Space Weather Modeling Framework: present and future

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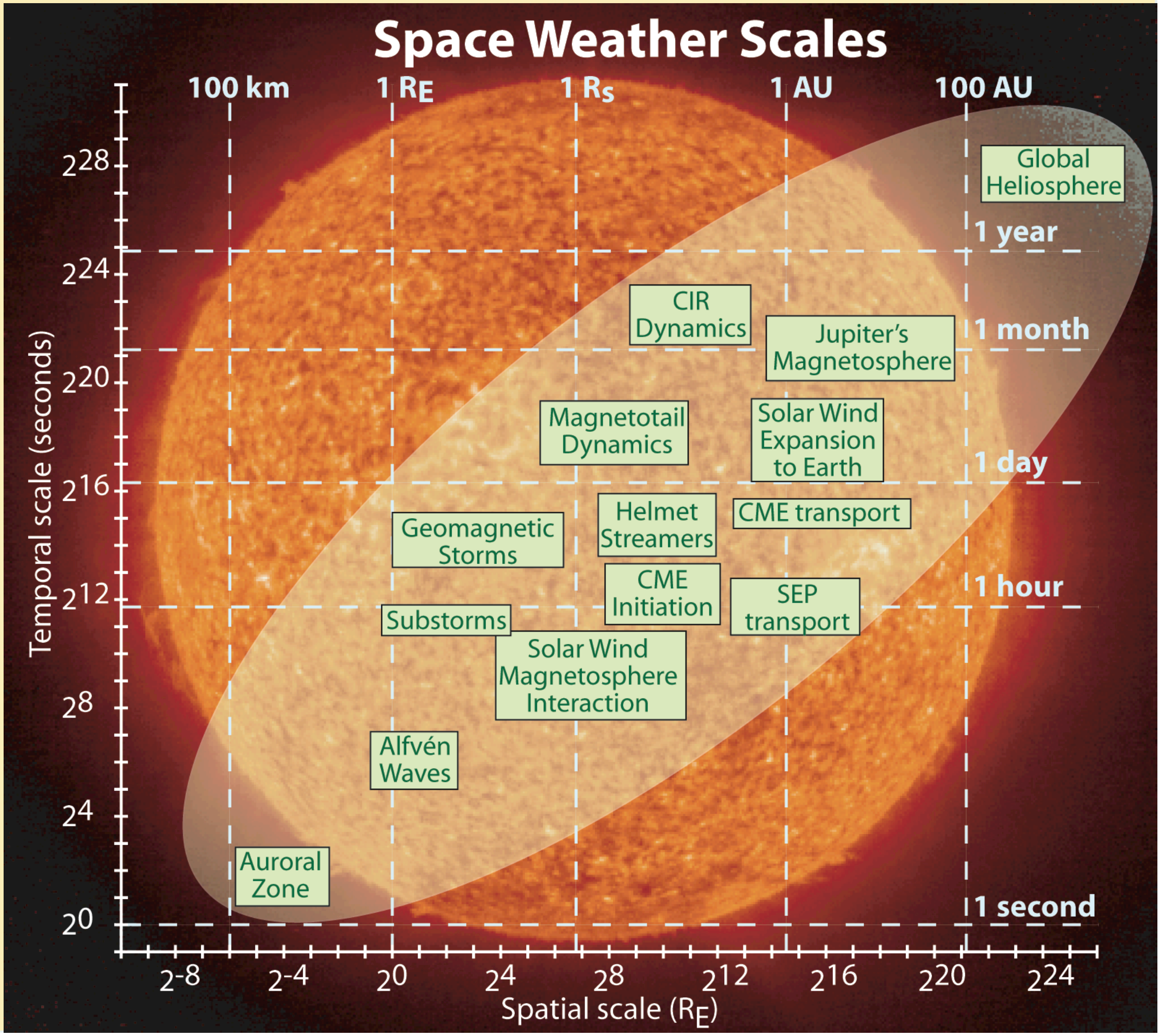
Outline

- Space Weather Modeling Framework
- Present and future models
- Present and future physics in BATSRUS
  - Hall MHD
  - Multi-ion MHD
  - MHD with non-isotropic pressure
- Summary

The Challenge of Scales

- **Temporal scale:**
  $\sim 2^{28} \approx 2.5\text{x}10^{8}$
- **Length scale:**
  $\sim 2^{28} \approx 2.5\text{x}10^{8}$
- **Volume ratio:**
  $\sim 2^{84} \approx 2\text{x}10^{25}$



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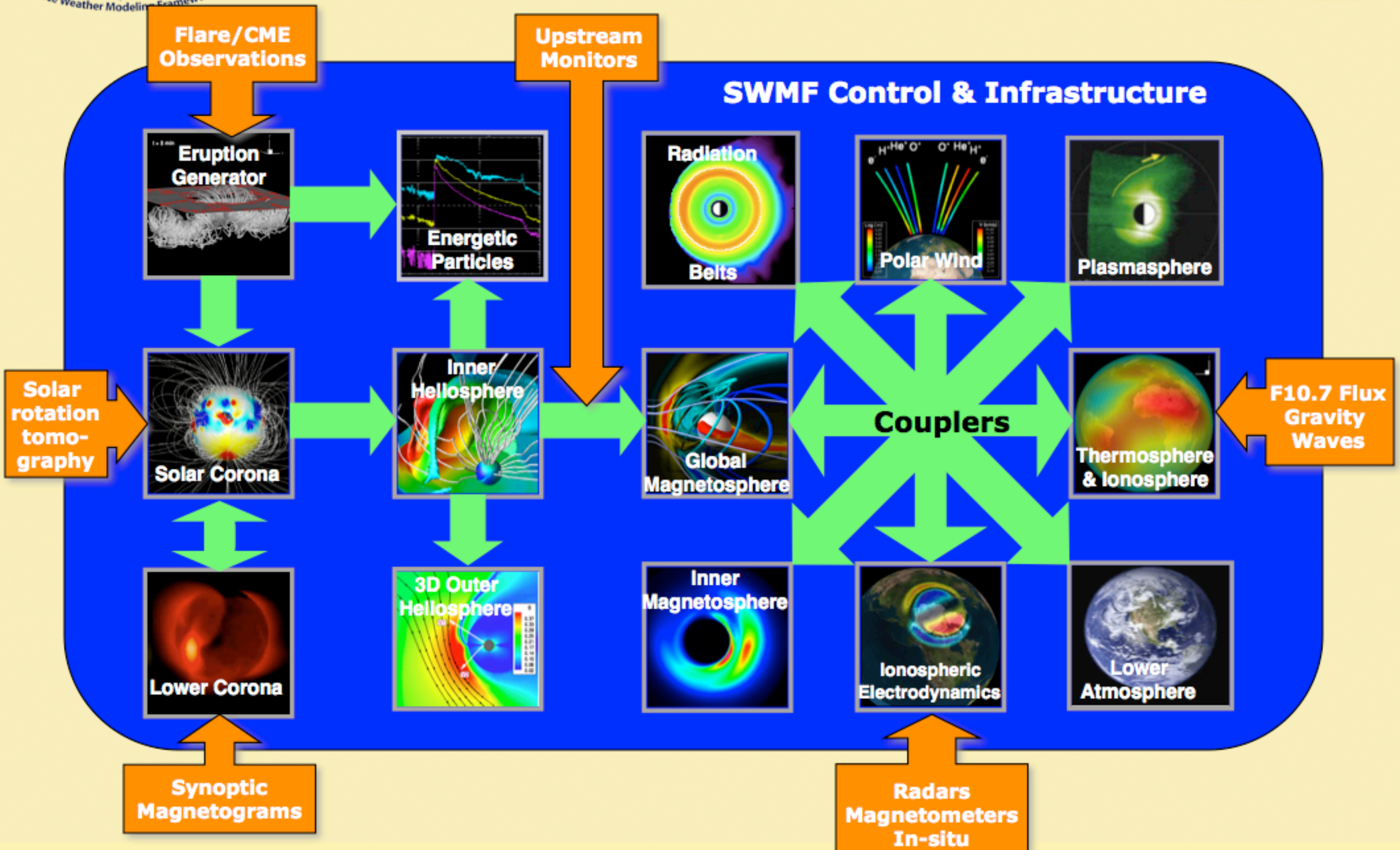
From Codes To Framework

- The Sun-Earth system consists of many different interconnecting domains that are independently modeled.
- Each physics domain model is a separate application, which has its own optimal mathematical and numerical representation.
- Our goal is to integrate models into a flexible software framework.
- The framework incorporates physics models with minimal changes.
- The framework can be extended with new components.
- The performance of a well designed framework can supercede monolithic codes or ad hoc couplings of models.

Space Weather Modeling Framework



SWMF is freely available at http://csem.engin.umich.edu and via CCMC

Center for Space Environment Modeling
SWMF
Space Weather Modeling Framework

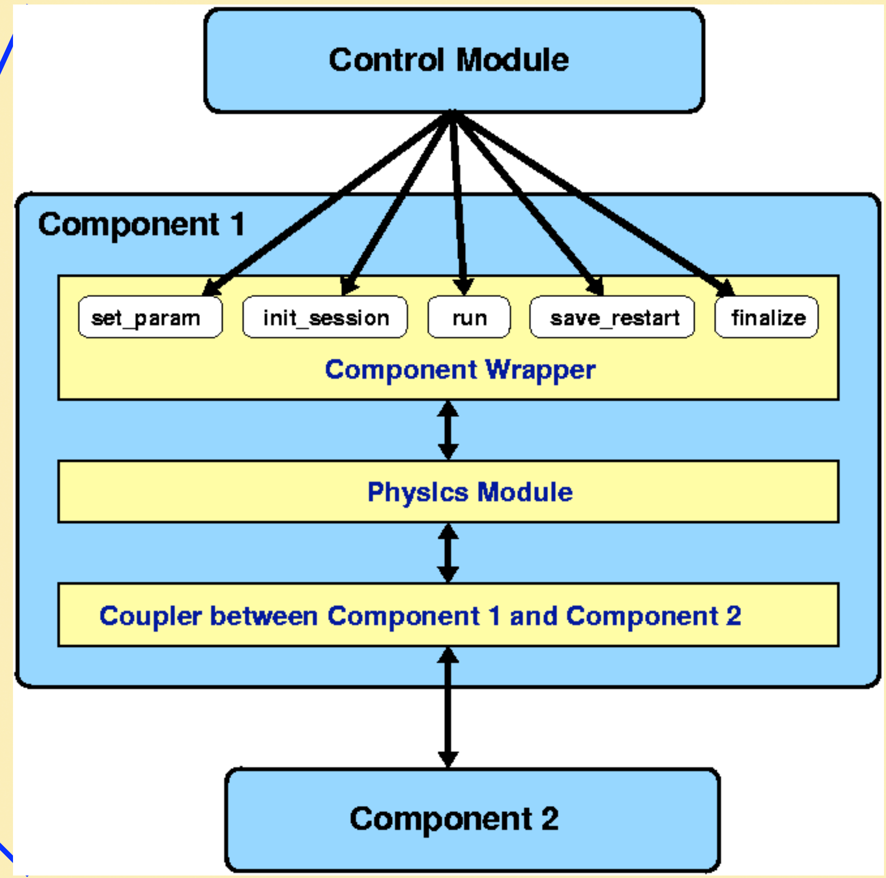
Physics & Empirical Models in SWMF

	Physics Domain	ID	Physics / Empirical Models
1.	Solar Corona	SC	BATS-R-US
2.	Eruptive Event Generator	EE	BATS-R-US / breakout, TD, GL
3.	Inner Heliosphere	IH	BATS-R-US
4.	Outer Heliosphere	OH	BATS-R-US
5.	Solar Energetic Particles	SP	Kóta & FLAMPA
6.	Global Magnetosphere	GM	BATS-R-US / Tsyganenko
7.	Inner Magnetosphere	IM	RCM, CRCM, HEIDI, RAM+SCB
8.	Ionosphere Electrodynamics	IE	RIM / Weimer
9.	Upper Atmosphere	UA	GITM / MSIS, IRI
10.	Radiation Belt	RB	RBE
11.	Polar Wind	PW	PWOM
12.	Plasmasphere	PS	DGCPM
13.	Lower Atmosphere	LA	SOCOL

