Advanced Space Weather Modeling

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(University of Michigan)
14 domains represented by 18 different models
594K lines of Fortran, 177K lines of C++ with MPI & OpenMP
Scripts, Makefiles, visualization macros, documentation, nightly tests.
SWMF is freely available at http://csem.engin.umich.edu/tools/swmf and via CCMC
Couple MHD and PIC

MHD with embedded PIC model (MHD-EPIC): combine the efficiency of the global fluid code with the physics capabilities of the local PIC code

- PIC covers part of the simulation domain
- MHD provides the initial state and boundary conditions for PIC
- PIC overwrites the overlapped MHD cells
Ideal MHD equations:
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0
\]
\[
\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot [\rho \mathbf{u} \mathbf{u} + \mathbf{I} \left( p + \frac{1}{2\mu_0}B^2 \right) - \frac{1}{\mu_0} \mathbf{B} \mathbf{B}] = 0
\]
\[
\frac{\partial e}{\partial t} + \nabla \cdot \left[ \mathbf{u} \left( e + p + \frac{1}{2\mu_0}B^2 \right) - \frac{1}{\mu_0} \mathbf{u} : \mathbf{BB} \right] = 0
\]
\[
\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{uB} - \mathbf{Bu}) = 0
\]
\[
e = \frac{p}{\gamma - 1} + \frac{\rho u^2}{2} + \frac{B^2}{2\mu_0}
\]

Particle-in-Cell:
\[
\nabla \cdot \mathbf{E} = \frac{\rho q}{\varepsilon_0},
\]
\[
\nabla \cdot \mathbf{B} = 0,
\]
\[
\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E},
\]
\[
\frac{d\mathbf{x}_p}{dt} = \mathbf{v}_p,
\]
\[
\frac{d\mathbf{v}_p}{dt} = \frac{q_s}{m_s} \left( \mathbf{E}_p + \mathbf{v}_p \times \mathbf{B}_p \right),
\]
\[
\frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t} = \nabla \times \mathbf{B} - \mu_0 \mathbf{j},
\]

Initialize PIC from MHD

- Calculate Electric field from Ohm’s law:
  \[ \mathbf{E} = -\mathbf{u} \times \mathbf{B} + \frac{\mathbf{J} \times \mathbf{B}}{q_e n_e} \]
- Assume charge neutral: \( n_i = n_e \)
- Ion and electron velocities can be obtained from the fluid momentum and current:
  \[ n(m_i \mathbf{u}_i + m_e \mathbf{u}_e) = \rho \mathbf{u}_{MHD} \quad n(q_i \mathbf{u}_i + q_e \mathbf{u}_e) = \mathbf{J}_{MHD} \]
- Pressure
  1) Assume a fixed \( p_i/p_e \) ratio:
  \[ p_i = (1 - \alpha) p_{MHD} \quad p_e = \alpha p_{MHD} \]
  2) Solve the electron pressure equation:
  \[ \frac{\partial p_e}{\partial t} + \nabla \cdot (p_e \mathbf{u}_e) = (\gamma - 1)(-p_e \nabla \cdot \mathbf{u}_e) \]
- Generate macro-particles from Maxwellian distribution
3D MHD-EPIC Simulation Setup

Physical parameters
- Artificially increase ion inertial length by a factor of 16, so $d_i \sim 1/6 \, R_E$.
- $m_i/m_e = 100$
- Typical solar wind conditions: $\rho = 5 \, \text{amu/cm}^3$, $U_X = -400 \, \text{km/s}$, $B = [0,0,-5] \, \text{nT}$

Hall MHD with separate electron pressure equation
- MHD domain: $-224 < x < 32$, $-128 < y, z < 128 \, R_E$
- At the magnetopause $\Delta x = 1/16 \, R_E$ (~400km)
- MHD uses ~20% CPU time

PIC
- PIC domain: $8 < x < 12$, $-6 < y < 6$, $-6 < z < 6 \, R_E$
- $\Delta x = 1/32 \, R_E$: 5 cells per $d_i$ (for $f = 16$)
- 216 particles per cell per species: 8B total
- Consuming ~80% simulation time

~18000 core hours modeling 1min

Yuxi Chen et al. Journal of Geophysical Res. 2017
FTE simulation: Magnetic Reconnection and Flux Rope Formation

