MHD Simulations of Fast Magnetic Reconnection

S.E. Kruger, D.D. Schnack, Z. Mikic, R. Lionello

`krugers@saic.com`

SAIC/CESS

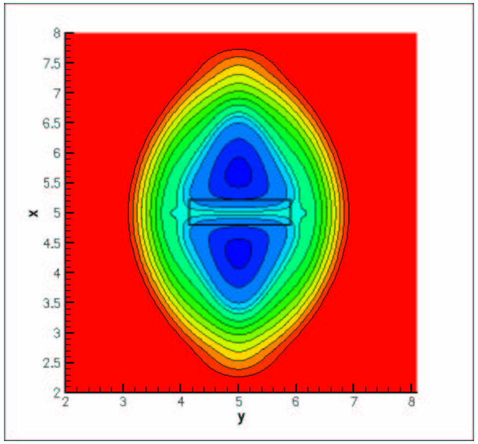
Outline

- Conventional Wisdom on Magnetic Reconnection
  - Sweet-Parker reconnection
  - Petschek reconnection
- Topological nonequilibria
- Mikic-Lionello Results
- NIMROD Results

Properties of Analytic Models

Analytic models generally:

- Assume quasi-steady state
- Quasi-ideal: can only solve "outer-region"
- Done in a subdomain



Two dominant types of reconnection models in 2D systems:

- Y-point models

  Sweet-Parker, Syrovatskii

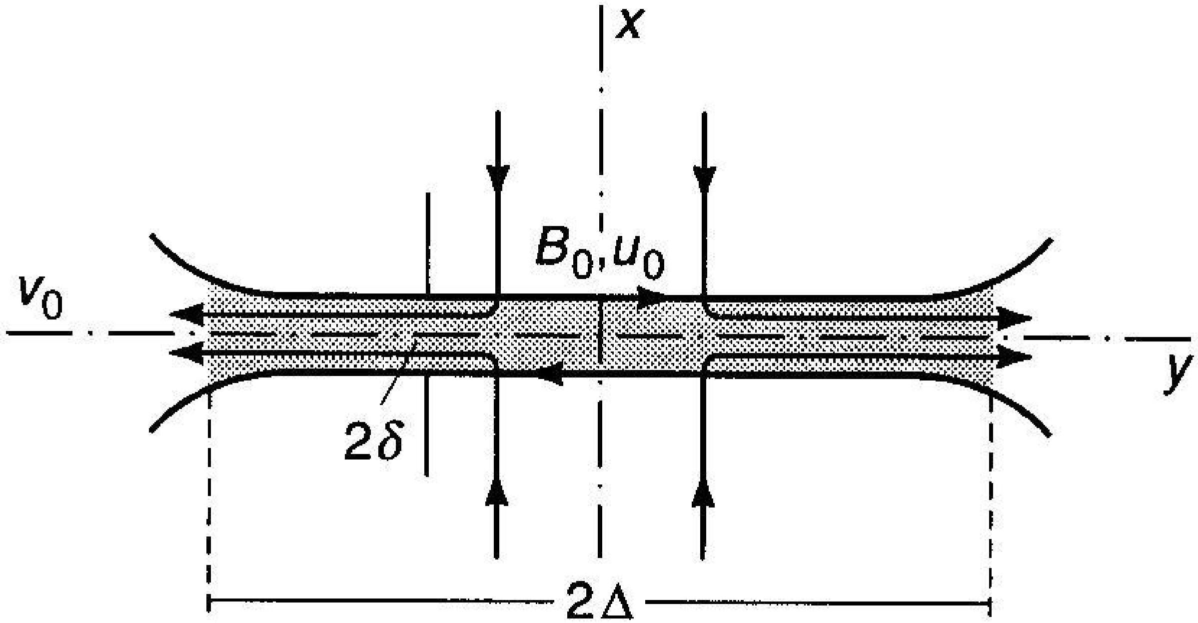
- X-point models

  Petschek-like (Petschek, Sonnerup, ...)

Sweet-Parker Model Gives SlowReconnection Due to Throttling

A Sweet-Parker sheet is characterized by six quantities:

- B_0 upstream field. u_0 upstream flow.
- δ width of the sheet. Δ length of the sheet.
- v_0 downstream flow. η resistivity.



