Magnetic Reconnection: An Ultimate Problem in Nonlinear Plasma Physics

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Modern Challenges in Nonlinear Plasma Physics A Conference honoring the career of Dennis Papadopoulos June 15-19, 2009, Halkidiki, Greece
I worked with different advisors in radio astronomy, cosmology, QED, pulsars, but I chose Dennis because of the 4 P’s:
- **Phenomenal physicist**: was always late but still gave people hard time at seminars/colloquia
- **Parade of generals**: constant parade of military higher ups through the department
- **Posh**: Mercedes convertible
- **People**: Cargill, Goodrich, Hizanidis, Menyuk, Rowland, Sprangle, Vlahos, Akimoto, Ghosh, Fung, Taaheri, ...
Magnetic Reconnection has Many Applications:

- Planetary magnetospheres → magnetopause, magnetotail
- Solar corona → flares, prominences, coronal mass ejections
- Laboratory fusion machines
- Astrophysical problems:
  - stellar flares
  - galactic magnetotails
  - accretion disks
  - pulsar winds
  - gamma-ray bursts
  - jets from AGN

\[ \text{Hydrogen} \]
\[ \text{Electron-Positron} \]
Reconnection in Space Plasmas
Current Sheet

Current layer + corresponding field reversal

Current Layer

Guide Field

Neutral Sheet \( \Rightarrow \vec{B}_G = 0 \)
Magnetic Reconnection

Diffusion Region

X-point

Separatrix
Simple Models
Early Models - Resistive MHD

Sweet-Parker - 1957

Petschek - 1964

\[ \frac{U_{in}}{V_A} = \frac{\delta}{D} = \frac{1}{\sqrt{S}} \]

\[ S \equiv \frac{4\pi V_A D}{\eta c^2} = \frac{\tau_R}{\tau_A} \sim 10^{10} \rightarrow 10^{14} \]

\[ \frac{U_{in}}{V_A} \sim \frac{1}{\log(S)} \]
Baffling Trends

- Both Sweet-Parker and Petschek models have major flaws but have formed the basis of much research in reconnection physics.

- Many researchers continue to use them in modeling solar corona, magnetosphere, ...

- There is a fixation on the reconnection rate which masks a lot of important physics.
During this Talk:

- Show results from recent state-of-the-art simulations to illustrate the complexity of the reconnection process

- Compare 2D vs. 3D results to see whether 2D studies have any relevance
Making Breakthrough Simulations – 100-1000x larger

- Use open boundary conditions: Daughton, Scudder, Karimabadi, 2006
- Roadrunner super computer at LANL is enabling Trillion-particle simulations
- Implement collisions in Full PIC using Fokker-Planck treatment of collision operator
- Our largest simulation to date on reconnection: Physical domain $(200 d_i)^3$
  $1024^3$ cells, 0.32 trillion particles
Physics Questions

- Can long stable current sheets exist in nature?
- Are there other means of annihilating the magnetic field besides reconnection?
- Can fast reconnection occur in large scale systems in collisionless, and collisionless regimes? Magnetosphere is $\sim 1000 d_i$, and solar flares are $> 10^6 d_i$.
- Can reconnection occur in high beta plasmas?
- Does reconnection turn off or is it quasi-steady?
Collisionless Limit
2D simulation: cyclical formation of plasmoids
Surprising New Results

1. Highly elongated electron layer
2. Rate controlled by this layer
3. Unstable to plasmoid formation
4. Inherently time dependent

\[ D_e \sim 25d_i \]

Two orders of magnitude larger than previous estimates!

Similar conclusions in K. Fujimoto, PoP, 2006
Essential Physics of Electron Expansion

Generalized Ohm’s law

\[ \mathbf{E} + \frac{\mathbf{U}_e \times \mathbf{B}}{c} = \eta \mathbf{J} - \left[ \frac{1}{en_e} \nabla \cdot \mathbf{P}_e + \frac{m_e}{e} \frac{d\mathbf{U}_e}{dt} \right] \equiv \mathbf{S} \]

Combine with Faraday’s Law

\[ \frac{\partial B_z}{\partial t} = - \frac{\partial (U_{ex} B_z)}{\partial x} - \left( \frac{\partial c S_y}{\partial x} \right) \]

Need contribution to get steady state

Near x-point:

\[ U_{ex} B_z \propto x^2 \rightarrow \frac{\partial B_z}{\partial t} < 0 \]

Layer will expand without non-ideal term to balance
Multi-Scale Structure of the Electron Layer

Karimabadi, Daughton & Scudder, 2007 GRL

$\Delta_e \rightarrow$ Total length of non-ideal region

1. Region of uniform electron inflow
2. Maximum electron outflow
3. Size of out-plane current layer
Reconnection Rate Remains Fast

Remarkably insensitive to system size!

See Daughton & Karimabadi, 2007
Testable New Predictions

1. Much longer electron diffusion region \( D_e \sim 3 - 5d_i \)
2. Elongated non-gyotropic electron jets \( \Delta_e > 10d_i \)
3. Filled-in quadrupole structure out to \( \Delta_e \)
4. Electrostatic potential structure
5. Continuous reconnection - rate modulated in time
6. Plasmoid production - range of sizes for both anti-parallel and guide field geometry

Observational evidence from Cluster - Eastwood et al, JGR, 2007
Collisional Limit
Collisional Reconnection

- Two different behavior based on system size
  - Stable Sweet-Parker and low rate for small system
  - Unstable Sweet-Parker and high rate for large system
Unstable Sweet-Parker Layer

Daughton et al. 2009 a,b
## What About 3D?

### Linear Vlasov Theory + Simulation Parameters

- \( m_i = m_e \)
- \( T_i = T_e \)
- \( \rho_i = L \)

<table>
<thead>
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<th>Guide Field</th>
<th>Drift-kink ( k_y^*L )</th>
<th>( \gamma/\omega_{ci} )</th>
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<tr>
<td>0</td>
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<td>0.258</td>
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<td>stable</td>
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<tr>
<td>- 1.0 ( B_0 )</td>
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<td>0.130</td>
</tr>
</tbody>
</table>

### 3D VPIC Simulations

- \( 200d_i \times 20d_i \times 200d_i \) cells
- \( 16 \times 10^9 \) particles
Current Sheet Instabilities

Reconnection

Magnetic Island

Instabilities in the current direction
3D simulation of anti-parallel case

- Islands
- Kink Mode
3D simulation of anti-parallel case
Formation of Standing Structure
2D vs 3D Comparison

![Graph showing Total Energy and Reconnection Inflow Rate](image)
Kinking Produces Folded Flux Ropes

Pinches off here to form a plasmoid-ring

Plasmoid-rope
Compare Large vs Small Case

- Wavelength & layer thickness are near the same
- Kinking leads to folding and detached current tubes

Small Run

Large Run

See Cut
3D simulation of guide field case
3D simulation of guide field case
Summary

- Need to move away from simple models even in the collisional case
- Fully kinetic results at odds with reduced models
- 2D studies useful but 3D adds significant modification to the details
- Depending on the specific question, 2D results may be invalid (e.g., particle acceleration in the presence of a strong guide field)