Resistive MHD Simulations of X-Line Retreat and Competing Reconnection Sites

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[3] Supported by the NSF-REU solar physics program at the CfA

52nd Annual Meeting of the APS Division of Plasma Physics November 8–12, 2010

With thanks to: Carl Sovinec, John Raymond, Kelly Korreck, Paul Cassak, Mitsuo Oka, Jun Lin, & Chengcai Shen

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X-line m otion is fre que ntly obs erved during m agnet ic rec onnec tion in nature and the lab oratory. Ex am ple s include :

X-line retre at in E arth’s m agnet otail (e .g., Runov et al. 2003; Eastwo o d et al. 2010)

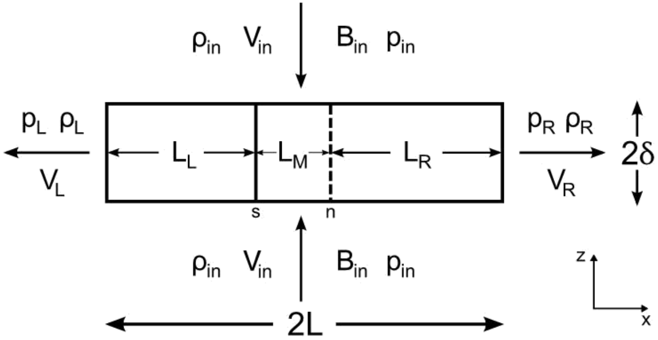
Current s he ets that form in the wakes of coronal mass eje ctions (CMEs)

Radial motion of the diﬀ us ion re gion during s pherom

a me rging (e .g., Inomoto et al. 2006; Gray et al. 2010;
k Ono et al. 1997; se e also Murphy & Sovinec 2008)

De spite t he pre vale nce of X- line re treat, it is standard practic e to c ompare in situ me as ure ments to part ic le-in-c ell (PIC) sim ulations of roughly s tationary reconnec tion layers

In this p oster, we pre sent re sistive MHD sim ulations of X-line retreat and comp eting X-lines and derive an e xpre ssion for the rate of X-line retre at



ρ_{in} V_{in}
B_{in} p_{in}
p_L ρ_L
V_L
L_L
L_M
L_R
p_R ρ_R
V_R
2δ
s
n
ρ_{in} V_{in}
B_{in} p_{in}
2L
z
x

Thnec tion layer with asym me tric downstre am pre ss ure. Re
e connec tion is assume d to b e s teady in an inertial
abreference frame .
ov‘n’ de note s the m agnetic fie ld null and ‘s’ denote s the
e flow stagnation p oint
fig
ure
re
pre
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a
lon
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rec
on

R

2 in+ L a pL R+ ρ L V2 L 2 R2

Bμ0

a pin d

2 VinL Following Cas sak & Shay (2007), we integrat e ove r this control volume and find relations approximating conse rv

ati on of mass, momentum, and energy

$2\rho_{in}V_{in}L \sim \rho_L V_L d + \rho_R V d$

$\rho_L V_L^2 + p_L \sim \rho_R V_R^2 + p_R$

$\sim V V_R^2 d + a p + \rho_R V$

where a = γ / (γ - 1) and we ignore ups tre am kinetic ene rgy/dow ns tre am kinetic energy and as sume the contribution from te ns ion along the b oundary is sm all or eve n.

V2 L , In the incom pre ssible lim it pρ 2 + Δ p 2 2ρ± Δ p
R
~ 4 c2 in 2
ρ

using p̄ = $\frac{p_L + p_R}{2}$, E_y, $\Delta p = p_R$ η (V_L - p_L, and c^2_{in} = $\frac{B^2_{in}}{\mu_0 \rho_{in}}$ + $\frac{a\, p_{in}}{\rho_{in}}$

0L

~ B_{in} By assuming res istive dis sipation, the elec
then given by
+ V_R) 2 µ

The sc aling relations show that the rec onne ction rate is weakly se ns it iv e to as ymm etric dow ns tream pres sure

If one outflow jet is blo c ked, rec onne ction will b e almos t as quic k

Rec onne ction will s low dow n gre atly only if b oth outflow

jets ske d
are The curre nt shee t res p onds to as ymm etric dow ns
blo tream press ure by c hanging its thickness or le ngt h

Howe ver, this analysis makes three major as sumptions :

- The curre nt shee t is stationary
- The curre nt shee t thicknes s is uniform
- Magne tic t ension contribute s s ymm etrically along t he b oundaries

To make furthe r progres s, we m us t do numerical s im ulations

Thm ulations start from a p erio dic Harris shee t which is p
e erturb ed at two ne arby lo c ations ($x = \pm 1$)Dom ain: -30 =
2- x = 30, -12 = z = 12Sim ulation parame ters: $\eta = 10^{-3}$, β_8=
D 1, $S = 10^3$–10^4, Pm = 1, $\gamma = 5/3$, d_0= 0.1
si De fine :