Sweet-Parker Model Gives SlowReconnection Due to Throttling

- Mass conservation: $u_0 \Delta = v_0 \delta$.
- Ohm's law: $u_0 B_0 = \eta j \simeq \eta \frac{B_0}{\delta}$.
- Force balance: $\frac{B_0^2}{2} = p_m - p_0$ and $\frac{v_0^2}{2} = p_m - p_0$.

The reconnection rate is

$$\partial_t \psi = E = u_0 B_0 \sim \eta^{1/2}.$$

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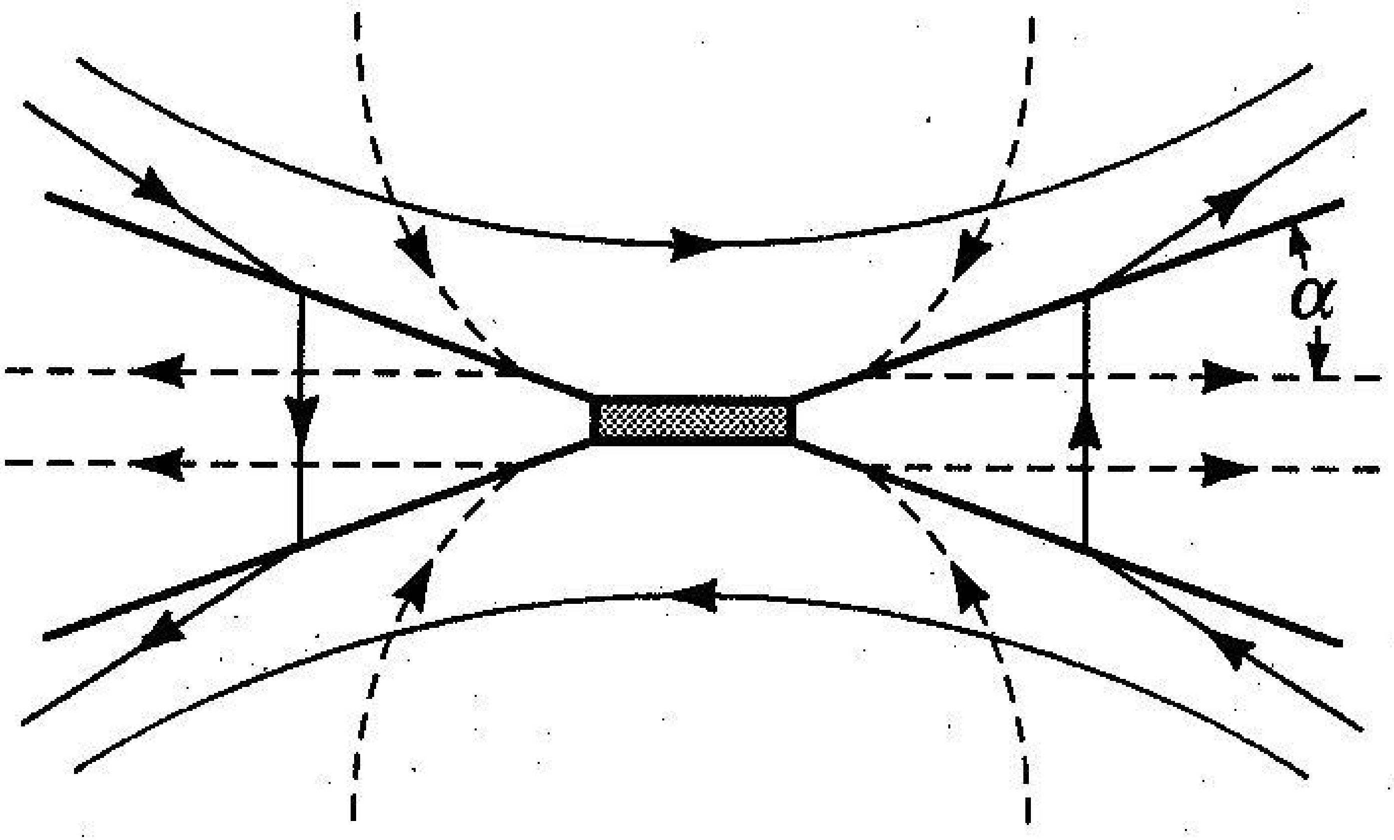
Too slow!

