# Inner Magnetosphere Modeling with RAM-SCB

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***Aims:***

Develop a comprehensive model of the inner magnetosphere that will include:

- A **kinetic ring current /radiation belt model** coupled with a 3-D force balance model that calculates self-consistently the magnetic field and inductive electric field
- An **MHD model** coupled to an ionospheric model that calculates self-consistently the convection electric field
- Simulate stormtime ring current dynamics and assess the effect of non-dipolar magnetic field and the feedback of **self-consistently computed magnetic field**

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# Magnetically Self-consistent Model (RAM-SCB)

Ring current-atmosphere interactions model (RAM)
[Jordanova et al., 1994, 2006]

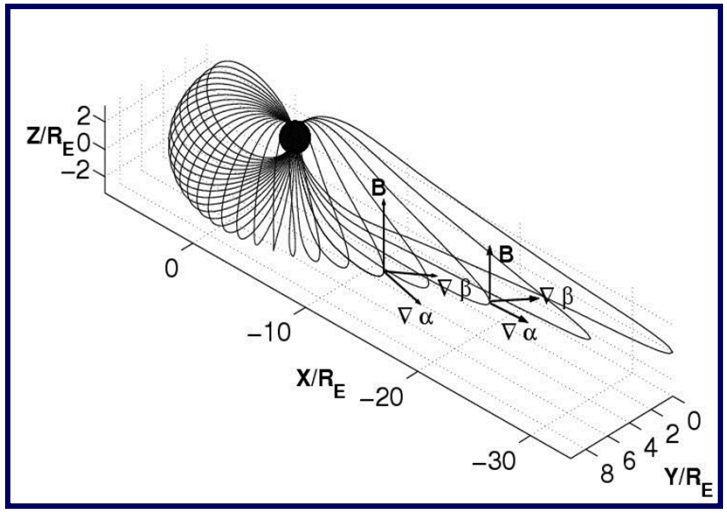
- Bounce-avg. Boltzmann equation for $H^+$, $O^+$, and $He^+$ ions and electrons
- Including all major loss processes & radial diffusion
- Convection/corotation E-field (empirical)
- Updated to general B field
- Coupled with a plasmasphere model

Pressure →

← B-field

3D equilibrium code
[Cheng, 1995; Zaharia et al., 2004]

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




- Euler potentials (flux coordinates)
- Empirical B-field BCs

# Model Development: Self-Consistent Magnetic Field (RAM-SCB)

- Gradient-curvature and electric drift velocities:

$$\langle \vec{v}_{GC} \rangle = \frac{2p}{q\tau_B B_o} \nabla_o I \times \vec{e}_o ; \quad I = \int_s^{s'} \sqrt{1 - \frac{B(s)}{B_m}}\, ds \; ; \qquad \langle \vec{v}_{conv} \rangle = \frac{\vec{E}_o \times \vec{B}_o}{B_o^2}$$

- Hydrogen Density:

$$\langle H_{DENS} \rangle = \frac{1}{4 R_0 h(\mu_0)} \oint \frac{N_H(s)}{\sqrt{1 - \frac{B(s)}{B_m}}}\, ds \qquad \text{where} \qquad h(\mu_0) = \frac{1}{2R_0} \int_s^{s'} \frac{1}{\sqrt{1 - \frac{B(s)}{B_m}}}\, ds$$

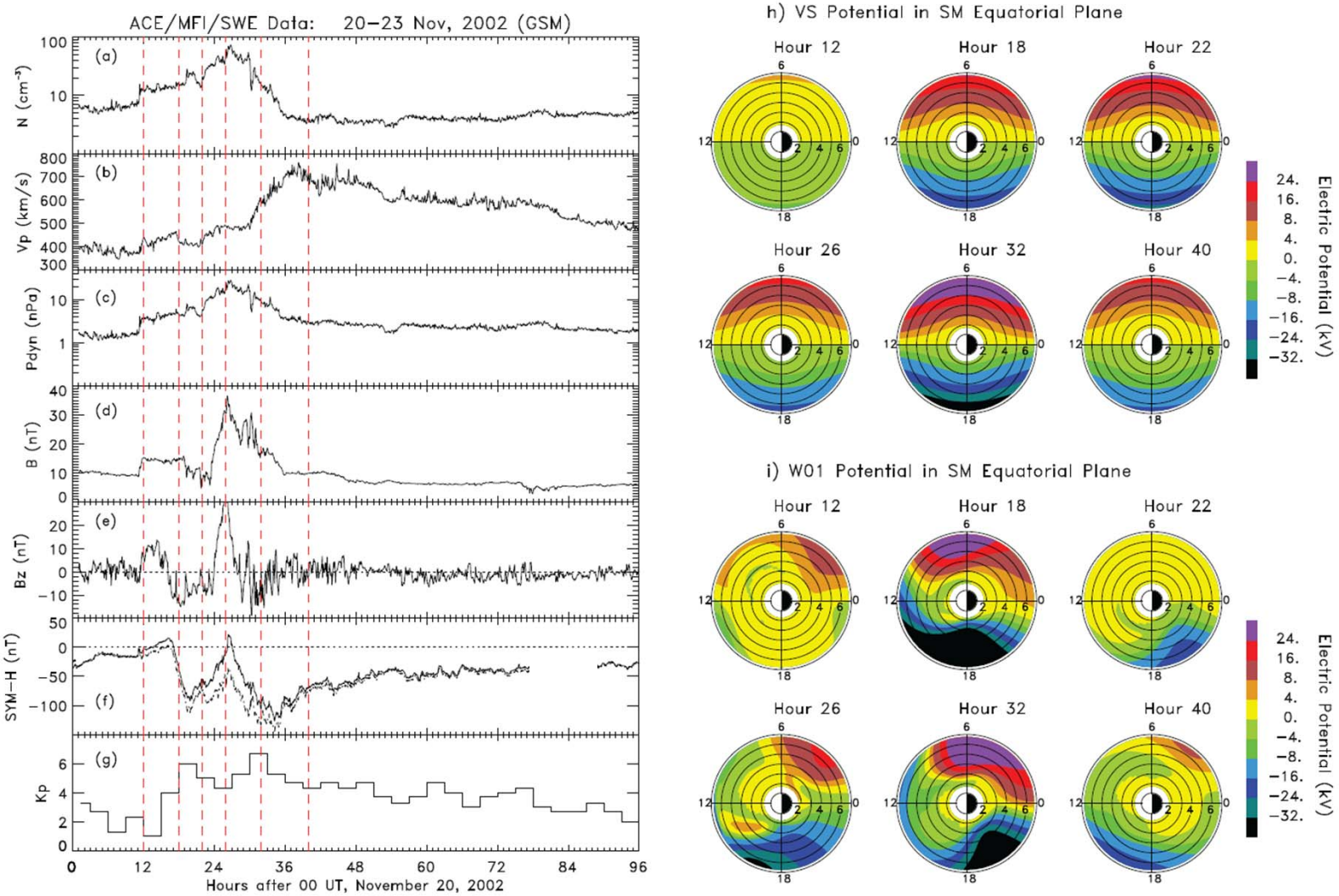
- Self-consistently calculated magnetic field in force balance with anisotropic plasma pressures from RAM:

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

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

where $\mathbf{B} = \nabla\alpha \times \nabla\beta$, $\sigma = 1 + (P_\perp - P_{||})/B^2$ and $\alpha$ and $\beta$ are the Euler potentials