- x_n is the p osition of the X-line
- x_s is the p osition of the flow s tagnat ion p oint
- $V_x(x_n)$ is the ve lo city at the X- line
- $\frac{dx_n}{dt}$ is the ve lo c ity of the X- line
- $\hat{x}$ is the outflow dire ction, $\hat{y}$ is the out-of-plane direc tion, and $\hat{z}$ is the inflow direc tion
- We s how only x = 0 s inc e t he sim ulation is s ymm etric

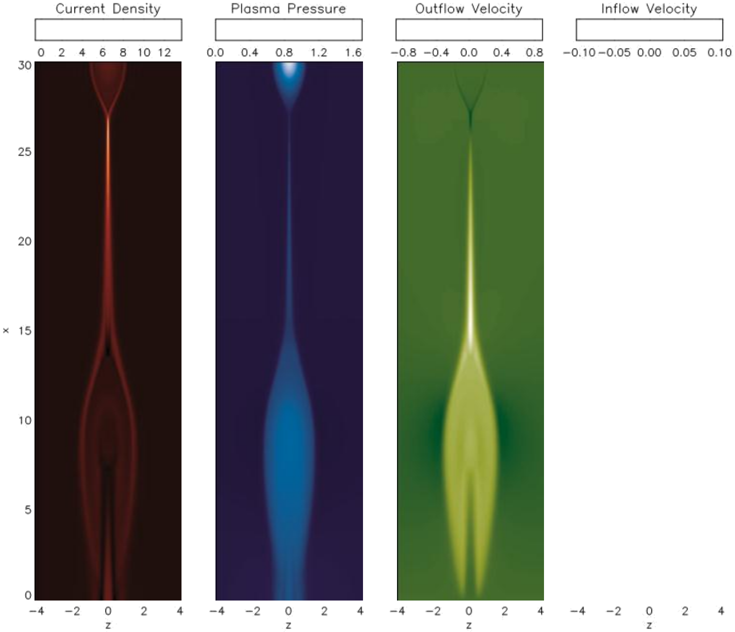
In dim ensionless form, the equations use d for
the se sim ulations are

$\nabla \cdot B = 0$ (3) $\rho \;\; \partial V \partial t + V \cdot \nabla V \;\; = J \times B - \nabla p - \nabla \cdot \rho v \nabla V$ (4)$\partial \rho \, \partial t + \nabla$
$\cdot (\rho V) = \nabla \cdot D \nabla \rho$ (5) $\rho \gamma - 1 \;\; \partial T \, \partial t + V \cdot \nabla T \;\; = p2 \nabla \cdot V - \nabla \cdot q + Q$ (6)
$\partial \quad \partial t$
B

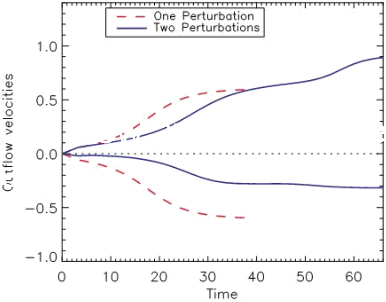
$= \quad \times (\eta J - V \times B) + \kappa_{divb} \nabla \nabla \cdot B$ (1) $J = \nabla \times B$

$-\nabla$ (2)

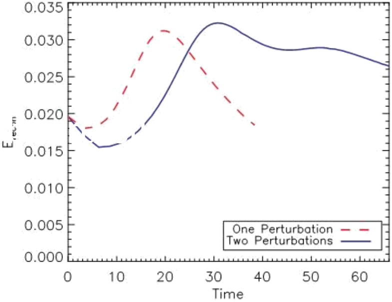
Dive rge nc e cleaning is use d to preve nt the acc um ulation of divergence e rror



Current Density
0 2 4 6 8 10 12
Plasma Pressure
0.0 0.4 0.8 1.2 1.6
Outflow Velocity
−0.8 −0.4 0.0 0.4 0.8
Inflow Velocity
−0.10 −0.05 0.00 0.05 0.10
x
30
25
20
15
10
5
0
−4 −2 0 2 4
z



One Perturbation
Two Perturbations
1.0
0.5
0.0
−0.5
−1.0
velocities
0
10
20
30
40
50
60
Time



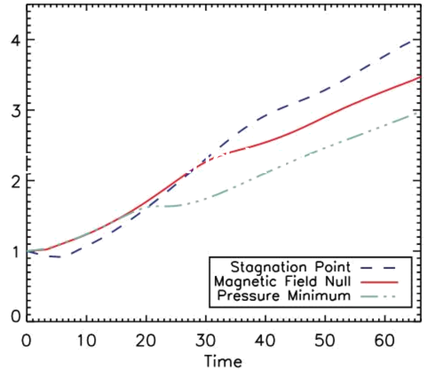
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
E
One Perturbation
Two Perturbations
0
10
20
30
40
50
60
Time

