The plasmoid instability during asymmetric inflow magnetic reconnection

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Motivation

- In recent years, it has been discovered that high aspect ratio current sheets are susceptible to the formation of plasmoids (Loureiro et al. 2007; Huang et al. 2010)
  - Breaks up the current sheet into a chain of X-points and islands
  - Growth rate scales as $S^{1/4} V_A / L$
  - The reconnection rate asymptotes at $\sim$0.01 for large S (!)
- Most simulations of the plasmoid instability assume reconnection with symmetric upstream fields
  - Simplifies computing and analysis
  - Plasmoids and outflows interact in one dimension
- Asymmetry affects the scaling and dynamics of the plasmoid instability
- In 3D, flux ropes twist and writhe and sometimes bounce off each other instead of merging
- Asymmetric inflow reconnection simulations offer clues to 3D dynamics

Asymmetric Magnetic Reconnection (in 2D)

- *Asymmetric inflow reconnection* occurs when the upstream magnetic fields and/or plasma parameters differ
    - Dayside magnetopause
    - Tearing in tokamaks, RFPs, and other confined plasmas
    - Merging of unequal flux ropes
    - 'Pull' reconnection in MRX
- *Asymmetric outflow reconnection* occurs, for example, when outflow in one direction is impeded
    - Flare/CME current sheets
    - Planetary magnetotails
    - Spheromak merging and 'push' reconnection in MRX
- Asymmetric inflow reconnection often occurs at the boundaries between different plasmas
- Asymmetric outflow reconnection often occurs during explosive events

Cassak & Shay (2007) consider the scaling of asymmetric inflow reconnection

- Assume Sweet-Parker-like reconnection with different upstream magnetic fields (B_L, B_R) and densities (ρ_L, ρ_R)
- The outflow velocity scales as a hybrid Alfvén velocity:

$$V_{out} \sim V_{Ah} \equiv \sqrt{\frac{B_L B_R \left(B_L + B_R\right)}{\rho_L B_R + \rho_R B_L}} \tag{1}$$

- The X-point and flow stagnation point are not colocated

NIMROD simulations of asymmetric plasmoid instability

- Reconnecting magnetic fields are asymmetric:

$$B_y(x) = \frac{B_0}{1+b} \tanh\left(\frac{x}{\delta_0} - b\right) \tag{2}$$

- Magnetic asymmetry factor: $R_0 \equiv \frac{B_L}{B_R} \in \left\{\frac{1}{8}, \frac{1}{4}, \frac{1}{2}, 1\right\}$
- Uniform initial density
- $\beta_0 = 1$ in higher magnetic field upstream region
- A small number of localized initial magnetic perturbations placed asymmetrically along $z = 0$ near center of domain
- Domain: up to $-150 \leq x \leq 150$, $-16 \leq z \leq 16$
- (Hybrid) Lundquist numbers up to 10^5
- Boundary conditions: periodic along outflow direction and conducting wall along inflow direction

NIMROD solves the equations of extended MHD using a finite element formulation (Sovinec et al. 2004, 2010)

- In dimensionless form, the resistive MHD equations used for these simulations are

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times (\eta \mathbf{J} - \mathbf{V} \times \mathbf{B}) + \kappa_{divb} \nabla \nabla \cdot \mathbf{B} \tag{3}$$

$$\mathbf{J} = \nabla \times \mathbf{B} \tag{4}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{5}$$

$$\rho \left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = \mathbf{J} \times \mathbf{B} - \nabla p - \nabla \cdot \rho \nu \nabla \mathbf{V} \tag{6}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = \nabla \cdot D \nabla \rho \tag{7}$$