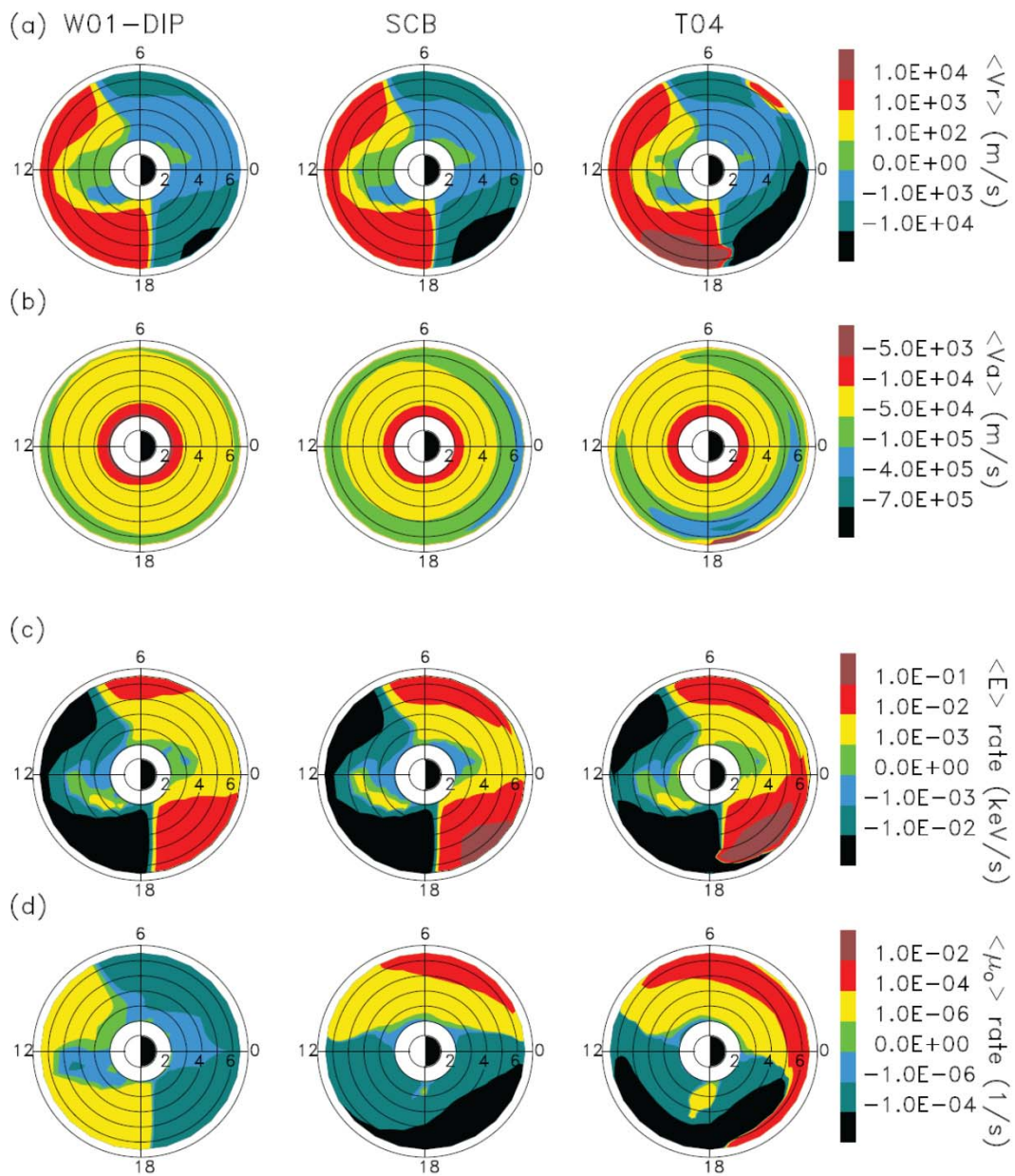
# November 2002 Storm:
# IP Conditions, Geomagnetic Indices & Electric Potential



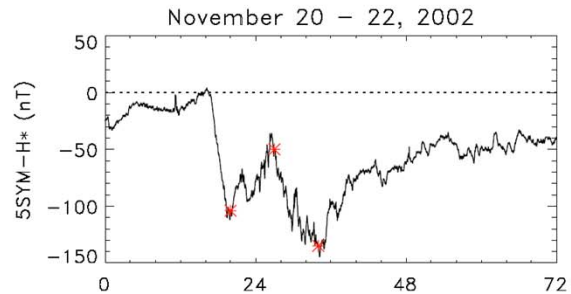

- Double-dip geomagnetic storm with *Dst*~-85 nT at hour 21 and *Dst*~-130 nT at hour 35
- Strong enhancement of convection potentials during storm main phase

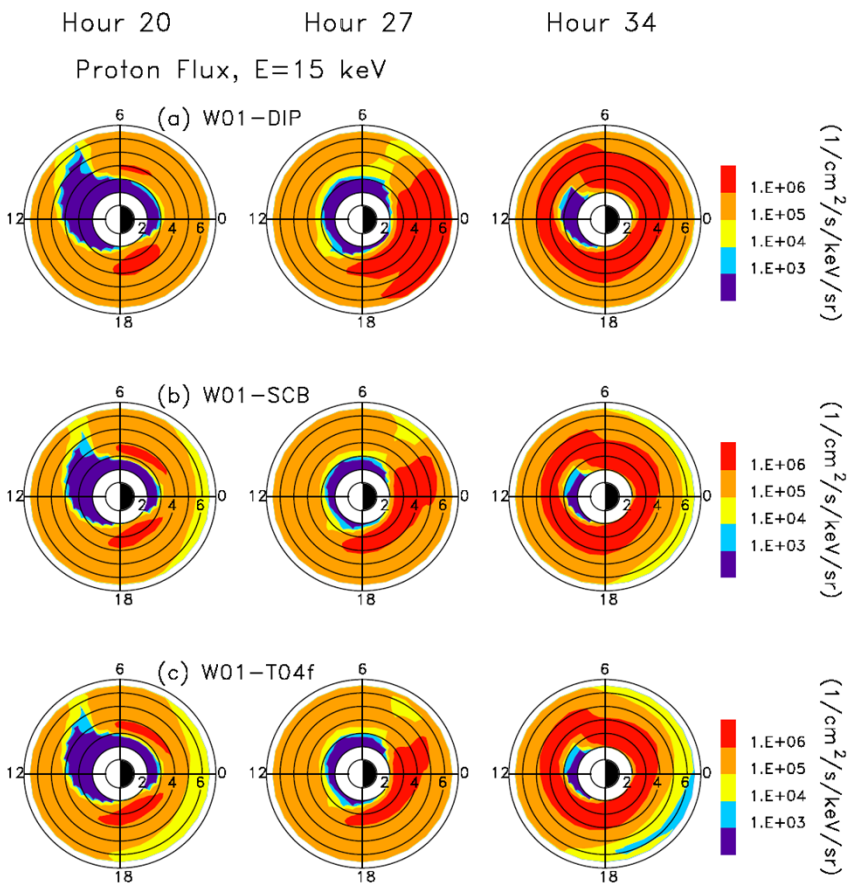
# November 2002 Storm: Bounce-averaged Rates of Change

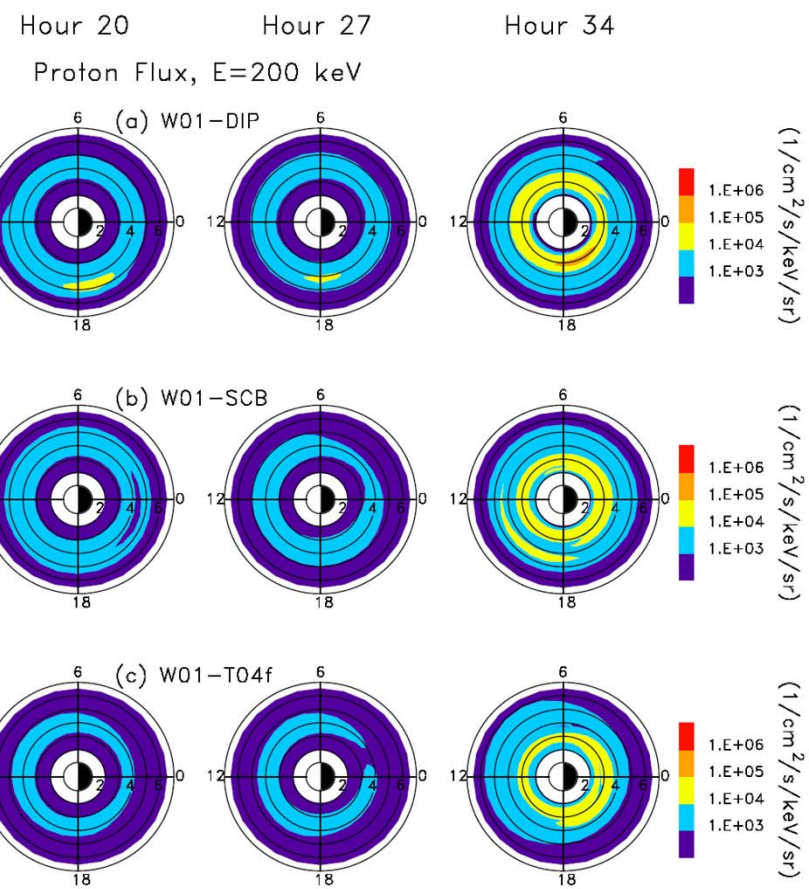
- Rates in the **dipole, SCB,** and **T04** magnetic field in the SM equatorial plane for E=100 keV and PA=45º ions
- The bounce-averaged **radial** & **azimuthal velocities**, **energy** & **pitch angle rates** increase at *L*>4 on the dusk-midnight side in the non-dipole case
- Lead to faster westward ion drifts, larger acceleration, and drift shell-splitting in a non-dipolar B field



