Asymmetry and the plasmoid instability during magnetic reconnection in partially ionized chromospheric plasmas

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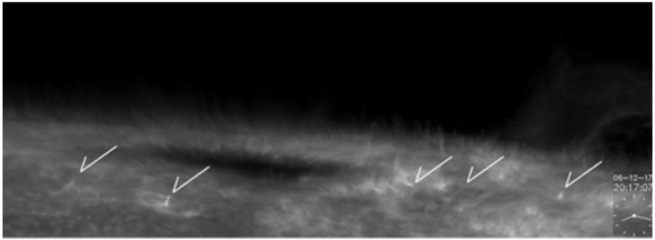
Triennial Earth-Sun Summit
Indianapolis, Indiana, USA
April 26–30, 2015

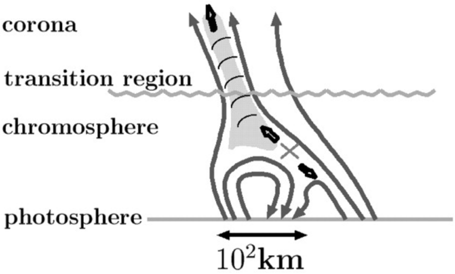
Magnetic reconnection is ubiquitous in the chromosphere



Hinode/SOT
Shibata et al. (2007)

- 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

We use the plasma-neutral module of the HiFi framework (Meier & Shumlak 2012; Leake et al. 2012, 2013)

- Separate continuity, momentum, and energy equations for ions and neutrals
  - Ionization and recombination (non-equilibrium ionization)
  - Momentum/energy transfer between species
  - Charge exchange
  - Resistivity
  - Hall effect
  - Optically thin radiative losses
  - Isotropic neutral thermal conduction
  - Anisotropic ion thermal conduction
- Leake et al. (2012, 2013) simulate symmetric chromospheric reconnection
  - Reconnecting field drags ions into current sheet $\rightarrow$ enhancement of ion density
  - Recombination helps remove ions from current sheet

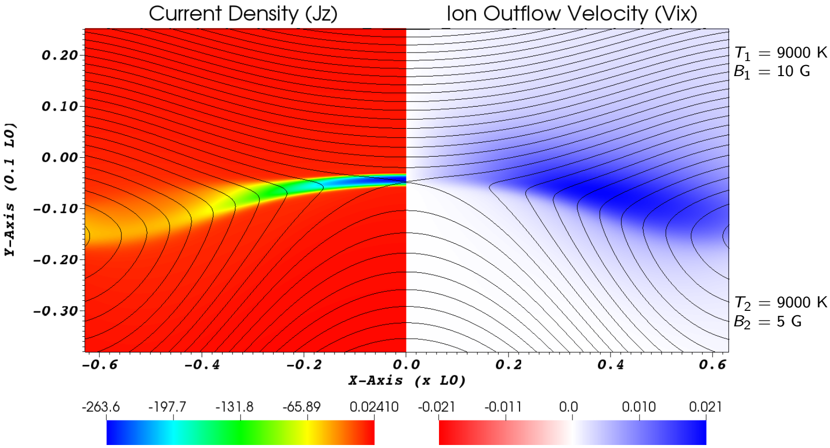
We perform simulations with symmetric and asymmetric upstream temperatures and magnetic field strengths

- Specify $\mathbf{B}$ and T on each side
- Calculate n_i and n_n so there is approximate total pressure balance ($\beta \gtrsim 3$) while assuming initial ionization equilibrium
- Need initial ion-neutral drift so forces acting on ions can balance forces acting on neutrals
- Focus on single case with symmetric T and asymmetric $\mathbf{B}$:[1]

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

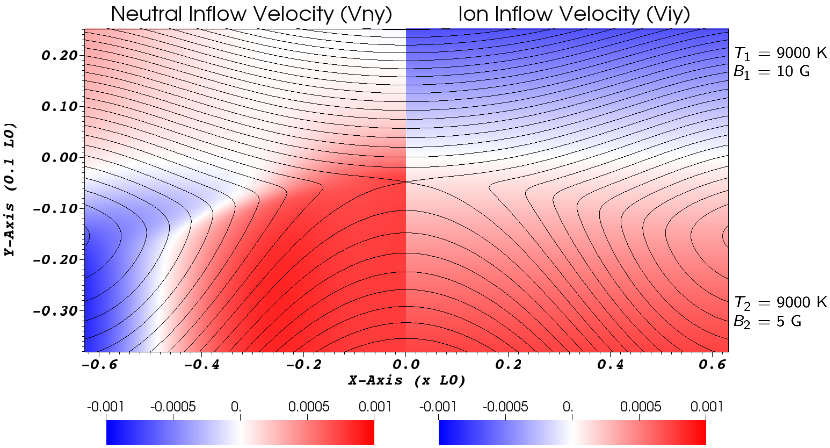
[1]The normalizations are $B_0 = 10$ G, $L_0 = 10$ km, $V_0 = 126$ km s^{-1}, and $n_0 = 3 \times 10^{16}$ m^{-3}. For details, see Murphy & Lukin (ApJ, in press)

