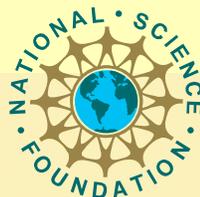


# SWMF at the CCMC and Plans for the Future

Gábor Tóth

Center for Space Environment Modeling





# Outline



## **M** New SWMF features

- Polar Wind Outflow Model (PWOM)
- Radiation Belt Models (RBE and SALAMMBO)
- Plasmasphere Model (DGCPM)
- Graphical User Interface

## **M** New BATS-R-US features

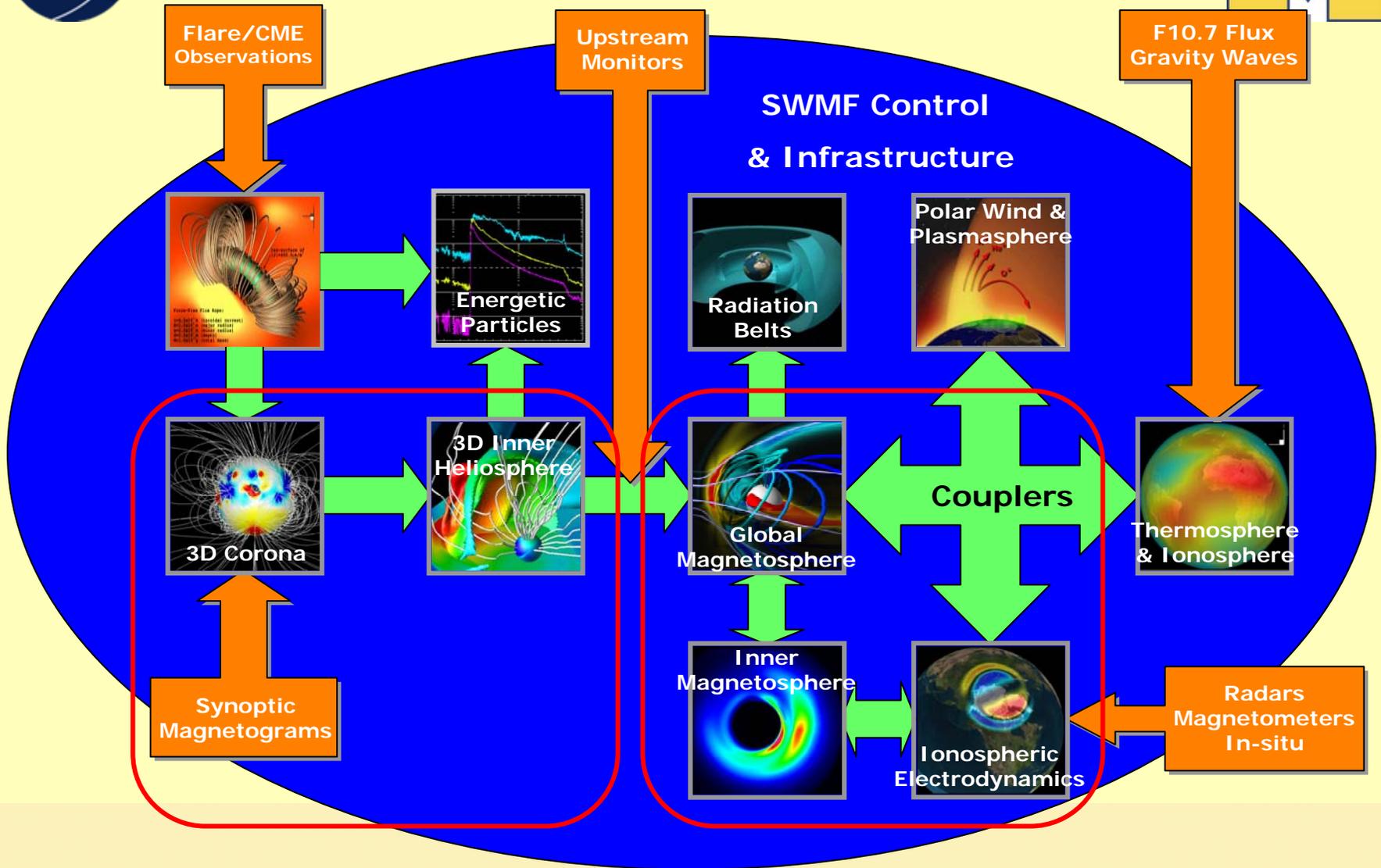
- Hall MHD
- Multifluid MHD
- Improved Roe solver and new HLLD solver
- Non-gyrotropic resistivity model (by Masha)

## **M** Validation Efforts

## **M** Future deliveries to CCMC



# Space Weather Modeling Framework



Available at the CCMC as runs-for-request



# Physics Models in SWMF



<u>Physics Domain</u>	<u>ID</u>	<u>Model(s)</u>	
1. <b>Solar Corona</b>	SC	BATS-R-US	used by CCMC
2. <b>Inner Heliosphere</b>	IH	BATS-R-US	
3. <b>Global Magnetosphere</b>	GM	BATS-R-US	
4. <b>Inner Magnetosphere</b>	IM	RCM	
5. <b>Ionosphere Electrodynamics</b>	IE	RIM	
6. <b>Solar Energetic Particles</b>	SP	Kóta & FLAMPA	at CCMC
7. <b>Eruptive Event Generator</b>	EE	BATS-R-US	
8. <b>Upper Atmosphere</b>	UA	GITM	
9. <b>Polar Wind</b>	PW	PWOM	under development
10. <b>Plasmasphere</b>	PS	DGCPM	
11. <b>Radiation Belt</b>	RB	RBE & SALAMMBO	



# The Global Ionosphere-Thermosphere Model (GITM)

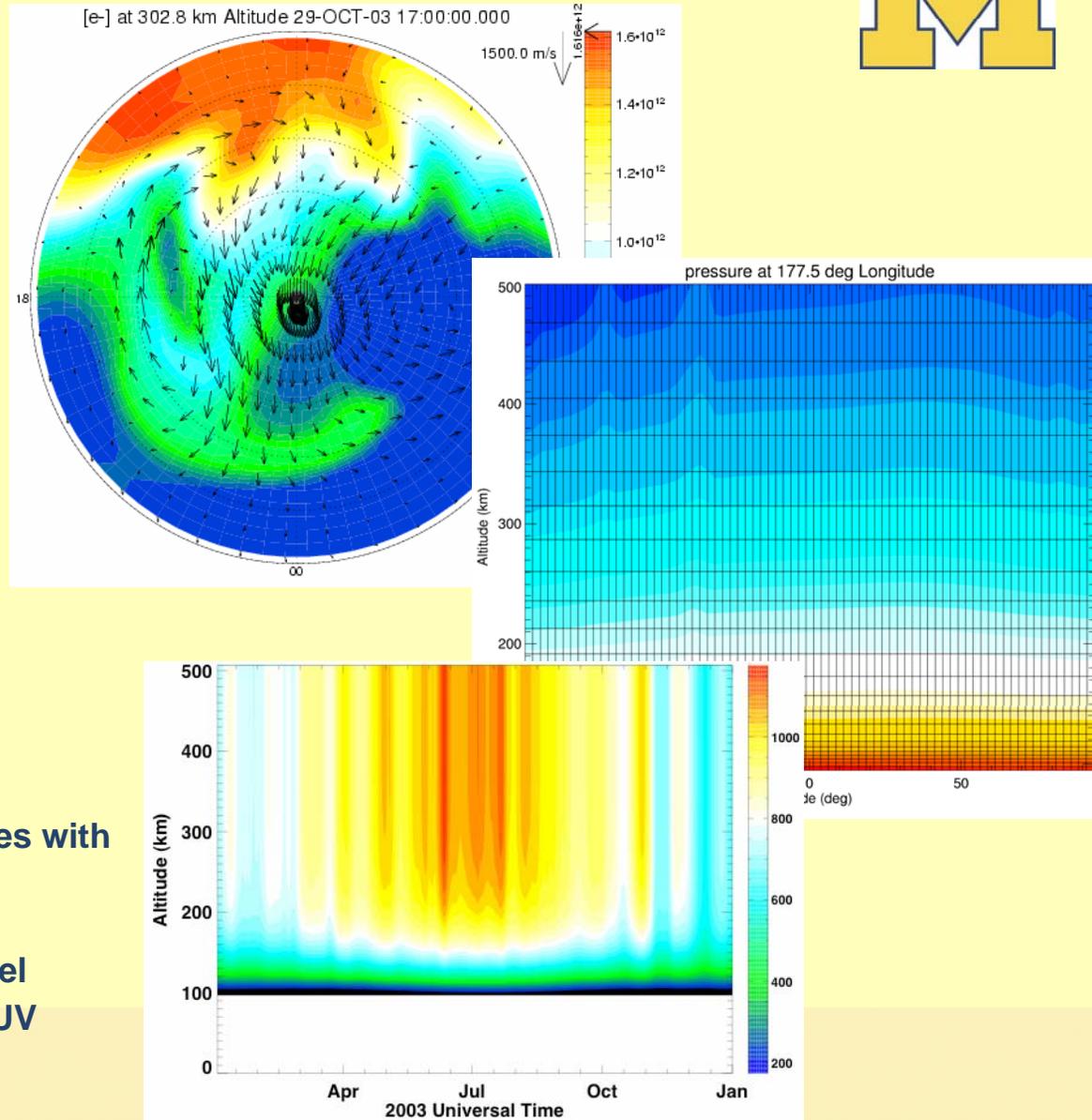


## GITM solves for:

- 6 Neutral & 5 Ion Species
- Neutral winds
- Ion and Electron Velocities
- Neutral, Ion and Electron Temperatures