# Ring Current $H^+$ Flux: Main Phase



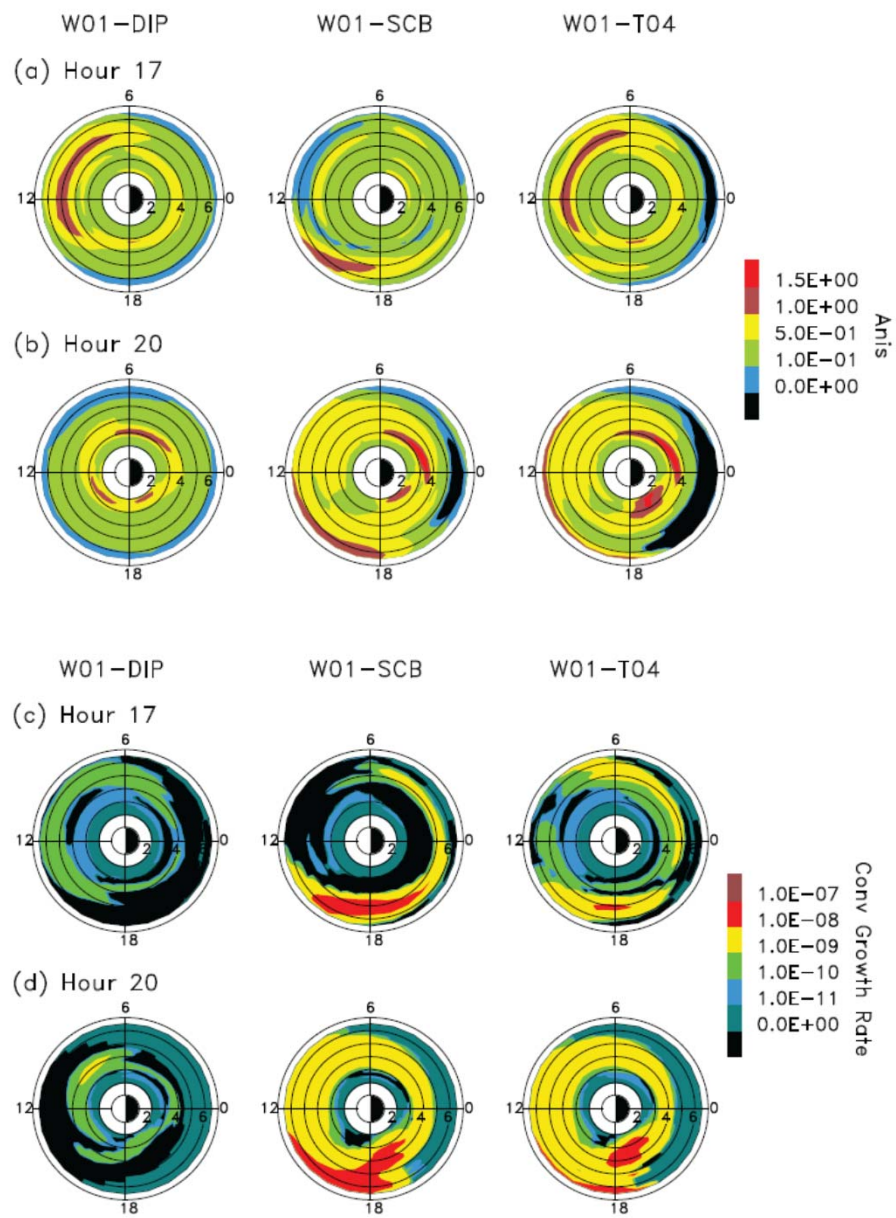



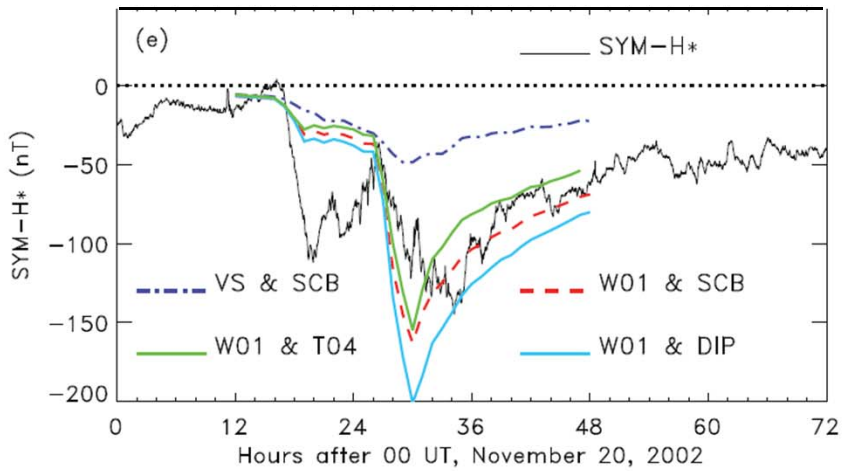

- Initial ring current injection from midnight proceeding towards dayside as the storm develops
- Largest fluxes are obtained with dipole B field; weakest with T04S model
- The **drift shell splitting** is seen when non-dipole B-field is used

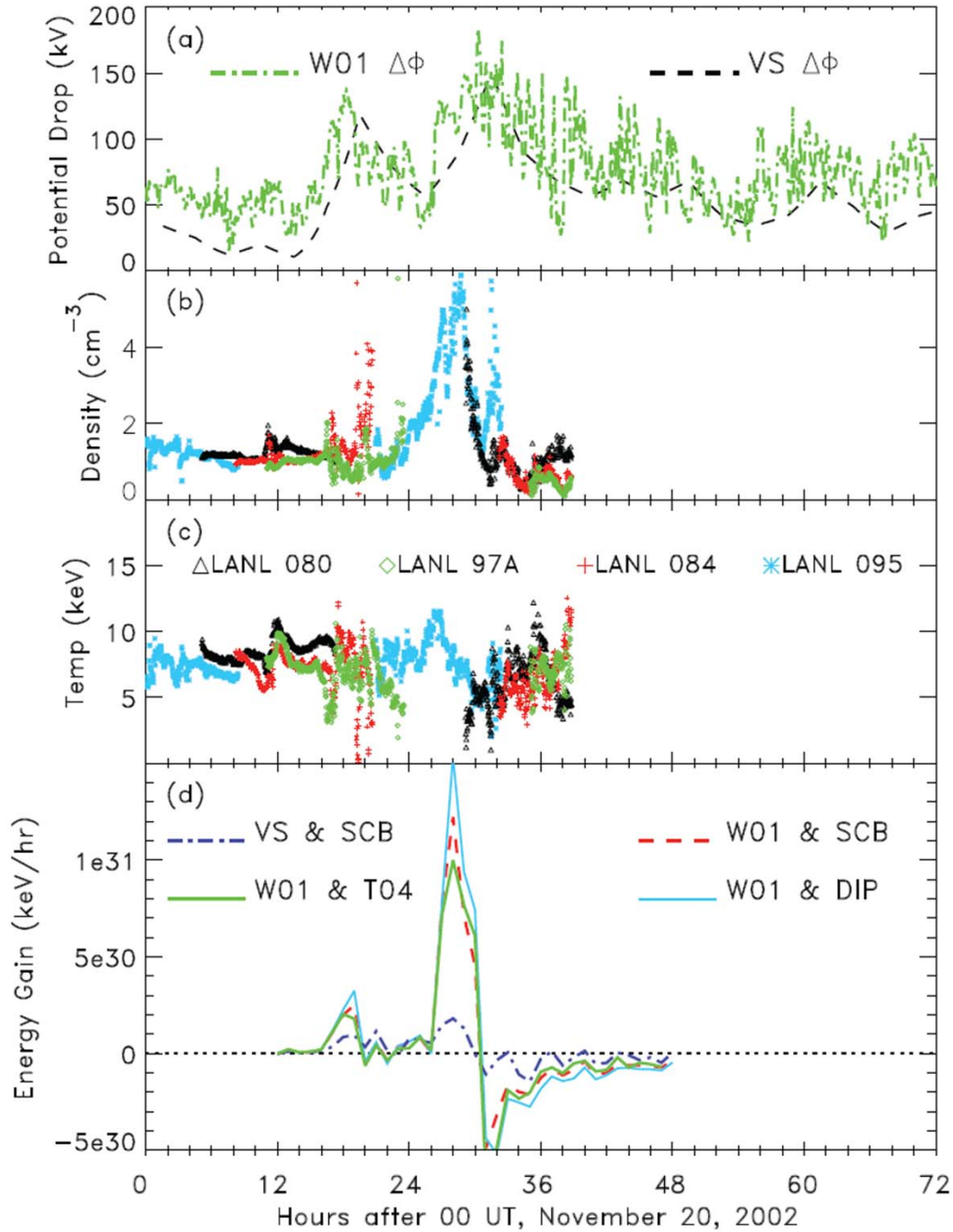
# Ring Current $H^+$ Anisotropy and EMIC Wave Growth

- Considering only charge exchange and loss to atmosphere, no wave-particle interactions
- Initially positive anisotropy occurs at lower L~5 shells on the dayside
- During the main phase large positive anisotropy develops at L>6 on the dayside or near the plasmapause using non-dipolar B field; negative anisotropy on the nightside
- The positive anisotropy causes the excitation of intense EMIC waves in the non-dipolar case



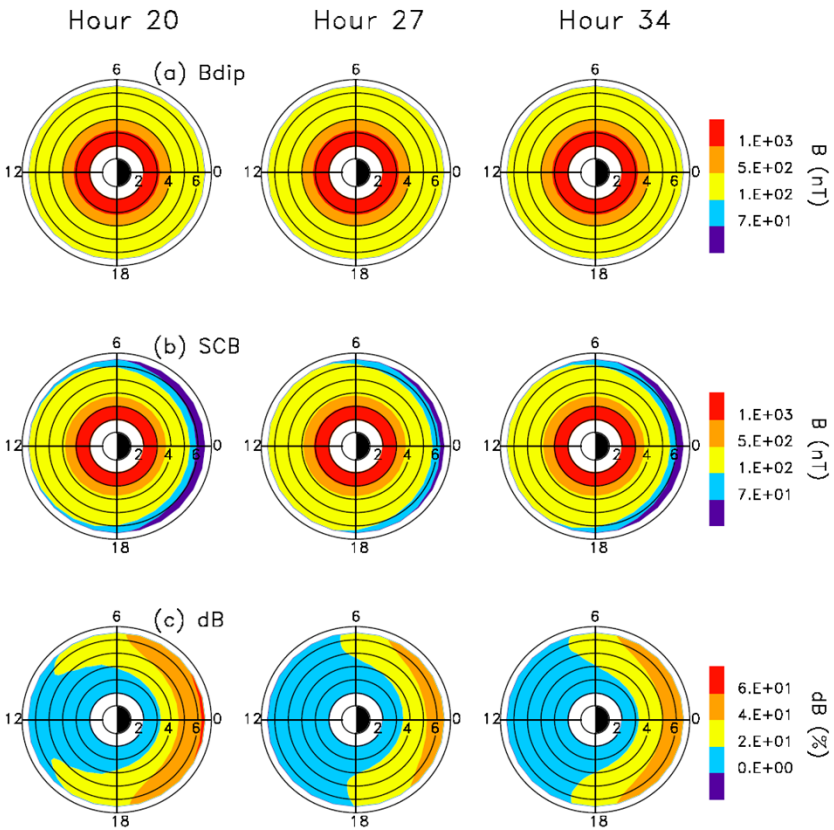
# Ring Current Development and Dst Index

