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THE SPREADING OF THREE-DIMENSIONAL MAGNETIC RECONNECTION IN ASYMMETRIC GEOMETRY

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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 them, magnetic reconnection is arguably the most active 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. Many three-dimensional properties of magnetic reconnection in such asymmetric geometry remain unclear. The research team used first-principle simulations to explore the 3D kinetic physics that control this critical energy conversion process.

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 harm satellites, astronauts, GPS systems, radio communication, and power grids on the ground. Magnetic reconnection is the critical player in solar wind–magnetosphere coupling, and space weather in general. Fundamental questions in reconnection research include: Is there a simple principle that determines the orientation of the reconnection x-line (the null line where magnetic reconnection occurs) in such an asymmetric current sheet? How fast does reconnection spread out from a point source? The answers to these questions remain unclear given our current understanding of magnetic reconnection, and the research team aims to study its 3D nature. This work is a crucial step in the quest for predicting the location and rate of flux transfer at Earth's magnetopause, and will thus improve the forecast of space weather.

METHODS & CODES

This project employed the particle-in-cell code VPIC, which solves the relativistic Vlasov–Maxwell system of equations using an explicit charge-conserving approach. Charged particles were advanced using Leapfrog with sixth-order Boris rotation, then the current and charge density were accumulated on grid points to update electromagnetic fields. Marder divergence cleaning was employed to ensure the divergence was free of the magnetic field. The level of error was bounded by the numerical round-off effect.

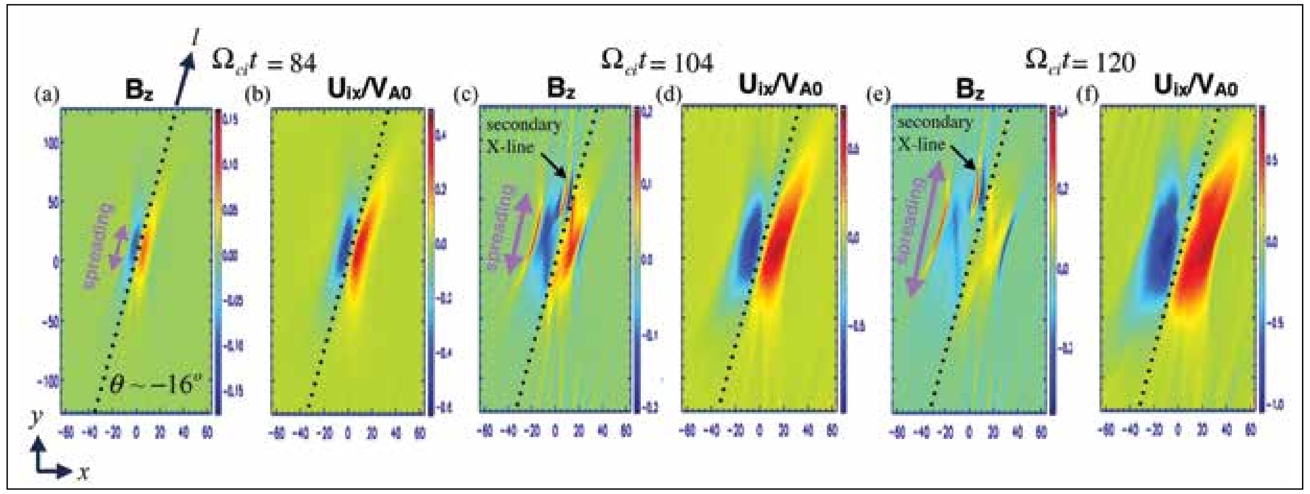

Figure 1: X-line spreading observed in the (normalized) reconnected magnetic field B_z/B_0 and ion outflow U_{ix}/V_{A0} at three different times. The x-line spreads along the orientation labeled as the l axis that is indicated by dotted black lines.

