3D NATURE OF COLLISIONLESS MAGNETIC RECONNECTION AT EARTH'S MAGNETOPAUSE

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PI: Yi-Hsin Liu[1]
Co-PIs: Michael Hesse[2], William Daughton[3]
Collaborators: Tak Chu Li[1], Ari Le[3], Shan Wang[4]

[1]Dartmouth College
[2]University of Bergen
[3]Los Alamos National Laboratory
[4]University of Maryland, College Park

EXECUTIVE SUMMARY

Earth's magnetosphere (a region formed from its magnetic fields) 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 the mechanisms, magnetic reconnection, which refers to the breaking and reconnecting of oppositely directed magnetic field lines in a plasma, is arguably the most active process at the center of many spectacular events in our solar system.

Magnetic reconnection not only allows the transport of solar wind plasmas into Earth's magnetosphere, but also releases magnetic energy and changes the magnetic topology. At Earth's magnetopause, magnetic reconnection proceeds between the shocked solar wind plasmas and the magnetosphere plasmas. Many 3D properties of magnetic reconnection in such an asymmetric geometry remain unclear. In this work, we used first-principle simulations to explore the 3D kinetic physics that control this critical energy-conversion process.

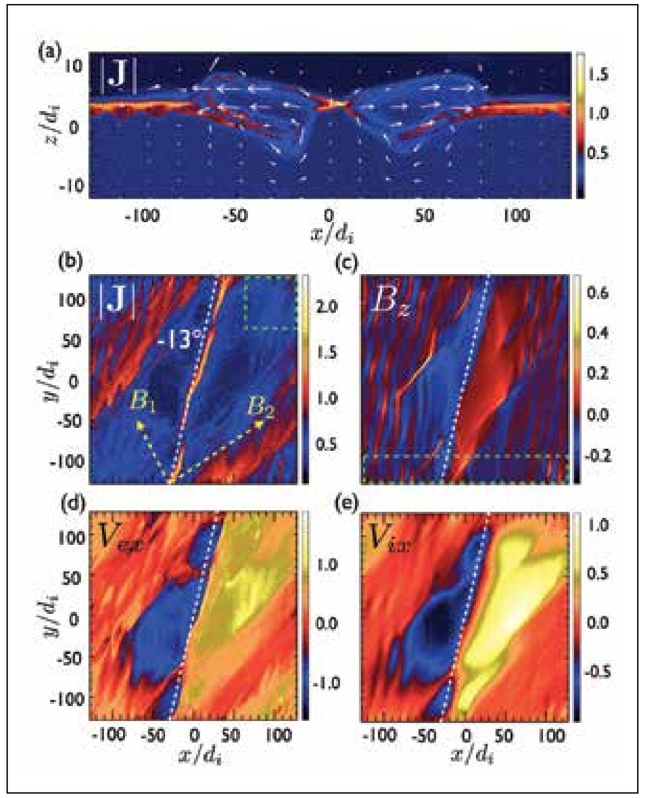

Figure 1: In (a), the total current density on a 2D plane where y = 0. In (b), the x–y cut of the current density across the location of the intense current near the x-line. Similarly, in (c), the reconnected field; in (d), the electron outflow; in (e), the ion outflow.

RESEARCH CHALLENGE

Massive solar eruptions drive magnetic storms that impact Earth's magnetosphere and 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 and magnetosphere coupling, and in 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 (the null line where magnetic reconnection occurs), which points in the direction that maximizes the speed characterizing the reconnection outflow, in such an asymmetric current sheet?" The solution of this problem remains unclear with our current understanding of magnetic reconnection; thus, we aim to study the 3D nature of reconnection. It will be a crucial step in the quest to predict the location and rate of flux transfer at Earth's magnetopause, improving the forecast of space weather.

METHODS & CODES

This project employs the particle-in-cell code, VPIC [1], which solves the relativistic Vlasov–Maxwell system of equations using an explicit charge-conserving approach. Charged particles are advanced using the leapfrog method 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.

