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Title: Unlocking the Secrets of Van Allen Radiation Belt Dynamics

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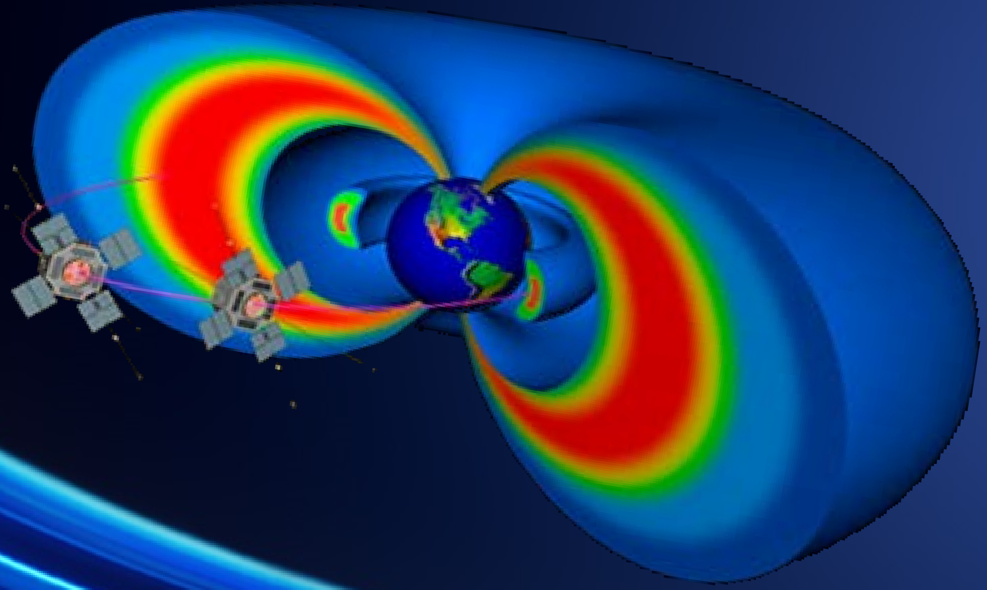
Intended for: Talk slides for personal job interview based on the two published JGR and GRL papers with approved LA-UR numbers.

Issued: 2015-02-22

Unlocking the Secrets of Van Allen Radiation Belt Dynamics



Dr. Weichao Tu
Los Alamos National Lab

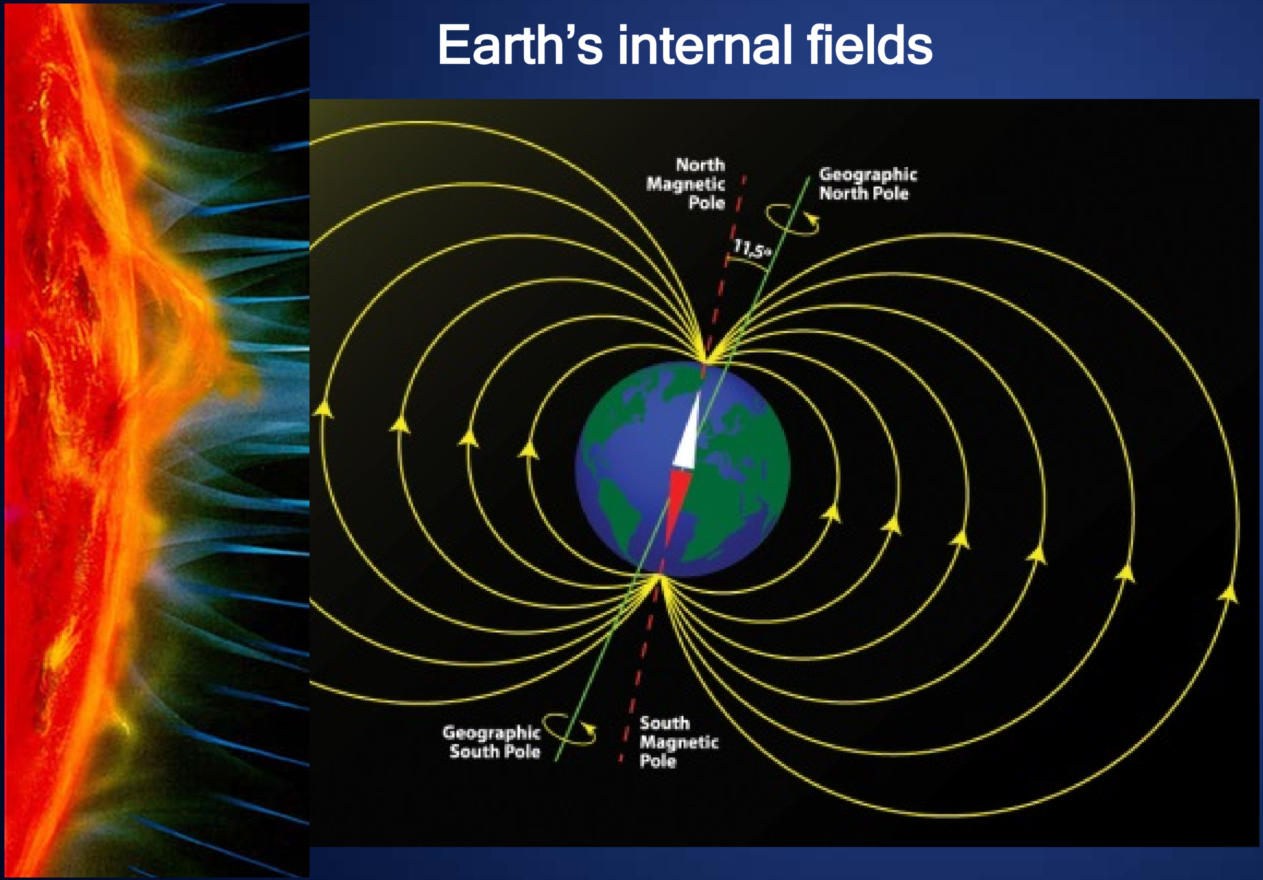
West Virginia University
2015/02/26

Outline

- Overview: Van Allen Radiation Belts and Why do we care?
- Introduction: Characterizing the radiation belt dynamics
- Modeling Work: Source, Transport, and Loss
- Conclusion: Challenges and Opportunities

Earth’s Magnetosphere

- Charged particles in solar wind are swept by Earth’s magnetic fields, creating a cavity called the Magnetosphere.



Earth’s internal fields

Earth’s Magnetosphere

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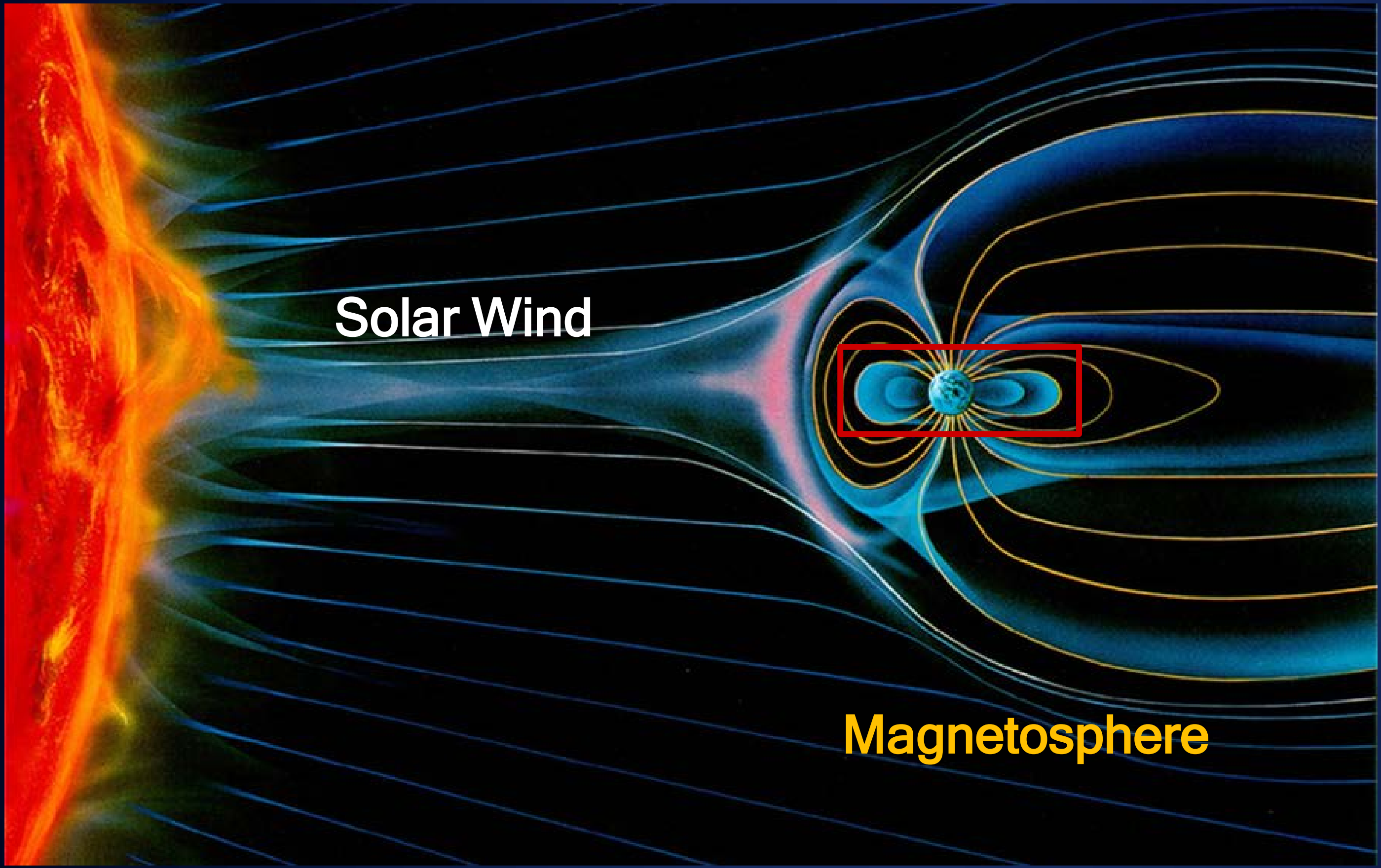
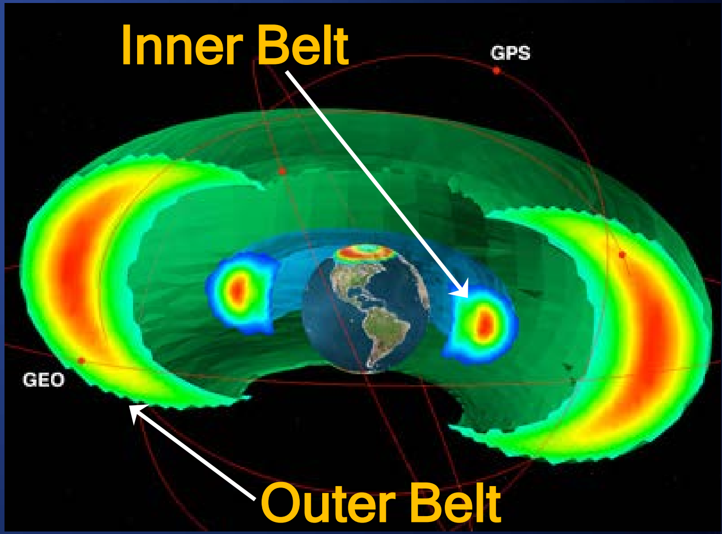


Van Allen Radiation Belts

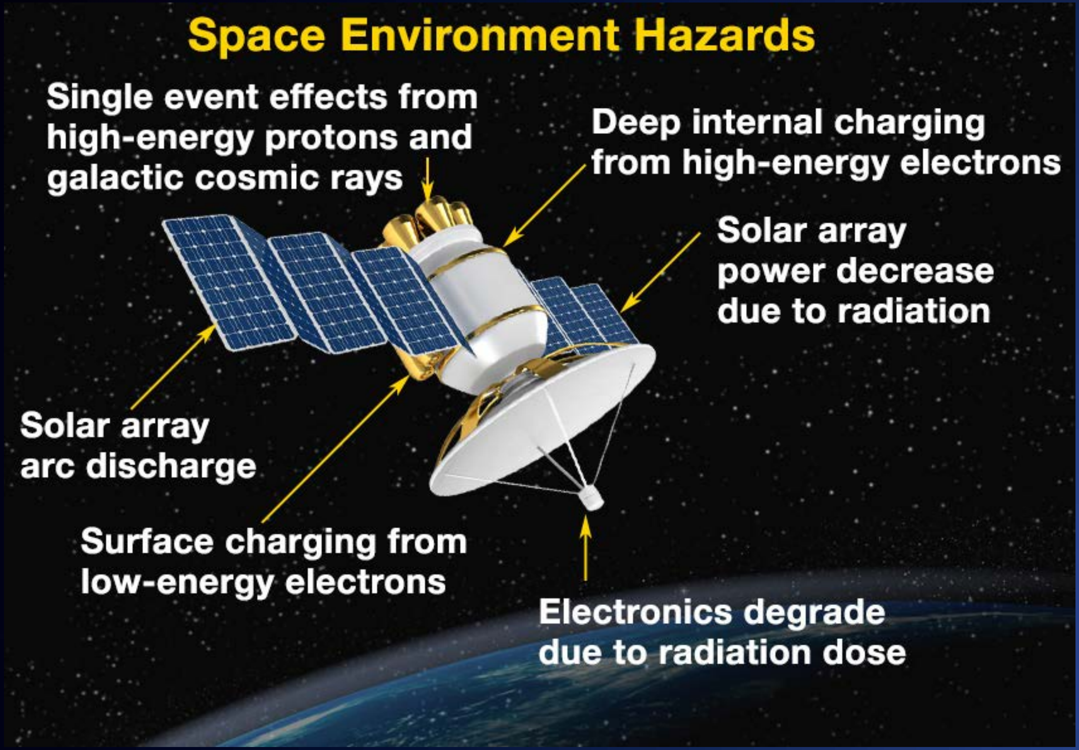
- Discovery! In 1958 by Explorer 1 and 3 under Dr. James Van Allen.

Explorer 1 launch: 1958

- Belts of energetic charged particles trapped by Earth's magnetic fields.
- Inner belt
  - 1,000-6,000 km altitude
  - Protons (10s-100s MeV)
    Electrons (10s-100s KeV)
- Outer belt
  - 13,000-60,000 km altitude
  - Electrons (0.5-10 MeV)



Space Weather Effects



- Near-Earth radiation environment causes significant threats to spacecraft electronics.

- Several satellite ‘anomalies’ have been associated with variations in the energetic particle environment.

04/20/10 02:05 PM ET

Orbital Blames Galaxy 15 Failure on Solar Storm

By Peter B. de Selding

PARIS — The in-orbit failure of the Orbital Sciences-built Intelsat Galaxy 15 telecommunications satellite April 5 was likely caused by unusually violent solar activity that week that damaged the spacecraft's ability to communicate with ground controllers, Orbital officials said April 20.

Galaxy 15 satellite. Credit: Orbital Sciences' photo

Similar events have occurred, if less

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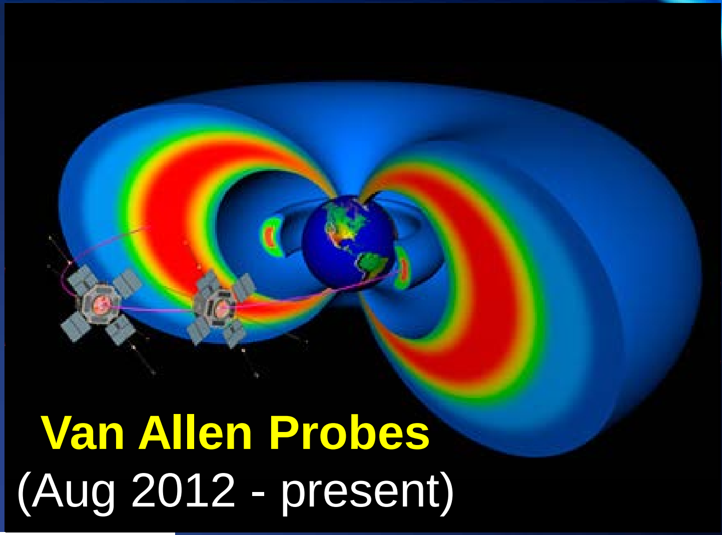
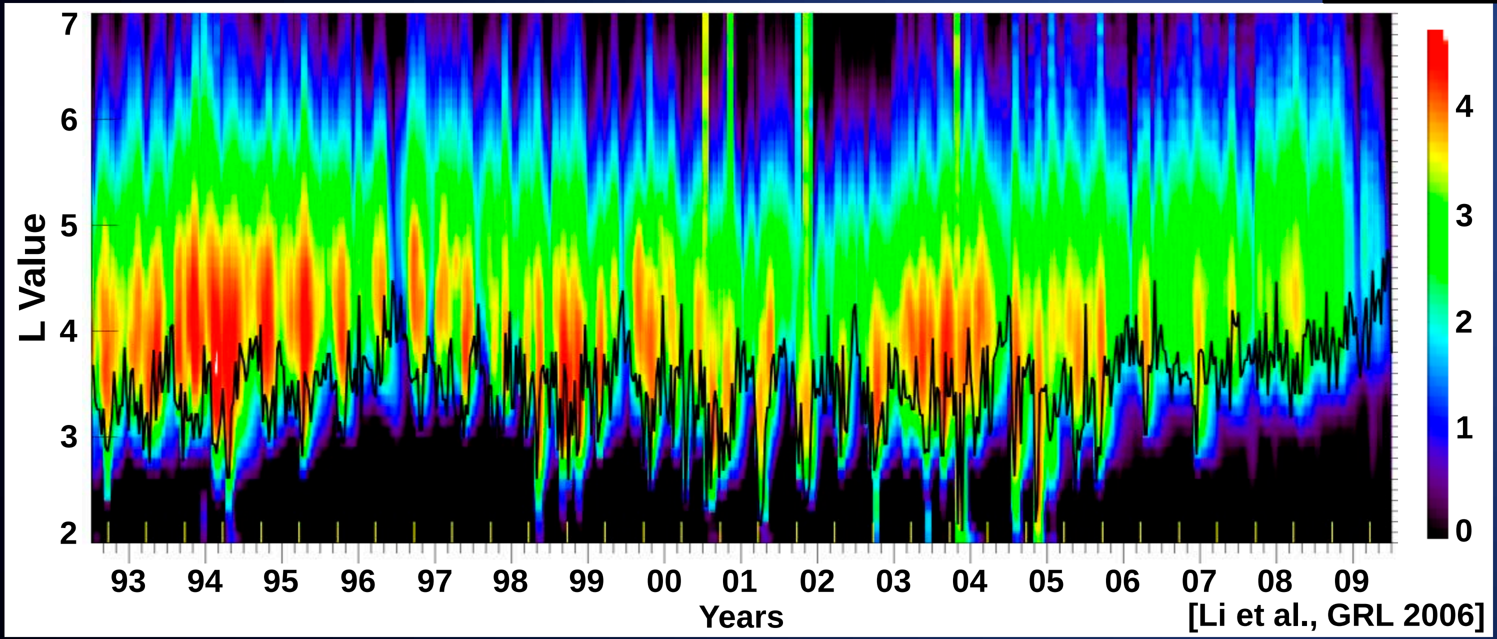
Outer Radiation Belt Variability

- Outer electron belt is very dynamic!
  - Electron flux can increase or decrease by orders of magnitude.
  - Variation time scale: from days to years
- Understanding the dynamics is the No.1 goal of the NASA Van Allen Probes Mission.



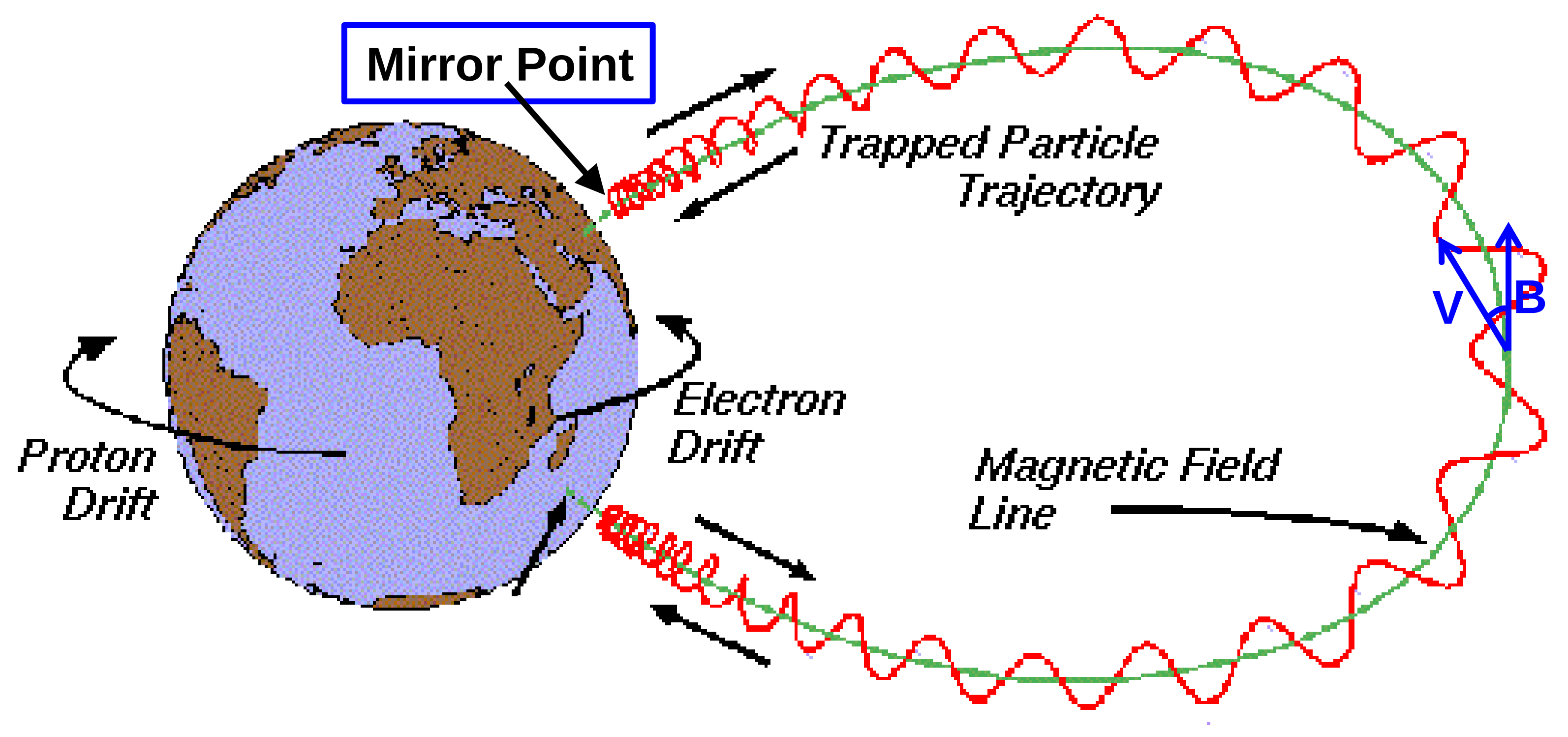
Van Allen Probes
(Aug 2012 - present)



[Li et al., GRL 2006]

- Color-coded: 2-6 MeV Electron Flux (in log).

