The plasmoid instability during asymmetric inflow magnetic reconnection

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Introduction

- Magnetic reconnection is the breaking and rejoining of magnetic field lines in a highly conducting plasma
- The classical Sweet-Parker model predicts that the reconnection rate scales as $S^{-1/2}$ (where $S \sim \frac{LV_A}{\eta}$)
  - Too slow to explain solar flares and fast reconnection elsewhere
- 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. 2011)
  - Breaks up the current sheet into a chain of X-lines and islands
  - The reconnection rate asymptotes at $\sim$0.01 for large S
- The role of this instability may be to bring structure down to small enough scales that collisionless effects become important (Shepherd & Cassak 2010)

Motivation

- 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

- *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
    - ‘Push’ reconnection in MRX
- Asymmetric inflow reconnection often occurs at the boundaries between different plasmas
- Asymmetric outflow reconnection often occurs during explosive events

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

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times (\eta \mathbf{J} - \mathbf{V} \times \mathbf{B}) + \kappa_{divb} \nabla \nabla \cdot \mathbf{B} \tag{1}$$

$$\mathbf{J} = \nabla \times \mathbf{B} \tag{2}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{3}$$

$$\rho \left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = \mathbf{J} \times \mathbf{B} - \nabla p - \nabla \cdot \rho \nu \nabla \mathbf{V} \tag{4}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = \nabla \cdot D \nabla \rho \tag{5}$$

$$\frac{\rho}{\gamma - 1} \left(\frac{\partial T}{\partial t} + \mathbf{V} \cdot \nabla T \right) = -\frac{p}{2} \nabla \cdot \mathbf{V} - \nabla \cdot \mathbf{q} + Q \tag{6}$$

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

NIMROD simulations of asymmetric plasmoid instability

- Reconnecting magnetic fields are asymmetric:

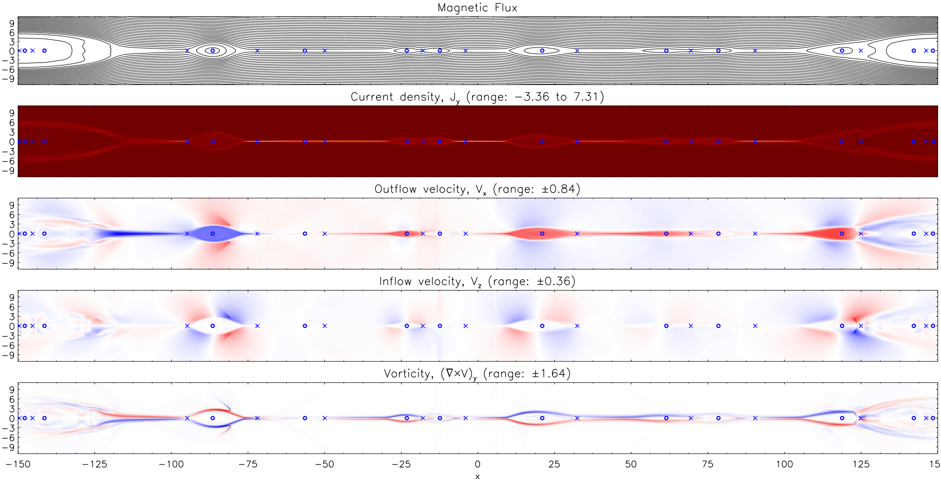
$$B_y(x) = \frac{B_0}{1+b}\tanh\left(\frac{x}{\delta_0} - b\right) \tag{7}$$

- A small number of localized initial magnetic perturbations placed asymmetrically along $z = 0$ near center of domain
- Symmetric case:
  - $\{B_1, B_2\} = \{1.00, 1.00\}$; $S_{Ah} \sim 1 \times 10^5$; $V_{Ah} = 1.0$
- Asymmetric case:
  - $\{B_1, B_2\} = \{1.00, 0.25\}$; $S_{Ah} \sim 5 \times 10^4$; $V_{Ah} = 0.5$
- Uniform initial density
- $\beta_0 = 1$ in higher magnetic field upstream region
- Domain: $-150 \leq x \leq 150$, $-16 \leq z \leq 16$
- Boundary conditions: periodic along outflow direction and conducting wall along inflow direction

