(aD_{ee}\frac{\partial f}{\partial E}\right) - \frac{1}{a}\frac{\partial}{\partial E}\left(a\frac{dE}{dt}f\right) \qquad (1)$$



Radiation Belt Environment Model

- **SAMPEX Data**
- **2-6 MeV electrons**

- **Fok et al., [2008]**
- **Radial displacement + chorus**
- **No cross terms**

- **Model**
- **Radial diffusion + wave-particle interaction due to chorus – steady state**

- **Model**
- **Transport only**

- **Chorus waves are essential to explain dynamics**

Space projects

- *NASA Radiation Belts Space Probes (RBSP):*
- *2 satellites*
- *Launch 2012*
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