Charged Particle Motions

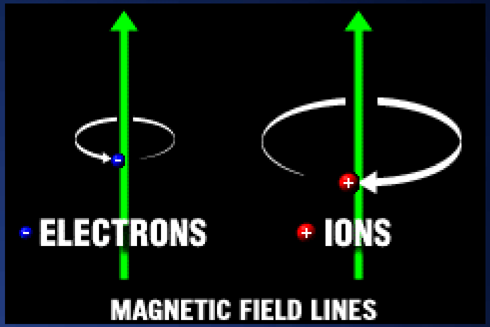


- Gyromotion: period of ~10^{-3} sec (milliseconds for MeV electrons)
- Bounce motion: period of ~10^{0} sec, depends on pitch angle
  - Pitch angle: angle between magnetic field and electron velocity
- Drift motion: period of ~10^{3} sec (10 minutes)

Adiabatic Invariants

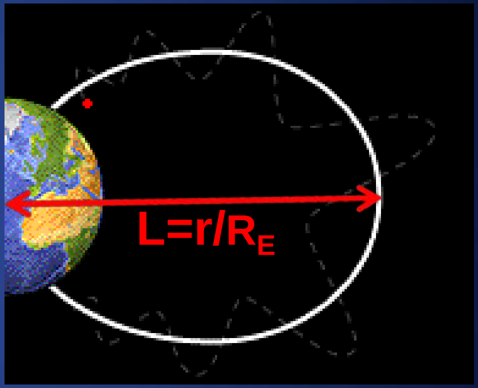
- Each periodic motion is associated with an adiabatic invariant.
  - 1st adiabatic invariant associated with the gyromotion (10^{-3} sec):

$$\mu = p_\perp^2 / 2m_0 B \text{ (1st)}$$



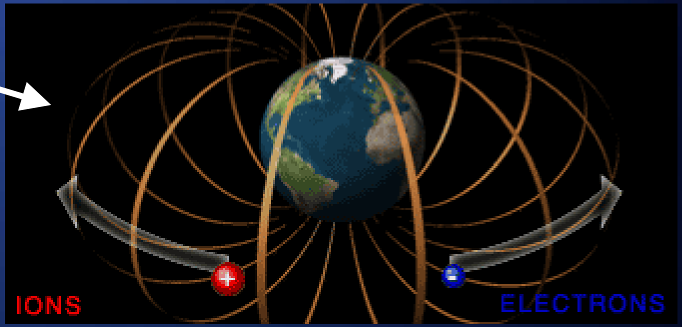
  - 2nd adiabatic invariant associated with the bounce motion (10^0 sec):

$$J = \oint p_\parallel ds \text{ (2nd)} \Rightarrow K = J / 2\sqrt{2m_0 \mu}$$



  - 3rd adiabatic invariant associated with the drift motion (10^3 sec):

$$\Phi = \oint \vec{B} d\vec{A} \text{ (3rd)} \Rightarrow L^* = 2\pi M / (\Phi R_E)$$



- The adiabatic invariant is conserved if the variation of the environmental field is slow compared to the period of that motion.

Describing the Radiation Belts

- The radiation belt can be completely described by its distribution function:

$$f = f(x, y, z, p_x, p_y, p_z)$$

— Phase Space Density

- It is more useful to equivalently write it in terms of adiabatic invariants:

$$f = f(x, y, z, p_x, p_y, p_z) = f(\mu, K, L, \phi_1, \phi_2, \phi_3)$$

- Since most radiation belt observations are phase-averaged:

$$f = f(\mu, K, L)$$

- Measured quantity: **differential flux**

$$j(E_{ch}, \alpha, \vec{r}) = dN / dA d\Omega dE dt$$

- f and j are related by:

$$f = j / p^2$$

Diffusion in Radiation Belts

- The evolution of phase space density are most often described as stochastic diffusion processes with respect to the violated adiabatic invariant, represented by the Fokker-Planck Equation:

$$\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L}\left(\frac{D_{LL}}{L^2}\frac{\partial f}{\partial L}\right) + \frac{1}{G}\frac{\partial}{\partial K}\left(G D_{KK}\frac{\partial f}{\partial K}\right) + \frac{1}{G}\frac{\partial}{\partial \mu}\left(G D_{\mu\mu}\frac{\partial f}{\partial \mu}\right)$$

- Since K(pitch angle *α*) and μ(pitch angle *α,* momentum *p*), common form:

$$\boxed{\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L}\left(\frac{D_{LL}}{L^2}\frac{\partial f}{\partial L}\right) + \frac{1}{\Gamma}\frac{\partial}{\partial \alpha}\left(\Gamma D_{\alpha\alpha}\frac{\partial f}{\partial \alpha}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial f}{\partial p}\right)}$$

Radial Diffusion **Pitch Angle Diffusion** **Energy Diffusion**

f: phase−averaged phase space density; $D_{LL}, D_{\alpha\alpha}, D_{pp}$: diffusion coefficients

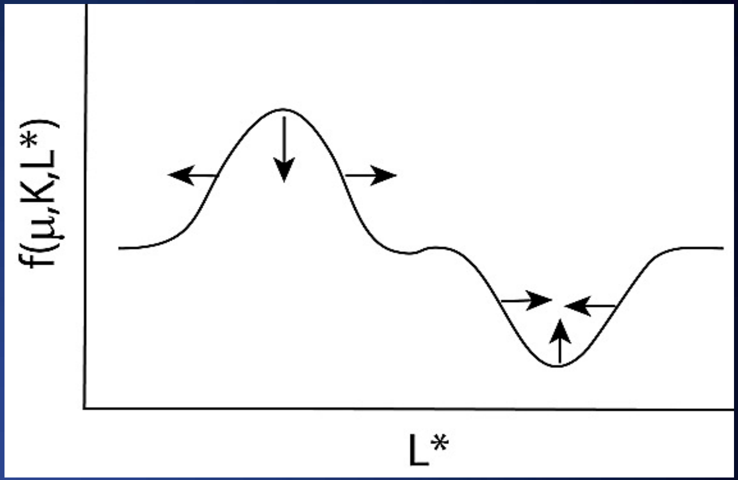
α: equatorial pitch angle; p: electron momentum

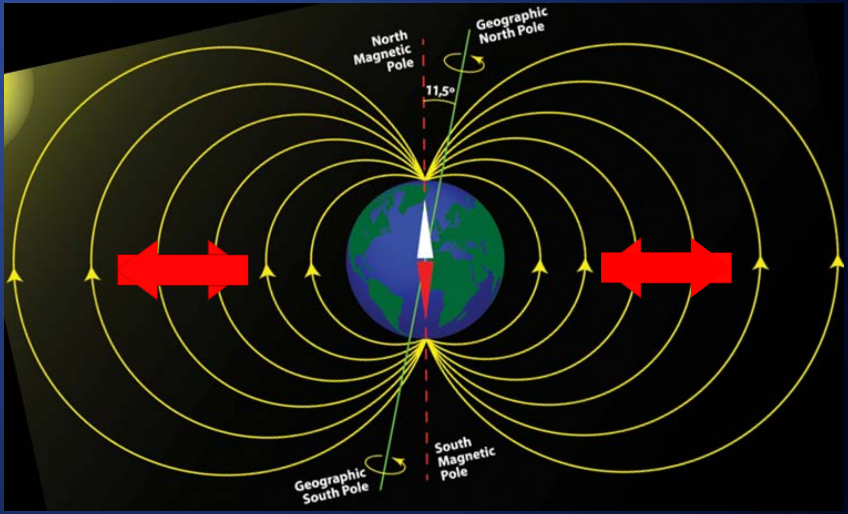
$\Gamma = T(\alpha)\sin(2\alpha), T(\alpha) \approx 1.38 - 0.32(\sin\alpha + \sqrt{\sin\alpha})$

Radial Diffusion

- Violates L but conserves μ and K.
- Driven by electron drift-resonance with ULF (Ultra Low Frequency) waves.
  - Resonance condition: $\omega = m\omega_{drift}$
- Acts to smooth out the PSD radial gradient.
  - Transport mechanism
- Inward radial diffusion
  - Acceleration mechanism
  - B enhanced, $\mu = p_{\perp}^{2} / 2m_{0}B$ conserved

    → electron energized
- Outward radial diffusion
  - Loss mechanism
  - Deceleration plus loss to the outer boundary



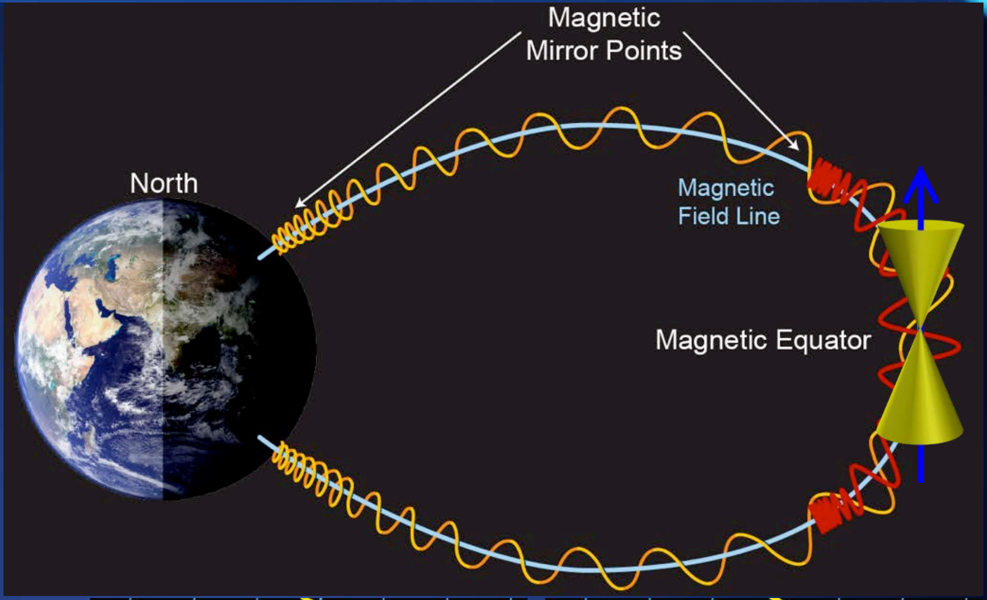


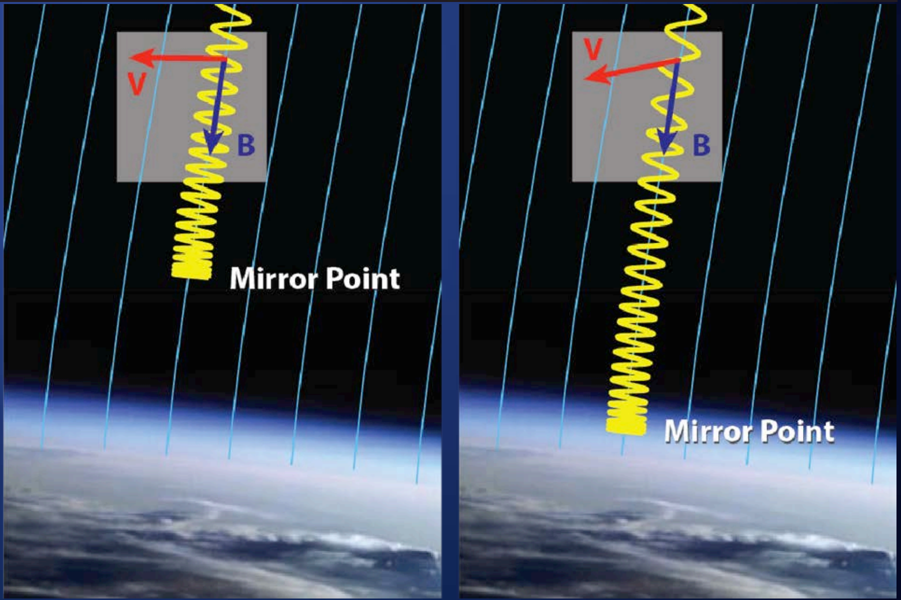
Pitch Angle Diffusion

- Violates μ, K, and L.
- Driven by electron cyclotron resonance with VLF (Very Low Frequency) waves.
  - Resonance condition:

$$\omega - k_{\|} v_{\|} = n\Omega_{gyro}$$

- Causes electron precipitation into atmosphere
  - Dominant electron loss mechanism in the heart of outer radiation belt.
  - Loss cone: the range of equatorial pitch angles within which the electrons will mirror below the atmosphere (100km).





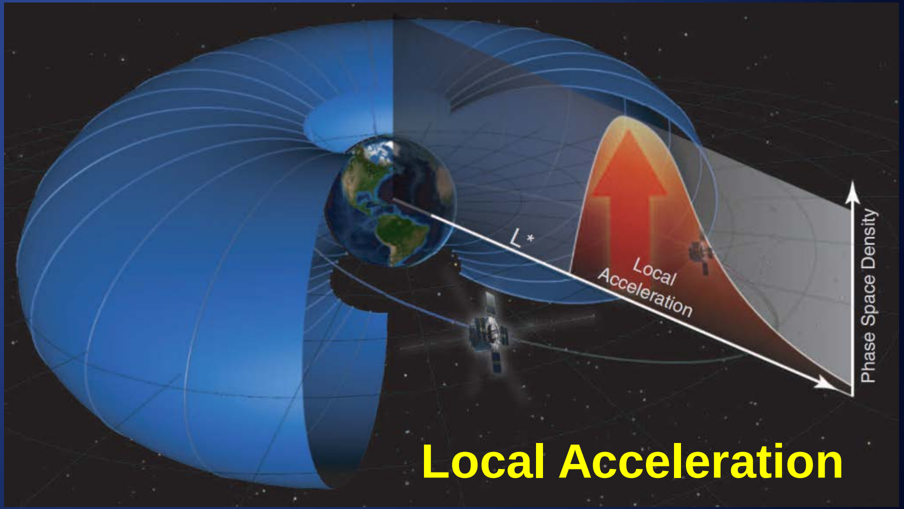
Energy Diffusion

- Violates μ, K, and L.
- Driven by electron cyclotron resonance with VLF (Very Low Frequency) waves.
    - Resonance condition:

$$\omega - k_{\parallel} v_{\parallel} = n\Omega_{gyro}$$

- Locally accelerates less-energetic electrons on the same L-shell
    - Important acceleration mechanism
    - Also called local acceleration
    - Distinguish acceleration mechanisms
        - Local acceleration vs. inward radial diffusion
        - Local peak vs. positive gradient

Inward Radial Diffusion



Local Acceleration

[Reeves et al., Science 2013]

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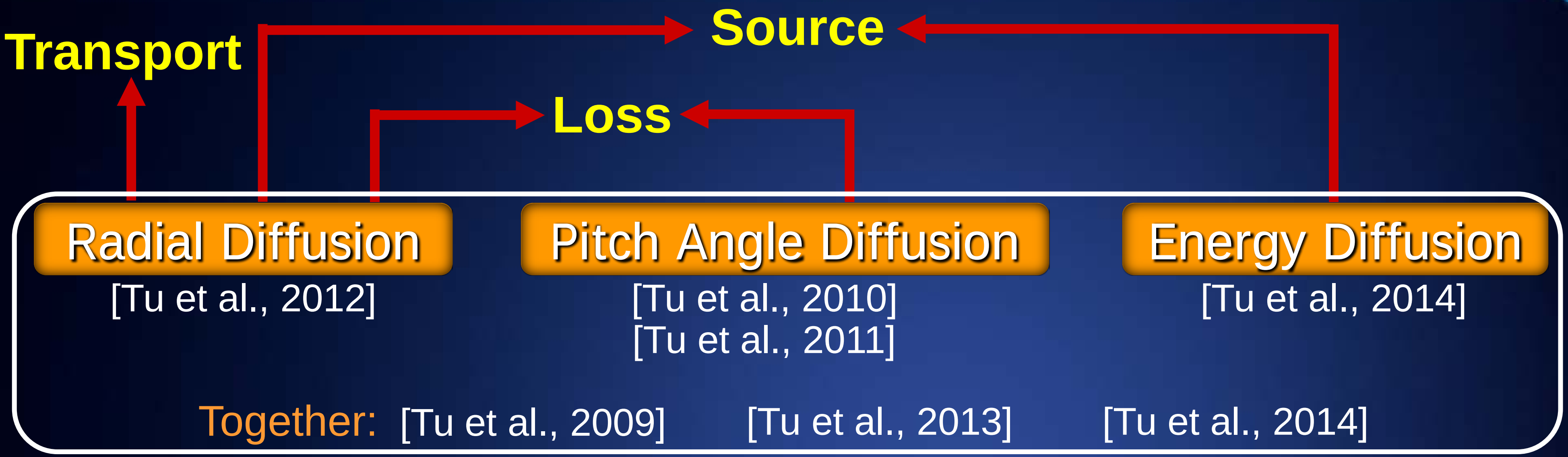
Modeling Work Overview



Transport

Source

Loss

Radial Diffusion

[Tu et al., 2012]

Pitch Angle Diffusion

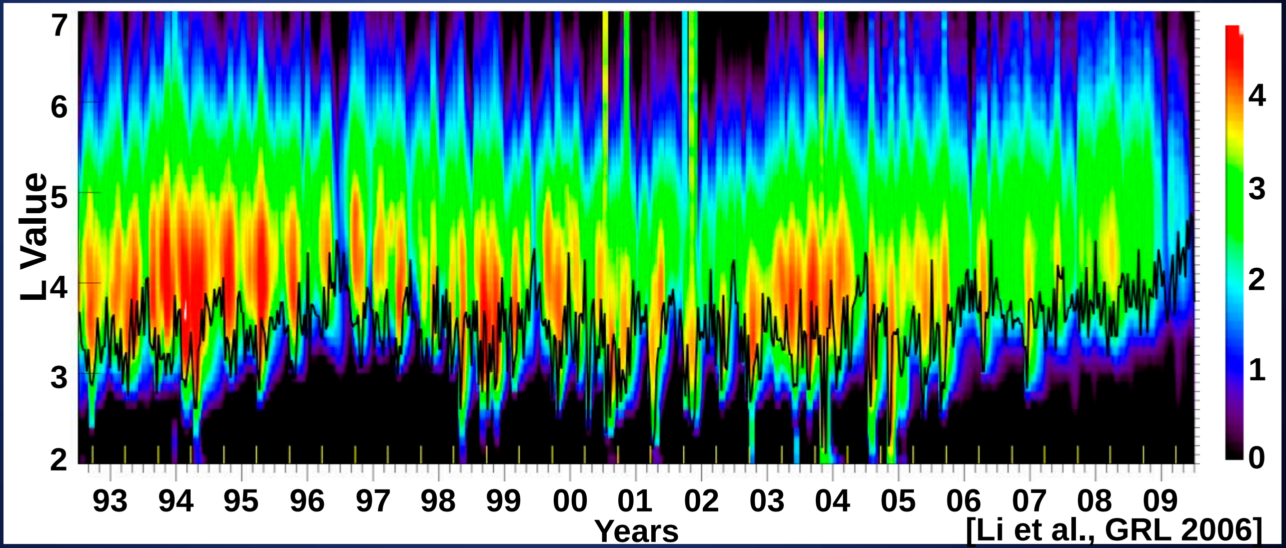
[Tu et al., 2010]
[Tu et al., 2011]

Energy Diffusion

[Tu et al., 2014]

Together: [Tu et al., 2009] [Tu et al., 2013] [Tu et al., 2014]

- The delicate balance between source, transport, and loss contributes to the variations of radiation belt electrons.



[Li et al., GRL 2006]

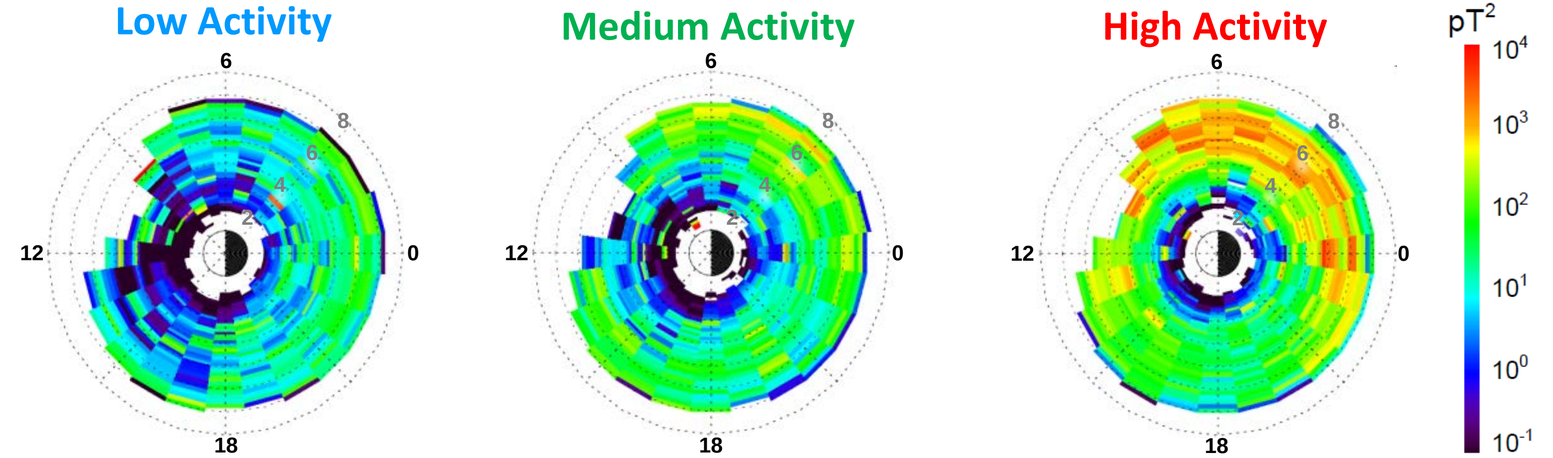
DREAM3D Diffusion Model

- DREAM3D: Dynamic Radiation Environment Assimilation Model in 3D
- Model Equation:

$$\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L}\left(\frac{D_{LL}}{L^2}\frac{\partial f}{\partial L}\right) + \frac{1}{\Gamma}\frac{\partial}{\partial \alpha}\left(\Gamma D_{\alpha\alpha}\frac{\partial f}{\partial \alpha}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial f}{\partial p}\right)$$

- Diffusion Coefficients: $D_{LL}, D_{\alpha\alpha}, D_{pp}$
  - Calculated based on spatial distribution and detailed properties of plasma waves, e.g., statistical wave maps.