In agreement with Se

aton (2008) and Re eve s et al. (2010), mos t of the energy go e s away from the obstructe d exit

Eve nt ually, re conne ction pro cee ds m ore quickly in retreat sim ulations than in othe rw is e equivalent s ymm etric, non- re treating simulations

The com parison w it h the single p e rturbation case is halted around t ˜ 40 b ec ause of the formation of an is land at x = 0



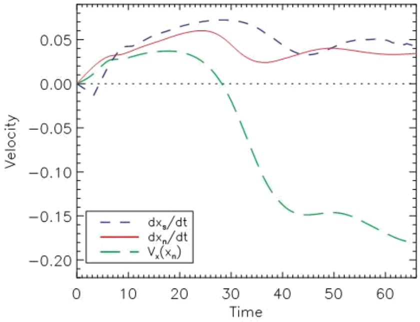
4
3
2
1
0
0
10
20
30
40
50
60
Time
Stagnation Point
Magnetic Field Null
Pressure Minimum

Surprisingly, the r

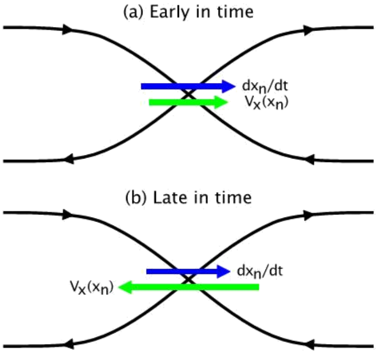
e lative p os itions of the X-line and flow stagnation p oint switc h!

This o ccurs s o that the s tagnation p oint will b e lo c ate d near where the t ension and press ure forc es cancel

Rec onne ction deve lops slow ly b e cause the X-line is lo cated near a pre ssure minim um e arly in t im e



0.05
0.00
−0.05
−0.10
−0.15
−0.20
Velocity
0
10
20
30
40
50
60
Time
dx_s/dt
dx_n/dt
$V_x(x_n)$



(a) Early in time
dx_n/dt
$V_x(x_n)$
(b) Late in time
dx_n/dt
$V_x(x_n)$

The stagnation p oint re treats m ore quickly than the X-line

Any diﬀ erence b etwee n $\frac{d\,x_n}{d\,t}$ and V_x $(x_n$) m us t b e due t o diﬀusion (e.g., Se aton 2008)

The ve lo c ity at the X- line is not t he ve lo c ity of the X- line

The inflow (z) c omp one nt of Faraday's law for t he 2D sym me tric inflow case is

$$\partial B_z \partial t = -\partial E_y \partial x \quad (7)$$

The conve ctive derivative of B_z at the X- line taken at the ve lo c ity of X-line re tre at, dx/ dt , is $\partial B_z \partial t$ x_n n+ $dx_n dt\, \partial B_z \partial x$ The RHS of Eq. (8) is ze ro b e caus e B $x z_n$= 0 (8)(x_n, z = 0) = 0 by definition for this geom etry.

From Eqs. 7 and 8: (9)

x

$dx_n dt =$

$\partial^2 B_z$ x (10)

+

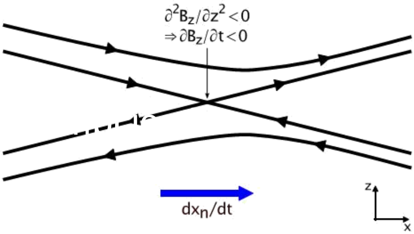
∂B
∂x

dt = V_{nx}($x_n$dxUsing E + V × B = η J ,∂ E_y/∂ x ∂ n ∂ z^2 n
we arriv e at) - η $\partial^2 B \partial x_{z2}$ B_z/∂ x

z

In the s imulations $\frac{\partial^2 B_z}{\partial z^2}$ $\frac{\partial^2 B_z}{\partial x^2}$

, so X- line retreat is caused by diffusion of the normal com p onent of t he magnetic field along the inflow dire ction Equation (9) c an also b e evaluated using additional t erms in the generalized Ohm 's law



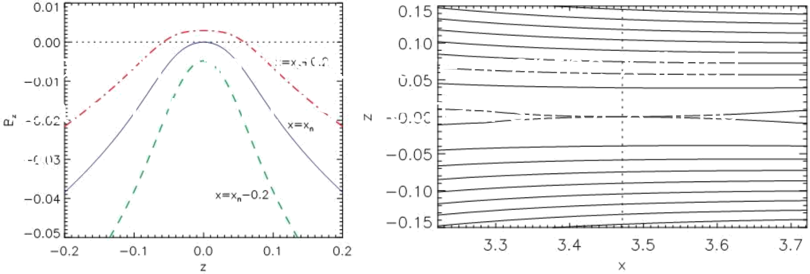
$\partial^2 B_z/\partial z^2 < 0$
$\Rightarrow \partial B_z/\partial t < 0$
dx_n/dt
z
x

