Computational Plasma Physics in the Solar System and Beyond

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Plasma physics (not medical!!!) - studying the interaction between charged particles and electromagnetic fields.

In most space physics problems - the plasma $\beta = \frac{P_{\text{magnetic}}}{P_{\text{thermal}}} \ll 1$

Magnetic fields dictate the plasma dynamics.

Plasma is commonly studied using:

• Fluid approximation - Magnetohydrodynamics (MHD).
• Kinetic treatment - particle description.
• Hybrid methods - kinetic ions, fluid electrons.
Main Science Problems
The problem of coronal heating:

The temperature of the solar corona is over a million degrees Kelvin (5000K at the photosphere).
1. Bimodal - fast wind and slow wind populations.
2. Faster than predicted this hydrodynamic model.
3. Inverse relations between wind speed and electron temperature - contradicts the hydrodynamic model.

The origin and evolution of stellar winds:

Hydrodynamic expansion (Parker 1958):

- Solar gravity
- Pressure gradient
Solar wind - planet interaction in the solar system:

- Earth’s magnetosphere
- Mars
- The Jovian magnetosphere
- The heliospheric termination shock

NASA illustration: http://mgs-mager.gsfc.nasa.gov/
http://lasp.colorado.edu/
http://lasp.colorado.edu/
BU Astronomy homepage
Coronal Mass Ejections (CMEs):

- 1000 billion kg, about $10^{15}$ ergs, average speed of 500 km/s

Geomagnetic storms - space weather
Space Weather

13 March 1989 0745 UT

http://www.windows2universe.org

http://science.nasa.gov
Developing Universal Numerical Models for Non-relativistic Plasma Environments

Theoretical challenges:
- Theoretical framework is incomplete.
- Physics-base.
- Reproduce the observations.
Numerical Challenge: Wide range of spatial and temporal scales:

- $2^0$ - Earth’s radius (5000 km)
- $2^8-2^9$ - Solar radius (500,000 km)
- $2^{16}$ - 1AU ($10^8$ km)

Magnetic reconnection - boundary layer, kinetic scale

Image by T. Gombosi
• Block-Adaptive-Tree-Solarwind-Roe-Upwind-Scheme (BATSRUS) - magnetohydrodynamic code
• Space Weather Modeling Framework (SWMF)
• Developed since the late 1990s - UM Space & Aerospace departments
• Tamás Gombosi
• Gábor Toth
Physics
- Classical, semi-relativistic and Hall MHD
- Multi-species, multi-fluid, 5-moment
- Anisotropic pressure for ion fluids
- Radiation hydrodynamics multigroup diffusion
- Multi-material, non-ideal equation of state
- Heat conduction, viscosity, resistivity
- Alfvén wave turbulence and heating

Numerics
- Parallel Block-Adaptive Tree Library (BATL)
- Cartesian and generalized coordinates
- Splitting the magnetic field into $B_0 + B_1$
- Divergence B control: 8-wave, CT, projection, parabolic/hyperbolic
- Numerical fluxes: Godunov, Rusanov, AW, HLLE, HLLD, Roe, DW
- Explicit, local time stepping, limited time step, sub-cycling
- Point-, semi-, part and fully implicit time stepping
- Up to 4th order accurate in time and 5th order in space

Applications
- Heliosphere, sun, planets, moons, comets, HEDP experiments

150,000+ lines of Fortran 90+ code with MPI parallelization
What’s New in BATS-R-US?

**Equations**
- Multi-fluid MHD with improved wave speeds, anisotropic pressure option (van der Holst, Toth)
- 5-moment closure: ion + electron fluids and Maxwell equations for B and E (van der Holst, Toth)

**Schemes**
- Dominant Wave + Rusanov/HLL (van der Holst, Toth)
- 5th order scheme with full AMR (Chen)
- Subcyling (Chen, Toth)
- Limited time step (Chen, Huang)
- Improved semi-implicit scheme (Chen, Toth)

**Grids**
- Round cube grid (Shou, Toth)
- Limited generalized coordinates (van der Holst, Manchester, Toth)
What’s New in BATS-R-US?

**Boundary conditions**
- Mixed cell and face based boundaries (Zhou)
- Resistive body (Jia, Daldorff, Chen, Zhou, Toth)
- Solid body (van der Holst)

**Geometric control of schemes/features**
- For AMR, Hall MHD, resistivity, viscosity, high order scheme (Toth)
- Load balancing for multiple schemes/features (Chen)

**Plotting options**
- Cuts in generalized coordinates (Toth)
- Shell/surface/circle plots (Welling)
- Box/plane/line plots (Szente)
- More scalar parameters (xSI, Mi...) saved (Toth)
- IDL macros improved in many ways (Toth)
- Cell centered Tecplot (3d tcp) output (Toth)
A software framework is a universal, reusable software environment that provides particular functionality (Wikipedia).

The Sun-Earth system consists of many different interconnecting domains that are independently modeled traditionally.

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 models and components.

The performance of a well designed framework can supersede monolithic codes or ad hoc couplings of models.
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
- BATSRLIS
- SP
- Kota
- 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
- set_param
- init_session
- run
- save_restart
- finalize

Physics Module

Coupler between Component 1 and Component 2

Component 1

Component 2
SWMF is freely available at http://csem.engin.umich.edu and via CCMC
**SWMF Code Summary 2014 → 2017**

**Source code:**
- 520K → 770K lines of source code
- 447K → 594K lines of Fortran
- 76K → 177K lines of C++
- 30K → 52K lines of Perl and shell scripts
- 0K → 3K lines of Python scripts
- 20K → 22K lines of IDL plotting scripts
- 18K → 22K lines of Fortran and C in the wrappers and couplers
- 14K → 24K lines of Makefiles
- 10K → 13K lines of XML description of input parameters

**SWMF runs on Unix/Linux/OSX systems with Fortran 95 and C++ compilers, MPI library, HDF5, OpenMP, and Perl interpreter.**

**The SWMF can run on a laptop or on tens of thousands of processors.**

**User manual with documentation of input parameters**

**Fully automated nightly testing with several machine/compiler combinations**

**These tests provide working examples for running the code**
My Work
Structure and dynamics of stellar coronae
Interaction between stars and planets
Stellar eruptions on close-in planets

3D view

Predicted Auroral structure

Cohen et. al 2011
Can close-orbit planet sustain their atmospheres?
Summary

• Computational plasma physics is challenging due to the wide range of scales and incomplete theory.

• The BATSRUS MHD code is highly versatile, advanced code to study non-relativistic plasmas.

• The SWMF enables to study multi-physics systems with much more accuracy and details.

• BATSRUS/SWMF are used to study different applications in space physics and astrophysics.
Thank You!!!