Statistical Chorus Wave Intensity Distribution [Tu et al., JGR 2013]



DREAM3D Results: Long-term Study

Electron phase space density data measured by CRRES satellite

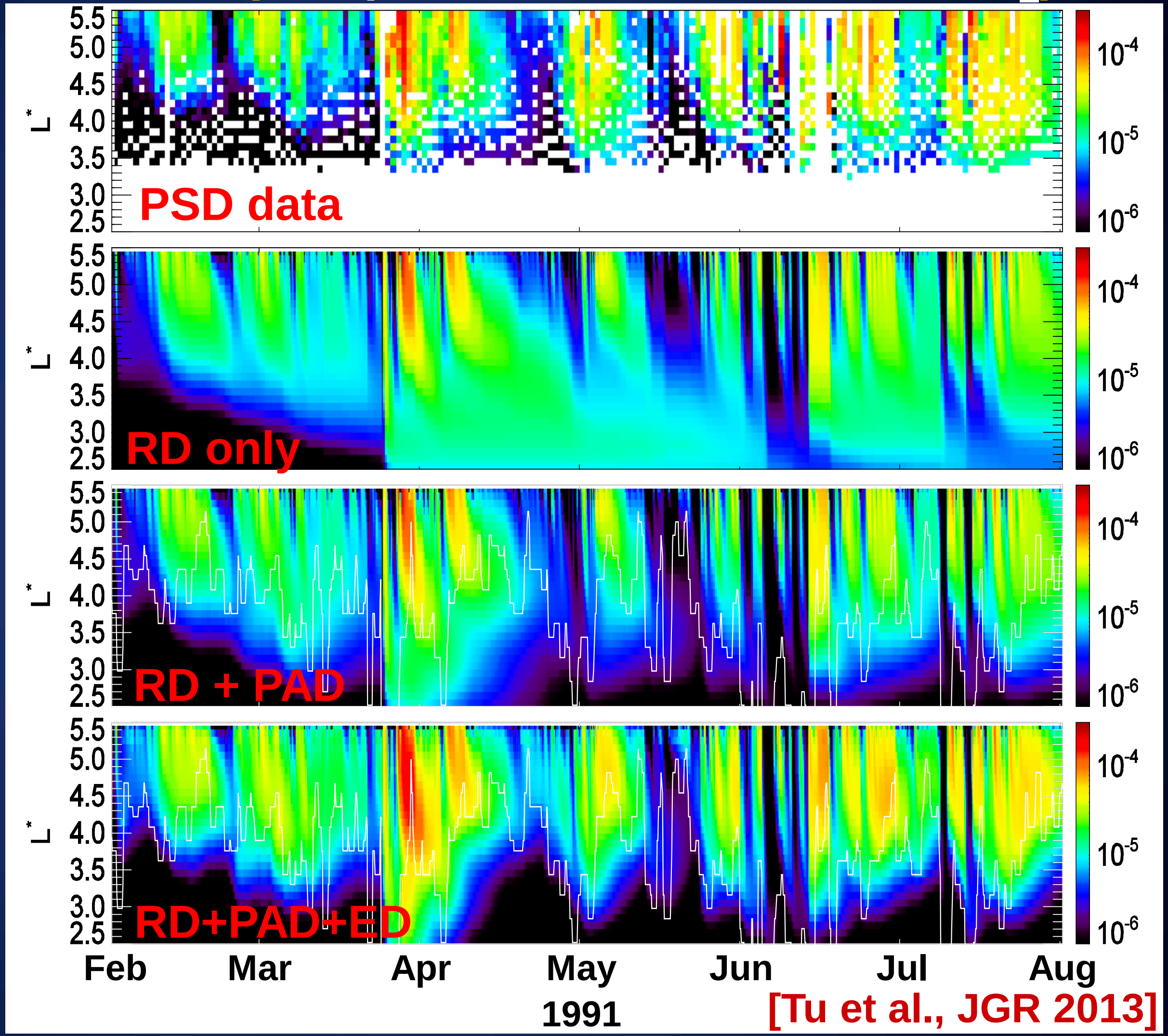
DREAM3D results with:

Radial diffusion only

Radial diffusion
+ Pitch angle diffusion

Radial diffusion
+ Pitch angle diffusion
+ Energy diffusion

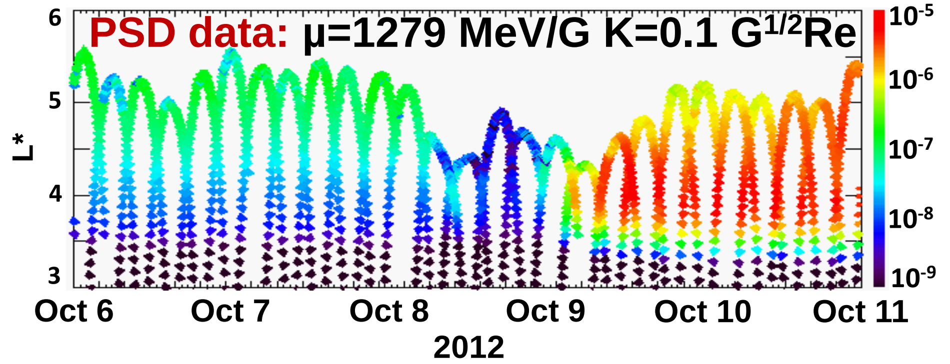
PSD (L^*,t, μ=523 MeV/G, K=0.03 $G^{1/2}R_E$)

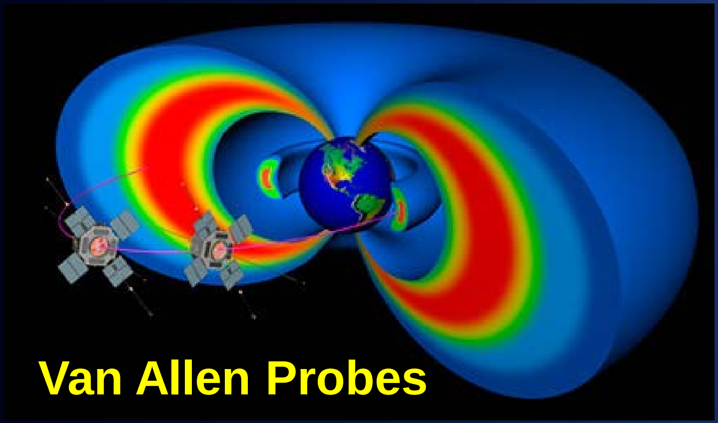


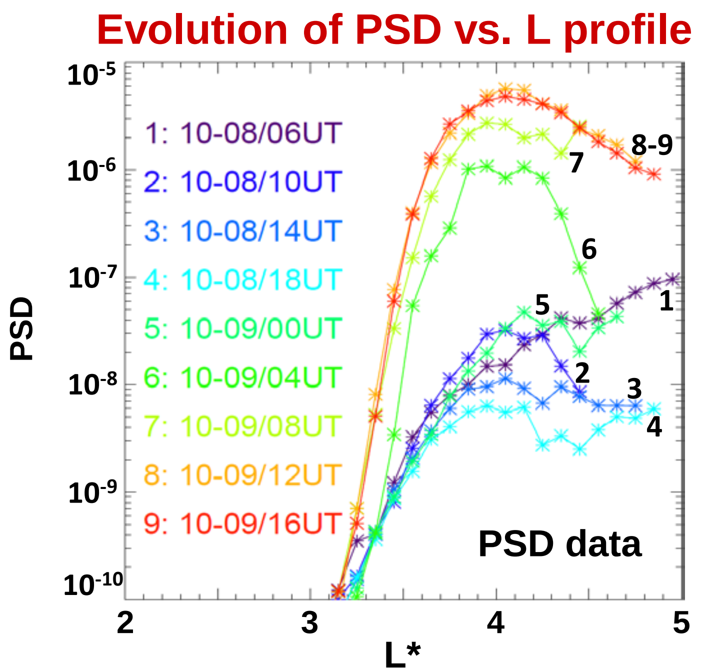
[Tu et al., JGR 2013]

DREAM3D Results: Event Study

- Van Allen Probes event
  - Remarkable radiation belt enhancement
  - Strong local peak of phase space density (PSD) vs. L





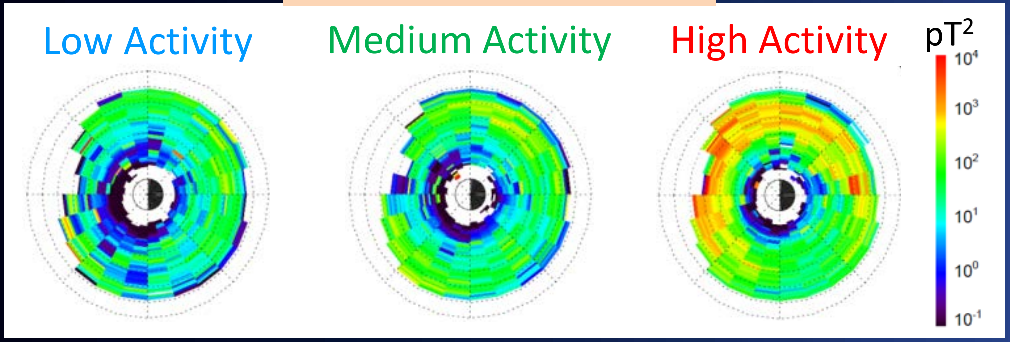


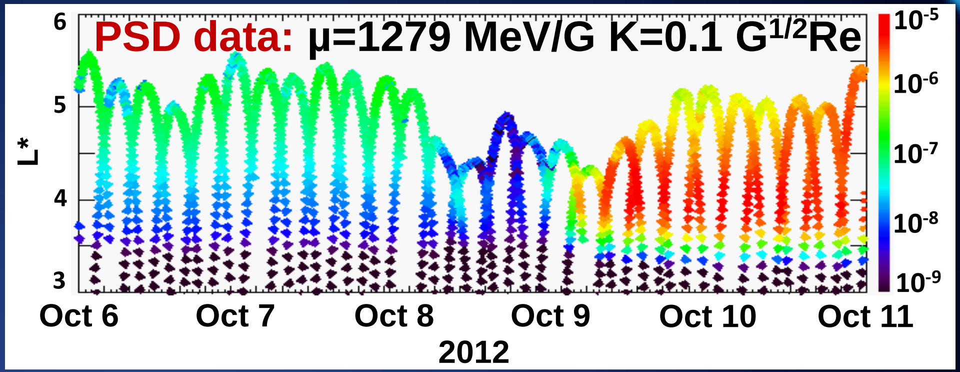
[Tu et al., GRL 2014]

DREAM3D Results: Event Study

- Modeling the strong enhancement
  - Standard setup: with statistical wave inputs

Statistical model





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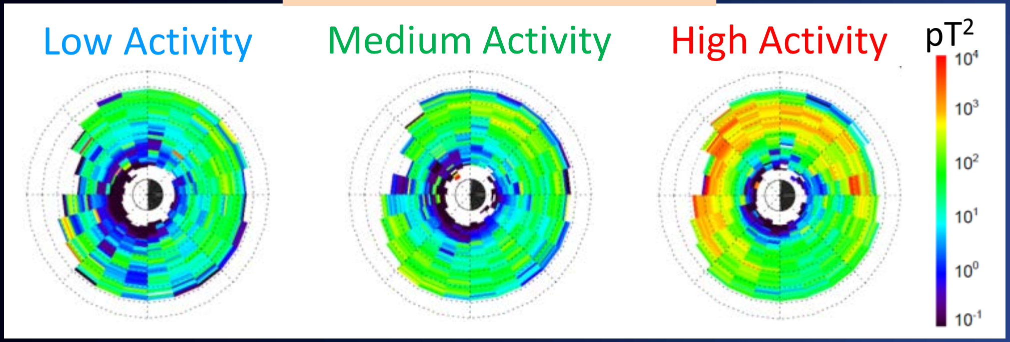
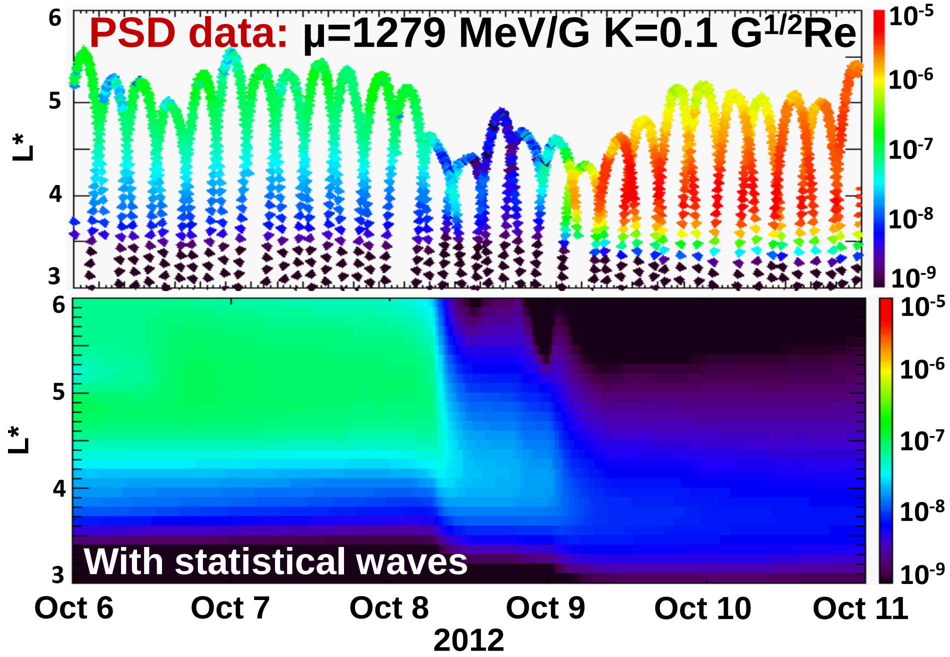


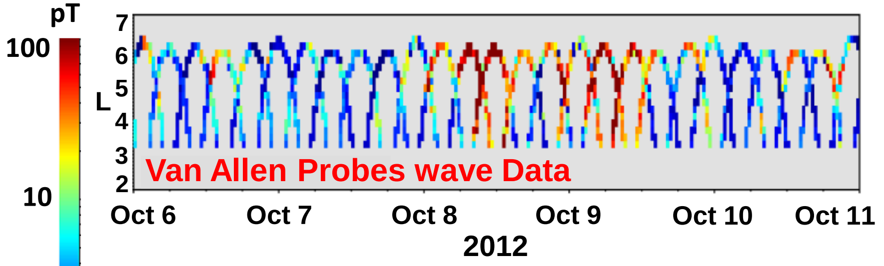


[Tu et al., GRL 2014]

DREAM3D Results: Event Study

- Modeling the strong enhancement
  - With event-specific wave inputs

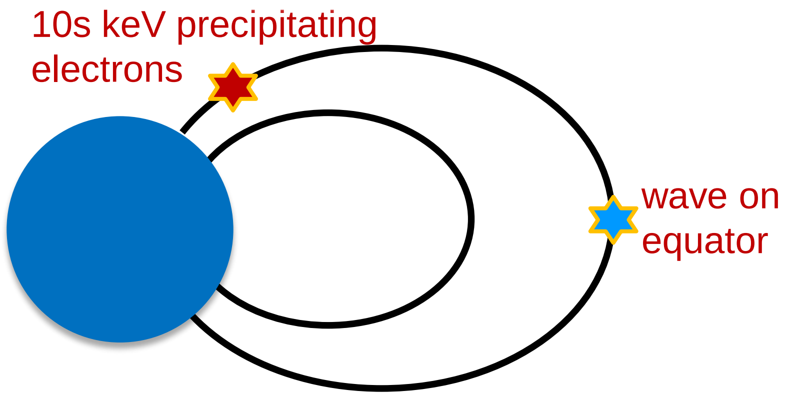
Event-specific wave model

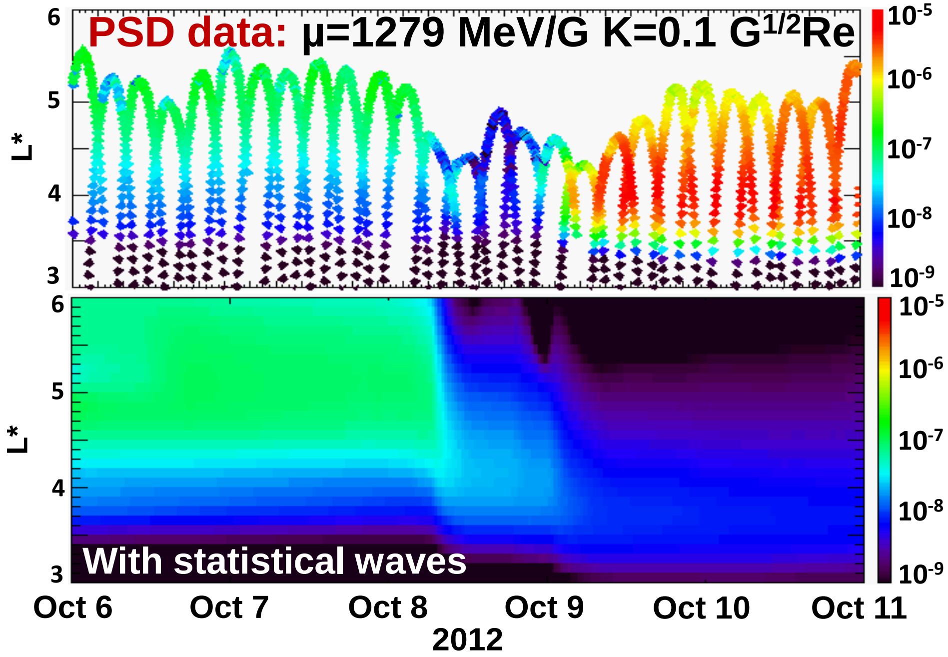


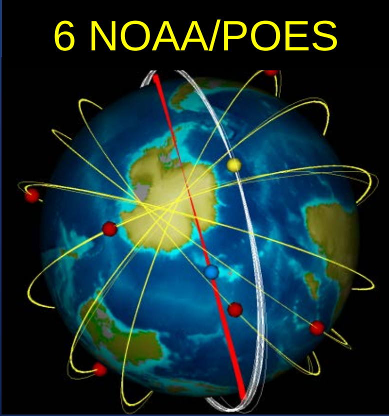
In situ wave measurements

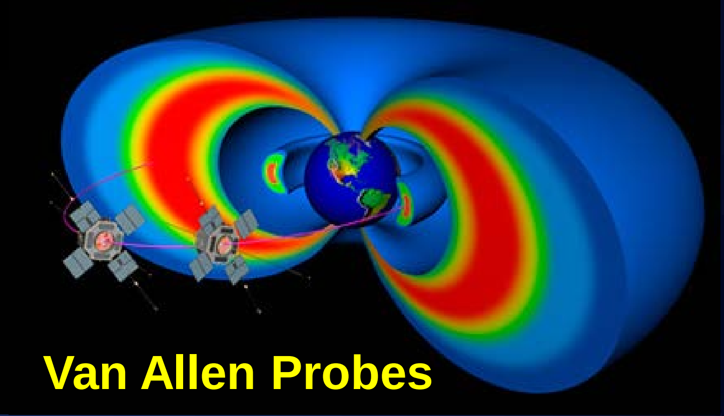
+

Low-altitude wave proxy





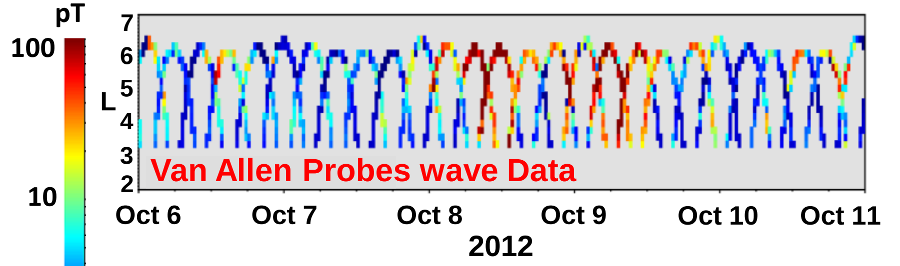




DREAM3D Results: Event Study

- Modeling the strong enhancement
  - With event-specific wave inputs

Event-specific wave model



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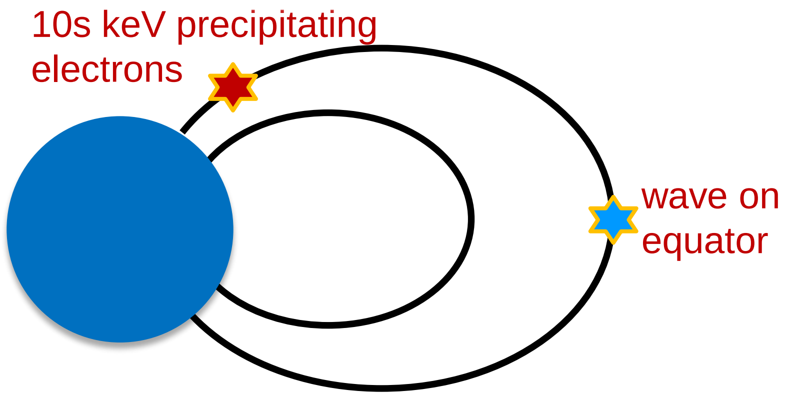
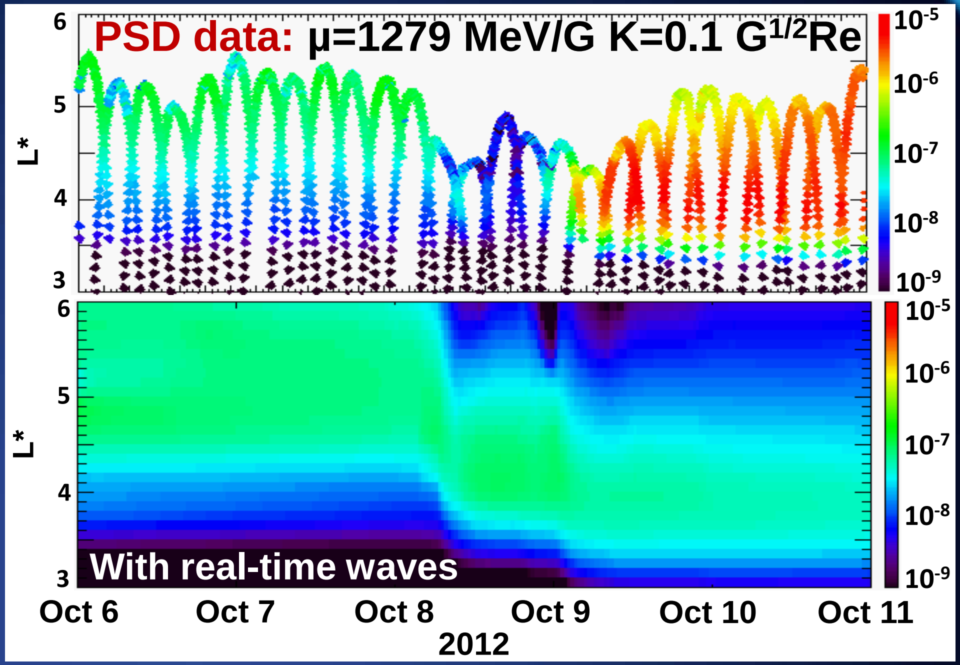
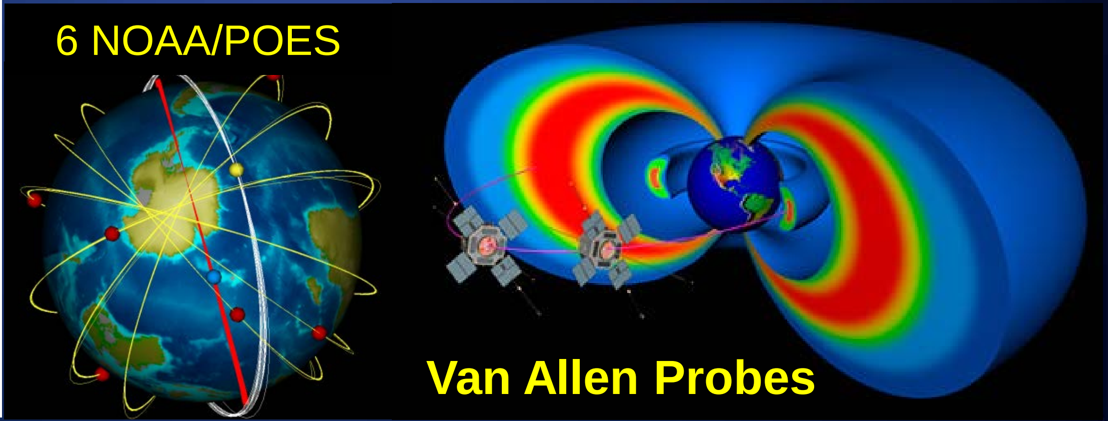
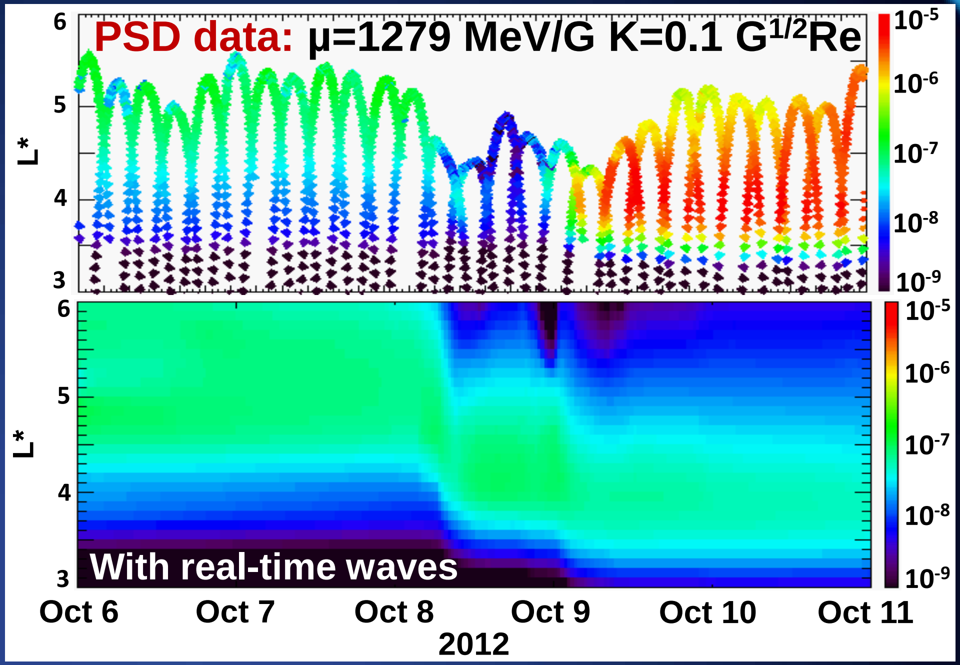