Petschek Model Gives Fast Reconnection

Petschek's configuration has an X-point caused by shocks:



Petschek Model Gives Fast Reconnection

Because the outflow is not throttling the reconnection rate, the maximum reconnection rate is proportional $1/\ln S$.

It's fast!

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It's fast!

Conventional Wisdom (according to Biskamp):

Nonlinear MHD, Cambridge University Press, 1993

"... the theory is in error both conceptually and formally. ... it appears quite hopeless to solve the matching problem analytically. ...Various simulations of self-consistent reconnecting systems have been performed... All develep extended current sheets."

Topological Nonequilibria

"Topological Nonequilibria" are configurations which evolve to configuations with contact discontinuities in the Ideal MHD model.

A magnetic field zero line is a line where $\mathbf{B}_\perp = 0$, where $\perp$ is with respect to a non-zero B_z.

The magnetic field remains zero on this line in the presence of ideal MHD flow.

Including this line may fundmentally alter the dynamics of the magnetic reconnection. See Vainshtein et al. *Phys. Rev. E* 2000.

Rosette Problem is Example of Topological Non-Eequilibrium

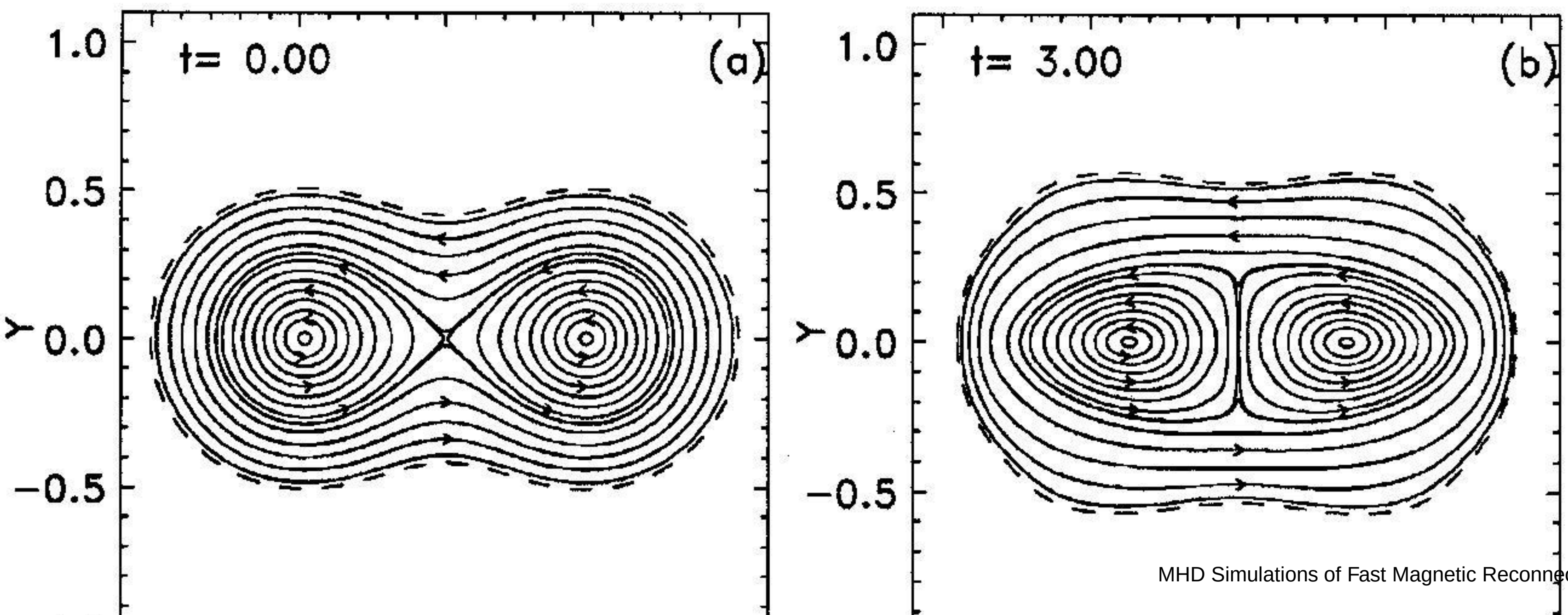
Initial conditions:

$$\psi = \sum_{i=1,2} \psi_i \exp\left(-\left(\frac{x - x_i}{\sigma}\right)^2 - \left(\frac{y - y_i}{\sigma}\right)^2 \right),$$

$$A_i = \{0.02, 0.02\}, \quad x_i = \{5.8, 4.2\}, \quad y_i = \{5, 5\},$$

$$\sigma = 0.4, \quad B_z = 0.1$$

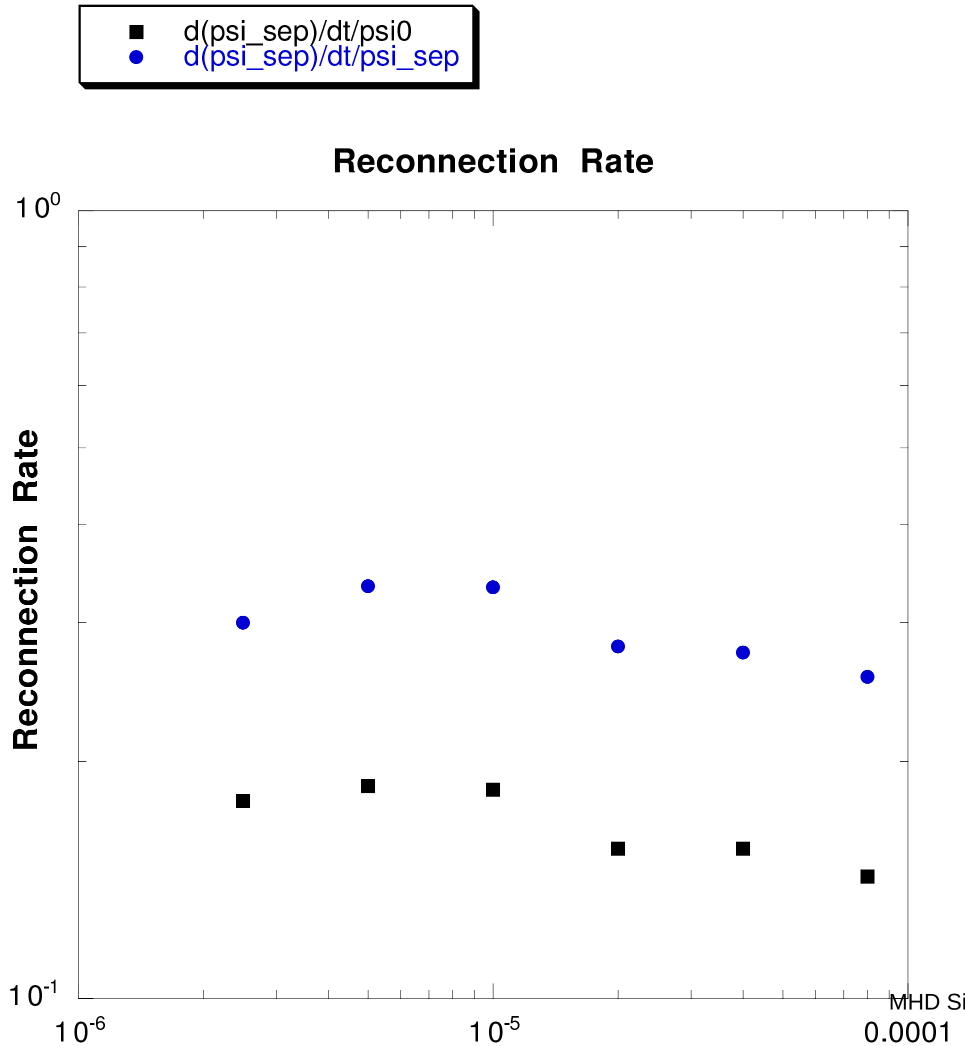
Under ideal MHD relaxation, current sheet is formed.



Is There Fast Reconnection?