Orange: under development

The SWMF Architecture

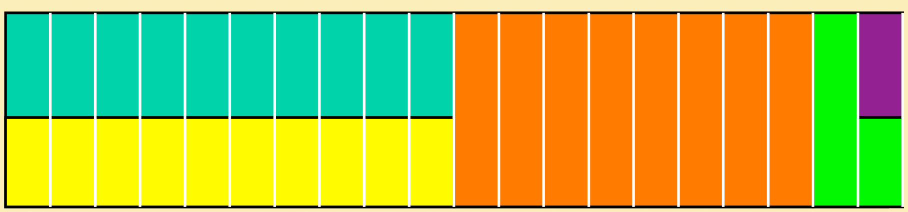
User Interface Layer	**Web based Graphical User Interface** configuration, problem setup, job submission job monitoring, result visualization
Superstructure Layer	**Framework Services** component registration, input/output execution control, coupling toolkit **Component Interface** component wrappers and couplers
Physics Module Layer	**SC** BATSRUS **SP** Kota **IM** RCM
Infrastructure Layer	**Utilities** physics constants, time and date conversion coordinate transformation, field line tracing parameter reading, I/O units, profiling

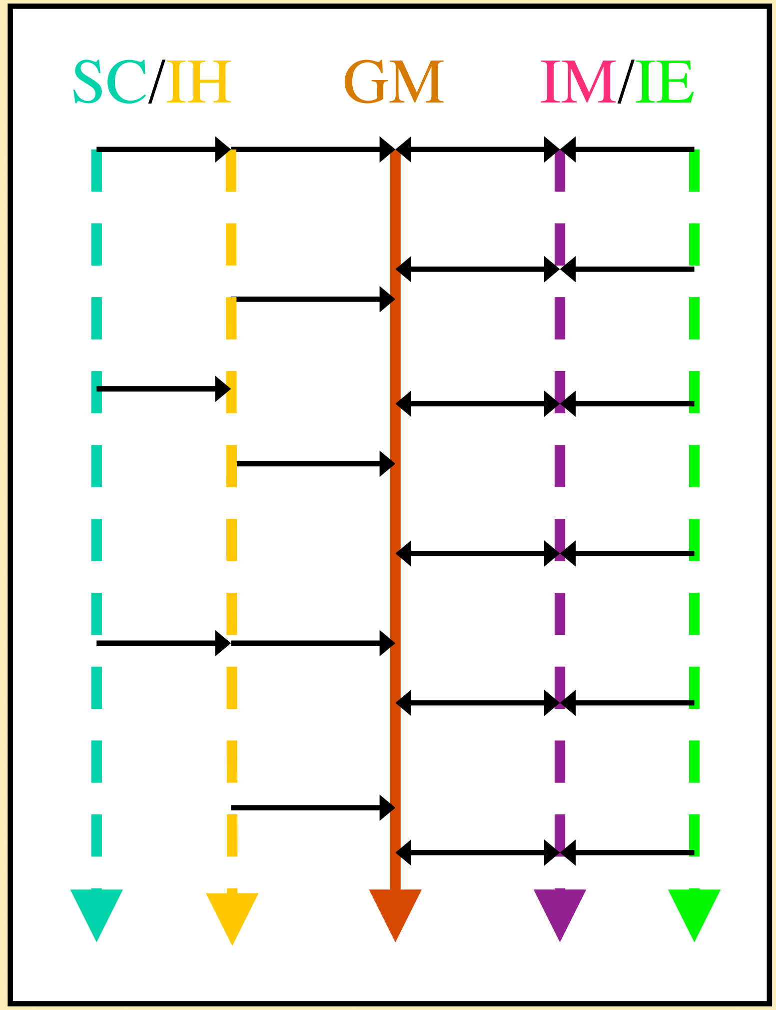


Parallel Layout and Execution

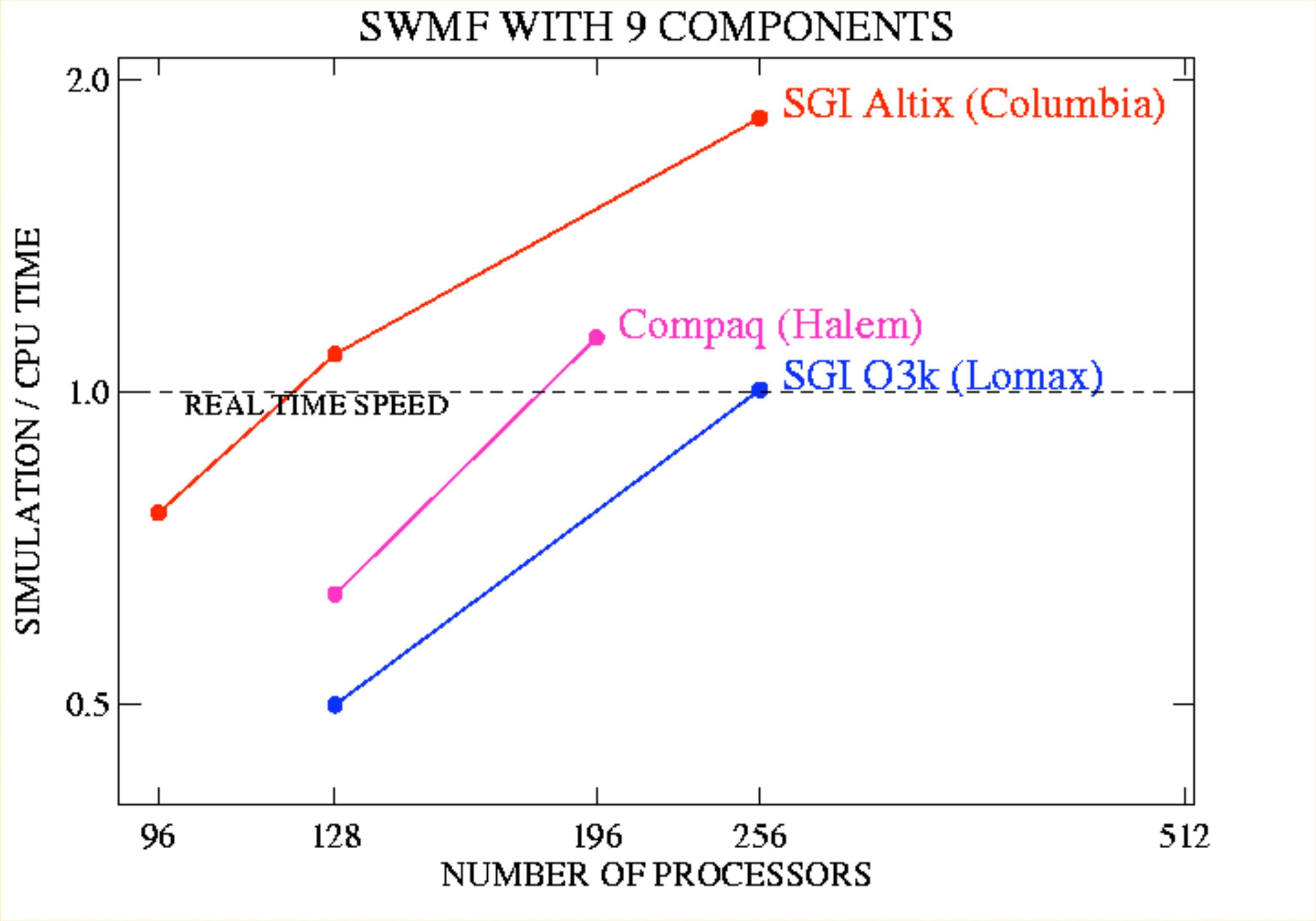
LAYOUT.in for 20 PE-s

```
ID   ROOT   LAST  STRIDE

#COMPONENTMAP

SC       0      9       1

IH       0      9       1

GM      10     17       1

IE      18     19       1

IM      19     19       1

#END
```

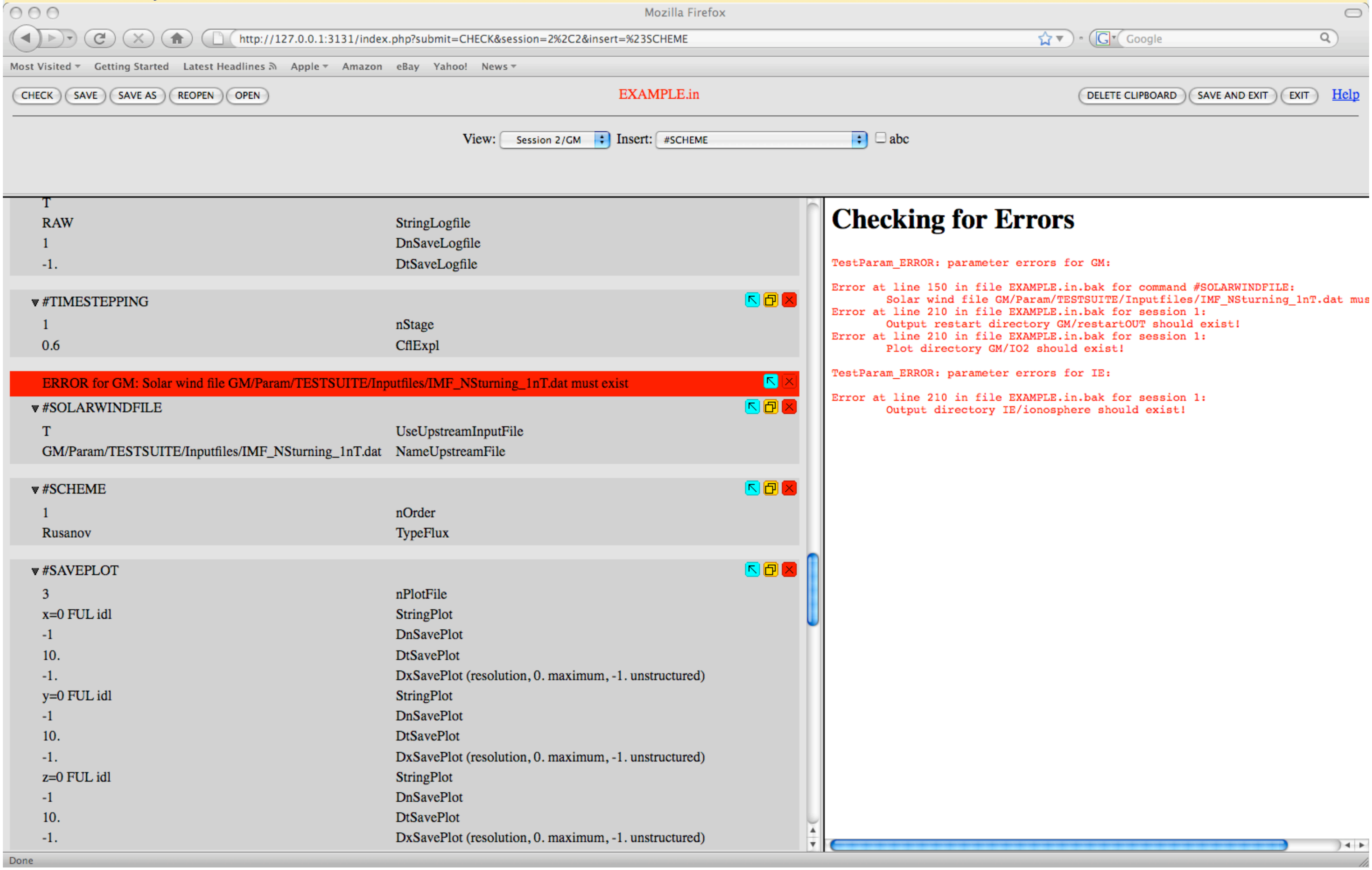




Performance of the SWMF



Parameter Editor GUI



SWMF Code Summary

- **Source code:**
  - 250,000 lines of Fortran in the currently used physics and empirical models
  - 34,000 lines of Fortran 90 in the core of the SWMF
  - 22,000 lines of Perl and shell scripts
  - 20,000 lines of IDL plotting scripts
  - 13,000 lines of Fortran 90 in the wrappers and couplers
  - 10,000 lines of Makefiles
  - 8,000 lines of XML description of input parameters
  - 6,000 lines of PHP scripts in the SWMF GUI
- **User manual with example runs and full documentation of input parameters**
- **Fully automated nightly testing on 7 different machine/compiler combinations**
- **SWMF runs on any Unix/Linux based system with a Fortran 90 compiler, MPI library, and Perl interpreter**
- **SWMF can run on a laptop with one or two components and scales well to several hundreds or even thousands of processors of the world's fastest supercomputers with all components running together.**

Nightly SWMF Tests

See explanations for the tests, the tables and the scores.