- \( B_x \) jumps from the negative peak \((z=0)\) to the positive peak \((z=1R_E)\)
- Bounded by the depressed magnetic field ‘trenches’ at \( z = -0.2R_E \) and \( z = 2R_E \)
- \( B_t \) reaches local minimum at the center

From Zhang et al. (2010)
FTEs colored by $u_{iz}$

- IMF is purely southward
- FTEs grow in the dawn-dusk direction
- The FTEs become tilted
- Two FTEs can merge into one

Yuxi Chen et al. J. Geophys. Res. 2018
Lower Hybrid Drift Instability (LHDI)

LHDI arises near the interface of magnetosheath and magnetosphere, where there is a sharp density gradient.

Simulation agrees with MMS observation:
- $E_M \sim 8 \text{ mV/m}$
- $k r_e \sim 0.4$, $\lambda \sim 16 \ r_e$
MHD-EPIC simulation of the magnetotail

Solar wind: 10 amu/cc, 500 km/s, $B_z = -5 \text{nT}$ changing to $-15 \text{nT}$ at $t \sim 6 \text{ hours}$. 

![Logarithmic plasma density plot](image)

time = 4h00m00s
The generation and evolution of Flux Transfer Events

- FTE grows in dawn-dusk direction
- Core field gradually increases
- The core field strength is anticorrelated with plasma pressure

Confirms that the magnetic field signature of a FTE can be found at the early stage of formation

Kinetic features

- lower hybrid drift instability (LHDI)
Spherical Wedge Active Region Model (SWARM) on Blue Waters

- Spherical wedge grid
- Gravity: $1/r^2$
- Tabular EOS ionization
- Radiative cooling
- 35 Mm deep (0.95 Rs)
- 5 levels of refinement
- 10x10x10 cell blocks
- 160 million grid cells
- 3 million time steps
- 288 hours on 16,384 cores: ~5 million CPU hours
Observed solar granulation

SWARM on BW
Add toroidal magnetic flux rope

Twist factor = 1

$10^{23} \text{ Mx flux}$

20 Mm deep (0.9714 Rs)
Magnetic Flux Emergence near the Photosphere

- $R = 1 \text{ Rs}$
- Magnetic field distribution dominated by convection
- Flux concentrated in downdrafts
- Magnetic field evolves parallel to polarity inversion line
- Shear flows driven by the Lorentz force
Next Step: SWARM + AWSoM Simulations

- Realistic size active region model (SWARM)
- Global solar corona model (AWSoM)
- 2-way coupling at every time step
- Allow erupting flux to expand into corona
- Self-consistent CME initiation
**Summary**

**Spherical Wedge Active Region Model (SWARM)**
- Largest simulation of an active region 150x300Mm
- Convection zone physics captured
- Flux emergence simulation and active region formation
- Manchester et al. AGU 2017

**MHD-EPIC simulation of Earth’s magnetosphere**
- Day side and tail reconnection are modeled
- First two-way coupled MHD-kinetic simulation of Earth’s magnetosphere
- Simulation of Flux Transfer Events formed by reconnection
- Kinetic features: lower hybrid drift instability (LHDI). Agrees with MMS observations.
- Chen et al. JGR 2017
**Why Blue Waters & Future Work**

**Future work**

- SWARM + AWSoM simulations:
  - Continue flux emergence simulations
  - Continue simulation coupled to global corona model
- MHD-EPIC simulations of Earth’s magnetosphere:
  - Do actual events and compare with MMS observations
  - Cover both magnetopause and magnetotail with PIC boxes to study magnetic storms and sub-storms

**Why Blue Waters?**

- Simple and easy access
- Large-scale file transfer made easy
- Large-scale data storage & with rapid retrieval
- Support staff is knowledgable and helpful
- Order of magnitude more allocation than on other systems
- Short turn-around times for large runs
- Good software environment, stable hardware
SuperDARN radar suggests the reconnection site propagates ~30km/s dawnward (Nishimura, GEM talk, 2017)

The edge of the reconnection site moves from $y=0.75R_E$ ($t=180s$) to $y=-0.25R_E$ ($t=320s$). The corresponding speed is ~60km/s