Self-similar evolution of fast magnetic reconnection in free-space: A new model for astrophysical reconnection

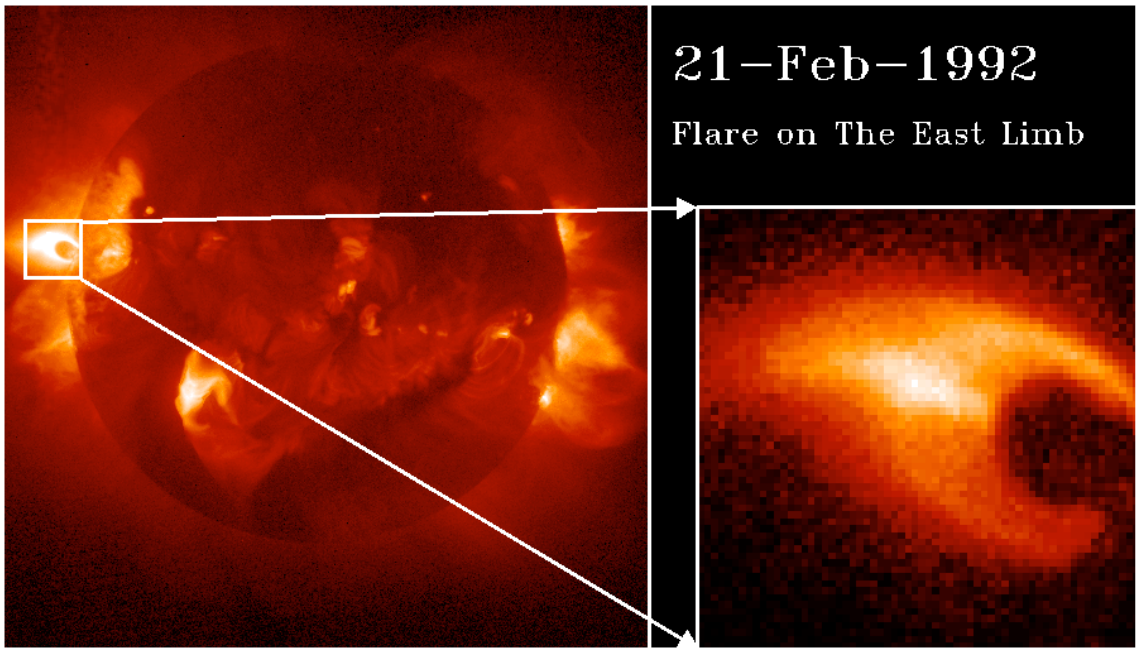
Shin-ya Nitta
新田 伸也
The Graduate University for Advanced Studies,
Hayama Center for Advanced Studies
E-mail: snitta@koryuw02.soken.ac.jp

§Introduction

Magnetic reconnection is

- Very powerful energy converter
- Very common in the universe

e.g., Solar Flares



§§Astrophysical Reconnection

Astrophysical Reconnection is characterized by

huge dynamic range of expansion

e.g., Solar flares

Initial system scale $\sim 10^0$ [m]

(Initial Current Sheet Thickness)

⇑

Final system scale $\sim 10^7$ [m]

(Maximum scale of reconnection system)

⇩

intrinsically Time-Dependent

Should be treated as

Spontaneous Evolution in Free Space

Cannot be described by previous models!

Aim of this work

Suitable reconnection model for astrophysical application?

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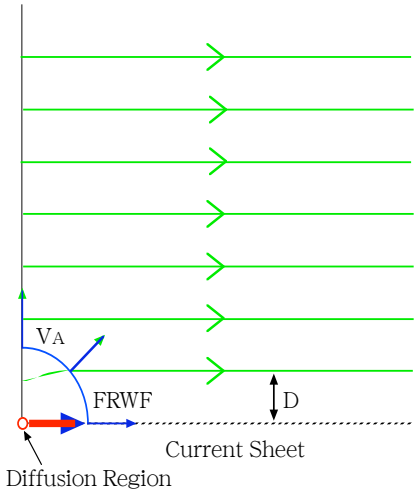
Self-Similar Evolution

§Evolution Process

1) Onset (Resistive Stage) $t < D/V_A$



Sweet-Parker-like or tearing

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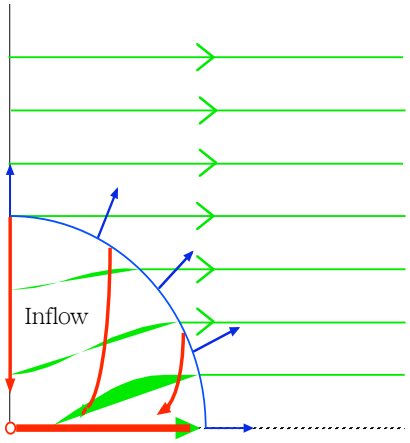
Formation of

Fast-mode Rarefaction Wave

2) Induction of Inflow $t \gtrsim D/V_A$



Propagation of FRWF

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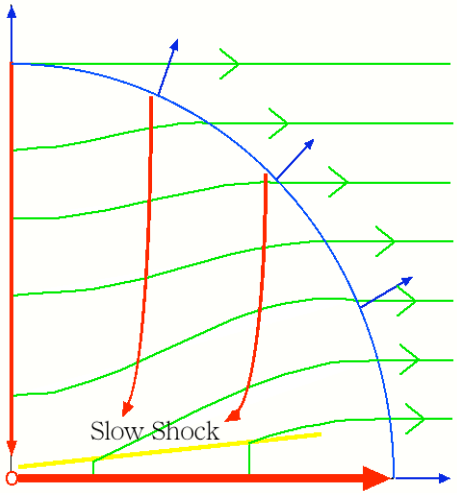
Induction of Inflow