## GITM Features:

- Solves in Altitude coordinates
- Can have non-hydrostatic solution
  - Coriolis force
  - Vertical Ion Drag
  - Non-constant Gravity
  - Massive heating in auroral zone
- Runs in 1D and 3D
- Vertical winds for each major species with friction coefficients
- Non-steady state explicit chemistry
- Flexible grid resolution - fully parallel
- Variety of high-latitude and Solar EUV drivers
- Fly satellites through model

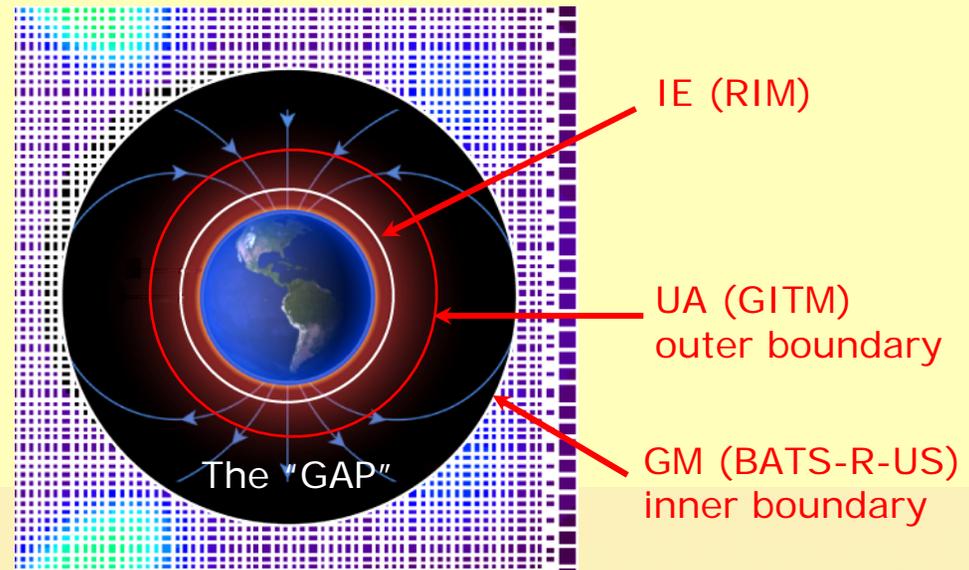




# Polar Wind Outflow Model (PWOM) (Alex Glocer)



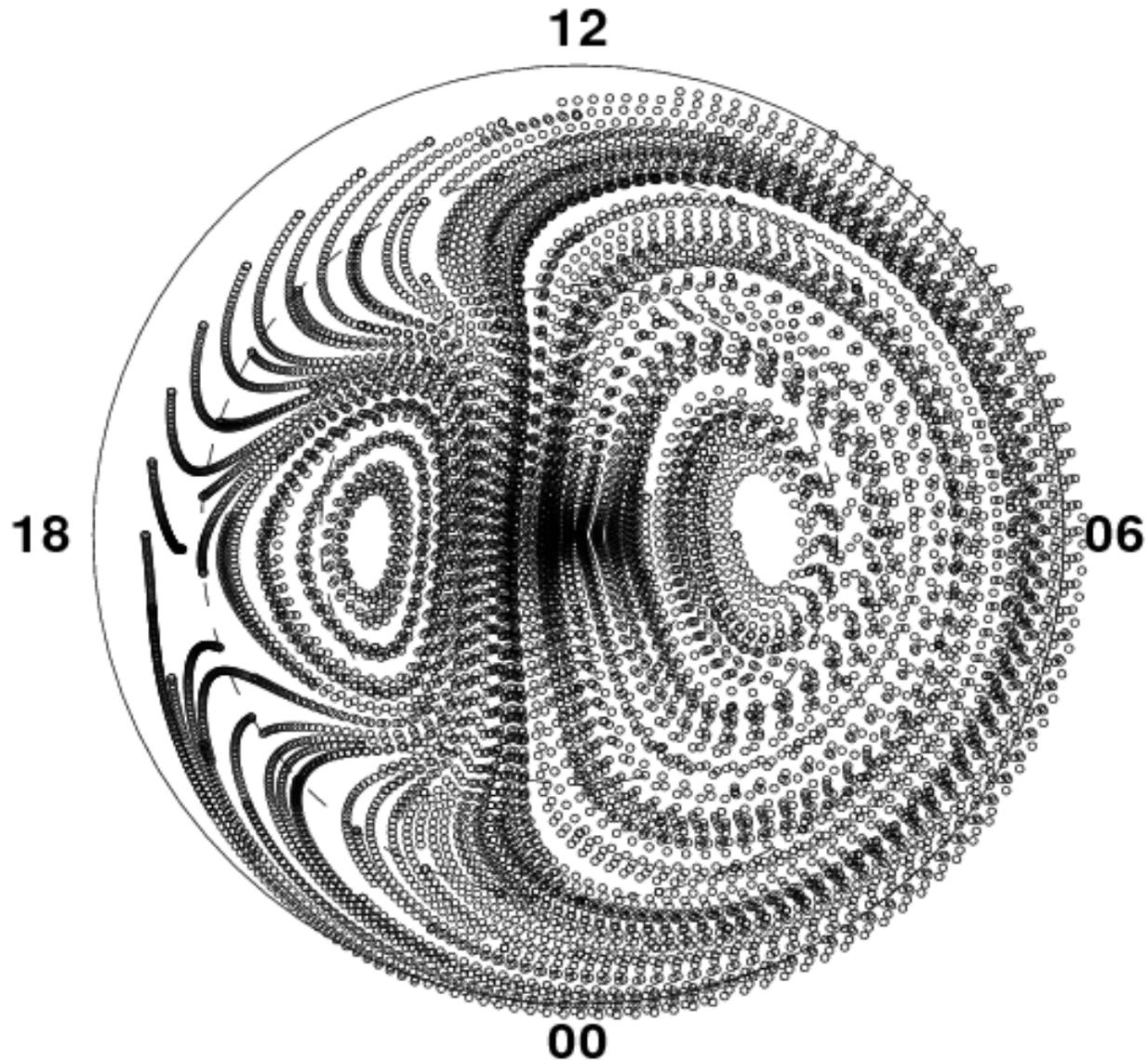
- PWOM solves the time-dependent gyrotropic field-aligned transport equations for  $H^+$ ,  $O^+$ ,  $He^+$  and  $e^-$  along multiple magnetic field lines.**
- Ion-neutral friction, charge exchange drag, field-aligned currents, topside heating, ion and electron heat conduction, solar zenith angle effects, centrifugal force, chemical sources and losses are all included.**
- PWOM is fully parallel**
- Fully implicit time integration**
- First order Godunov and second order Rusanov schemes**
- PWOM provides outflow fluxes (density and velocity) for  $H^+$  and  $O^+$  to GM.**
- PWOM obtains electric potential and field-aligned currents from IE.**





QuickTime™ and a  
BMP decompressor  
are needed to see this picture.

# Overlaid Points Show Convection Pattern





# Dynamic Global Core Plasma Model (Mike Liemohn)



## **M** DGCPM:

- 🌐 Ober et al. [1997] dynamic plasmasphere model
- 🌐 Solves the continuity equation for total flux tube content
  - 🌐 Ionospheric sources and sinks, dayside magnetopause loss
  - 🌐 Carpenter and Anderson [1992] saturation levels
  - 🌐 Fixed or variable ionospheric source

**M** Already very fast (much faster than real time)

**M** Already capable of handling arbitrary B and E

**M** Already modular and can run as part of the SWMF

**M** To do: coupling

- 🌐 It will affect density, but not pressure, in the MHD model
- 🌐 Distributing  $n_e$  along B-field lines is an open issue



# Radiation Belt Environment model (Mei-Ching Fok)



## **M** RBE:

- Solves the 2D drift equations for radiation belt  $e^-$  or  $H^+$
- Includes multiple energies (0.2 - 4 MeV) and pitch angles