Logfile of creating the SWMF manuals, BATSRUS manuals, PWOM manual, and CRASH manuals.

Source code changed: diff -r SWMF SWMF_yesterday

Summary of test differences between SWMF_TEST_RESULTS/2009/10/13 and SWMF_TEST_RESULTS/2009/10/12

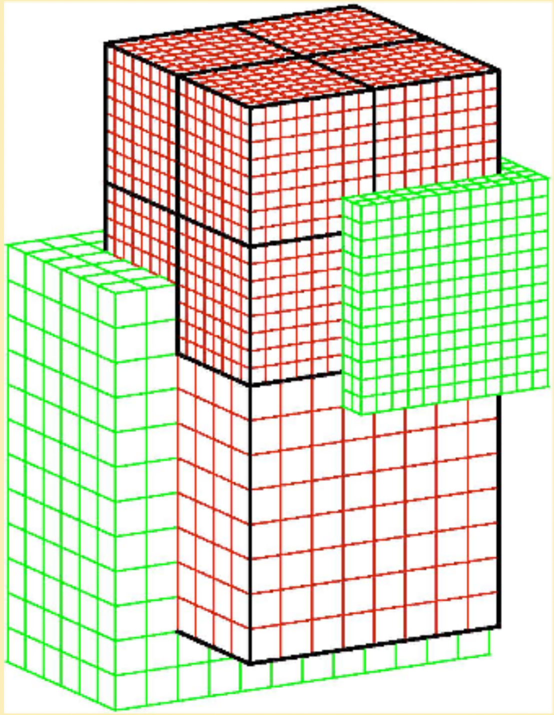
Test results and scores for 7pm 10/13
ALL: 78.8%, CCHM: 100.0%, CWMM: 76.5%, CRASH: 93.5%

75 SWMF tests
60 BATSRUS tests

test / machine	columbia results log file	grendel results log file	grid results log file	mesh results log file	nyx results log file	nyx_pgf90 results log file	xena results log file
GM/BATSRUS/test_2bodyplot	result	result	result	result	result	result	result
GM/BATSRUS/test_comet	result	result	passed	result	result	result	result
GM/BATSRUS/test_corona	passed	passed	passed	passed	passed	passed	passed
GM/BATSRUS/test_coronasph	passed	passed	passed	passed	passed	passed	passed
GM/BATSRUS/test_earthsph	passed	passed	passed	passed	passed	passed	passed
GM/BATSRUS/test_eosgodunov	result	result	passed	result	passed	passed	passed
GM/BATSRUS/test_func	1 test	passed	passed	passed	passed	2 tests	passed
GM/BATSRUS/test_graydiffusion	passed	passed	passed	passed	passed	passed	passed
GM/BATSRUS/test_hallmhd	passed	passed	passed	passed	passed	passed	passed
GM/BATSRUS/test_hyades2d	passed	passed	passed	passed	passed	passed	passed
GM/BATSRUS/test_levelset	passed	passed	passed	passed	passed	passed	passed
GM/BATSRUS/test_magnetometer	result	passed	passed	result	passed	passed	passed
GM/BATSRUS/test_mars	passed	passed	passed	passed	passed	passed	passed
GM/BATSRUS/test_mhdions	passed	passed	passed	passed	passed	passed	passed
GM/BATSRUS/test_mhdnoncons	passed	passed	passed	passed	passed	passed	passed
GM/BATSRUS/test_multifluid	passed	passed	passed	passed	passed	passed	passed
GM/BATSRUS/test_multiion	passed	passed	passed	passed	passed	passed	passed
GM/BATSRUS/test_saturn	passed	passed	passed	passed	passed	passed	passed
GM/BATSRUS/test_shocktube	passed	passed	passed	passed	passed	passed	passed
GM/BATSRUS/test_titan	passed	passed	passed	passed	passed	passed	passed
GM/BATSRUS/test_titan_restart	passed	passed	passed	passed	passed	passed	passed
GM/BATSRUS/test_venus	passed	passed	passed	passed	passed	passed	passed
GM/BATSRUS/test_venus_restart	passed	passed	passed	passed	passed	passed	passed

BATS-R-US

Block Adaptive Tree Solar-wind Roe Upwind Scheme

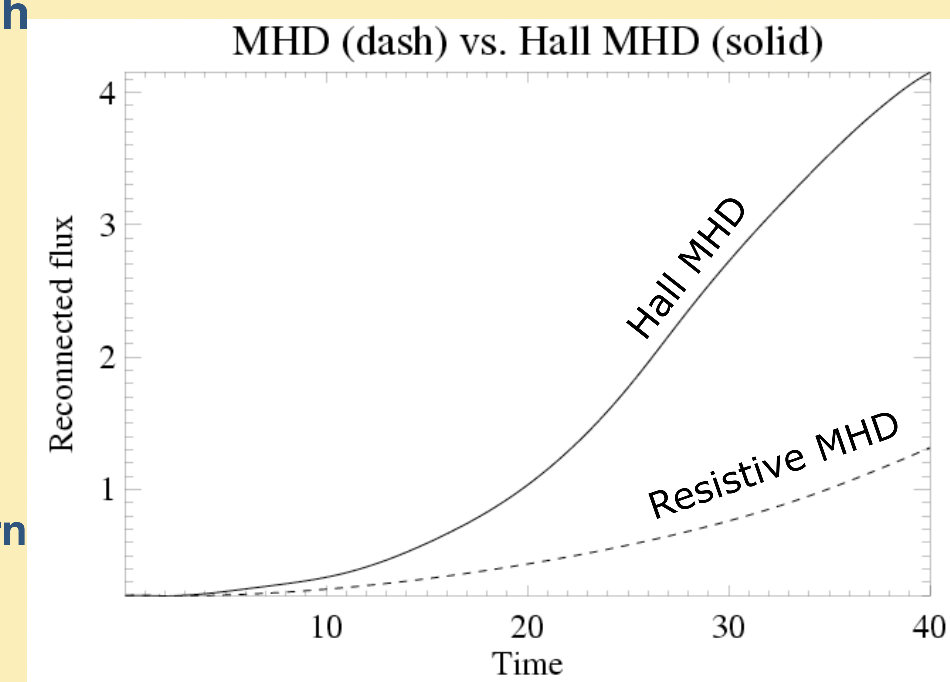


- **Physics**
  - Classical, semi-relativistic and Hall MHD
  - Multi-species, multi-fluid, anisotropic pressure
  - Radiation hydrodynamics with multigroup diffusion
  - Multi-material, non-ideal equation of state
  - Solar wind turbulence, Alfven wave heating
- **Numerics**
  - Conservative finite-volume discretization
  - Parallel block-adaptive grid
  - Cartesian and generalized coordinates
  - Splitting the magnetic field into $B_0 + B_1$
  - Divergence B control: 8-wave, CT, projection, parabolic/hyperbolic
  - Shock-capturing TVD schemes: Rusanov, HLLE, AW, Roe, HLLD
  - Explicit, point-implicit, semi-implicit, fully implicit time stepping
- **Applications**
  - Sun, heliosphere, magnetospheres, unmagnetized planets, moons, comets…
- **100,000+ lines of Fortran 90 code with MPI parallelization**

Hall MHD

- Hall physics can play a critical role in collisionless magnetic reconnection.
- 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.
- Full particle codes are expensive and/or noisy (3D time dependent).
- The GEM reconnection challenge (Birn et al., JGR, 106, 3715, 2001) concluded that **Hall physics is the minimum physics needed to achieve fast reconnection.**

$$\mathbf{E} = -(\mathbf{u}+\mathbf{u}_H)\times\mathbf{B} + \eta\mathbf{j} \qquad \mathbf{u}_H = -\frac{\mathbf{j}}{en_e}$$



GEM Challenge simulation with BATS-R-US

Hall MHD Equations

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v})$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} = -\nabla \cdot (\mathbf{v}\rho\mathbf{v} + \bar{I}p + \bar{I}\mathbf{B}^2/2 - \mathbf{B}\mathbf{B})$$

$$\frac{\partial e}{\partial t} = -\nabla \cdot \left[\mathbf{v}\left(\frac{\gamma p}{\gamma - 1} + \frac{\rho \mathbf{v}^2}{2}\right) + (\mathbf{v} + \mathbf{v}_H) \cdot (\bar{I}\mathbf{B}^2 - \mathbf{B}\mathbf{B})\right]$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} = \nabla \times [(\mathbf{v} + \mathbf{v}_H) \times \mathbf{B}]$$

$$v_H = -\frac{\mathbf{J}}{ne} = -\frac{\nabla \times \mathbf{B}}{ne}$$

$$e = \frac{p}{\gamma - 1} + \frac{\rho \mathbf{v}^2}{2} + \frac{\mathbf{B}^2}{2}$$

- **Electron inertia and pressure are neglected for now**

Algorithmic Challenges in Hall MHD

- The fastest wave speed is the Whistler wave speed, estimated as

$$c_w = c_f + \frac{|B|\,\pi}{e\,n\,\Delta x}$$

so the stability (CFL) condition for explicit schemes becomes:

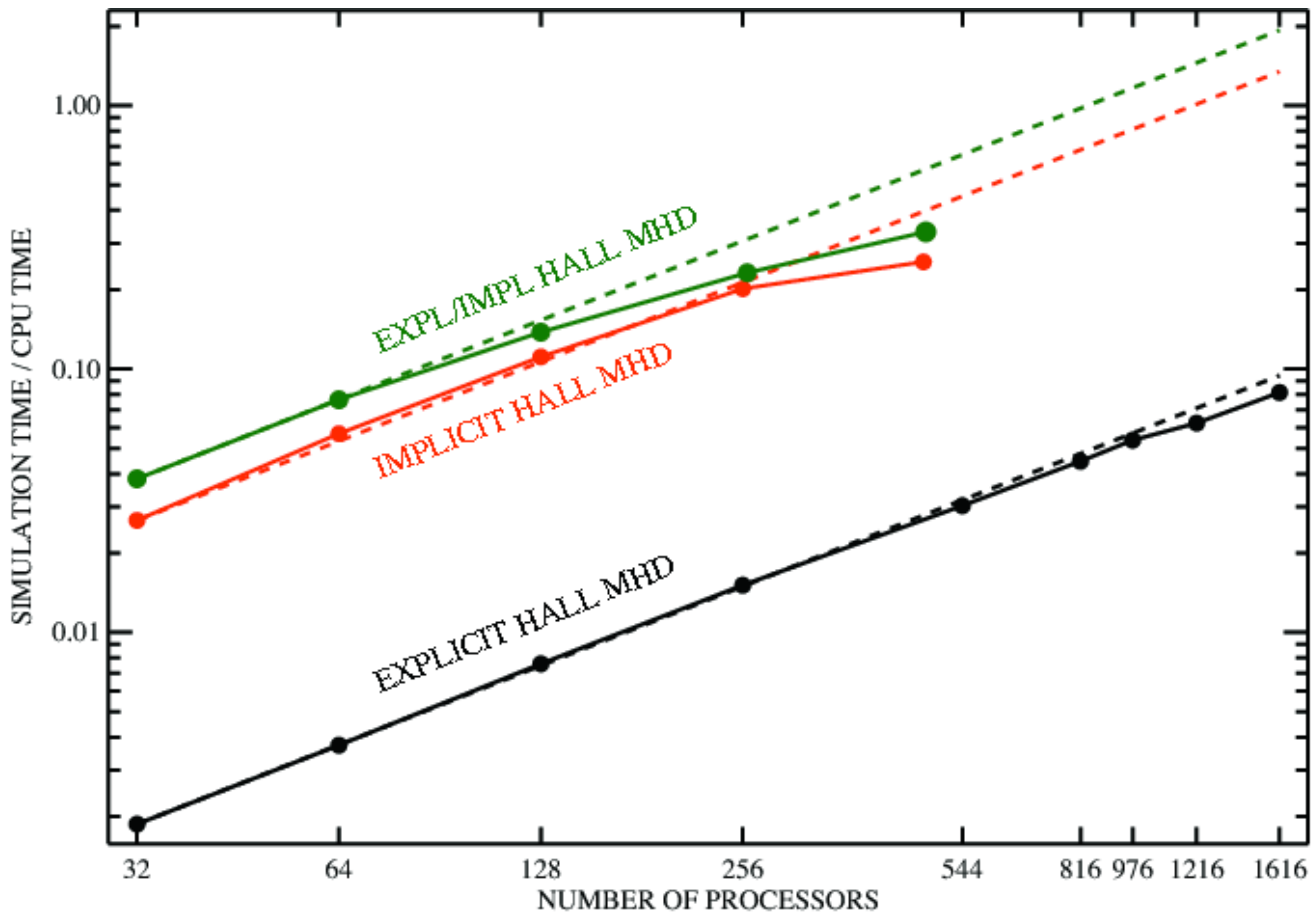
$$\Delta t < \frac{\Delta x}{|u| + c_w} \propto \Delta x^2$$

- Implicit time stepping is necessary for 3D time-accurate simulations when we are not interested in modeling the shortest wavelength Whistler waves, and want to do simulations with much longer dynamic time scales.

