The Collisonal-Collisionless Phase Transition in Partially Ionized Magnetic Reconnection

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Outline

• Partially ionized reconnection is interesting, and relatively unexplored

• Kinetic simulations of partially ionized reconnection
  – When does fast reconnection occur and how fast is it?
  – Inflow modeling using neutral hydrodynamics
  – Comparison with fluid simulations

• Application of Landau theory to reconnection phase transitions
Partially ionized plasmas are common

- Many space, astrophysical, and laboratory systems are only partially ionized
  \[ \chi = \frac{n_i m_i}{n_i m_i + n_n m_n} < 1 \]

- Neutrals couple through complex collisional processes
  - Elastic collisions
  - Ionization / recombination
  - Excitation / de-excitation

- Reconnection in partially ionized plasmas is not well studied but important in the solar chromosphere
  - UV bursts
  - Jets/spicules
  - Heating
  - Minority species transport
Single X-line reconnection can be slow or fast

Fast

- Slow reconnection (Sweet-Parker)
  - Rate of reconnection depends on the Lundquist number

- Fast reconnection is system size independent
  - Localized to scales < d_i = c/ω_{pi}
  - Demonstrated extensively in theory, simulation, and experiment
  - Rate ~ 0.1 usually

Slow

- Most of our knowledge on fast reconnection in fully ionized plasmas is empirical
  - Why is the rate always ~ 0.1?
  - "Hall term" is responsible (Birn et al., 2001)

\[
\frac{v_{in}}{v_A} \sim 0.1
\]
\[
\frac{v_{in}}{v_A} \sim \frac{1}{\sqrt{S}}
\]

\[E + v \times B = \frac{J \times B}{en_e} + \cdots\]
Fast reconnection is not well understood in partially ionized plasmas

- Partially ionized theory for fast reconnection is based in part on fully ionized results
  - Malyshkin and Zweibel 2011
  - Constant rate ~ 0.1
  - Hall effects start at a larger scale

- Fast reconnection is seen in MRX experiments, but the rate is ionization fraction dependent
  - Lawrence et al. 2013

- Hall reconnection not observed in chromospheric multi-fluid simulations (Murphy et al. 2015, Ni et al. 2018)
  - “... the Hall effect does not appear to be significant in the reconnection process.”
Partial ionization is predicted to change the reconnection phase diagram

### Modified phase diagram for single X-line reconnection following Malyshkin and Zweibel 2011
- **Ion MHD** - Neutrals play no role
- **Well coupled** - Globally, ions and neutrals can be treated as a single fluid
  - **Hall** - Fast reconnection
  - **Single-Fluid** - Sweet-Parker
- **Two-Fluid** - Ions and electrons are coupled to neutrals, but neutrals don’t feel ions
- **Three-Fluid** - Ions and electrons decouple

### Inaccessible
- Electron-neutral collisions set a minimum resistivity. Inelastic processes (ionization, radiation) become important.

\[
\chi = 0.001, \quad \lambda_{in}/d_i = 1, \quad \beta_e = 0.01
\]

\[
m_i = m_i \quad \text{Heuristically} \quad m_i \rightarrow m_i/\chi
\]
Partial ionization is predicted to change the reconnection phase diagram

- Modified phase diagram for single X-line reconnection following Malyshkin and Zweibel 2011
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- **Inaccessible** - Electron-neutral collisions set a minimum resistivity. Inelastic processes (ionization, radiation) become important.
Our Approach – Particle-In-Cell Simulations

- First fully kinetic simulations of partially ionized reconnection
- Particle in cell simulations including neutrals capture both fluid and kinetic physics accurately
  - Transport physics is modeled ab-initio and includes realistic parameter dependencies
- Coulomb and neutral collisions included via Monte-Carlo pair-particle collisions
  - Takizuka and Abe 1977, Daughton et al. 2009
  - Wang et al. 2017, Xu et al. 2017
- VPIC Particle-in-cell code (LANL)
  - Open source, https://github.com/lanl/vpic
  - Fully explicit electromagnetic PIC

Cross-sections

Transport coefficients

Ion-neutral friction

Neutral viscosity

\( \chi = 0.1 \)

\(~4\times10^7\) cells

\(1.1\times10^{11}\) particles

200 \( d_i \)

800 \( d_i \)

Numerical Setup

- Start simple and study the fundamental physics
  - Coulomb collisions
  - Ion + neutral collisions
  - Neutral + neutral collisions

- No electron-neutral collisions
  - e-n cross-section is 100-1000x smaller than Coulomb cross-section
  - Original Malyshkin-Zweibel theory neglected e-n collisions
  - Requires larger mass-ratio to properly include