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**

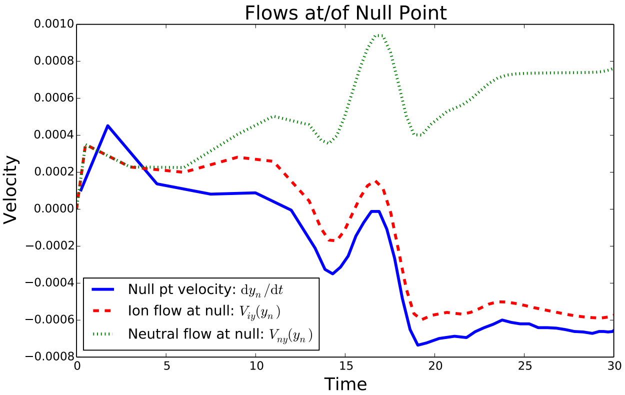


- Asymmetric decoupling between ions and neutrals in inflow
- Higher neutral pressure on bottom $\rightarrow$ neutrals flow upward

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

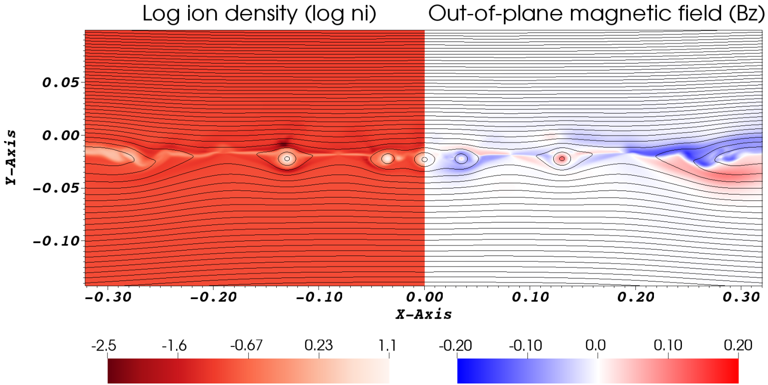
- The X-point is located at $y_n(t)$ along $x = 0$
- We compare three different quantities:
  - $\frac{\mathrm{d}y_n}{\mathrm{d}t}$: the velocity *of* the null point
  - $V_{iy}(y_n)$: the ion flow *at* the null point
  - $V_{ny}(y_n)$: the neutral flow *at* the null point
- Differences between $\frac{\mathrm{d}y_n}{\mathrm{d}t}$ 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?



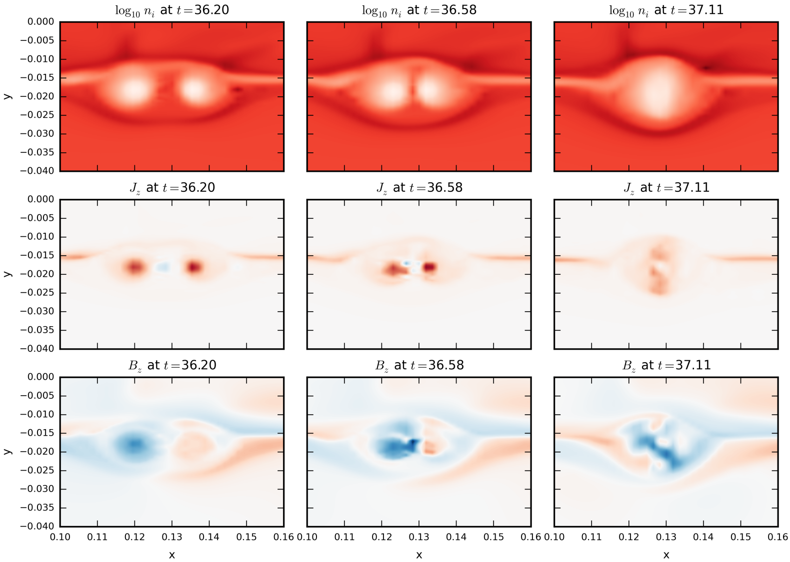
- The null point drifts into the weak **B** upstream region
- Ion and neutral flows are in opposite directions
- Small difference between ion flow and null point velocity

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

Secondary reconnection due to plasmoid merging



- Plasmoids develop a strong core magnetic field due to the Hall effect which gets modified during merging

Numerical challenges

- We used an artificial density diffusivity to ensure that density gradients can be resolved
- The resolution requirements are stringent:
  - Along inflow direction, very high resolution is required over a greater distance because of current sheet drifting
  - Along outflow direction, very high resolution is required to resolve secondary merging
- A future possibility would be evolving the logarithm of density to ensure that the density remains positive definite
- A guide field may reduce current sheet thinning

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 **B** and T
  - Tight coupling of ions and neutrals in outflow
  - Asymmetric decoupling in inflow
- Magnetic asymmetry $\Rightarrow$ neutral flows through current sheet
  - Neutrals swept along with outflow originate from low-**B** side
- Plasmoid development late in time
  - Reaching scales where Hall effect becomes important
- Future work includes
  - Investigating dynamics of plasmoid instability
  - Non-equilibrium ionization to track elemental fractionation
  - 3D effects during partially ionized reconnection
  - Connecting to solar observations and laboratory experiments

- Most work on diversity in astronomy focuses along a single dimension of identity
  - Most often: either gender, race, or LGBTIQ+ identity
  - People with more than one of these identities often left behind
  - Often missing is work on inclusion of disabled astronomers
- This meeting will take a multi-dimensional (intersectional) approach to diversity, equity, and inclusion.
- Registration now open at `http://vu.edu/ia2015`
- Some travel support available for students and early career scientists
  - Early registration/travel support application deadline is May 1