Explicit/Implicit Scheme
(Toth et al. JCP, 2006)

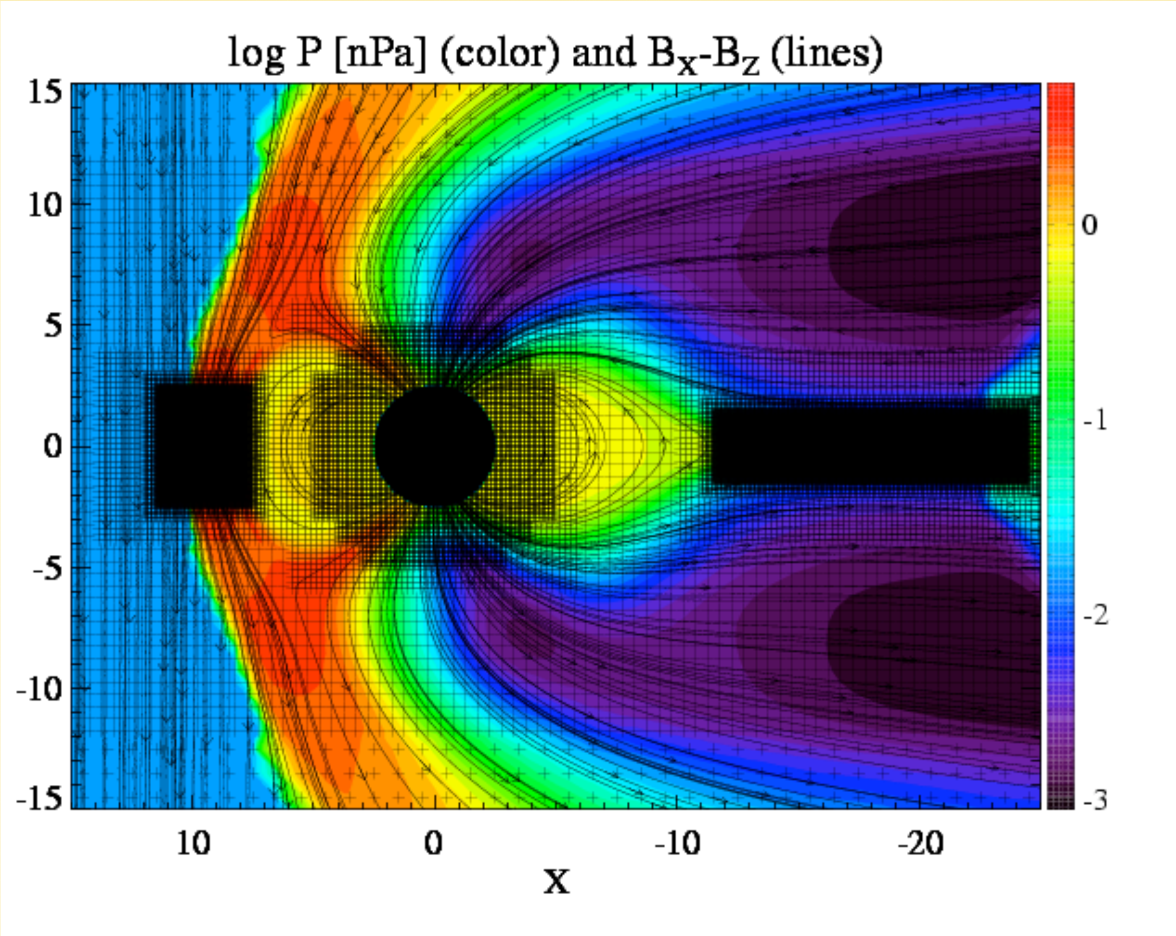
- **Fully implicit scheme has no limitation on the time step, but each iteration is expensive**
  - typically 20-30 times more than explicit time step
- **Fully explicit is inexpensive for one iteration, but numerical stability limit can results in a very small time step**
- **Set time step based on accuracy requirement:**
  - Solve blocks with unrestrictive stability condition explicitly
  - Solve blocks with restrictive stability condition implicitly
  - Load balance explicit and implicit blocks separately

Parallel Scaling for Hall MHD



Grid: 4848 blocks with 8x8x8 cells (2.5 million cells) ranging from 8 to 1/16 R_E. Simulations done on an SGI Altix machine.

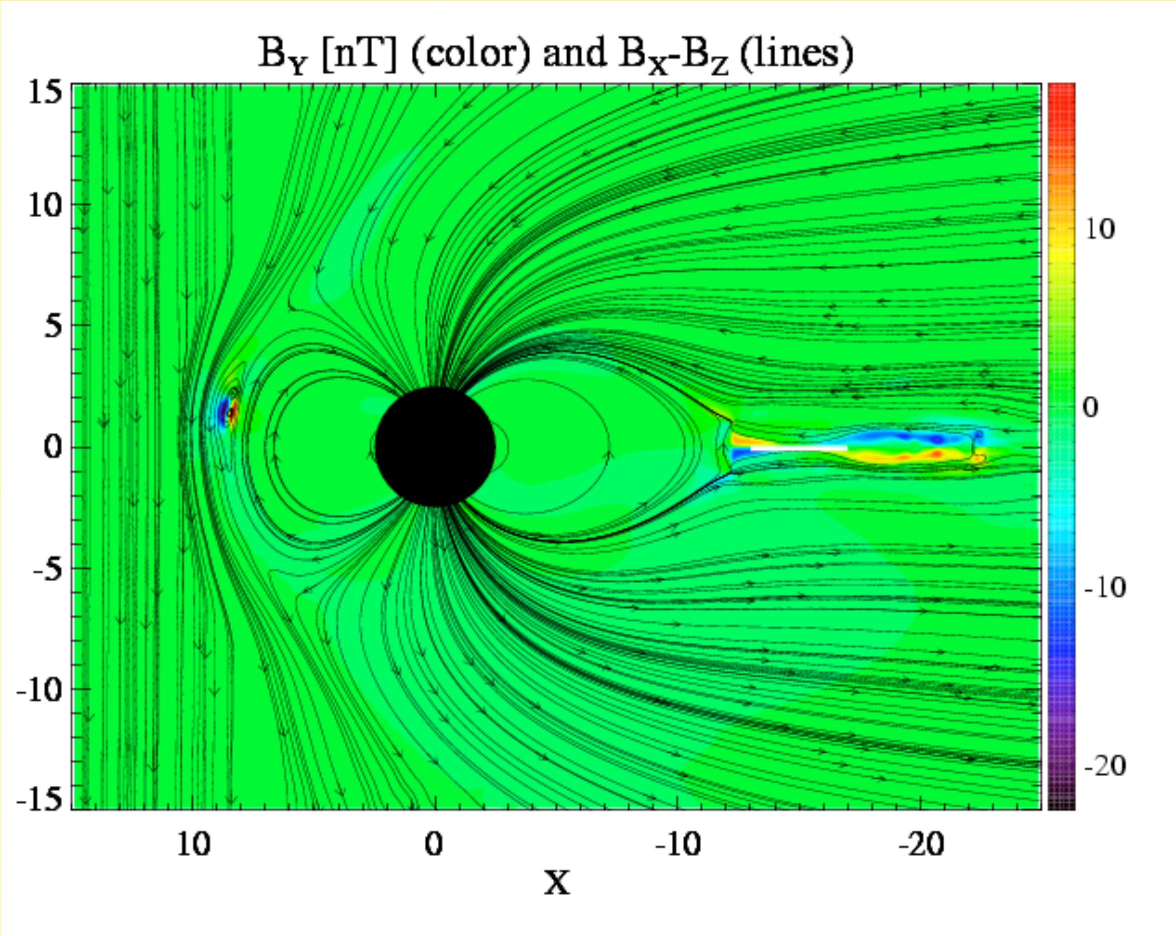
Grid for Magnetosphere Run



71,000 blocks with 4x4x4 cells ranging from 8 to 1/32 R_E

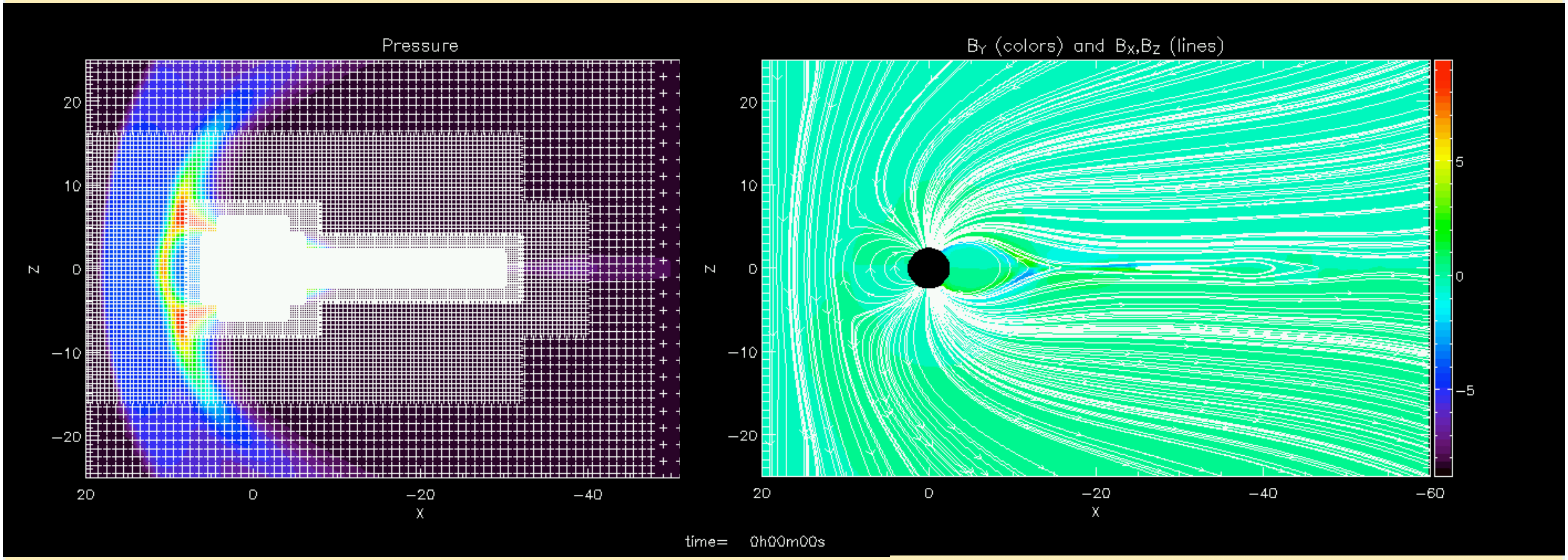
Refined at dayside magnetopause and tail reconnection

"Steady State" Hall MHD Solution



Local time stepping does not converge to a true steady state:
Solution is time dependent!