3) Similarity Stage (Petschek-like at center) $t \gg D/V_A$



Formation of Slow-Shock

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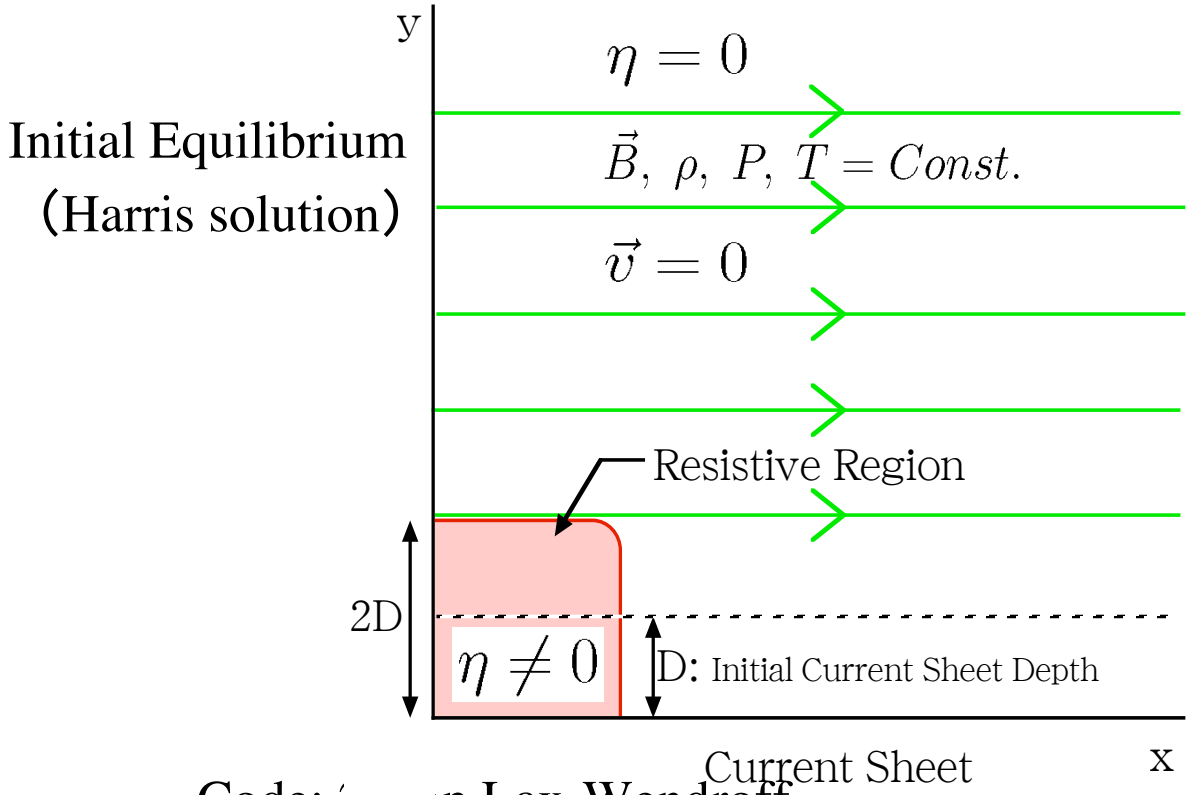
Fast-mode Rarefaction Dominated