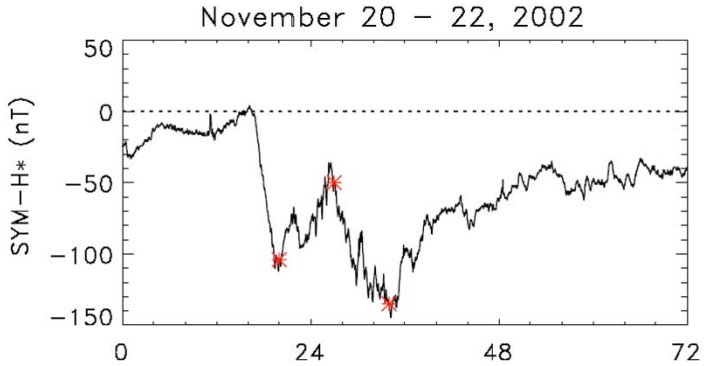


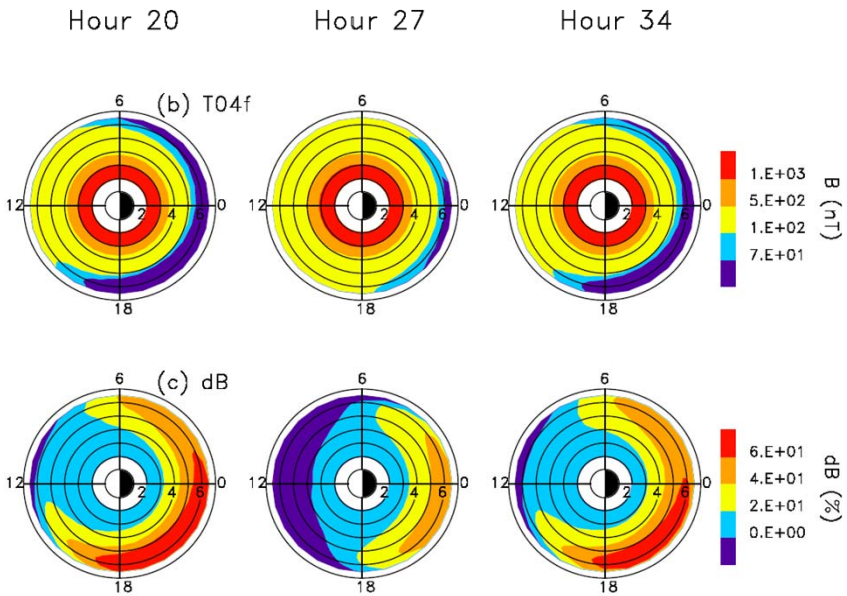




The calculated **ring current injection & Dst** using T04 or self-consistent B field is **smaller** reflecting the big stretching of the magnetic field during disturbed times

# Magnetic Field Comparisons




Large magnetic field depressions occur on the nightside during disturbed times when self-consistent B field and T04S models are used

# Induced Electric Fields

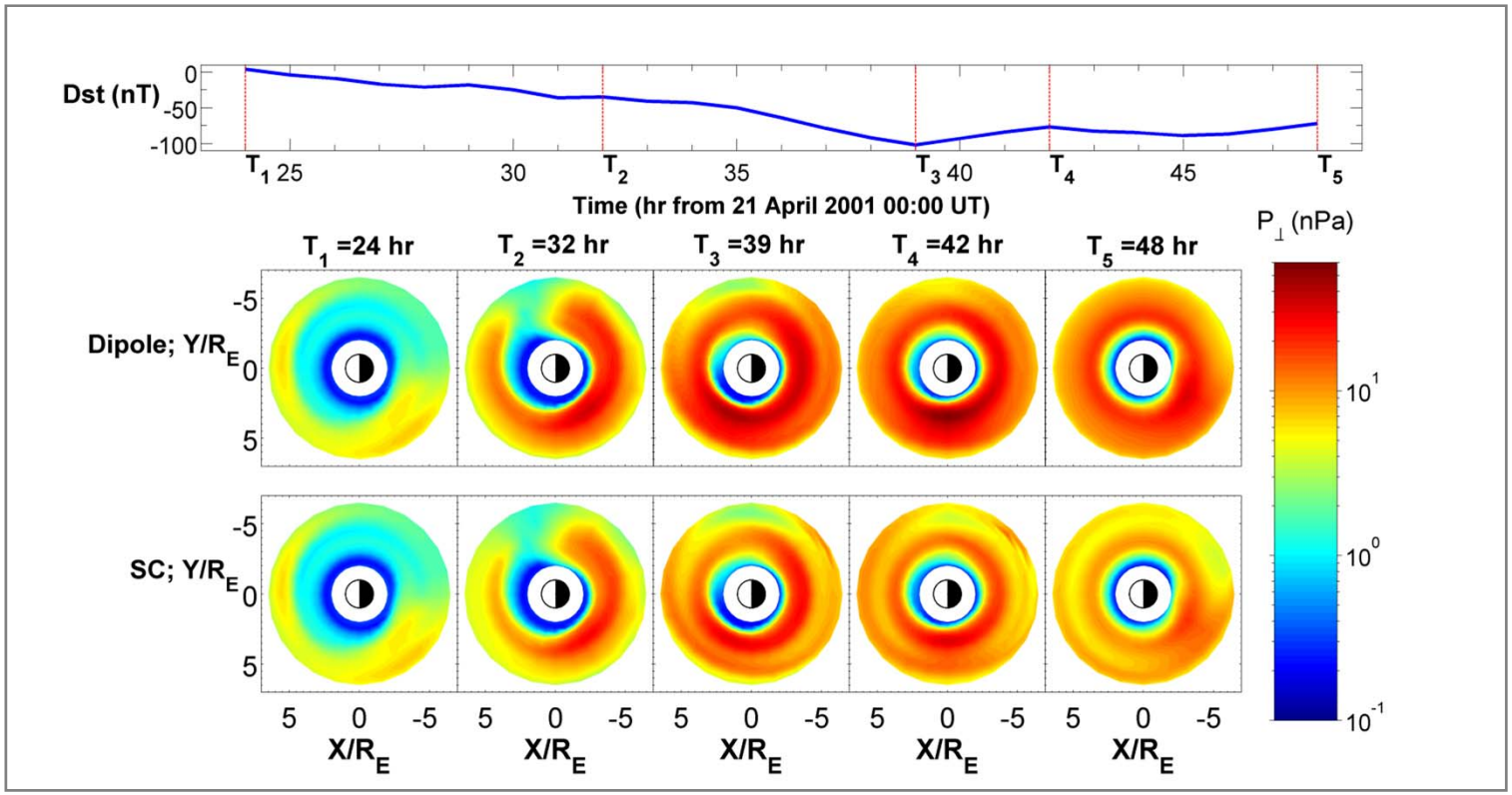
- RAM-SCB - magnetically self-consistent
- RAM - fixed grid - **E-fields induced by B changes** need to be considered
- Calculating E-fields **in 3-D code (SCB)** - Euler potential formulation
  - total field (e.g. Schindler and Birn, [1978]; Hesse et al., [1997]):

$$\mathbf{E} = -\frac{\partial \alpha}{\partial t}\nabla\beta + \frac{\partial \beta}{\partial t}\nabla\alpha - \nabla\psi$$

  - ionospheric potential $\psi \equiv \Phi$ (**neglecting $E_{||}$** and assuming **no ionospheric "field slippage"** on time scale of significant B value change)
  - much easier than integrating Faraday's law in Cartesian coordinates: B-field in "integrated" form (Euler potentials)