Hall MHD Magnetosphere Simulation

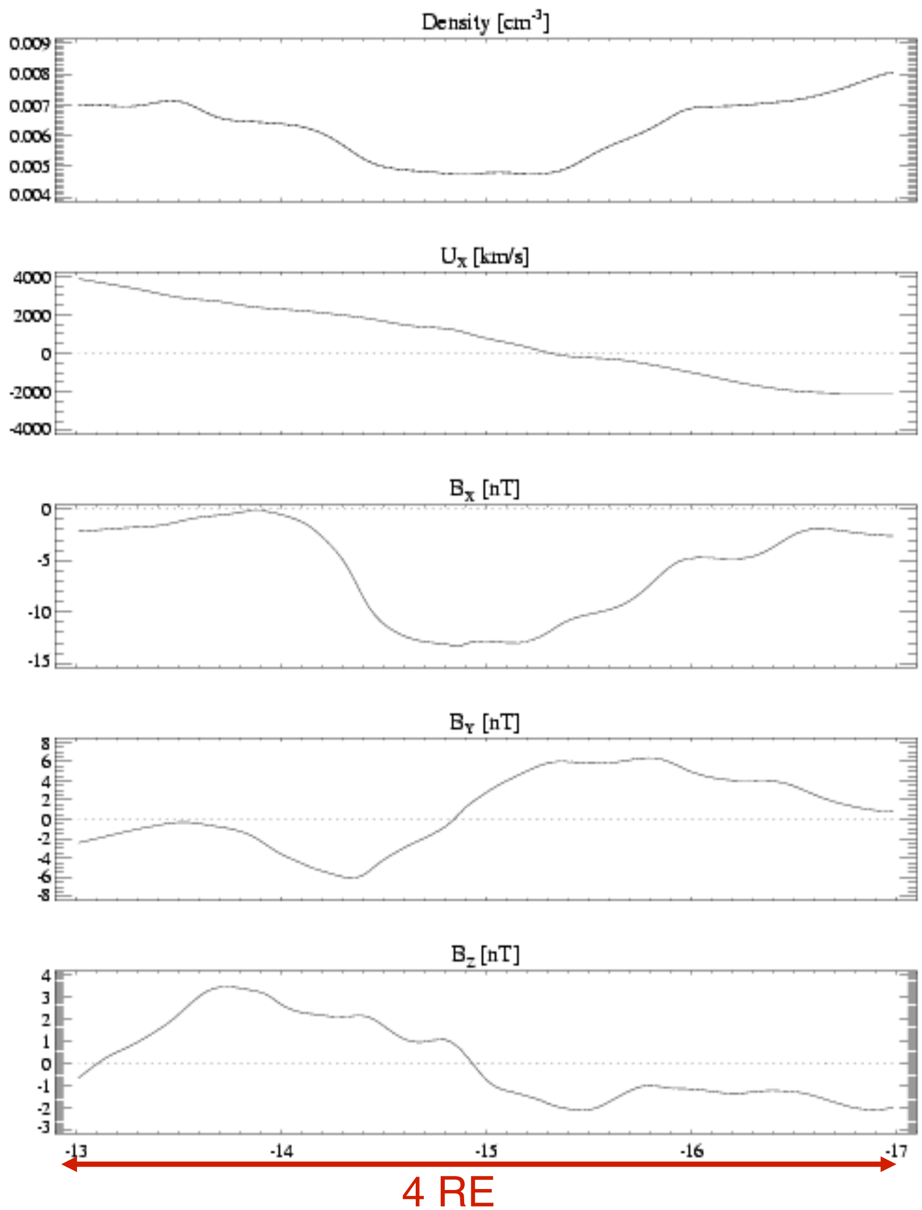


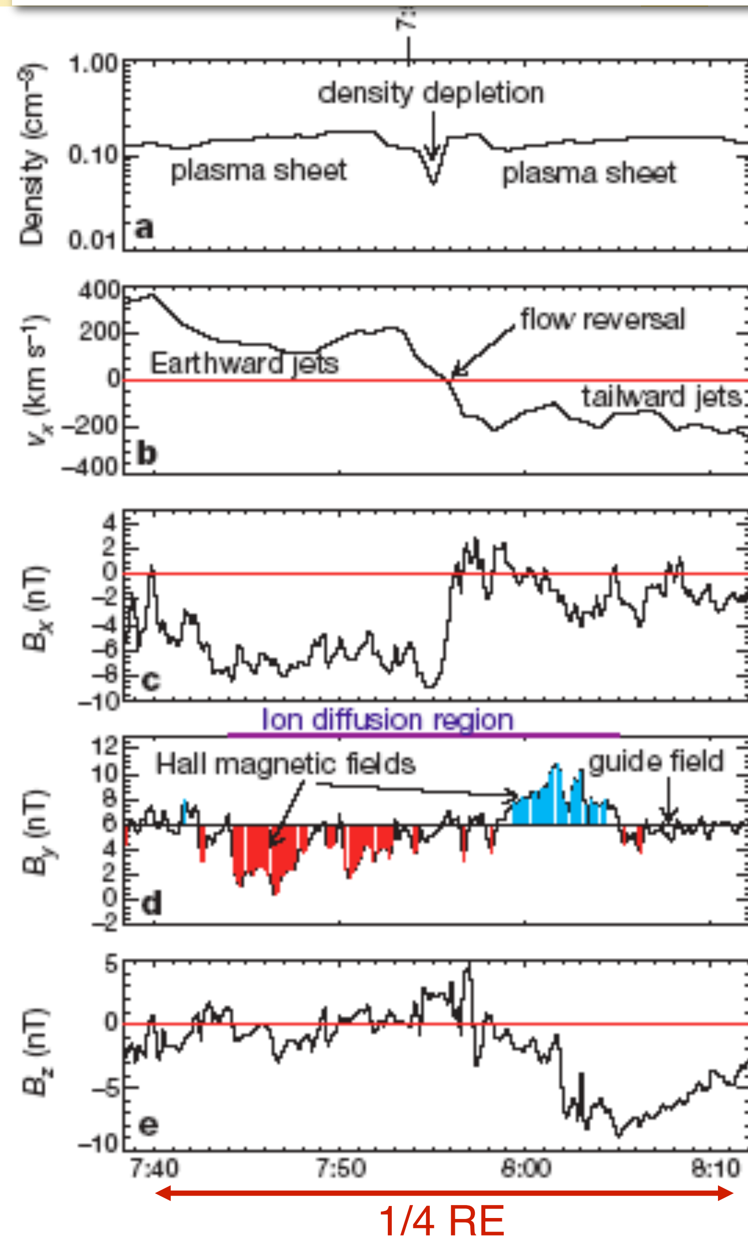
4804 blocks with 8x8x8 cells (total 2.5 million cells) ranging from 8 to 1/16 R_E.

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

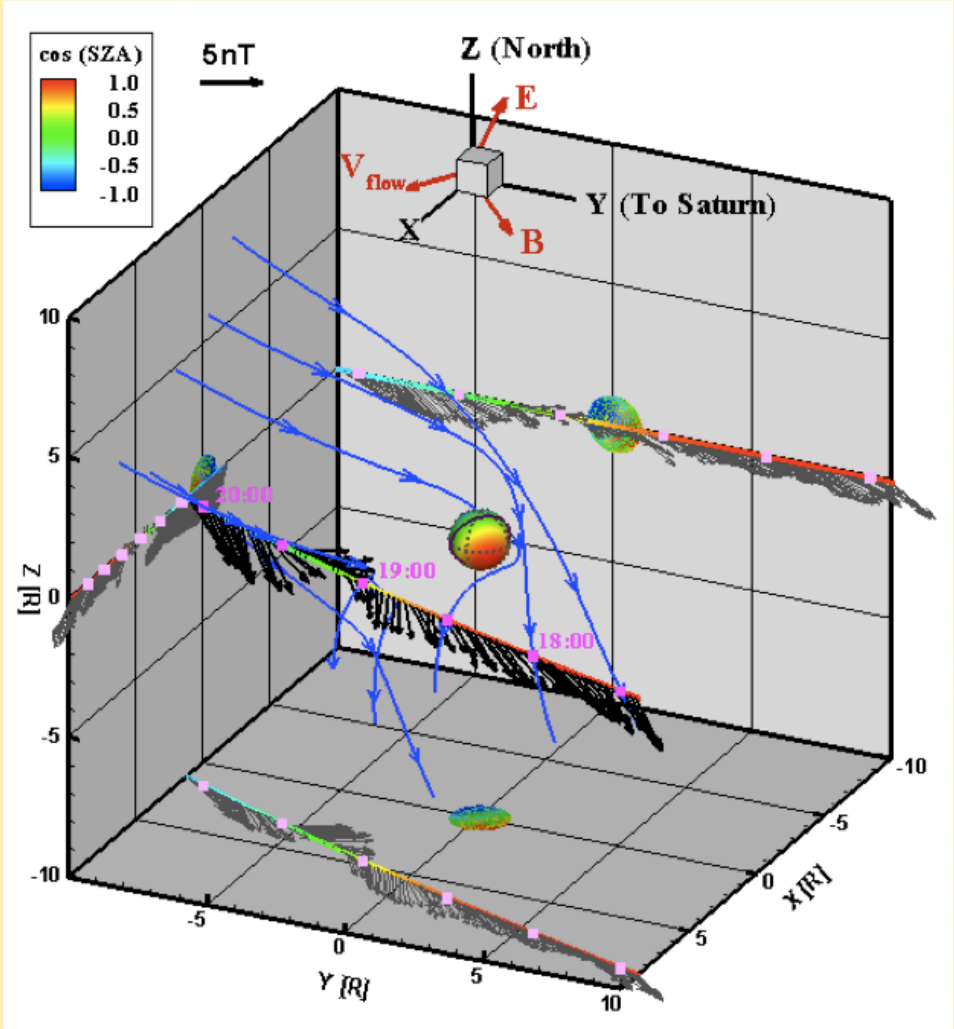
1D cut near X-point
Hall MHD simulation

Wind satellite observations
Oieroset et al. Nature 412, 26 (2001)





Cassini T9 Flyby at Titan
(Ma et al, GRL 2007)



Comparison of Measured and Modeled Magnetic Fields for Cassini Titan T9 flyby

(Ma et al, GRL 2007)

- Steady state simulation on spherical grid with multi-species (Hall) MHD.
- Hall MHD result (solid line) matches observations (magenta line) significantly better than ideal MHD simulation (dashed line).

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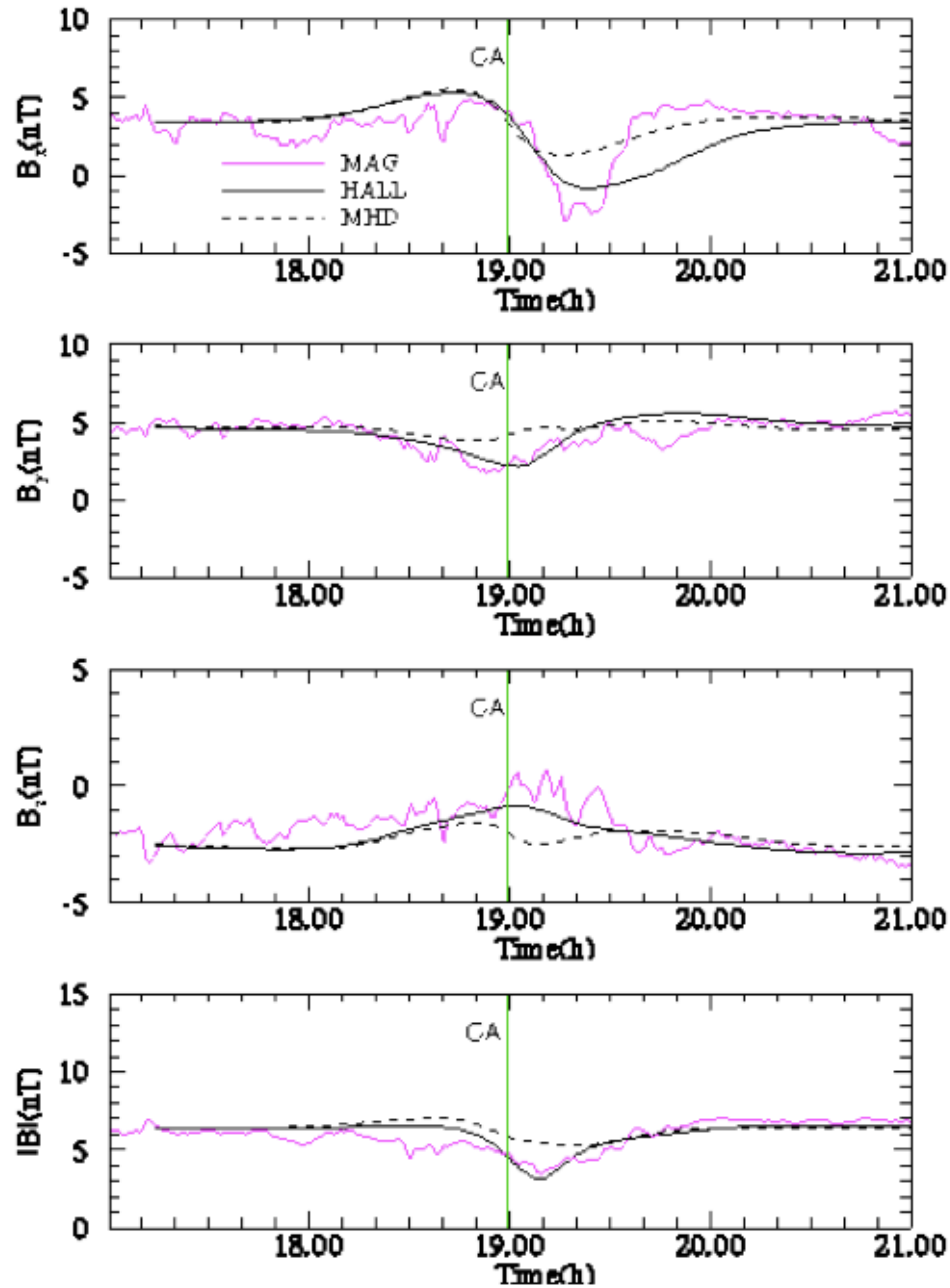