- Initial Harris sheet with a uniform neutral background
  - Not an exact equilibrium, but rapidly relaxes over a collision time $\sim \Omega_i$

- Unequal particle weights to reduce cost
  - Benchmarked at $\chi = 0.1$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_i/m_e$</td>
<td>40</td>
</tr>
<tr>
<td>$\omega_{pe}/\Omega_e$</td>
<td>2</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.3</td>
</tr>
<tr>
<td>$\nu_{ei}/\Omega_e$</td>
<td>0.02</td>
</tr>
<tr>
<td>$\lambda_{in}/d_i$</td>
<td>0.5</td>
</tr>
<tr>
<td>$T/Ry$</td>
<td>0.15 (2 eV)</td>
</tr>
<tr>
<td>$\chi$</td>
<td>0.01 - 1</td>
</tr>
<tr>
<td>$L_z/d_i$</td>
<td>100, 200, 400, 800</td>
</tr>
<tr>
<td>nppc/species</td>
<td>100-1000</td>
</tr>
</tbody>
</table>
Transition to fast reconnection occurs at smaller scales than previously predicted

- Partially-ionized Sweet Parker scaling observed in the initial, collisional phase, $R = S^{-1/2} \chi^{1/4}$
- All cases satisfy the condition predicted by Malyshkin and Zweibel: $\delta < d_i \chi^{-1/2}$
- But $\delta < d_i$ is more closely correlated with the transition
  - Consistent with fluid simulations where no transition is observed and $d_i \chi^{-1/2} > \delta > d_i$
- However, ion diffusion region width does scale with the bulk inertial length
Rate is ionization fraction dependent

- Relative to the bulk Alfvén speed (ion+neutral mass) rate is always > 0.08
  - *Fast reconnection*
- Below $\chi \sim 0.1-0.2$ rate is system size dependent and ionization fraction independent
Rate is ionization fraction dependent

- Relative to the bulk Alfven speed (ion+neutral mass) rate is always > 0.08
  - Fast reconnection

- Below $\chi \sim 0.1-0.2$ rate is system size dependent and ionization fraction independent
  - Decreasing ionization fraction increases the neutral beta
    \[
    \beta_n = \beta_i \frac{8\pi n}{B^2} = \frac{\beta_i}{\chi}
    \]
  - For small domains, the rate appears to scale with the perpendicular magneto sonic speed
Momentum balance in the Inflow

- Electric field balanced by the electron pressure tensor at the X-line
  \[ E_{NG} \equiv -\left( \nabla \cdot P_e \right)_y / en \]

- At a steady-state X-line, the single fluid momentum equation reduces
  \[
  m_e n_e \frac{dv_e}{dt} = -en_e \left( E + \frac{v_e \times B}{c} \right) - \nabla \cdot P_e - R_{ie} \\
  m_i n_i \frac{dv_i}{dt} = en_i \left( E + \frac{v_i \times B}{c} \right) - \nabla \cdot P_i + R_{ie} + R_{in} \\
  m_n n_n \frac{dv_n}{dt} = -\nabla \cdot P_n - R_{in},
  \]

  \[ en_e E_{NG} = \left( \nabla \cdot (P_i + P_n) \right)_y \]
Momentum balance in the Inflow

\[ e n_e E_{NG} = (\nabla \cdot (P_i + P_n))_y \]

- In partially ionized plasmas, charge-exchange efficiently couples ions and neutrals \textit{kinetically}
  - To lowest order \( n_n P_i = n_i P_n \)
- \( P_n \) is easier than \( P_i \), can estimate with a hydrodynamic closure (viscosity)
- Gives the relationship

\[ E_{NG} = -\frac{m_n \nu_s}{e} \chi \frac{\partial^2 v_{n,y}}{\partial x^2} \]

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Local inflow model

- The local inflow velocity differs from the rate (not a true steady-state)

- By evaluating the momentum balance in the ion diffusion region, we can predict the inflow velocity
  - Use neutral viscosity to close ion and neutral pressure tensors

\[
\frac{u_{x,in}}{v_{A,in}} = \frac{\chi^{1/2}}{\frac{\Delta_0}{d_i} \Re^2 - \Re}
\]

\[
\Re \equiv \Delta_0 v_{A,in} / \nu_s
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\]
Multi-fluid simulations do not reproduce PIC results