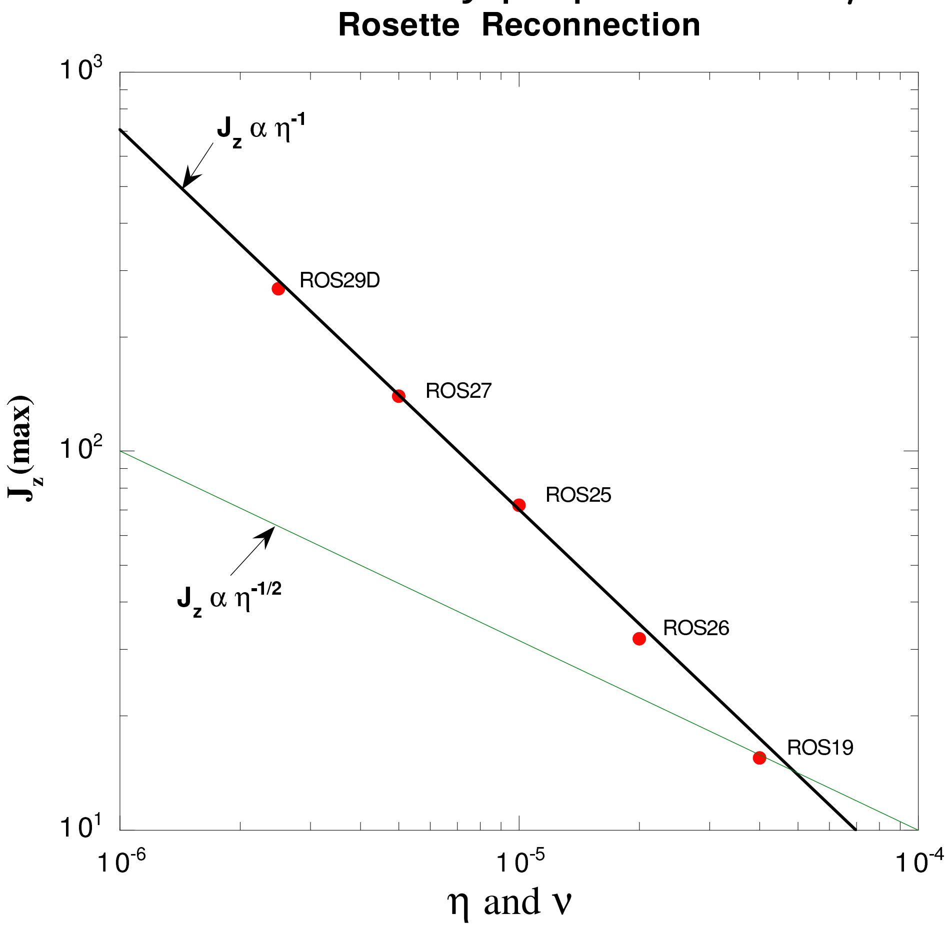
- Mikic-Lionello have performed 2D MHD simulations of “rosette” problem.
- There is evidence of fast reconnection.

Reconnection rate is independent of η:



