Inner Magnetospheric Modeling with the Rice Convection Model

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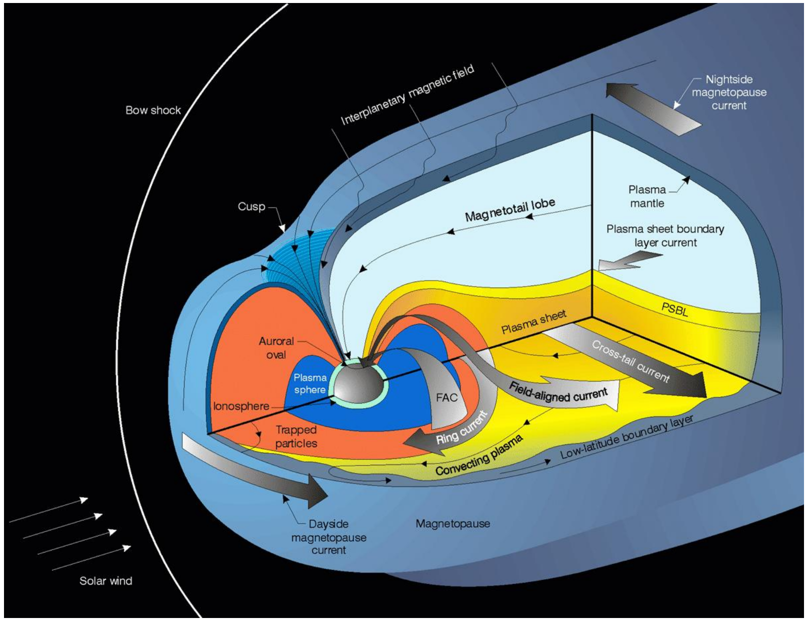
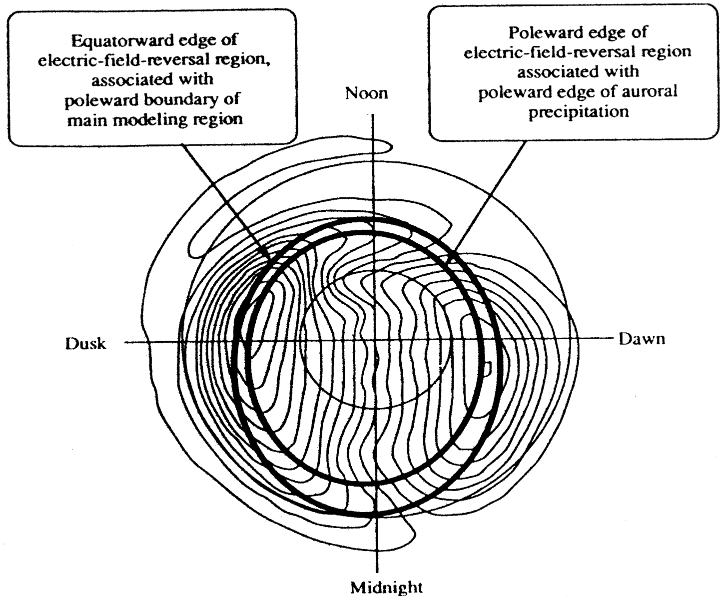
Outline

- Role of entropy and bubbles in ring current injection
- Review and status of models
  - Sample results from the Rice Convection Model (RCM±E)
  - Sample results from the RCM coupled to Global MHD
- Summary and Plans

The Rice Convection Model (RCM)





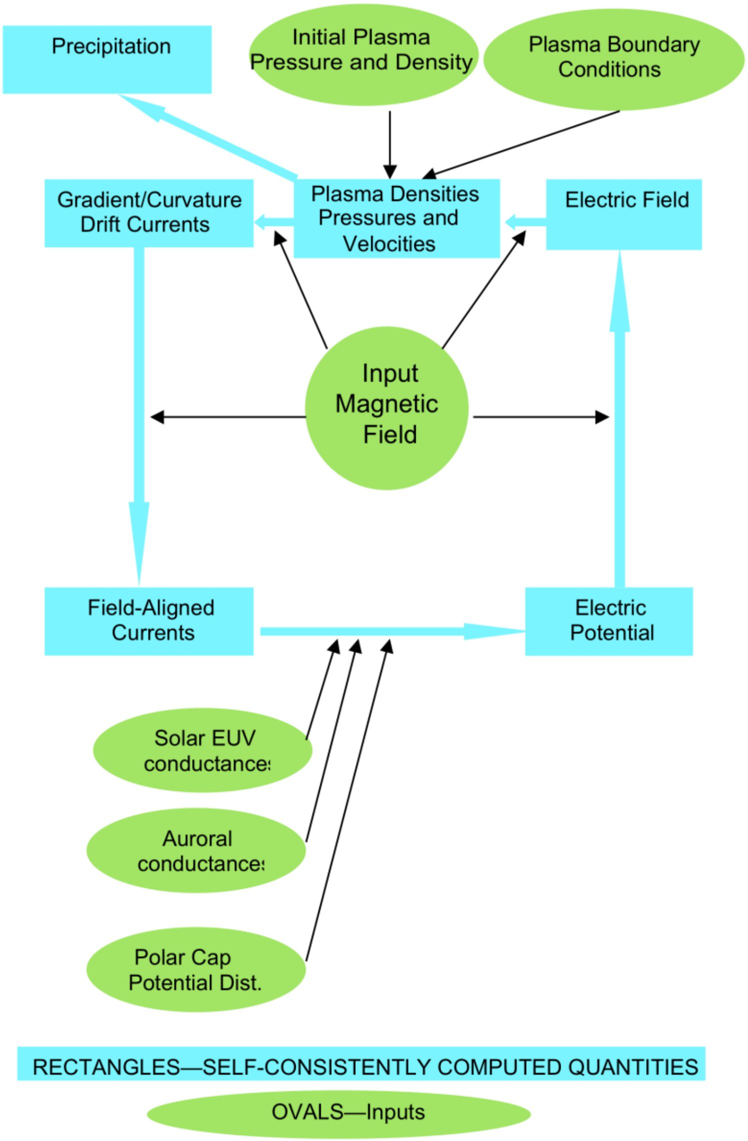
• The RCM Modeling region in the ionosphere, the modeling region includes the diffuse auroral oval (the boundary lies in the middle of the auroral oval, shifted somewhat equatorward from the open-closed field line boundary).

• The magnetosphere modeling region includes the inner/central plasma sheet, the ring current, and the plasmasphere.

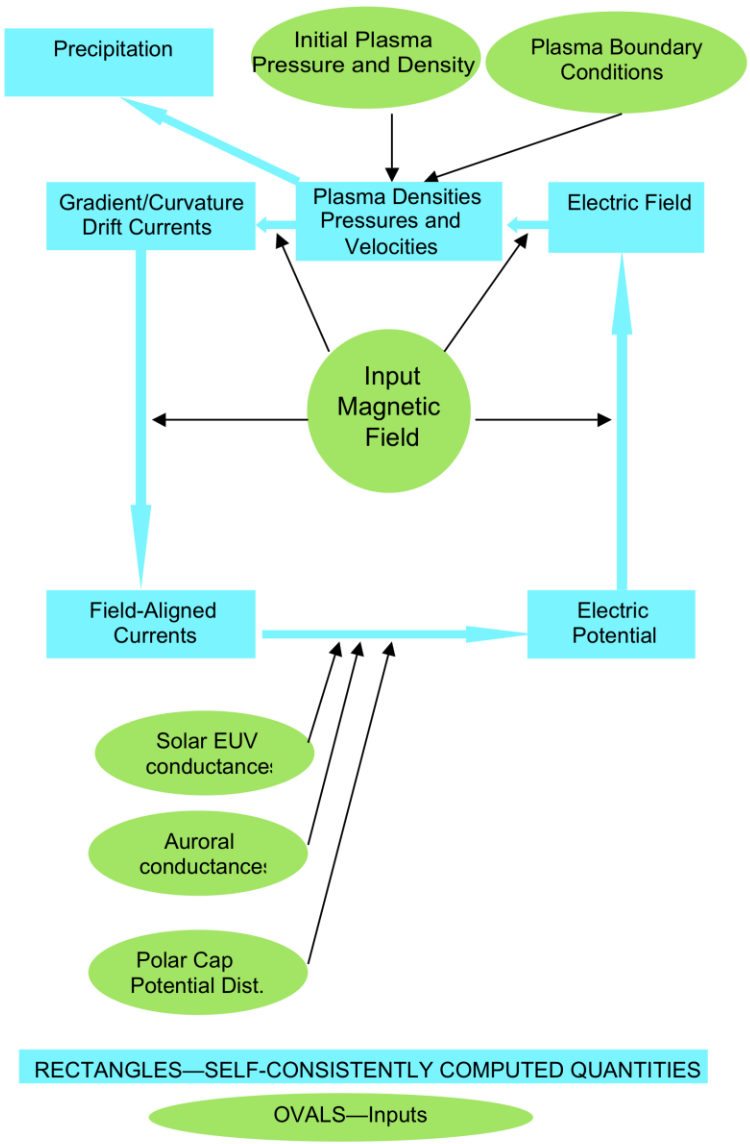
•Plasma is assumed to be isotropic and slow flow. (Anisotropic version is also available).

•Region-2 Field-Aligned currents (FAC) connect magnetosphere and ionosphere.

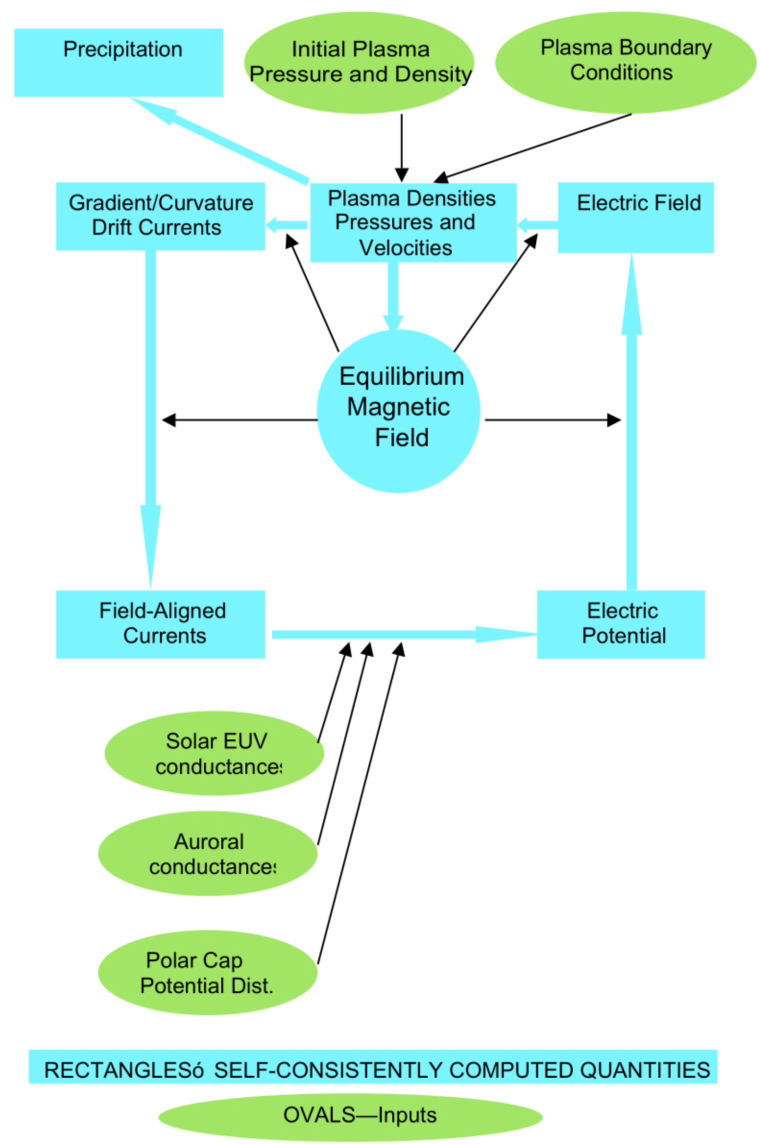
RCM - Logical Loop



RCM - Logical Loop



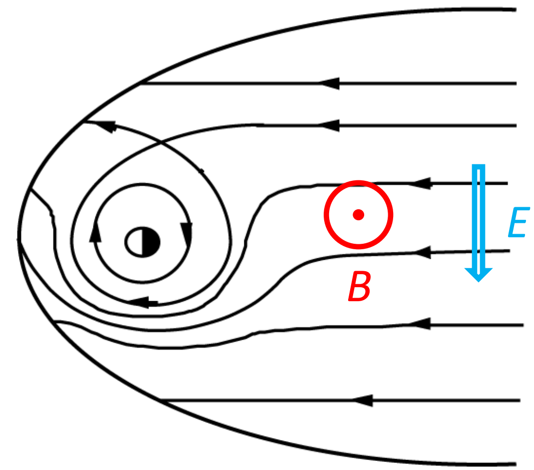
RCM-E Logical Loop



The importance of entropy parameter $PV^{5/3}$

- [illegible]

  where S is the kinetic theory definition of entropy; C_1 *is a constant related to the number of particles in the flux tube, the shape of* the plasma distribution function and the particle mass; C_2 is a constant related to *number of particles in the flux tube* [*Wolf et al.,* 2009].



- In ideal MHD, $PV^{5/3}$ is conserved along a flow streamline.