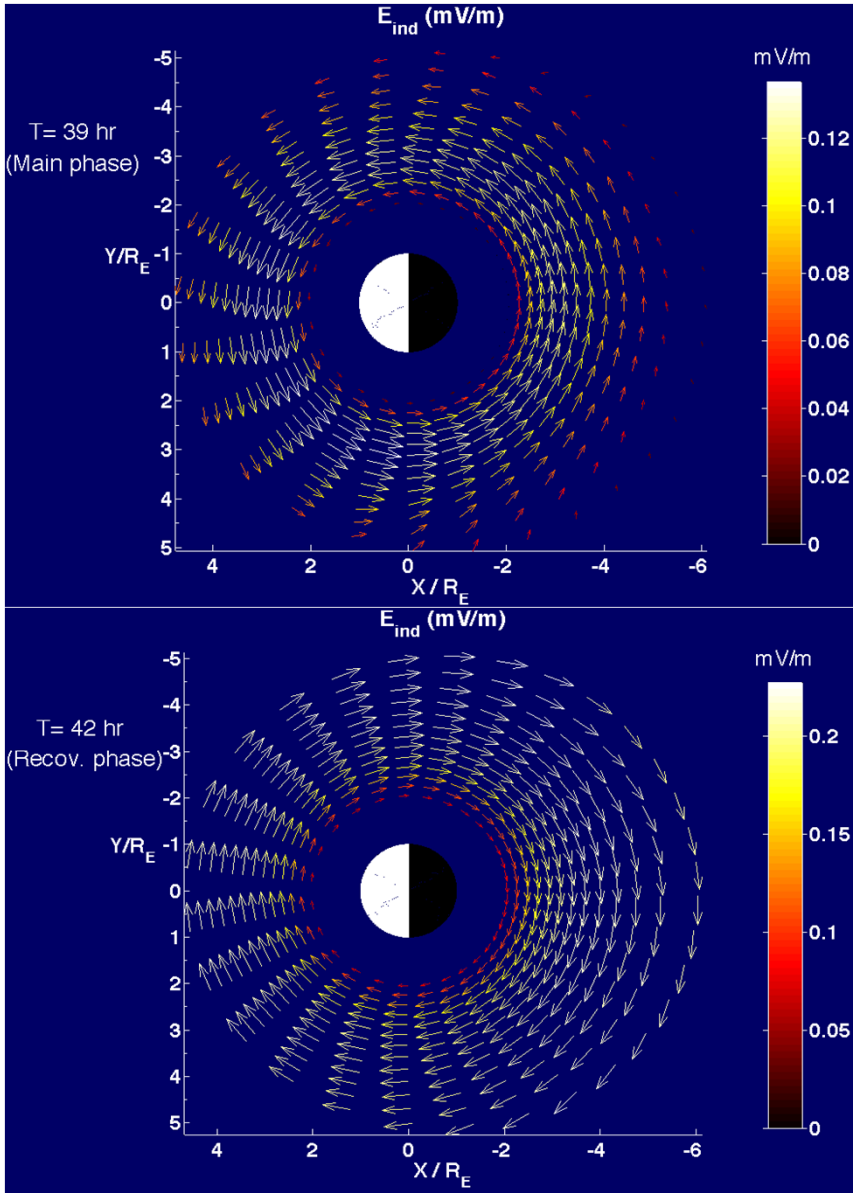
- Are the storm-time induced E-fields important? (vs. convective fields)

# April 21, 2001 Storm Simulation




- Largest pressure at dusk-premidnight in storm main phase
- Self-consistent (SC) pressure is lower vs. RAM dipolar run (30 nPa max. vs. 60 nPa)
- Fine SC structure: local gradients, double peaks; larger pressure farther away

# Induced E - Main Phase vs. Recovery




- Main phase ➔ field line stretching = flux decrease on night side
- Dusk sector - (weakly) oppose convection field
- **$E_{ind}$ depends on magnetic flux boundary change** ($Kp_{38}$= 5.2; $Kp_{39}$= 5.7)
- **$E_{ind}$** x **B will drive particles away from Earth - adiabatic effect**

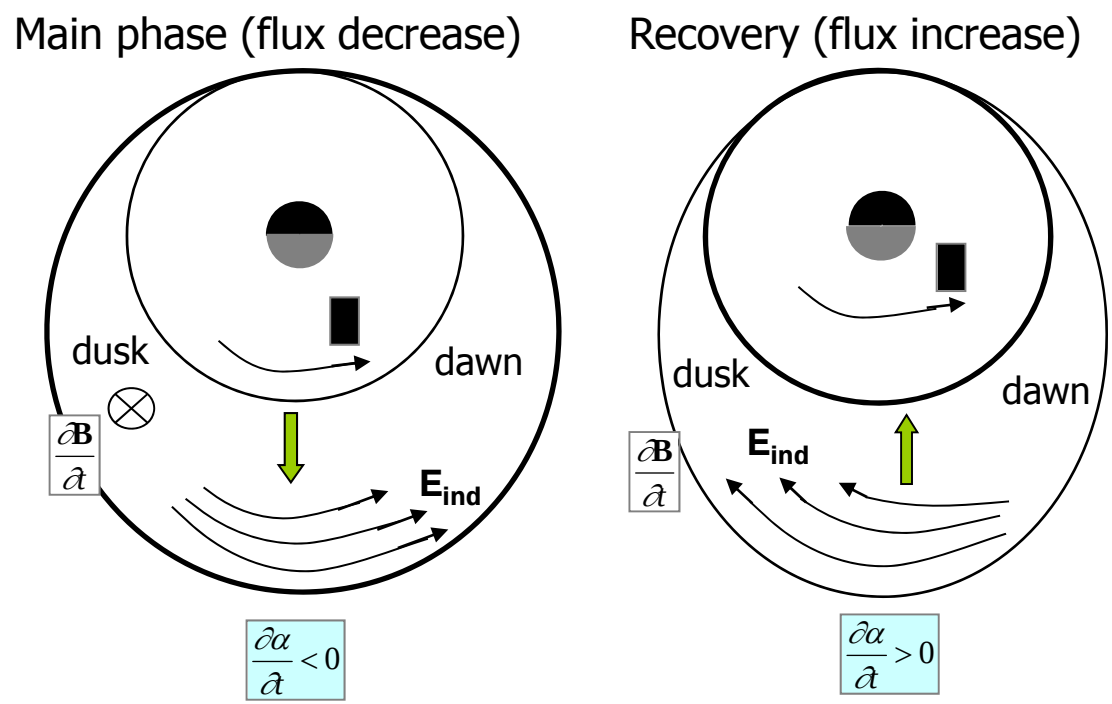
- Recovery phase ➔ less stretching = flux increase on night side
- $Kp_{41}$ = 6; $Kp_{42}$ = 5.5
- Field compression ➔ **$E_{ind}$** x **B will drive particles Earthward**

# Lenz's Law - Magnetic Flux Change

$$\mathbf{E}_{ind} \cdot \nabla \alpha \approx 0$$

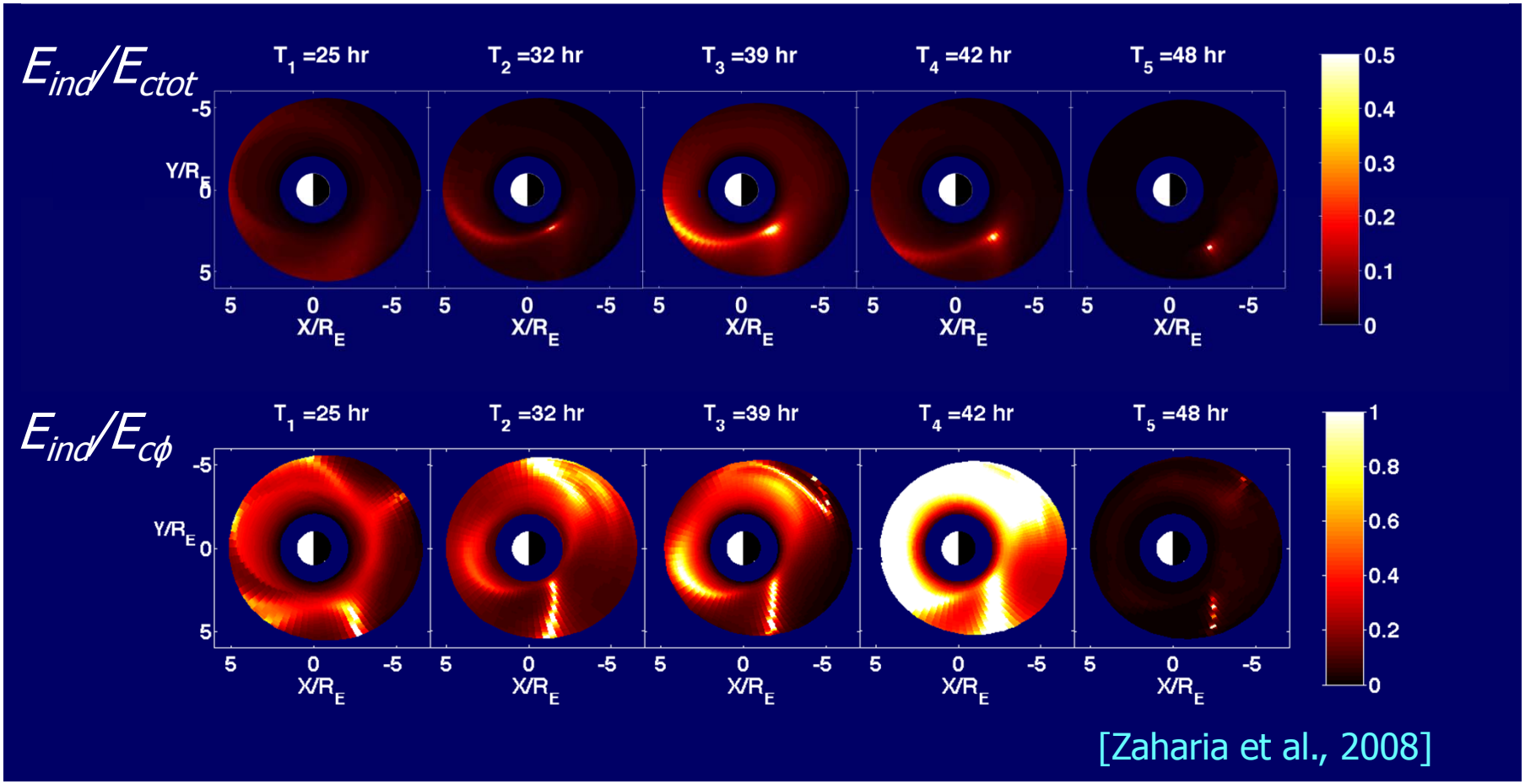
$$\mathbf{E}_{ind} \cdot \nabla \beta \approx -\frac{\partial \alpha}{\partial t} |\nabla \beta|^2$$

