Asymmetric Magnetic Reconnection in Partially Ionized Chromospheric Plasmas

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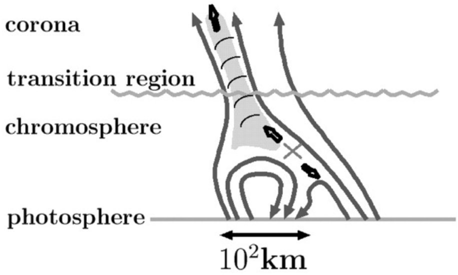
Magnetic reconnection is ubiquitous in the chromosphere

- Plasma in the solar corona is typically $\sim$fully ionized
- The chromospheric ionization fraction ranges from $\lesssim$0.01–0.5
- Reconnection time scales $\lesssim$ ionization/recombination time scales $\Rightarrow$ plasma often not in ionization equilibrium
- We perform simulations of asymmetric magnetic reconnection in partially ionized chromospheric plasmas
- Motivating questions:
  - How does asymmetry impact chromospheric reconnection?
  - What are the dynamics of the plasmoid instability?

Asymmetric reconnection in chromospheric jets



Shibata et al. (2007)

- Asymmetric inflow reconnection often occurs at the boundaries between different domains of plasma
  - Example: Earth's dayside magnetopause
- Chromospheric jets occur when newly emerged flux reconnects with pre-existing overlying flux
  - Naturally asymmetric!
- The chromosphere is a dynamic magnetized environment
  - Asymmetric reconnection should be the norm

HiFi is an implicit, modular spectral element framework with significant flexibility in the equations it solves

- Module for partially ionized plasmas
  - Meier & Shumlak (2012); Leake et al. (2012, 2013)
- Separate continuity, momentum, and energy equations for ions and neutrals
- Continuity equations include ionization and recombination
  - Non-equilibrium ionization
- Includes momentum/energy transfer between ions and neutrals, charge exchange, resistivity, and the Hall effect
- Thermal conduction is
  - Isotropic for neutrals
  - Anisotropic for ions
- Leake et al. (2012, 2013) present HiFi simulations of symmetric partially ionized reconnection
  - Ions pulled into sheet by reconnecting field
  - Recombination becomes important in continuity equation

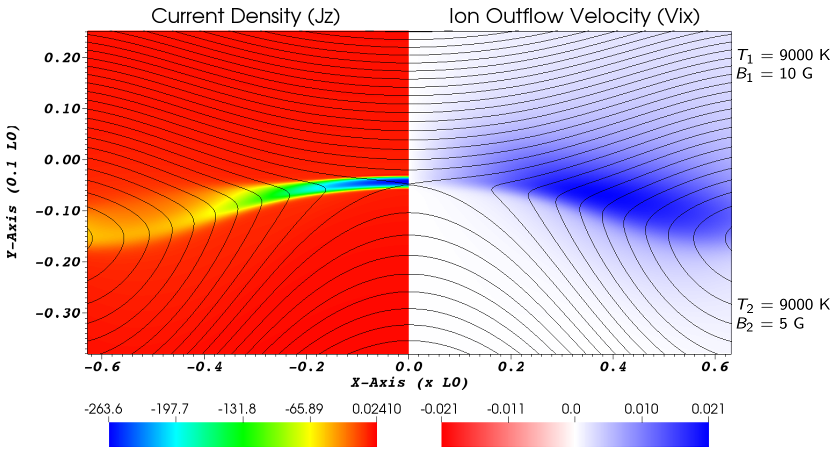
We perform simulations with symmetric and asymmetric upstream temperatures and magnetic field strengths

- Specify **B** and T on each side, and calculate n_i and n_n so there is approximate total pressure balance (with $\beta \gtrsim 3$)
  - Assume initial ionization equilibrium
- Initial conditions require ion-neutral drift so forces acting on ions can balance forces acting on neutrals
- Electric field applied for $t < 5$ initiates reconnection
- We focus on one simulation with symmetric T and asymmetric **B**:[1]

$$T_1 = T_2 = 9000 \text{ K}$$
$$B_1 = 10 \text{ G}, B_2 = 5 \text{ G}$$

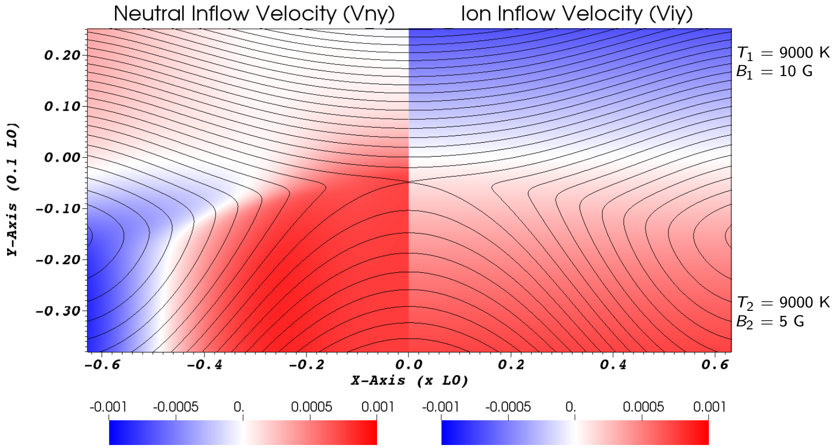
[1] The normalizations are $B_0 = 10$ G, $L_0 = 10$ km, $V_0 = 126$ km s^{-1}, and $n_0 = 3 \times 10^{16}$ m^{-3}