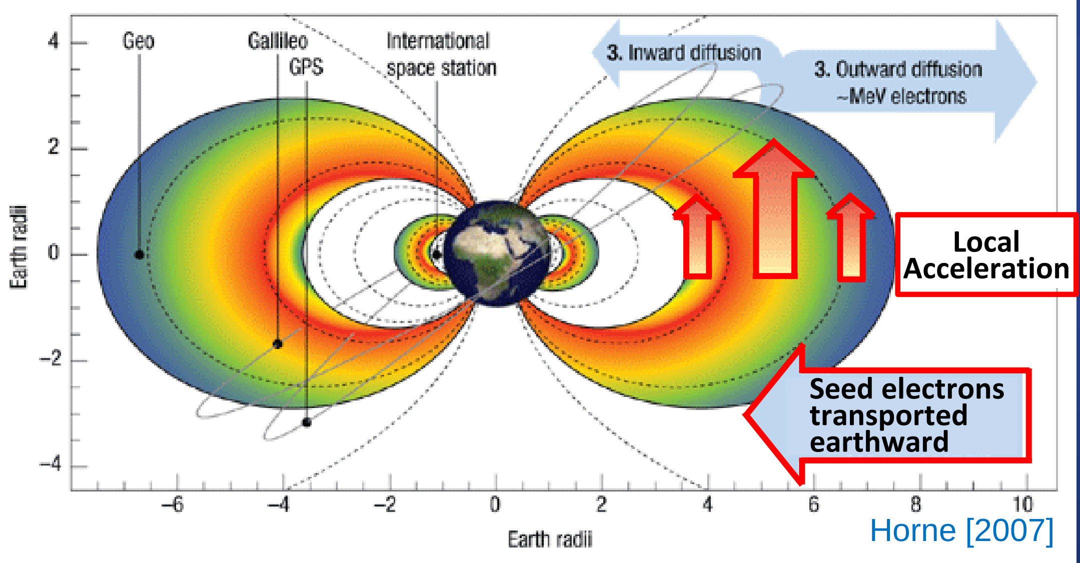
DREAM3D Results: Event Study

- Modeling the strong enhancement
  - With event-specific wave inputs
  - With event-specific seed electrons (low-energy, 100keV)



PSD data: μ=1279 MeV/G K=0.1 $G^{1/2}$Re

With real-time waves



Local Acceleration

Seed electrons transported earthward

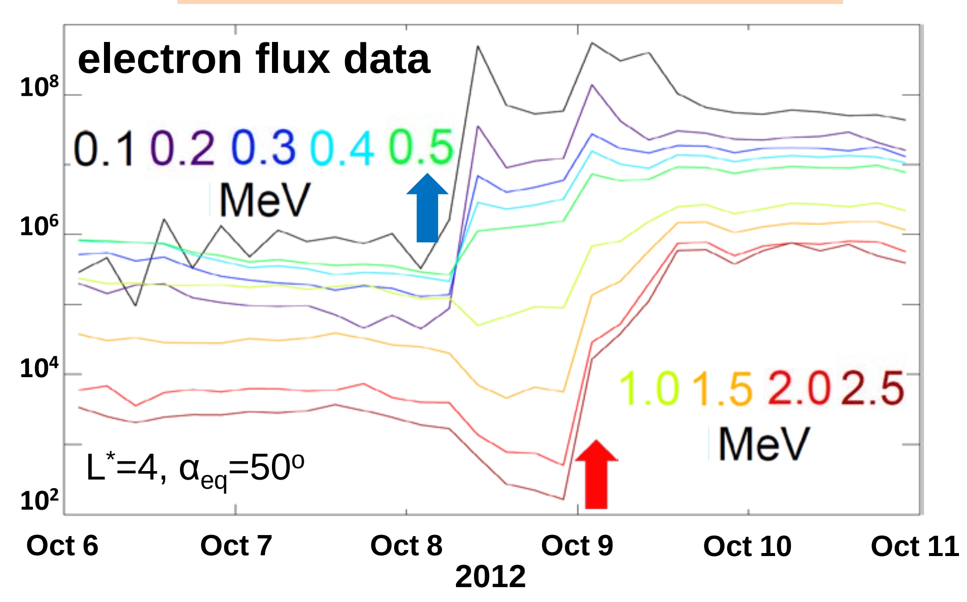
Horne [2007]

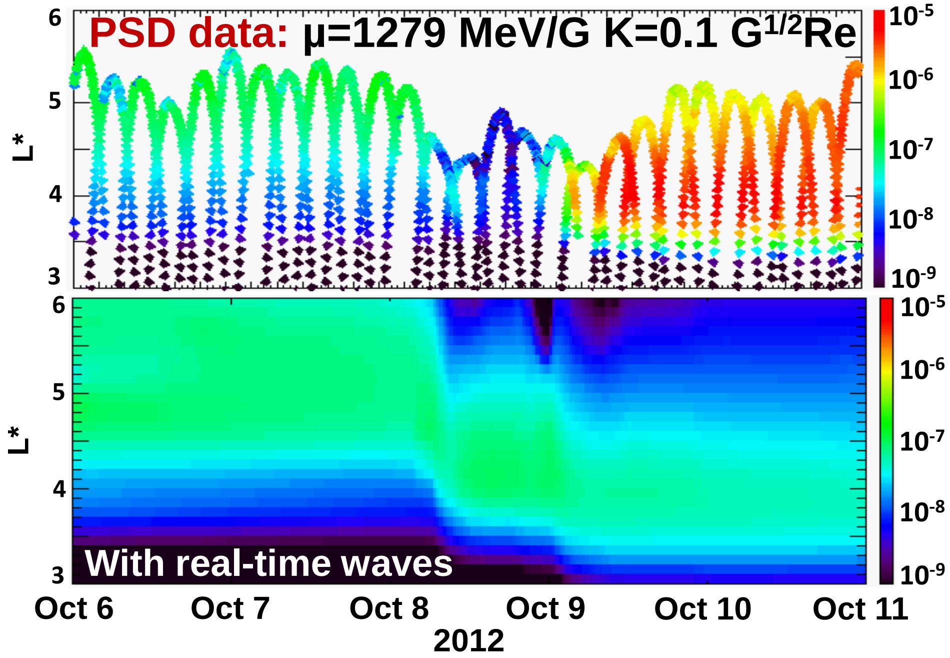
[Tu et al., GRL 2014]

DREAM3D Results: Event Study

- Modeling the strong enhancement
  - With event-specific wave inputs
  - With event-specific seed electrons (low-energy, 100keV)

Event-specific seed population





[Tu et al., GRL 2014]

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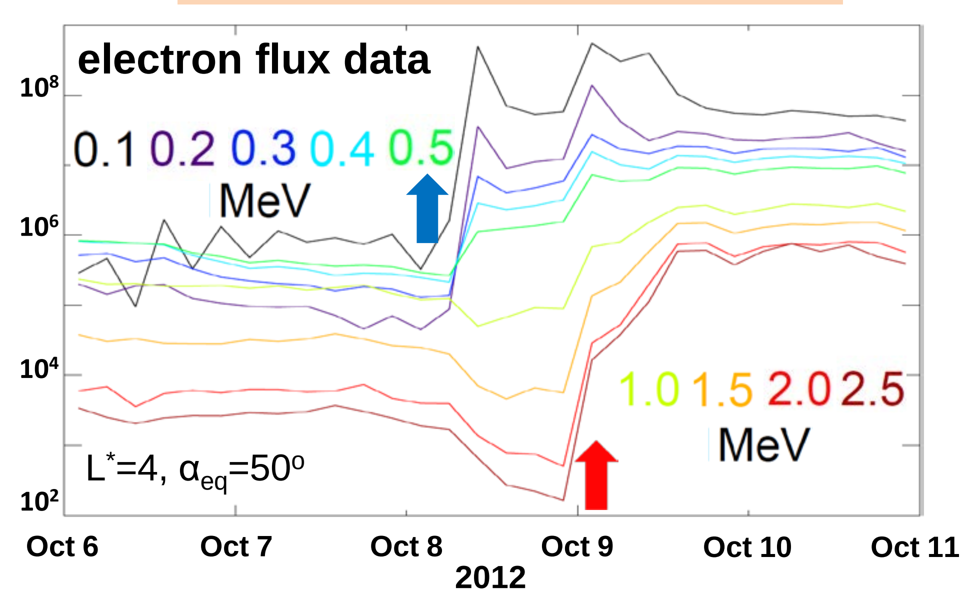
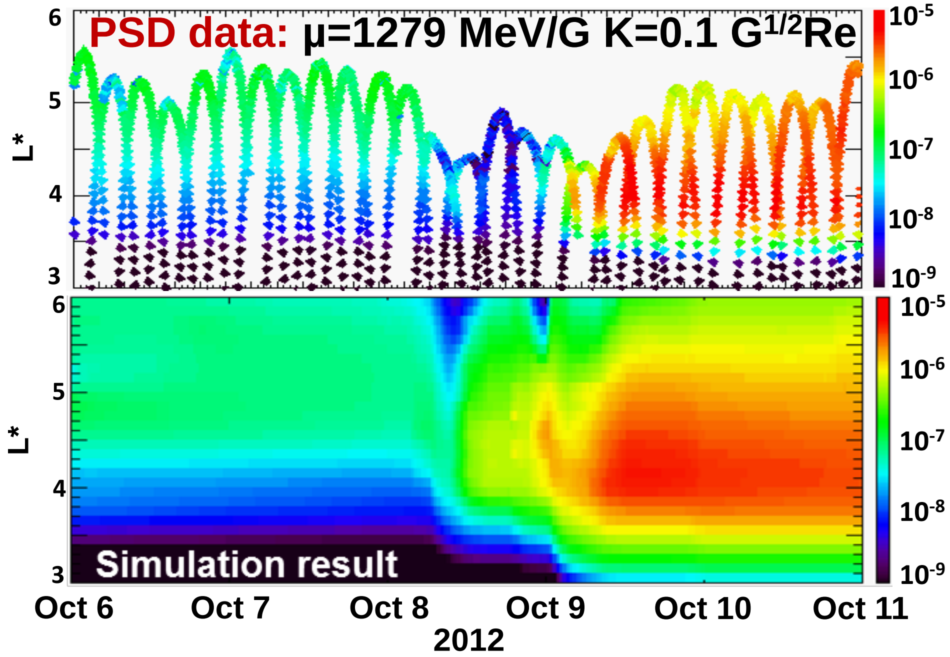
  - With event-specific seed electrons (low-energy, 100keV)

Event-specific seed population





- Both the event-specific wave model and seed population are critical to recreate the remarkable electron enhancement.

[Tu et al., GRL 2014]

DREAM3D Results: Media Report

- Reported by NASA news and many other major media.
- Model inputs were forced to rely on interpreting historical data prior to the launch of the Van Allen Probes in August 2012.
- Incorporate real-time information in the simulations for the first-time.

New NASA Van Allen Probes Observations Helping To Improve Space Weather Models

March 7, 2014

New NASA Van Allen Probes observations helping to improve space weather models

New NASA Van Allen Probes observations helping to improve space weather models

Date: March 7, 2014

Source: NASA/Goddard Space Flight Center

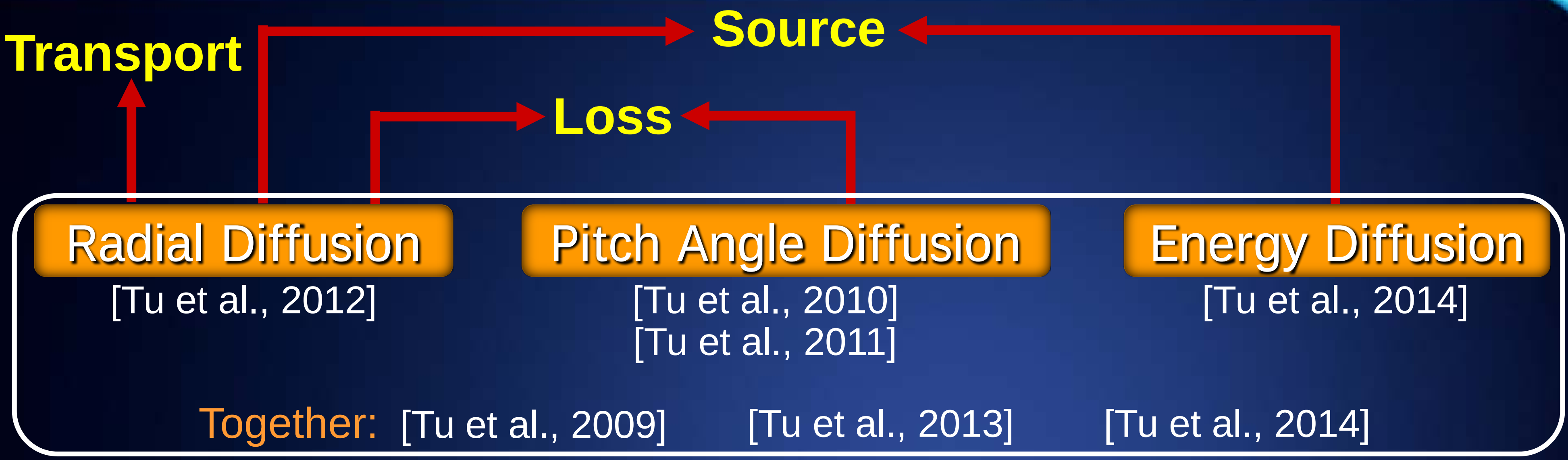
New NASA Van Allen Probes Observations Helping To Improve Space Weather Models

Posted on **March 10, 2014**

Van Allen Probes Helping To Refine Space Weather Computer Models

March 10, 2014

Modeling Work Overview



Transport

Source

Loss

Radial Diffusion

[Tu et al., 2012]

Pitch Angle Diffusion

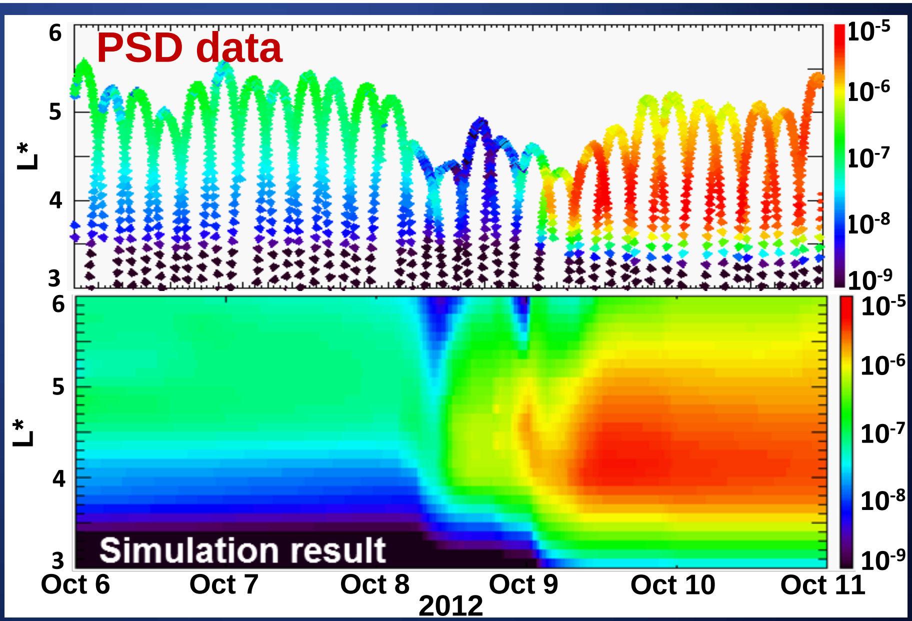
[Tu et al., 2010]
[Tu et al., 2011]

Energy Diffusion

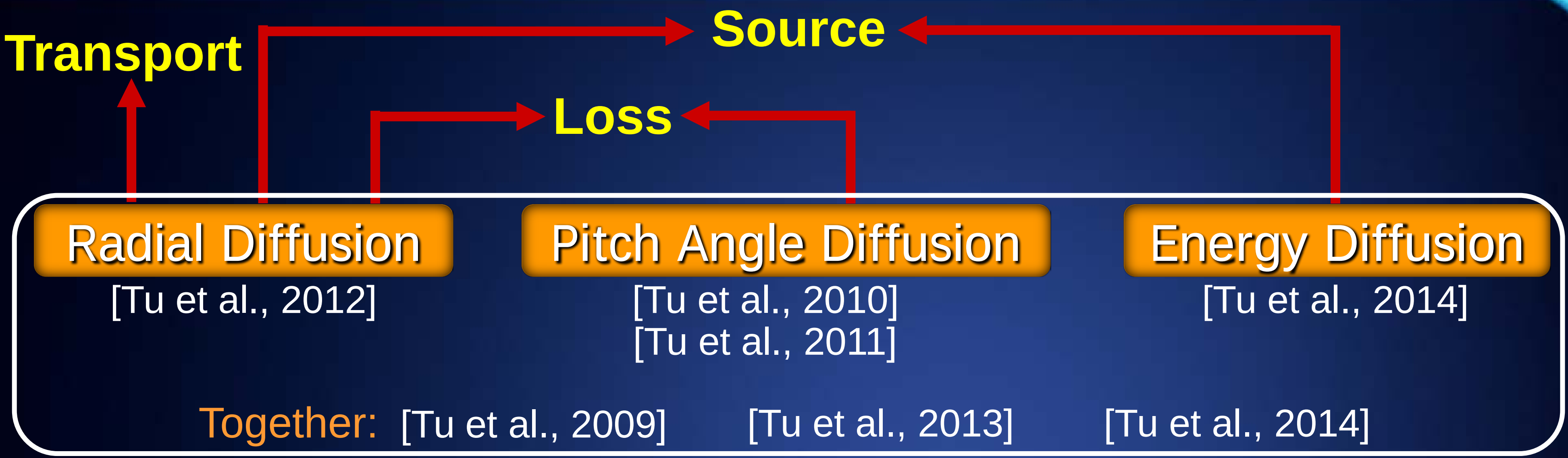
[Tu et al., 2014]

Together: [Tu et al., 2009] [Tu et al., 2013] [Tu et al., 2014]

- The fast electron loss is not well-reproduced by the DREAM3D diffusion model



Modeling Work Overview



Transport

Source

Loss

Radial Diffusion

[Tu et al., 2012]

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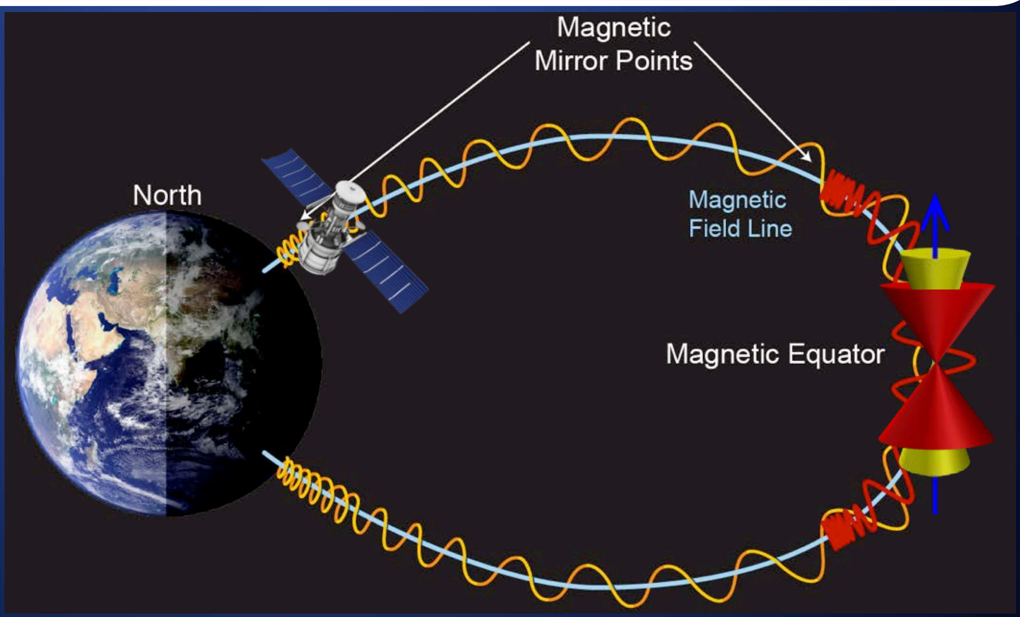
[Tu et al., 2010]
[Tu et al., 2011]

Energy Diffusion

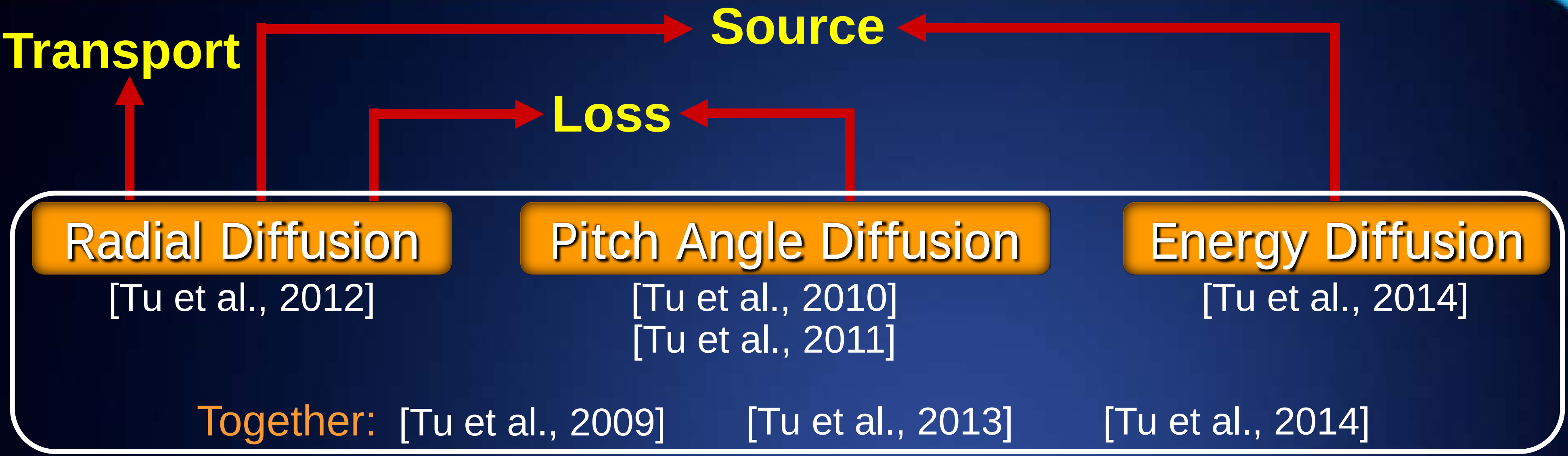
[Tu et al., 2014]

Together: [Tu et al., 2009] [Tu et al., 2013] [Tu et al., 2014]

- Other projects:
  - Better model the precipitation loss by directly simulating the precipitating electron observed at low altitude.



Modeling Work Overview



Transport

Source

Loss

Radial Diffusion

[Tu et al., 2012]

Pitch Angle Diffusion

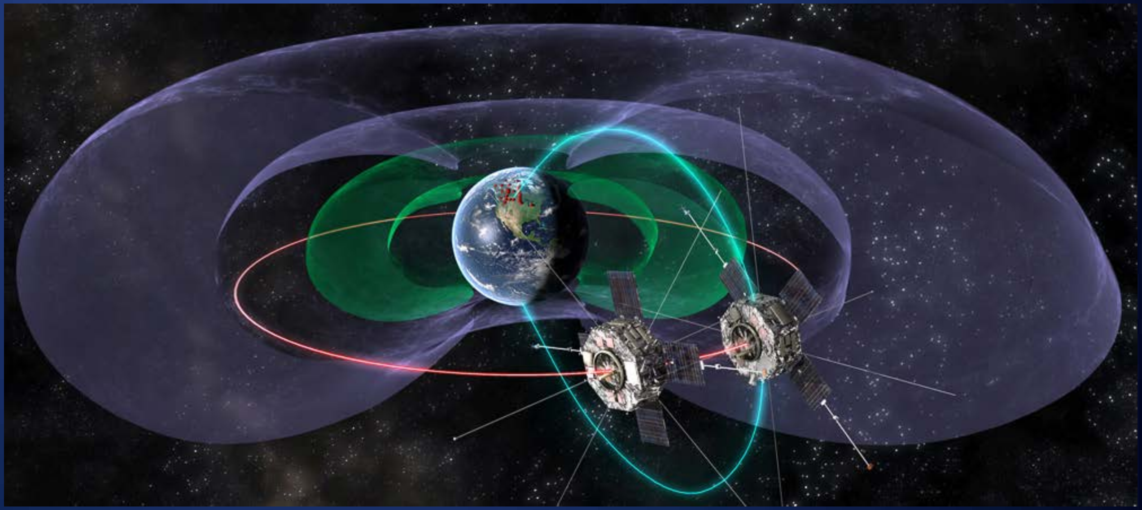
[Tu et al., 2010]
[Tu et al., 2011]

Energy Diffusion

[Tu et al., 2014]

Together: [Tu et al., 2009] [Tu et al., 2013] [Tu et al., 2014]

- Other projects:
  - Better model the radial diffusion by including event-specific ULF waves.