**M** Already very fast (faster than real time)

**M** Already capable of handling arbitrary B

**M** Runs stand-alone as well as part of the SWMF

## **M** Coupling

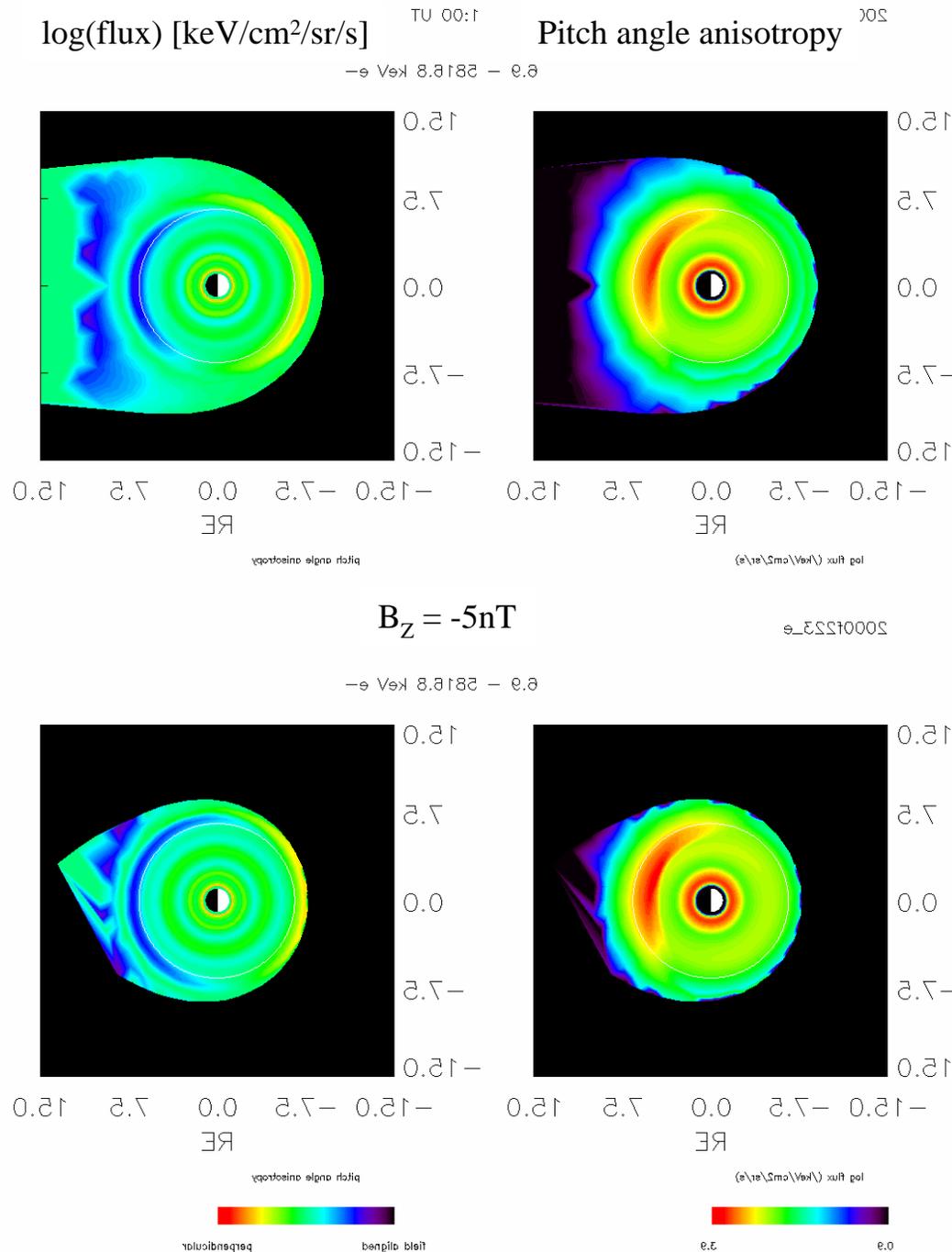
- RBE obtains magnetic field strength and radial distance along closed field lines, and solar wind conditions from GM
- To do: coupling with IE (currently uses Weimer's model)



# Standalone RBE (with Tsyganenko 2004)

vs.

# Coupled Model in SWMF



# SPACE WEATHER MODELING FRAMEWORK

- SWMF GUI
- Home
- SWMF Manual
- REFERENCE Manual
- Create Code Directory
- Configure Code
- GM-IE-IM**
- Compile Code
- Manage Codes
- Create Run Directory
- Setup & Execute Run
- Monitor & Process Run
- Manage Runs
- Create Plots
- Manage Plots
- LINKS
- CSEM

## SWMF GUI: Configure Code "GM-IE-IM"

### Configuration Summary

The selected component versions and settings are:

GM/BATSRUS	grid: 8,8,8,400,100
IE/Ridley_serial	grid: 91,181
IH/Empty	
IM/RCM2	
PW/Empty	
RB/Empty	
SC/Empty	
SP/Empty	
UA/Empty	

[View issued command log](#)

### Configuration Options

Uninstall to throw out configuration changes and start from scratch.

- GM:  BATSRUS  Empty
- IE:  Ridley\_serial  Empty
- IH:  Empty  BATSRUS  BATSRUS\_share
- IM:  RCM2  Empty  RCM
- PW:  Empty  PWOM
- RB:  Empty  RBE  Rice  RiceV5
- SC:  Empty  BATSRUS
- SP:  Empty  FLAMPA  Kota
- UA:  Empty  GITM  GITM2

Extra configure options:  [View Config.pl help for options](#)

### Set Component Grid

Set grid for GM:

Set grid for IE:

**I'm done configuring the code, prepare for compiling.**

# GUI: Code Control

- M** Components of the framework can be easily selected for use.
- M** Some components have multiple versions or even alternative models.





# Parameter Editor GUI



Browser address bar: [http://127.0.0.1:3131/ndex.php?action=set\\_value&id=1,1,2,1&value=T&name=DoSaveRestart](http://127.0.0.1:3131/ndex.php?action=set_value&id=1,1,2,1&value=T&name=DoSaveRestart)

Navigation: CHECK SAVE SAVE AS REOPEN OPEN

File: run/PARAM.in

Actions: DELETE CLIPBOARD SAVE AND EXIT EXIT Help

View: Session 1/CON Insert: #SAVERESTART abc

▼ #TIMEACCURATE

T DoTimeAccurate

#SAVERESTART DONE RESET

T DoSaveRestart

-1 DnSaveRestart (integer, min=-1)

-1 DtSaveRestart (real, min=-1)

▼ #UPDATEB0

-1.0 DoUpdateB0

▼ #DIPOLE

0.0 DipoleStrength

▼ #STOP

100 MaxIteration

10.0 tSimulationMax [sec]

▲ Section CON

▼ Section GM

▼ #USERINPUT

tralala

▲ #USERINPUT

▼ #TIMESIMULATION

100.0

▼ #NSTEP

## Manual

```
#SAVERESTART
T DoSaveRestart (Rest of parameters read if
-1 DnSaveRestart
-1. DtSaveRestart
```

The DoSaveRestart variable determines whether restart information should be saved or not. The rest of the parameters are read only if DoSaveRestart is true. For steady state runs the frequency of saving restart information is given by the DnSaveRestart variable in terms of the number of time steps nStep, while for time accurate run, the DtSaveRestart variable determines the frequency in terms of the simulation time tSimulation in seconds. Negative frequencies mean that no restart information is saved during the run, but they do not exclude the saving of the restart information at the very end.

The default is given above, which means that restart information is saved at the end of the run.

## SPACE WEATHER MODELING FRAMEWORK

## SWMF GUI: Create Plots for "2003-Oct-29"

COMPONENT [GM](#)

## Select desired plot options and 'Update Plot'

Plotfile: T=Hour:Min:Sec N=Iterations (6 files found)

T=0004:00:00 N=0018764

## Contour

Variable: VS: U\_x [km/s] Range:  Min/Max  Custom

## Slice:

Slice 1:  No Slice  X=  Y=  Z= 0.Slice 2:  No Slice  X=  Y=  Z= 0.Plot grid on slices?  No  Yes

## Isosurface:

 No  Yes Variable = p [nPa] Value = 50.

## View:

Center at: X= 0. Y= 0. Z= 0. with view width 30.

Perspective angles: Phi= 80. Theta= 160. ([Help me with view angles.](#))

## Vector Traces:

Plot last closed fieldlines?  No  Yes (5-10 minutes render time)

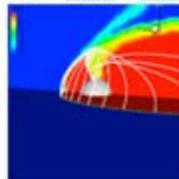
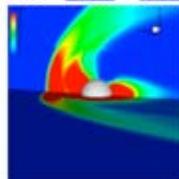
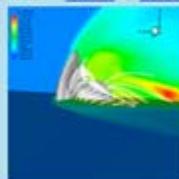
## Body:

Plot sphere at origin?  No  Yes with radius 2.7

## Text Label:

Label:  (wait ~1 minute unless fieldlines plotted)

Copyright © 2006. All rights reserved.

Plottype: 3Dplt  
GM Plot Styles008 [movie](#) [delete](#)010 [movie](#) [delete](#)013 [movie](#) [delete](#)GUI:  
VisualizationSWMF GUI  
Home  
SWMF Manual  
REFERENCE ManualCreate Code Directory  
Configure Code  
Compile Code  
Manage CodesCreate Run Directory  
Setup & Execute Run  
Monitor & Process Run  
Manage Runs

## Create Plots

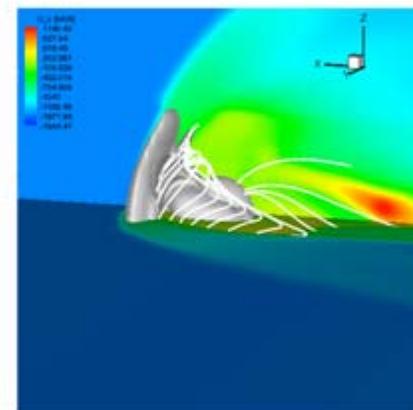
1998-05-04\_SWMF  
2000-07-15\_SWMF  
2001-03-31\_SWMF  
2001-08-04\_SWMF  
2002-04-17\_SWMF  
2003-11-20\_SWMF  
2003-Oct-29  
debug1  
debug2

## Manage Plots

LINKS  
CSEM

UNIVERSITY OF MICHIGAN

- M** Visualize run output using quality templates with many customizable options.
- M** Outputs postscript, png, animated gif, ...

