Numerical Simulations of 3D Reconnection: rotating footpoints

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Contents: - numerical setup
- description of results
- reconnection rates
- energetics
- conclusions
3D Reconnection

- **2D magnetic skeleton:**
  - X-point \((B=0)\)
  - Separatrix curves

- **3D magnetic skeleton:**
  - Null points \((B=0)\)
  - Separatrix surfaces:
    - Outline connectivity domains
  - Separator:
    - Intersection of 2 separatrix surfaces
Flux comes through surface in concentrated sources
  » Magnetic carpet

Photospheric flux reprocessed in 8 - 19 hours (Hagenaar et al. 2003)
  » Effect on coronal heating?

Start with array of intense flux tubes (B~10^3 G, <100km)
  » Simple motions
  » Very rapid build up of current (Priest et al. 2002)

Coronal field recycled much faster in 1.4 hours (Close et al. 2004)

Investigate elementary heating event, driven by simple photospheric motion
Basic Model

- Model reconnection driven by rotating photospheric footpoints
  - 3D numerical box:
    » \( z=0 \): 2 +ve sources
    » \( z=L \): 2 –ve sources
    » counter-rotate

- Consider 2 variations of setup:
  - Without background field
    » flux tubes fan out quickly
    » separatrix surfaces
  - With (vertical) background field
    » flux tubes confined
    » “fluxtube-separatrix” surfaces
Dynamical Evolution (1)

- Flux ‘domains’ are forced to interact
- Twisted current sheets form along separatrix surfaces
- Field lines reconnect to other sources + (periodic) domain outside box
Component of electric field along field lines ($E_{\text{par}}$) is a good indicator of reconnection

- Build up of $E_{\text{par}}$ along field lines close to current sheets
- Field lines with high $E_{\text{par}}$ reconnect in subsequent snapshot

no background field
Dynamical Evolution (3)
Current at z=0.5

- No background field:
  - current sheet along coinciding separatrix surfaces
  - as sources rotate, develops into x-type configuration

- With background field:
  - ring of current at edge of domain due to velocity shear
  - “fluxtube-separatrix” surfaces initially apart
  - development of x-type configuration
  - strong outflow velocities cause ‘bowshock’ currents
- No background field:
  - stagnation point flow
  - outflow velocities comparable to inflow
    - (slow) shock along separatrices

- With background field:
  - velocity shear at edge of domain
  - stagnation point flow
  - fast outflow velocities
    - fast (bow)shock
Connectivity Structure

- Dynamical evolution of connectivity is complex!

- No background field (confining): substantial number of field lines reconnect to neighbouring domain

- With background field: most field lines connect to neighbouring domain when ‘bowshock’ currents collide with edge current
Reconnection rate

- Fixed amount of flux associated with each field line
- Work out amount of reconnected flux as field lines change connectivity

» Reconnection starts later (at larger angle) with background field
» Amount of reconnected flux increases faster with background field
Poynting flux describes flow of energy through the boundaries:

\[-\int \left( \mathbf{E} \times \mathbf{B} \right) / \mu_0 \cdot dS = \int \frac{\partial}{\partial t} \left( \frac{B^2}{2\mu_0} \right) dV + \int \frac{j^2}{\sigma} dV + \int \mathbf{v} \cdot (\mathbf{j} \times \mathbf{B}) dV\]

Inflow of electromagnetic energy = rise in magnetic energy + Ohmic + work done by Lorentz force
Energetics

- Start of driving:
  » magnetic energy increases

- Onset of reconnection:
  » tension in magn field is reduced:
    • build up magn energy slows down
  » strong currents + outflow:
    • Ohmic dissipation increases
    • Work done by Lorentz force increases (+ kin energy & visc diss)

- Later stages:
  » No background field: reconnection slows down
  » Background field: reconnection of fieldlines to neighbouring domain
Conclusions

- Numerical simulation of 3D reconnection driven by rotation of flux sources
  - Very efficient build up of current sheets ~ tectonics model
  - No background field: separatrix surfaces present
  - With background field: quasi-separatrix surfaces created by driving

- Comparison of setup with and without background field:
  - reconnection along twisted current sheet
  - complex evolution of connectivity structure
  - different reconnection rates
  - large differences in final stages of experiments

- Further comparisons with:
  - potential evolution – free magnetic energy?
  - reconnection rate of standard reconnection models
  - different types of photospheric motions (e.g. twisting, shearing)
Numerical Code

- **3D MHD Code:**
  - finite difference method.
  - third order predictor-corrector method.
  - sixth order spacial partial derivatives.
  - fifth order spacial interpolation.
  - fourth order viscosity and resistivity
- Numerical box (1,1,1) with grid resolution (129,128,128)

\[
\frac{\partial \rho}{\partial t} = -\nabla \cdot \rho \mathbf{v} \\
\frac{\partial \rho \mathbf{v}}{\partial t} = -\nabla \cdot (\rho \mathbf{v} \mathbf{v} + \tau) - \nabla P + \mathbf{j} \times \mathbf{B} \\
\frac{\partial e}{\partial t} = -\nabla \cdot (e \mathbf{v}) - P \nabla \cdot \mathbf{v} + Q_{joule} + Q_{visc} \\
\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \\
\mathbf{E} = -\mathbf{\nabla} \times \mathbf{B} + \eta \mathbf{j} \\
\mathbf{j} = \nabla \times \mathbf{B} \\
P = e(\gamma - 1) \\
T = P / \rho
\]
Dynamical Evolution (1a)

no background field
Dynamical Evolution (1b)