ENABLING BREAKTHROUGH KINETIC SIMULATIONS OF THE MAGNETOSPHERE

Allocation: NSF/11.1 Mnh
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SCIENTIFIC GOALS

Over 90% of the visible universe is in the plasma state. Fundamental plasma processes, such as magnetic reconnection, turbulence, and shocks, play a key role in the dynamics of many systems in the universe across a vast range of scales. Examples of such systems are laboratory fusion experiments, the Earth's magnetosphere, the solar wind, the solar corona and chromosphere, the heliosphere, the interstellar medium, and many astrophysical objects. In most of these settings the plasma is weakly collisional, which implies that microscopic processes on and below the scale of the ion gyroradius play an important role, especially inside various boundary layers. This presents tremendous challenges for computational modeling due to the extreme separation of scales associated with the relevant systems.

ACCOMPLISHMENTS TO DATE

We highlight our latest progress in the areas of magnetic reconnection, plasma turbulence, and fast shocks as captured in global simulations of the magnetosphere. One of the outcomes of these studies is the dynamic interplay between these seemingly distinct processes. This synergy is demonstrated using specific examples from our work on Blue Waters.

Three-dimensional fully kinetic simulations of decaying plasma turbulence, where the initial perturbation imposed on a system at large scales seeds a turbulent cascade. The cascade transports energy from the injection scale down to the electron kinetic scales, where it is ultimately dissipated by kinetic processes. A unique feature of these simulations is that they describe for the first time in a self-consistent manner a number of distinct dissipation mechanisms, thus helping assess their relative efficiency.

Global 2D fully kinetic simulations of interaction between solar wind and the magnetosphere focus on understanding how magnetic reconnection couples microscopic electron kinetic physics and macroscopic global dynamics driven by the solar wind. These simulations enable us, for the first time, to study reconnection in the complex environment of the Earth's magnetosphere, whereas all previous works were based on local simulations starting with simple and highly idealized equilibrium configurations. Many important effects that influence reconnection, such as curvature of the magnetopause, convection, inhomogeneous shear flows, and others, are absent in previous works.

In addition, we conducted the most detailed 2D and 3D global hybrid simulations of the interaction between solar wind and the magnetosphere (3D shown in Fig. 1). These simulations focus on how ion kinetic processes at the bow shock, a standing shock wave in front of the magnetosphere, drive turbulence in a region behind the shock called the magnetosheath. In the hybrid simulation model, the ions are treated kinetically, while electrons are treated as a massless fluid. Consequently, the electron kinetic scales are not resolved, reducing the range of scales to be resolved by more than three orders of magnitude and allowing simulation of larger scales compared to the fully kinetic case.

Our simulations are at the forefront of research in their respective communities. The simulations of decaying turbulence revealed the formation of current sheets with thicknesses from electron kinetic to ion kinetic scales. The possibility that such current sheets provide an efficient dissipation mechanism that is necessary to terminate the turbulent cascade has recently attracted considerable attention. The significance of this work is that formation of the current sheets was demonstrated in essentially first-principles simulations, which include all of the possible dissipation mechanisms.

Moreover, we demonstrated that the overall partition of the dissipated energy, the question of primary importance for solar wind studies, is not consistent with the previous assumption that resonant damping of wave-like fluctuations is the dominant dissipation mechanism.

The global hybrid and global fully kinetic simulations demonstrated the complex dynamics of the magnetosphere, where shock physics, turbulence, and reconnection interact in a complex manner not seen before in simulations. Some of the highlights include: (a) The first demonstration of potentially damaging space weather effects due to formation of high-velocity jets in the magnetosphere. Such jets form due to ion kinetic effects and are completely absent in traditional global simulations used for space weather, which are based on MHD. There has been recent detection of such jets in observations of the magnetosheath using *in situ* spacecraft measurements. (b) The first demonstration of the structure of the ion foreshock in 3D that exhibits a helical pattern. (c) The discovery that turbulence-generated large amplitude waves in the ion foreshock have more global consequences than previously thought. In particular, rather than being stopped at the Earth's magnetopause they get past it and reach deep inside the Earth's magnetotail. These results indicate that global kinetic simulations are critical to development of accurate space weather forecasting capabilities.

HOW BLUE WATERS PROJECT STAFF HELPED

Blue Waters staff helped the team implemented SSE4 vector instructions in VPIC kernels and provided I/O best practices for file transfers with Globus Online. The Blue Waters team also helped with visualization, including installation of a version of ParaView to enable use of the LIC technique.

WHY THE RESEARCH MATTERS

The Earth is embedded in the Sun's extended atmosphere. As such, massive electromagnetic storms on the Sun can reach the Earth, wreaking havoc on our technological systems. There is a 12% chance in the next 10 years of a solar storm of the magnitude of the 1859 Solar Superstorm that caused telegraph communications failure around the world. Such a perfect storm would cause over $2 trillion in damage today. The consequences of such a storm would be far reaching, with effects to the electric power grid that could take up to a decade to completely repair, widespread service disruptions in global satellite communications and GPS systems, and up to $100 billion of damage to satellites. On 23-24 July 2012, our society narrowly averted (by a margin of seven days) a geomagnetic storm as large as the 1859 event. Thus it is critical to develop accurate forecasting capabilities for space weather. Given that solar wind interaction with the Earth's magnetosphere is dominated by kinetic effects, the use of global kinetic simulations is critical in development of accurate forecasting capabilities.