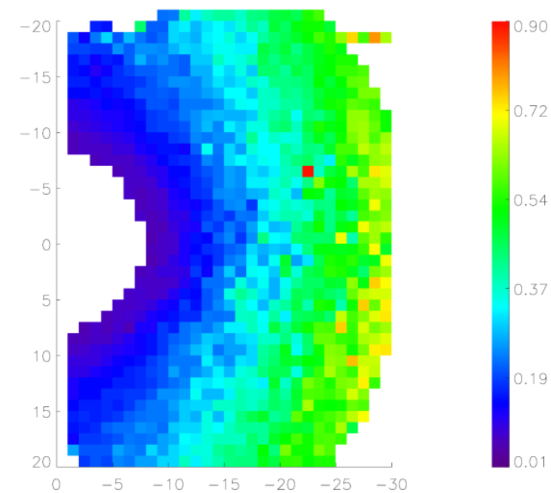
- Possible mechanisms why $PV^{5/3}$ decreases earthward

  (1) ionospheric precipitation

  (2) charge exchange with the geo-corona

  (3) gradient/curvature drift

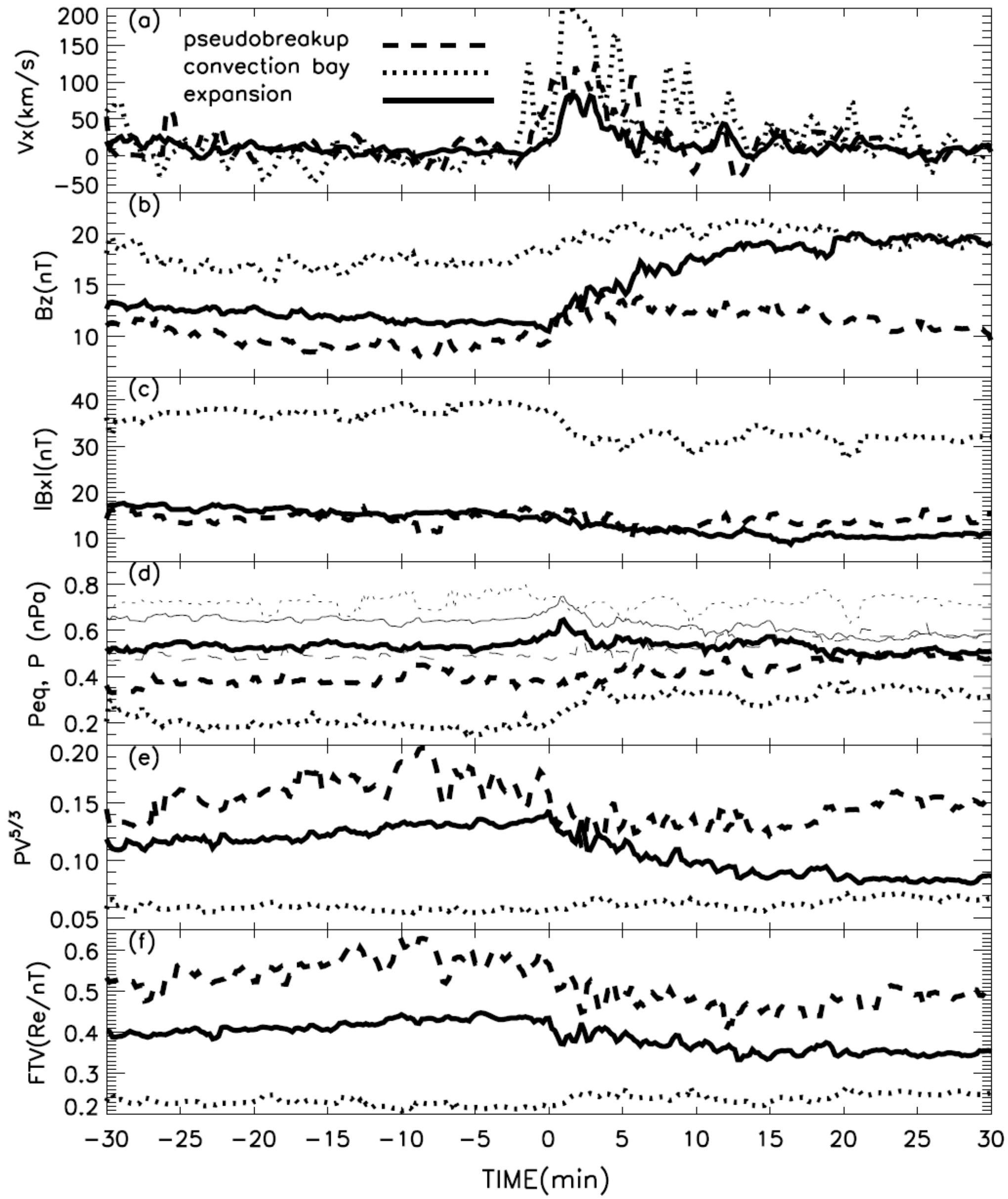
  (4) non-adiabatic reduction (bubbles)



[*Yang*, 2009]

Superposed epoch study of Entropy

- 54 substorms, 15 pseudobreakups, and 9 convection bays from Gary Erickson's list of Geotail events
- T=0 as local onset as the start of a clear *in-situ* magnetic dipolarization
- Events at X~-10R_E (on average) in the plasma sheet
- $PV^{5/3}$ is estimated using analytic formula based on force-balanced B-field models [*Wolf et al.*, 2006]
- Substorm expansions show clear decrease of $PV^{5/3}$ associated with permanent B_Z dipolarization.
- Pseudobreakups show gradual recovery of $PV^{5/3}$ associated with transient dipolarization followed by re-stretching .
- Convection bays show consistently low $PV^{5/3}$ associated with dipole-like B_Z and small plasma pressure.



[*Yang et al.*, 2010, GRL]

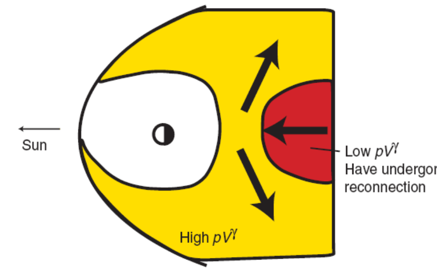
Bubbles in the plasma sheet

- Bubbles are flux tubes with depleted entropy parameter $PV^{5/3}$, as compared to their background [*Pontius and Wolf, 1990*].
- Ideally, a bubble will move earthward until it reaches a location where the background $PV^{5/3}$ equals its own.
- It has been widely accepted that BBFs are plasma sheet bubbles.

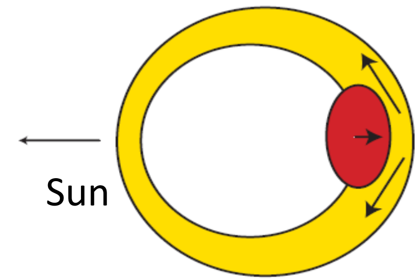
  Observations: e.g., *Sergeev et al. [1996]; Kauristie et al. [2000]; Nakamura et al. [2001]; Lyons et al.* [2003]; *Walsh et al. [2009]*

  Simulations: e.g., *Chen and Wolf [1993, 1999]; Birn et al. [2004]; Lemon et al. [2004]; Zhang et al. [2008, 2009a, 2009b]; Yang et al. [2008]*
- Violation of frozen-in-flux condition creates bubbles. e.g., magnetic reconnection; current disruption
- Recent work has indicated that dynamics effects can in some cases be important

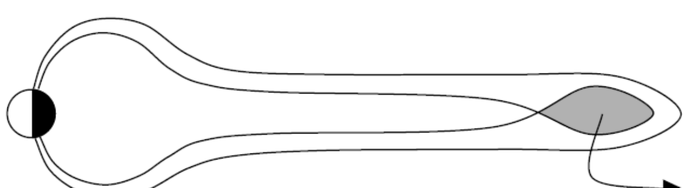
Equatorial view



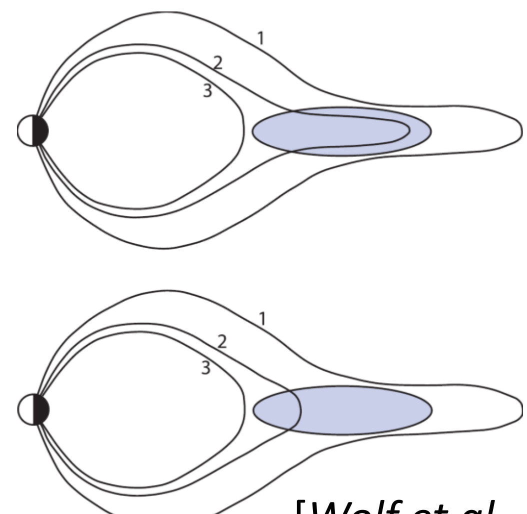
Ionospheric view



Wolf et al. [2002]



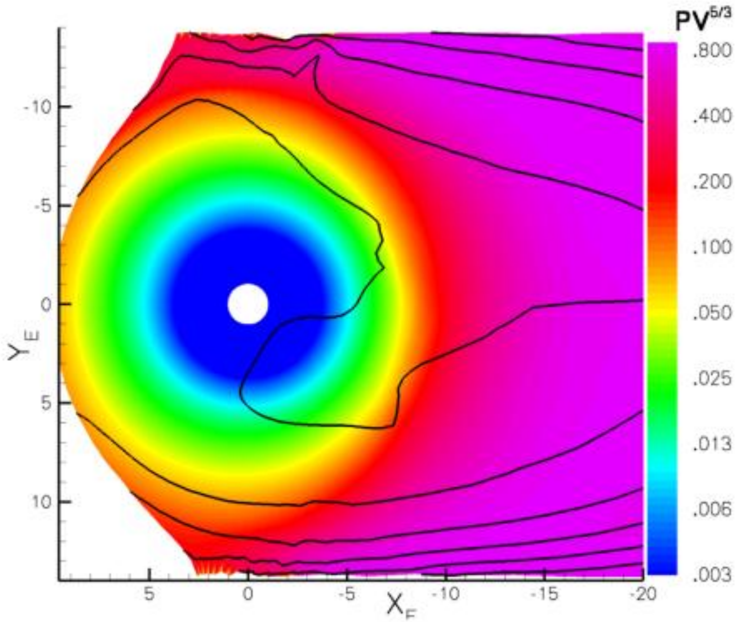
[*Sitnov et al.*, 2005, GRL]

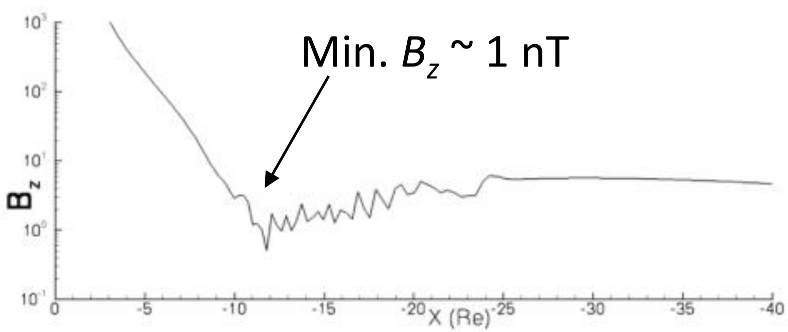


[*Wolf et al.*, 2009, JGR]

RCM-E Models of Strong, Steady Adiabatic Convection

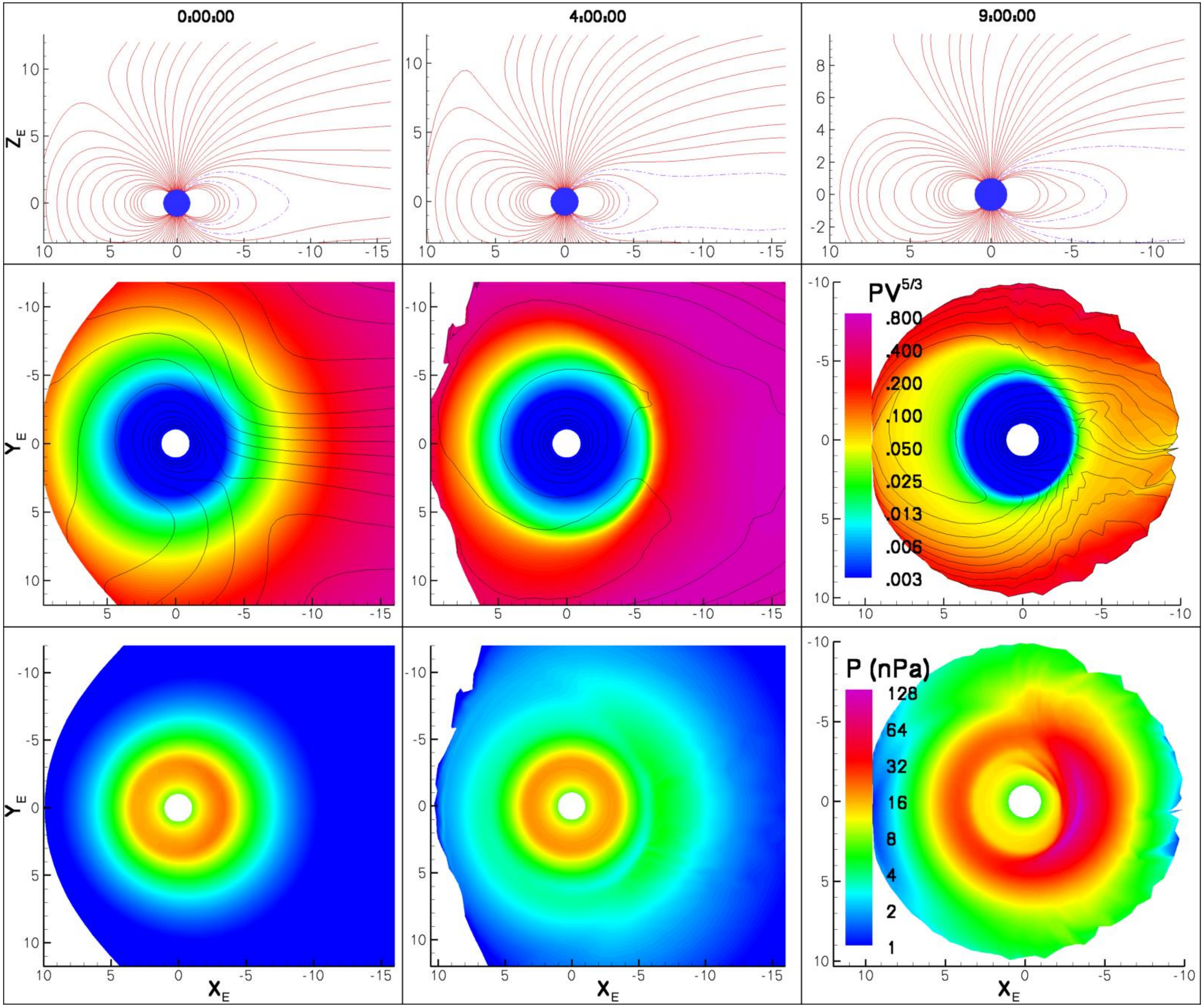
- When we enforce strong convection for hours in the RCM-E code, which keeps recalculating the magnetic field to keep it in approximate force balance with the RCM-computed $PV^{5/3}$ values, we always get a configuration that is highly stretched in the inner plasma sheet.
- $PV^{5/3}$ was assumed to be uniform on a boundary out in the tail.
- When we run RCM-E for a long time with a strong potential drop, the configuration reaches a highly stretched configuration
  - Nothing like a substorm expansion
  - No injection into the ring current





120 kV potential drop.