Plot Results: M\_var\_3\_00040000\_0018764.plt  
http://localhost:8080/plot\_results/createplot.php  
File=M\_var\_3\_00040000\_0018764.plt, T=0004:00:00 N=0018764, Style=013

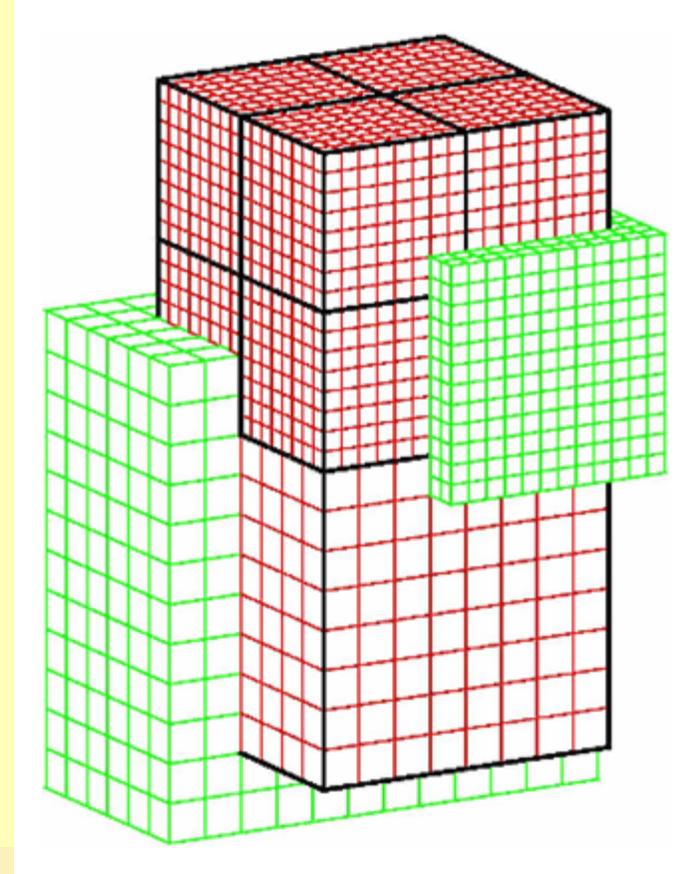


# MHD Code: BATS-R-US



## *Block Adaptive Tree Solar-wind Roe Upwind Scheme*

- M** Conservative finite-volume discretization
- M** Shock-capturing TVD schemes
  - Rusanov, HLL/AW, **Roe**, **HLLD**
- M** Parallel block-adaptive grid
- M** Cartesian and generalized coordinates
- M** Explicit and implicit time stepping
- M** Classical, semi-relativistic and **Hall MHD**
- M** Multi-species and **multi-fluid MHD**
- M** Splitting the magnetic field into  $B_0 + B_1$
- M** Various methods to control divergence  $B$



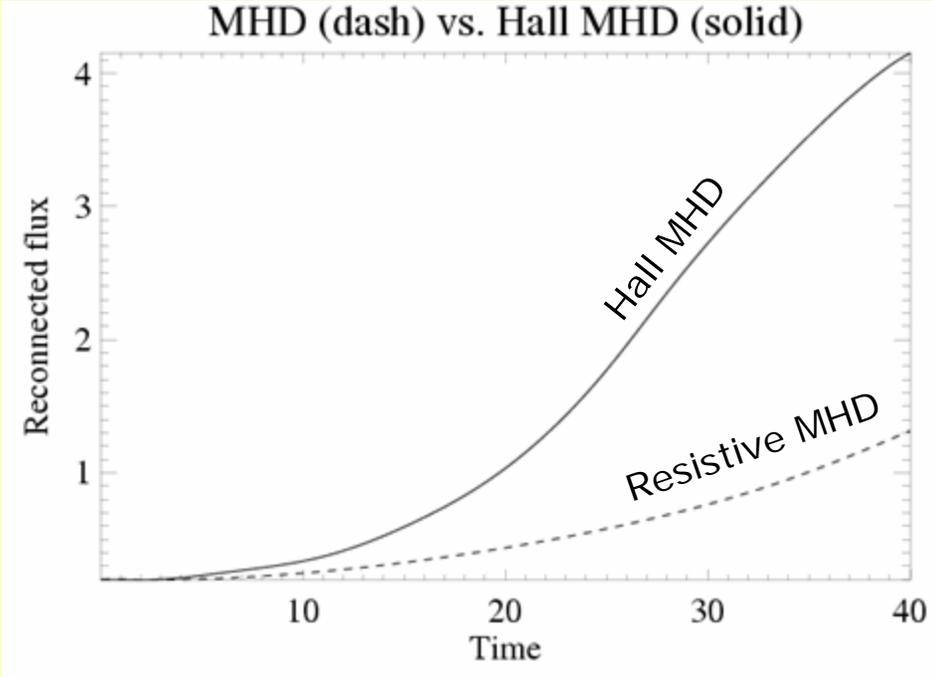


# Hall MHD (Gabor Toth & Yingjuan Ma)

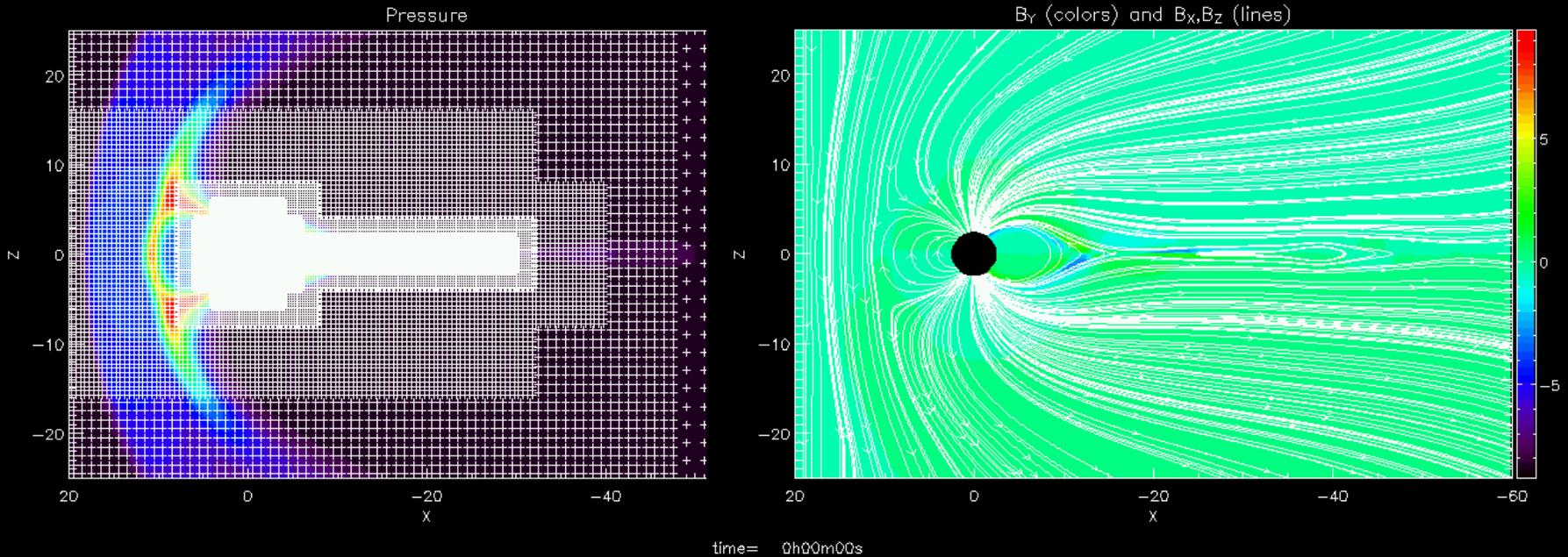


- Hall physics can play a critical role in collisionless magnetic reconnection.
- The GEM challenge on reconnection physics concluded that Hall physics is the minimum physics needed to achieve fast reconnection (Birn et al., JGR, 106, 3715, 2001).
- Physically, the Hall term decouples the ion and electron motion on length scales comparable to the ion inertial length ( $\delta = c/\omega_{pi} = V_A/\Omega_{ci}$ ). In essence, the electrons remain magnetized while the ions become unmagnetized.
- Consequences:
  - Whistler wave (very fast)
  - Introduces asymmetry
  - Ion kinetics can lead to fast reconnection

$$\mathbf{E} = -(\mathbf{u} + \mathbf{u}_{H}) \times \mathbf{B} + \eta \mathbf{j} \quad \mathbf{u}_{H} = -\frac{\mathbf{j}}{c4\pi e}$$