Anisotropic MHD

- **What is it?**
  - Different pressures parallel and perpendicular to the magnetic field
- **Where does it matter in space physics?**
  - Reconnection
  - Magnetosphere
  - Inner magnetosphere
  - Solar wind heating

Resistive MHD with electrons and anisotropic ion pressure

Mass conservation: $$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

Momentum: $$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u} + P) = \mathbf{J} \times \mathbf{B}$$

$$P = (p_\perp + p_e) I + (p_\parallel - p_\perp)\mathbf{b}\mathbf{b} \qquad p = \frac{2p_\perp + p_\parallel}{3}$$

Induction: $$\frac{\partial \mathbf{B}}{\partial t} + \nabla \times \mathbf{E} = 0$$

Pressure: $$\frac{\partial p_\perp}{\partial t} + \nabla \cdot (p_\perp \mathbf{u}) = \frac{1}{3\tau}(p_\parallel - p_\perp) + \frac{2}{\tau_{ie}}(p_e - p) - p_\perp \nabla \cdot \mathbf{u} + p_\perp \mathbf{b} \cdot (\nabla \mathbf{u}) \cdot \mathbf{b}$$

$$\frac{\partial p_\parallel}{\partial t} + \nabla \cdot (p_\parallel \mathbf{u}) = \frac{2}{3\tau}(p_\perp - p_\parallel) + \frac{2}{\tau_{ie}}(p_e - p) - 2p_\parallel \mathbf{b} \cdot (\nabla \mathbf{u}) \cdot \mathbf{b}$$

$$\tau_{ie} = \frac{2}{3}\frac{M_i}{\eta e^2 n_e}$$

Electron pressure:

$$\frac{\partial p_e}{\partial t} + \nabla \cdot (p_e \mathbf{u}) = (\gamma - 1)\left[-p_e \nabla \cdot \mathbf{u} + \eta \mathbf{J}^2 + \nabla \cdot (\kappa \mathbf{b}\mathbf{b} \cdot \nabla T_e)\right] + \frac{2}{\tau_{ie}}(p - p_e)$$

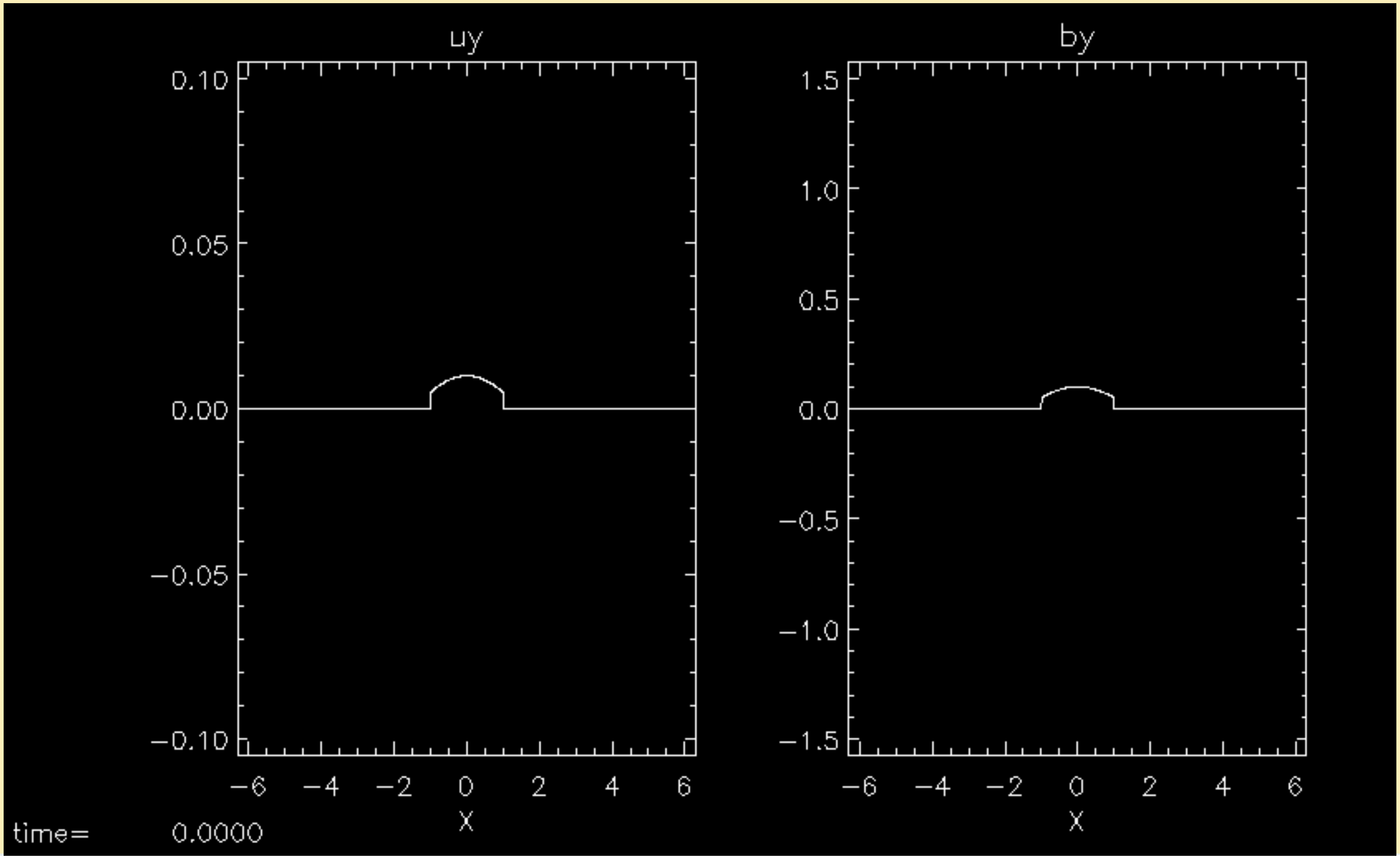
Electric field: $$\mathbf{E} = -\mathbf{u} \times \mathbf{B} + \eta \mathbf{J} \qquad \mathbf{b} = \mathbf{B}/B$$

Current: $$\mathbf{J} = \nabla \times \mathbf{B}$$

Alfven waves with anisotropic pressure

Circularly polarized Alfven wave propagates at $v_A = \sqrt{(\mathbf{B}^2 + p_\perp - p_\parallel)/\rho}$

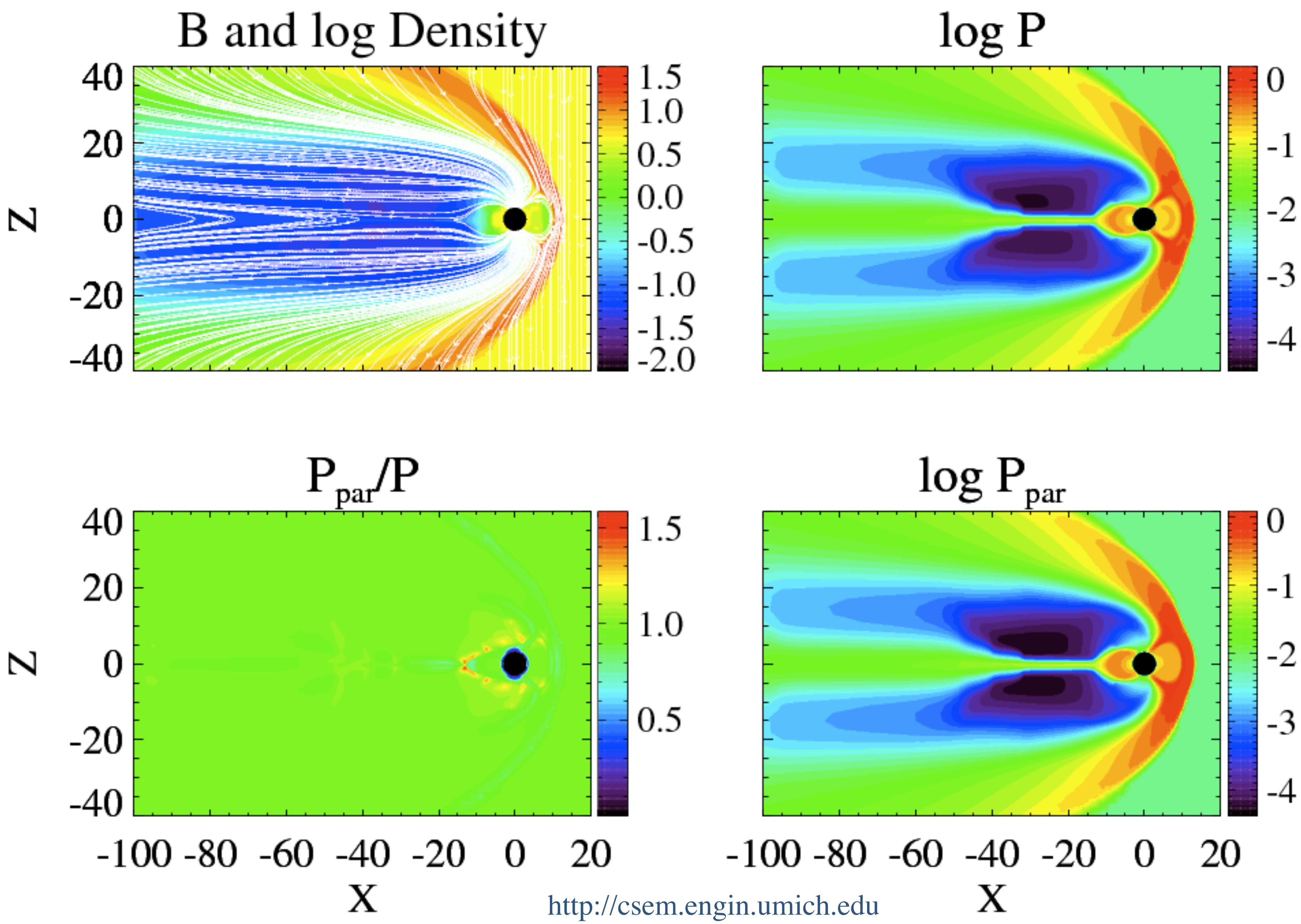
This can become unstable if the parallel pressure is large enough!