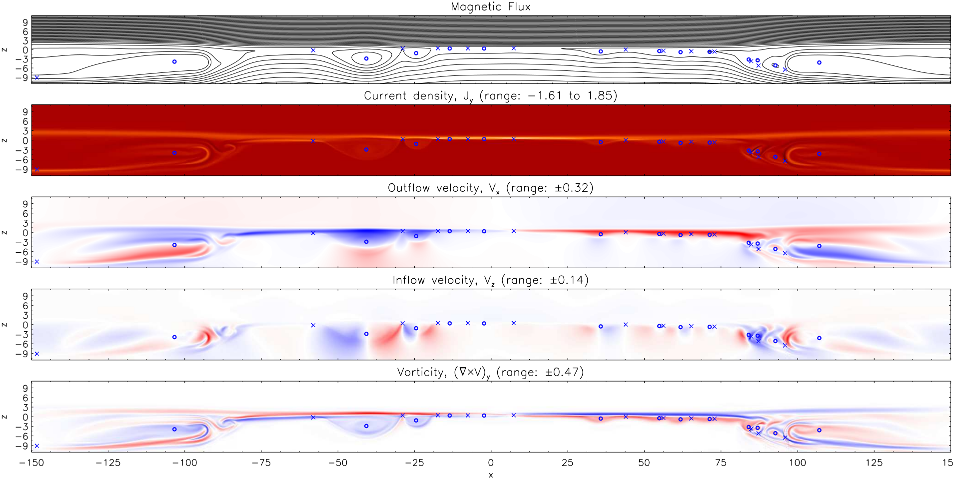
Numerical considerations

- Mesh packing needed over longer portion of inflow direction
  - X-lines 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
  - Symmetric perturbations led to asymmetric magnetic pressure imbalance
  - Resolved by using weak, localized perturbations and increasing the size of the domain along the inflow direction

Plasmoid instability: symmetric inflow



Plasmoid instability: asymmetric inflow



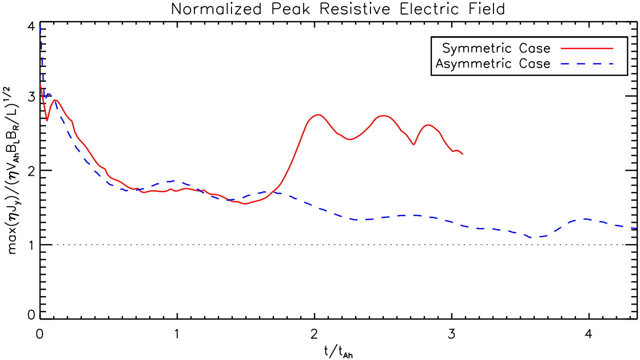
Key features of symmetric inflow simulation

- X-points and O-points all located along $z = 0$
  - Makes it easy to find nulls
- X-lines often located near one exit of each current sheet
  - Characteristic single-wedge shape
- There is net plasma flow across X-lines
  - Flow stagnation points not co-located with X-line
  - The velocity of each X-line differs from the plasma flow velocity at each X-line (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}
- Current sheets thicker than symmetric case
- X-lines 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

The asymmetric case shows little enhancement in the reconnection rate from the predicted value



- Use formulae from Cassak & Shay (2007); Birn et al. (2011):

$$E_{predict} = \sqrt{\frac{\eta V_{Ah}}{L} B_L B_R} \qquad t_{Ah} = \frac{L}{V_{Ah}} \qquad L = 100$$

- Note: S_{Ah} is lower by a factor of two for the asymmetric case

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 0.01 or 0.1?
    - How do reconnection sites interact in 3D?
    - What mistakes are we making by using 2D simulations to interpret fundamentally 3D behavior?

On the motion of 3D nulls (with C. Parnell & A. Haynes)

- Murphy (2010) derived an exact expression for the rate of X-line retreat when it is restricted to 1D

$$\frac{\mathrm{d}x_n}{\mathrm{d}t} = \left.\frac{\partial E_y/\partial x}{\partial B_z/\partial x}\right|_{x_n} = V_x\left(x_n\right) - \eta\left[\frac{\frac{\partial^2 B_z}{\partial x^2} + \frac{\partial^2 B_z}{\partial z^2}}{\frac{\partial B_z}{\partial x}}\right]_{x_n} \qquad (8)$$

- The 3D equivalent for the motion of isolated magnetic nulls is

$$\frac{\mathrm{d}\mathbf{x}_n}{\mathrm{d}t} = \left(\nabla\mathbf{B}\right)^{-1}\nabla\times\mathbf{E} = \mathbf{V}\left(\mathbf{x}_n\right) - \left[\eta\left(\nabla\mathbf{B}\right)^{-1}\nabla^2\mathbf{B}\right]_{\mathbf{x}_n} \qquad (9)$$

- This provides insight into how nulls form, move, and disappear
  - Plasma flow across nulls allowed by resistive diffusion
  - When the Jacobian matrix $\nabla\mathbf{B}$ is singular, nulls are either appearing or disappearing
  - Newly formed null-null pairs initially move apart very quickly
- Allows convenient tracking of nulls in 2D and 3D simulations

Conclusions

- We compare two simulations of the plasmoid instability with symmetric and asymmetric upstream magnetic fields
- Features of the asymmetric simulation include:
    - X-line 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
        - Circulation within each island
    - Turbulence in the downstream region
    - Broader current sheets than the symmetric case
    - The reconnection rate is not greatly enhanced above the predicted value for asymmetric reconnection without plasmoids
- We have derived an exact expression describing the motion of magnetic nulls in 3D

Future Work

- Scaling study of asymmetric inflow plasmoid instability
    - How does asymmetry affect the onset criterion?
        - Is it a function of $S_{Ah} = \frac{LV_{Ah}}{\eta}$?
    - Is the reconnection rate significantly enhanced above the Cassak-Shay prediction as in the symmetric case?
- 3D simulations of $\geq$2 competing reconnection sites
- Asymptotic matching analysis to determine the onset criterion and properties of the linear asymmetric plasmoid instability
    - Anybody interested?
- Investigate the role of additional terms in the generalized Ohm's law on the 3D motion of nulls