GEM Challenge simulation with BATS-R-US

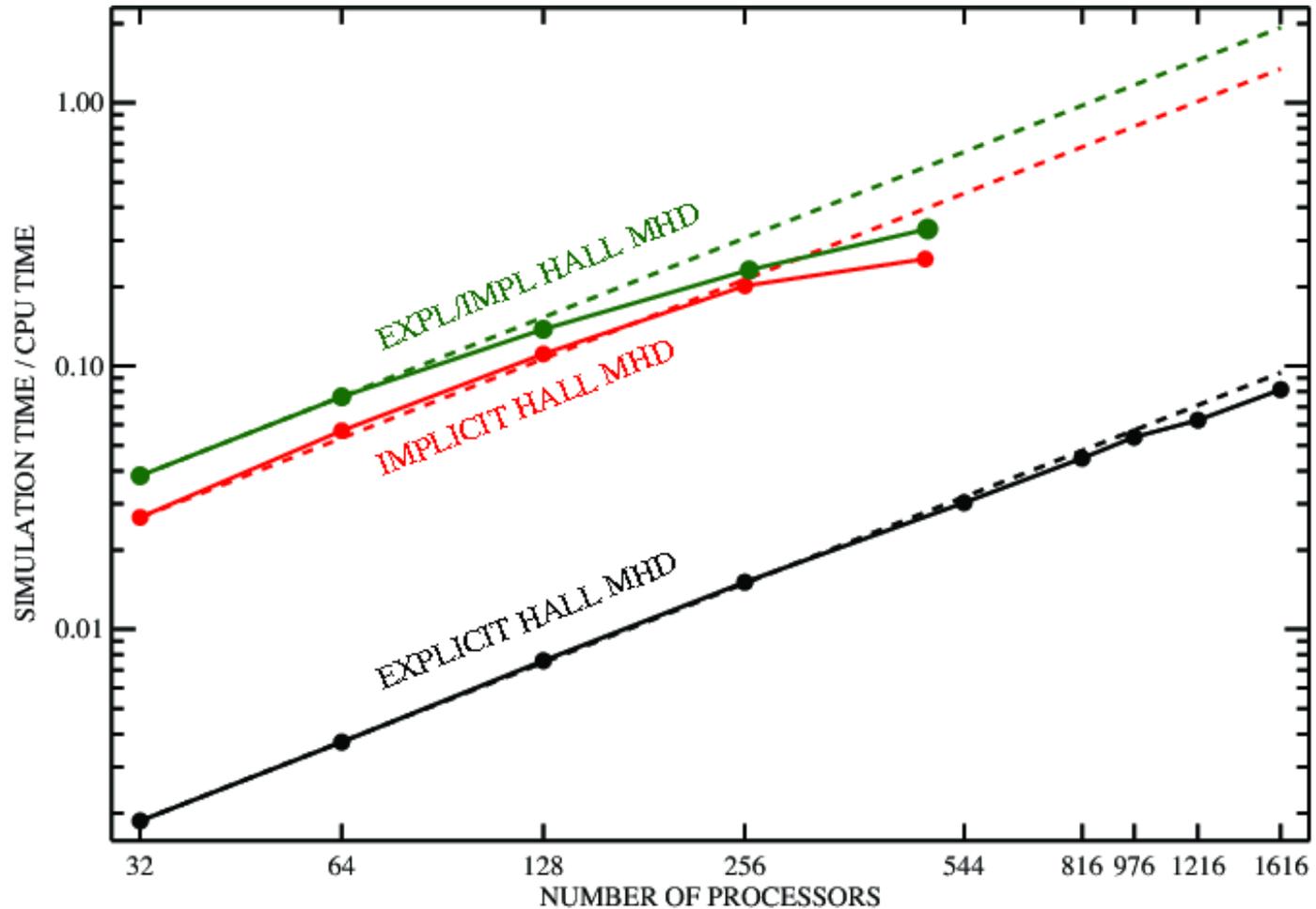


48,04 blocks with 8x8x8 cells  
(total 2.5 million cells) ranging  
from 8 to  $1/16 R_E$ .

Solution shows blobs of plasma  
detaching in the tailward direction.  
Time scale is a few minutes.



# Parallel Scaling for Hall MHD



Grid: 4804 blocks with 8x8x8 cells (2.5 million cells) ranging from 8 to 1/16  $R_E$ . Simulations done on an SGI Altix machine.



# Non-Gyrotropic Reconnection Model (Masha Kuznetsova)



## Idea:

- Use full particle and hybrid simulations to construct a phenomenological but quantitatively accurate reconnection model

## Algorithm:

- Find reconnection sites
- Fit an appropriately sized 'box' around it
- Modify the electric field (and thus the induction equation) based on the model.

## Advantage:

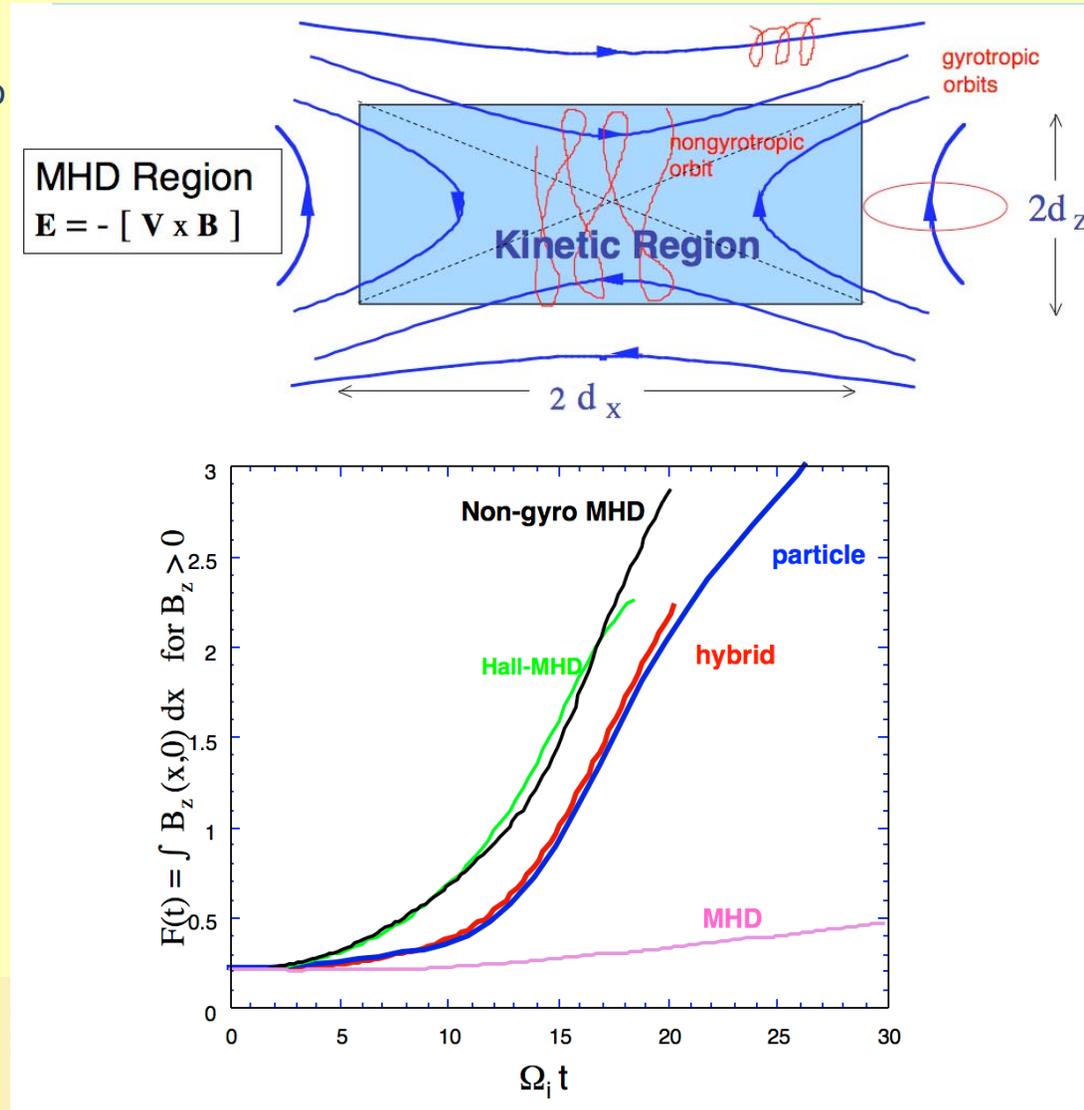
- Allows fast reconnection
- Efficient and simple