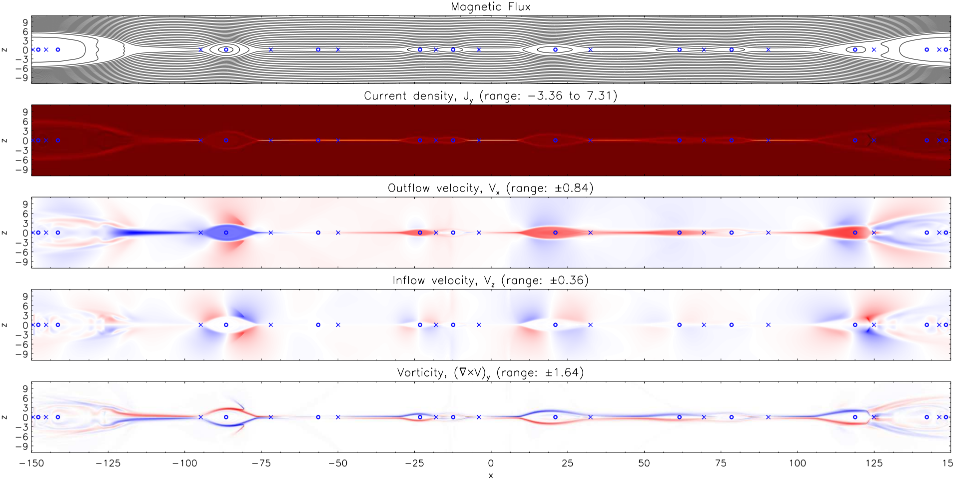
$$\frac{\rho}{\gamma - 1} \left(\frac{\partial T}{\partial t} + \mathbf{V} \cdot \nabla T \right) = -\frac{p}{2} \nabla \cdot \mathbf{V} - \nabla \cdot \mathbf{q} + Q \tag{8}$$

- Divergence cleaning is used to prevent the accumulation of divergence error

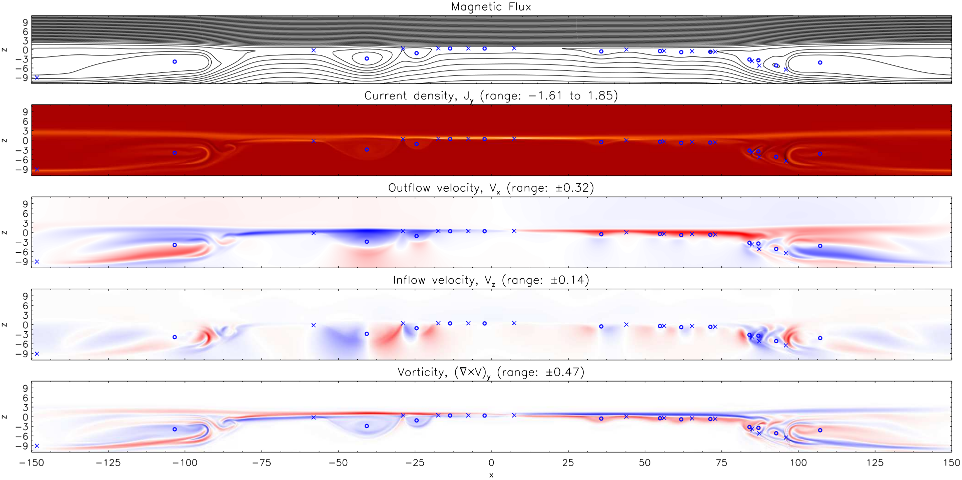
Numerical considerations

- Mesh packing needed over longer portion of inflow direction
  - X-points drift toward strong magnetic field upstream region
  - Somewhat less resolution required along outflow direction than in symmetric case
  - Higher resolution required in weak **B** upstream region than in strong **B** upstream region
- Preliminary simulations showed sloshing/oscillatory behavior
  - If a symmetric perturbation takes away δB from each side, then the strong field side will have a total pressure excess of $(1 - R)B_0\delta B$
  - Resolved by using weaker, more localized perturbations

Plasmoid instability: symmetric inflow ($R_0 = 1$)



Plasmoid instability: asymmetric inflow ($R_0 = 0.25$)



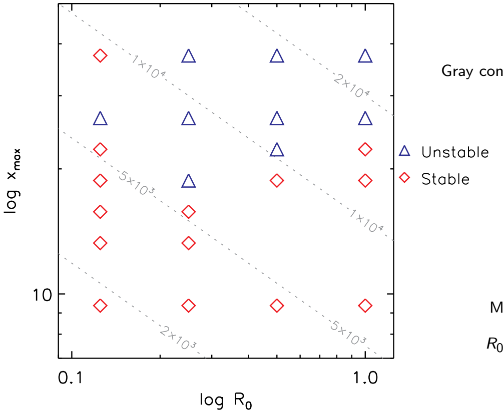
Key features of symmetric inflow simulation

