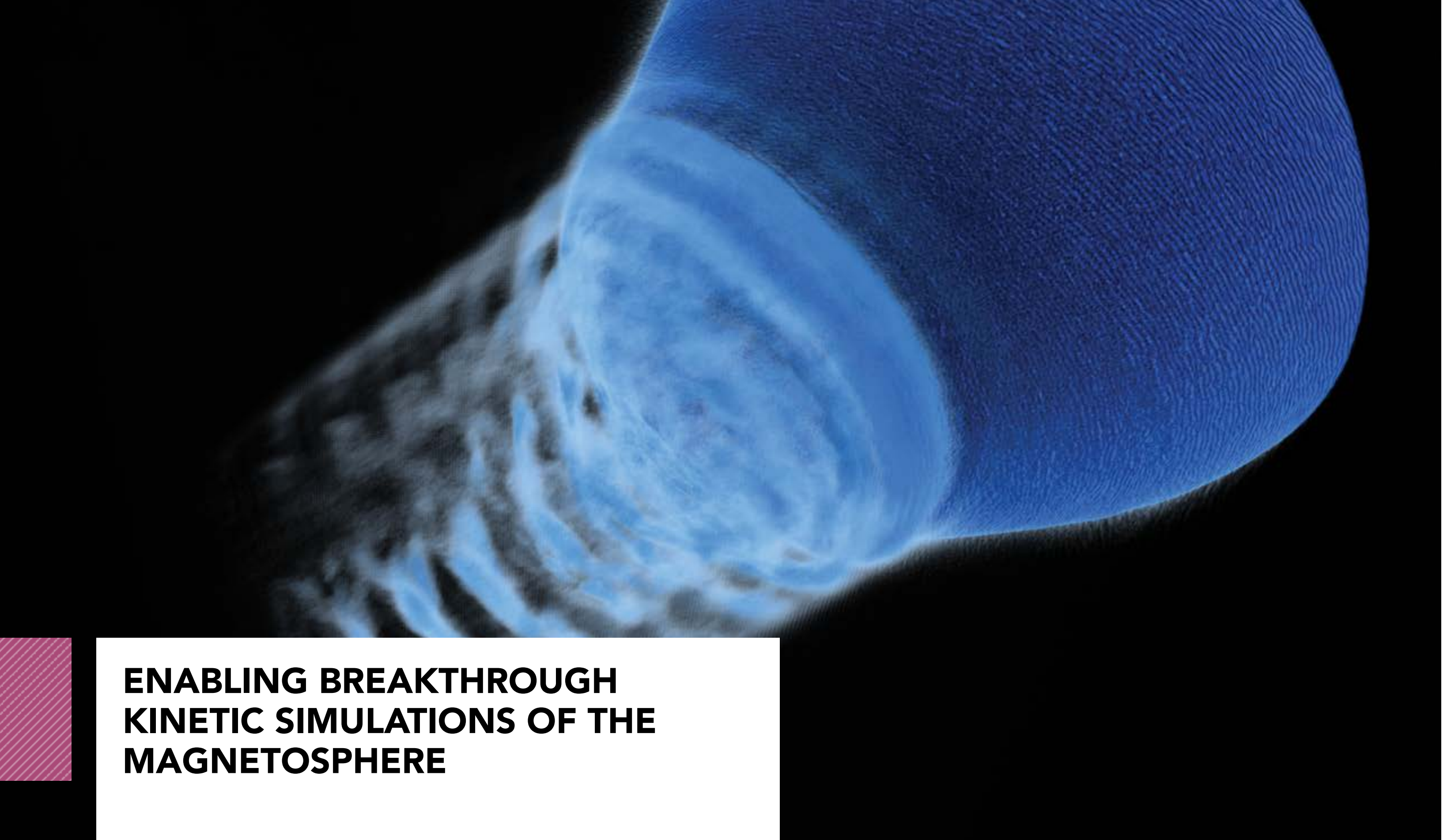

FIGURE 1 (BACKGROUND): Structure of the ion foreshock in 3D global hybrid simulation of the Earth's magnetosphere. Perturbations generated in the foreshock by ions reflected from the bow shock were convected back into the shock, got amplified, and led to both small-scale turbulence and global perturbations in the region behind the shock (called the magnetosheath).

ENABLING BREAKTHROUGH KINETIC SIMULATIONS OF THE MAGNETOSPHERE

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EXECUTIVE SUMMARY:

We present recent results from large-scale kinetic plasma simulations aimed at advancing the basic understanding of phenomena such as magnetic reconnection and plasma turbulence, and the degree to which they affect global dynamics of the Earth's magnetosphere.