## Disadvantage:

- Finding reconnection site is not easy
- Ad-hoc parameters need tuning

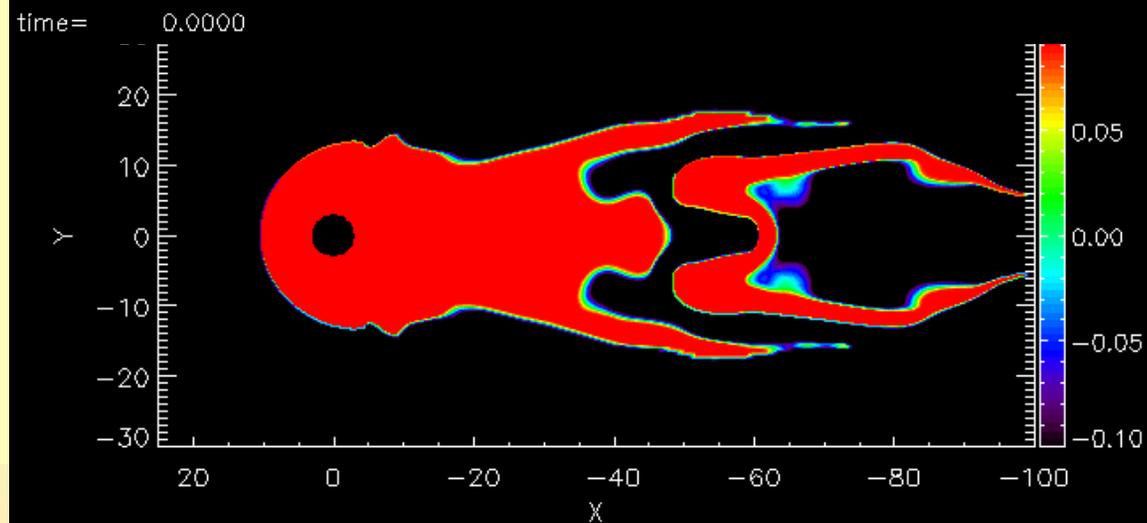
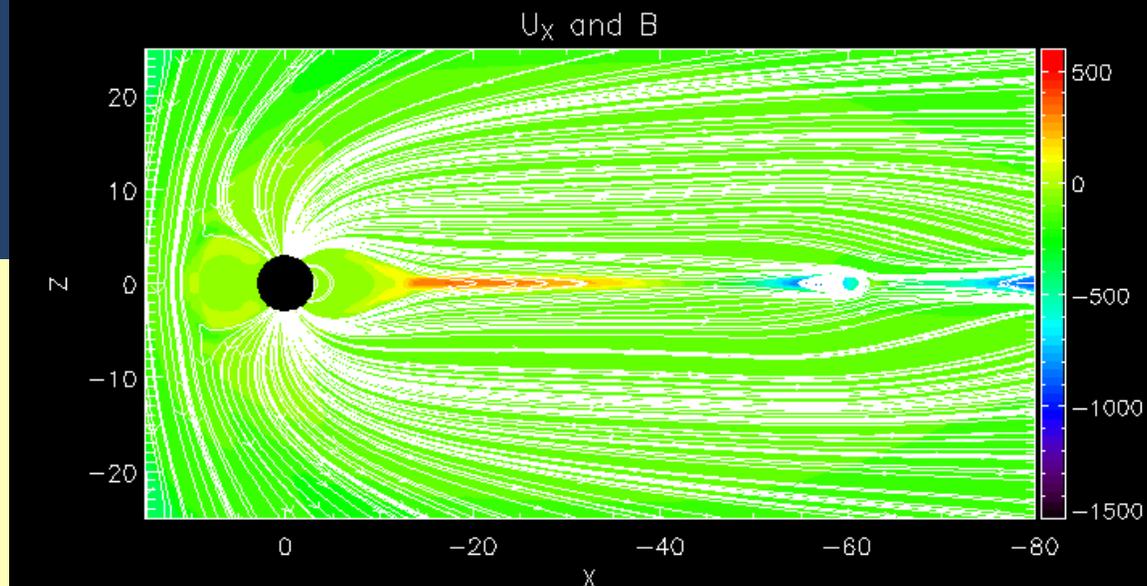
## To do:

- Find reconnection site and its orientation in general configurations
- Validate/tune model against/for events



# Non-Gyrotropic Reconnection Model simulation with the latest version of BATS-R-US

- Solution shows large blobs of plasma detaching in the tailward direction (similar to Masha's earlier results).
- Time scale is more than an hour.
- Reconnection line is strongly curved in the  $Y=0$  plane.





# Multi-Fluid MHD (Gabor Toth & Yingjuan Ma)



- Multi-Fluid MHD has many potential applications
  - ionospheric outflow, outer heliosphere interaction with inter stellar medium, etc.
- We have implemented a general multi-fluid solver with arbitrary number of ion and neutral fluids.
- Each fluid has a separate density, velocity and temperature.**
- The fluids are coupled by collisional friction/charge exchange and/or by the magnetic field.
- We are still working on improving the stability/efficiency of the scheme.

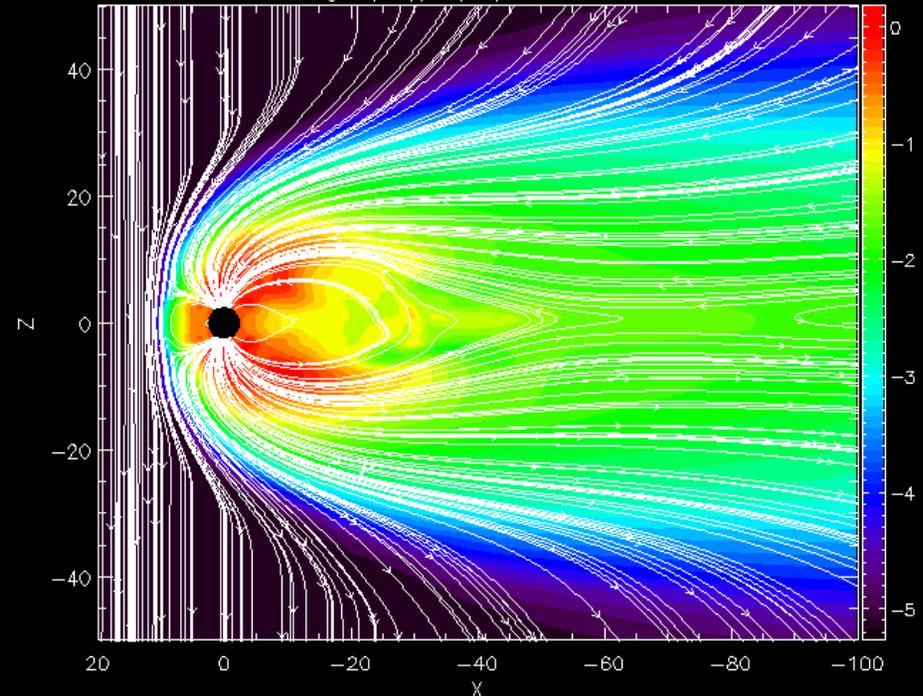
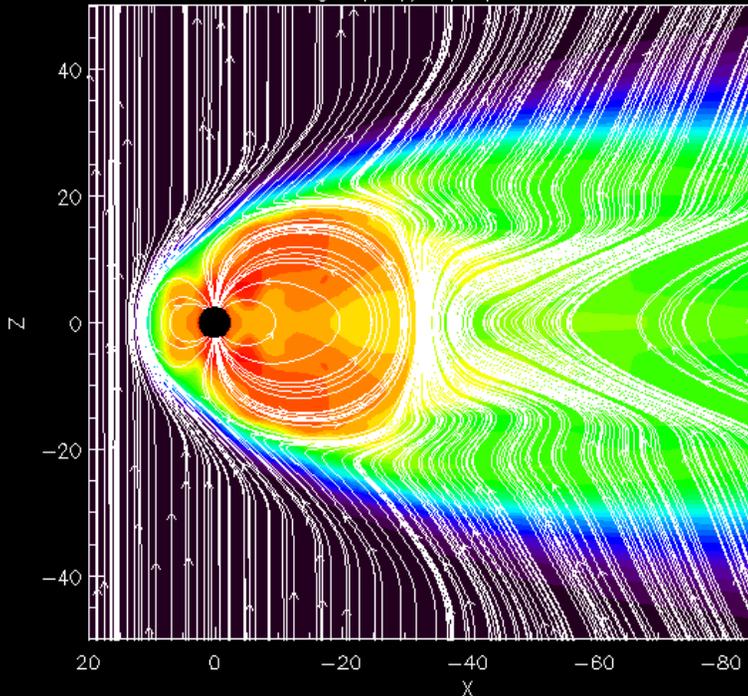
$B_z = +5\text{nT}$

$n(\text{O}^+)/n(\text{H}^+)$

$B_z = -5\text{nT}$

$\log n(\text{O}^+)/n(\text{H}^+)$  and  $B_x - B_z$

$\log n(\text{O}^+)/n(\text{H}^+)$  and  $B_x - B_z$

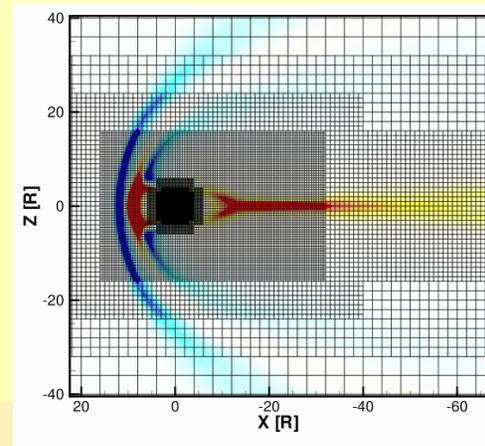
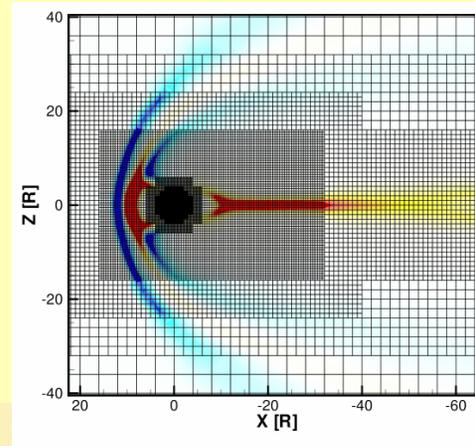
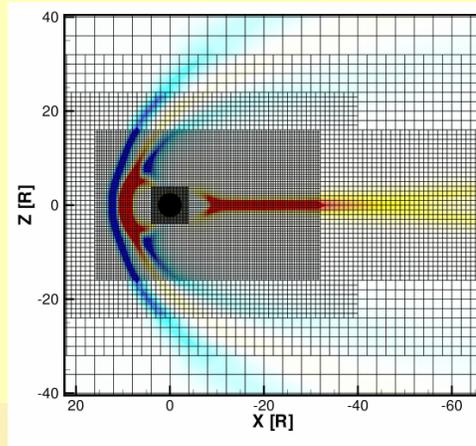
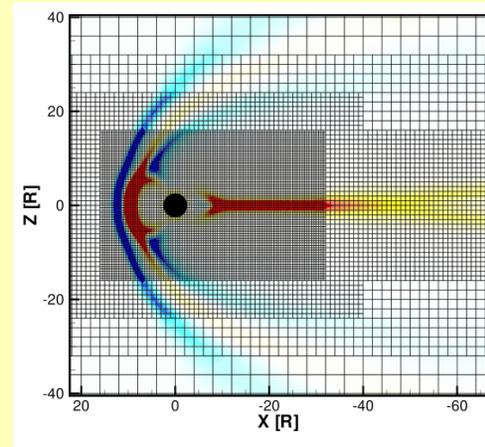
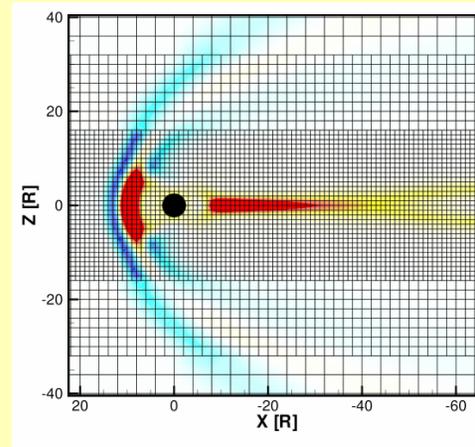