(Petschek-like) Fast Reconnection

§Numerical Approach



Code: 2-step Lax-Wendroff

Parameters & Normalization

Parameters

$$\beta \equiv \frac{P_0}{{B_0}^2/8\pi} = 0.2$$

$$R_m \equiv \frac{V_{A0}}{\eta/D} = 24.5$$

Normalization

Dimension	Unit
[L/T]	C_{s0}
[L]	D
[M/L^3]	ρ_0

⇨

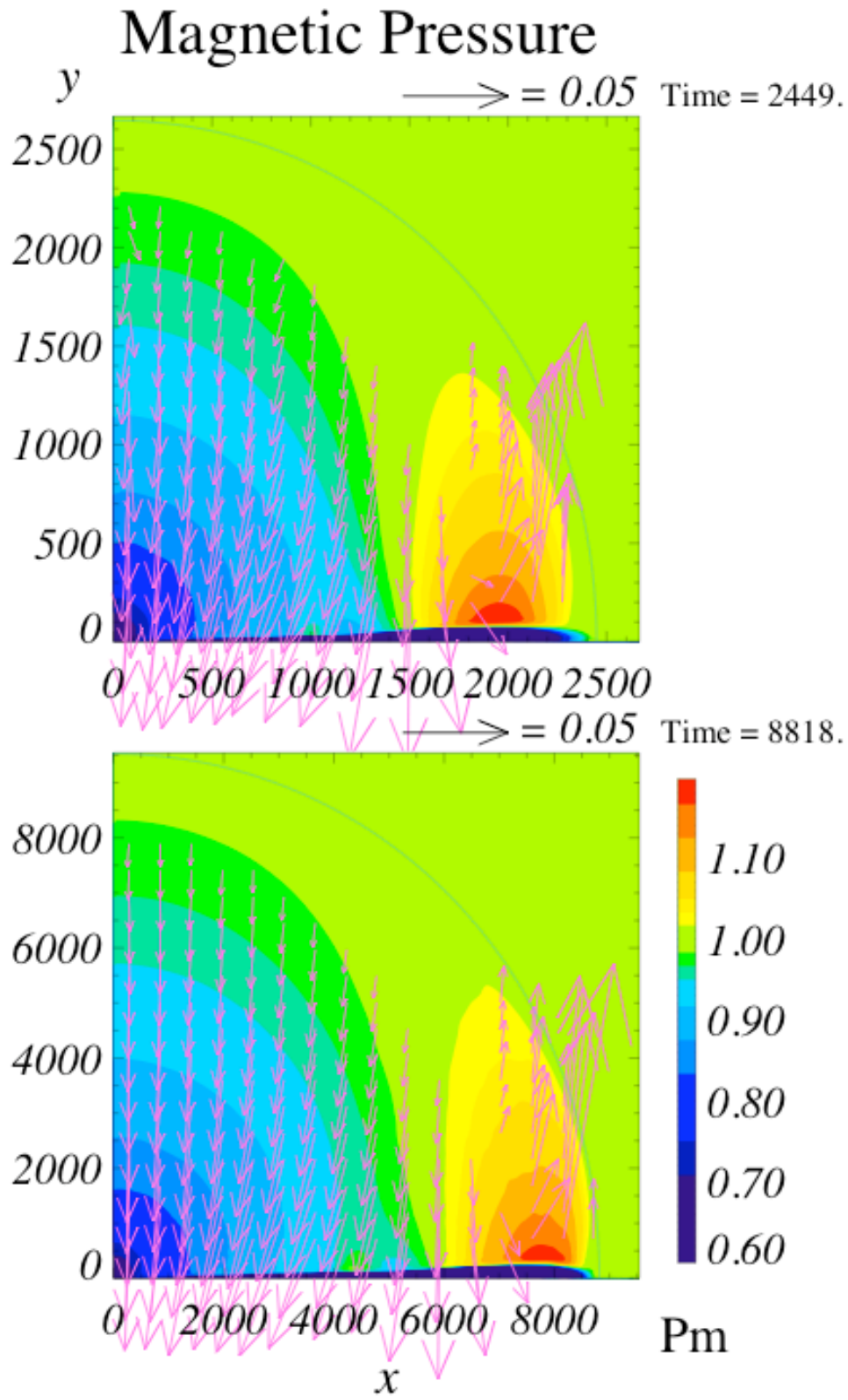
$P_0 \sim 0.6$

$B_0 \sim 8.7$

$V_{A0} \sim 2.4$

$\eta = 0.1$

§§Simulation Result



Self-Similarly Expanding !

with Fast-mode Rarefaction Wave Front

§Analytical Approach

§§Inflow Region

Zoom-out coordinate

$$\vec{r} \equiv (V_A t)\vec{r'}$$
$$\vec{v} = V_A \vec{v'} + \vec{r'}$$
$$\rho = \rho_0 \rho'(\vec{r'})$$
$$\vec{B} = V_A \sqrt{\mu_0 \rho_0}\vec{B'}(\vec{r'})$$
$$P = \beta/2 \cdot \rho_0 {V_A}^2 P'(\vec{r'})$$
$$\text{where } \beta \equiv (C_s/V_A)^2$$

Linear perturbation method

Equilibrium (0th)+Deviation (1st) by reconnection

Grad-Shafranov Eq.

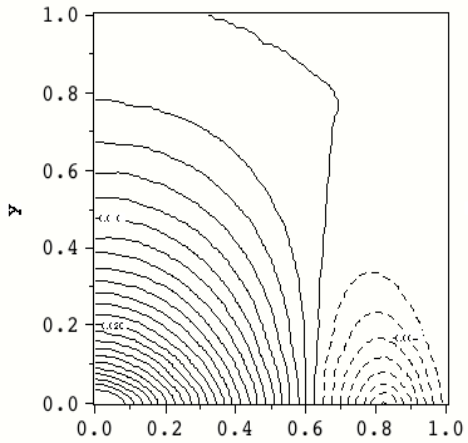
$$(1-x^2)\frac{\partial^2 A'_1}{\partial x^2} - 2xy\frac{\partial^2 A'_1}{\partial x \partial y} + (1-y^2)\frac{\partial^2 A'_1}{\partial y^2} = 0$$

$$\vec{B'_1} = \vec{\nabla'} \times A'_1 \vec{k}$$
$$v'_{1x} = 0$$
$$v'_{1y} = x\frac{\partial A'_1}{\partial x} + y\frac{\partial A'_1}{\partial y} - A'_1$$
$$\rho'_1 = \frac{\partial A'_1}{\partial y}$$
$$P'_1 = \gamma\frac{\partial A'_1}{\partial y}$$