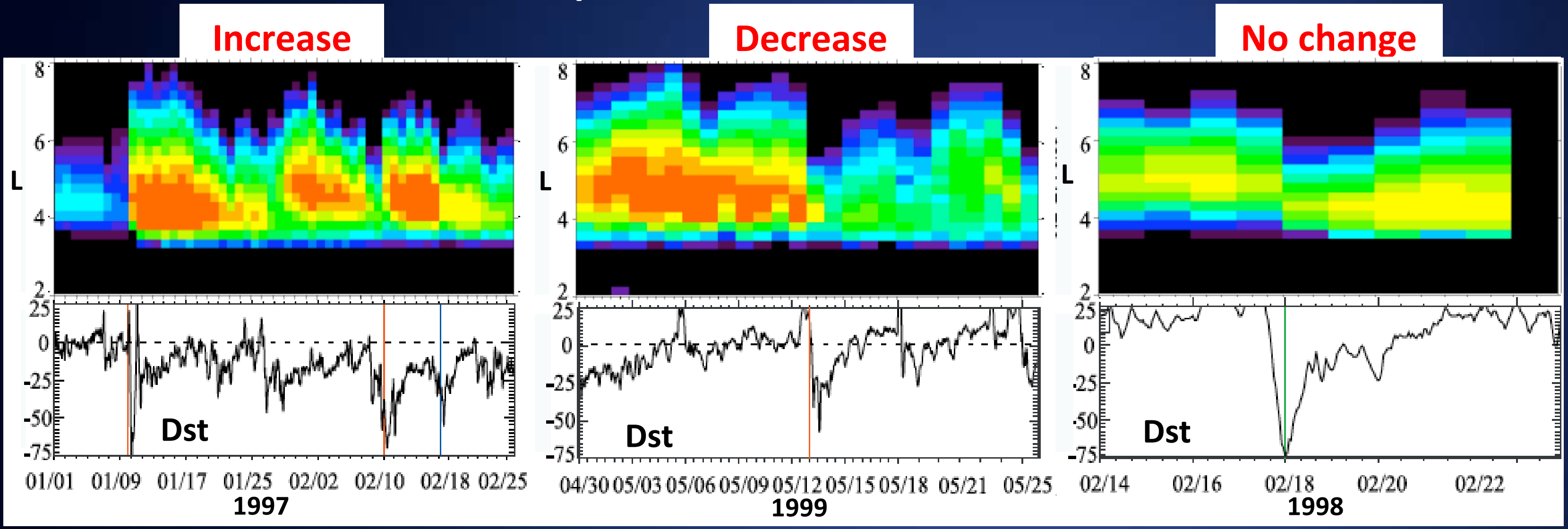
Outline

- Overview: Van Allen Radiation Belts and Why do we care?
- Introduction: Characterizing the radiation belt dynamics
- Modeling Work: Source, Transport, and Loss
- Conclusion: Challenges and Opportunities

Predictability of Outer Belt Electrons

- Similar sized geomagnetic storms can produce net increase (50%), decrease (20%), or no change (30%) of radiation belt electron flux.

POLAR/HIST 1.2-2.4 MeV electron flux


Increase

Decrease

No change

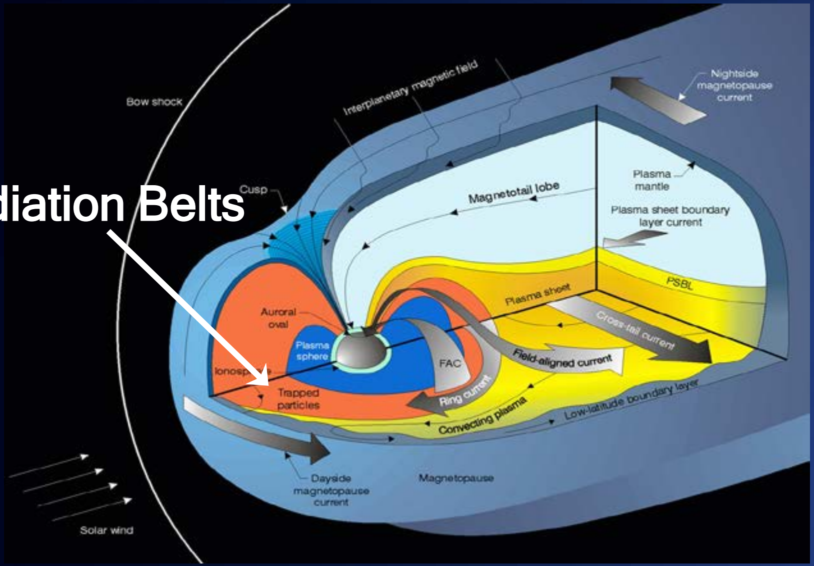
Dst: index for geomagnetic disturbance level

Reeves et al. [2003]

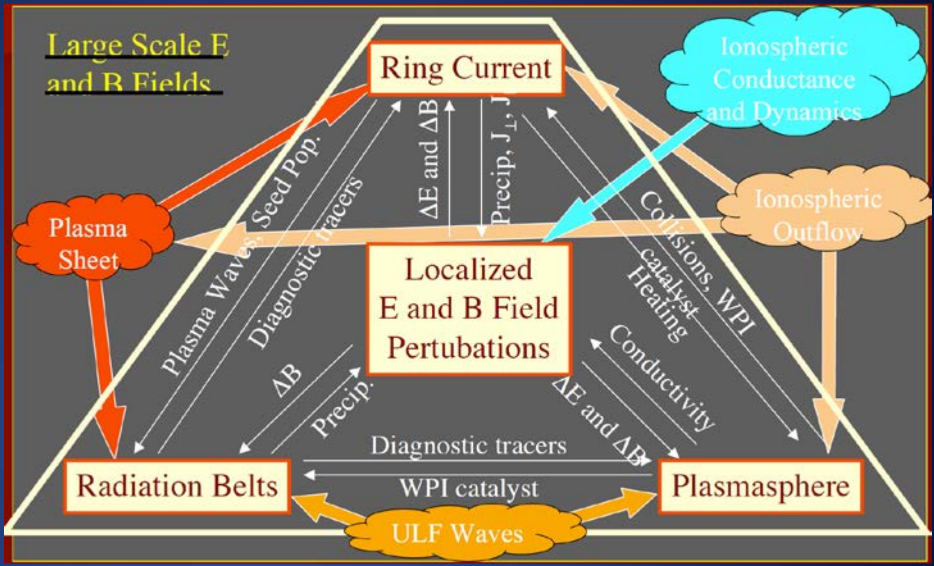
- Challenge: Can we reproduce the variability and, more importantly, predict the various responses?
- Opportunities: Improve the model inputs & Include new physics.

Coupling with Other Systems

- Radiation belts are strongly coupled with other plasma and current systems in the Earth's magnetosphere.



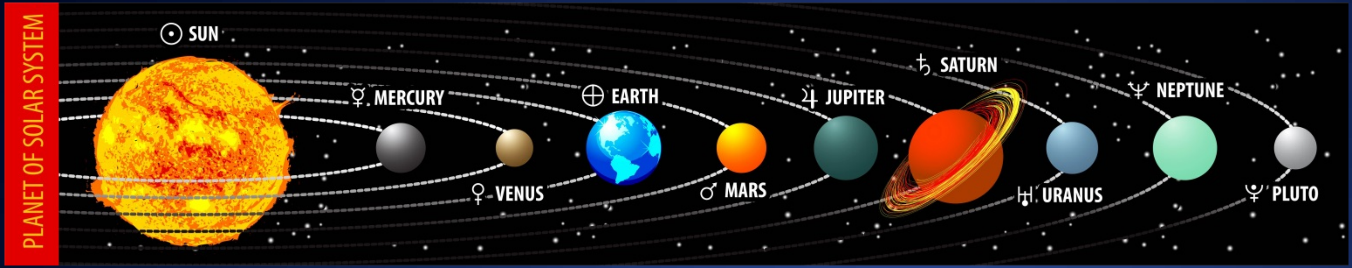
Radiation Belts



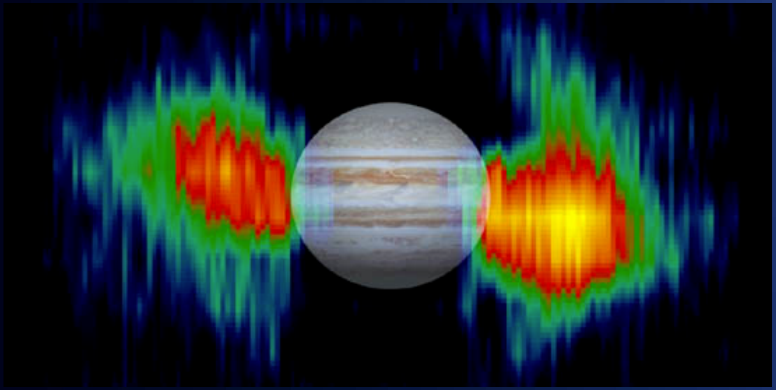
- Challenge : How to physically model radiation belts in the highly coupled system?
- Opportunities: Comprehensive models that couple radiation belts to other systems in a self-consistent approach.

Radiation Belts Beyond Earth

- Radiation belts have also been discovered in other planets.

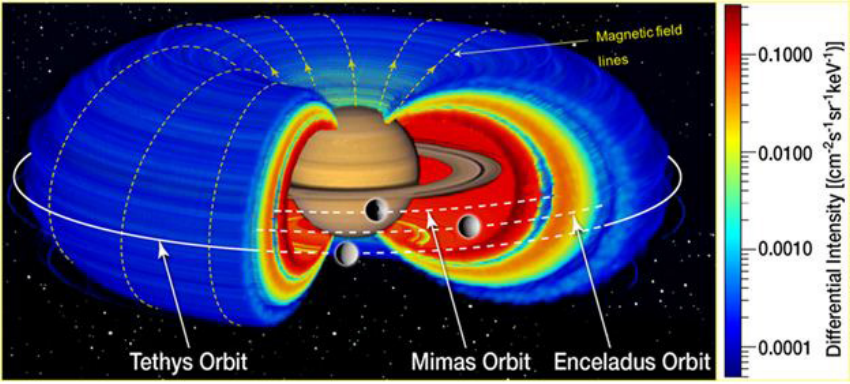


Jupiter's Radiation Belts



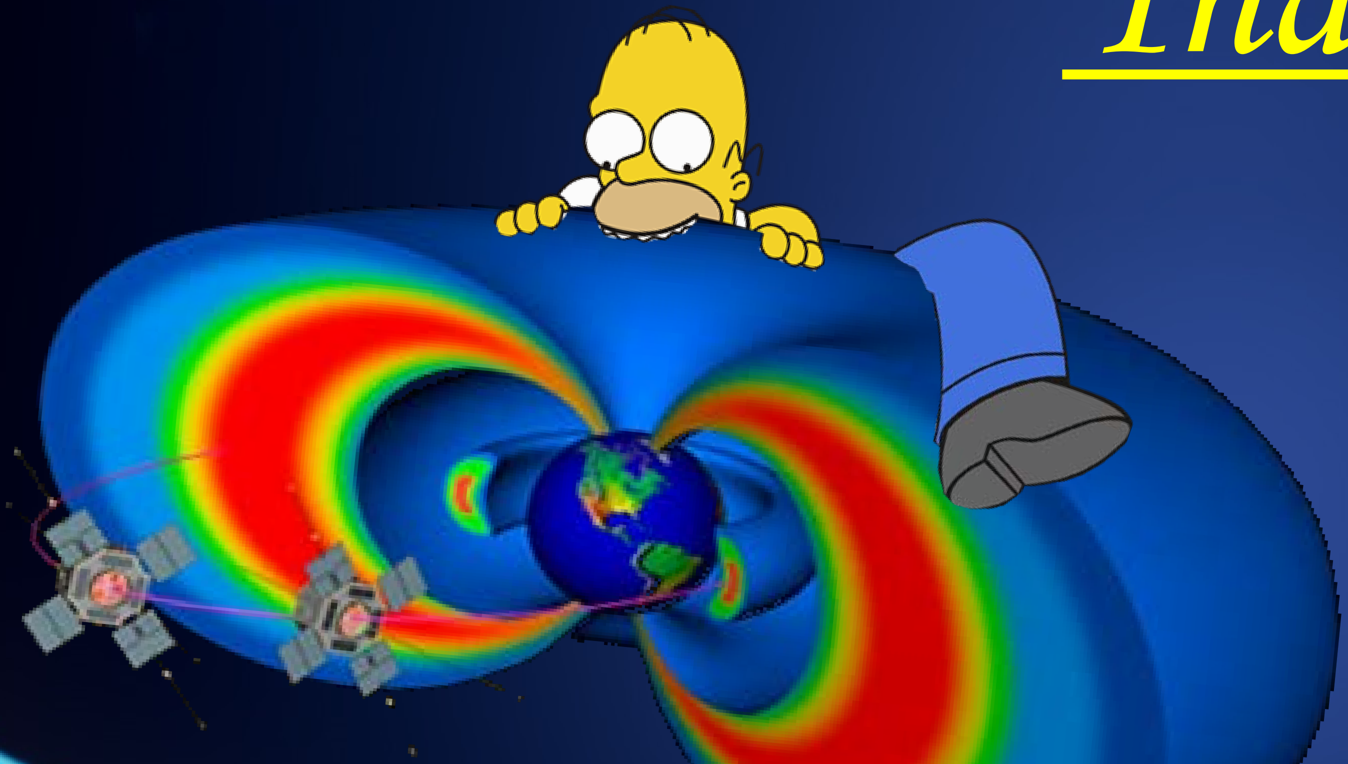
NASA

Saturn's Ion Radiation Belts

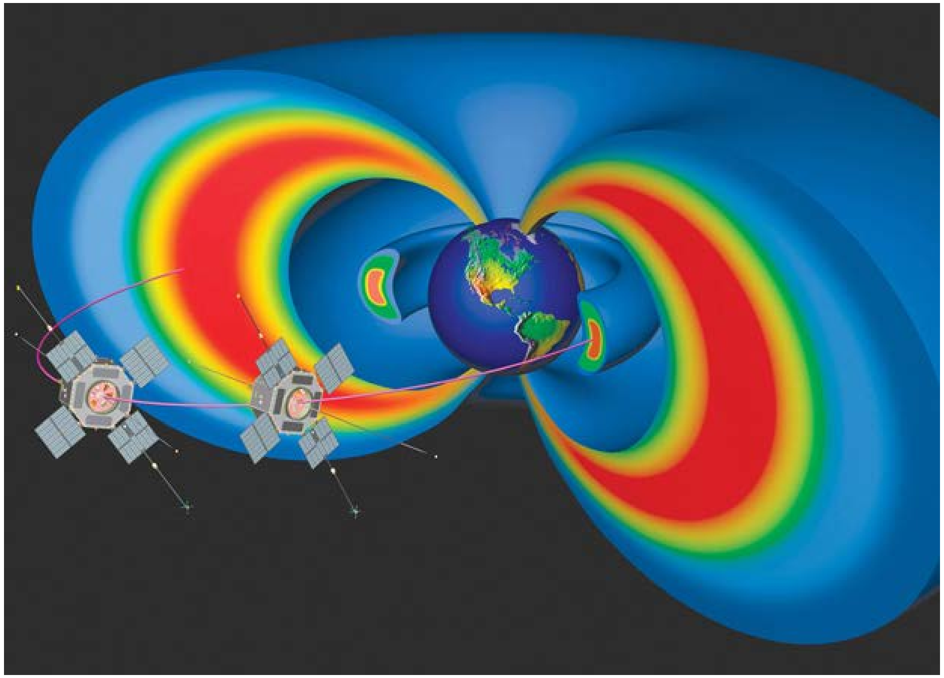


- Challenge & Opportunities: How do the radiations belts within very different planetary systems compare with each other? Can we extract what we learn between systems?

Thank you!



Research Plan: Modeling the Dynamics of Energetic Particles in Space



Weichao Tu

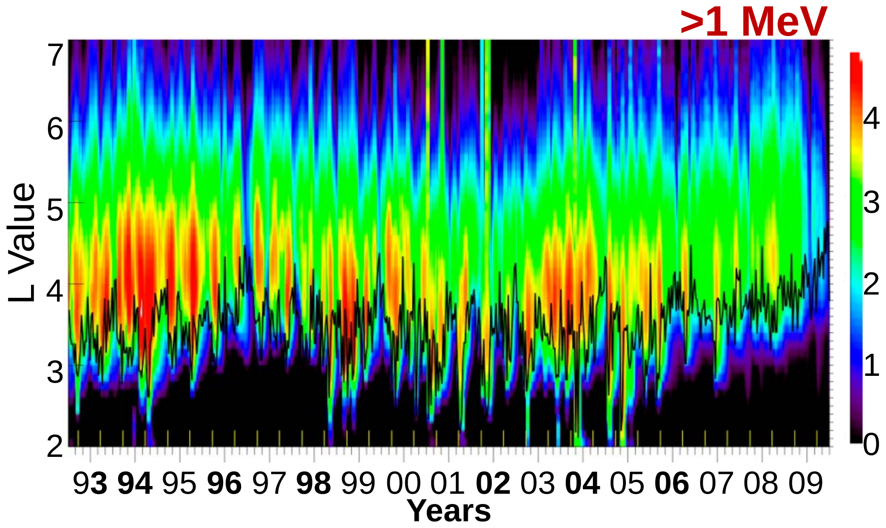
Los Alamos National Lab

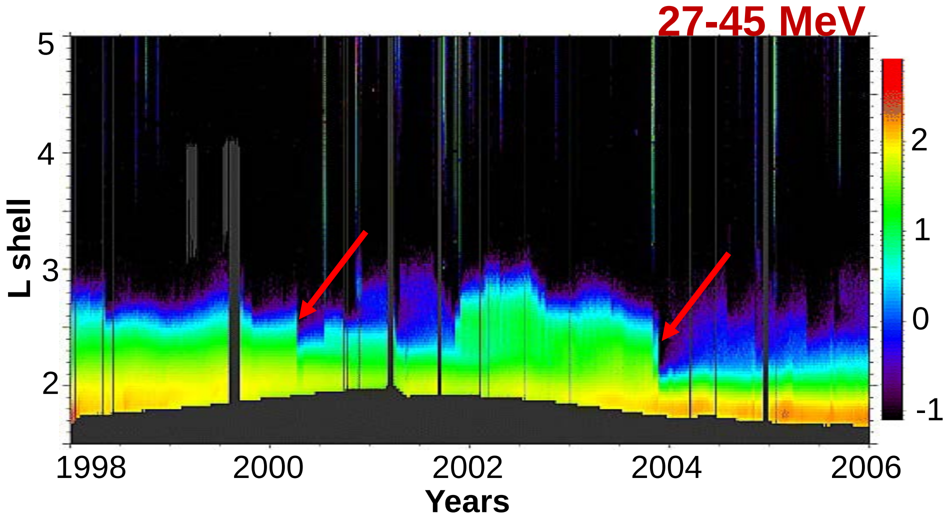
West Virginia University

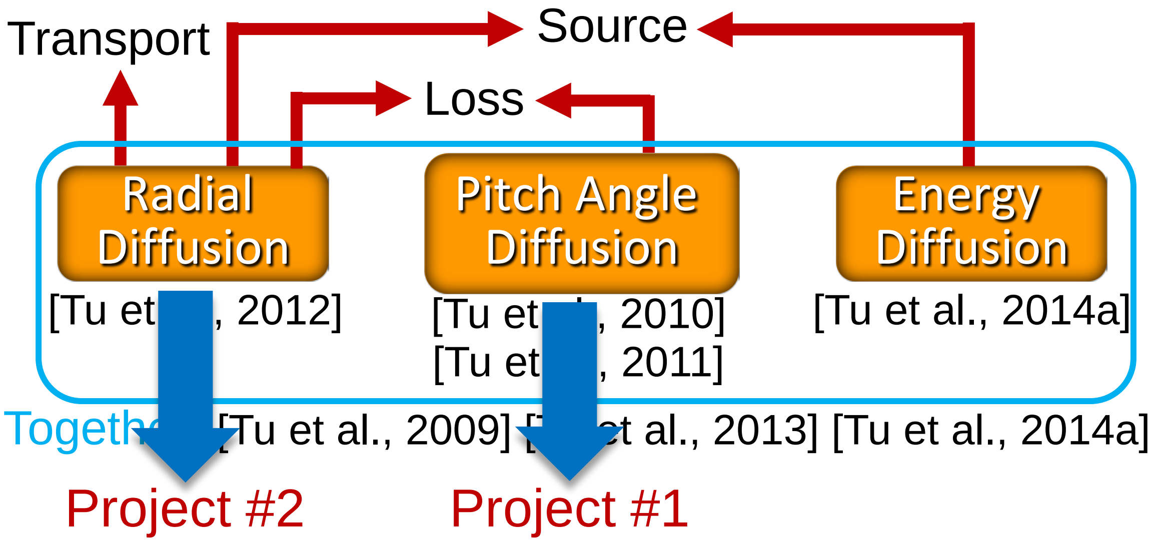
2015/02/26

Outline of Previous Work

- Radiation Belt Electrons
- Radiation Belt Protons







Transport

Source

Loss

Radial Diffusion

[Tu et , 2012]

Pitch Angle Diffusion

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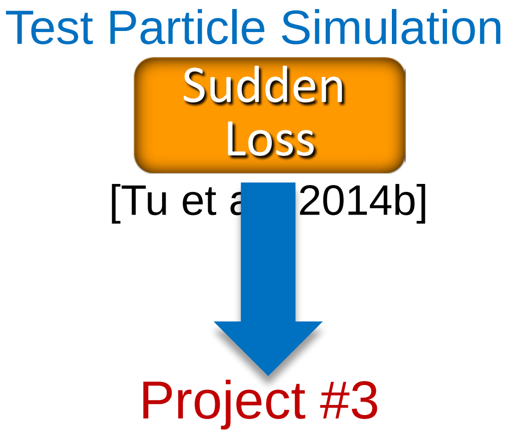
Energy Diffusion

[Tu et al., 2014a]

Togeth [Tu et al., 2009] [et al., 2013] [Tu et al., 2014a]

Project #2

Project #1



Test Particle Simulation

Sudden Loss

[Tu et a 2014b]

Project #3

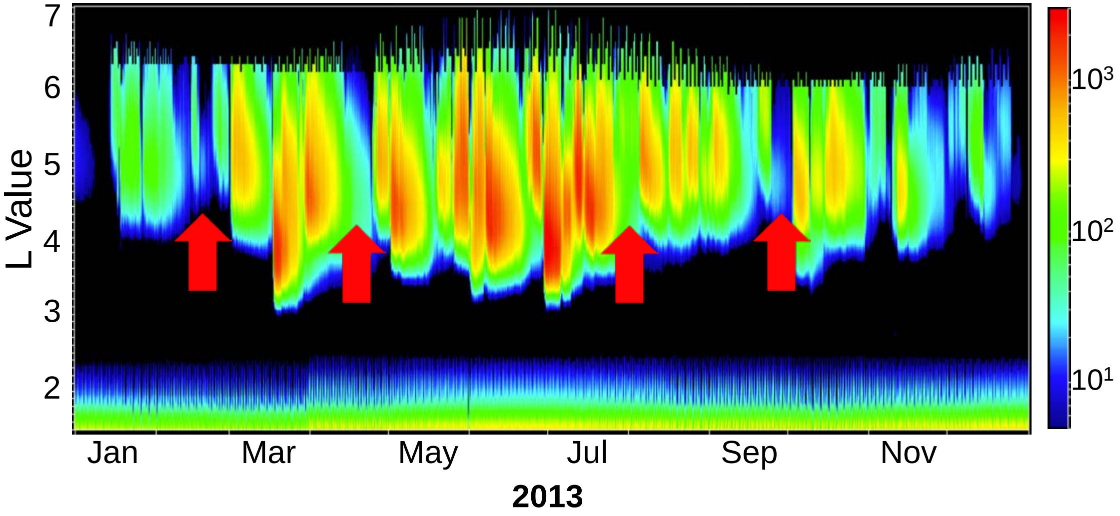
Project 1: Modeling the Precipitation Loss

- *Topic:* Study the precipitation of radiation belt electrons during the rapid dropout events
- *My Role:* PI (with another Co-I from Los Alamos National Lab)
- *Funding Source:* Selected for funding by NSF/GEM (Geospace Environment Modeling) program
- *Funding per Year:* FY15 ($97K) and FY16 ($120K)

➢ Electron dropout:
  - Electron flux drop by orders of magnitude on timescale of hours.