# Verification Study: Effect of Numerics on CPCP



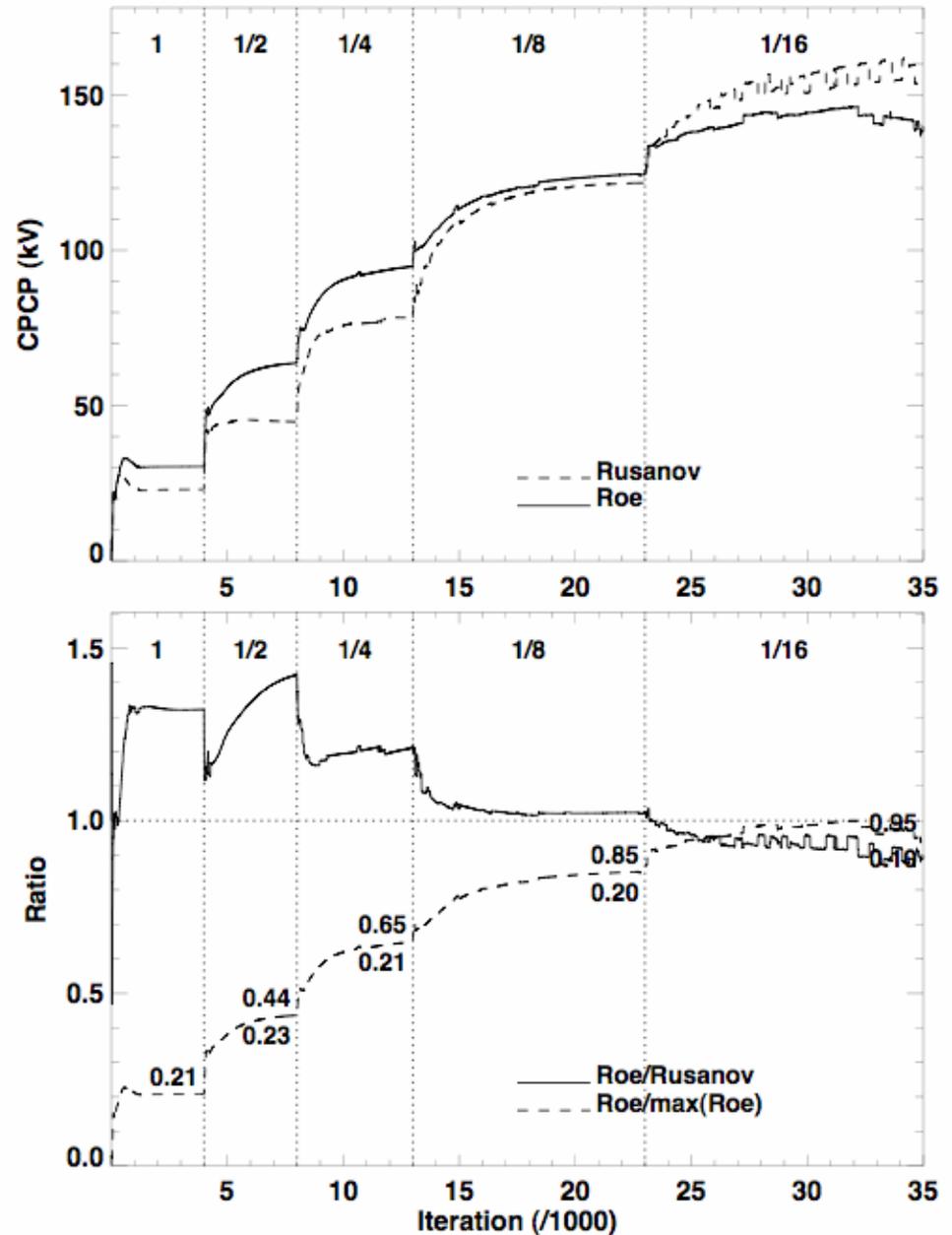
- Change resolution from 1.0 Re near body to 1/16 Re near body
- Run to steady state at each resolution
- Use various solvers/options to investigate numerical effects



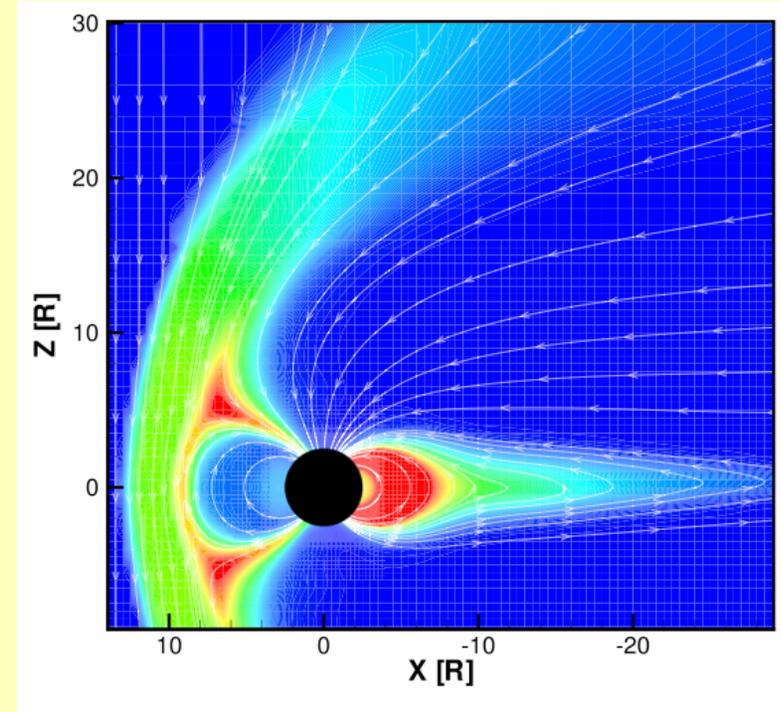
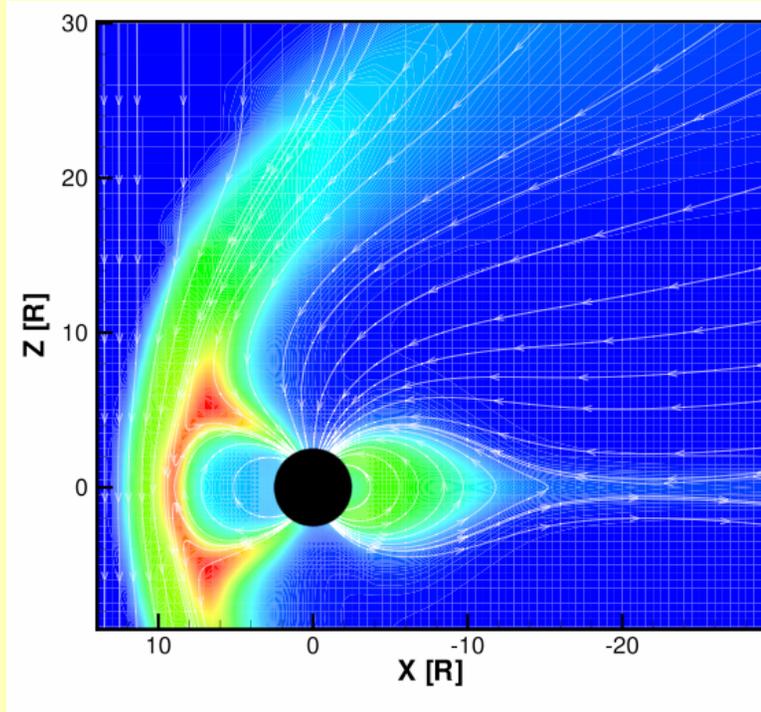
# Grid Convergence and Rusanov vs Roe Scheme



- The CPCP starts to converge at the highest resolutions only**
- Rusanov scheme is a very robust algorithm**
- Roe solver has much less numerical diffusion**
- Roe has larger CPCP than Rusanov on coarse grids (as expected), but smaller CPCP at high resolution. Why???**



