Space Weather Modeling Framework: present and future

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http://csem.engin.umich.edu
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
**Temporal scale:**
\[ \sim 2^{28} \approx 2.5 \times 10^8 \]

**Length scale:**
\[ \sim 2^{28} \approx 2.5 \times 10^8 \]

**Volume ratio:**
\[ \sim 2^{84} \approx 2 \times 10^{25} \]
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
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<tr>
<th>Physics Domain</th>
<th>ID</th>
<th>Physics / Empirical Models</th>
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<tr>
<td>1. Solar Corona</td>
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<td>2. Eruptive Event Generator</td>
<td>EE</td>
<td>BATS-R-US / breakout, TD, GL</td>
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<td>3. Inner Heliosphere</td>
<td>IH</td>
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<td>5. Solar Energetic Particles</td>
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<td>Kőta &amp; FLAMPA</td>
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<td>7. Inner Magnetosphere</td>
<td>IM</td>
<td>RCM, CRCM, HEIDI, RAM+SCB</td>
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<td>8. Ionosphere Electrodynamics</td>
<td>IE</td>
<td>RIM / Weimer</td>
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<td>9. Upper Atmosphere</td>
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<td>10. Radiation Belt</td>
<td>RB</td>
<td>RBE</td>
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<td>11. Polar Wind</td>
<td>PW</td>
<td>PWOM</td>
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<td>12. Plasmasphere</td>
<td>PS</td>
<td>DGCPM</td>
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<td>13. Lower Atmosphere</td>
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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
- Kola
- IM
- RCM

Infrastructure Layer
- Utilities
  - physics constants, time and date conversion
  - coordinate transformation, field line tracing
  - parameter reading, I/O units, profiling

Control Module

Component Wrapper

Physics Module

Coupler between Component 1 and Component 2

Component 1
- set_param
- init_session
- run
- save_restart
- finalize

Component 2
Parallel Layout and Execution

LAYOUT.in for 20 PE-s

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#COMPONENTMAP

#END
Performance of the SWMF

SWMF WITH 9 COMPONENTS

- SGI Altix (Columbia)
- Compaq (Halem)
- SGI O3k (Lomax)

REAL TIME SPEED

SIMULATION / CPU TIME

NUMBER OF PROCESSORS

96 128 196 256 512
Checking for Errors

TestParam_ERROR: parameter errors for GM:
Error at line 150 in file EXAMPLE.in.bak for command #SOLARWINDFILE:
Solar wind file GM/Param/TESTSUITE/inputsfiles/IMF_NSNumbering_1nT.dat must exist
Output restart directory GM/restartGUI should exist.
Error at line 210 in file EXAMPLE.in.bak for session 1:
Plot directory GM/plot directory Gn/plot should exist.
TestParam_ERROR: parameter errors for IE:
Error at line 210 in file EXAMPLE.in.bak for session 1:
Output directory IE/ionosphere should exist.

Parameter Editor GUI

View: | Session 2/GM | Insert: | #SCHME | abe

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<th>StringLogfile</th>
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ERROR for GM: Solar wind file GM/Param/TESTSUITE/inputsfiles/IMF_NSNumbering_1nT.dat must exist

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<th>StringPlot</th>
<th>DnSavePlot</th>
<th>DtSavePlot</th>
<th>DxSavePlot (resolution, 0. maximum, -1, unstructured)</th>
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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
REAL: 78.8%, CCHM: 100.0%, CWMM: 76.5%, CRASH: 93.5%

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75 SWMF tests
60 BATSRUS tests
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, Alfvén 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

http://csem.engin.umich.edu
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 \( \delta = \frac{c}{\omega_{pi}} = \frac{V_A}{\Omega_{ci}} \).

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.
Hall MHD Equations

\[
\begin{align*}
\frac{\partial \rho}{\partial t} &= - \nabla \cdot (\rho \mathbf{v}) \\
\frac{\partial \rho \mathbf{v}}{\partial t} &= - \nabla \cdot (\mathbf{v} \rho \mathbf{v} + \bar{I}p + \bar{I}B^2/2 - \mathbf{BB}) \\
\frac{\partial e}{\partial t} &= - \nabla \cdot \left[ \mathbf{v} \left( \frac{\gamma p}{\gamma - 1} + \frac{\rho \mathbf{v}^2}{2} \right) + (\mathbf{v} + \mathbf{v}_H) \cdot (\bar{I}B^2 - \mathbf{BB}) \right] \\
\frac{\partial \mathbf{B}}{\partial t} &= - \nabla \times \mathbf{E} = \nabla \times [(\mathbf{v} + \mathbf{v}_H) \times \mathbf{B}]
\end{align*}
\]

\[\mathbf{v}_H = - \frac{\mathbf{J}}{ne} = - \frac{\nabla \times \mathbf{B}}{ne} \]

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

Electron inertia and pressure are neglected for now
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.
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 result in a very small time step

Set time step based on accuracy requirement:
- Solve blocks with unrestricitive stability condition explicitly
- Solve blocks with restrictive stability condition implicitly
- Load balance explicit and implicit blocks separately
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.

http://csem.engin.umich.edu
71,000 blocks with 4x4x4 cells ranging from 8 to 1/32 $R_E$
Refined at dayside magnetopause and tail reconnection
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 $\frac{1}{16} R_E$.

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

http://csem.engin.umich.edu
1D cut near X-point
Hall MHD simulation

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

http://csem.engin.umich.edu
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).

http://csem.engin.umich.edu
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: \[ \frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u} + \mathbf{P}) = \mathbf{J} \times \mathbf{B} \]

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

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

Pressure:

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

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

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: \[ \mathbf{E} = -\mathbf{u} \times \mathbf{B} + \eta \mathbf{J} \]

Current: \[ \mathbf{J} = \nabla \times \mathbf{B} \]

\[ \tau_{ie} = \frac{2}{3 \eta_e^2 n_e} \quad \frac{M_i}{\tau_{ie}} \]

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Alfvén waves with anisotropic pressure

Circularly polarized Alfvén wave propagates at

\[ v_A = \sqrt{\frac{B^2 + p_\perp - p_\parallel}{\rho}} \]

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 \( \tau \)
BATS-R-US only, dipole axis aligned with Z

Steady solar wind: \( n = 5 \text{ /cc}, v = 400 \text{ km/s}, B_Z = -5 \text{ nT} \)

Solve for energy and parallel pressure near bow shock

Enforce stability conditions

Relaxation rate towards isotropy: \( \tau = 20 \text{ s} \)

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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
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

http://csem.engin.umich.edu
O\textsuperscript{+}/H\textsuperscript{+} Ratio for March 31 Storm

\textbf{Multi-Fluid vs. Multi-species}

- Similar near Earth
- Different further away
<table>
<thead>
<tr>
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**Magnetic Field vs Goes 8 Satellite**

**Multi-fluid MHD with O⁺ outflow**

**Single-fluid MHD with no outflow**

![Graph 1](http://csem.engin.umich.edu)

![Graph 2](http://csem.engin.umich.edu)

![Graph 3](http://csem.engin.umich.edu)

![Graph 4](http://csem.engin.umich.edu)

![Graph 5](http://csem.engin.umich.edu)

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![Graph 8](http://csem.engin.umich.edu)
Velocities vs Cluster Satellite

**H⁺ Velocity**

**O⁺ Velocity**

![Graphs showing H⁺ and O⁺ velocities vs time]
Velocity Differences and Magnetic Field

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http://csem.engin.umich.edu
O⁺ Escape from Mars Ionosphere

Multi-fluid MHD

Multi-species MHD

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**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.**