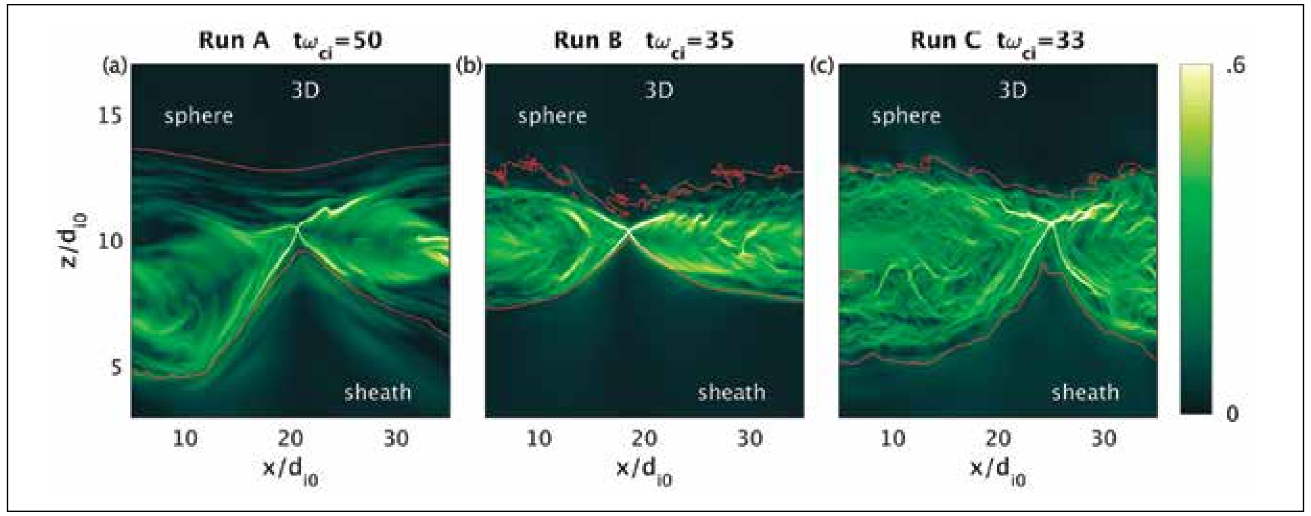

Figure 2: The magnetic field exponentiation factor σ from a plane of seed points in each 3D simulation. The ridges of large values highlight the quasi-separatrix layer, which is an approximate x-line, and pair of separatrices. The red contour in each panel marks where the electron mix measure is 0.99.

RESULTS & IMPACT

The orientation and stability of the reconnection x-line in asymmetric geometry was studied in 3D systems. We initiated reconnection at the center of a large simulation domain to minimize the boundary effect. The resulting x-line had sufficient freedom to develop along an optimal orientation, and it remained laminar. Companion 2D simulations indicated that this x-line orientation maximizes the reconnection rate, which has an important implication. We then designed 3D simulations with one dimension being short to fix the x-line orientation but long enough to allow the growth of the fastest growing oblique tearing modes. This numerical experiment suggested that reconnection tends to radiate secondary oblique tearing modes if it is externally (globally) forced to proceed along an orientation not favored by the local physics. The development of oblique structure easily leads to turbulence inside small periodic systems. This result could help interpret the local geometry of reconnection events observed by the Magnetospheric Multiscale Mission (MMS) and perhaps help determine an appropriate LMN coordinate. The question we are exploring is also relevant to the upcoming ESA–CAS joint mission, the Solar wind Magnetosphere Ionosphere Link Explorer (SMILE), which will study the development of reconnection lines at Earth's magnetopause using X-ray and UV imagers.

In separate work, plasma parameters were selected to model MMS magnetopause diffusion region crossings with a varying guide field strength. In each case, strong drift-wave fluctuations were observed in the lower-hybrid frequency range at the steep density gradient across the magnetospheric separatrix. These fluctuations give rise to cross-field electron particle transport. In addition, this turbulent mixing led to significantly enhanced electron parallel heating in comparison to 2D simulations. Comparing different methods of quantifying the anomalous dissipation revealed complications. Nevertheless, the anomalous dissipation from short wavelength drift fluctuations appeared weak for each case, and the reconnection rates observed in 3D were nearly the same as in 2D models. The 3D simulations exhibited a number of interesting and new features that are consistent with recent MMS observations.

WHY BLUE WATERS

Because the x-line has a dimensional range 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 the magnetohydrodynamics scale. A representative 3D run in this project traced the motion of two trillion charged particles under the interaction of self-generated electromagnetic fields, which are evaluated on six billion grids. The output data can easily have a size of hundreds of terabytes 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.

PUBLICATIONS & DATA SETS

Yi-Hsin Liu, Y.-H., et al., Orientation and Stability of Asymmetric Magnetic Reconnection X-line. *Journal of Geophysical Research*, 123:6 (2018), DOI:10.1029/2018JA025410.

Ari Le, W.D., et al., Drift Turbulence, Particle Transport, and Anomalous Dissipation at the Reconnecting Magnetopause. *Physics of Plasmas*, 25 (2018), DOI:10.1063/1.5027086.