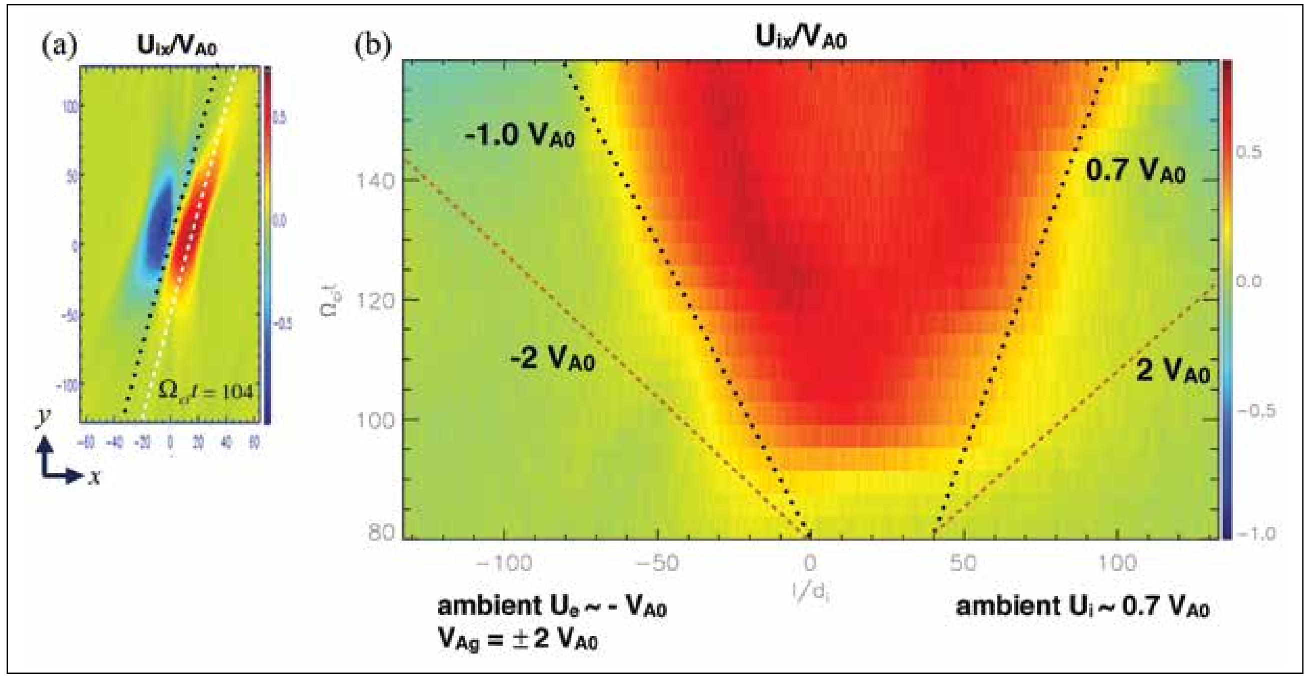

Figure 2: X-line spreading measured from the ion outflow speed U_{ix}: (a) A cut of U_{ix} across the initial x-line on the x–y plane at time t = $104/\Omega_{ci}$. The spreading of Uix is sampled at the dashed white line. (b) The time stack plot of the sampled U_{ix}.

RESULTS & IMPACT

The spreading of magnetic reconnection in asymmetric current sheets was studied in the third year of this project. The result has an application to the reconnection that occurs at Earth's magnetopause. The research team 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 the signal of fast reconnection spread out from two ends of the x-line. The team measured the spreading speed and found that it exhibited a strong dependence on the thickness of the initial current sheet. They mapped out a criterion for the Alfvénic spreading of fast reconnection and explored its physics origin. While the criterion appears to be stringent, this study suggests that under typical conditions at Earth's magnetopause, the reconnection x-line is unlikely to demonstrate Alfvénic spreading at the local Alfvén speed regardless of the guide field strength. An Alfvénic spreading is expected only if the typically thick magnetopause current sheet is substantially compressed (perhaps by the solar wind) to a state strongly unstable to the collisionless tearing instability.

These results compared favorably with recent magnetopause observations using SuperDARN radars and THEMIS satellites. In addition, this new result is important to NASA's ongoing Magnetospheric Multiscale Mission, which was designed to study the kinetic physics of the reconnection x-line. The results could also be relevant to the ongoing European Space Agency (ESA)–Japan Aerospace Exploration Agency Mercury mission, BepiColombo, and the upcoming ESA–Chinese Academy of Sciences joint mission, Solar Wind Magnetosphere–Ionosphere Link Explorer, which will study the development of reconnection lines at Earth's magnetopause using X-ray and UV imagers.

WHY BLUE WATERS

Because the x-line has a dimension down to the 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 that spans from the electron kinetic scale to the magnetohydrodynamics scale. A representative 3D run in this project traces 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 easily have a size of hundreds of terabytes for each run. Blue Waters provides not only the computational resource for the calculation but also the online storage for the output and restart files.

PUBLICATIONS & DATA SETS

Y.–H. Liu, M. Hesse, T. C. Li, M. Kuznetsova, and A. Le, "Orientation and stability of asymmetric magnetic reconnection x-line," *J. Geophys. Res.*, vol. 123, pp. 4908–4920, May 2018.

T. C. Li, Y.–H. Liu, M. Hesse, and Y. Zhu, "Three-dimensional x-line spreading in asymmetric magnetic reconnection," *J. Geophys. Res.*, submitted, 2019, arXiv: https://arxiv.org/abs/1907.02025v1.