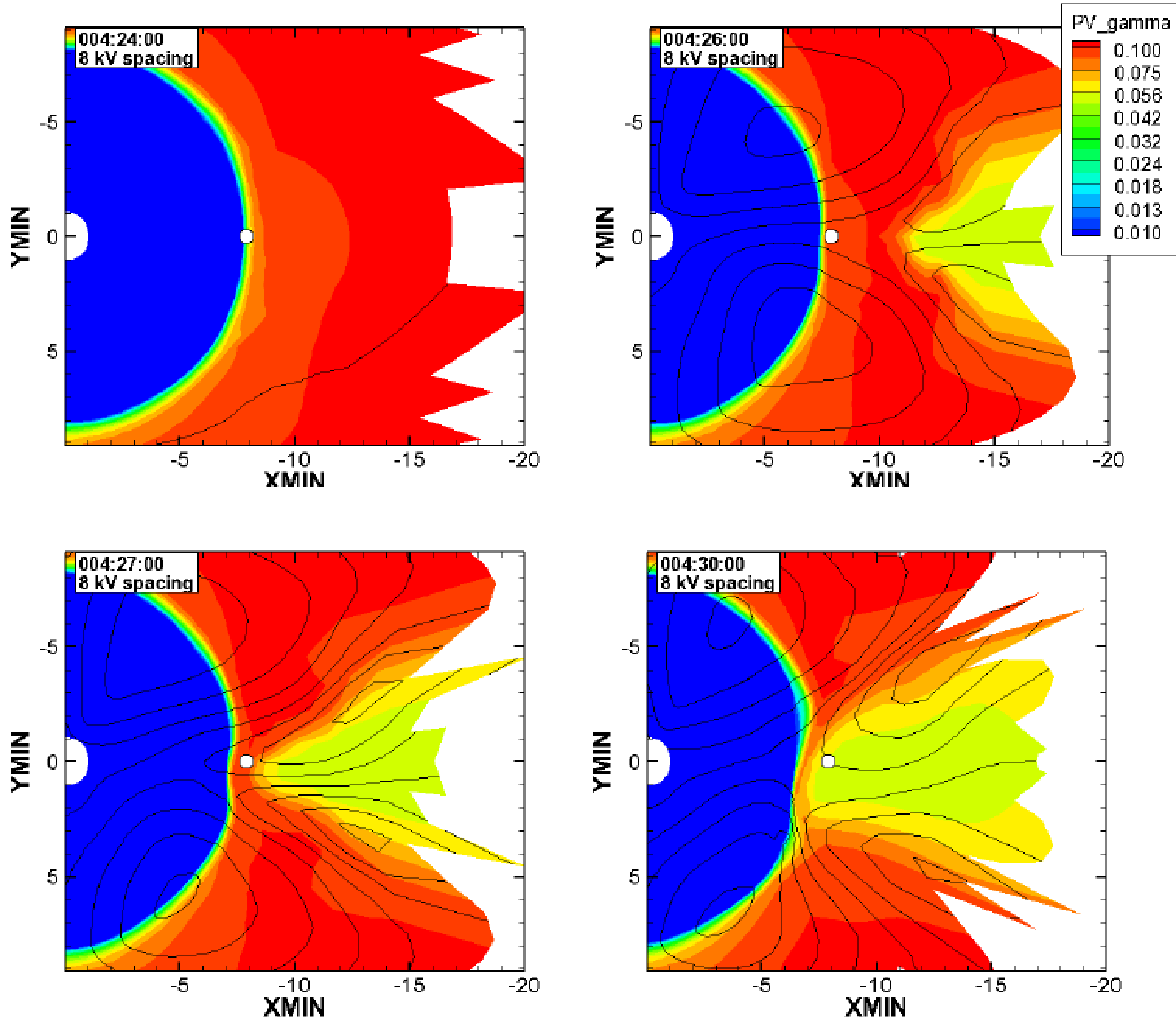
C. Lemon (*Ph.D. Thesis*, Rice, 2005)



(*Lemon,* Ph.D. thesis, Rice, 2005; GRL 2004)

RCM Simulations of Bubble Injections

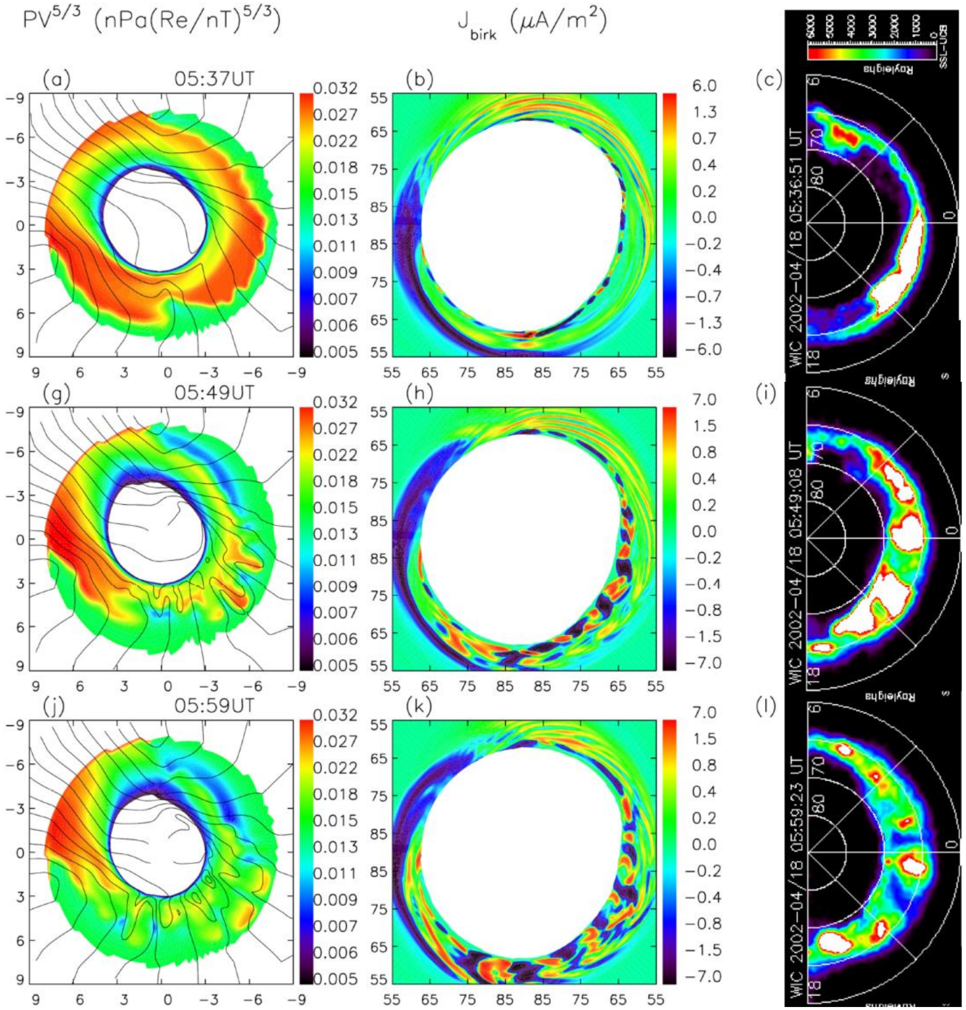
- Black curves are equipotentials, mapped from ionosphere.
- Circle shows plasma sheet inner edge at end of growth phase.
- Once introduced at the boundary, bubble pushes its way earthward.
- Current wedge forms on sides of bubble, creating westward potential E in bubble.
- Inductive field is also westward. Note that some of the original higher-$PV^{5/3}$ *flux* tubes get pushed earthward ahead of the bubble.



From Song, PhD Thesis, Rice, 2010

RCM simulation of the 2002-04-18 sawtooth event

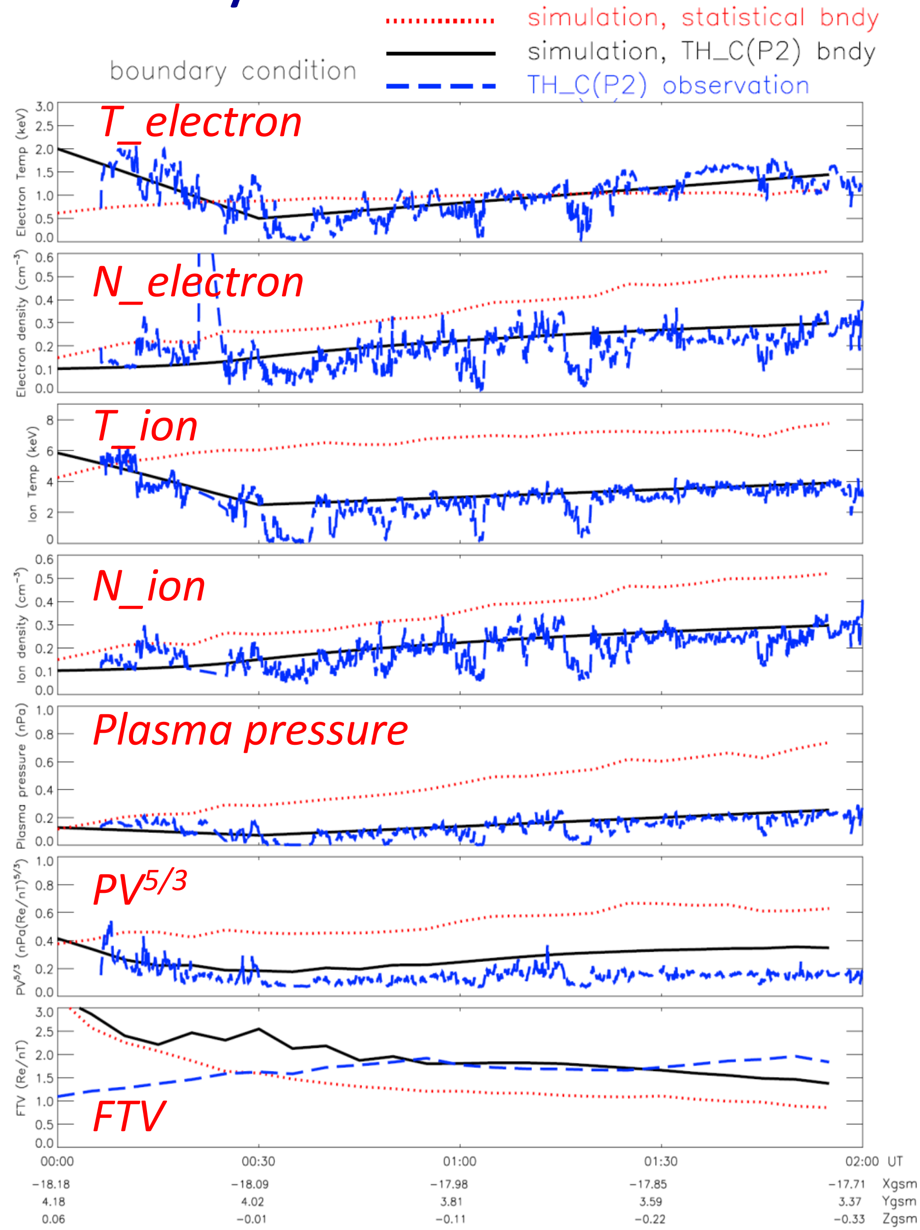
- A sawtooth event involves dispersionless particle injection over a wide range of local time, which suggests a reduced-*PV*$^{5/3}$ region that stretches across most of the width of the tail.
- This leading edge of the large bubble is interchange unstable.
- Plasma convection shows interlaced high-and-low plasma in the inner magnetosphere with down and up FACs along their sides.
- The IMAGE/WIC data show quasi-periodic finger-like aurora during this sawtooth event, which can be interpreted as the manifestation of interchange processes.