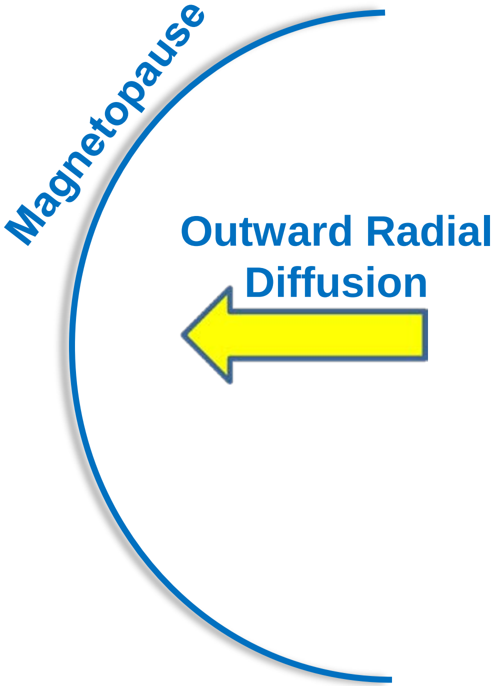
➢ Where do the electrons go?
  - One of the most important outstanding questions in radiation belt studies.

1 MeV Electron Flux Data



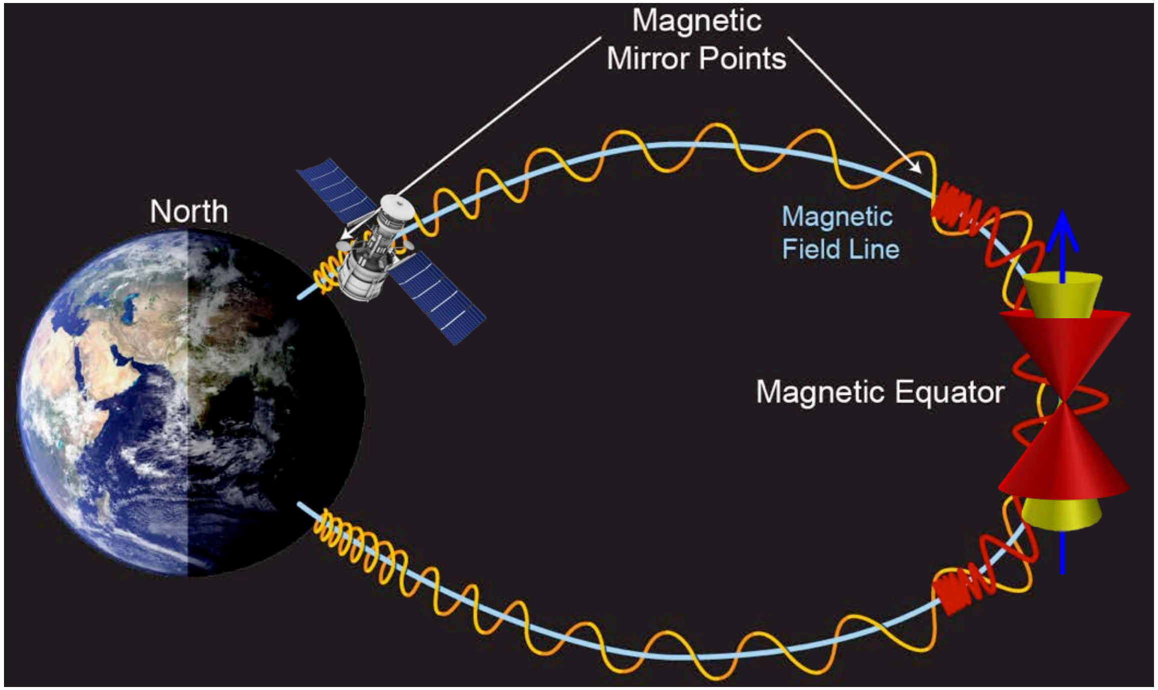
Project 1: Modeling the Precipitation Loss

- Loss Mechanisms: Outward radial diffusion and Precipitation Loss
- Quantifying the precipitation loss is challenging:
  - Near-equator measurements cannot resolve the electron distribution near and inside the loss cone (angular resolution not enough).
  - Low-altitude electron measurements are ideal to determine the precipitation loss.



Magnetopause

Outward Radial Diffusion



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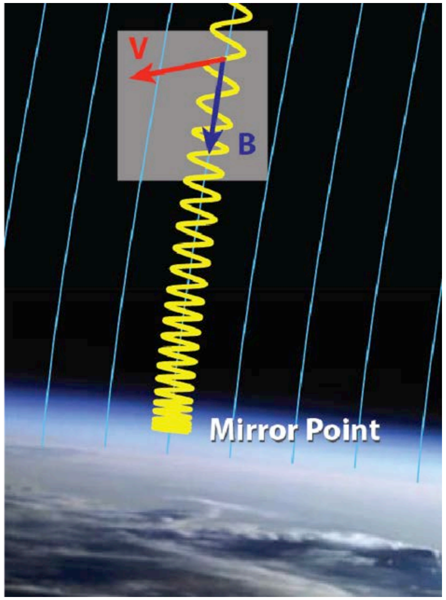
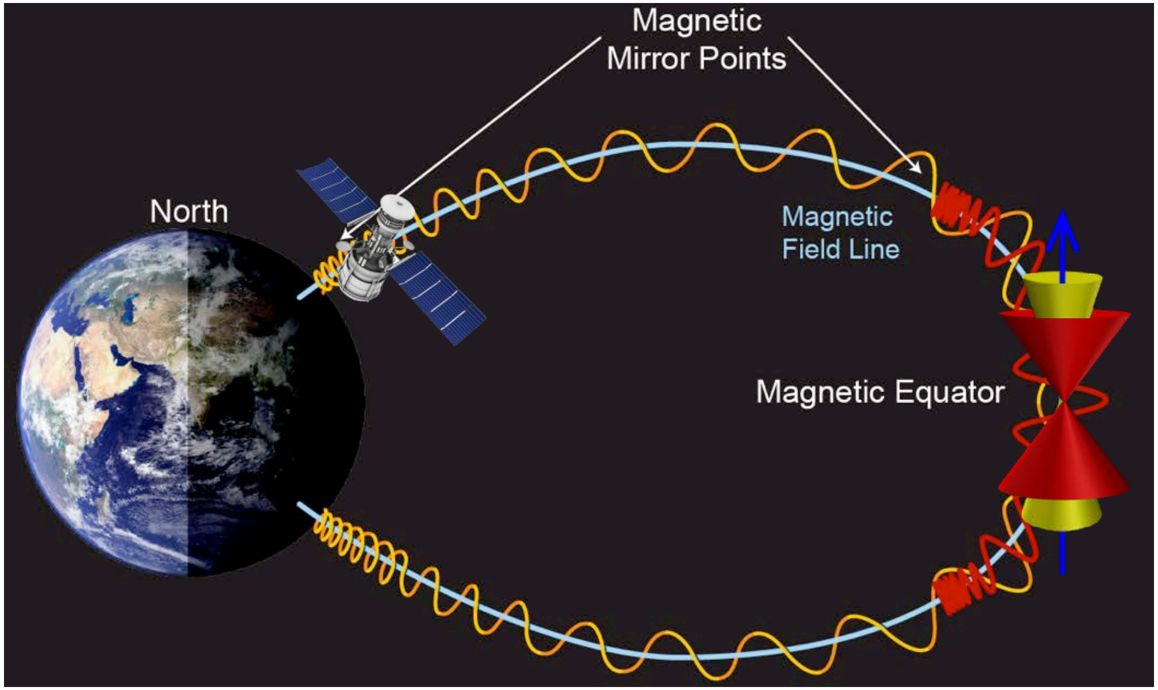
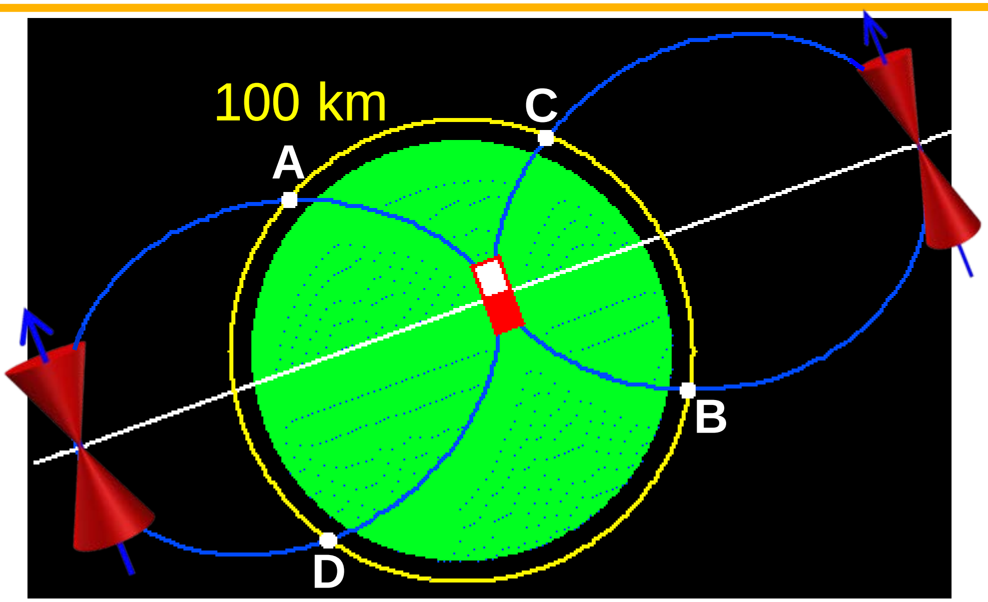


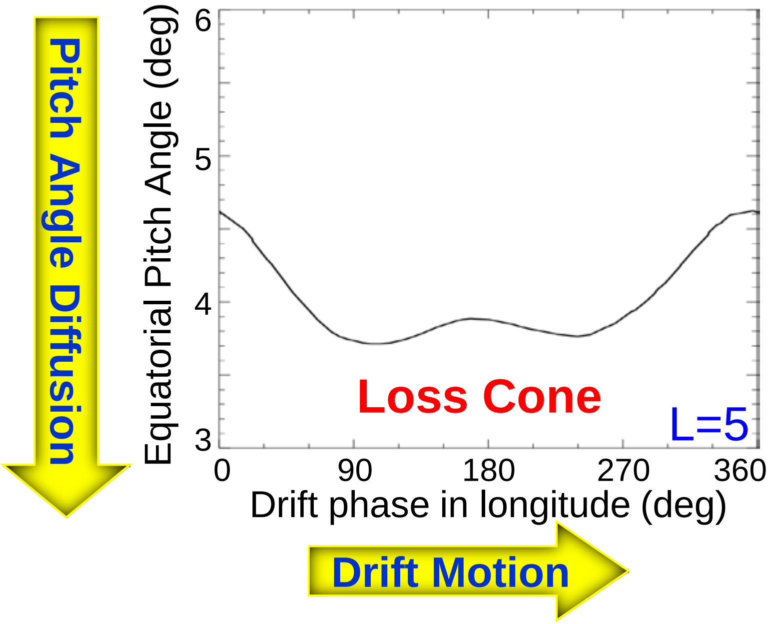
Electron precipitation



Low-altitude Electron Distribution

- Low-altitude electron distribution has strong drift-phase (longitude) dependence.
  - Earth’s dipole is off center, resulting In a longitude-dependent loss cone.





[Tu et al., JGR 2010]

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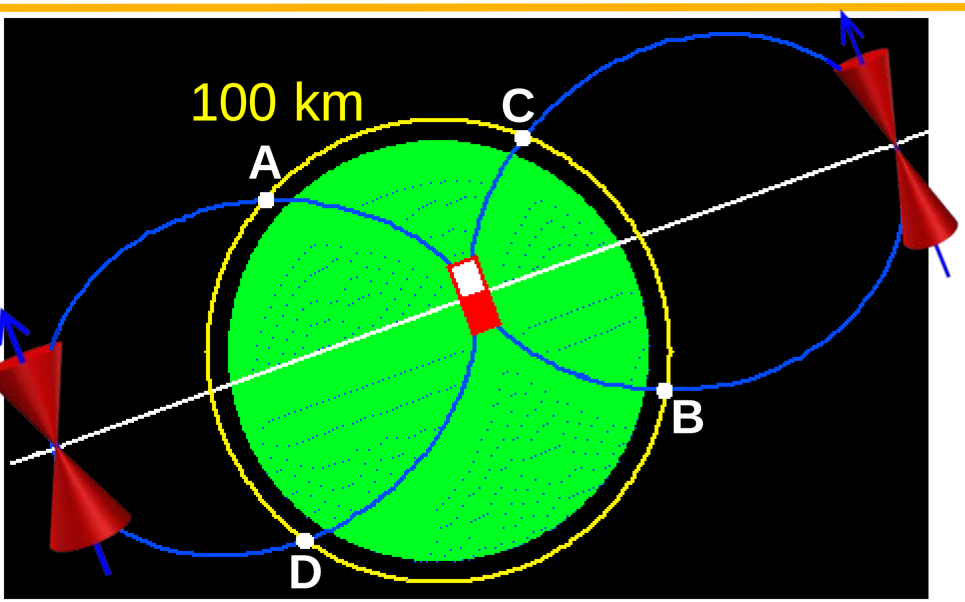
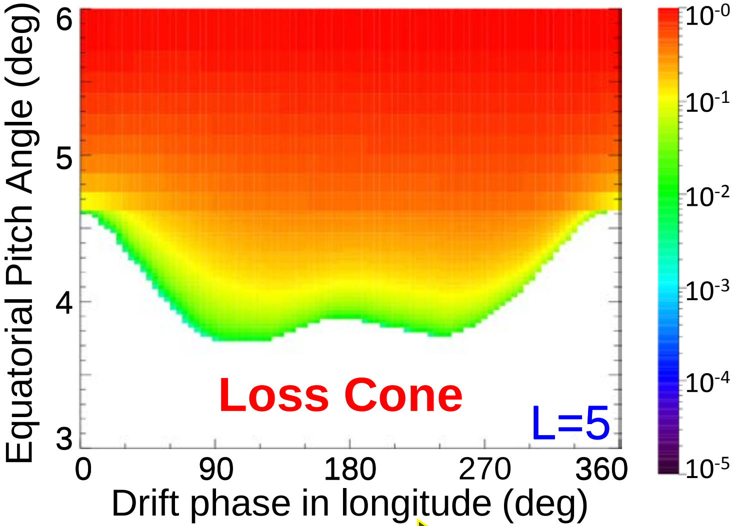


Electron intensity



Pitch Angle Diffusion

Drift Motion

PA diffusion dominates over Drift

[Tu et al., JGR 2010]

Low-altitude Electron Distribution

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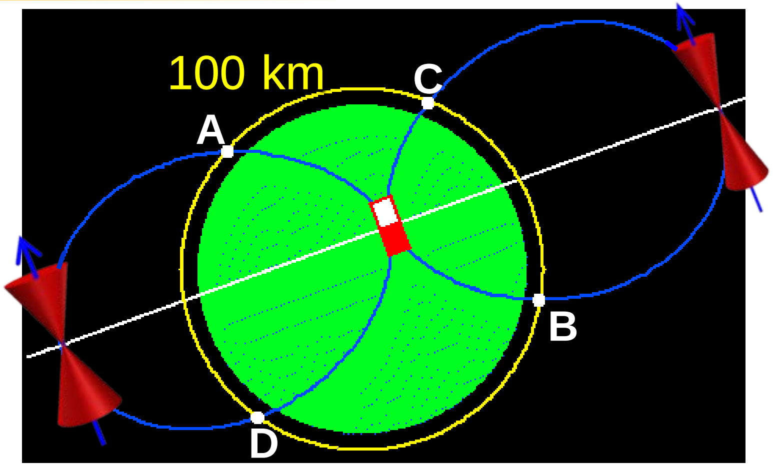
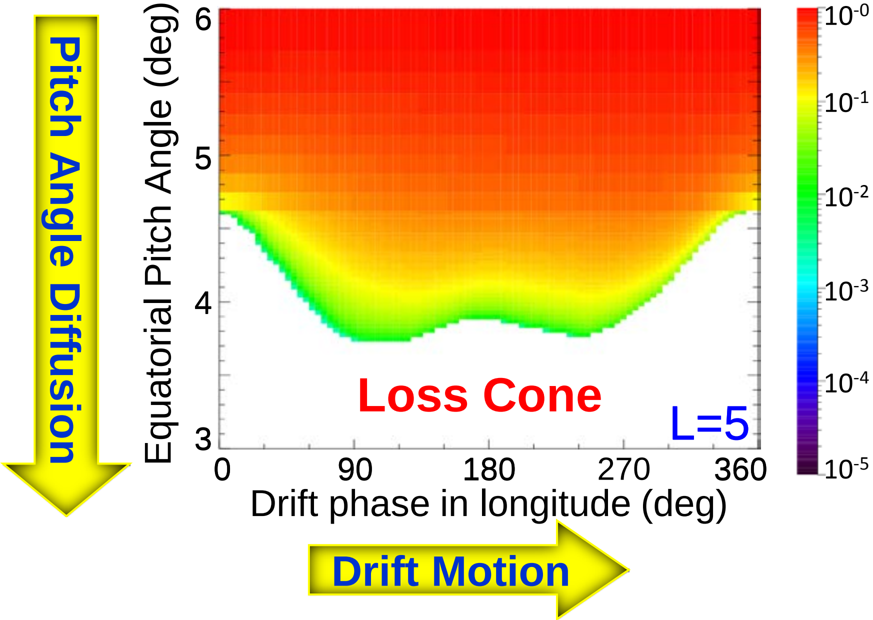
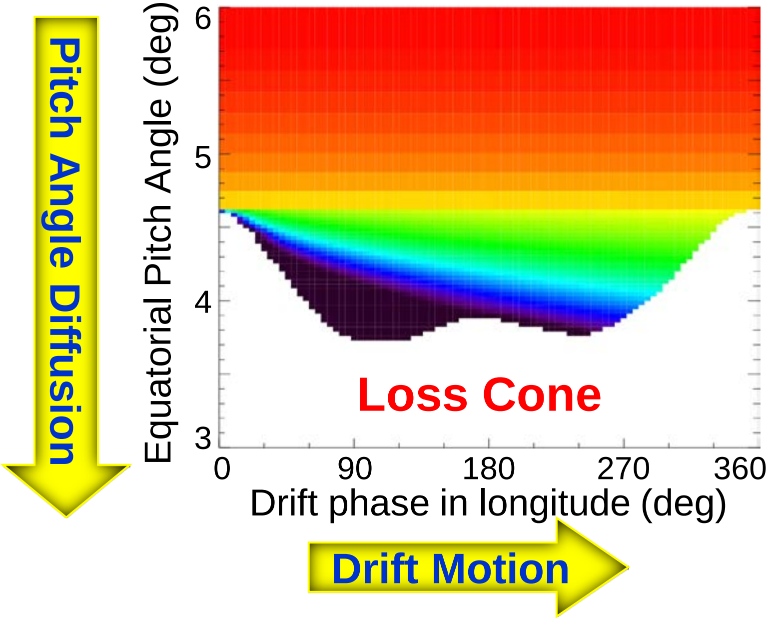


Electron intensity



PA diffusion dominates over Drift



Drift dominates over PA diffusion

Low-altitude Electron Distribution

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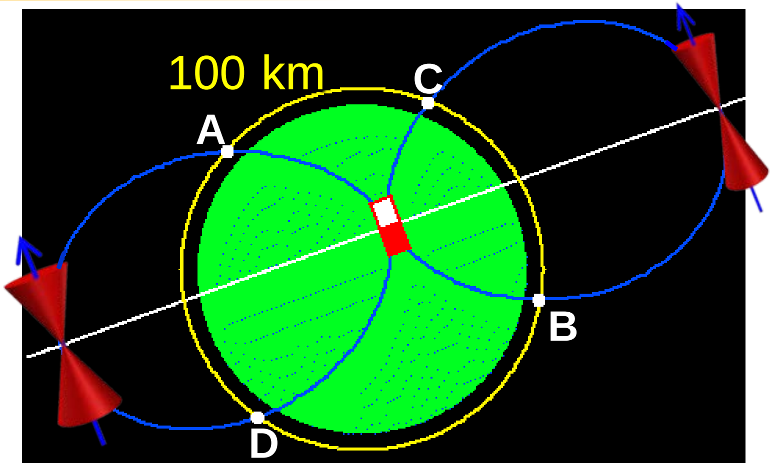
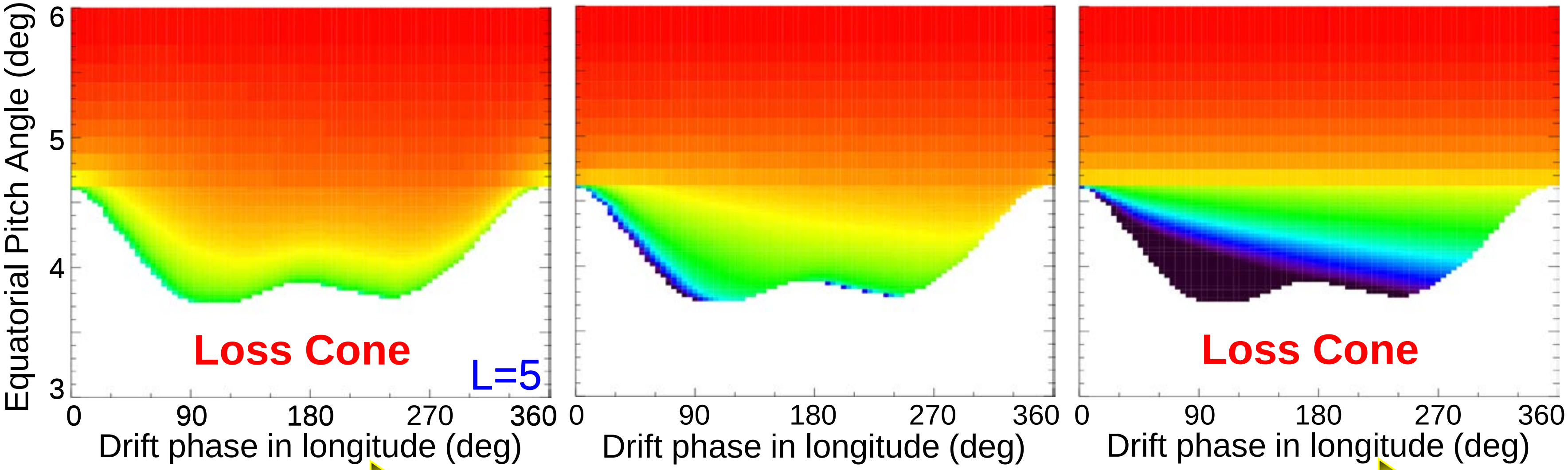