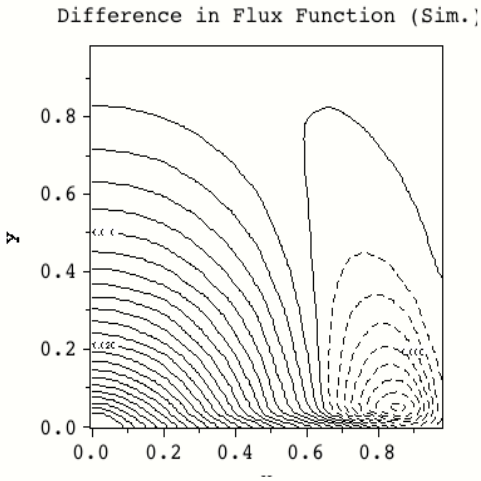
§ § Solution for Inflow Region

Flux Function

Analytic

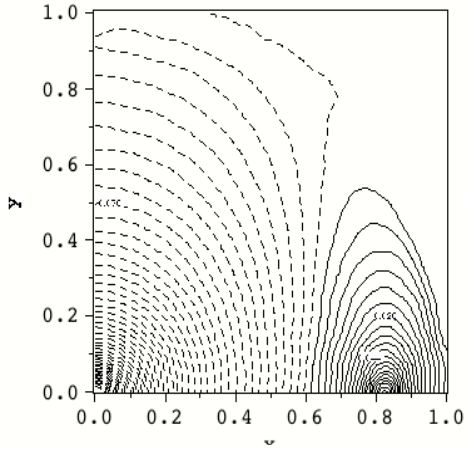


Simulation

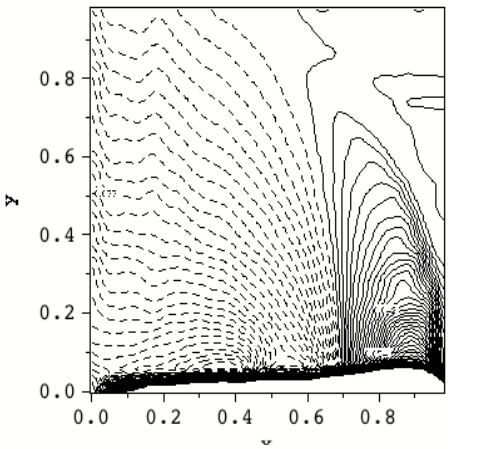


Density

Analytic

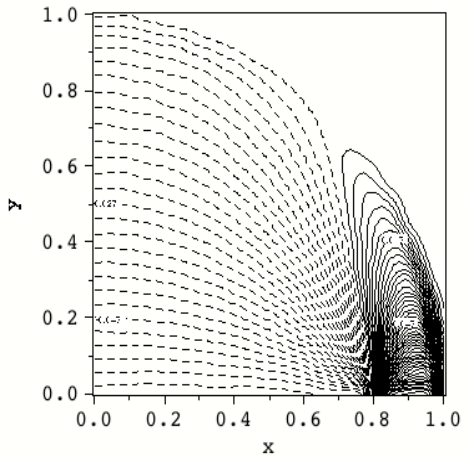


Simulation

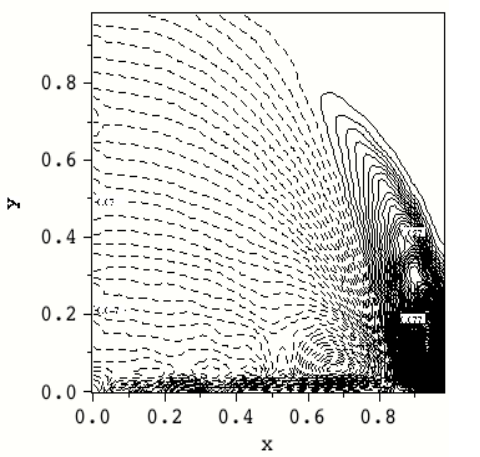


Velocity (y-comp.)

Analytic



Simulation



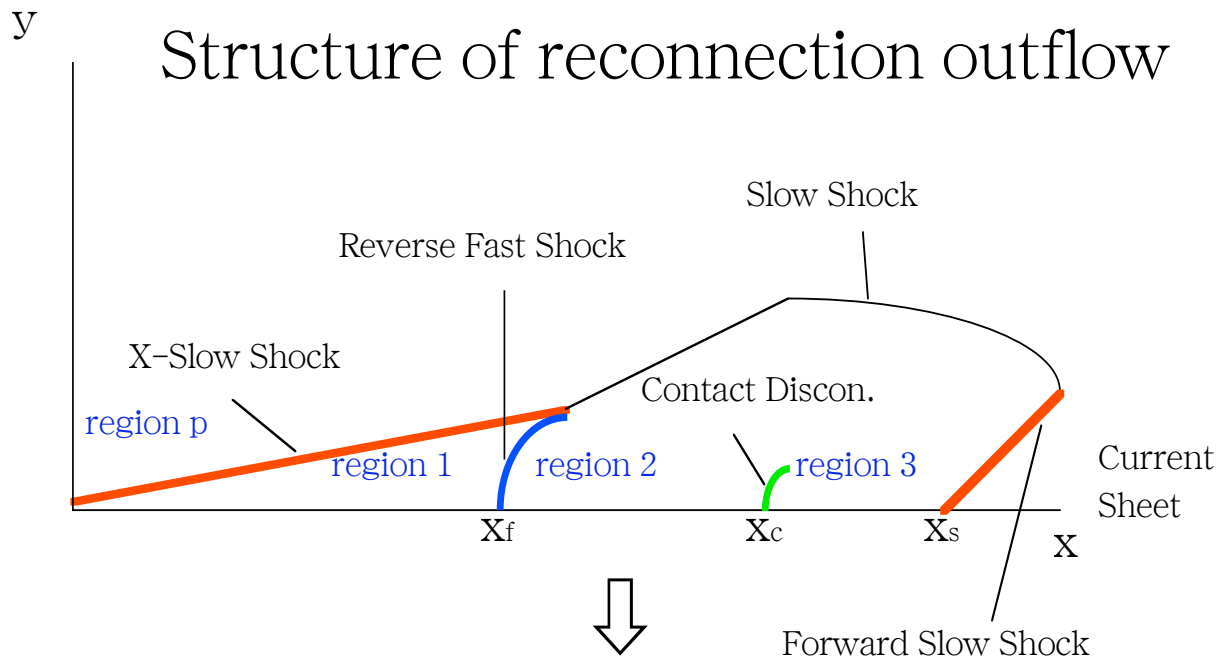
Fairly Consistent!

