Quantifying Surface and Internal Charging Parameters Through Flying Virtual Satellites in the RAM-SCB Inner Magnetosphere Model

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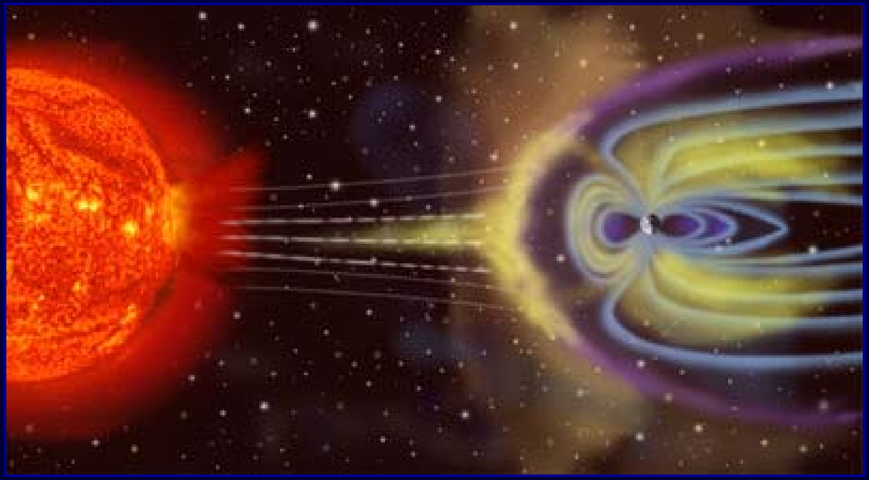
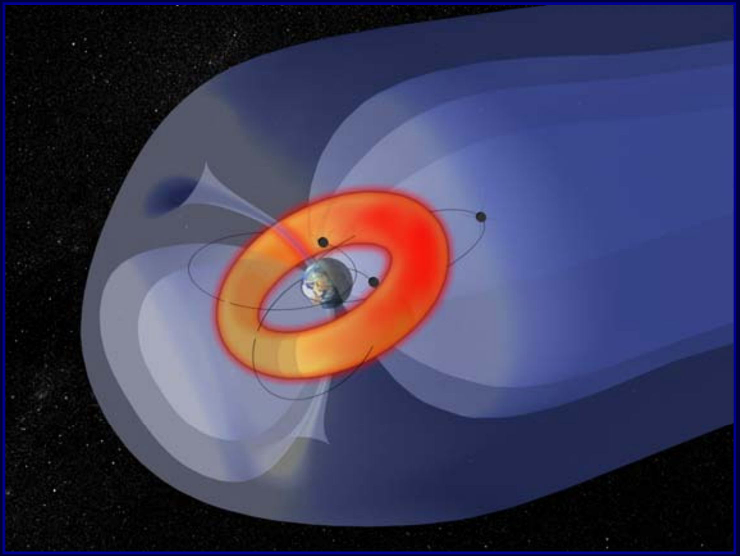
Outline

- Goal: quantifying the ambient environment along satellite orbit, relevant to spacecraft charging, by “flying” virtual satellites in model domain
- Physics-based model: Ring Current Atmosphere Interactions Model with Self-Consistent Magnetic (B) field (RAM-SCB)
  - Importance of interaction between particles and fields
  - Can be driven by global model (e.g. SWMF) or data-driven (e.g. LANL)
  - Full 3-D and pitch angle anisotropy
  - Particles include contributors to both surface and internal charging
- Results: RAM-SCB geomagnetic storm simulation
  - Proof of principle: virtual satellites in RAM-SCB; virtual spectrograms
- Potential of virtual spacecraft in space weather models to prescribe the environment relevant to spacecraft charging

Storm-time Inner Magnetosphere



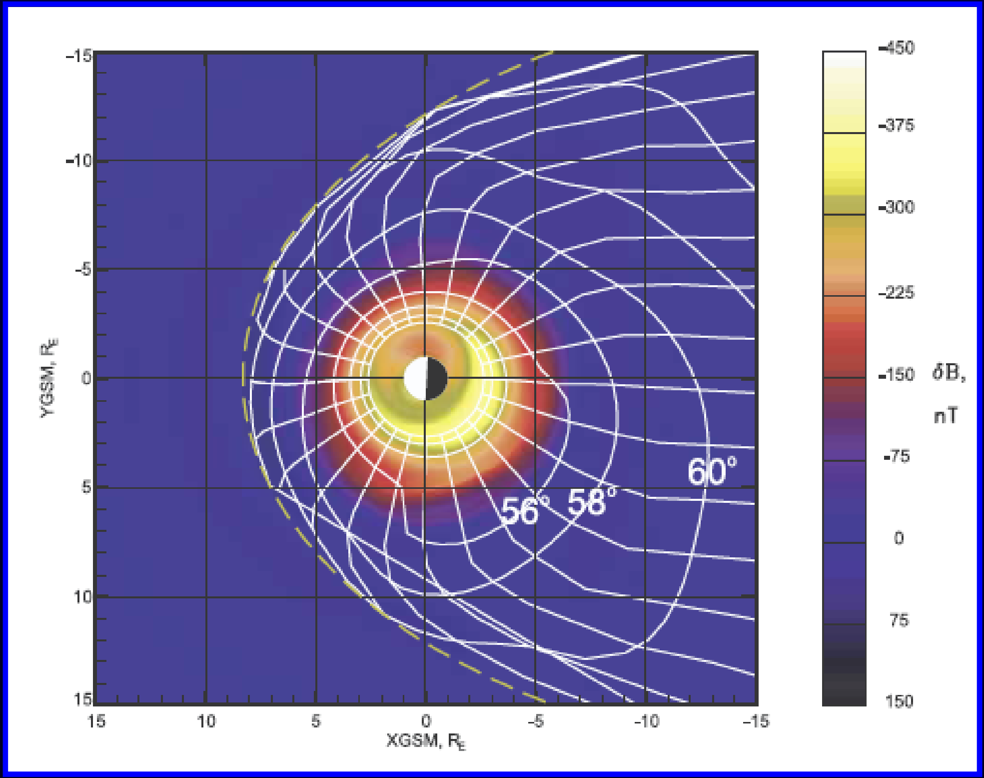


From Daglis, [2006]

- Challenge: to understand and model the space environment, specifically geomagnetic storm changes in the inner magnetosphere:
  1. Major changes in the geomagnetic field
  2. Ring current (keV to 10s of keV) enhancement (➔ surface charging)
  3. High-energy (MeV and 100s of keV) electron flux enhancement (➔ internal charging)
     - Affected by plasma-excited waves
     - Dependent on the magnetic field

