Orientation and Stability of Magnetic Reconnection X-line at Earth’s Magnetopause

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Why it matters?
Magnetic Reconnection.
— an efficient mechanism that converts magnetic energy to plasmas kinetic energy

1. Inflow brings in magnetic flux
2. Field lines break & reconnect
3. Reconnected field line shoots out plasma
4. Pressure drop sucks in plasma inflow

A self-driven process!!!
Earth’s magnetosphere

- Reconnection occurs at both the magnetopause & magnetotail.
- Reconnection at the magnetotail drives magnetospheric substorm & causes aurora.
- **Space Weather**: a strong geomagnetic storm (e.g., 1859 Carrington Event, 1989 Quebec blackout) could do damage to **satellites**, **astronauts**, **GPS system**, **power grids on Earth**... etc
A billion $ NASA mission designed to study magnetic reconnection

Magnetospheric Multiscale Mission (MMS)

March 12, 2015

ATLAS rocket

http://mms.gsfc.nasa.gov

• MMS leads us into a stage where the 3D electron-scale structure of magnetic reconnection, in nature, can be measured in an unprecedented manner.

 tight tetrahedron formation: separation down to 7 km!
100x faster for electrons measurement (30 ms)
30x faster for ions measurement (150 ms)
The trailer of MMS ...
Key Challenge, Why Blue Waters? & Our accomplishments to date
Pro: A first-principle description with rich kinetic physics being captured ✔
Con: It demands considerable computational resource, especially for 3D systems (Challenge!)

Particle-in-cell Simulations

Lorentz Force

\[ \mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \]

Maxwell Equation

\[ \nabla \cdot \mathbf{B} = 0 \]
\[ \nabla \times \mathbf{B} = \frac{4\pi}{c} \mathbf{J} + \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t} \]
\[ \nabla \cdot \mathbf{E} = 4\pi \rho \]
\[ \nabla \times \mathbf{E} = -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} \]

\( (\mathbf{E}, \mathbf{B}, \mathbf{J}, \rho) \)
\( \text{(v, x)} \)
The 3D nature of magnetic reconnection
-- how it differs from the conventional 2D picture?
Q: What determines the orientation of the x-line?

Hypothesis: the system may tend to maximize
— the reconnection rate.
— the outflow speed.
— principle of maximum entropy?
— or ...??

• Simulation on BW provides a first-principle test!
The question to solve

Q: Which plane does reconnection “preferred”?
Result I: X-line Orientation

- A well-defined x-line orientation develops!!

(Liu et al., JGR, 2018)
• Check out the stability of this x-line~
What can companion 2D simulations tell us?

- 2D simulations suggest that the 3D system selects a state with (or at least near) the maximal reconnection rate!
  —i.e., maximizing the energy release!

(Liu et al., JGR, 2018)
Numerical experiment with Quasi-2D boxes -- laminar vs. turbulent x-line!?

In comparison...

(Liu et al., JGR, 2018)

- Small periodic systems have often over-estimated the turbulence level.
Result II: Spread of reconnection x-line in Earth’s magnetopause geometry

Work-in-progress:
What determines the spread speed of the x-line?!
— Alfvén speed?
— Current carrier speed?
— Or ... something else?
Result III: Defining the $x$-line in the turbulent layer

(*parameters chosen to match real MMS events)

Turbulence caused by the lower-hybrid drift instability (LHDI).
Using Lyapunov exponent of field lines (Quasi-separarix layer) to trace the turbulent $x$-line.

(Le et al., Physics of Plasmas, 2018)
Result IV: Reconnection rate in laminar 2D vs. turbulent 3D x-line

(*parameters chosen to match real MMS events)

• Surprisingly, 3D turbulence does not affect the global reconnection rate!
  (ps: the rate measurement based on the electron mixing on the sphere side does not work because of the cross-field transport by the turbulence)

(Le et al., Physics of Plasmas, 2018)
Broader Impact

Space Science

Geomagnetic storms, substorms!

Astrophysics

Crab Nebula

Super flares!

Solar flares!

Fusion device

e.g., ITER Tokamak @ France
Magnetic Reconnection is the key process that releases the magnetic energy stored in space, astrophysical and laboratory plasma systems.

— The 3D nature of magnetic reconnection remains unclear!
— Blue Waters provides the opportunity to explore this challenging problem.

Using Blue Waters, we have studied:
— The orientation of 3D x-lines.
  *the 3D system tends to maximize the reconnection rate!
— The spread of 3D x-lines.
— The laminar vs. turbulent x-lines.
— 3D reconnection rate.

Broader Impact:
— for instance, help interpret the 3D geometry in MMS observations.

• A. Le et al., Drift turbulence, particle transport, and anomalous dissipation at the reconnecting magnetopause, Physics Plasmas, 25, 062103, (2018)
• T. C. Li et al., Spread of asymmetric magnetic reconnection x-line, work in progress (2018)
Progress of Particle-in-Cell simulations

- VPIC: ~8 million particle pushes/sec, MPI + OpenMP hybrid architecture.

- Resource required for a typical run in our BW project:
  ~2 trillion particles; ~ 6 billion cells;
  ~12 million CPU-hours; using ~260 K cores;
  ~200 TB output (including restart files)
Blue Waters Team Contributions

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