Electron intensity

Pitch Angle Diffusion



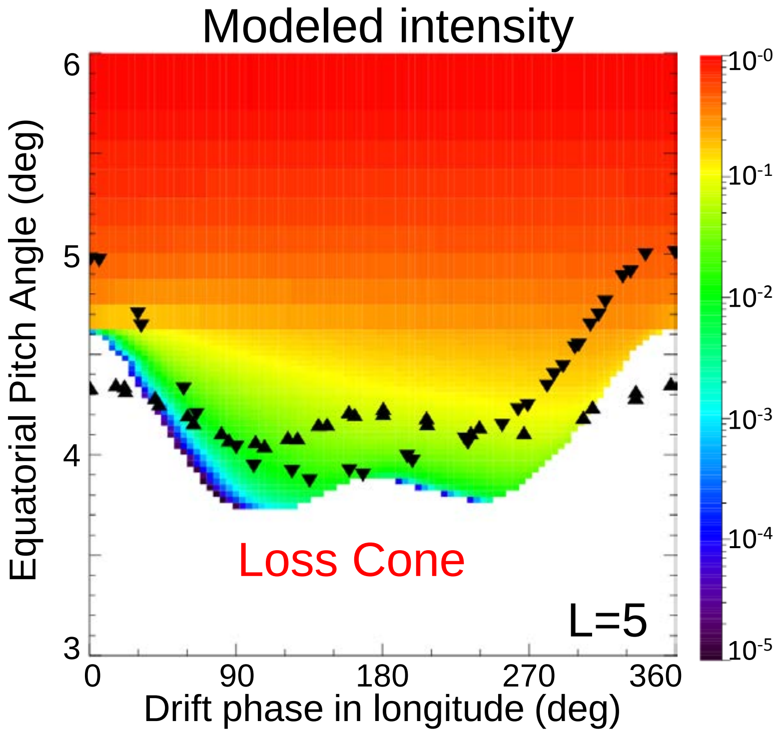
Drift Motion

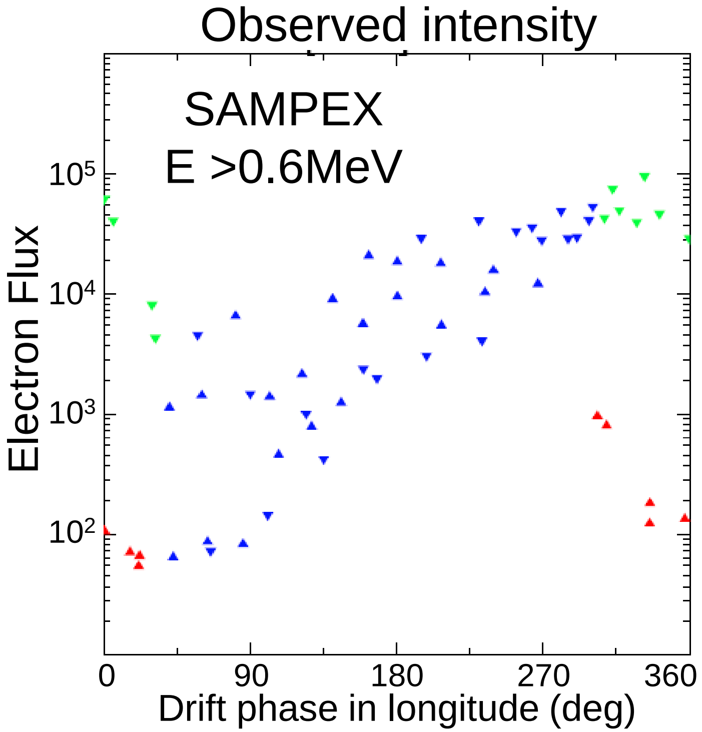
Drift Motion

PA diffusion dominates over Drift

Drift dominates over PA diffusion

Drift-Diffusion Model


Modeled intensity

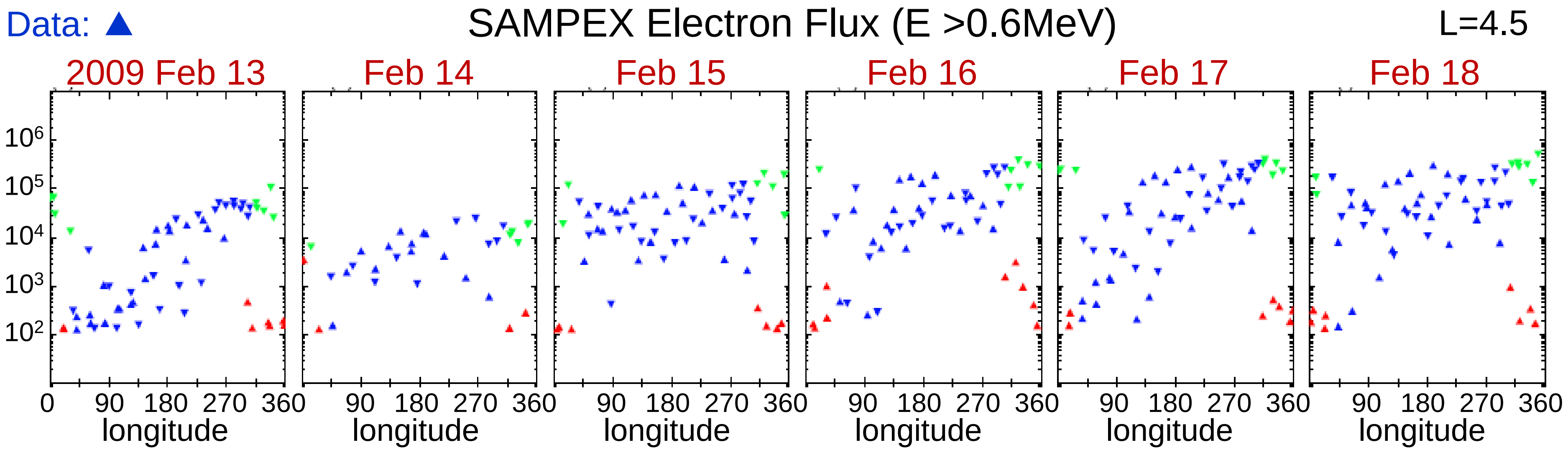

Observed intensity

- Developed a Drift-Diffusion Model to simulate the low-altitude electron distribution as a balance of pitch-angle diffusion, azimuthal drift and possible sources (S):

$$\text{For given L and E:}\ \frac{\partial f}{\partial t}+\omega_d\frac{\partial f}{\partial \phi}=\frac{1}{\Gamma}\frac{\partial}{\partial \alpha}\left(\Gamma \boxed{D_{\alpha\alpha}}\frac{\partial f}{\partial \alpha}\right)+S$$

Event Simulation Results

- Resolve the variations of the pitch angle diffusion rate, $D_{\alpha\alpha}$, by best fitting the low-altitude electron distribution observed by SAMPEX.


Data: ▲

SAMPEX Electron Flux (E >0.6MeV)

L=4.5

Event Simulation Results

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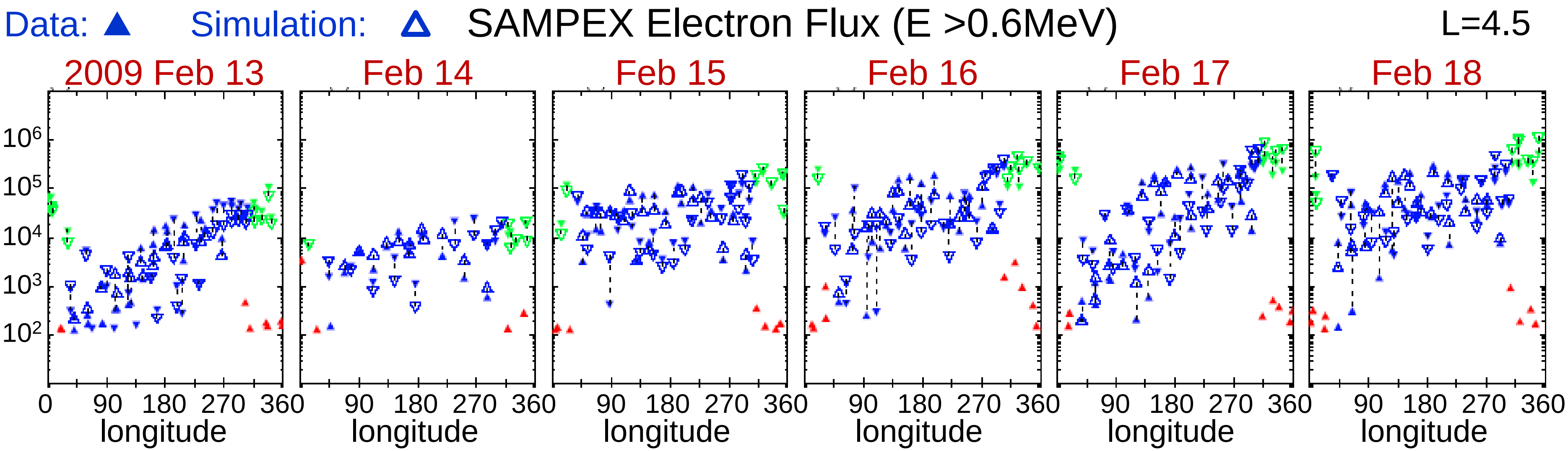
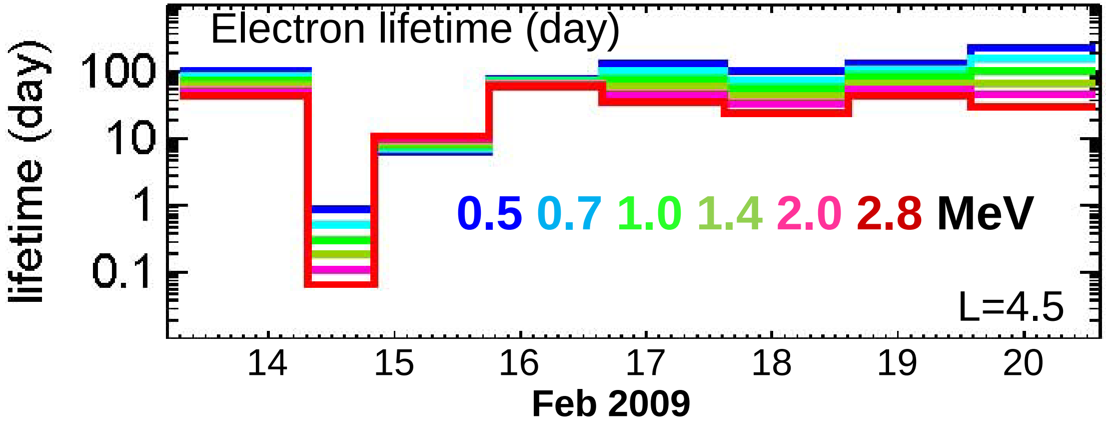


- Derived electron lifetime based on the resolved variation of $D_{\alpha\alpha}$.



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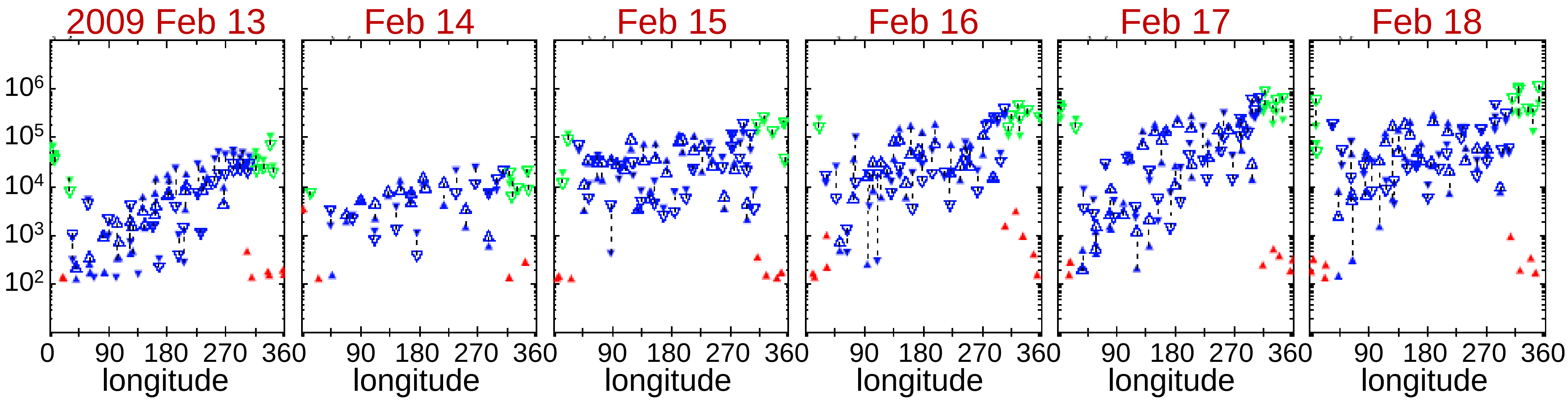
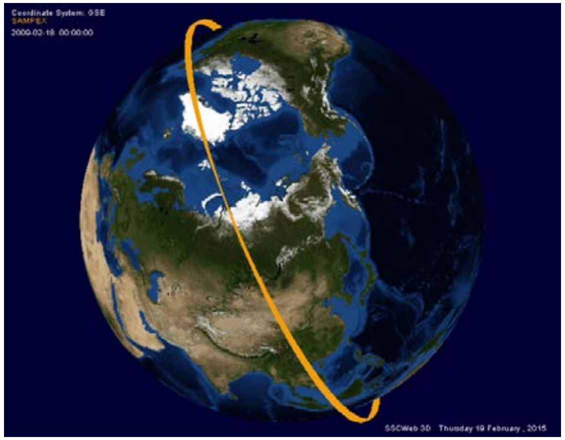
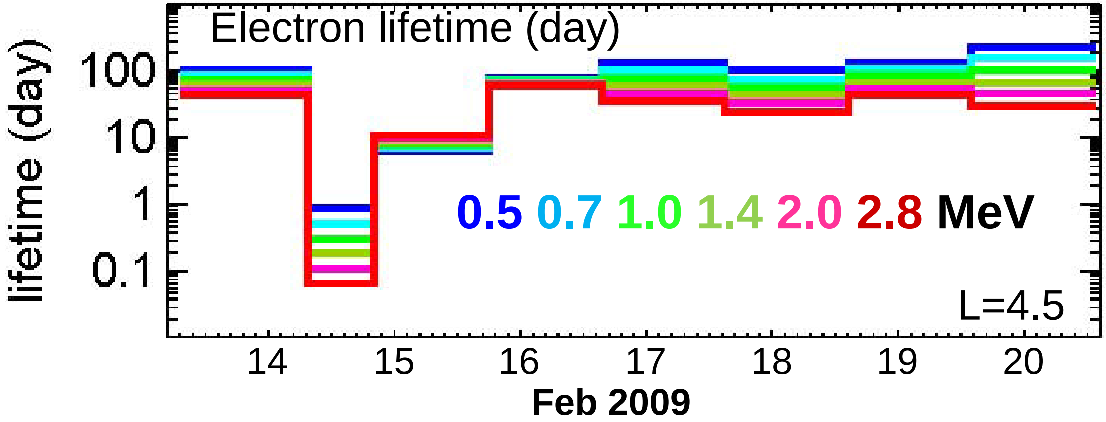
Data: ▲ Simulation: △ SAMPEX Electron Flux (E >0.6MeV) L=4.5



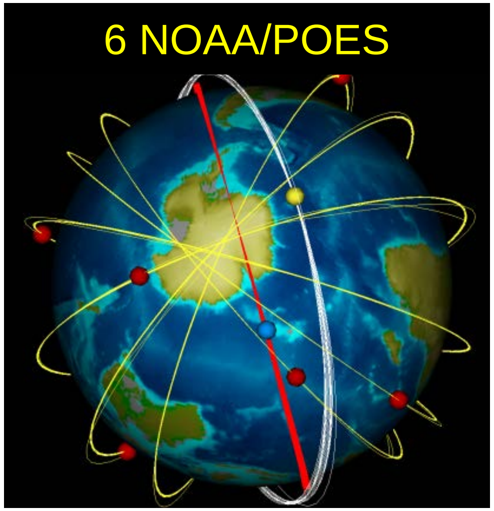


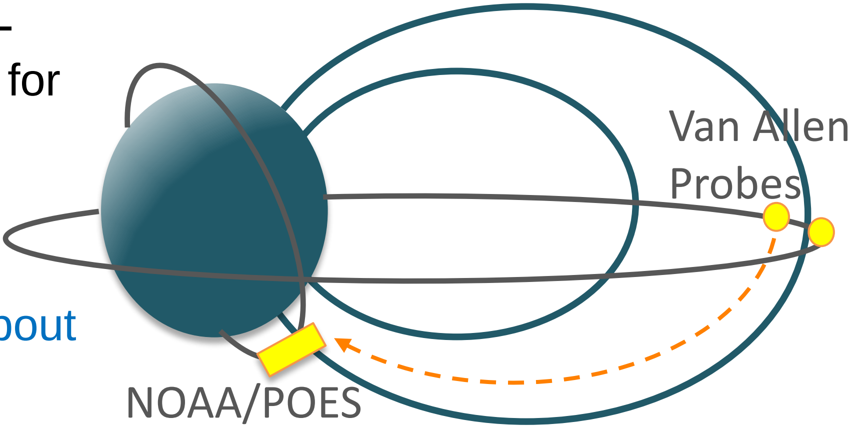


Project 1: Proposed Work

1. Quantify electron precipitation loss with high temporal and spatial resolution.
   - Multiple NOAA/POES satellites covering a wide range of longitudes
   - Outcome: $D_{\alpha\alpha}$ every 2-3 hours
2. Conjunction studies with high-altitude wave data
   - Link the resolved $D_{\alpha\alpha}$ with in situ wave data from Van Allen Probes
   - Outcome: Uncover the underlying wave-particle interactions that are responsible for the fast dropout.

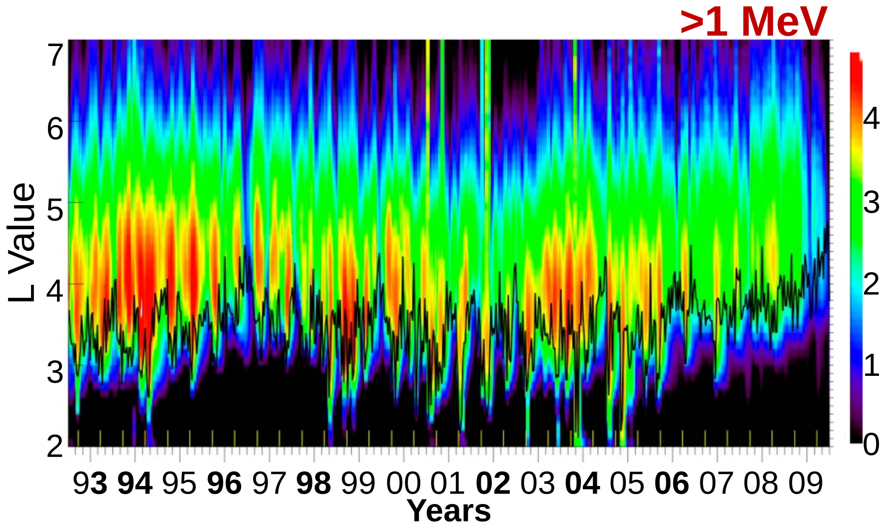
0. Statistical survey of the dropout events
   - Survey both the Van Allen Probes and NOAA/POES data to categorize the dropout events as: precipitation-loss dominant, outward RD dominant, and contributions from both.


6 NOAA/POES

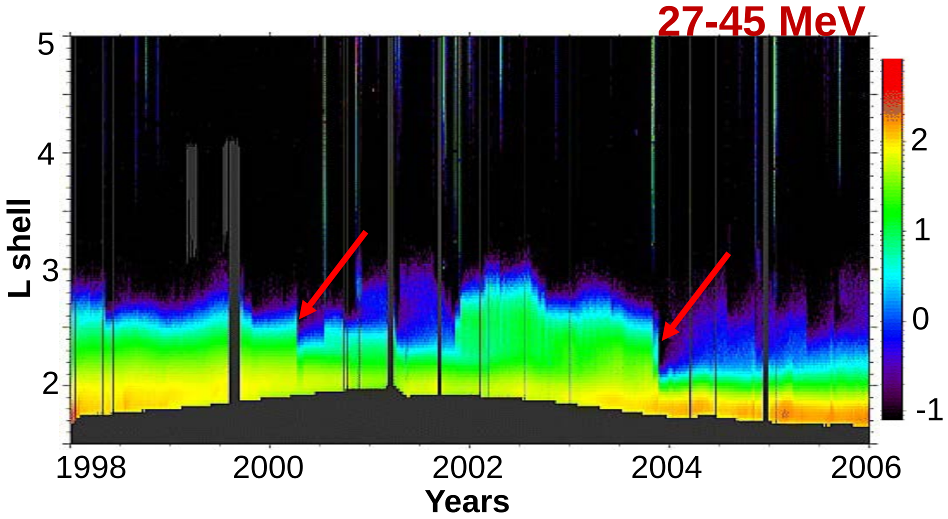


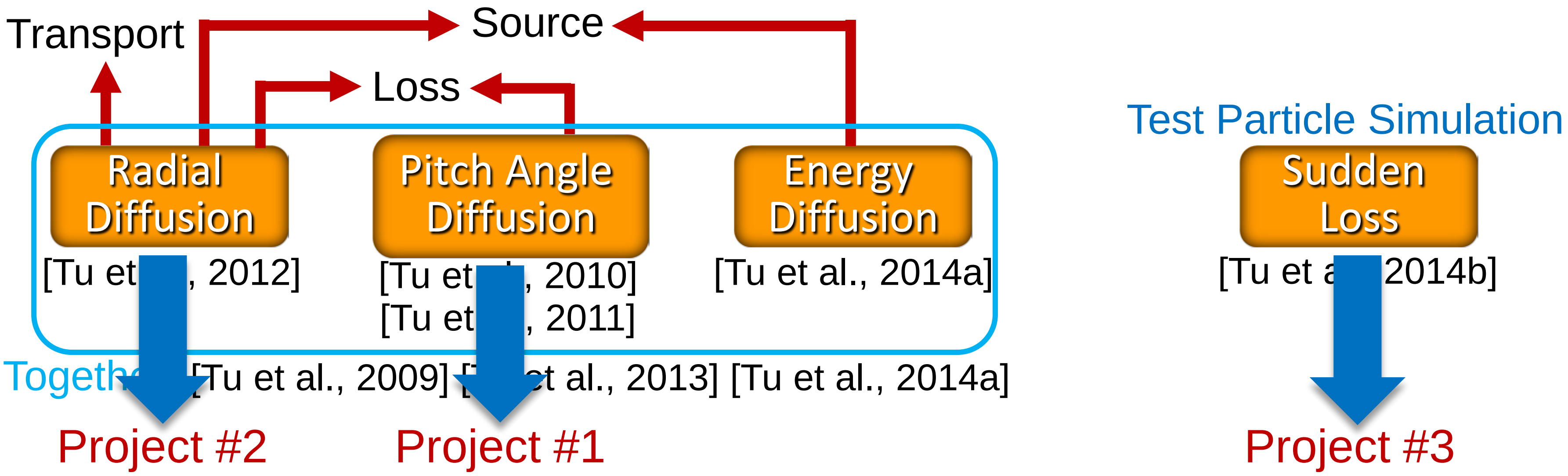
Outline of Previous Work

- Radiation Belt Electrons



- Radiation Belt Protons





Transport

Source

Loss

Test Particle Simulation

Radial Diffusion

[Tu et , 2012]

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Energy Diffusion

[Tu et al., 2014a]

Sudden Loss

[Tu et a 2014b]

Togeth [Tu et al., 2009] [et al., 2013] [Tu et al., 2014a]

Project #2

Project #1

Project #3

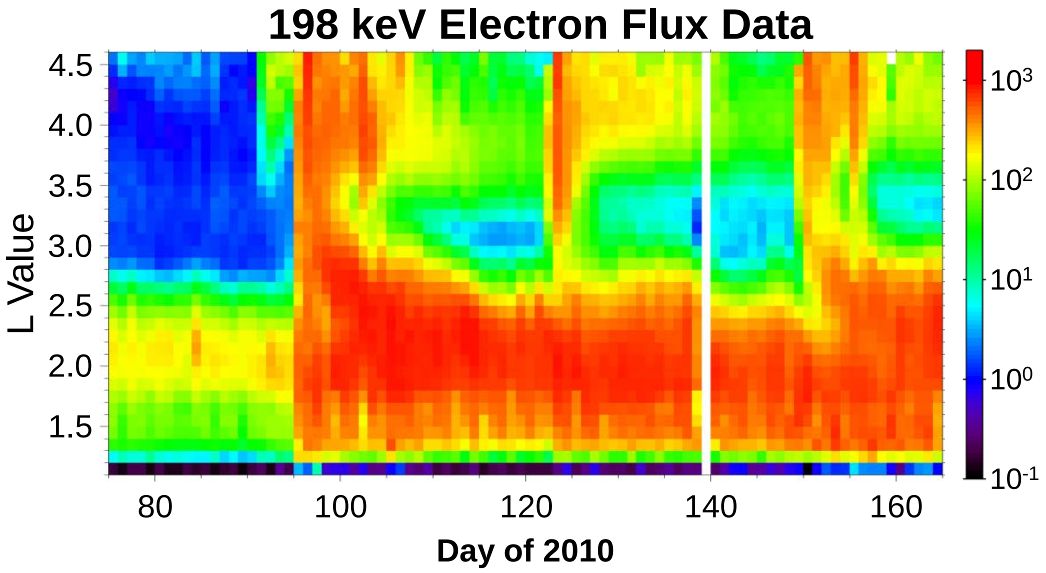
Project 2: Quantifying the Radial Diffusion Rate

- *Topic:* Formation and decay of the inner electron radiation belt
- *My Role:* Institutional PI (with the other PIs from Air Force Research Lab and the Laboratory for Atmospheric and Space Physics)
- *Funding Source:* Selected for funding by NASA/HGI (Heliophysics Guest Investigators) program
- *Funding per Year* (my portion only): FY14 (\$25K), FY15 (\$26K), FY16 (\$27K)

➢ Inner radiation belt electrons (10s-100s keV) are characterized by occasional rapid increase followed by gradual decrease.

