Major Advances in Understanding of Collisionless Plasmas Enabled through Petascale Kinetic Simulations

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+ many great collaborators

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Key challenge: understanding of the Sun-Earth connection (aka Space Weather)
Why it Matters: Space Weather has tangible socio-economic impacts

Potential Impact of Large-Scale Event according to “Report on Space Weather Observing Systems: Current Capabilities and Requirements For The Next Decade”

- **Electric Power Grid:** Large-scale blackouts and permanent damage to transformers, with lengthy restoration periods.

- **Global Satellite Communications:** Widespread service disruptions to financial, telemedicine, government, and Internet services.

- **Global Positioning System (GPS) Positioning and Timing:** Degradations of military weapons accuracy, air traffic management, transportation, precision survey/construction, agriculture, energy exploration, ship navigation/commerce, financial transactions, and cell phone/broadband.

- **Satellites & Spacecraft:** Loss of satellites and capabilities, of space situational awareness (including detection of hostile actions), and increased risk to astronaut safety, etc.

Estimated cost of a severe geomagnetic storm (such as the 1859 “super storm”) on the satellite industry alone could be approximately $50 - $100 billion.

The potential consequences on the Nation’s power grid are even higher, with **potential costs of $1 - 2 trillion** that could take **up to a decade to completely repair**.
Our focus is on several fundamental physics issues

I. Magnetic Reconnection

Global evolution

Narrow boundary layers with highly stressed magnetic field

Microscopic kinetic physics

The sun

The Earth’s magnetosphere

NASA/SDO/AIA/GSFC
Magnetic Reconnection

\[ \frac{d\psi}{dt} = \int \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{S} - \oint (\mathbf{U} \times \mathbf{B}) \cdot d\ell \]

\[ \psi = \int_{s} \mathbf{B} \cdot d\mathbf{S} \]
Our focus is on fundamental physics issues
II. Turbulence in Collisionless Plasma

What is the dissipation mechanism in collisionless plasmas?

*Alexandrova, et al., 2009
BW is one of the largest resources available today

Both turbulence and reconnection are characterized by large separation of scales and require highly expensive simulations

\[
\frac{\partial f_s}{\partial t} + \mathbf{v} \cdot \nabla f_s + \frac{q_s}{m_s} \left( \mathbf{E} + \frac{1}{c} \mathbf{v} \times \mathbf{B} \right) \cdot \nabla \mathbf{v} f_s = \sum_{s'} C\{f_s, f_{s'}\}
\]

+ Maxwell’s equations

**Fully kinetic simulation**

(all species kinetic; code: VPIC)

~up to 10^{10} cells

~up to 4\times10^{12} particles

~120 TB of memory

~10^{7} CPU-HRS

~up to 500,000 cores

**Large scale hybrid kinetic simulation:**

(kinetic ions + fluid electrons;

codes: H3D, HYPERES)

~up to 1.7\times10^{10} cells

~up to 2\times10^{12} particles

~130 TB of memory
Results: the first 3D simulations of collisionless plasma turbulence that simultaneously resolve kinetic physics and large scale dynamics.

Science target: dissipation of cascading energy in collisionless plasmas: coherent structures vs resonant wave-particle interactions vs stochastic mechanism; Findings: current sheets and their properties; Applications: solar wind, solar corona, astrophysics, etc
Results: properties of the fluctuations
Results: 2D Global Fully Kinetic Simulations

Local model: physics of reconnection, but no global geometry or drive

middle ground: all of physics + 2D geometry

Global 3D models: reconnection is unphysical

NASA/Goddard Space Flight Center Scientific Visualization Studio
Results: 2D Global Fully Kinetic Simulations

Science target: coupling between magnetic reconnection and global geometry and the influence of external driving; Findings: unsteady, multiple X-line reconnection, structure of FTEs, etc, Applications: the Earth’s magnetosphere, other planetary magnetospheres
Results: Global fully kinetic simulation

a) islands generated by sheath turbulence
FTEs

b) shock surface is broken up
Science target: coupling between shock physics, magnetosheath turbulence, and global disturbances

Nearly radial IMF

MHD: smooth
(Tang et al., JGR, 118, 2013)

Kinetic: turbulence & large-scale perturbations

2D hybrid simulation (~10K cores on NASA Pleiades)

density \times \text{sign}(V_x)

Reflected ions drive foreshock turbulence that interacts with the shock & drives magnetosheath turbulence
Results: Turbulence in 3D Global hybrid Simulations (focus on ion kinetic effects)
Results: Turbulence in 3D Global hybrid Simulations
• The project “Major Advances in Understanding of Collisionless Plasmas Enabled through Petascale Kinetic Simulations” attacks fundamental plasma physics issues highly relevant to space weather research
• Blue Waters provides unique capabilities for conducting the required simulations
• Major results to date:
  • Global fully kinetic simulations of magnetic reconnection
  • First large-scale 3D simulations of decaying collisionless plasma turbulence
  • 3D global hybrid simulations addressing coupling between shock physics & magnetosheath turbulence