# Pressure in the $Y=0$ Plane Rusanov vs Roe



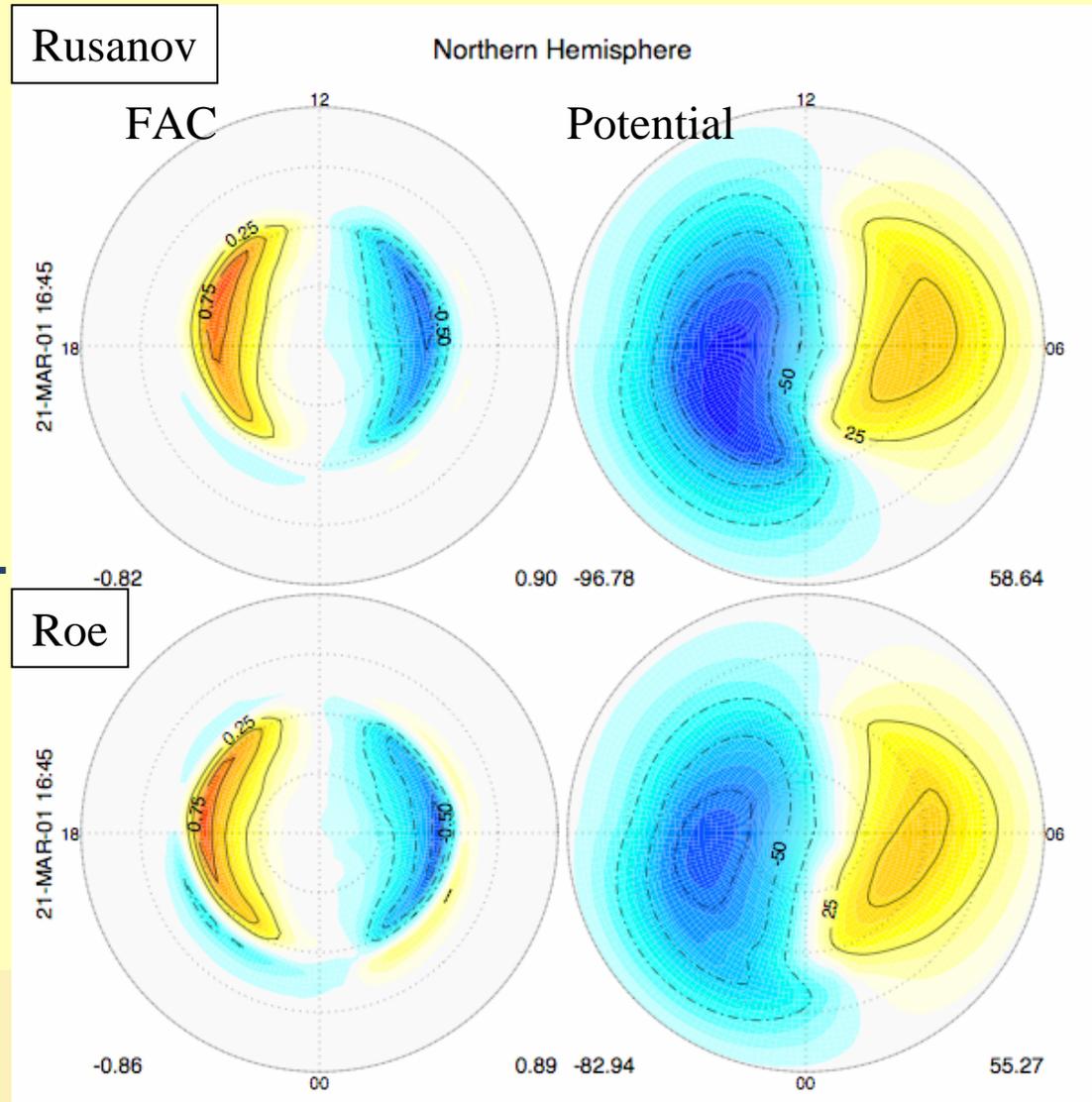
- M** Pressure in the tail is MUCH larger for the Roe solver
- M** Field-lines are greatly stretched in tail
- M** Solution looks much better!



# Ionosphere solution for Rusanov (top) vs Roe (bottom)



- Notice Region-2 currents on night-side in Roe simulation (bottom).
- Stronger region-2 currents allow Pedersen currents to close towards lower latitudes, thereby reducing the potential.
- This is why the Roe solver produces a lower potential.

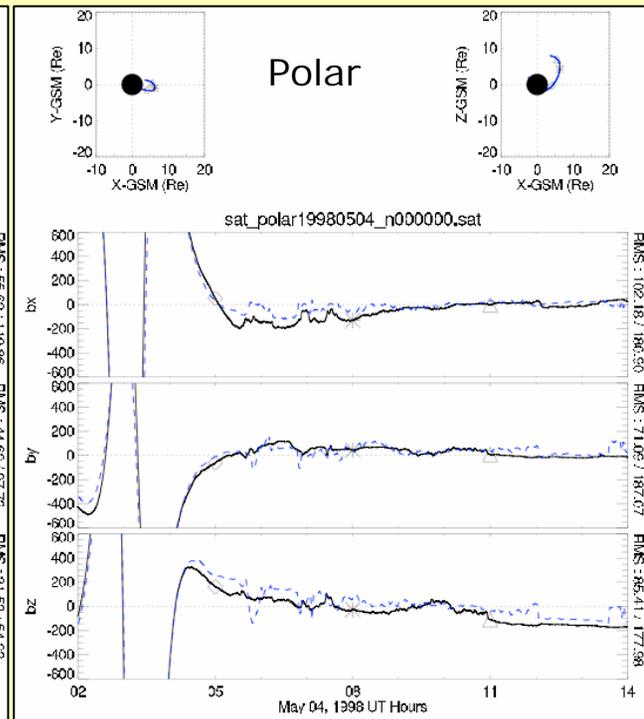
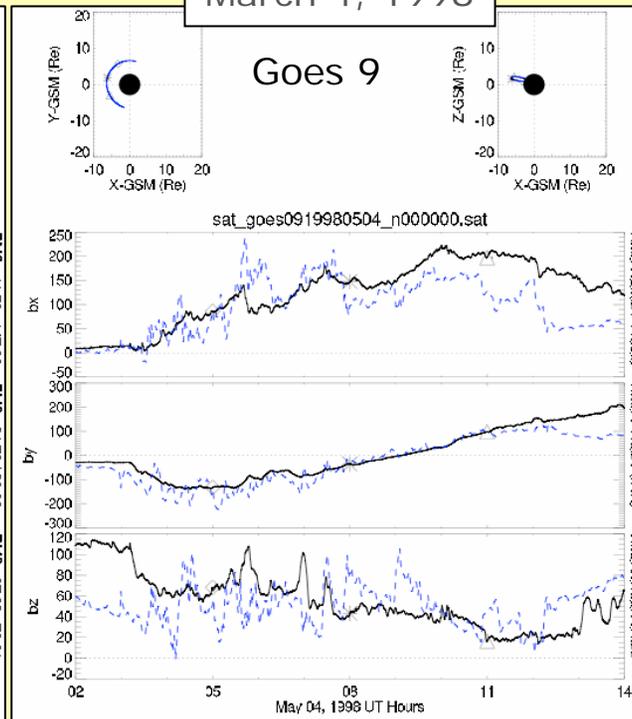
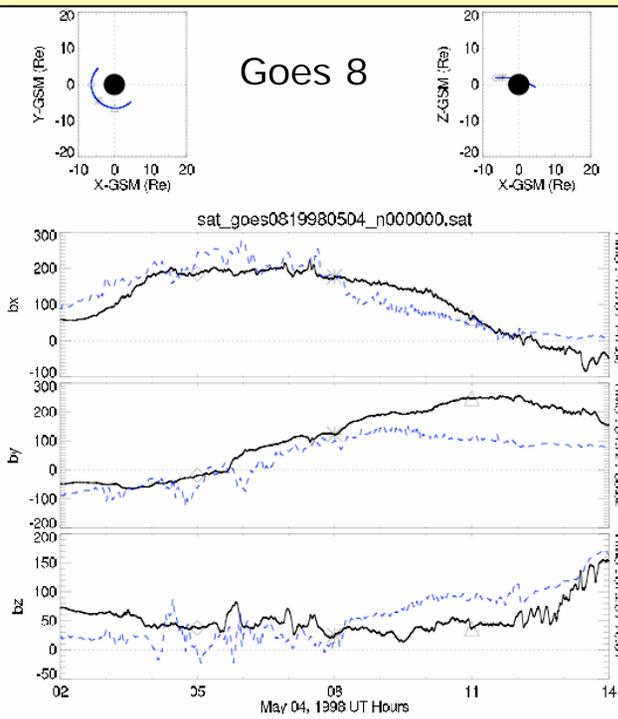




# Multi-Spacecraft / Multi-Storm Validation (Aaron Ridley)



March 4, 1998



- Started to systematically and quantitatively validate the SWMF
- Track improvements in the code in a quantitative manner
- Run 10 time-periods ranging from quiet to superstorm
- Automatically downloads code and runs each event
- We validate against 150+ magnetometers, DMSP, CHAMP, GOES, Polar...



## Future Deliveries to CCMC



- M** CCMC already has a recent version of the SWMF.
- M** **GITM** could be added to the magnetosphere simulations.
- M** **Improved Roe solver** could be a new option in BATS-R-US.
- M** **Hall and Multi-Fluid MHD** could also be used after some validation and improvements.
- M** **PWOM, RBE, SALAMMBO and DGCPM** will be delivered once they are fully coupled and tested.
- M** **SWMF GUI and Parameter Editor** may be useful for CCMC.