Dipole Approximation Breaks Down in the Storm-time Inner Magnetosphere

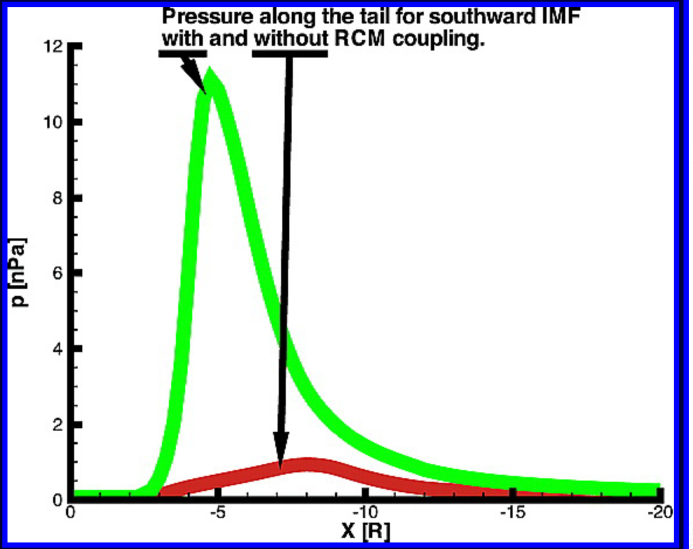
- Observations ➔ strong magnetic field decrease during storms



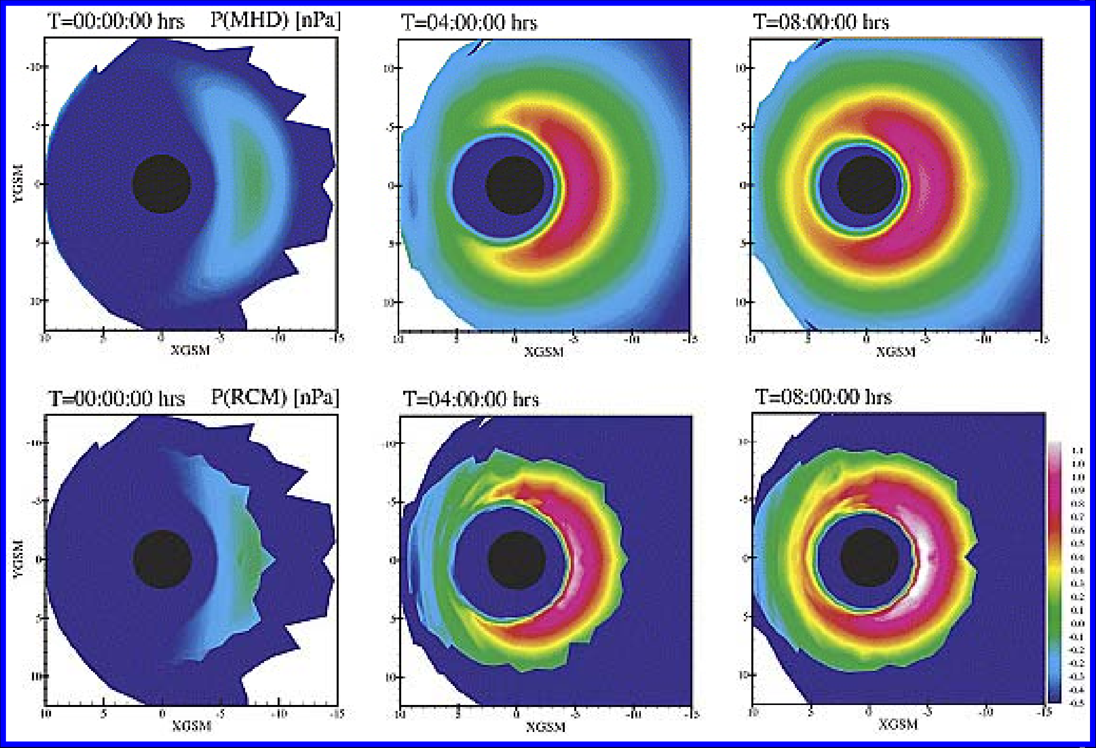
04/06/00 22:00 UT Dst = -250 nT
From *Tsyganenko et al., [2003]*

- Dipole approximation breaks down at 3-4 R_E
- The changed field significantly influences plasma/rad. belt particles

Need for Physics-based Kinetic Models



De Zeeuw et al., 2004



- Plasma also changes the field
- Global magnetohydrodynamics (MHD) models:
  - Fully self-consistent, but unrealistic in inner magnetosphere
  - Ring current energy density ~ 1/10th of observed values
  - Causes: Coarse resolution; lack of gradient/curvature drifts and heat flux *[Heinemann and Wolf, 2001]*

RAM-SCB: Self-consistent Kinetic Inner Magnetosphere Model

Ring current-atmosphere interactions model (RAM)

[Jordanova et al., 1994, 2006]

- Bounce-av. Boltzmann eq.
- Applied convective + corotation E-field
- Updated to general magnetic (B) field

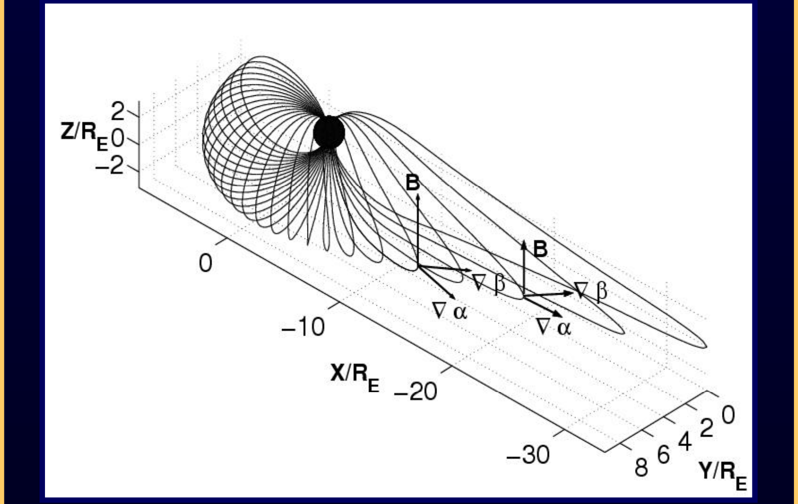
Pressure

B-field

3D equilibrium code

[Cheng, 1995; Zaharia et al., 2004; Zaharia, 2008]