$$\mathbf{E}_{ind} \cdot \nabla \theta = 0$$



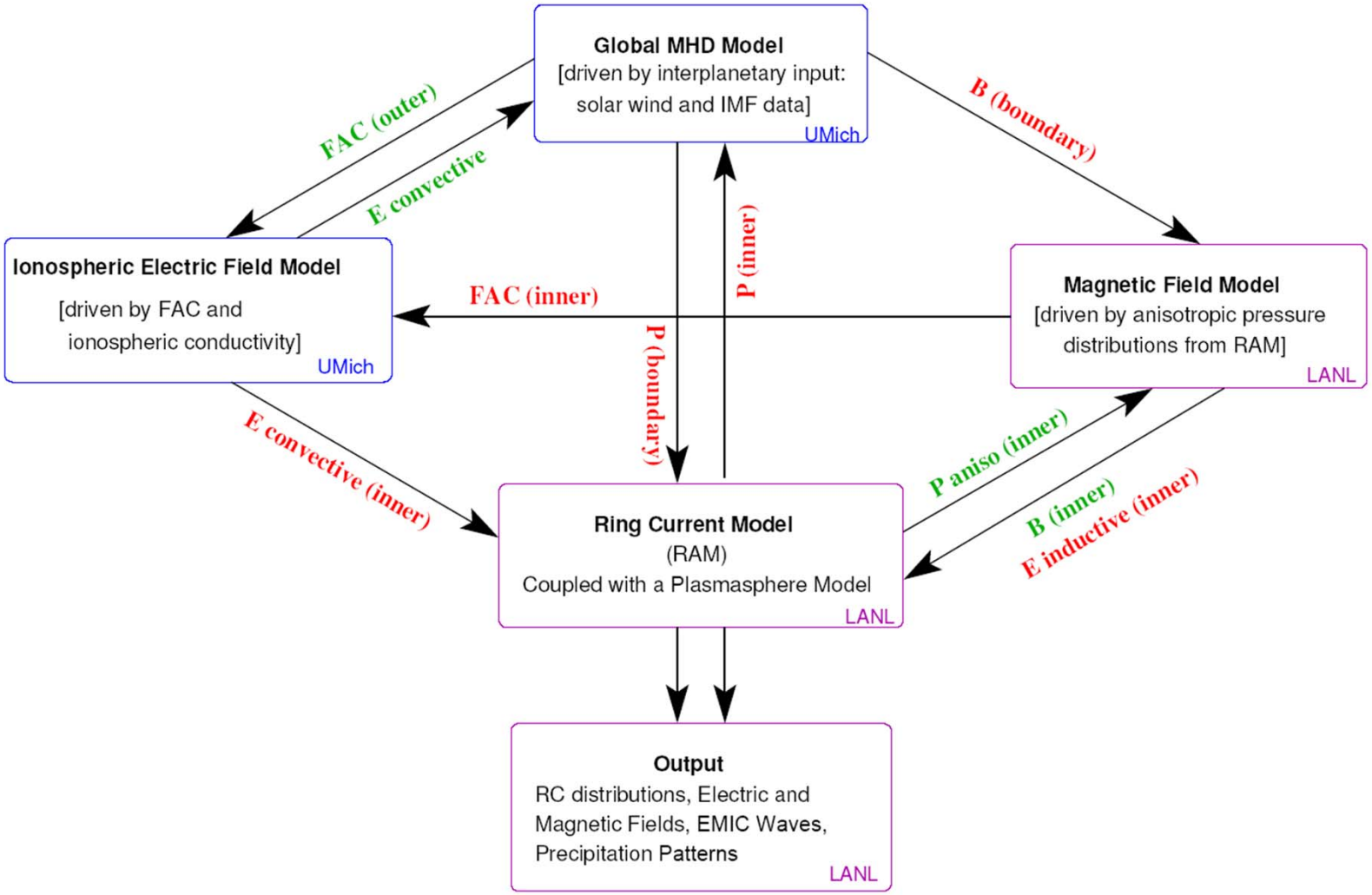

- Neglect radial $E_{ind}$; only azimuthal $E_{ind}$
- Decrease of magnetic flux (main phase) ➔ eastward inductive E; **opposite to convective E**
- Increase of flux (recovery phase) ➔ westward inductive E; same direction as convective E
- Effect: **(slightly) less energization during main phase; more during recovery phase; changed radial transport due to ExB drift**

# Induced vs. Convection/Corotation E




- Obtained from **magnetically SC April 2001 storm simulation** (1-hour coupling)
- Comparison with $E_c$ = Weimer01 (convective) + corotation fields
- Main phase/recovery: small 0.2 mV/m (vs. $E_c$ ~ 1.5 mV/m) ~1/7 $E_{cM}$
- Can dominate azimuthal component of $E_c$ ➔ change radial transport **E** x **B**

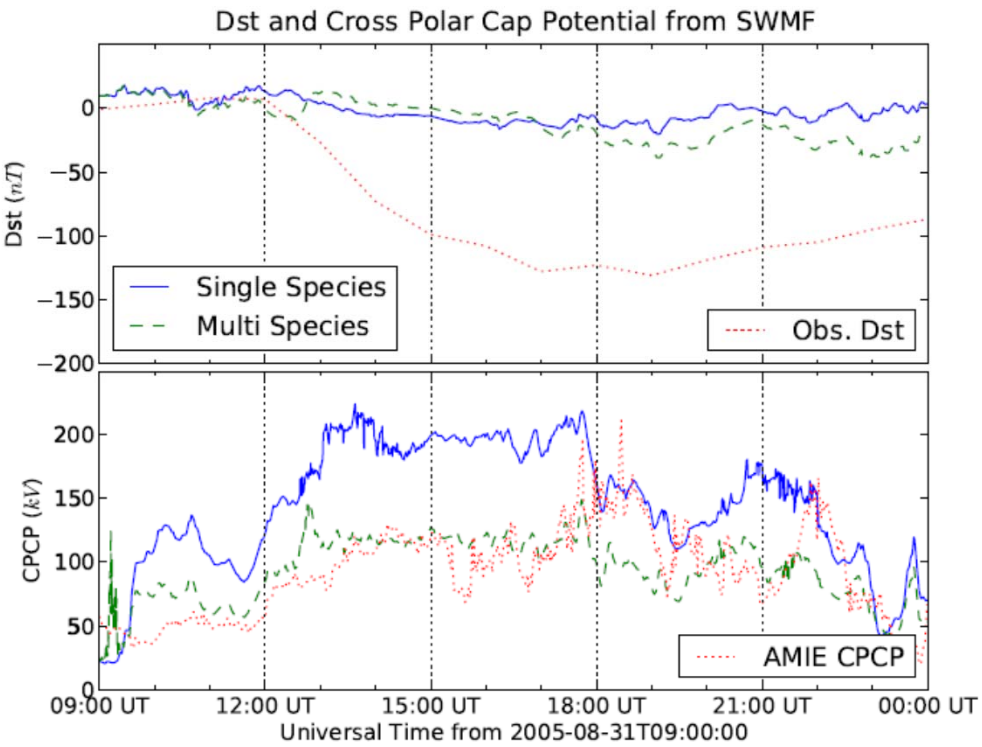
# Coupling of RAM-SCB with SWMF/BATSRUS Model