The X-line moves i

n the direct ion of increasing total rec onnec tion ele ctric fi eld strength

X-line retre at o c curs through a c ombination of adve ction by bulk plasma flow and diffusion of the norm al c omp one nt of the magne tic fi eld

X-line m otion de p e nds intrinsically on lo cal paramet ers ev aluate d at the X-line



B_z
z
x=x_n
x=x_n−0.2
z
x

Negative B_z diffuses from above and below into the region of the X- line

Left: $B_z(z)$ along thre e lo cations near the X-line .

Right : Magne tic fl ux contours near the X-line.

NIMROD re sistive MH D sim ulations w it h multiple initial X-line p erturbat ions we re analyzed by A. K . Young

Isolated or s trong p erturbations are m ore like ly to survive

Initial X-lines surrounded by other initial X-lines are les s like ly to s urvive , but X- lines which have ro om to dev elop in one outflow direc tion do have a b e tte r chance of deve loping (se e als o two-fluid sim ulations by N akam ura et al. 2010)

Early on, winning X-lines have plasm a pre ssure facilitat ing outflow rather than im p e ding it

Whe n an X-line is lo cated near one exit of the curre nt shee t, the flow stagnation p oint is lo c ated b etwee n the X-line and a ce ntral plas ma pre ss ure maximum
Flow across the X-line in the opp os ite direc tion of X-line mot ion do es o cc ur, but infrequently

If $x_s > x_n$, then usually $V_{pla\ smoi\ d}$

SHASTA s imulations by C. C. Shen a
the dire ction of plasm oid ejec tion is
lative lo cations of the fl ow s tagnatio
> 0

The induction equation is

$$\frac{\partial B}{\partial t} + V \cdot \nabla B = B \cdot \nabla V - B (\nabla \cdot V) + \eta \nabla^2 B , \quad (11)$$

where in our 2-D geometry,

$$\eta \nabla^2 B_z = \eta \left(\frac{\partial^2 B_z}{\partial x^2} + \frac{\partial^2 B_z}{\partial z^2} \right) . \quad (12)$$

The term $\eta \frac{\partial^2 B_z}{\partial x^2}$

a ts to s mo oth profile. This te rm can mov e or re duce the num b er of c out the $B_z(x)$ X-lines (where $B_z = 0$), but not c reate ne w X-lines.

The te rm $\eta \frac{\partial^2 B_z}{\partial z^2}$ brings in B_z along t he inflow direc tion. This te rm can mov e or inc re as e the num b e r of X-lines , but by sym me try cannot caus e pre -exis ting X- line s to dis app e ar.

X-line m otion o c curs freque nt ly during re connec tion in s pace , astrophysic s, and t he lab oratory

Res istive MHD simulat ions of X- line retreat/as ymm etric outflow re connec tion show t hat m ost of the energy is dire cte d away from the obstructe d exit

Late in time there is s ignific ant fl ow across the X- line in the opp osite dire ction of X-line re tre at

An expres sion for the rate of X-line ret re at shows that X-line mot ion is due to either adve ction by the bulk plasm a fl ow or by diffusion of the norm al c omp one nt of the m agnet ic fie ld

Sim ulations of m ultiple X- line re connec tion show t hat:

- Initial X-lines with ro om to de velop on at le as t one s ide are more likely to s urvive

The flow stagnation p oint is typic ally lo c ate d b e tween t he X-line and a c entral plasma pres sure m axim um

Sim
ulation:

T w o - fl u i d s i m

ulations of X-line re tre at

3-D sim ulations of X-line retreat with initial p erturbations offs et from each other in the out -of- plane direct ion

Examine X- line b e havior during the plasm oid inst ability

Inv estigate X- line dynamic s in two and thre e dim ensions for realis tic geome tries such as c oronal jets , CME c urrent s he ets , planetary m agnetot ails, and sphe rom ak me rging e xp e rim ents

Inv estigate X- line mot ion in asym me tric inflow re connec tion

The ory:

De rive e xpre ssions for neutral line and X-line m otion in 3-D

De termine the rat e of retre at of the flow st agnation p oint

Examine the c ons eque nces of a se parat ion b etwe en 3-D magnetic field nulls and flow s tagnation p oints

Exp erime nt and observation (suggest ions for othe rs):

- Characte rize X- line motion during lab oratory rec onnec tion
- Find signat ures of X-line retreat in m agne totail (M. O ka)

Obse rve e ffec ts of asym me tric outflow in CME c urrent s he ets