§§Reconnection Outflow

Quasi-1D structure divided by

several discontinuities

Reconnection jet collides with current sheet plasma



Shock tube approximation

22 eqs. (junction conditions)

for

22 unknowns

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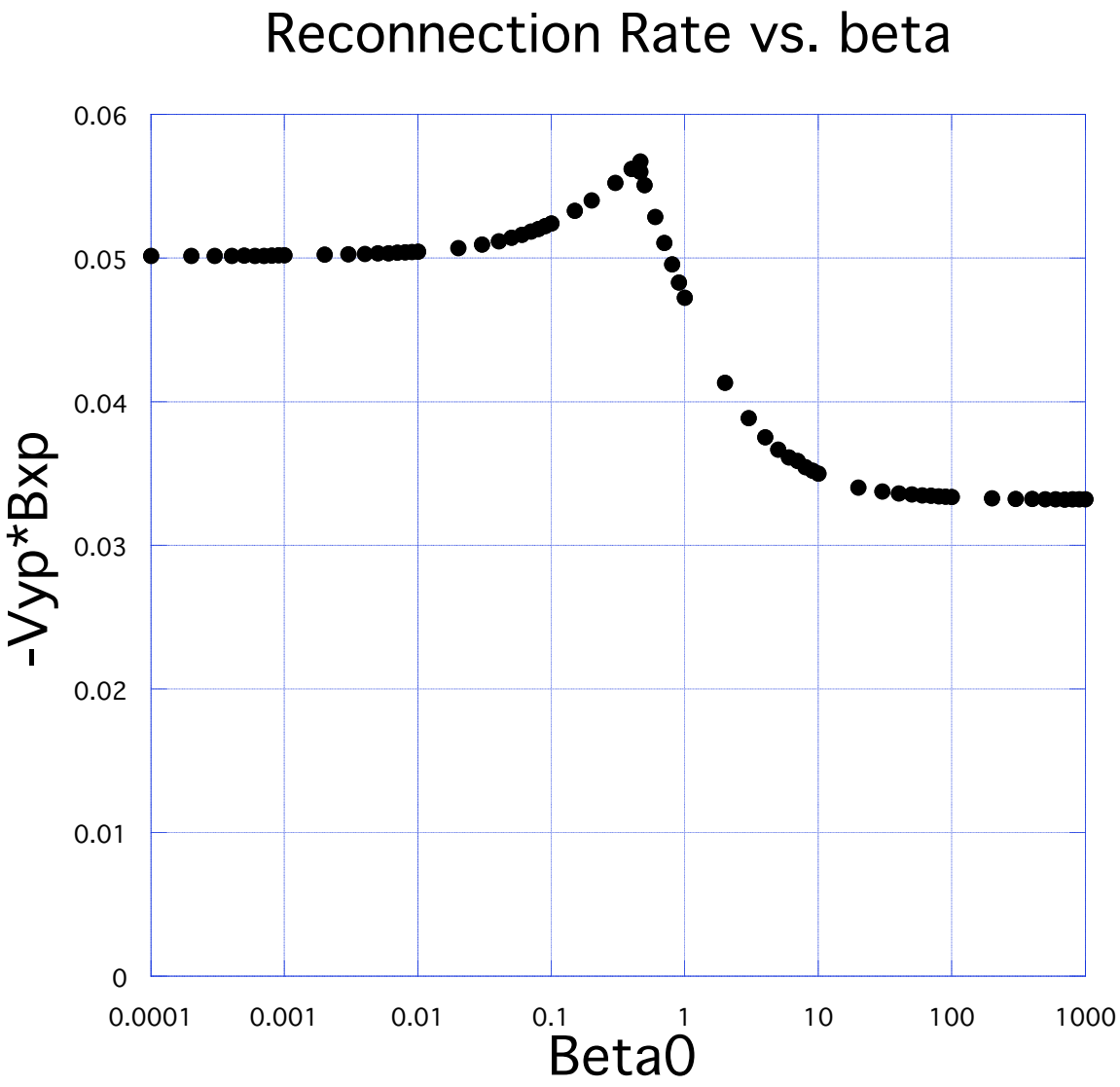
Quantities in outflow

spontaneously determined!!

§§Reconnection Rate



Rec. rate R ～ 0.05 for low β

(almost const. indep. of β)