$$\mathbf{J}\times\mathbf{B} - \nabla\cdot\mathbf{P} = 0$$



- Euler potential formulation

RAM-SCB Formalism: RAM

- RAM-SCB: particle/field dynamics on time scales > bounce/Alfven times
- Kinetic Ring Current Atmosphere Interactions Model (RAM):
  - Evolution of bounce-averaged distribution function *[Jordanova et al., 1994]*
  - Energy range: 100 eV to 500 keV
  - Generalized to arbitrary (closed-line) magnetic field geometry
  - 4 coordinates: 2 spatial (R, φ) + energy E, pitch angle α (μ_0 = cos α)

$$\left\langle \frac{dF_t}{dt} \right\rangle = \frac{\partial F_t}{\partial t} + \frac{1}{R_o^2}\frac{\partial}{\partial R_0}\left(R_o^2 \left\langle \frac{dR_0}{dt} \right\rangle F_t \right) + \frac{\partial}{\partial \varphi}\left(\left\langle \frac{d\varphi}{dt} \right\rangle F_t \right) +$$

$$\frac{1}{\sqrt{E}}\frac{\partial}{\partial E}\left(\sqrt{E} \left\langle \frac{dE}{dt} \right\rangle F_t \right) + \frac{1}{h(\mu_o)\,\mu_o}\frac{\partial}{\partial \mu_o}\left(h(\mu_o)\,\mu_o \left\langle \frac{d\mu_o}{dt} \right\rangle F_t \right) =$$

$$= \left\langle \frac{dF_t}{dt} \right\rangle_{losses}$$

- Most physically complete model; different losses: charge exchange, Coulomb collisions, wave-particle interactions, losses to atmosphere

RAM-SCB Formalism: SCB

- Single-fluid plasma equation of motion:

$$\underset{\text{mass density}}{\rho} \quad \bullet \quad \underset{\text{acceleration}}{\left[\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v}\right]} = \underset{\text{force density}}{\mathbf{J}\times\mathbf{B} - \nabla\cdot\mathbf{P}}$$

- Plasma and fields in the near-Earth magnetosphere (< 10 R_E) in quasi-force balance (slow-flow approximation; *Wolf, [1983]*)

$$\mathbf{J}\times\mathbf{B} = \nabla\cdot \mathrm{P}$$

$$\text{With } \nabla\cdot\mathrm{P} = \nabla P_\perp - \nabla\cdot\left[\left(P_\perp - P_\parallel\right)\mathbf{bb}\right]$$

$$\Downarrow$$

$$\sigma\mathbf{J}\times\mathbf{B} = \nabla P_\perp - (\mathbf{B}\cdot\nabla\sigma)\mathbf{B} + (1-\sigma)\nabla\left(\frac{B^2}{2}\right) \qquad \text{Force balance equation}$$

$$\sigma = 1 + \frac{P_\perp - P_\parallel}{B^2}$$

$$\nabla\times\mathbf{B} = \mu_0\mathbf{J} \qquad \text{Ampere's law}$$

$$\nabla\cdot\mathbf{B} = 0 \qquad \text{No magnetic monopoles}$$

- B-field in Euler potential representation:

$$\nabla\cdot\mathbf{B} = 0 \quad \Rightarrow \quad \mathbf{B} = \nabla\alpha\times\nabla\beta$$

α, β = Euler potentials

(Clebsch coordinates or flux coordinates)

α = magnetic flux function

β = angle - like variable

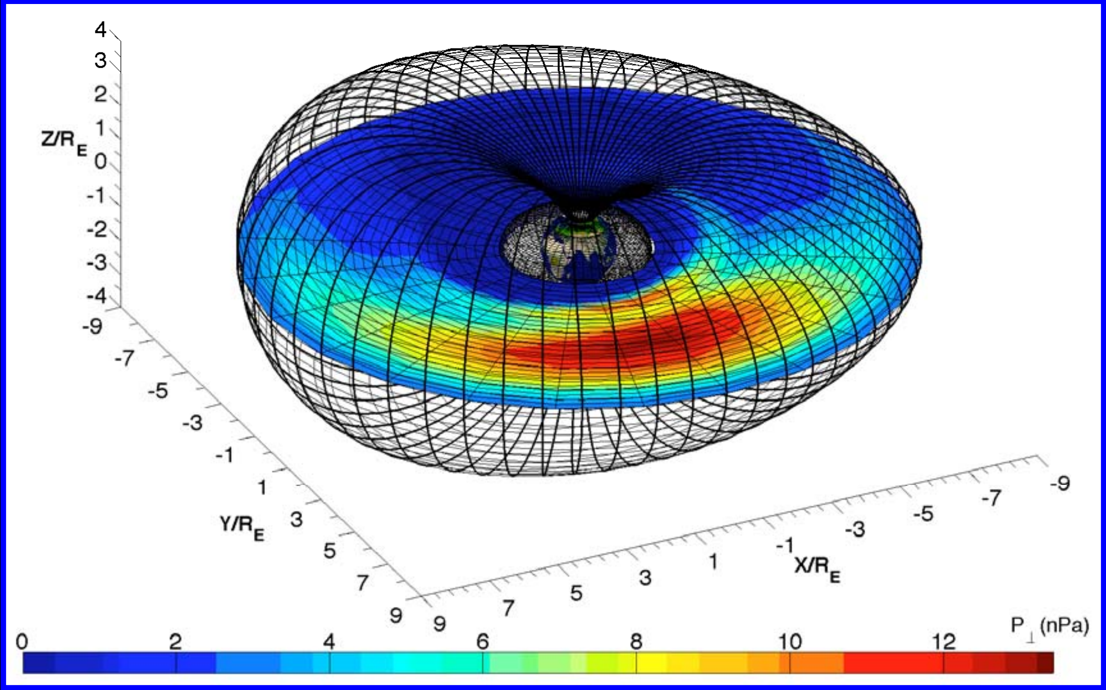
- Coupled quasi-2D elliptic PDEs, solved iteratively *[Zaharia et al., 2004;2008]*

$$\sigma\nabla\cdot\left[(\nabla\alpha)^2\nabla\beta - (\nabla\alpha\cdot\nabla\beta)\nabla\alpha\right] = -\mu_0\frac{\mathbf{B}\times\nabla\alpha}{B^2}\cdot\left[\nabla P_\perp + (1-\sigma)\nabla\left(\frac{B^2}{2}\right)\right]$$

$$\sigma\nabla\cdot\left[(\nabla\alpha\cdot\nabla\beta)\nabla\beta - (\nabla\beta)^2\nabla\alpha\right] = \mu_0\frac{\mathbf{B}\times\nabla\beta}{B^2}\cdot\left[\nabla P_\perp + (1-\sigma)\nabla\left(\frac{B^2}{2}\right)\right]$$

