THREE-DIMENSIONAL NATURE OF COLLISIONLESS MAGNETIC RECONNECTION AT EARTH'S MAGNETOPAUSE

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EXECUTIVE SUMMARY

Earth's magnetosphere shields the planet from constant bombardment by supersonic solar winds. However, this magnetic shield, called the magnetopause, can be eroded by various plasma mechanisms. Among them, magnetic reconnection is arguably the most important process. Reconnection not only allows the transport of solar wind plasmas into Earth's magnetosphere but also releases the magnetic energy and changes the magnetic topology. At Earth's magnetopause, magnetic reconnection proceeds between the shocked solar wind plasmas and the magnetosphere plasmas. The magnetosheath plasma has a typical magnetic field strength of ~20 nanoteslas and density of ~5 per cc. The magnetosphere plasma has a magnetic field strength of ~60 nanoteslas and density of ~0.5 per cc. The magnetic fields on these two sides can shear at any angle. Many three-dimensional properties of magnetic reconnection in such asymmetric geometry remain unclear. We use first-principle simulations to explore the 3D kinetic physics that control this critical energy conversion process.

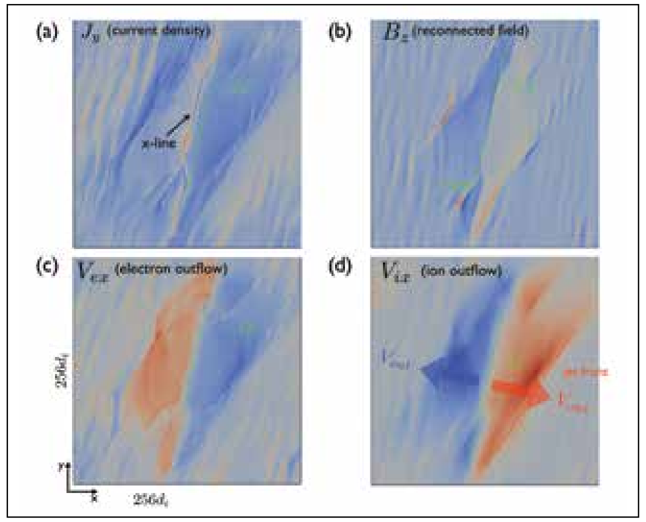

Figure 1: Quantities shown on the 2D interface between the magnetosphere plasma and magnetosheath plasma. The current density, reconnected field, electron outflow, and ion outflow all illustrate the reconnection x-line with a well-defined orientation and extent.

RESEARCH CHALLENGE

Massive solar eruptions drive magnetic storms that impact Earth's magnetosphere and produce space weather. The consequential electromagnetic waves, electric currents, and energetic particles can do harm to satellites, astronauts, GPS systems, radio communication, and power grids on the ground. Magnetic reconnection is the key player in such solar wind-magnetospheric coupling, and space weather in general. One fundamental question in reconnection study is: Is there a simple principle that determines the orientation of the reconnection x-line in such an asymmetric current sheet? The solution of this problem remains unclear with our current understanding of magnetic reconnection, and we aim to resolve this issue. Ultimately, we hope to develop an adequate understanding of the 3D nature of asymmetric magnetic reconnection itself, which is a crucial step in the quest for predicting the location and rate of flux transfer at Earth's magnetopause. A better understanding of the nature of magnetic reconnection will advance the modeling of space weather.

METHODS & CODES

This project employs the particle-in-cell code VPIC [1]. VPIC solves the relativistic Vlasov–Maxwell system of equations using an explicit charge-conserving approach. Charged particles are advanced using Leapfrog with 6th-order Boris rotation, then the current and charge density are accumulated on grid points to update electromagnetic fields. Marder divergence cleaning frequently is employed to ensure the divergent free of the magnetic field. The level of error is bounded by the numerical round-off effect. These 3D kinetic simulations are now generating large amounts of data [~O(100) TB] for each run. We have met this challenge with help from visualization experts at LANL and LBNL to develop parallel readers that interface between these large VPIC data sets and the open-source package ParaView.

RESULTS & IMPACT

During the first award year, we have conducted several petascale simulations on Blue Waters to study the three-dimensional nature of the reconnection x-line. We identify features in these simulations that can potentially bring the most scientific merit. Our approach of inducing a solitary x-line is working well in a large-scale 3D simulation. We initialize the x-line at the center of the box and then let the x-line expand freely and form a well-defined orientation. Here, the orientation is measured as ~13°, close to the angle that bisects the total magnetic shear angle made by magnetic fields on two sides of the current sheet. In comparison with other existing work, where the interaction between multiple x-lines often complicates the orientation measurement, this approach provides an ideal setup for the x-line to grow in a certain "preferential" orientation. Also, we measured the expanding/spreading velocity of the reconnection x-line, decided whether there is an intrinsic reconnection x-line extent in a fully three-dimensional system, and studied the turbulent nature of reconnection.