[*Yang et al.*, 2008, JGR]

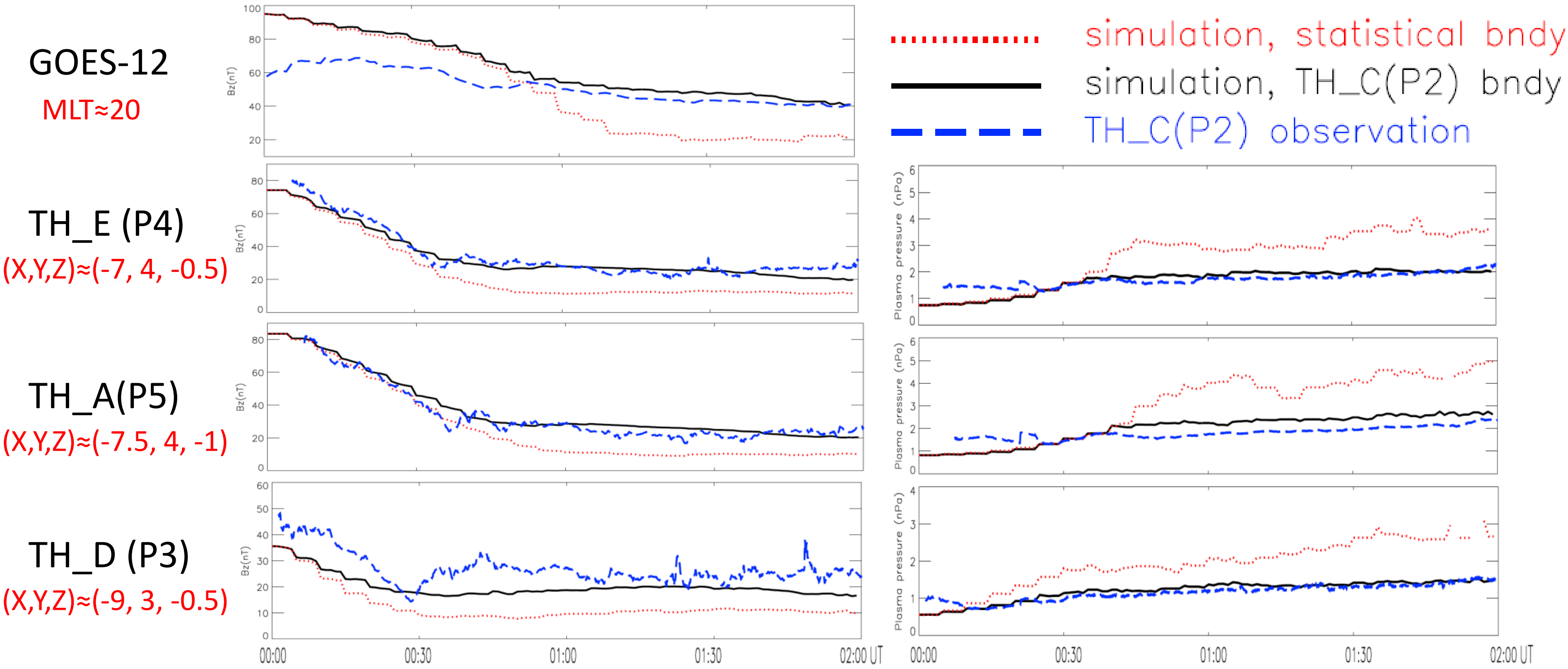
RCM-E simulation of 2009-03-13 SMC event
The effect of plasma boundary conditions

- Two RCM-E simulations with different plasma boundary conditions. The RCM high-latitude boundary maps to ~-20R_E at nightside.
- Data-driven plasma boundary conditions using TH_C (P2) (X,Y,Z)≈(-18, 4, 0) observations (black lines).
- Statistical model plasma boundary conditions using *Tsyganenko and Mukai* [2003, JGR] model (red lines).
- Flux tube volume *(FTV)* is obtained from the self-calculated magnetic field model in the equilibrium solver.
- *$PV^{5/3}$* on the boundary is substantially lower in the data-driven simulation than in the empirical-model-driven simulation.



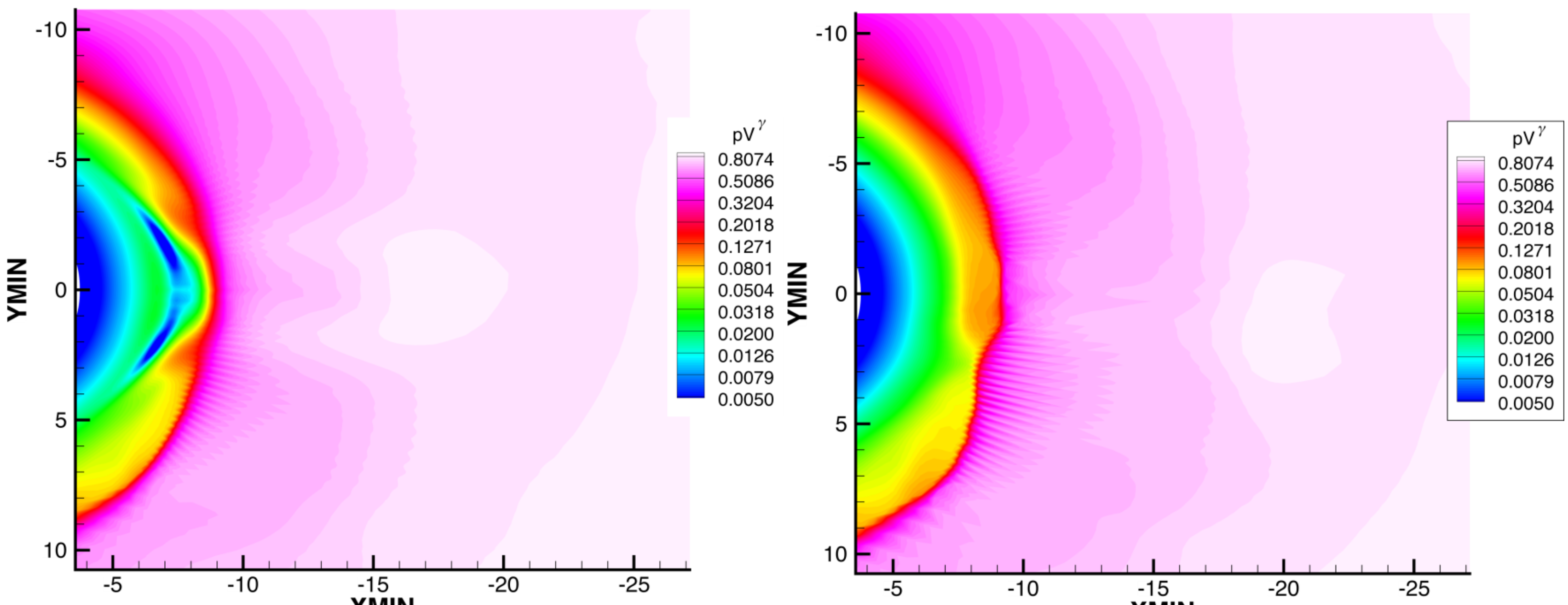
[Data courtesy of THEMIS team]

RCM-E – SMC Simulation: Comparison with Observations



- Simulation results with data-driven boundary conditions (black lines) show better agreement with observations (blue lines).
- Simulation results with data-driven boundary conditions (black lines) show larger B_Z and smaller plasma pressure in the near-Earth plasma sheet than the simulation with statistical boundary conditions (red lines).
- Continuous feeding of low $PV^{5/3}$ plasma produces a thick plasma sheet, which may explain why SMCs can last for hours without a substorm expansion since certain instabilities may not build up to threshold in such a configuration.

Modeling the Consequences of Violation of Frozen-in Flux at the end of a Substorm Growth Phase using the RCM-E

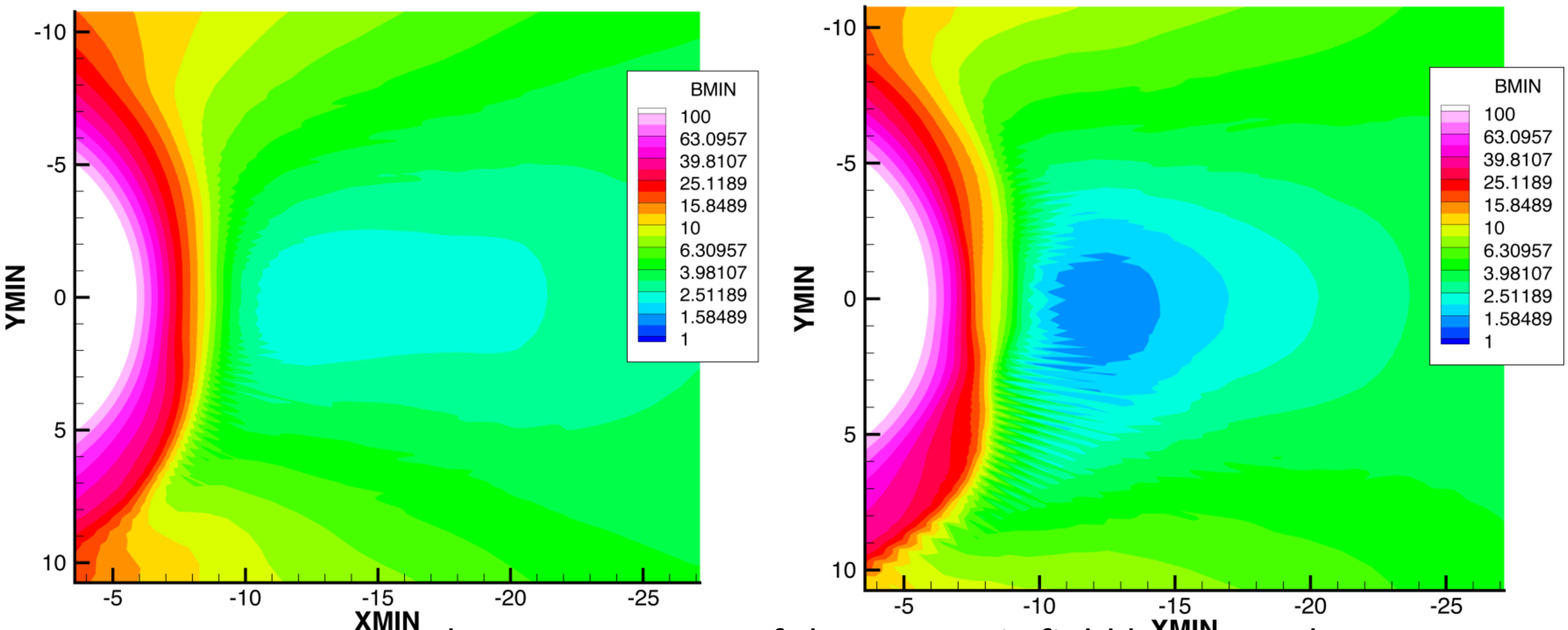


Violation of frozen-in flux implies that magnetic field lines slip on the plasma, creating a plasma bubble (region of reduced entropy parameter) just earthward of the disruption.

A plasma blob (region of increased entropy) appears on the tailward side. To represent this in the model, we imposed a bubble and blob on the RCM-E growth-phase configuration.

Then we followed the subsequent evolution. The bubble surges earthward and blob moves tailward.

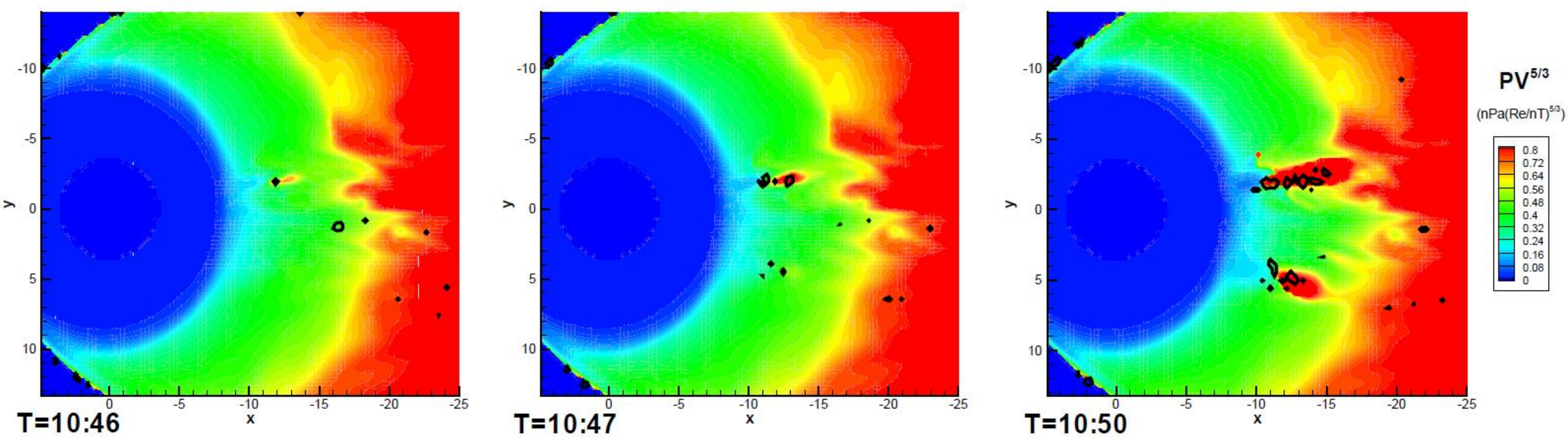
Modeling the Consequences of Violation of Frozen-in Flux at the end of a Substorm Growth Phase using the RCM-E – Effect on the Magnetic field