RAM-SCB Model Setup

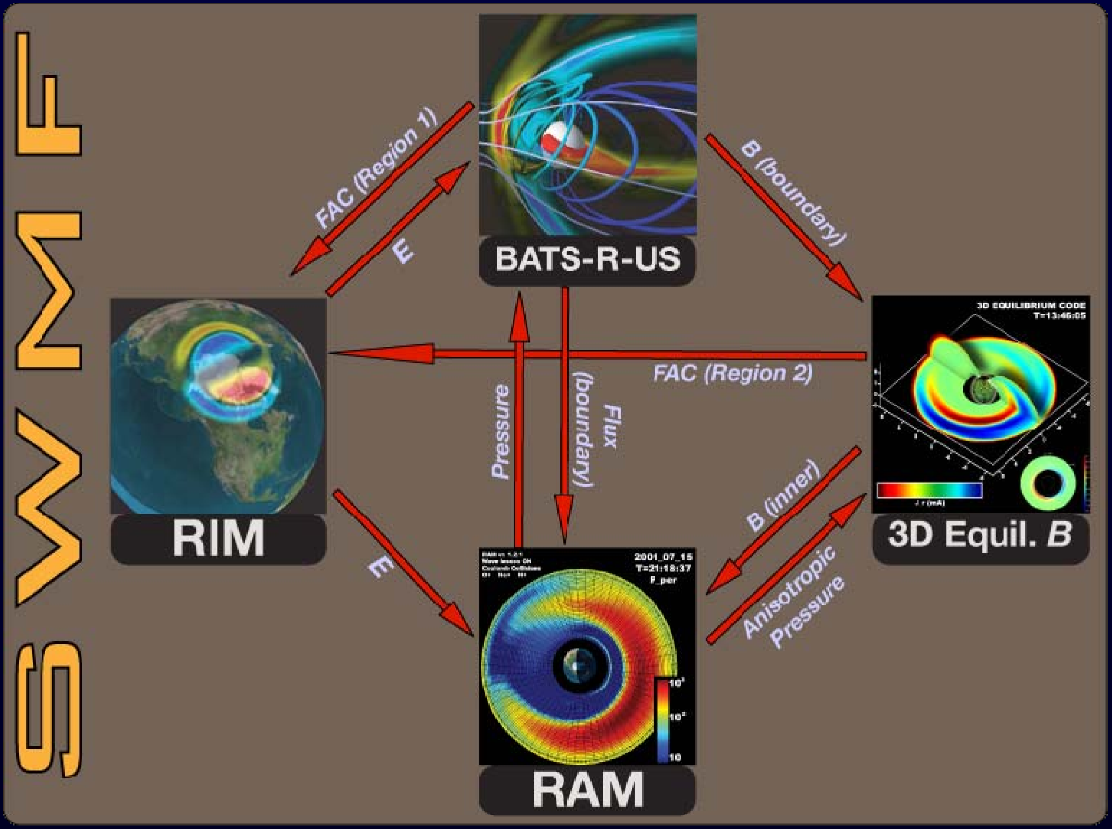
$$\mathbf{B} = \nabla\alpha \times \nabla\beta$$



RAM-SCB domain (T89 boundary)

- Coupling freq.: 5 min.
- Plasma sheet boundary:
  - 6.6 R_E – LANL obs. (MPA/SOPA)
  - Empirical plasma models/global codes (BATSRUS MHD)
- B-field boundary:
  - Empirical (T89, T04S)
  - BATSRUS MHD code
- E-field: empirical (Volland/Stern, Weimer) or from IE model
- Dipole tilt included (RAM in equatorial SM plane)

RAM-SCB Inside Space Weather Modeling Framework (SWMF)



- Alternative RAM-SCB input: plasma & magnetic boundaries from BATS-R-US, electric potentials from ionospheric electrodynamics (IE) solver *[Zaharia et al., submitted to J. Geophys. Res., 2010]*

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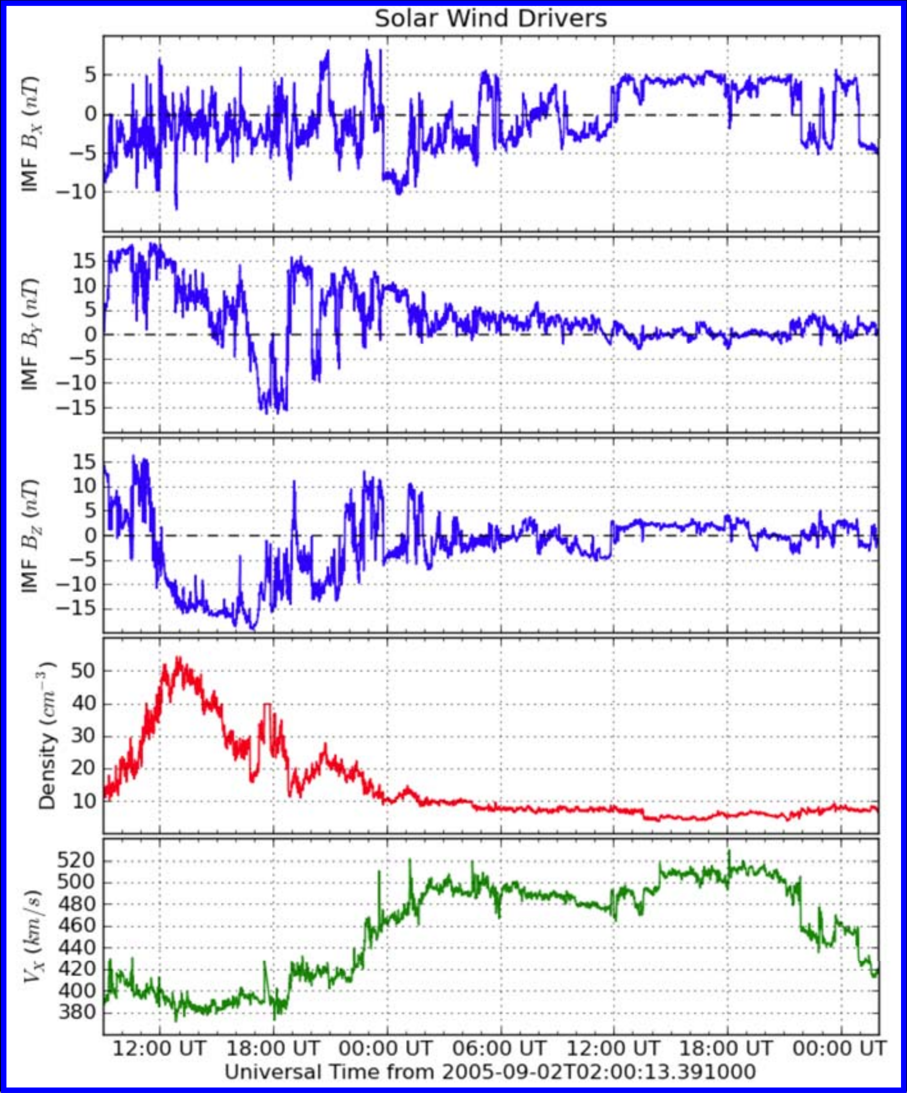
Simulated Event: Sep. 2005 Geomagnetic Storm