Limiting the Anisotropy

- **Instabilities**
  - Fire-hose: $$\frac{p_\parallel}{p_\perp} > 1 + \frac{B^2}{p_\perp}$$
  - Mirror: $$\frac{p_\perp}{p_\parallel} > 1 + \frac{B^2}{2p_\perp}$$
  - Proton cyclotron: $$\frac{p_\perp}{p_\parallel} > 1 + 0.847\left(\frac{B^2}{2p_\parallel}\right)^{0.48}$$
  - In unstable regions we reduce anisotropy so it becomes stable
- **Ion-ion, ion-electron and/or wave-ion interactions:**
  - Push ion pressure towards isotropic distribution with time rate τ

Idealized Steady Magnetosphere Run



Anisotropic MHD Applications

- **Reconnection studies (combined with Hall MHD)**
  - GEM challenge
- **Magnetospheric simulations: Xing Meng's poster**
  - Quiet time and storm time
  - Comparison with data (e.g. Cluster, Themis)
- **Coupling with inner magnetosphere models**
  - HEIDI, CRCM and RAM-SCB resolve pitch angle
- **Solar corona modeling**
  - Solar wind heating is an anisotropic process

Multi-Fluid MHD

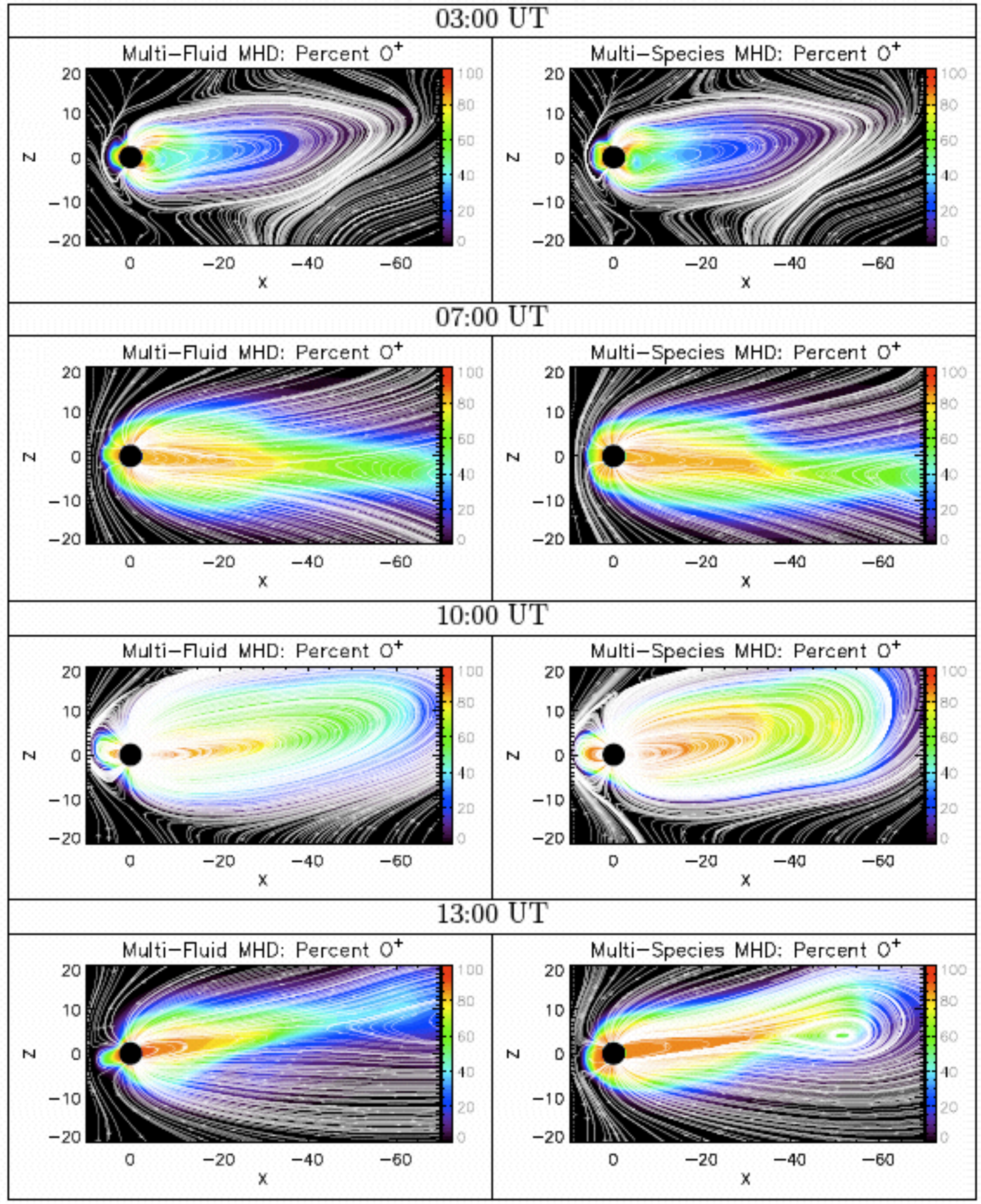
- Each fluid has separate densities, velocities and temperatures.
- Multi-Fluid MHD has many space physics applications
  - ionospheric outflow: coupling with PWOM
  - Earth magnetosphere (Glocer et al, 2009, JGR)
  - Martian ionosphere
  - Outer Heliosphere (Opher et al, 2009, Nature)
- Fluids are coupled by collisions, charge exchange and chemical reactions.
- Ion fluids are coupled by the magnetic field.
- BATS-R-US now contains a general multi-fluid solver with arbitrary number of ion and neutral fluids.

Multi-Fluid Magnetosphere Simulations
(Glocer et al, 2009, JGR)

- **Modeling two magnetic storms**
  - May 4, 1998
  - March 31, 2001
- **Multi-fluid BATS-R-US running in the SWMF coupled with**
  - Polar Wind Outflow Model
  - Ridley Ionosphere-electrodynamics Model
  - Rice Convection Model (inner magnetosphere)
- **Comparison with**
  - single fluid model
  - global indexes (Dst, CPCP)
  - in situ satellite measurements

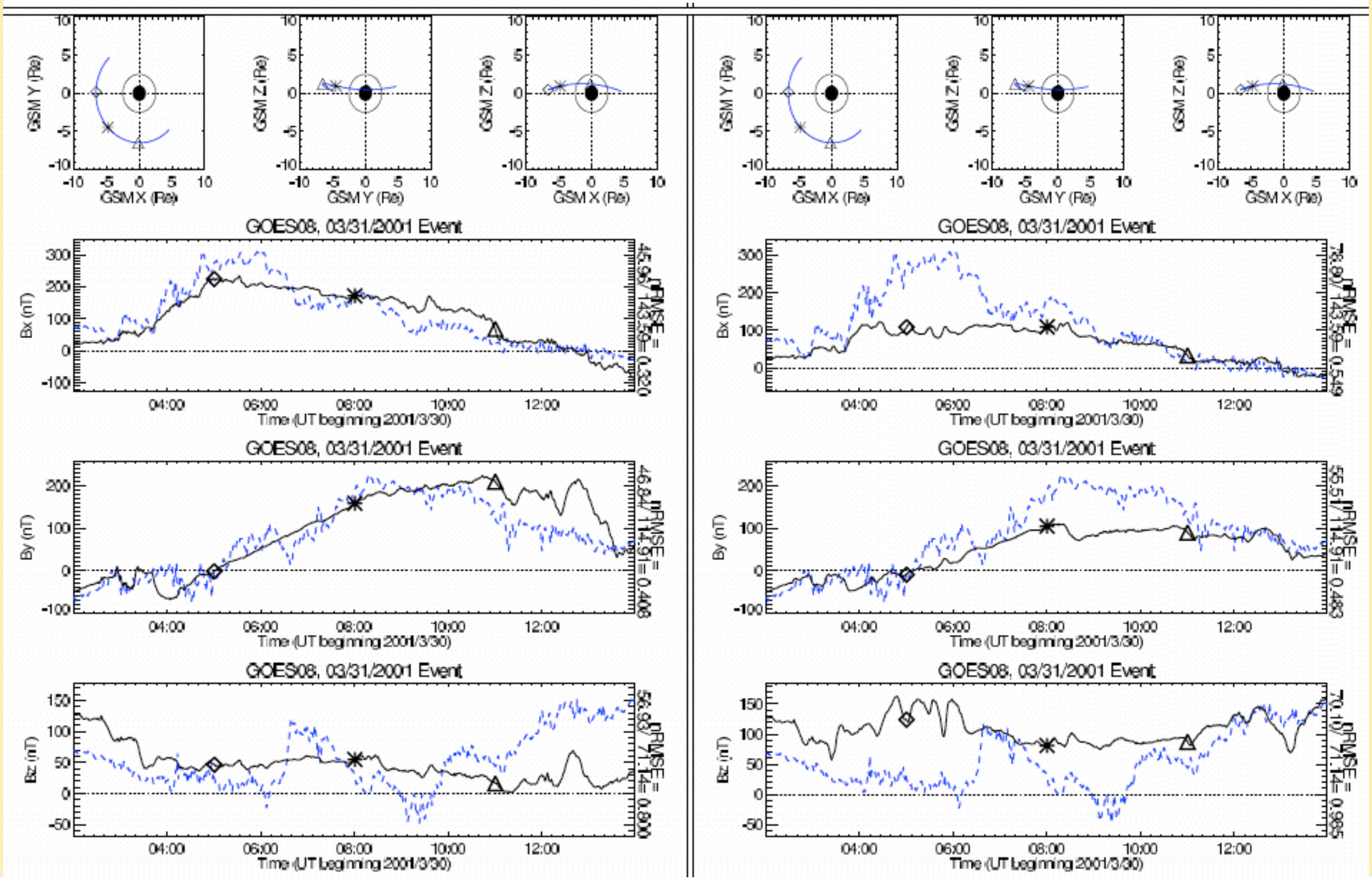
O^+/H^+ Ratio for March 31 Storm

- **Multi-Fluid vs. Multi-species**
  - Similar near Earth
  - Different further away