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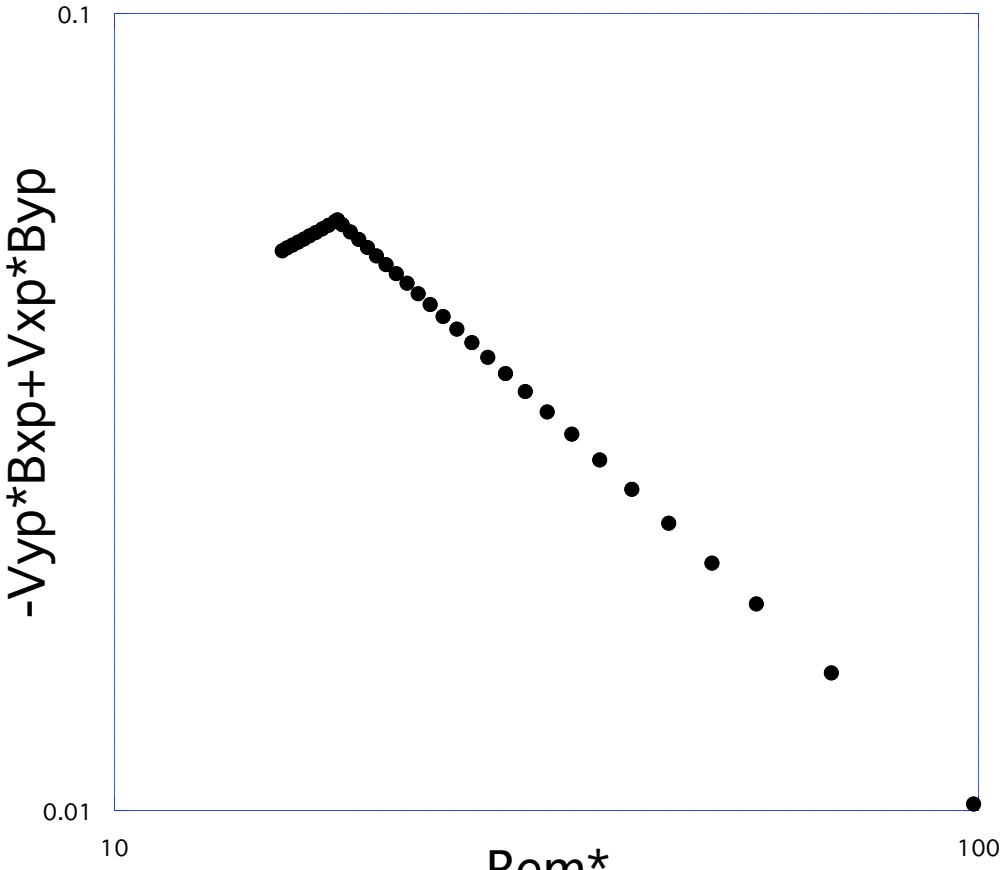
Spontaneous inhalation of inflow

(induced by fast-mode rarefaction)

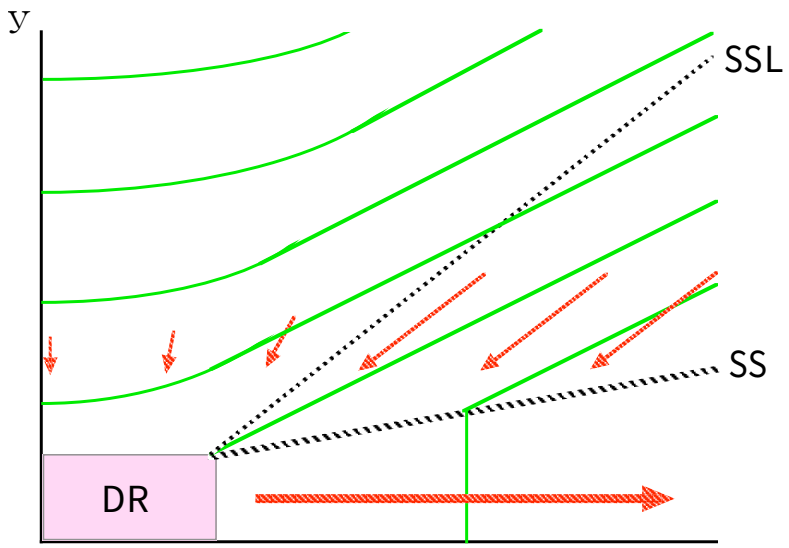
Reconnection Rate vs. Mag. Reynolds Num.



$$(Rem^* \equiv V_{A0}/V_{dif}^*)$$

converging inflow: |Vxp| ↑ as Rem* ↑

⇨Vp, Bp → parallel at inflow region



$$R \equiv Vp \times Bp \propto Rem^{*\wedge(-1)}$$

§Observational Inspection

We can inspect Self-Similar Model

by ***Solar-B***

"Dimming" around reconnection point

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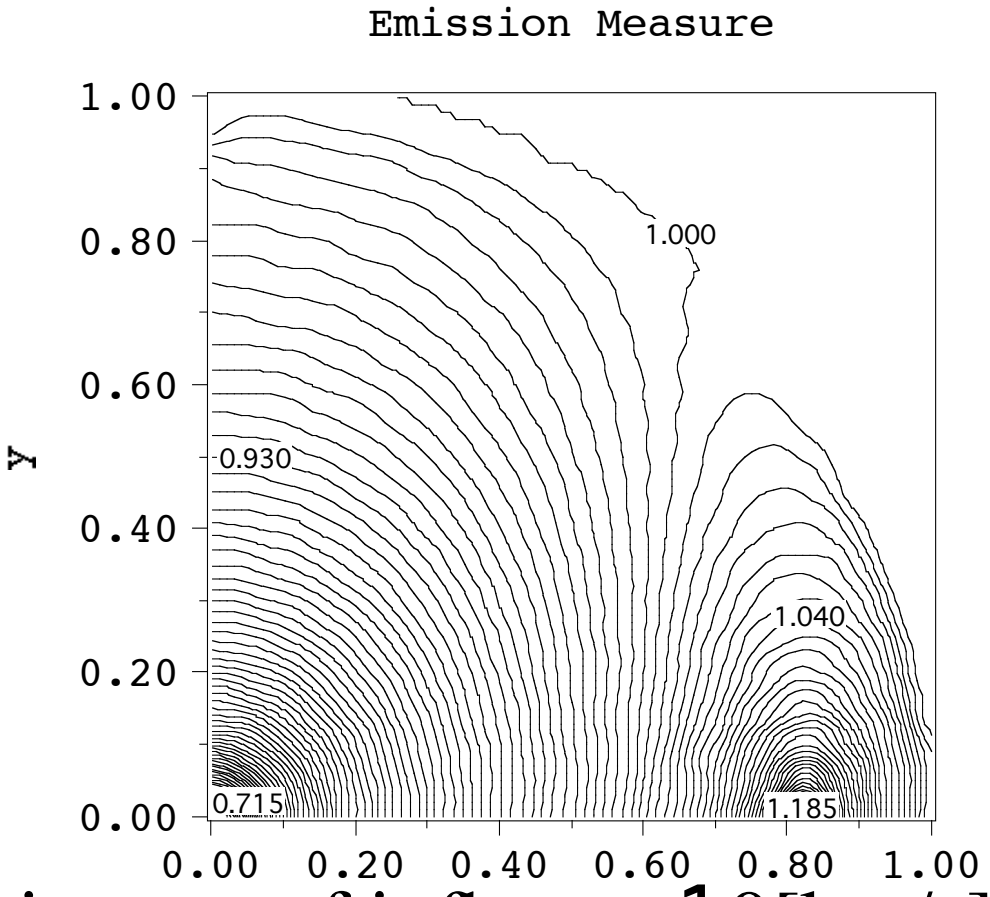
Rarefied region by FRW