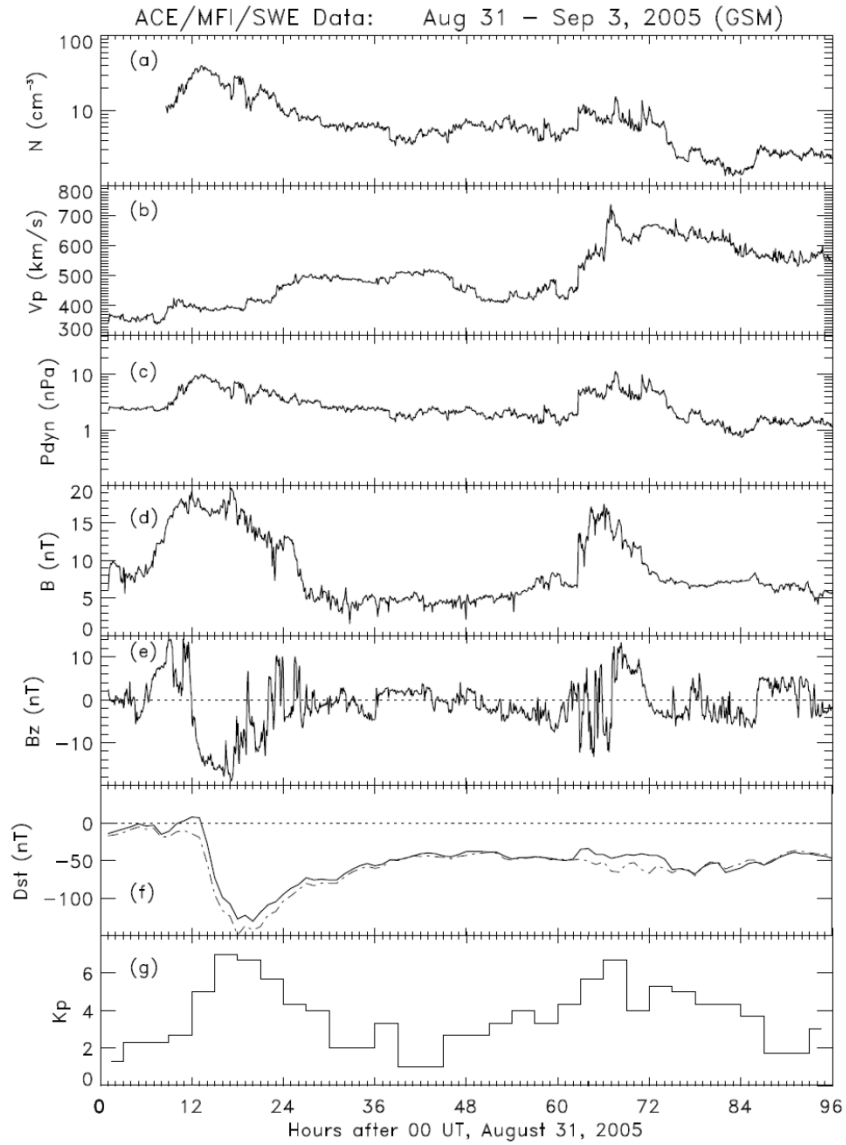



Modules in our comprehensive IM model and coupling between them

# SWMF/BATSRUS Simulation: 31 August 2005

- **No coupling with RAM-SCB**

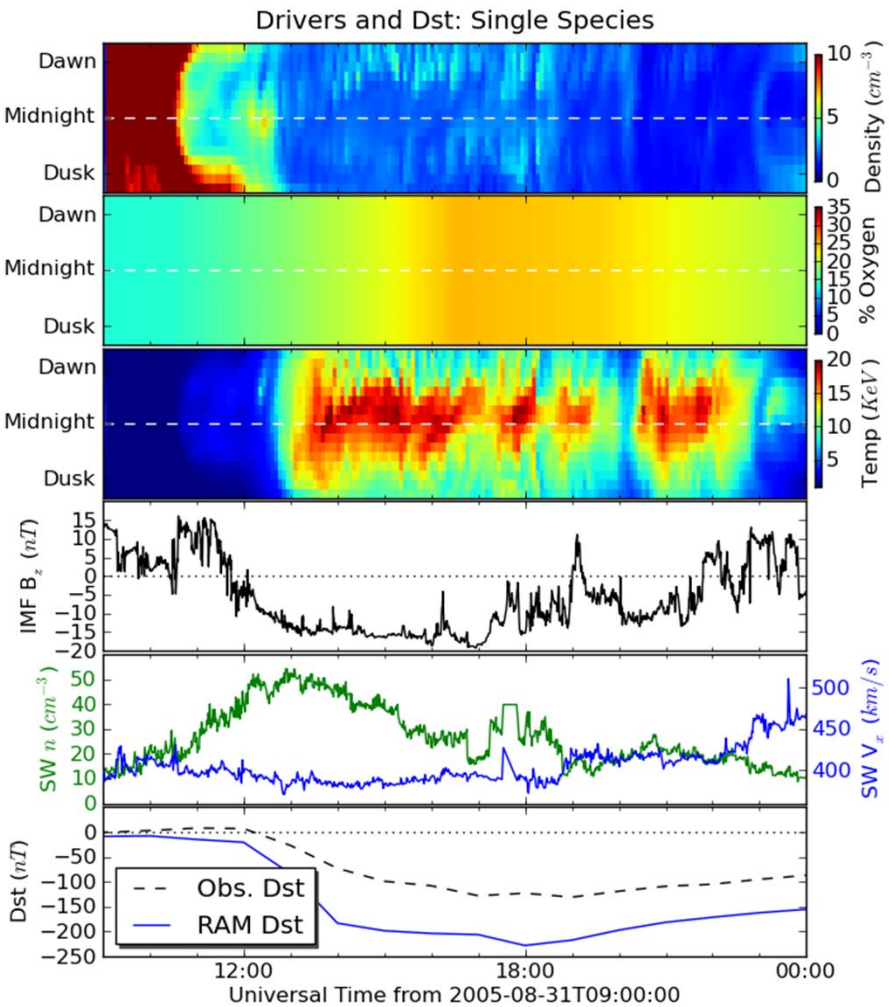


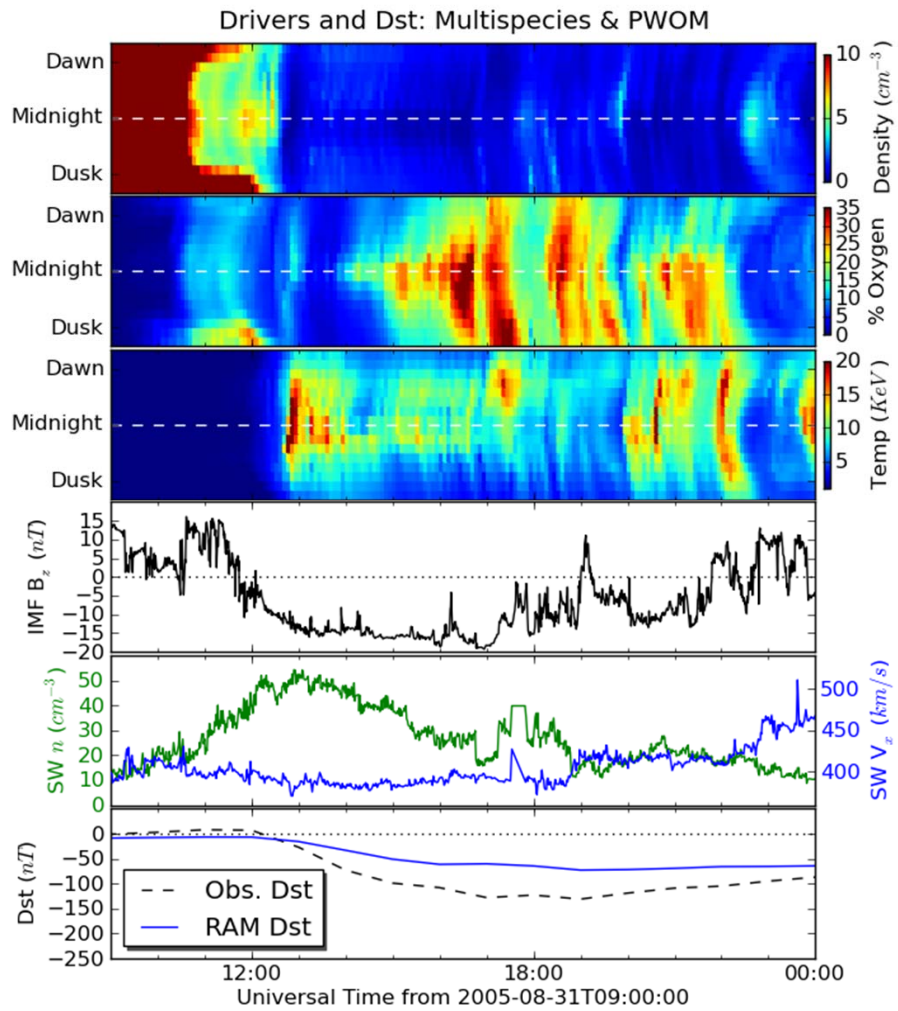

- Large storm selected for study by the LWS TR&T Focus Team on IM plasma storm time redistribution