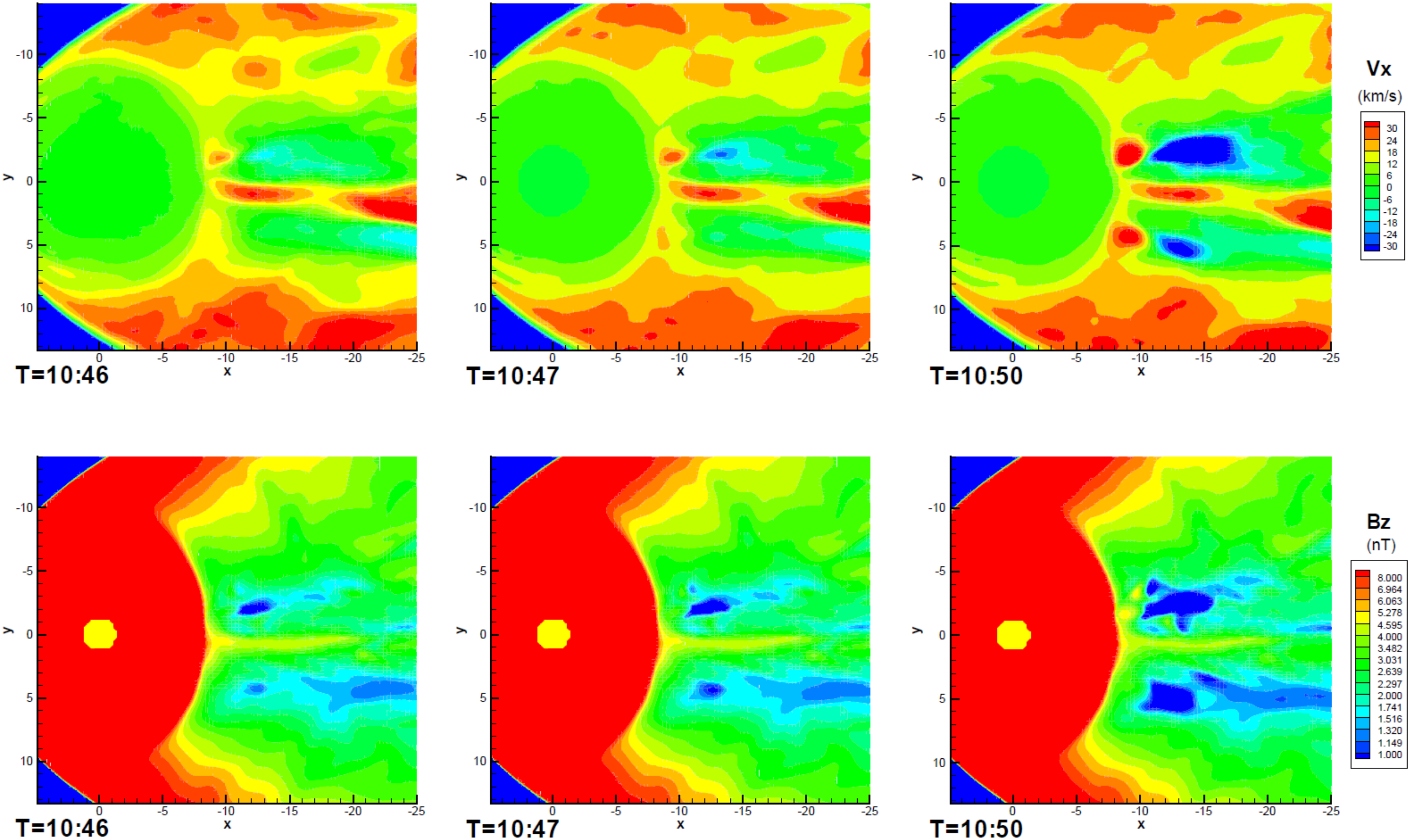
As a consequence, the z-component of the magnetic field between the bubble and blob decreases dramatically.

We speculate that, in the real system, the positive feedback would thin the current sheet more and more until reconnection occurs.

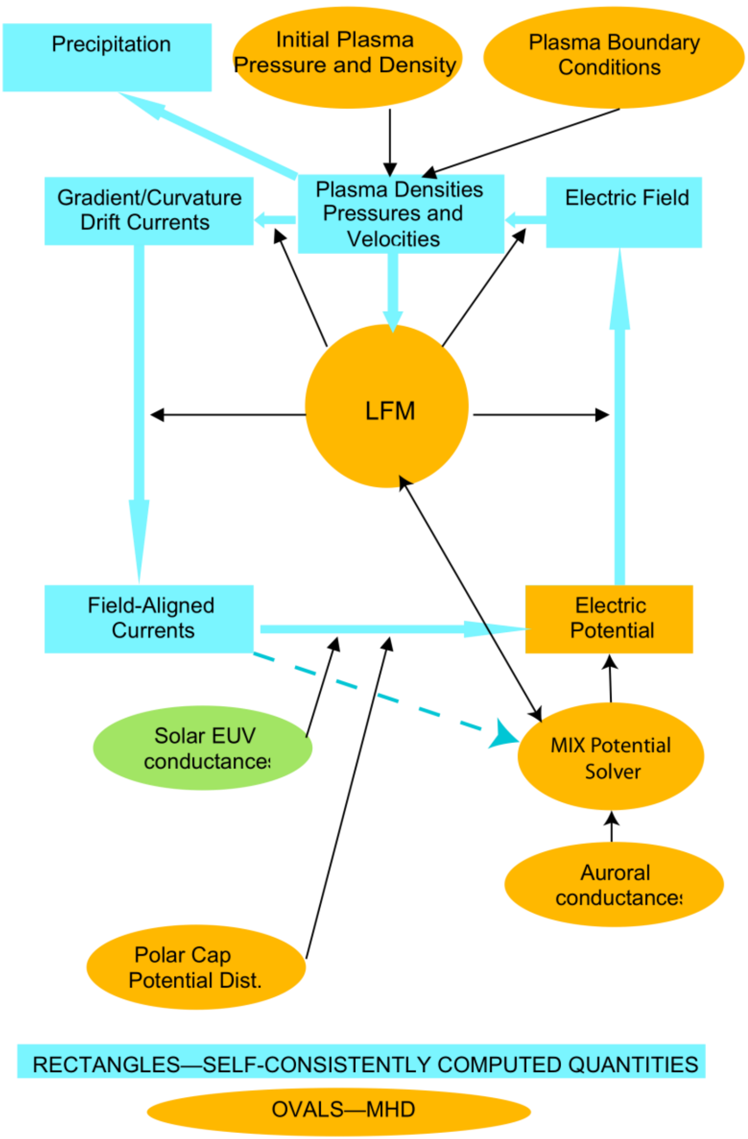
OpenGGCM Simulation of Bubble-blob pairs in 2007/03/23 substorm event simulation



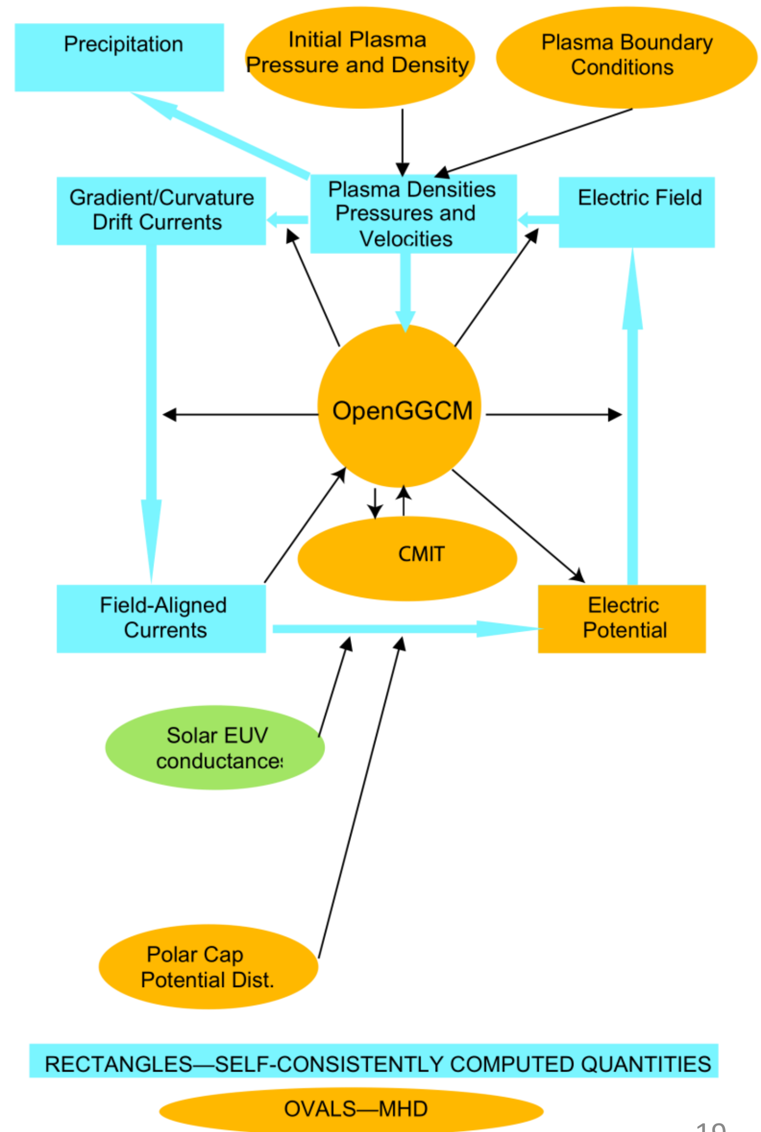
- Color contours - $PV^{5/3}$ on the equatorial plane
- Black circles – regions of non-zero anomalous resistivity


Vx
(km/s)
30
24
18
12
6
0
-6
-12
-18
-24
-30
Bz
(nT)
8.000
6.964
6.063
5.278
4.595
4.000
3.482
3.031
2.639
2.297
2.000
1.741
1.516
1.320
1.149
1.000
T=10:46
T=10:47
T=10:50
T=10:46
T=10:47
T=10:50
x
y
0
-5
-10
-15
-20
-25
-10
-5
0
5
10

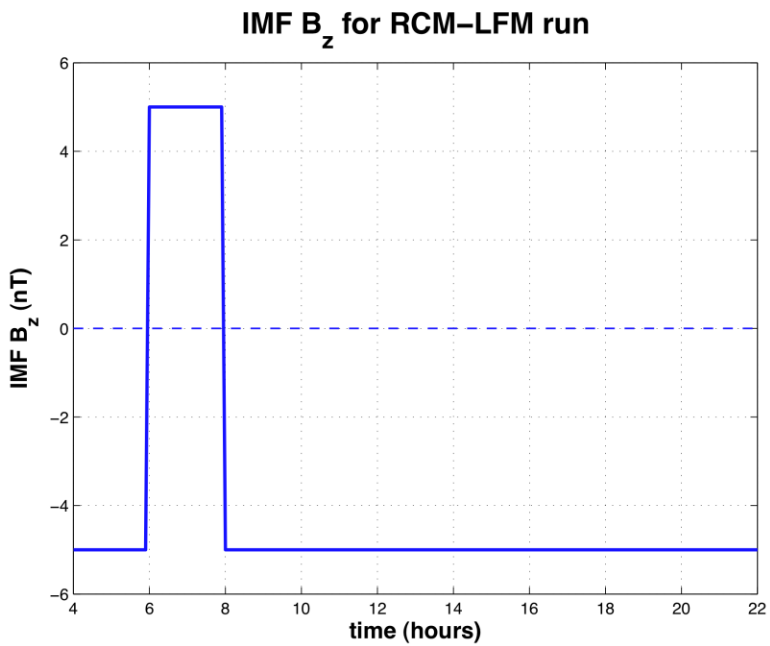
RCM LFM Logical Loop



RCM OpenGGCM Logical Loop

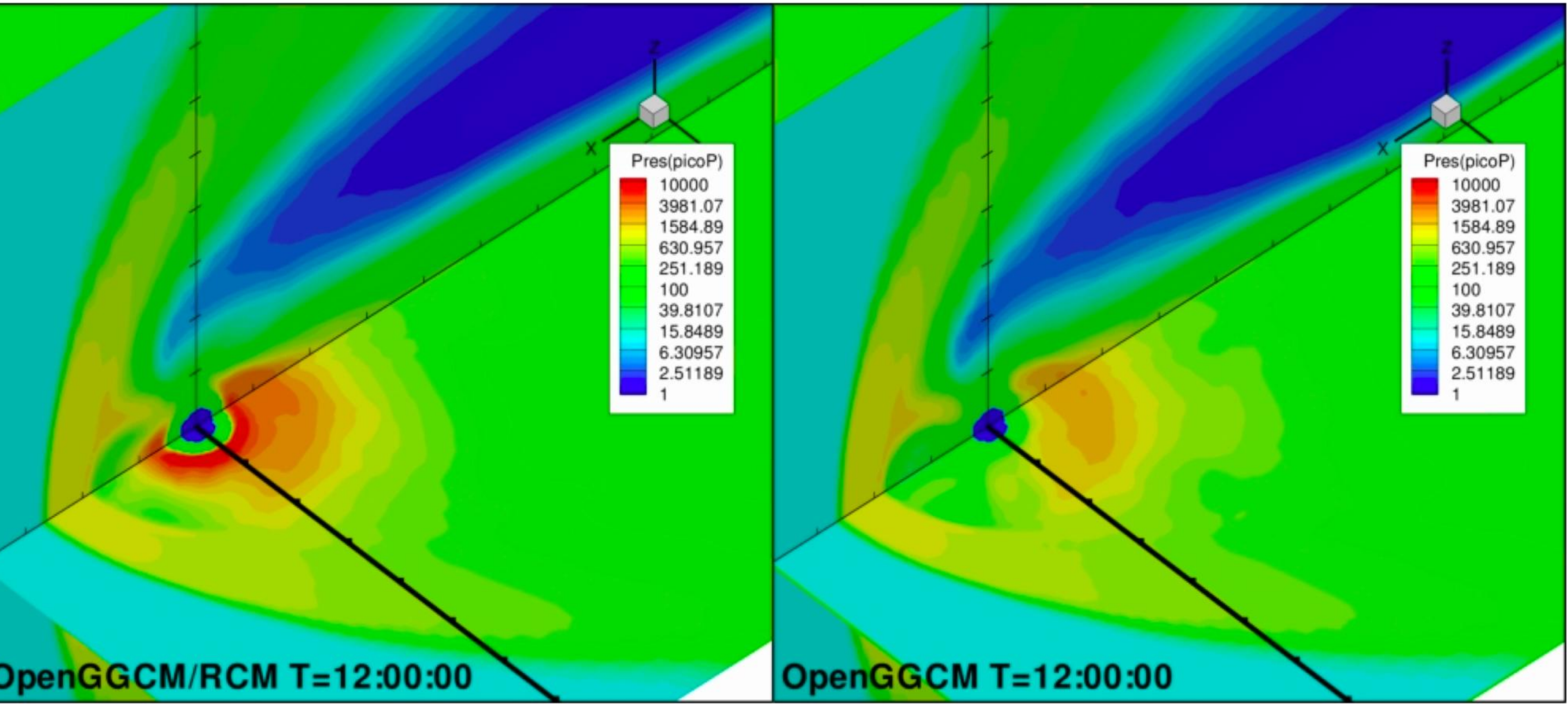


Work in Progress: Computer Experiments using the Coupled OpenGGCM-RCM and LFM-RCM