Existence of inflow ~ 10[km/s]

Expanding in V_{A0} ~ 1000[km/s]

Duration ~ 100[s]

§Summary

Spontaneous Evolution of

Fast Magnetic Reconnection in Free Space

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Self-Similar Solution

(verified by numerical simulation/analytical study)

A new model of Magnetic Reconnection

Self-Similar Evolution of Fast Reconnection

Properties

- Expanding with propagation of FRW
- Petschek-like structure in central region
  (Fast-mode rarefaction dominated)
- Reconnection rate R ～ 0.05

(for small Rem*<20, insensitive to β)

⇦ spontaneous inhalation of inflow

- Reconnection rate R ∝Rem*^(-1)

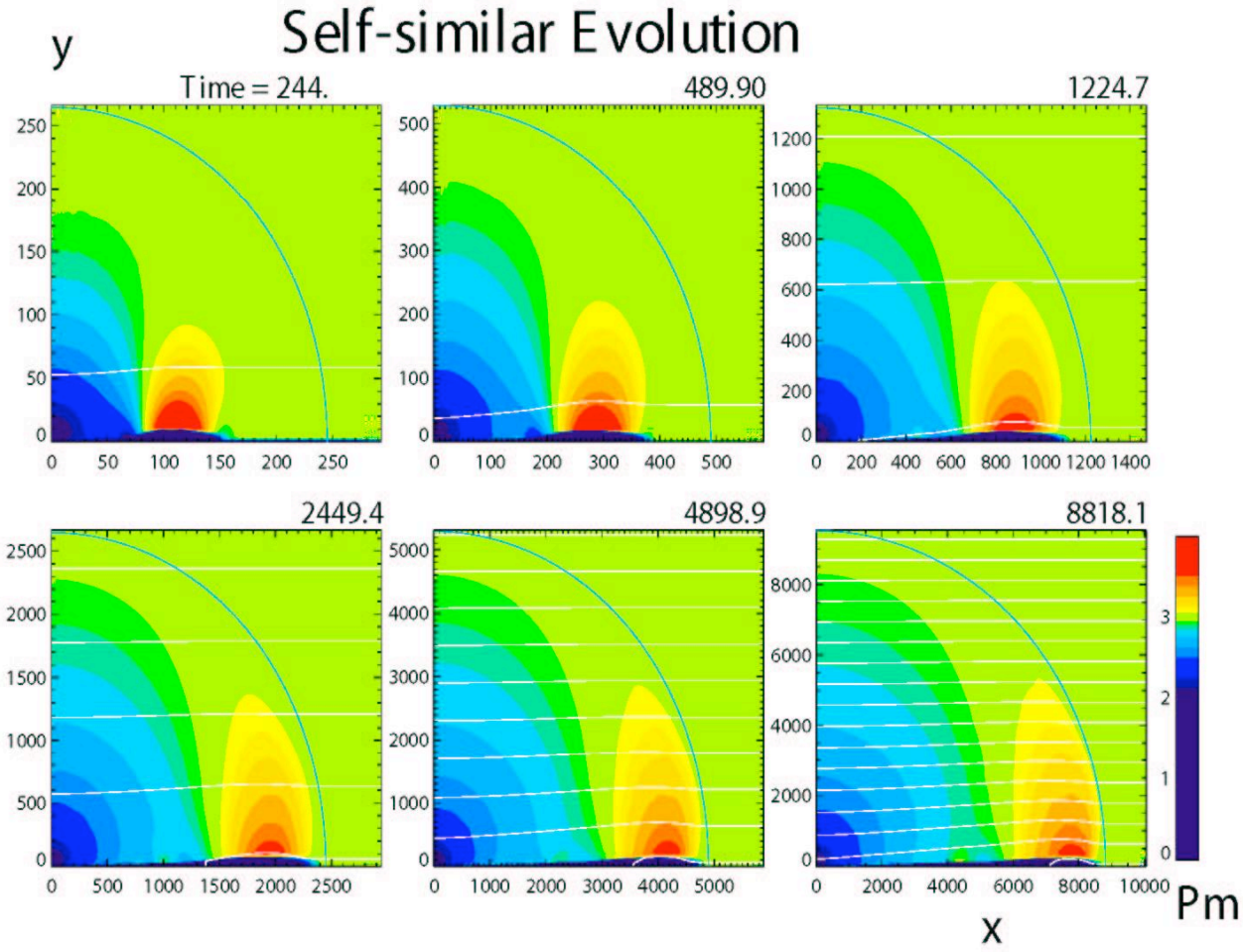
(for large Rem*≫20, insensitive to β)