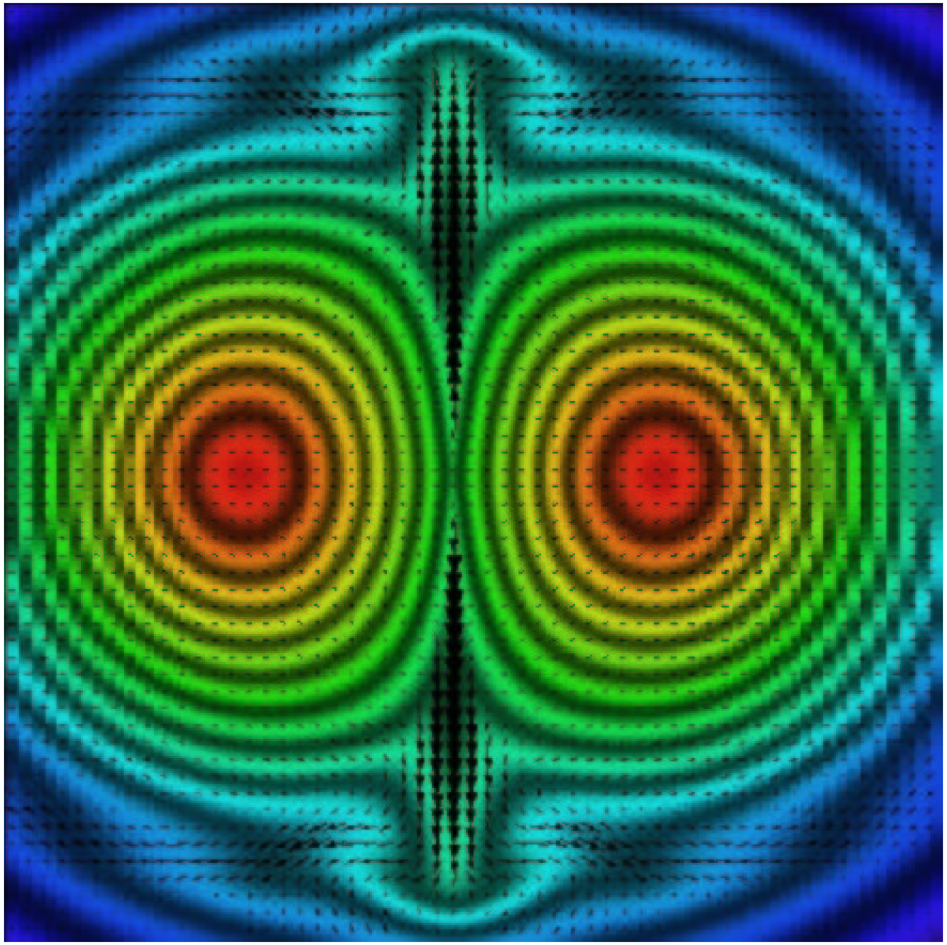
Is There Fast Reconnection?

$\max J_z$ is inversely proportional to η:



Is There Fast Reconnection?

Magnetic flux and plasma flow:



NIMROD Offers Attractive Features For Problem

Caveats to Mikic-Lionello results:

- Results may not be numerically converged
- In doing the numerical convergence studies, it is observed that an increase in resolution leads to slower reconnection

NIMROD has some advantages for benchmarking the problem:

- Slab geometry with flexible boundary conditions:
  Periodic non-periodic
  Doubly-Periodic
  Non-Periodic
- Scales well on MPP systems

Verify With Biskamp Problem

To understand results from the rosette problem, compare with well-verified problem that gives Sweet-Parker scaling. See:

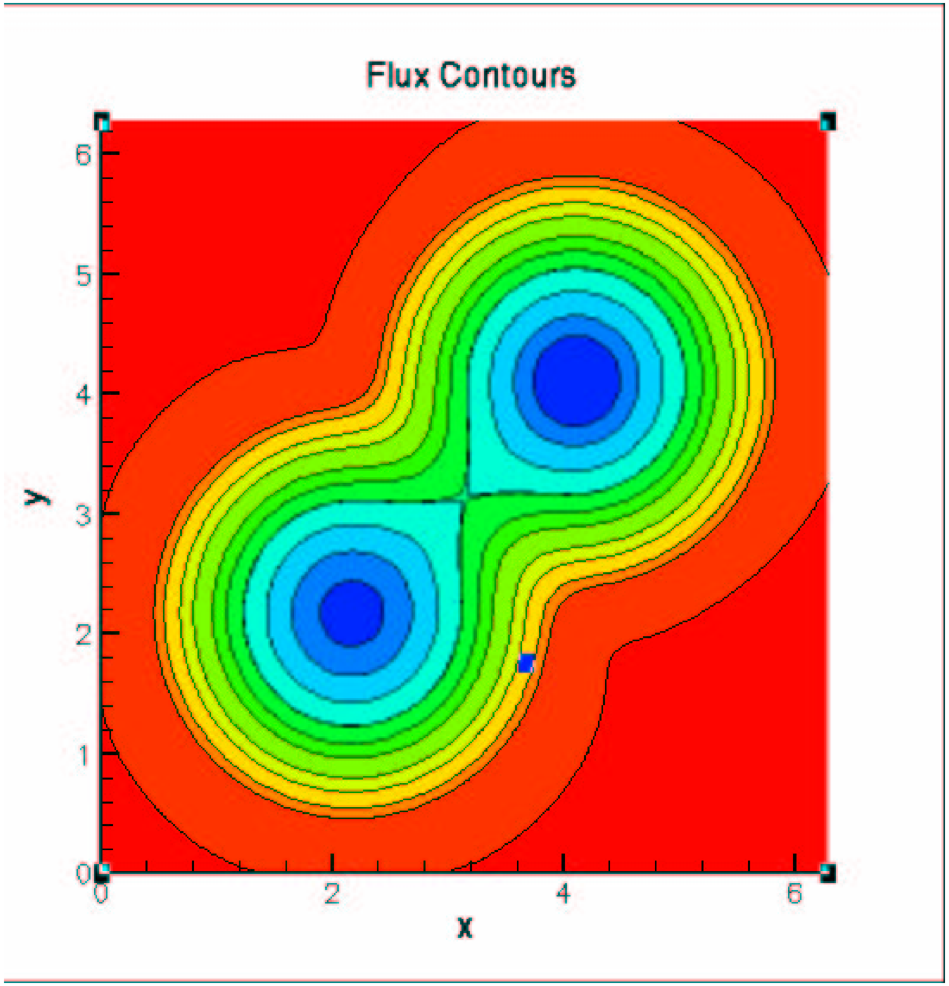
Biskamp and Schwarz, *Physics of Plasmas* **8** (2001) 4729
Biskamp, Schwarz, and Drake, *PRL* **84** (1995) 3850