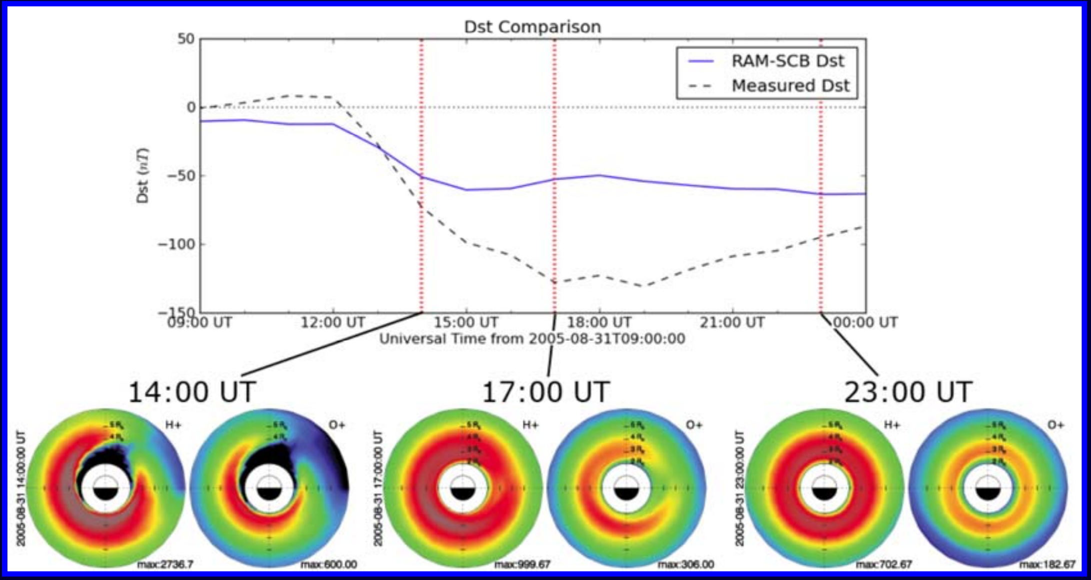


- Aug. 31, 2005 large CME-driven storm; min. SYM-H = -116 nT
- Main phase /early recovery (9:00 UT to 24:00 UT) simulated
- RAM-SCB inputs:
  - Plasma conditions at outer boundary by LANL geo. obs.
  - Ion composition by Young et al. [1982] empirical relationship:

$$n_{O+}/n_{H+} = 4.5 \times 10^{-2} \exp \left[0.17\,Kp + 0.010\,F_{10.7}\right]$$

- Convection electric field: Weimer 2001 empirical model
- B-field boundary by the T89 empirical model

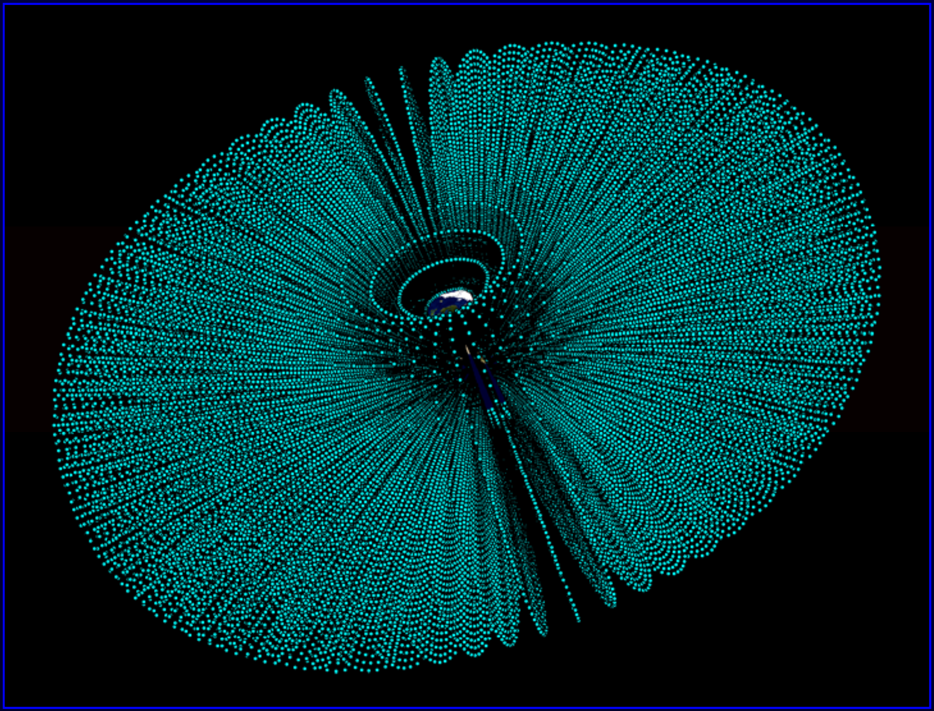
Results – Ring Current and Dst



- Contribution to ring current by H+ and O+ for 3 times: early storm (14:00 UT), observed Dst peak (17:00 UT), early recovery (23:00 UT)
- RAM-SCB underpredicts the total ring current energy (and Dst)
    - Dst obtained with Dessler-Parker-Sckopke (DPS) formula from energy density inside geosynchronous orbit only
    - Magnetotail current contribution (up to 50% e.g. *Ganushkina et al., [2004]*) not included