- Multifluid partially ionized plasmas have been modeled extensively with the HiFi partially ionized module
  - Neutral fluid and Hall plasma fluid model from Leake et al. 2012, 2013

\[
\frac{\partial}{\partial t} (m_i n_i v_i) + \nabla \cdot (m_i n_i v_i v_i + p_i + p_e) = \sum_i \left( J \times B + \mathbf{R}_i^{\text{in}} + \mathbf{P}_i^{\text{ext}} m_i v_i \right) - \mathbf{R}_i^{\text{ext}} m_i (V_n - V_i) + \mathbf{R}^{\text{in}} - \mathbf{R}^{\text{ext}},
\]

\[
\frac{\partial}{\partial t} (m_i n_i v_n) + \nabla \cdot (m_i n_i v_n v_n + p_n) = -\mathbf{R}_i^{\text{in}} + \mathbf{P}_i^{\text{ext}} m_i v_n + \mathbf{R}^{\text{in}} m_i (V_i - V_n) - \mathbf{R}_i^{\text{ext}} + \mathbf{R}^{\text{ext}},
\]

\[
E + V_i \times B = \eta J + \frac{\nabla P_e}{\epsilon_n} - \frac{m_e \nu_{ce}}{e} (V_i - V_n).
\]

- Plots taken at peak reconnection time
Multi-fluid simulations never achieve fast reconnection

- Current sheet never thins below $d_i$ in the partially ionized cases

- Rate is only weakly dependent on ionization fraction and inconsistent with Sweet-Parker scaling
  - Previous studies also demonstrated non-Sweet-Parker dependence, $R \sim S^{-1.1}$ (Leake et al. 2012)
  - Currently not well-understood

- Open opportunity and a need for efficient and flexible multi-fluid codes to study reconnection physics
  - Benchmark and test numerical methods
  - Two vs. three fluid
  - Different transport models
  - 3D effects
What do we know about partially ionized reconnection?

<table>
<thead>
<tr>
<th>Slow Rate Scaling</th>
<th>Theory</th>
<th>Two-Fluid</th>
<th>Experiment</th>
<th>PIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S^{-1/2} x^{-1/4} )</td>
<td>( \sim S^{-1.1} )</td>
<td>( \sim \log \chi )</td>
<td>?</td>
<td>( \sim x^{-1/4} ) fixed S</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fast Reconnection</th>
<th>Yes</th>
<th>No?</th>
<th>Yes</th>
<th>Yes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transition to fast rec.</td>
<td>( d_i x^{-1/2} )</td>
<td>( &lt; &lt; d_i x^{-1/2} )</td>
<td>?</td>
<td>( d_i )</td>
</tr>
<tr>
<td>Ion diffusion width</td>
<td>( d_i x^{-1/2} )</td>
<td>?</td>
<td>?</td>
<td>( d_i x^{-1/2} )</td>
</tr>
<tr>
<td>Fast Rate Scaling</td>
<td>( \sim 0.1 )</td>
<td>?</td>
<td>( \sim x^{-1/2} )</td>
<td>( &gt; 0.08 x^{-1/2} )</td>
</tr>
</tbody>
</table>

Zweibel 1989  
Malyshkin and Zweibel 2011  
Leake et al. 2012  
Leake et al. 2013  
Murphy et al. 2015  
Ni et al. 2018  
Lawrence et al. 2013  
Jara-Almonte et al. 2019

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Summary and conclusions

• Performed the first fully kinetic simulations of partially ionized reconnection
  – Demonstrated the transition to fast reconnection at $\delta = d_i$
    • Occurs at a smaller scale than previously predicted
  – Rate scales with the bulk Alfven velocity in large systems
    • Consistent with previous experimental results

• Our multi-fluid simulations do not demonstrate fast reconnection
  – Hall term does not appear to be sufficient to trigger fast reconnection
  – Even in the resistive regime, scalings differ from Sweet-Parker

• Landau theory is a promising tool to quantitatively study reconnection phase transitions
  – Collisional-collisionless boundary is marked by a second-order ion-scale transition and a first-order electron-scale transition
  – Phase transition boundary is not modified by partial ionization
EXTRA SLIDES
Inflow Decoupling
The chromosphere is complex, dynamic, and not well-understood

- **UV bursts**
  - Highly localized, intense brightening
  - Typical energy $\sim 10^{28}$ erg

- **Jets and spicules**
  - Fast flows of hot plasma thought to be triggered by reconnection

- **Heating**
  - The solar temperature minimum is in the chromosphere, why is the upper atmosphere hotter?

- **Transport (first-ionization potential effect)**
  - Relative densities of minority species changes with scale height

(Peter et al. 2014) 
(Young et al. 2018)