Initial conditions (note exponentials):

$$\psi = \sum_{i=1,2} \psi_i \exp\left(-\left(\frac{x - x_i}{\sigma}\right)^4 - \left(\frac{y - y_i}{\sigma}\right)^4\right),$$

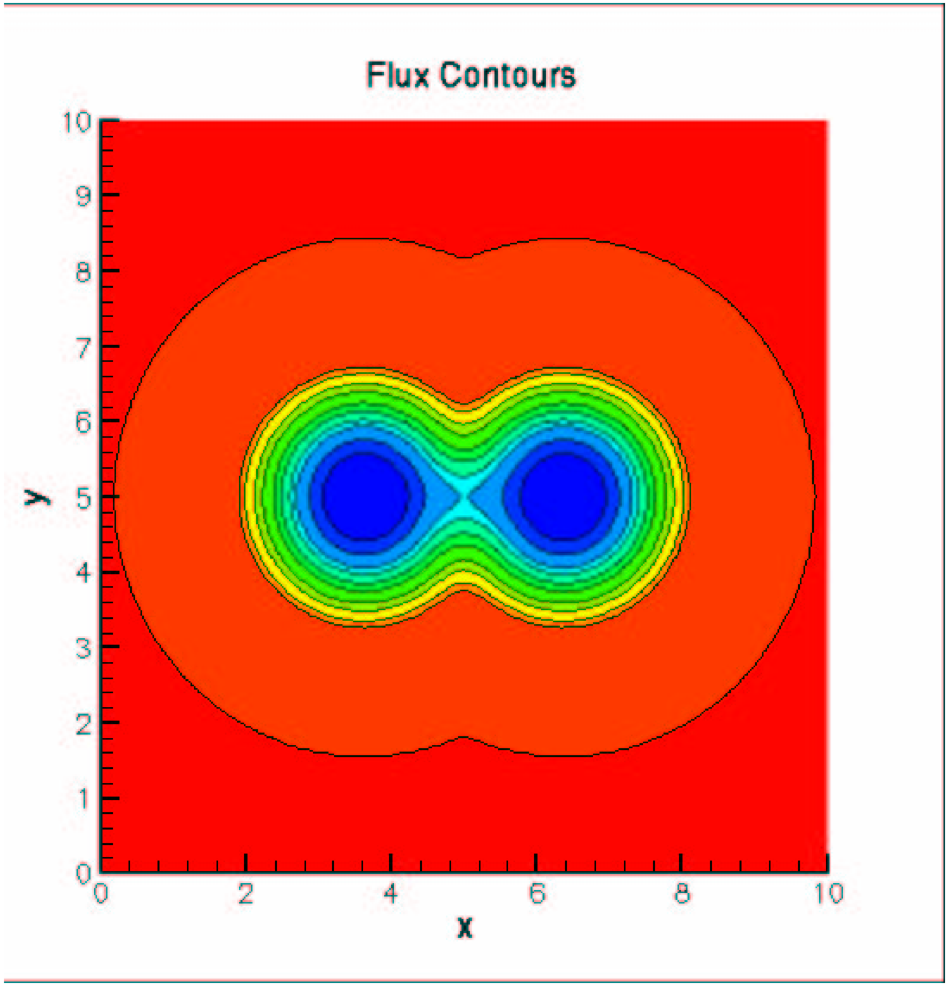
Comparison of test cases

Biskamp: doubly-periodic boundary conditions



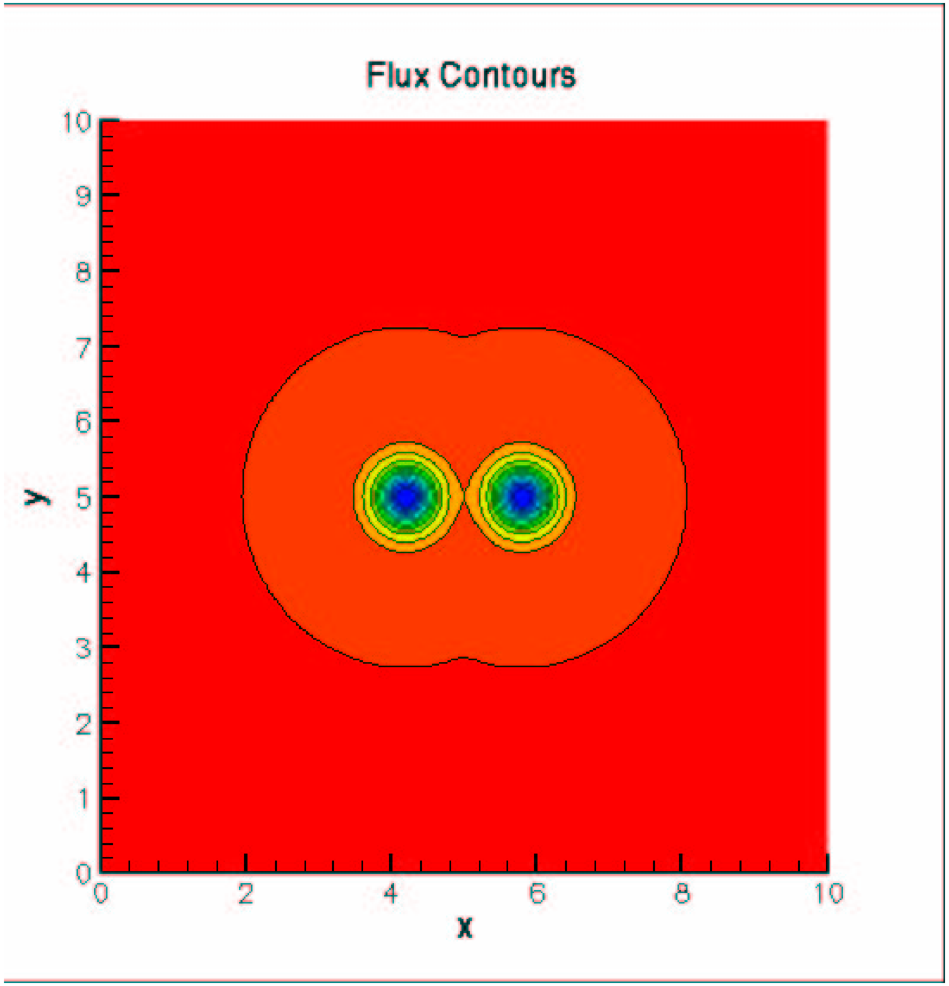
Comparison of test cases

Rotated Biskamp: conducting wall boundary conditions



Comparison of test cases

Rosette: conducting wall boundary conditions



Preliminary NIMROD Results

Summary

- Mikic-Lionello possibly see fast reconnection with MHD.
- If true, it emphasizes the importance of exterior configuration to understanding reconnection.
- The flexibility of NIMROD is being used to benchmark the result and compare to published results.