WHY BLUE WATERS

The goals of this work are characterized by extreme separation of spatial and temporal scales. Consequently, the relevant simulations require extreme computational resources and produce a large amount of data (in excess of 100 TB from a single run). Blue Waters is currently the most powerful tool available to conduct this work, enabling simulations of unprecedented scale and fidelity.

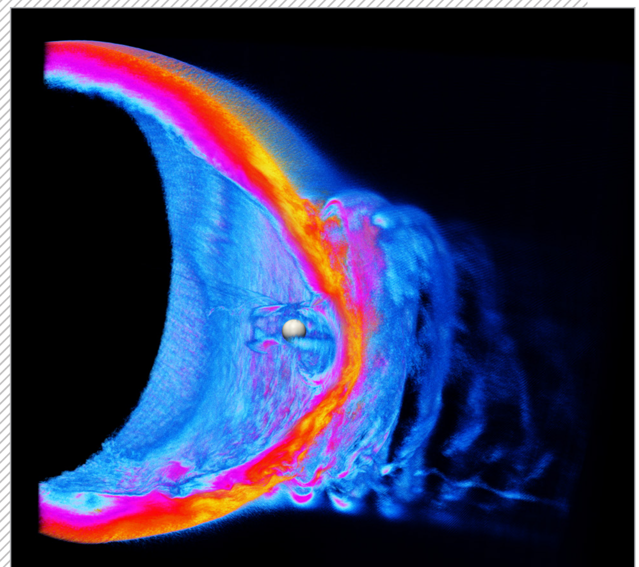

Figure 1. Structure of the Earth's magnetosphere simulated using a massively parallel 3D global hybrid code.

PRE-PETASCALE PREPARATION

We have been developing and improving techniques and algorithms to be able to perform efficient simulations at the petascale and to analyze the resulting datasets, which are complex and large. We also conduct smaller-scale simulations and our parameter search using our resources and use Blue Waters for very few select production runs.

LOOKING FORWARD TO THE NEXT TRACK-1 SYSTEM

Currently, small- and micro-scale helio phenomena are addressed only locally, which makes it difficult to predict their effect on the global solution. The improvement for small and micro scales requires 10^4 more computing time than in the best contemporaneous simulations. Total volume is not increasing, but the grid is 10 times finer in all directions locally. AMR and load balancing improvements are also required. Likewise, I/O issues for very large data files (40-50 TB) remain challenging.

Further improvements would involve the numerical simulation of the turbulent, multi-ion solar wind flow from the solar surface to the Earth's location and its further interaction with the interstellar medium. This will be necessary for the Solar Probe Plus mission to be launched by NASA in 2018. Currently, only some pieces of this approach are implemented, sometimes only locally. The physical times to be covered do not increase, but the grids will be finer at the same total physical volume. The problem will be in the division of the computational volume into sub-volumes to make the simulation feasible. Using new Track-1 supercomputing architecture will be essential to implement this challenge because of the additional physics it will require.

COMMUNITY IMPACT

The problems considered in this research are motivated by the need to better understand Earth's space environment and its interaction with the Sun, the major source of energy in the solar system. Collectively known as "space weather," this area of research is increasing in socio-economic significance due to our society's reliance on space-based communication and navigation technologies and the potential risk of catastrophic disruptions of the power grid and communication satellites caused by major solar events.

For example, turbulence simulations help us understand energy balance in the solar wind, the major driver of the Earth's magnetospheric activity. Similarly, global fully kinetic and hybrid simulations help us understand the response of the magnetosphere to external perturbations. Such simulations are critical for development of accurate space weather forecasting capabilities.

In addition to their significance for space weather, the processes and their interactions considered here are thought to play a role in many space and astrophysical settings. Consequently, the insights from this study are of great interest to a variety of fields.

PUBLICATIONS

Karimabadi, H., et al., The link between shocks, turbulence and magnetic reconnection in collisionless plasmas. *Physics of Plasmas*, 21 (2014), 062308, doi:10.1063/1.4882875.

Liu, Y.-H., W. Daughton, H. Karimabadi, and V. Roytershteyn, Bifurcated Structure of the Electron Diffusion Region in Three-Dimensional Magnetic Reconnection. *Phys. Rev. Lett.*, 110:26 (2013), 265004, doi:10.1103/PhysRevLett.110.265004.

This research is part of the Blue Waters sustained-petascale computing project, which is supported by the National Science Foundation (awards OCI-0725070 and ACI-1238993) and the state of Illinois. Blue Waters is a joint effort of the University of Illinois at Urbana-Champaign and its National Center for Supercomputing Applications.