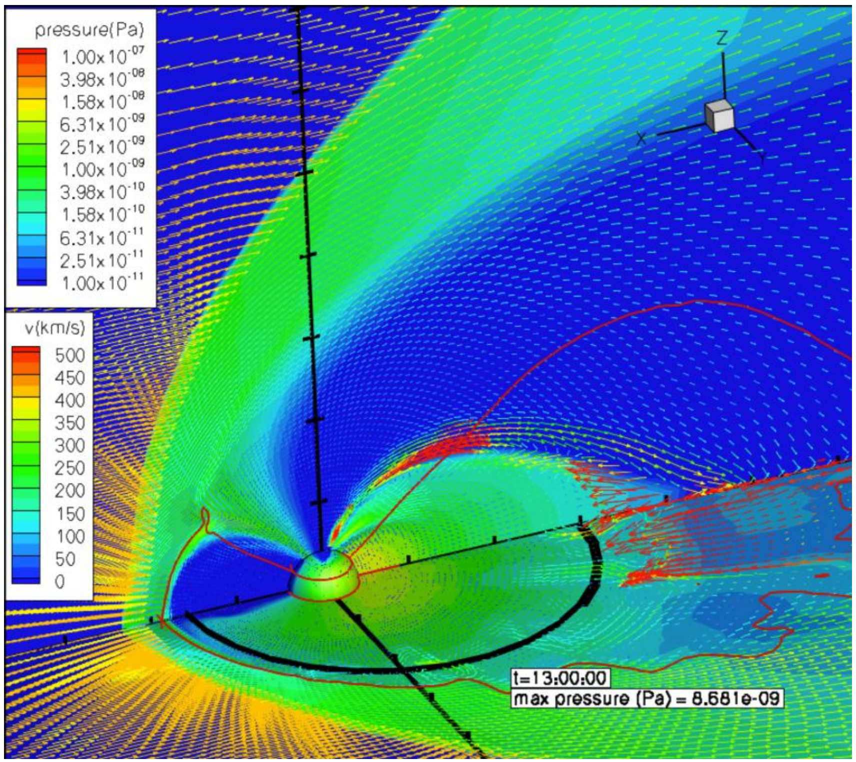
- We have been conducting a series of numerical experiments to determine if the coupled code produces physically and numerically reasonable results
- Solar Wind Conditions:
  - Speed of 400 km/s
  - Density of 5 particles/cc
  - Variable IMF (see figure)
- Ionosphere
  - Constant conductance, 5 S Pedersen, 0S Hall
  - RCM takes its electric field from the MHD code

OpenGGCM-RCM

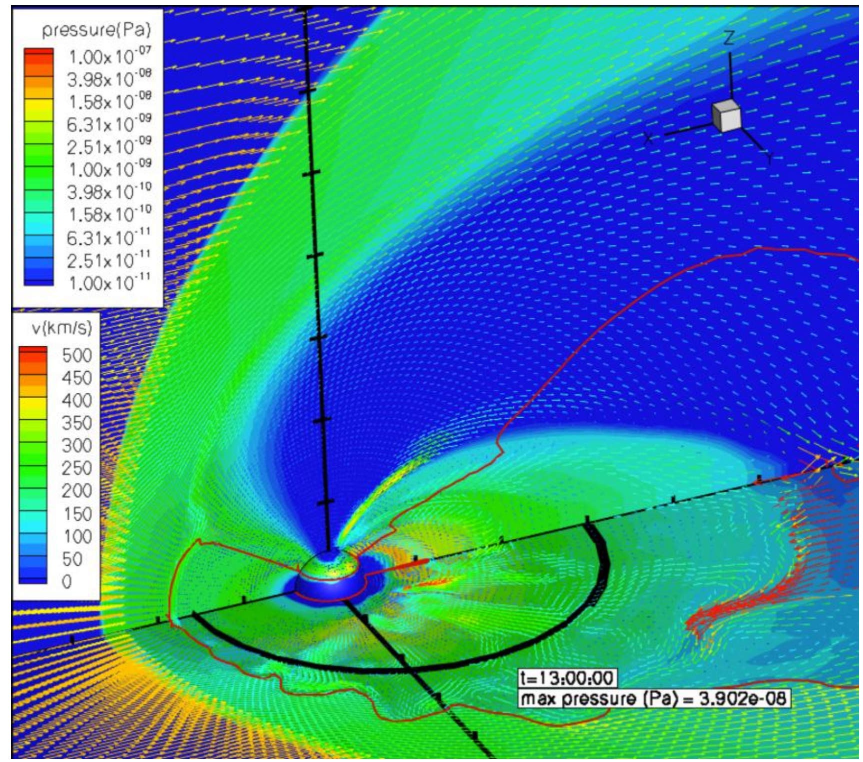


LFM-RCM: Sample results: Quadruple resolution (106x96x128)

LFM-MIX



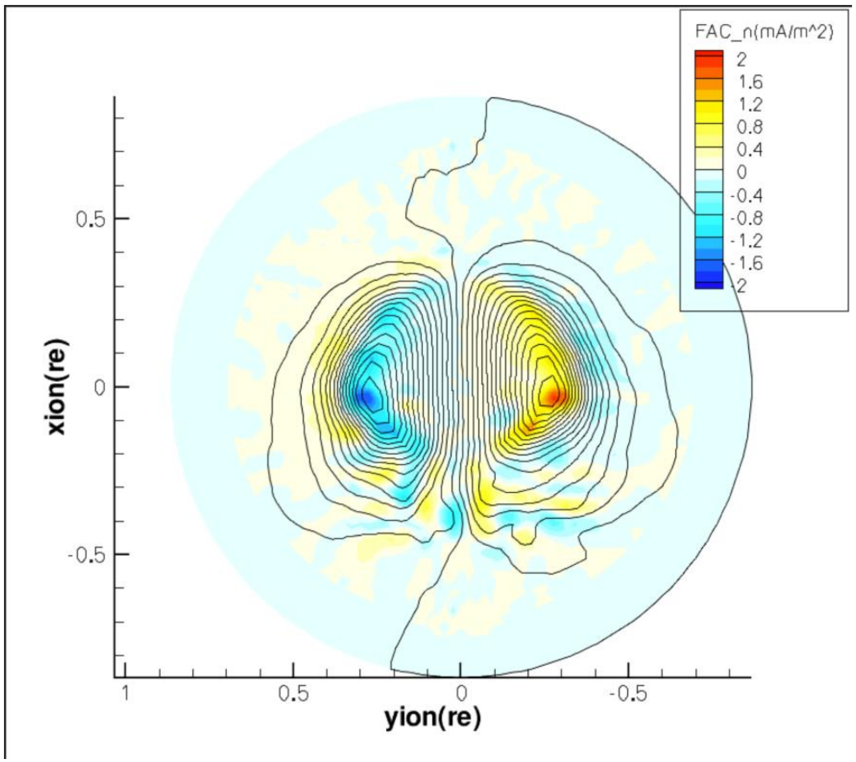
LFM-RCM-MIX



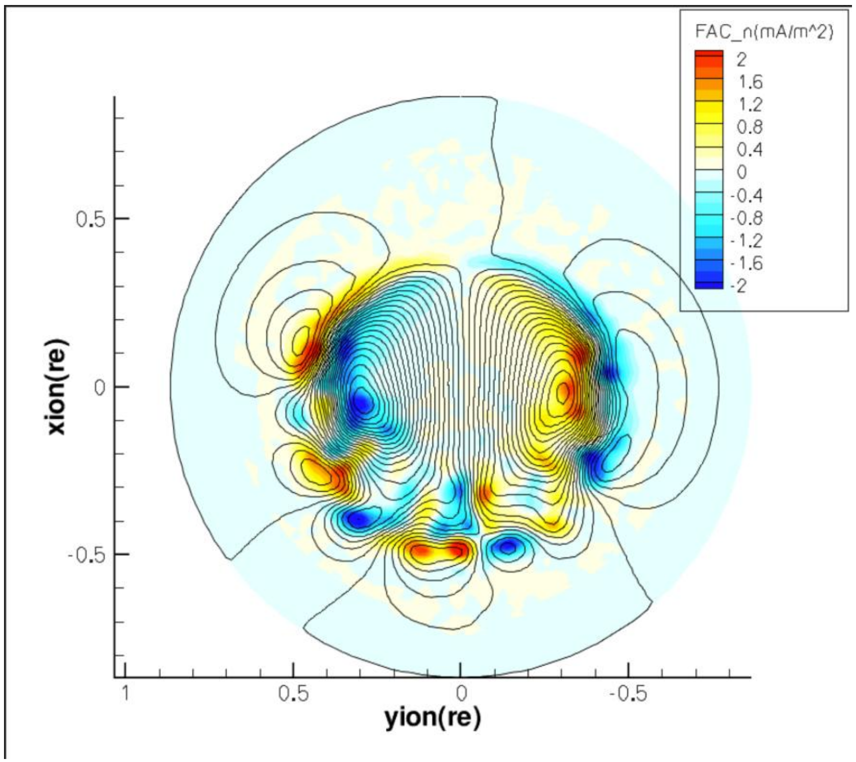
Key:	Contours:	Pressure (Pa)
	Vectors:	Velocity colored by speed (km/s)
	Red Line:	Bz=0 line
	Black ellipse:	RCM Boundary (approx).

MIX Ionosphere:
Quadruple resolution (106x96x128)

LFM-MIX



LFM-RCM-MIX



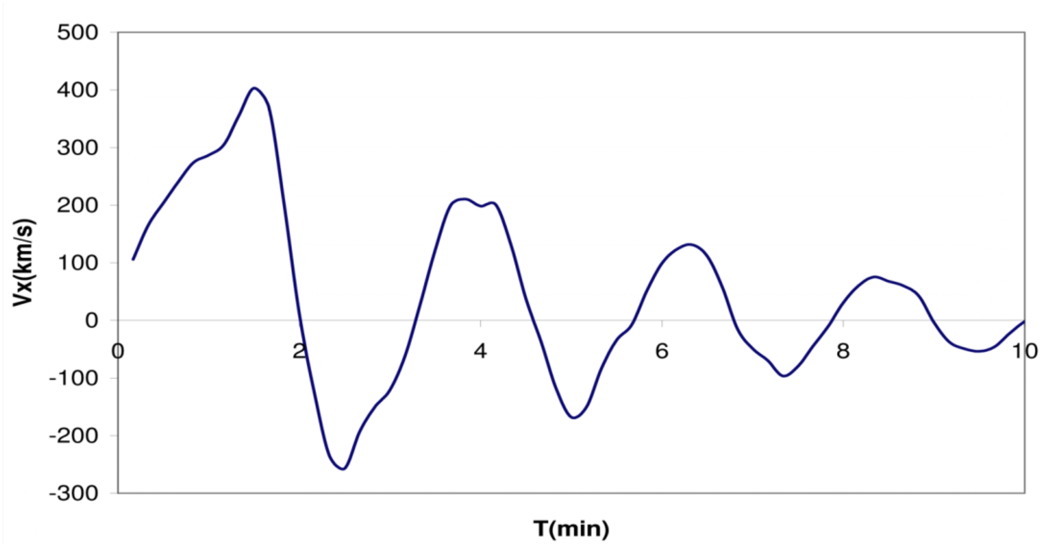
Key: Lines: Potential, 5 kV Spacing

Colors: Birkeland currents (positive is downward)

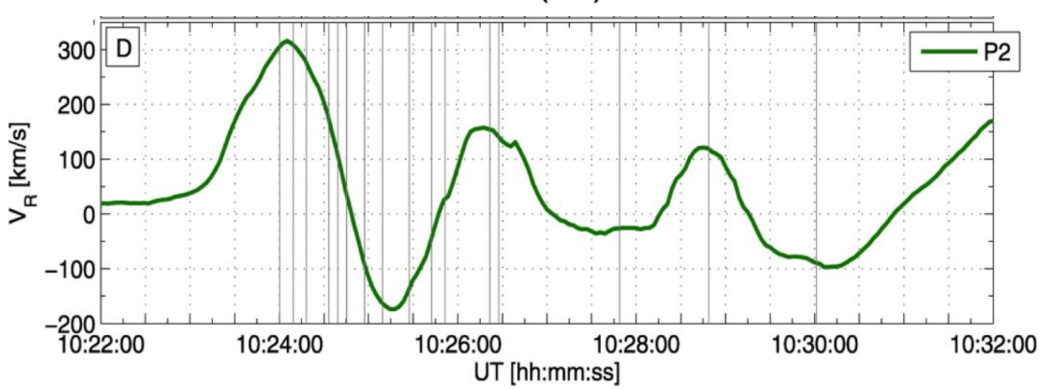
Interchange Oscillations?