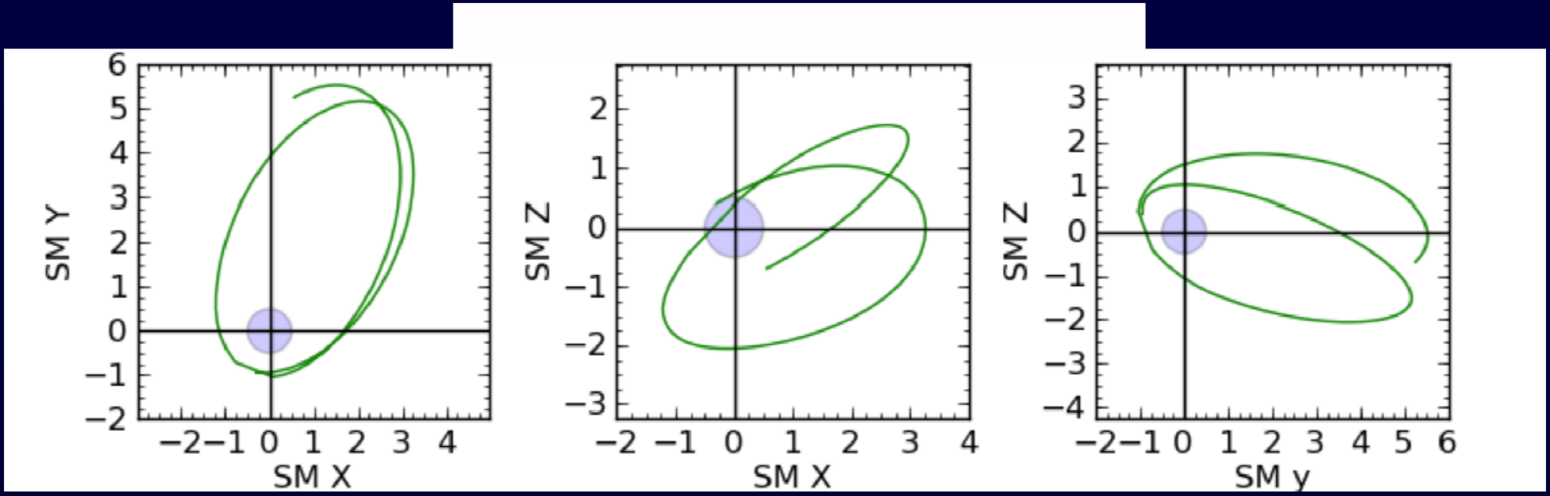
Results at Virtual Spacecraft Locations

- Output from RAM-SCB – inside irregular 3-D cloud
  - Post-processing needed for output at each location of interest



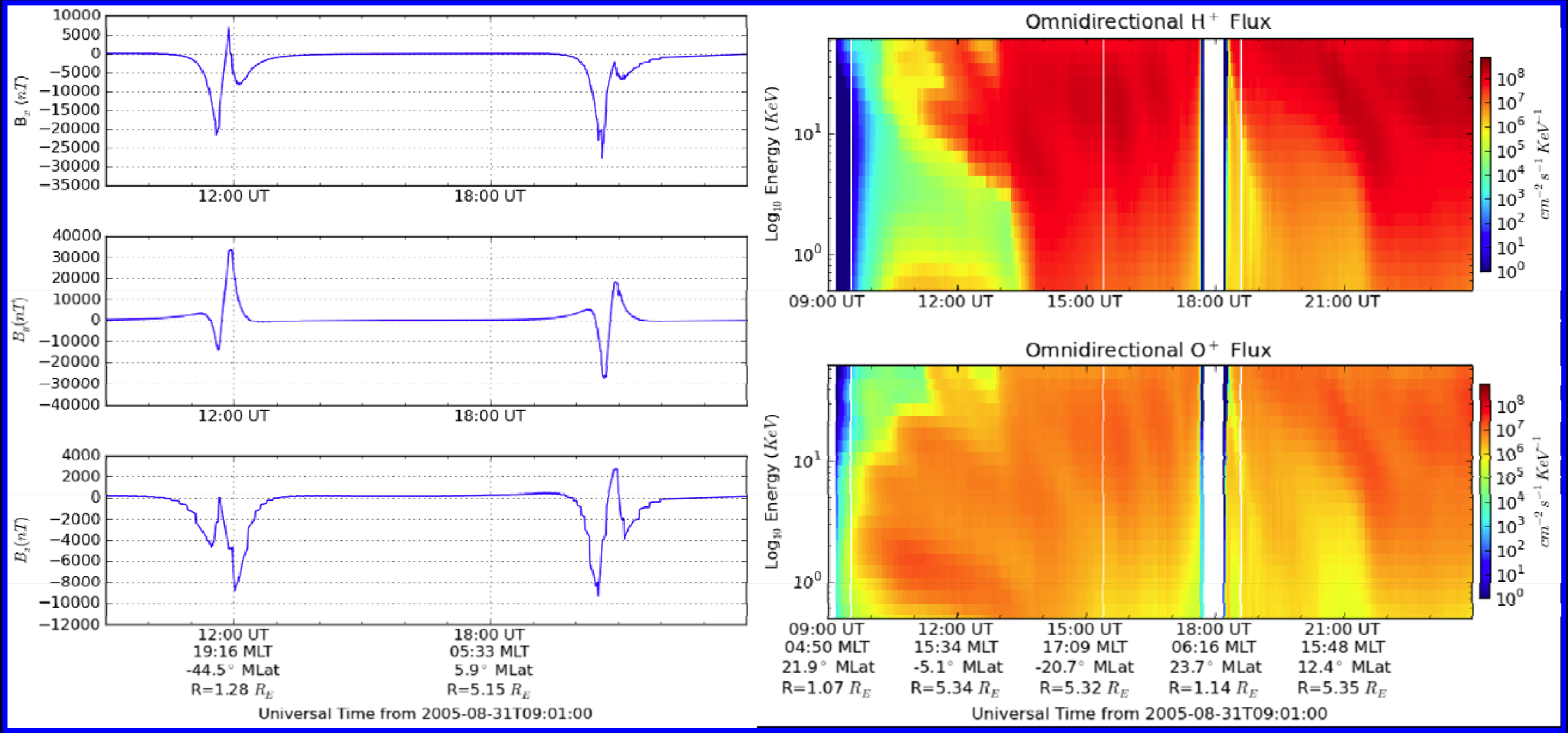
- Or: “fly” spacecraft in the simulation, obtain output at satellite location directly:
  1. For each point on satellite orbit, find grid nearest neighbors by k-d tree (octree) search method *[Kennel, 2004]*
  2. Interpolate (distance-weighted) among a set number of nearest neighbors
  3. For particle flux, use Liouville’s theorem to map distribution function from SM equatorial plane to all locations within 3-D domain