Current sheet structure: Symmetric T, Asymmetric **B**



- The ion and neutral outflows are tightly coupled
- Slightly arched current sheet; X-point on weak **B** side

Comparing inflow velocities: Symmetric T, Asymmetric **B**

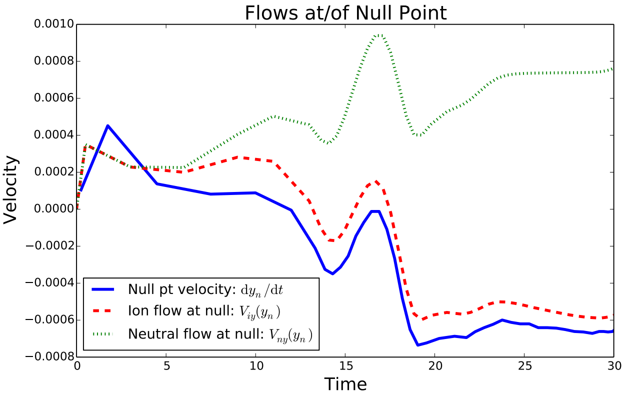


- Asymmetric decoupling between ions and neutrals in inflow
- Higher neutral pressure on bottom → neutrals flow upward

How do the ion and neutral velocities at the X-point differ from the velocity of the X-point?

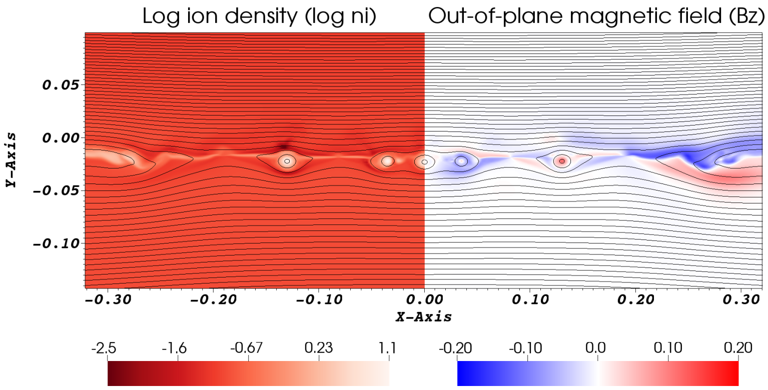
- The null point/X-point is at $y_n(t)$ along $x = 0$
- We compare three different quantities:
  - $\frac{\mathrm{d}y_n}{\mathrm{d}t}$: the velocity *of* the null point
  - $V_{iy}(y_n)$: the ion flow *at* the null point
  - $V_{ny}(y_n)$: the neutral flow *at* the null point
- Differences between $\frac{\mathrm{d}y_n}{\mathrm{d}t}$ and $V_{iy}(y_n)$ result from:
  - Resistive diffusion
  - The Hall effect
- Differences between V_{iy} and V_{ny} indicate momentum transfer between ions and neutrals

How do the ion and neutral velocities at the X-point differ from the velocity of the X-point?



- The null point drifts into the weak **B** upstream region
- Ion and neutral flows are in opposite directions
- Small difference between ion flow and null point velocity

Dynamics of the plasmoid instability



- Plasmoids bulge into weak field upstream region
- High ion density in plasmoids
- Hall fields locally a large fraction of reconnecting field
  - Beginning of transition to Hall reconnection?
  - Core fields in some plasmoids after merging

Connecting to solar observations and experiment

- Connecting to solar observations (e.g., *IRIS*)
  - Challenges
    - Non-equilibrium ionization of minor elements
    - Radiative transfer
    - Very short length scales
    - Confusion along line-of-sight
  - Opportunities
    - Predicting spectral signatures, velocities, physical conditions
    - Statistical properties of reconnection events (e.g., jets)
- Connecting to experiment (e.g., MRX; Lawrence et al. 2013)
  - Challenges
    - Limited separation of scales
    - Relatively modest plasma parameters
  - Opportunities
    - *In situ* diagnostic capabilities
    - Improved understanding of basic physics
    - Validation of simulation results

Summary & Conclusions

- The chromosphere is a dynamic magnetized environment, so asymmetric reconnection should be the norm
- We perform simulations of partially ionized reconnection with asymmetric upstream $\mathbf{B}$ and T
  - Tight coupling of ions and neutrals in outflow
  - Asymmetric decoupling in inflow
- Plasmoid development late in time
  - Reaching scales where Hall effect becomes important
- Magnetic asymmetry $\Rightarrow$ neutral flows through current sheet
  - Neutrals swept along with outflow originate from low-$\mathbf{B}$ side
- Future work includes
  - Investigating dynamics of plasmoid instability
  - Non-equilibrium ionization to track elemental fractionation
  - Connecting to solar observations and laboratory experiments