- Dick Wolf in collaboration with C. Chen have been using an 1-D ideal-MHD code that treats the motion of a underpopulated thin filament moving in the *xz* plane through a stationary background medium
- They have identified a phenomenon that they call "interchange oscillation”
  - A filament that is a plasma-sheet bubble, i.e., has lower entropy parameter $PV^{5/3}$ than the neighboring background, initially rushes earthward. It eventually comes to rest in a configuration where its shape is the same as the local background field lines, and its entropy parameter equals that of the background.
  - If the filament starts from beyond 10 Re, it exhibits an oscillation about that stable-equilibrium configuration.

Filament Code outputs - comparisons to THEMIS observations



Equatorial velocity of a bubble from the filament code simulations of Chen and Wolf

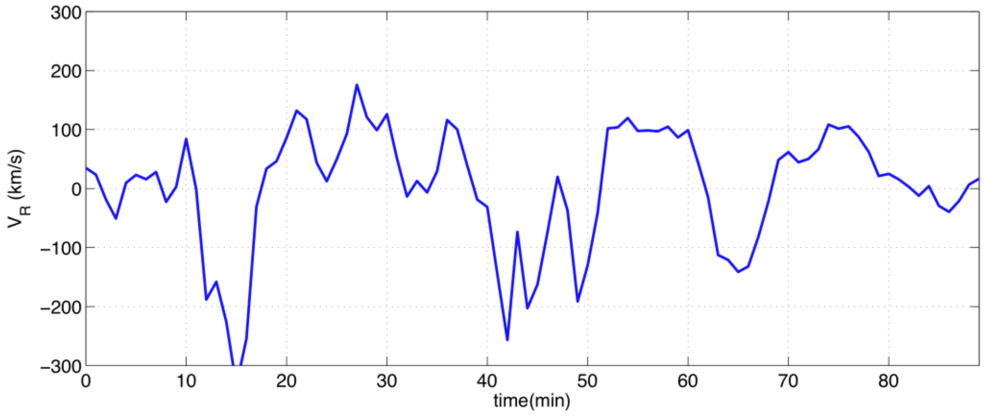


From: *Panov et al.*, *GRL*, *37*, L08103, doi: 10.1029/2009GL041971 using THEMIS observations

Figures courtesy of Dick Wolf

Oscillations in the coupled code

- Similar oscillations are seen in the high resolution coupled LFM-RCM
  - However the period of the oscillations is ~8 minutes, which is much longer than what THEMIS observed
    - This could be due to the density being too large
- The uncoupled LFM resolution results also show similar oscillations
  - But they are not as large and don't penetrate as close to the Earth
  - The RCM Coupling seems to 'enhance' the behavior



Using the RCM to model oscillations

- An explicit assumption of the RCM is that of slow flow and quasi-static equilibria
  - This is clearly not the case during these oscillations
- One option is to avoid using the RCM during these periods by adjusting the location of the RCM boundary
  - In which case LFM-RCM results do stabilize and the oscillations disappear
  - But it also means that significant portion of the inner magnetosphere is not treated by the RCM

Filament Code - RCM approximation - comparisons

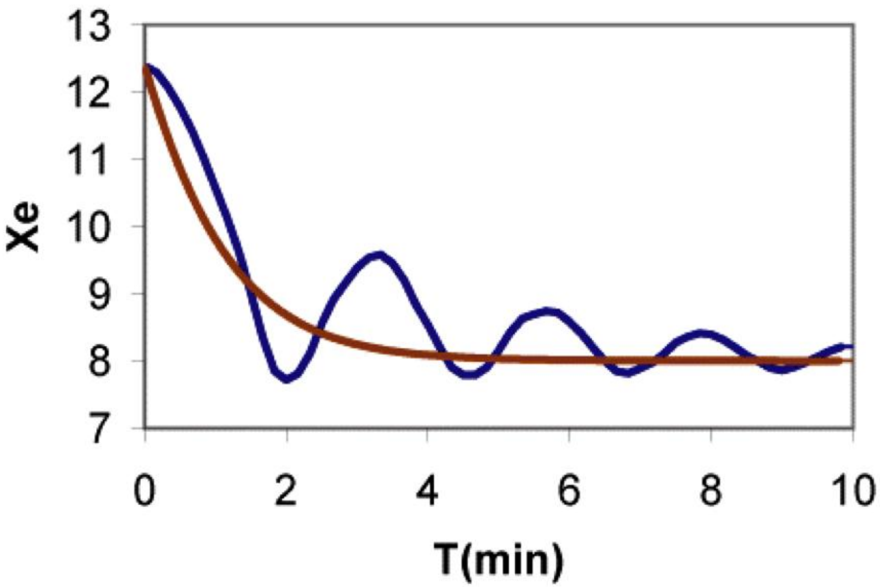


Figure courtesy of Dick Wolf

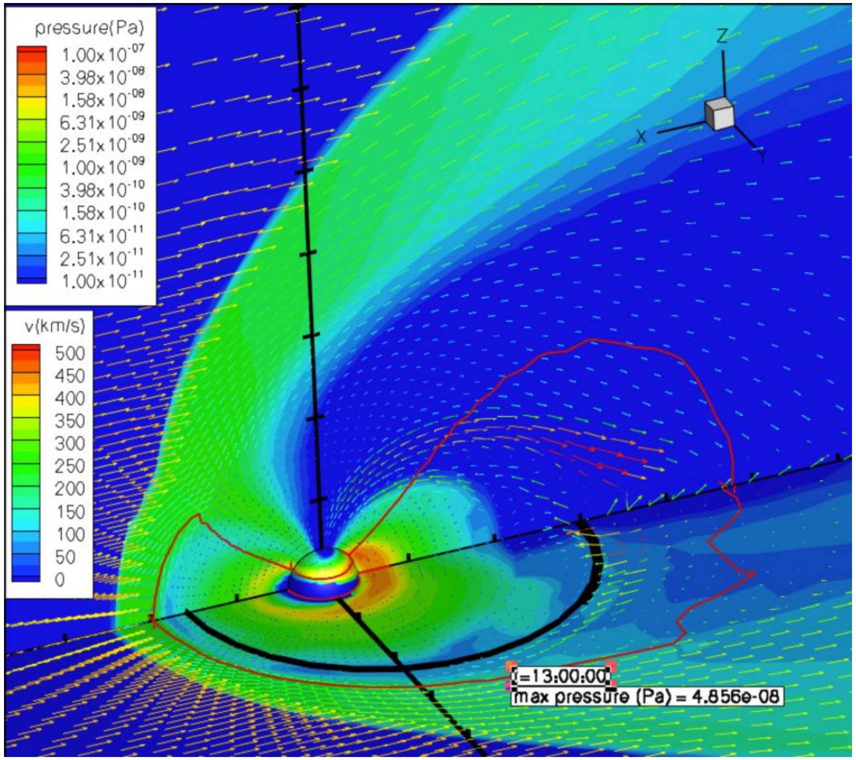
- Equatorial crossing point of filament vs. time (Xe is positive tailward and has units of R_E)
- The brown curves show the RCM approximation for the same situation

Modifying the RCM to include inertial effects

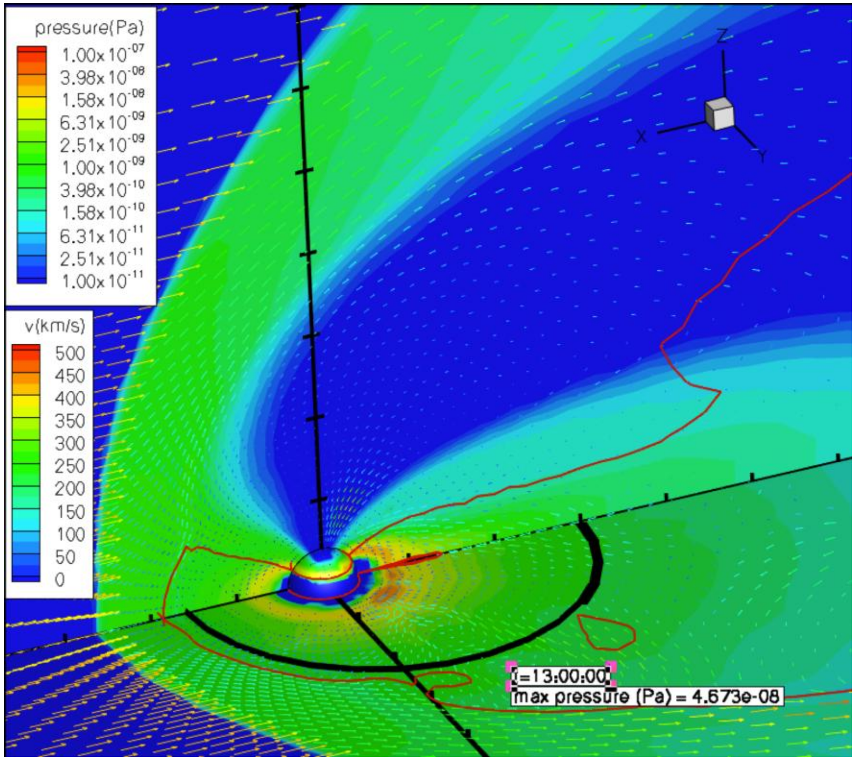
- We are currently working on modifying the RCM algorithms to include inertial effects, this involves several modifications:
  - Replace Vasyliunas-equation calculation scheme with a more generalized version using full MHD
  - Replace RCM to MHD nudging scheme
    - Current scheme enforces constant pressure and density along a fieldline
    - The new scheme will conserve RCM-specified $pV^{5/3}$ but at the same time preserve MHD computed variations along the fieldline (due to waves)
- We have developed the first version of this in the coupled OpenGGCM-RCM
  - Undergoing testing

Sensitivity Experiments using the LFM RCM to include a simple polar cap model

LFM-RCM-MIX – with polar cap model



LFM-RCM-MIX – without polar cap model

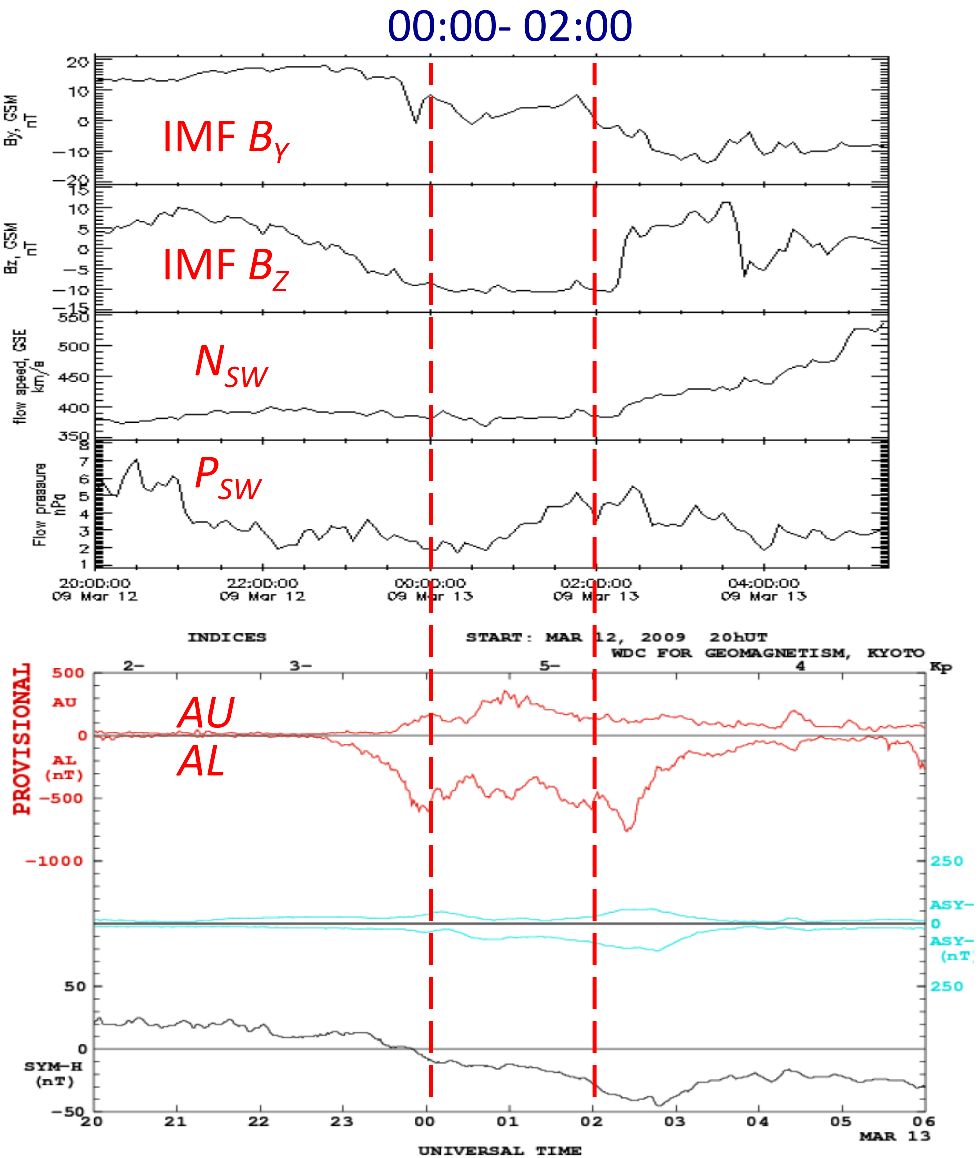


Key:		
	Contours:	Pressure (Pa)
	Vectors:	Velocity colored by speed (km/s)
	Red Line:	Bz=0 line
	Black ellipse:	RCM Boundary (approx).