Results: RBSP Virtual Spacecraft



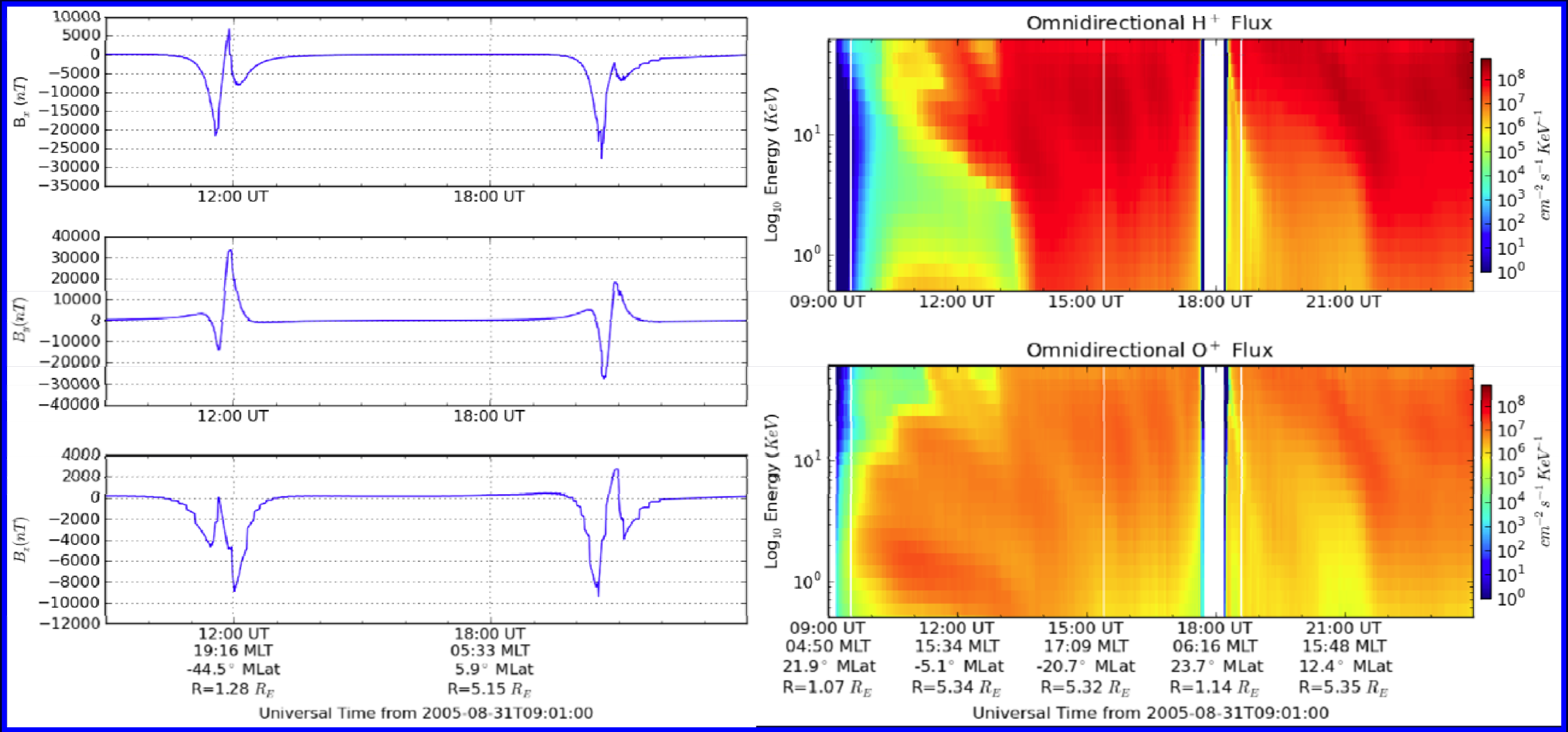
- Radiation Belt Storm Probes (RBSP)
  - slated to launch in 2012
  - 2-spacecraft mission will examine the radiation belts in-depth, including waves, magnetic and electric fields, and plasmas of ring current energies
- RBSP satellites included to examine what they would observe had they been in orbit for this event; using a portion of their early mission orbits
  - RBSP 1 spends most of the storm main phase in the noon/dusk quadrant; RBSP 2 lags behind slightly

Results: Spacecraft-Specific (1)



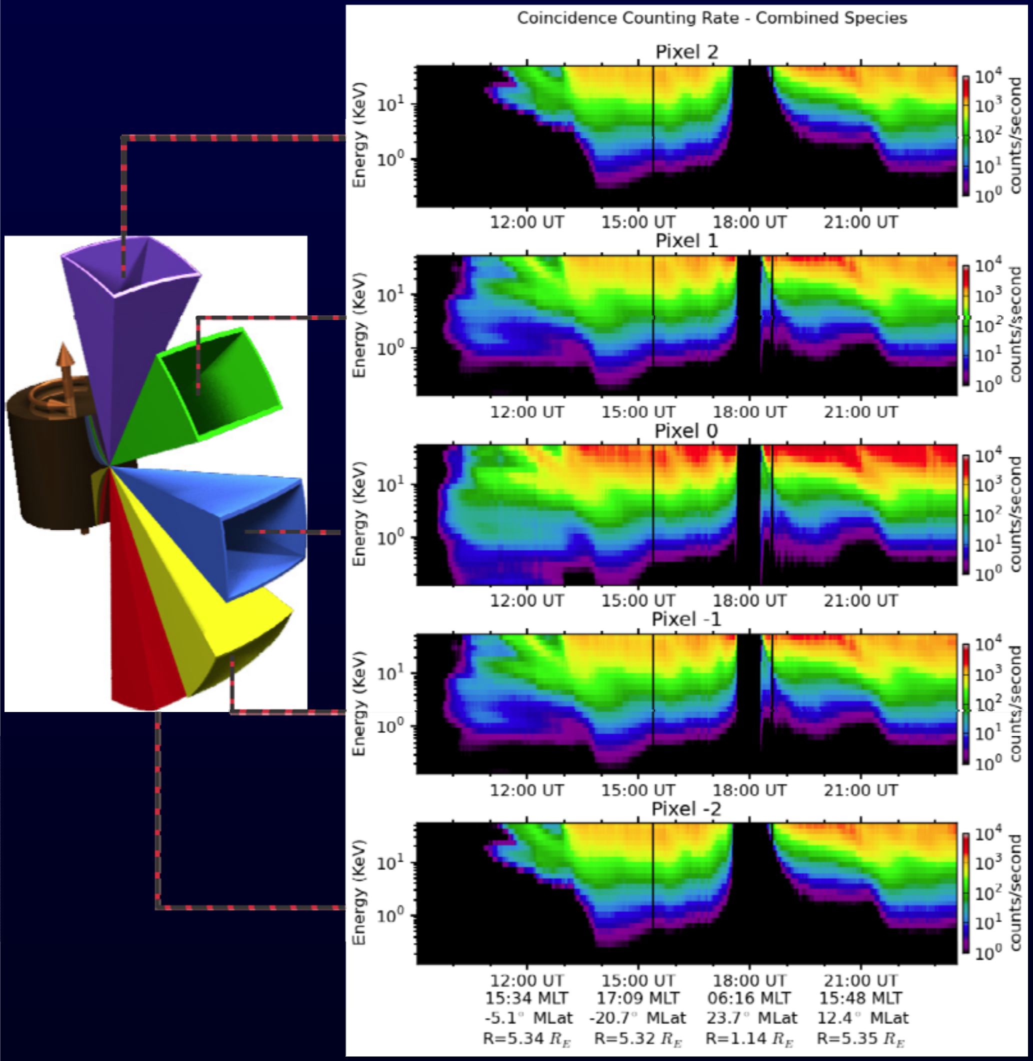
- Magnetic field at RBSP 1 on left
- Fields are obtained at spacecraft location by interpolating from 8 nearest neighbor grid points to satellite location