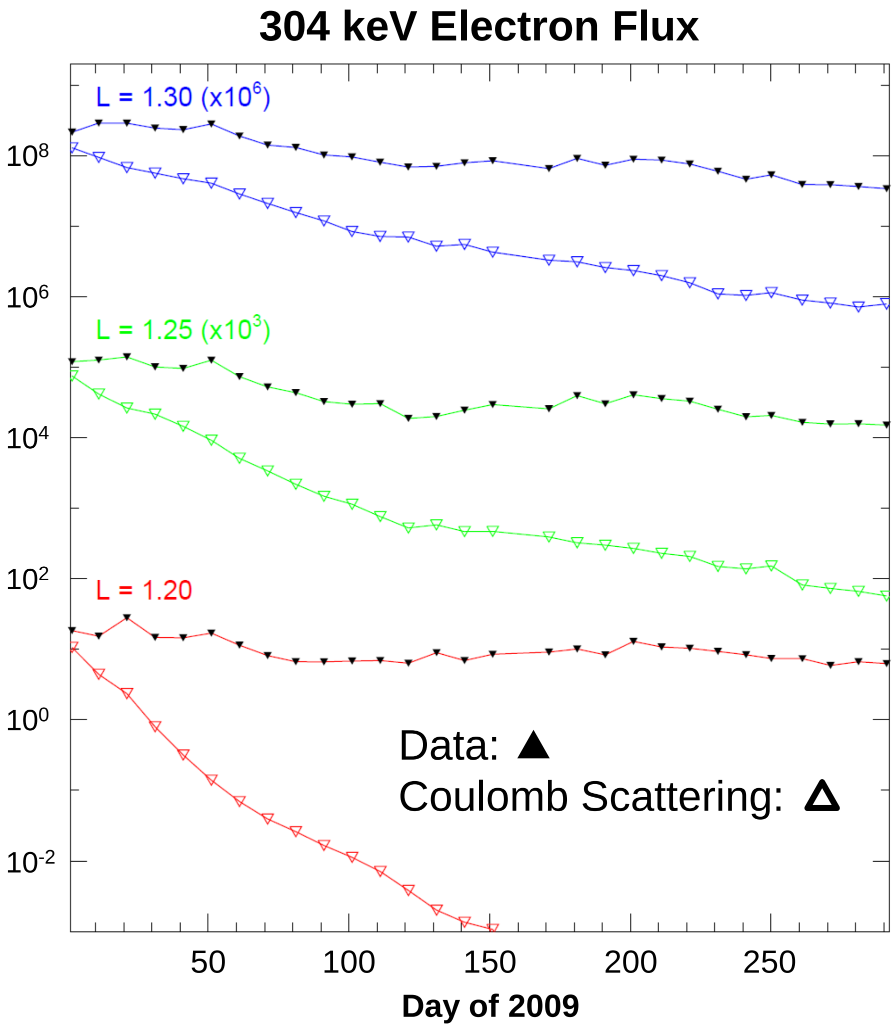
➢ The mechanisms of these formation and decay processes are unknown.

  – Rapid injection: Too fast to be inward radial diffusion.



Project 2: Quantifying the Radial Diffusion Rate

- Explaining the slow decay:
  - Losses at low L regions (L≤1.3) are mainly caused by Coulomb scattering on the atmosphere at low altitude.
  - However, data show much slower decay than the expected decay from Coulomb scattering.
- Is the observed slow decay due to continuous replenishment from inward radial diffusion?
  - Radial diffusion rate is not well-quantified, especially for low L regions.
  - The commonly used $D_{LL}(Kp)$ from Brautigam and Albert [2000] may not be accurate.



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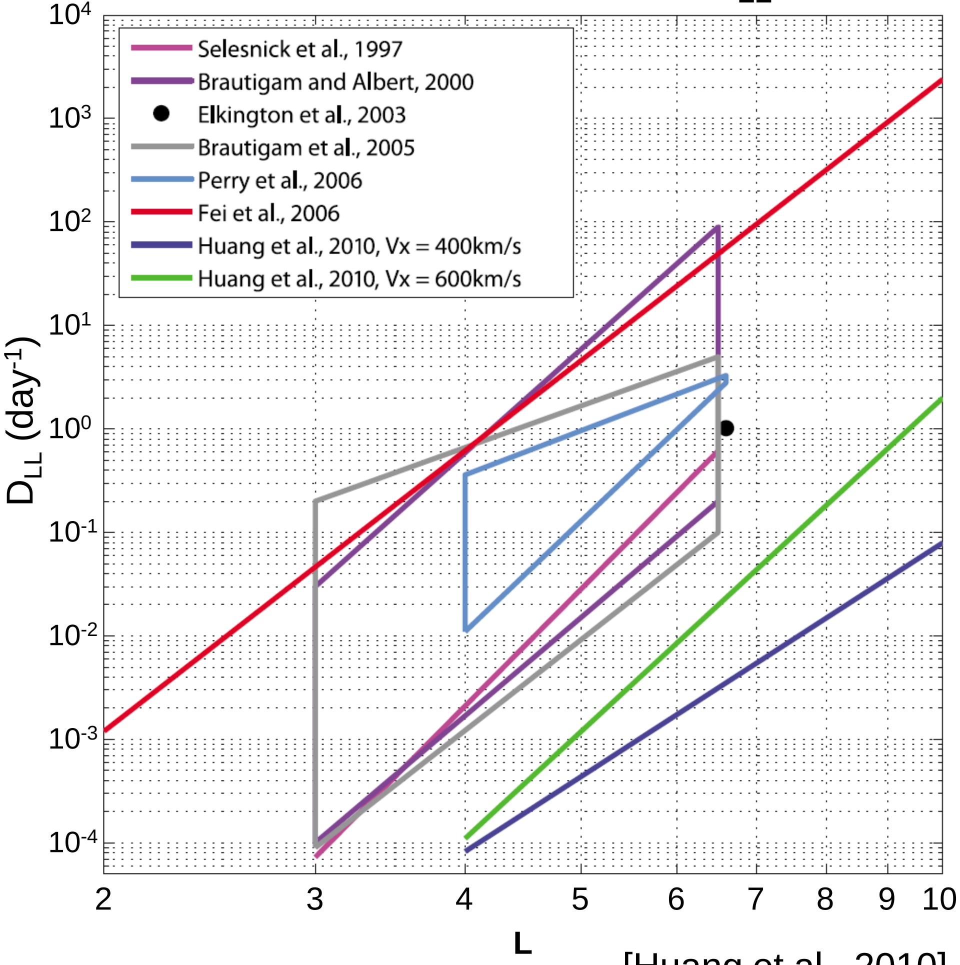
Recent estimations of D_{LL}



[Huang et al., 2010]

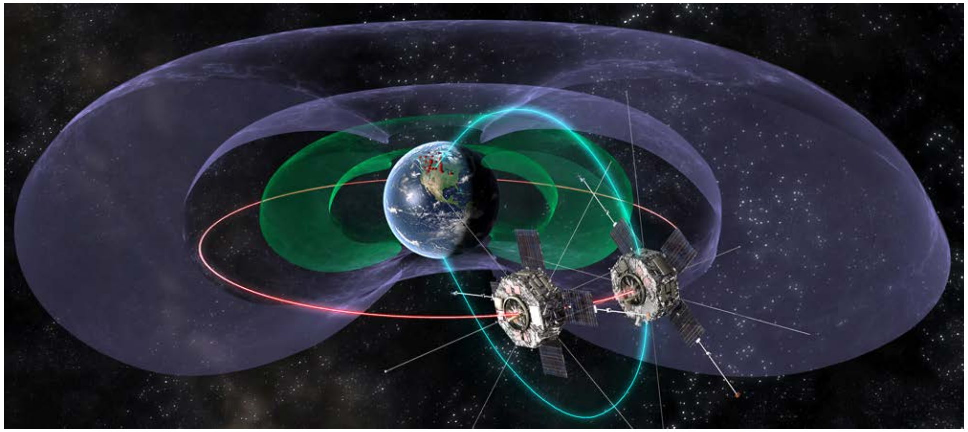
Project 2: Proposed Work

1. Physically quantify D_{LL} using real-time wave measurements
   - Drift resonance: $\omega = m\omega_{drift}$

$$\boxed{D_{LL} = \frac{L^4}{8R_E^4 B_E^2}\sum_m \left[\frac{m^2\mu^2}{q^2\gamma^2} P_m^B(m\omega_d) + L^2 R_E^2 P_m^E(m\omega_d)\right]}$$

[Fei et al., 2006]

   - Use ULF wave properties measured by Van Allen Probes, supplemented by ground magnetometer data.

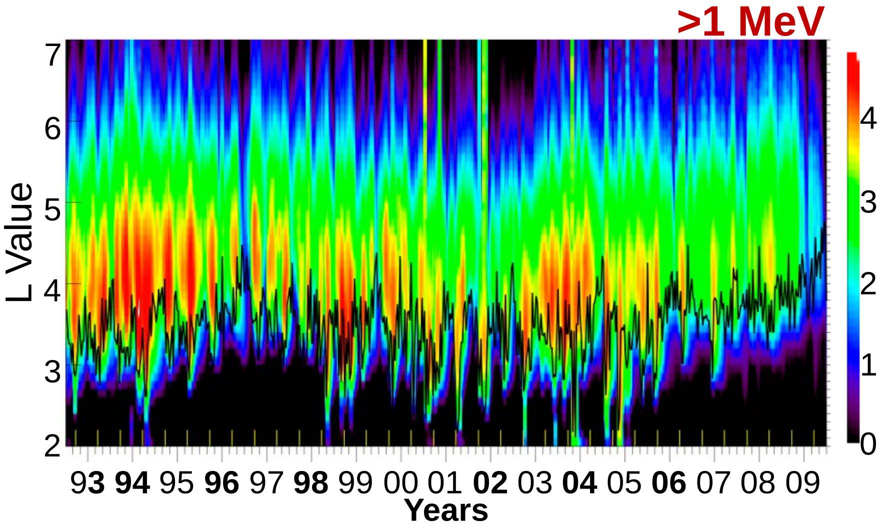


2. Theoretical work to extend the current formulation of D_{LL}
   - Include pitch angle (PA) dependence
   - Properly separate the inductive electric field and convective/electrostatic electric field

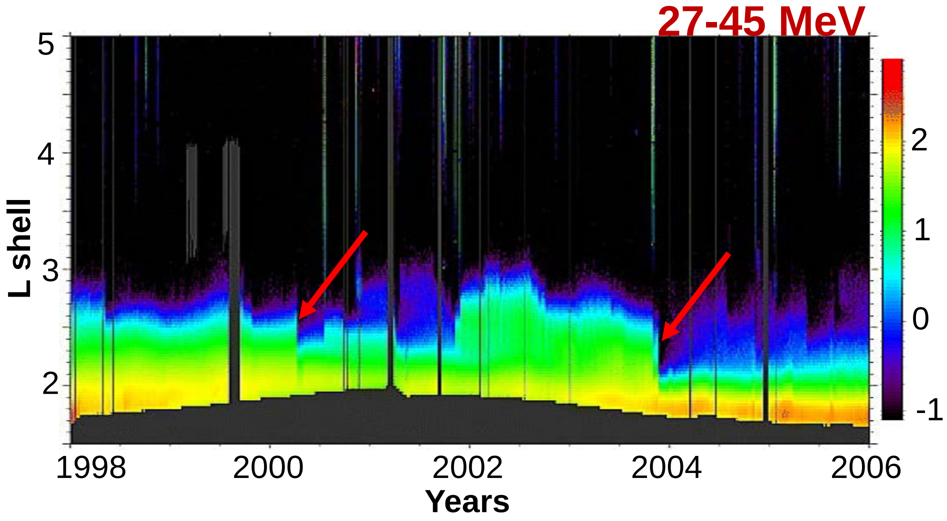
- **Outcome:** Event-specific and physical $D_{LL}(E,PA,t)$ for particles in both inner and outer belts

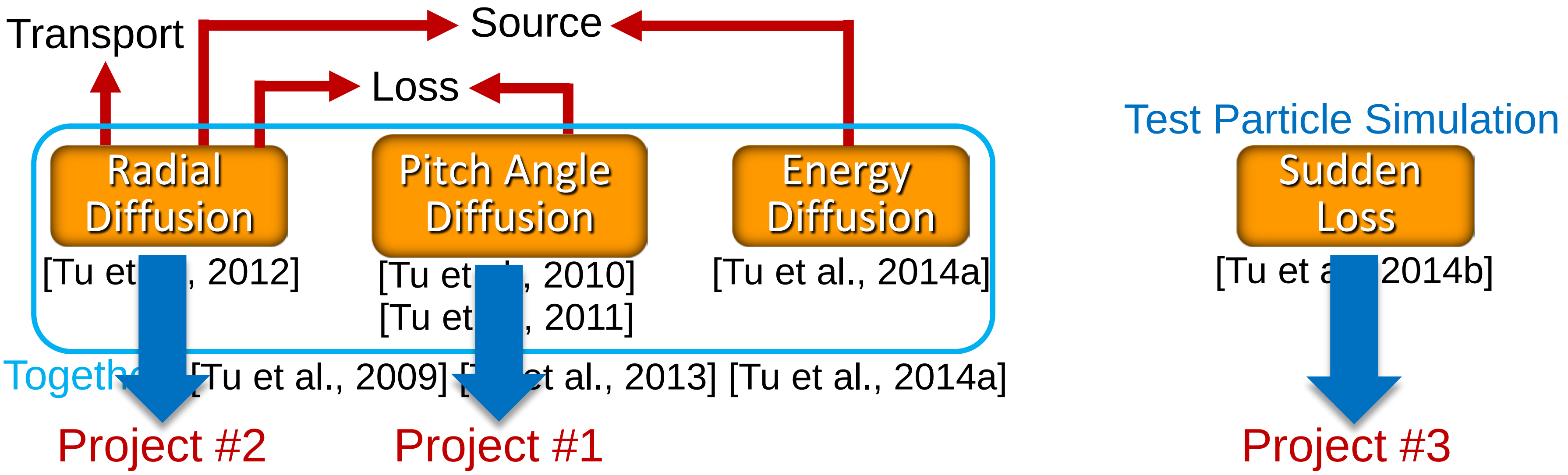
Outline of Previous Work

- Radiation Belt Electrons



- Radiation Belt Protons





[Tu et , 2012]

[Tu et , 2010]
[Tu et , 2011]

[Tu et al., 2014a]

[Tu et a 2014b]

Togeth [Tu et al., 2009] [et al., 2013] [Tu et al., 2014a]

Project #2

Project #1

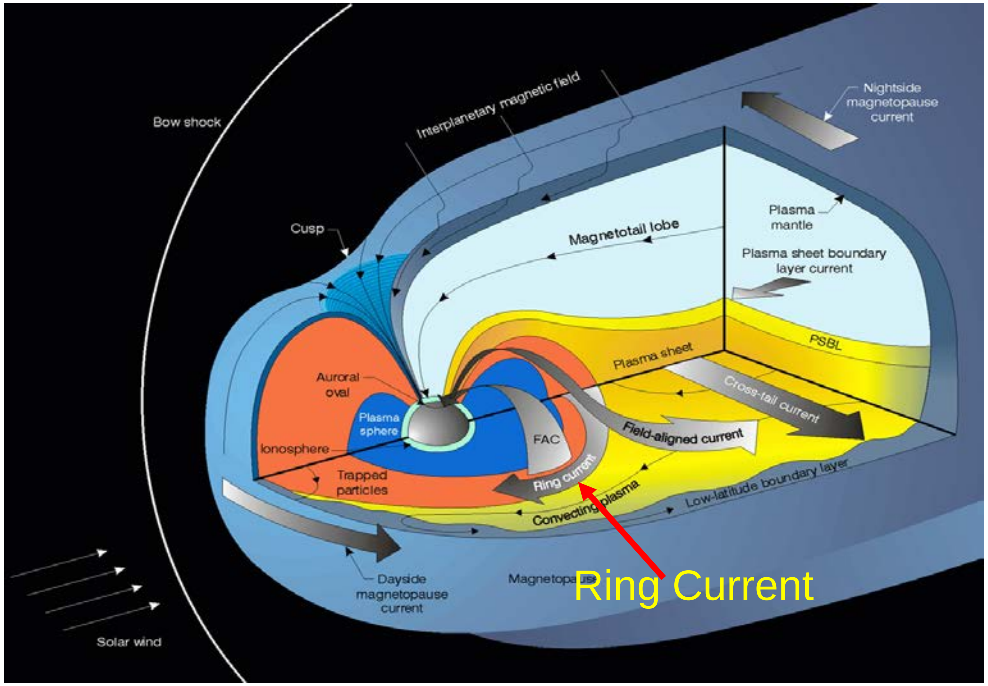
Project #3

Project 3: **Modeling Magnetic Field Line Curvature Scattering**

- *Topic:* The Effect of Magnetic Field Line Curvature Scattering on the Loss of Ring Current Ions
- *My Role:* PI (with other Co-Is from Los Alamos National Laboratory)
- *Funding Source:* Submitted to the 2014 NASA/HSR (Heliophysics Supporting Research) program (<u>currently under review in Step-2</u>)
- *Funding per Year:* FY15 ($121K), FY16 ($127K), FY17 (($140K)

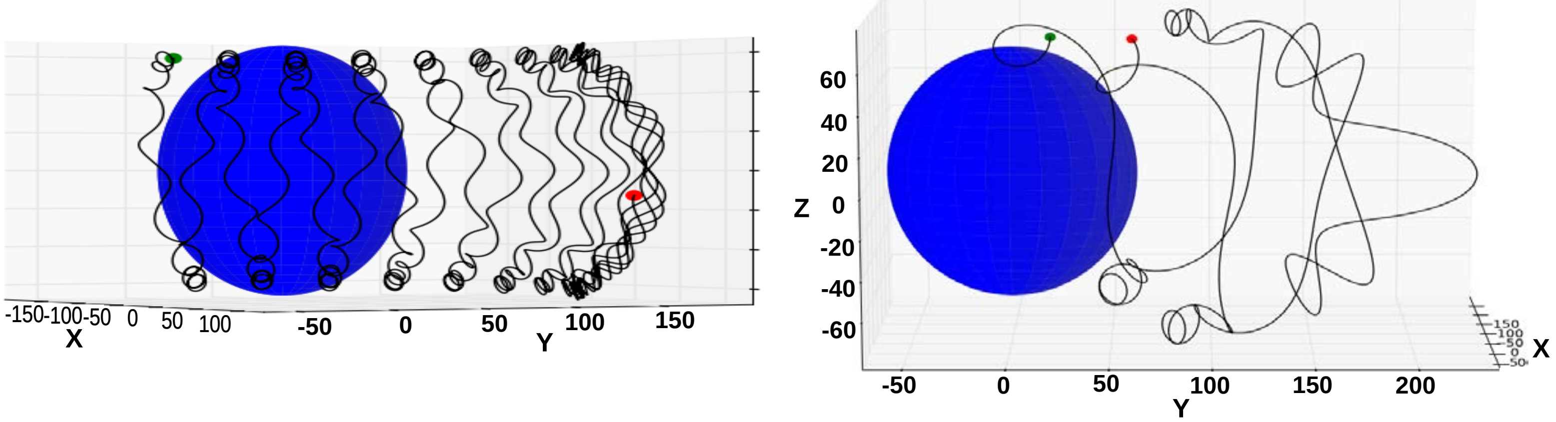
➢ Ring current co-locates with radiation belts, containing hot ions and electrons (1-100s keV).
  - Dominates the energy density of the inner magnetosphere.

➢ Understanding the dynamics of ring current ions is crucial for modeling the highly dynamic and coupled system of Earth's magnetosphere.



Project 3: Modeling Magnetic Field Line Curvature Scattering

- During geomagnetic storms, ring current developments strongly affects the magnetic field topology in the inner magnetosphere.
- In turn, the distorted magnetic field modifies the ion trajectories, and may lead to magnetic field line curvature scattering of ring current ions:
  - Trapped: $\rho_{gyro} << R_c$; Untrapped: $\rho_{gyro} \sim R_c$
- This can act as an important loss mechanism for ring current ions, but its relative importance has not yet been modeled or quantified.



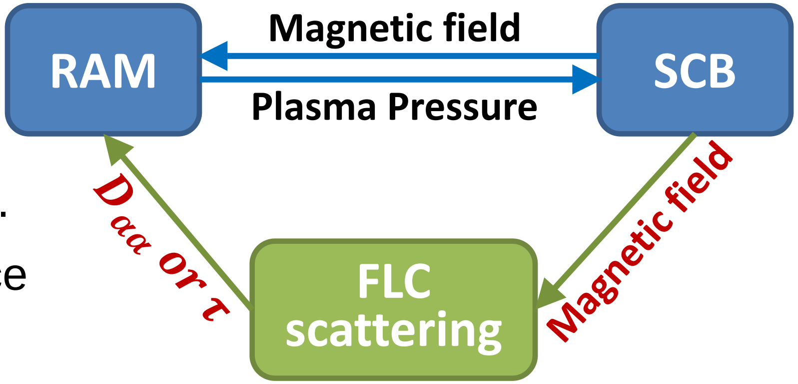
(a) $\rho_{gyro} << R_c$ at equator

(b) $\rho_{gyro} \sim R_c$ at equator

ρ_{gyro}: gyroradius; **R_c**: radius of curvature of the magnetic field line

Project 3: Proposed Work

1. Directly model the field line curvature (FLC) scattering of ring current ions
   - Use test particle code developed in Tu et al. [2014] for inner belt protons
   - Trace the full gyration, bounce, and drift motions of ring current ions under different geomagnetic disturbance conditions
   - Outcome: significance of FLC scattering loss, database for work #2.
2. Parameterize the FLC scattering loss of ring current ions
   - Can FLC scattering be described as a pitch angle diffusion process?
   - Outcome: diffusion coefficient $D_{\alpha\alpha}$ or ion lifetime τ (E,PA,B field topology parameters)
3. Self-consistently implement FLC scattering loss into ring current model
   - RAM-SCB model:
   - Simulate real events and compare with particle and field data from Van Allen Probes, THEMIS, NOAA/POES satellites.
   - Outcome: quantify the relative importance of FLC scattering in real events.



Long-Term Research Plan

- Radiation Belt Studies
  - Tie the project results together to provide better inputs to the comprehensive DREAM3D model. Can we explain the mysterious variability of the outer radiation belt?
  - Ultimate goal: from nowcast to forecast. Develop a reliable prediction model for the energetic particles in radiation belts.
  - Explore the radiation belts in other planets.
- Collaborations with colleagues in the West Virginia University
  - Wave-particle interactions: theoretical and observational studies for interactions of energetic particles with VLF waves, ULF waves, etc.
  - Substorm/tail reconnection: model the seed population transported from magnetotail to inner magnetosphere.
  - And more …
- Study the dynamics of energetic particles in space
  - In general (not limited to inner Magnetosphere), e.g., solar energetic particles, cosmic ray, etc.

Collaborations and Leadership

- I have built strong collaborations with colleagues from:
  - Air Force Research Lab, NASA, NOAA, LANL
  - University of Colorado at Boulder, Rice University, UCLA, etc.
- Active member of the science team for the NASA Van Allen Probes mission.
- Leadership:
  - Currently serving as one of the leaders of the NSF/GEM Focus Group on “Quantitative Assessment of Radiation Belt Modeling” (2014-2018)
  - Organized and chaired sessions in 2014 AGU Fall meeting, 2013 ‘AGU Meeting of the Americas’, etc.