Summary

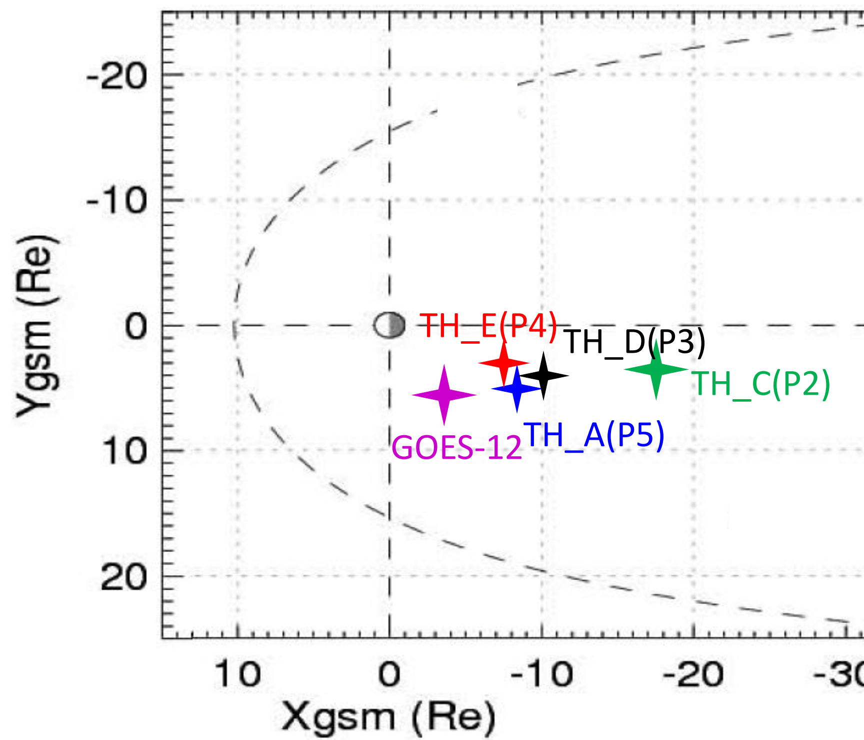
- We have an extensive collection of models focused on the inner magnetosphere and the coupling to the ionosphere. The models can self-consistently compute
  - Plasma moments, magnetic and electric fields
- Recent work has focused on understanding the transport of plasma from the plasma sheet into the inner magnetosphere and the role of depleted flux tubes
  - Most of the work has been on substorms (THEMIS)
  - In the future, we hope to also look at storms
    - Perhaps conjunction studies with THEMIS and RBSP?

RCM-E simulation of 2009-03-13 SMC event



[Data courtesy of ACE team and WDC for Geomagnetism, Kyoto]

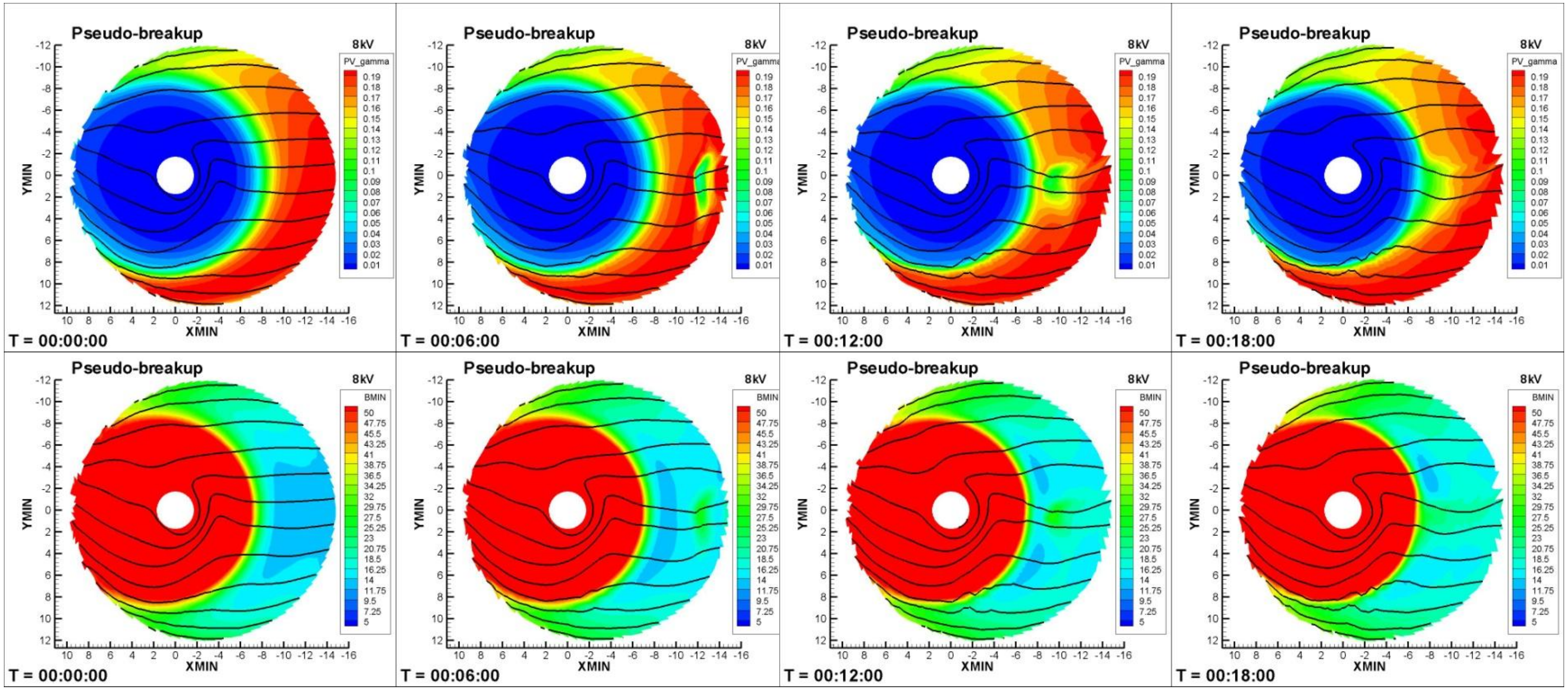
- Prolonged steady southward IMF B_Z (-5 to -10nT) and low solar wind velocity (380km/s)
- AL~500nT; AU~200nT; AE~700nT
- Sym-H~ as small as -40nT



RCM-E simulation of transient bubble injection

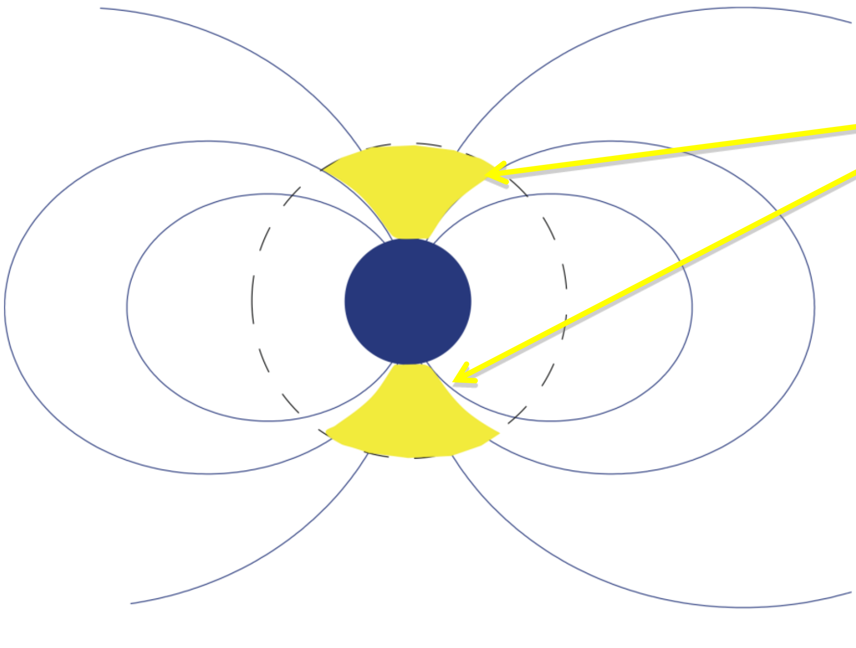
$PV^{5/3}$

B_Z



- Transient bubble injection causes weak dipolarization.
- Magnetic field re-stretches after the bubble passes by.
- This is consistent with superposed epoch results of pseudobreakups.

Sensitivity Experiments – Simple Polar Ionosphere Model



- Adds a specified amount of density in the polar regions
  - Applied in the nudging

$$\rho_{new} = \rho_{LFM} + (\rho_{ionos} - \rho_{LFM})\frac{\tau}{T}e^{-r/R_0}$$

- Where:

ρ_{LFM} = LFM density

ρ_{RCM} = RCM density

τ = LFM timestep

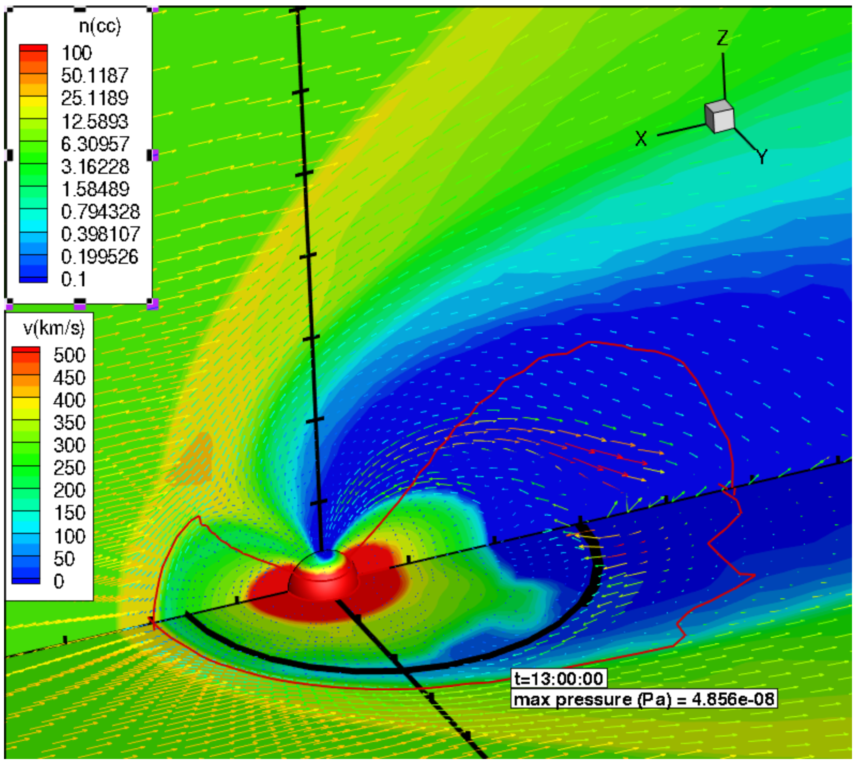
T = exchange time

r = distance from the Earth

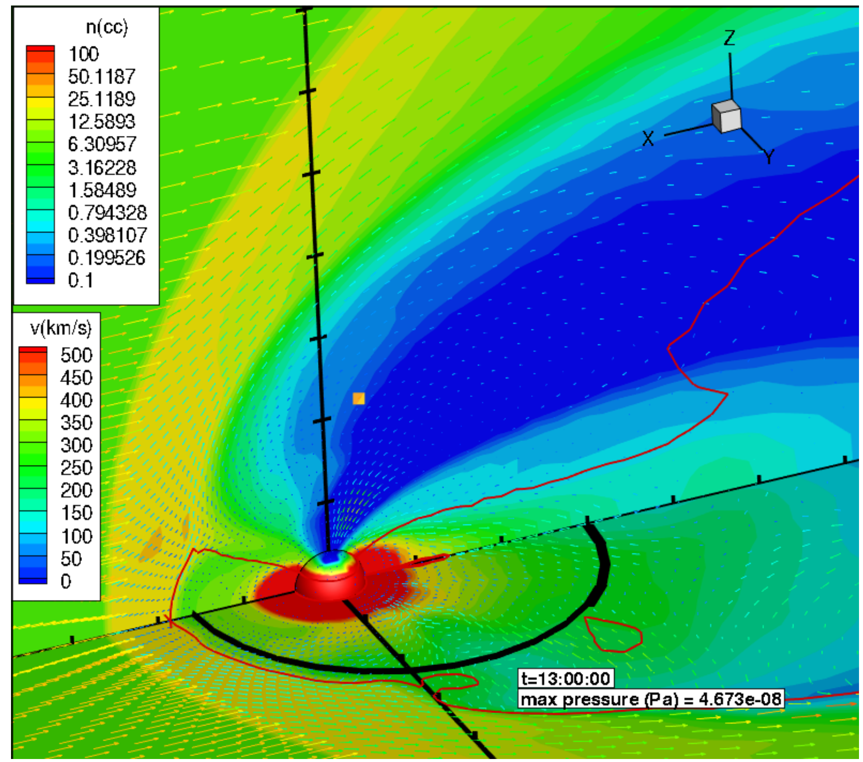
R_0 = Scale height (2 R_E)

Double resolution (53x48x64) – Using a Simple polar cap model

LFM-RCM-MIX – with polar cap model



LFM-RCM-MIX – without polar cap model



Key:		
	Contours:	Density (particles/cc)
	Vectors:	Velocity colored by speed (km/s)
	Red Line:	Bz=0 line
	Black ellipse:	RCM Boundary (approx).

RCM-E simulation of an idealized isolated substorm