- X-points and O-points all located along $z = 0$
  - Makes it easy to find nulls
- X-points often located near one exit of each current sheet
  - Characteristic single-wedge shape
- There is net plasma flow across X-points
  - Flow stagnation points not co-located with X-point
  - The velocity of each X-line differs from the plasma flow velocity at each X-point (see Murphy 2010)
- Outflow jets impact islands directly
  - No net vorticity in islands and downstream regions
  - Less noticeable turbulence in downstream regions
- Outflow velocity $\sim 5/6$ of Alfvén speed

Key features of asymmetric inflow simulation

- Maximum outflow velocity is $\sim 2/3$ of V_{Ah}
- X-points vary in position along inflow direction
- Islands develop preferentially into weak **B** upstream region
- Outflow jets impact islands obliquely
  - Islands advected outward less efficiently
  - Net vorticity develops in each magnetic islands
- Downstream region is turbulent
  - Plasmoids impacting and merging with downstream island
  - Several X-points and O-points
- Very little happening in strong **B** upstream region
  - Less resolution needed than in weak **B** upstream region
- Secondary reconnection events (when islands merge) have asymmetric inflow and outflow

Onset study: there exist domain sizes for which symmetric cases are stable but asymmetric cases are unstable



Domain size (outflow dir.)

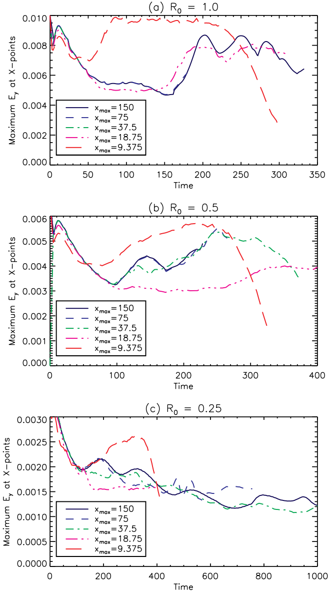
Gray contours: constant $S_{Ah} \equiv \frac{LV_{Ah}}{\eta}$

Magnetic asymmetry factor:

$R_0 \equiv \frac{B_{L0}}{B_{R0}} \in \left\{ \frac{1}{8}, \frac{1}{4}, \frac{1}{2}, 1 \right\}$

- Moderate asymmetry is weakly destabilizing
- Strong asymmetry makes it harder for plasmoids to form
- The onset criterion is not given by a critical hybrid Lundquist number, S_{Ahc}

The reconnection rate is still enhanced for asymmetric cases, but less enhancement with increasing asymmetry



What insights do these simulations provide for the 3D plasmoid instability?

- Daughton et al. (2011): plasmoids in 3D will be complicated flux rope structures
- Outflow jets will generally impact flux ropes obliquely
    - Momentum transport from outflow jets to flux ropes may be less efficient
    - Merging between colliding flux ropes may be incomplete
- Important questions:
    - How does the plasmoid instability behave in 3D?
        - What is the reconnection rate? Is it 10^{-3}, 10^{-2}, or 10^{-1}?
    - How do reconnection sites interact in 3D?
    - What mistakes are we making by using 2D simulations to interpret fundamentally 3D behavior?
    - How will these effects affect statistical models of islands?
        - Fermo et al. (2010), Uzdensky et al. (2010),
          Huang et al. (2012), Loureiro et al. (2012)

Conclusions

- We compare simulations of the plasmoid instability with symmetric and asymmetric upstream magnetic fields
- Features of the asymmetric plasmoid instability include:
  - X-point positions not all at same location along inflow direction
  - Islands develop into the weak **B** upstream region
  - Outflow jets impact islands obliquely
    - Less efficient outward advection of islands
    - Net vorticity in each island
  - Turbulence in the downstream region
  - The reconnection rate is still enhanced for the asymmetric case, but there's less enhancement for greater asymmetry
- The asymmetric plasmoid instability provides hints for how the plasmoid instability occurs in 3D

Future Work

- Asymptotic matching analysis to determine the onset criterion and properties of the linear asymmetric plasmoid instability
  - What is the growth rate as a function of asymmetry and resistivity/Lundquist number?
  - What is the eigenmode structure?
- Could features from these simulations be observed in solar, space, or laboratory plasmas?
- How does the transition to collisionless reconnection occur during the asymmetric plasmoid instability?
- Long term: 3D simulations of ≥ 2 competing reconnection sites