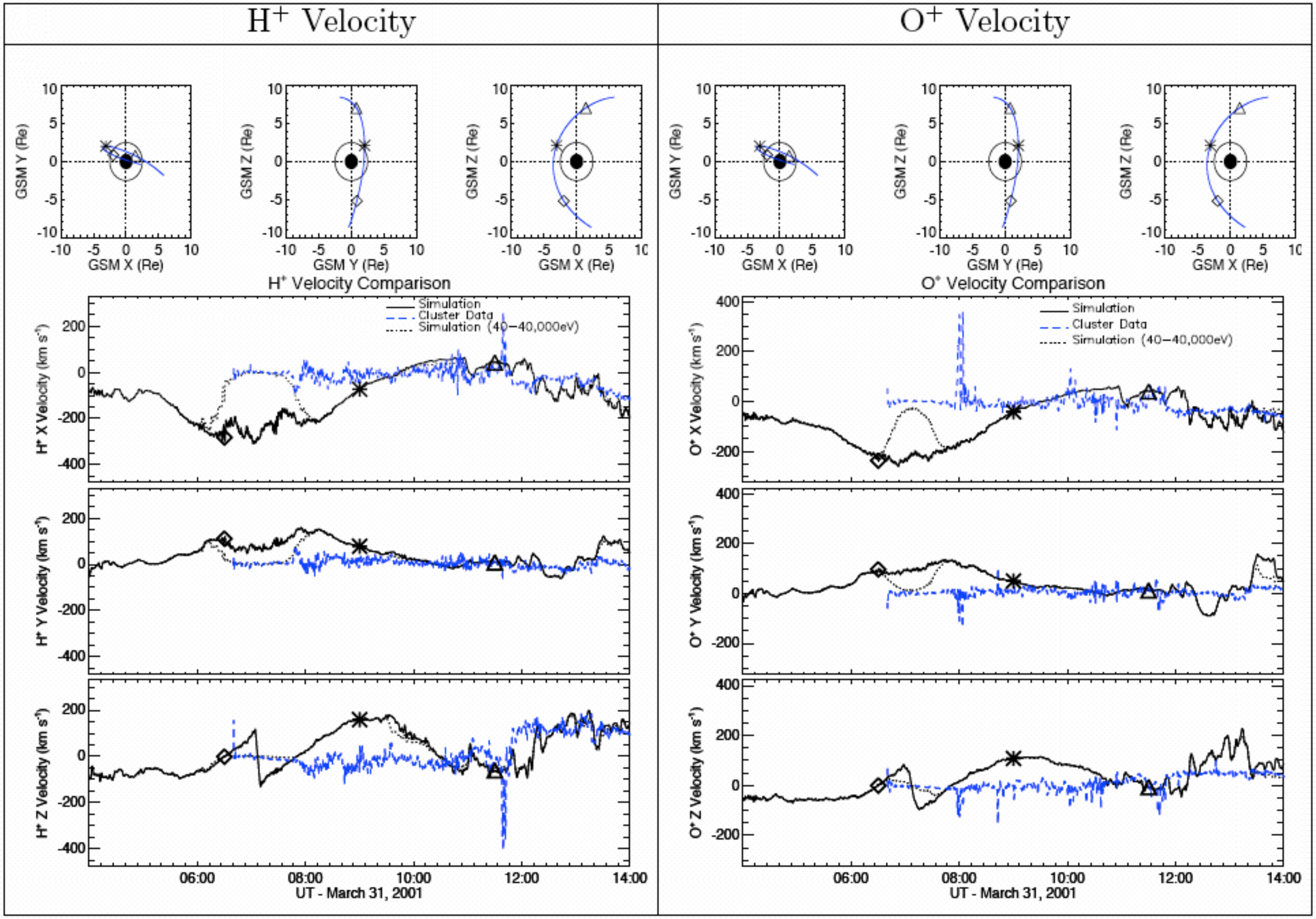


Magnetic Field vs Goes 8 Satellite

Multi-fluid MHD with O$^+$ outflow | Single-fluid MHD with no outflow

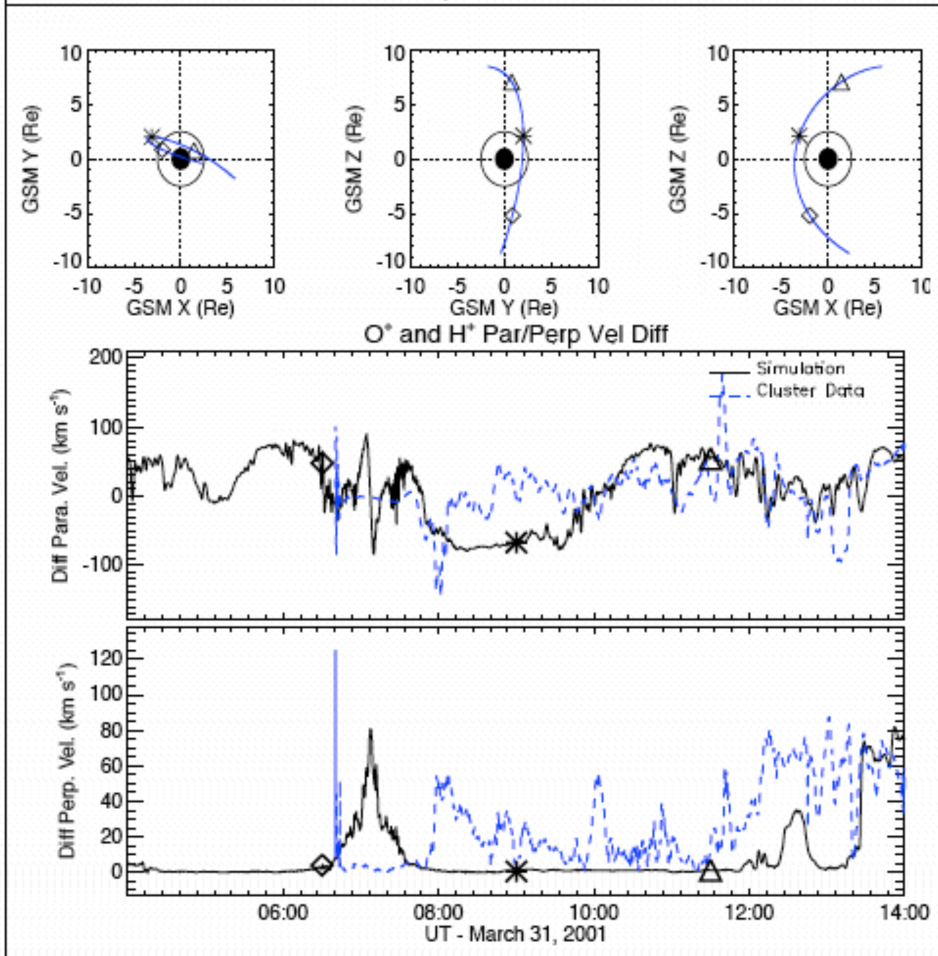


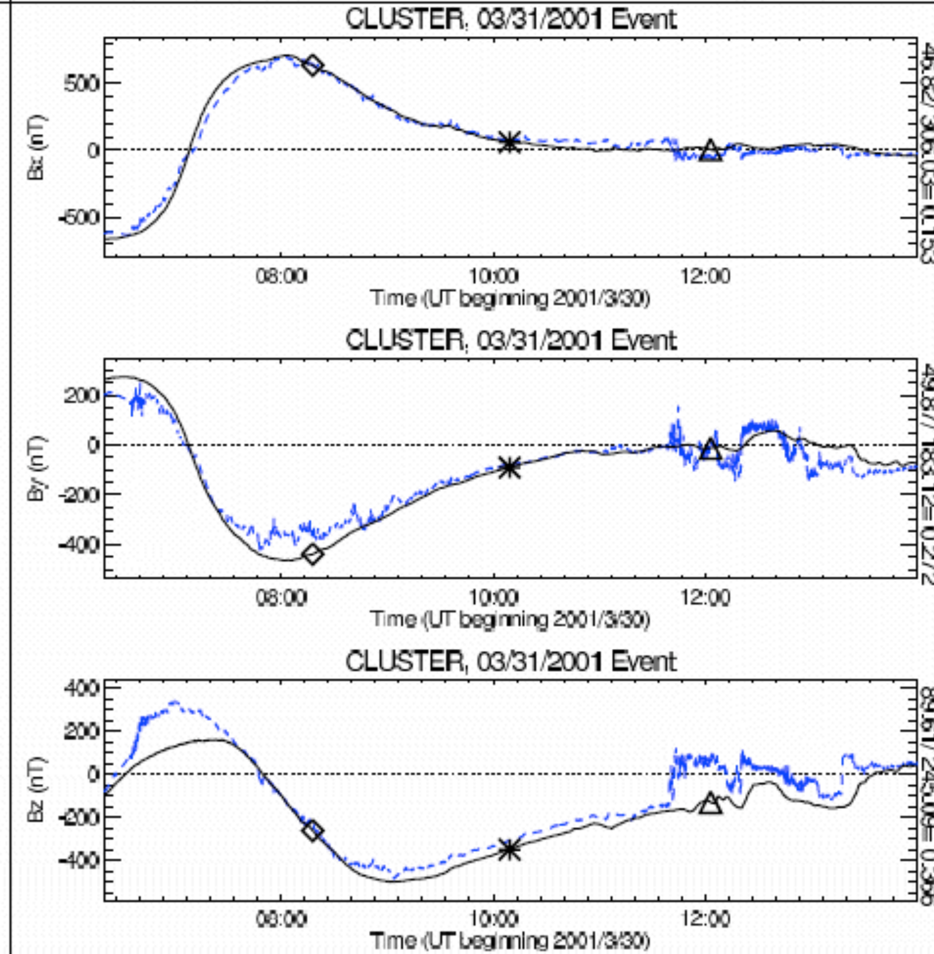
Velocities vs Cluster Satellite



Velocity Differences and Magnetic Field

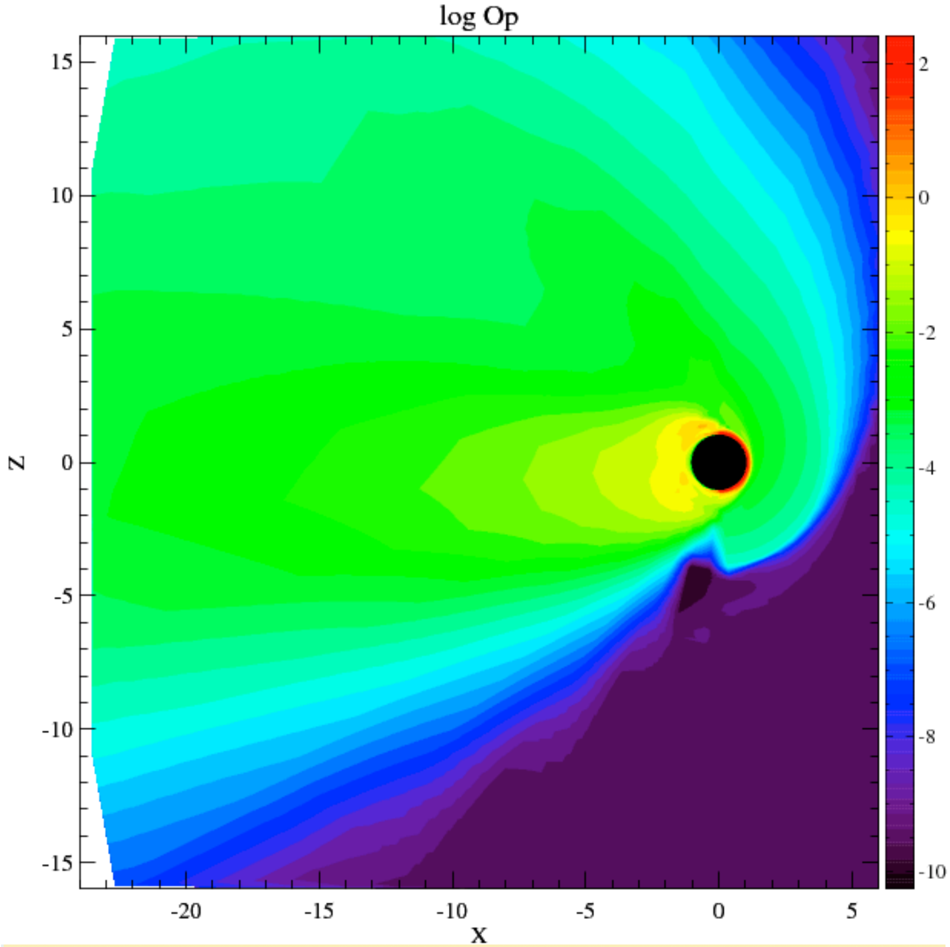
O^+ and H^+ Par/Perp Velocity Diff	Magnetic Field



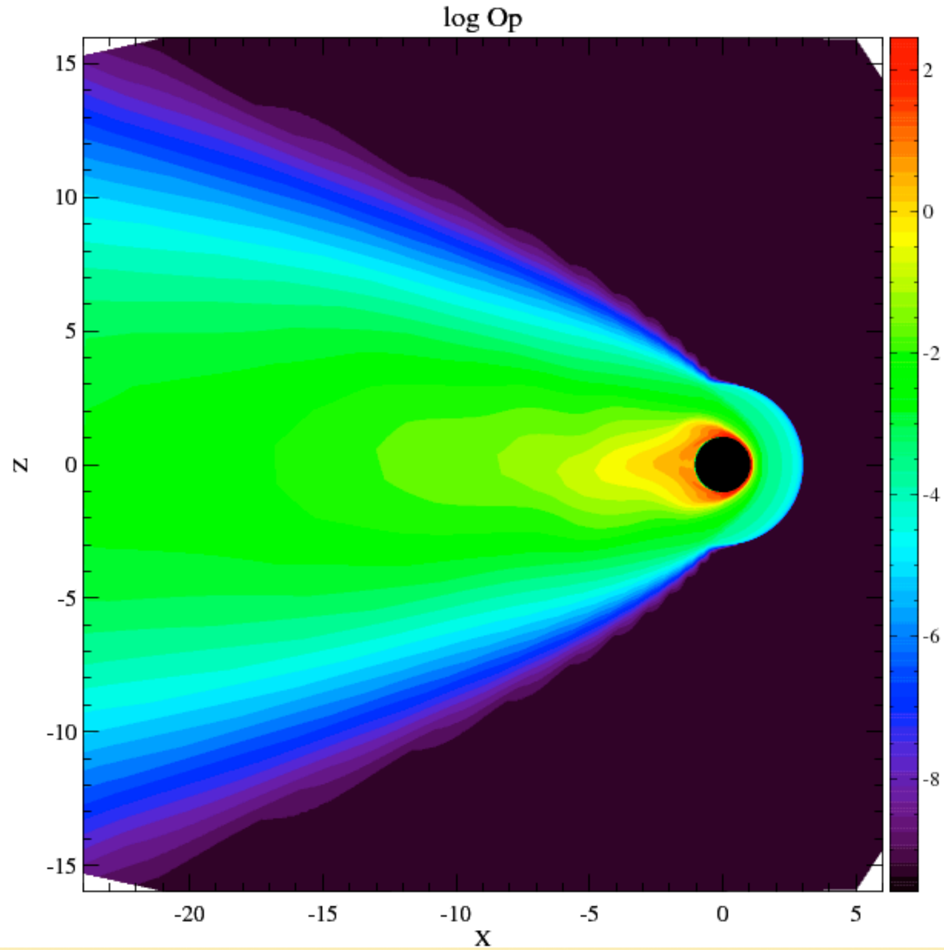


O+ Escape from Mars Ionosphere

Multi-fluid MHD



Multi-species MHD



Summary

- **SWMF is a mature tool for space physics and space weather**
  - Expanding dynamically with new components and physics models
  - Used for ever increasing number of space physics applications
  - Publically available source code with all models included
  - Available via CCMC for runs on request
- **BATSRUS is an efficient and flexible MHD++ code**
  - Flexible: dozens of applications, multiple equations
  - Adaptive in space: block adaptive generalized coordinate grid
  - Adaptive in time: explicit, (semi- and point-)implicit time discretizations
  - Efficient: scales to thousands of cores
- **The SWMF development is driven by improvements of existing algorithms and by new applications.**