INTRODUCTION

The ability to understand and forecast the behavior of the Earth's magnetosphere is becoming increasingly important as our society relies more and more on space-based technologies such as telecommunications, Global Positioning System, and others. The Earth's magnetosphere is a protective "bubble" formed when our planet's internal magnetic field interacts with the solar wind, a stream of plasma originating on the Sun. The magnetosphere responds dynamically to variations in the relatively steady solar wind and to more transient, sometimes explosive events on the Sun, such as coronal mass ejections. Many of the processes determining the behavior of the Earth's magnetosphere are very complex, involving plasma physics and often coupling global, large-scale dynamics to microscopic processes occurring on short spatial and temporal scales associated with plasma kinetic effects.

The goal of this project is to investigate this cross-scale coupling for two of the most ubiquitous plasma processes that are essential to the dynamics of the magnetosphere and the solar wind: magnetic reconnection and plasma turbulence. Magnetic reconnection is a process of rapid merging and breaking of the magnetic field embedded into plasma. Often explosive in nature, magnetic reconnection enables rapid release of magnetic energy accumulated in the system and is ultimately behind phenomena like magnetospheric sub-storms and solar eruptions. But reconnection can also operate in a more steady fashion in the solar wind and in the magnetosphere (for example, enabling solar wind plasma entry into the magnetosphere when conditions are favorable).

Similarly to fluid turbulence, turbulence in plasmas is a ubiquitous process that is thought to provide a crucial mechanism for energy, momentum, and mass transport in many systems across the universe. For example, the solar wind is known to be highly turbulent and many theories invoke energy input due to dissipation of turbulence to explain anomalous temperature profiles in the solar wind. Due to availability of in situ measurements provided by a fleet of spacecraft, the solar wind is an excellent laboratory for studying the basic physics of plasma turbulence.

While magnetic reconnection and plasma turbulence are two distinct physical processes, in large-scale systems they often interact and must be studied simultaneously. Moreover, in high-temperature rarified plasmas typical of those encountered in space, both turbulence and magnetic reconnection involve kinetic processes that depend on the details of interaction between the Earth's electromagnetic field and individual plasma particles (electrons and ions). Extreme separation of scales between typical spatial and temporal scales associated with kinetic physics and those associated with global dynamics is a formidable computational challenge and requires the largest available computational resources.

METHODS & RESULTS

The project utilized particle-in-cell (PIC) kinetic plasma simulations using two complementary approaches. Fully kinetic simulations that describe all plasma species using a Vlasov–Maxwell (or Vlasov–Boltzmann) system provided essentially a first-principles description of the plasmas of interest. Such simulations were conducted primarily using VPIC, a high-performance relativistic plasma simulations code [1], and focused on local modeling of magnetic reconnection and turbulence in various environments [2–8]. In the hybrid model, relatively heavy ions were still described kinetically while electrons were modeled as a massless fluid, allowing much larger systems to be considered in the situations where the dominant kinetic effects are associated with ions. The hybrid simulations for this project used simulation code H3D [9] and focused primarily on modeling global interaction of the solar wind with a magnetosphere, as illustrated in fig. 1. Below, we briefly discuss two of the topics considered in this project.

One of the most interesting results that emerged from recent global hybrid simulations was the coupling between bow shock, turbulence, and magnetic reconnection. While many individual pieces of physics had long been studied using spacecraft observations, analytical theory, and small-scale simulations, the degree to which such coupling affects global dynamics had only become apparent recently [10]. The majority of the existing results were obtained using 2D simulations that severely restricted the geometry of the plasma flow around magnetosphere. Blue Waters enabled the first 3D simulations, which provided a multitude of exciting new details (e.g., fig. 1).

The studies of plasma turbulence conducted on Blue Waters primarily focused on understanding mechanisms responsible for dissipation of turbulence in high-temperature rarified plasmas where Coulomb collisions are too infrequent to provide the required microscopic dissipation (see example in fig. 2). Under such conditions, the so-called collective modes provide the dissipation. The three most commonly discussed alternatives are damping associated with wave-like oscillations, dissipation associated with coherent structures sheets (e.g., current sheets, which are localized narrow regions where the magnetic field is highly sheared), and stochastic damping originating from the motion of individual ions in a turbulent electromagnetic field. In many plasmas of interest, these three basic processes are likely to operate simultaneously, but their relative efficiency may depend on the parameter regime. Fully kinetic simulations provide a unique model that is capable of seamlessly describing all of the relevant processes, which is essential to understanding how they interact with each other and which may be dominant under given conditions. This in turn will allow researchers to discriminate between various theoretically conceived scenarios regarding the role of turbulence in such systems as the solar corona and the solar wind.

WHY BLUE WATERS?

Due to the extreme separation of scales, the problems that need to be solved require the largest available computational resources.

In additional to providing the necessary computational time, Blue Waters is notable for its advanced infrastructure for data management and analysis.

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FIGURE 2: Current density in a 3D fully kinetic simulation of decaying plasma turbulence. This snapshot illustrates formation of several types of coherent structures, including planar current sheets, electron-scale magnetic holes, and flux ropes.