References

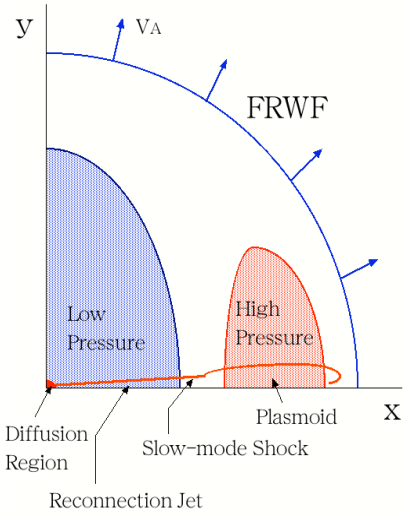
Nitta, Tanuma, Shibata, Maezawa ApJ, 550, 1119 (2001)
Nitta, Tanuma, Maezawa ApJ, 580, 538 (2002)
Nitta ApJ, 610, 1117 (2004)

§§Simulation Result

Evolution in Zoom-Out Coordinate



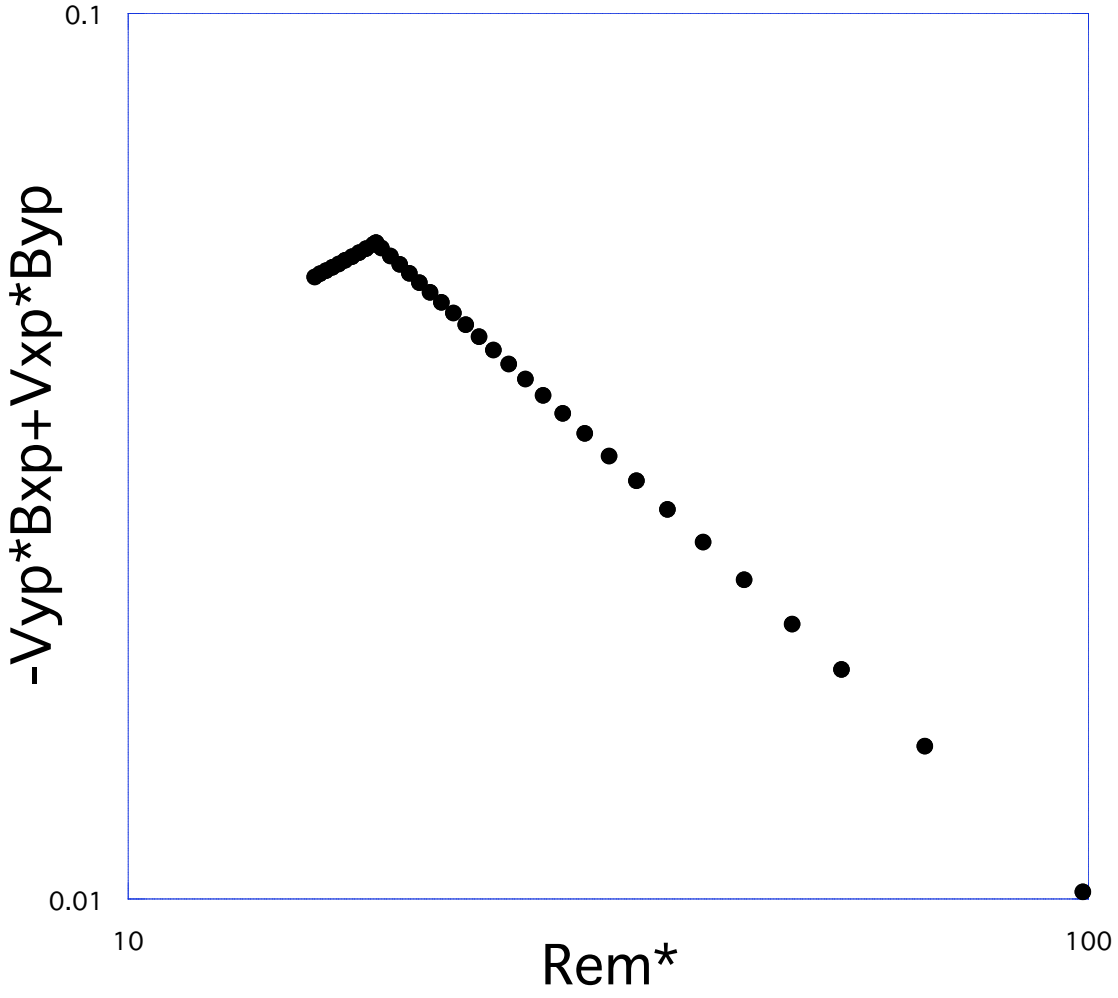
Features of reconnection system



Self-Similarly Expanding !

with propagation of Fast-mode Wave Front

Reconnection Rate vs. Mag. Reynolds Num.



$R \equiv Vp \times Bp \propto Rem^{*\wedge(-1)}$ ($Rem^{*} \equiv V_{A0}/V_{dif}^{*}$)

⇧

converging inflow: |Vxp| ↑ as Rem* ↑

⇨Vp, Bp → parallel at inflow region

⇨ $R \equiv Vp \times Bp$ ↓

A new model of magnetic reconnection: Self-similar evolving model

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