# One-way Coupling of RAM to SWMF/BATSRUS

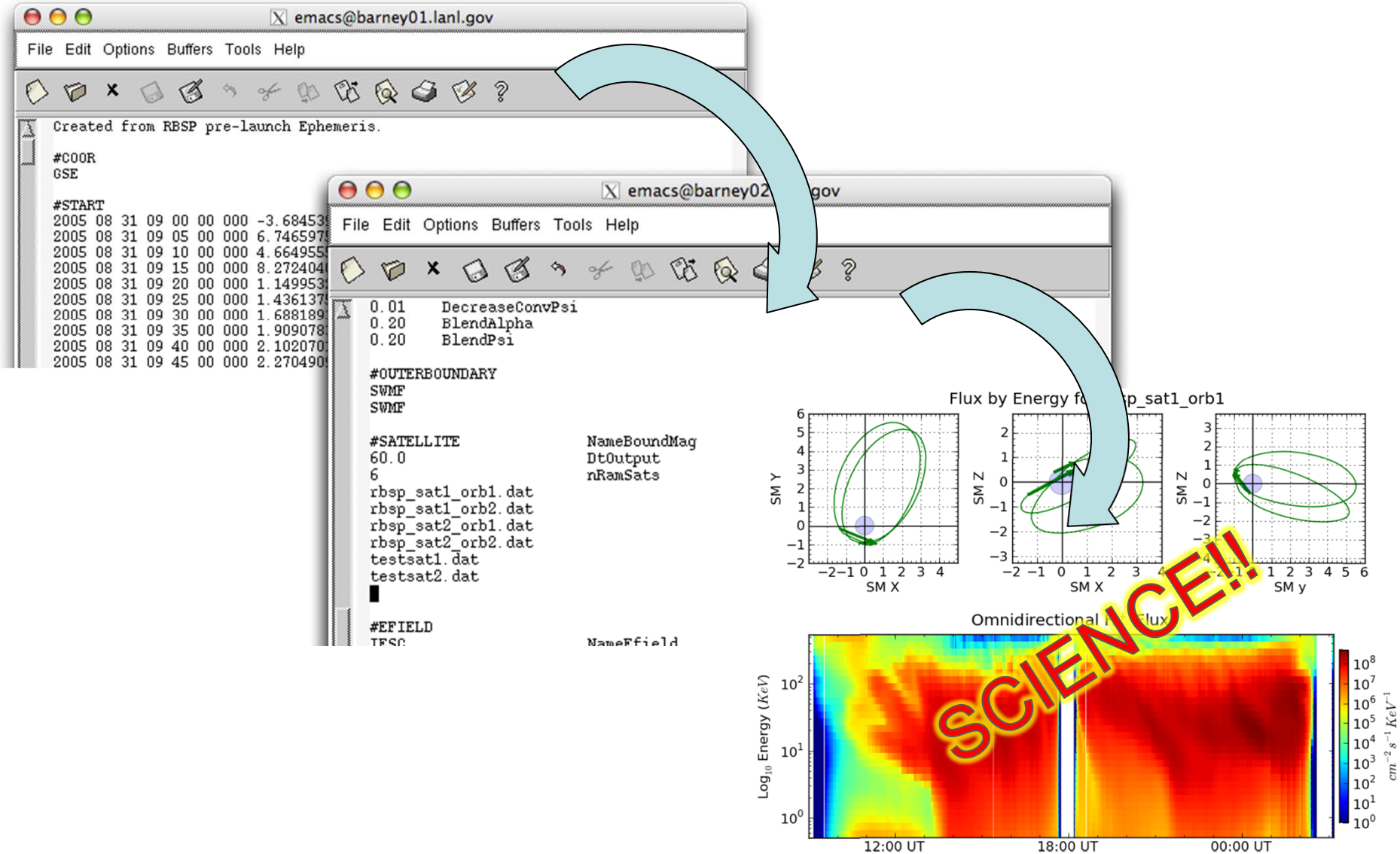
## A) Single Fluid (No PWOM)




## B) Multi Species & PWOM

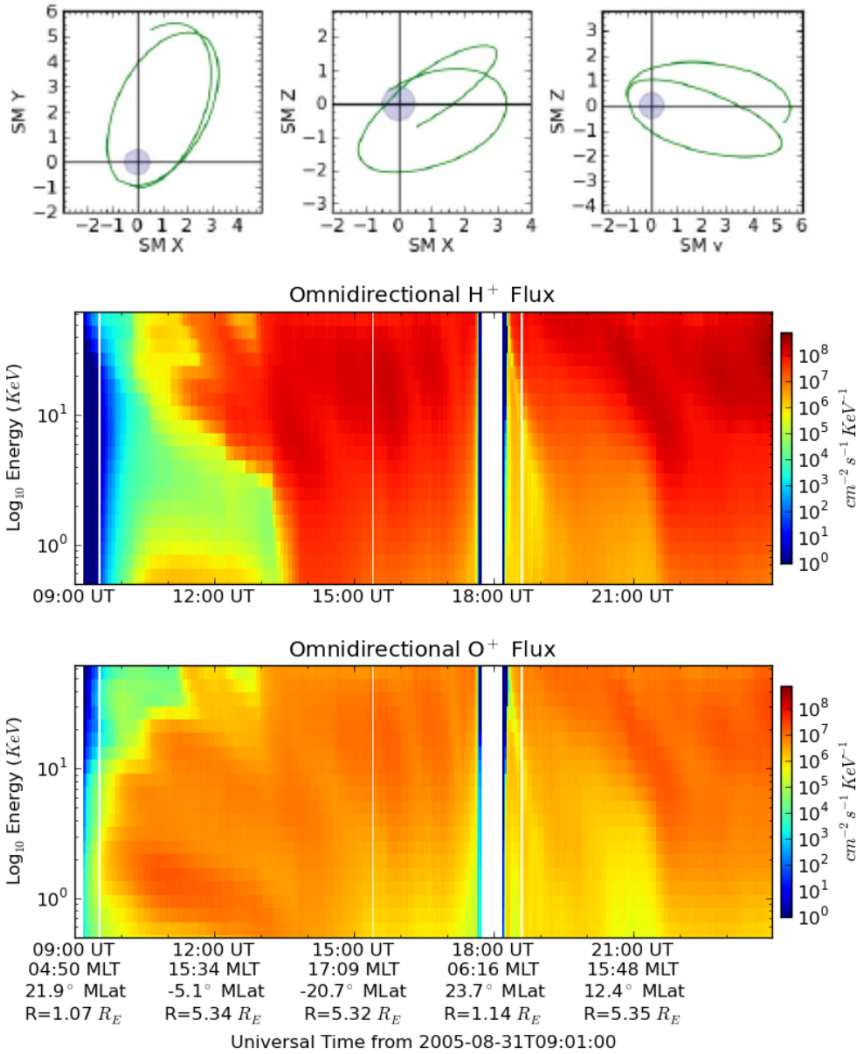


# Virtual Satellites in RAM-SCB: RBSP

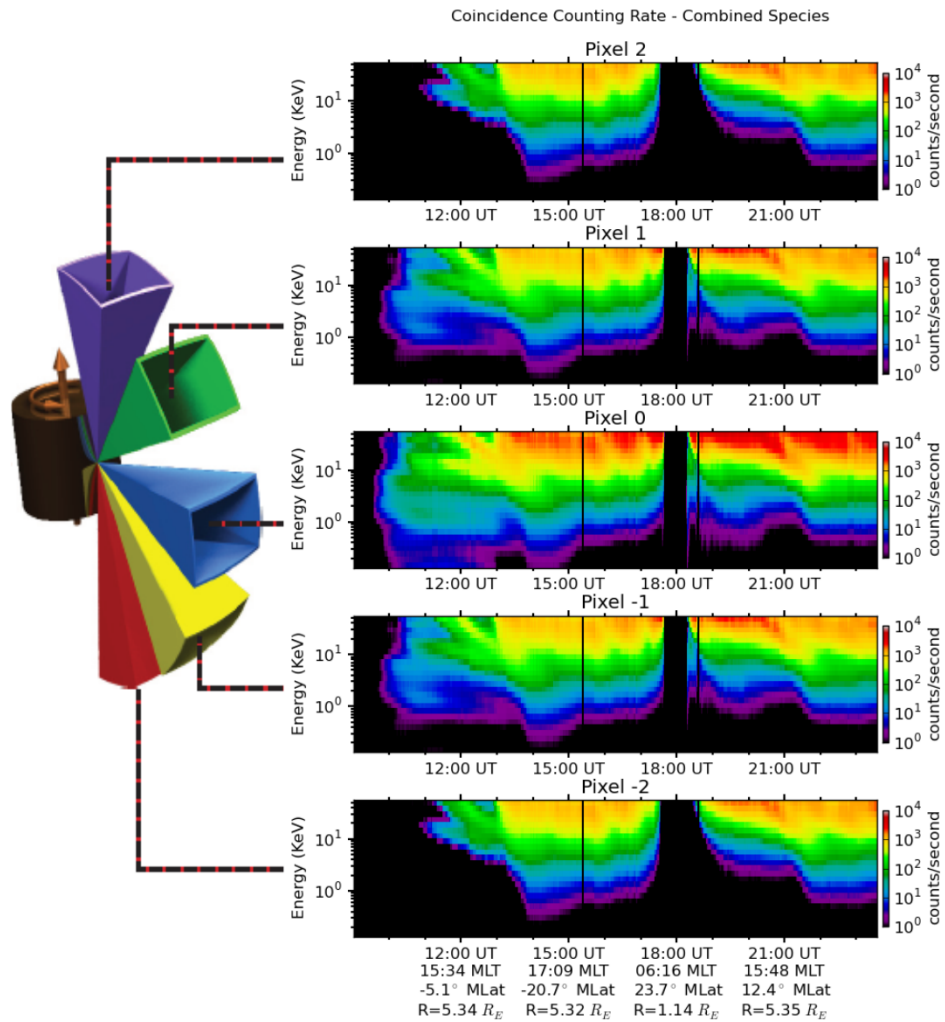


# Virtual Satellites in RAM-SCB: Example

## Fluxes from RAM-SCB along RBSP orbit




## The HOPE instrument on RBSP



# Summary and Conclusions

- Contributions to RBSP science:
  - Simulate the global distributions of both trapped and precipitating ring current ion and electron fluxes
  - Simulate inner magnetospheric magnetic and induced electric fields
  - Simulate global distributions of EMIC, chorus, and magnetosonic waves
  - Investigate how the plasma and fields change during **magnetic storms (temporal & spatial evolution)**
  - Study the effect on the radiation belt dynamics
  - Study the relation to ground-based observations
  - **...**