Results: Spacecraft-Specific (2)



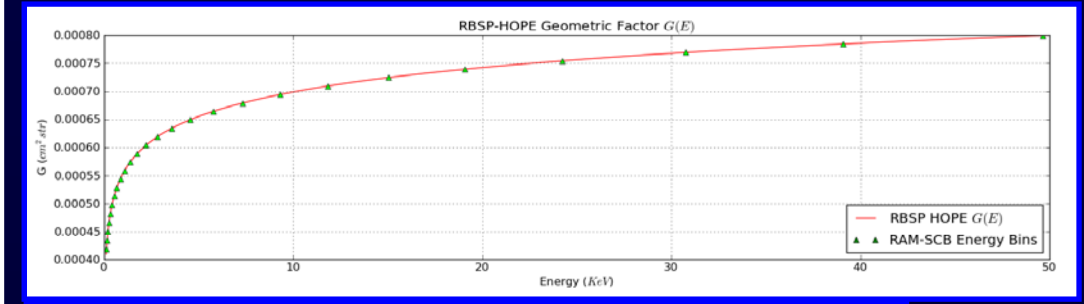
- Omnidirectional flux for H+ and O+ at RBSP 1 for RAM energies (100 eV to 500 KeV)
- Results “drop out” (e.g. 17:30 UT) when satellite leaves the simulation domain or when the grid nearest neighbors are beyond a set threshold

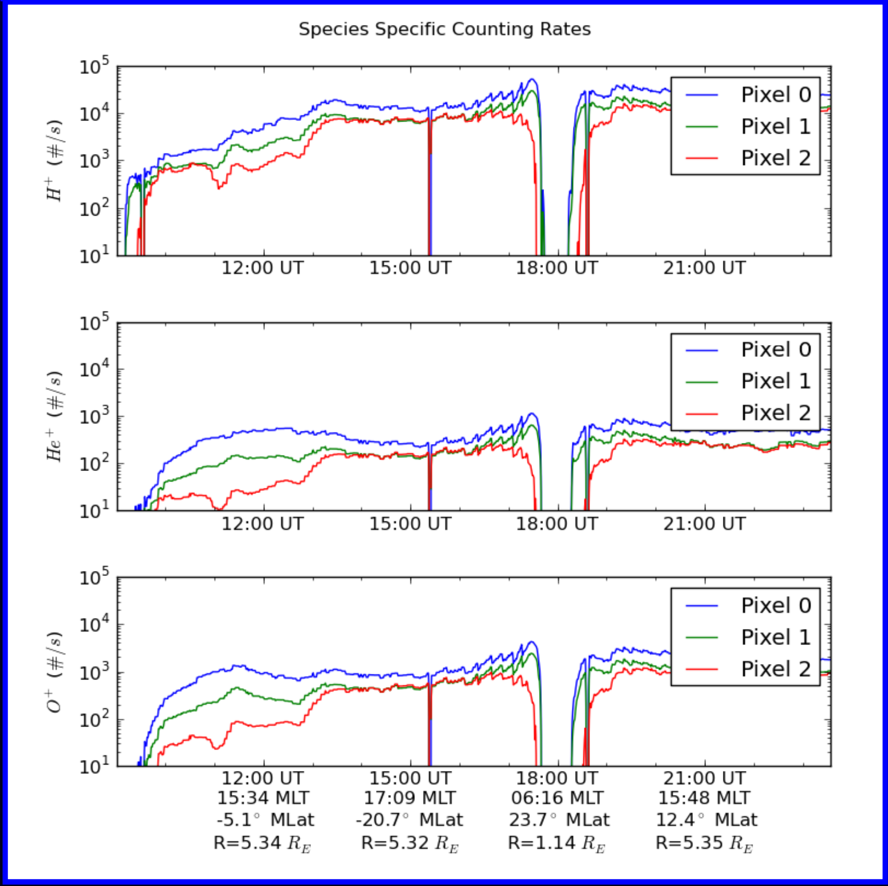
Results: Instrument-Specific, Combined Species



- Helium, Oxygen, Proton, Electron (HOPE) instrument on RBSP:
  - ions/e- from 1 eV to 50 KeV
  - 5 separate polar pixels
- Coincidence counting rates from directional flux: C=J*G*dE
  - J = directional flux
  - G = geometric factor
  - dE = width of energy bin
- RAM-SCB virtual satellite ➔ count rates for each pixel

Results: Instrument & Species-specific





- Spacecraft spin axis assumed parallel to local B
- RAM-SCB is gyrotropic
  ➔ results spin averaged
- RAM-SCB symmetric about 90º pitch angle
  ➔ pixels +/- 1 and 2 equivalent

Summary

- Motivation: To quantify space environment output at specific spacecraft from numerical space weather model
- Tool: RAM-SCB physics-based self-consistent inner magnetosphere model: kinetic model + 3D force balance code
- Results:
  - Proof of principle: technique of "flying" virtual satellites in RAM-SCB successfully developed/used to generate high-res. results along spacecraft orbit (RBSP)
  - Satellite-specific simulation results used to create instrument-specific count rates/virtual spectrograms
  - Method applied to the RBSP HOPE instrument to create a mock-up of low-level data products

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Virtual Satellites in Numerical Models

- “Virtual” satellites – powerful method to tie observations and simulations together

- Use of virtual satellites - many research and applications possibilities:
  - Obtain ambient space environment for spacecraft charging models
  - Perform one-to-one model-observation comparisons
  - Complement existing observations with virtual set not bound by instrument restrictions
  - Plan for future missions with data product mock-ups/observation predictions
  - Monitor spacecraft-specific environmental conditions with real-time simulations

Future Plans

- Model improvements:
  - Expand boundary to 9 or 10 R_E (to obtain geosynchronous model output)
  - Include electrons to RAM-SCB simulation
  - Develop real-time version and validate/determine performance vs. input parameters
- Virtual satellite technique improvements:
  - Allow B-field and spacecraft spin axis to be non-parallel
  - Use geometric factors that vary in look angle and across the detector
  - Expand the number of instruments simulated
- Use model environment output in spacecraft charging code (e.g. NASCAP-2K)