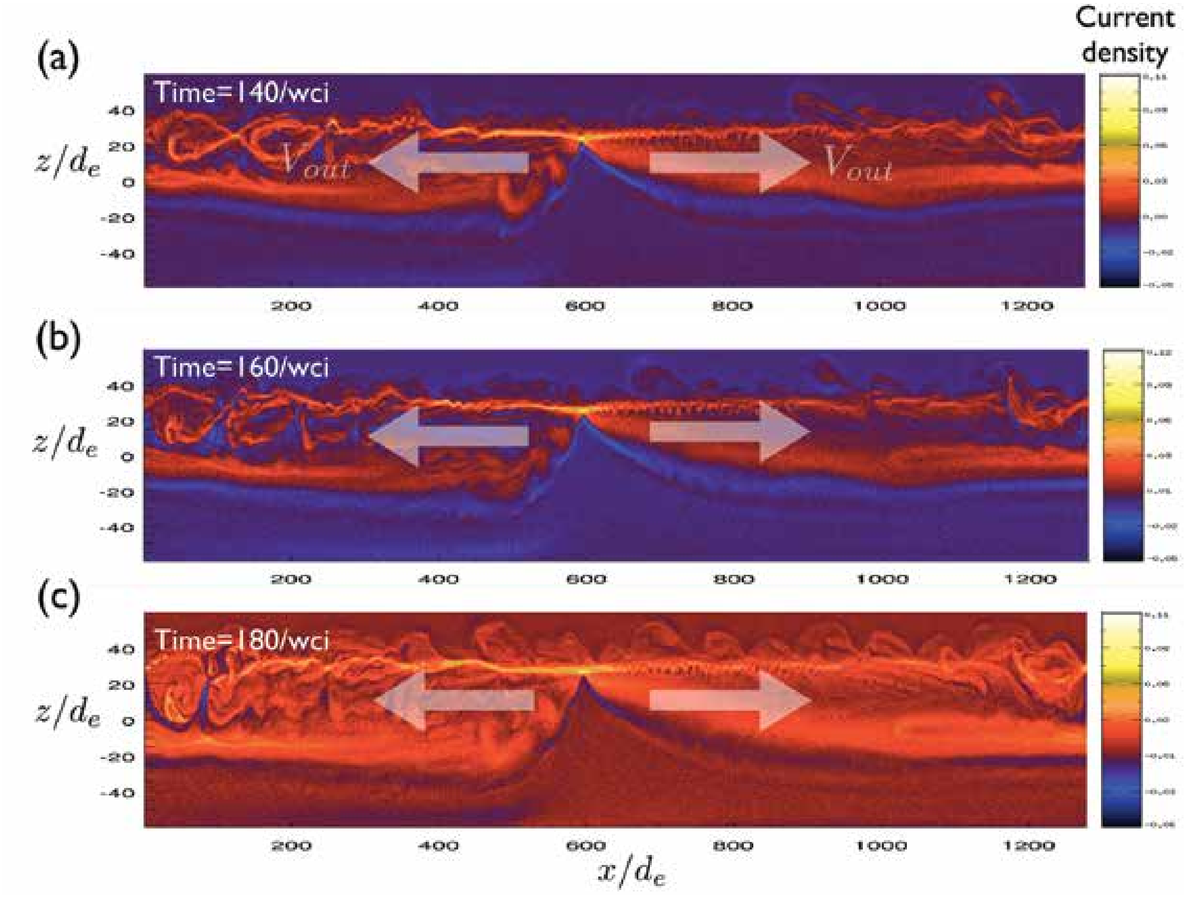

Figure 2: The current density on the reconnection plane in a sequence of time shows the self-generated turbulence during magnetic reconnection. The arrows indicate the reconnection outflows.

The same principle that determines the x-line orientation could interplay with global geometrical effects to determine the location and orientation of magnetic reconnection at Earth's magnetopause. Knowledge of the extent of x-line will enable space scientists to more accurately estimate the efficiency of flux transfer from solar wind to the Earth's magnetosphere. The work proposed here is relevant to the study of dayside reconnection during the first phase of NASA's Magnetospheric Multiscale Mission (MMS). The close tetrahedron deployment of the MMS spacecraft cluster and the equipped capability of high time-resolution provide an invaluable chance to reconstruct the three-dimensional geometry of the reconnection diffusion region.

WHY BLUE WATERS

Because the x-line has a dimension down to electron scale, a fully kinetic description is necessary. Given the available computational capability, it has become possible to use a first-principle kinetic simulation to investigate the dynamics of the x-line in a reasonably large 3D system, which spans from electron kinetic scale to magnetohydrodynamics scale. A representative 3D run in this project traces the motion of 2 trillion charged particles under the interaction of self-generated electromagnetic fields, which are evaluated on 6 billion grids. The output data easily have a size of hundreds of TBs for each run. Blue Waters not only provides the computational resource for the calculation but also the online storage for the output and restart files.