Title: Physics of Magnetic Reconnection

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Abstract: Understanding magnetic reconnection is one of the major challenges of plasma physics. It plays an essential role in a wide range of physical systems such as stellar flares, accretion disks, active galactic nuclei, astrophysical dynamos and closer to home, intense magnetic energy releases in the Earth's magnetosphere. It is a phenomena which can be created in the laboratory.

Magnetic reconnection occurs when oppositely directed components of field lines are broken and re-connected resulting in destruction of magnetic flux and topological rearrangement of magnetic field lines on very small scales. This can induce the release of magnetic energy on large scales resulting in high speed flows, heating and energetic particle production.

There is a strong connection between formation of singular structures in flows and magnetic reconnection which I will discuss and tie this into some of the laboratory and natural physical systems under recent study.

In addition to giving a contemporary overview on this subject I will discuss some open questions.

Colloqium – Perimeter Institute, Waterloo, Ontario, Jan. 24, 2007

Physics of Magnetic Reconnection

Richard D. Sydora

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Collaborators: K. Fujimoto, Univ. of Alberta
R. Grauer, Ruhr-Universitaet, Bochum, Germany

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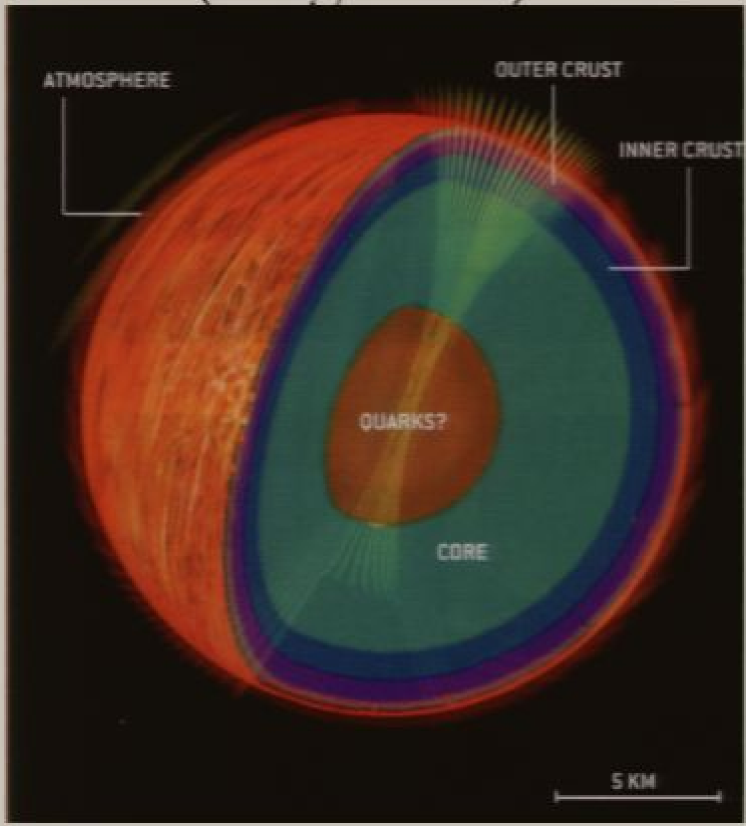
Outline

- Magnetic Fields and Plasmas
- Magnetic Reconnection(MR) – Physical Processes
- Magnetohydrodynamic(MHD) Model of MR
- 2-Fluid MHD Effects
- Kinetic Magnetic Reconnection (KMR) – Spatial Structure and Temporal Evolution
- Laboratory Connections
- Open Questions and Summary

Magnetic Fields in the Universe

(Magnetars)

$B_{surface} \sim 10^{14}\text{-}10^{15}$Gauss



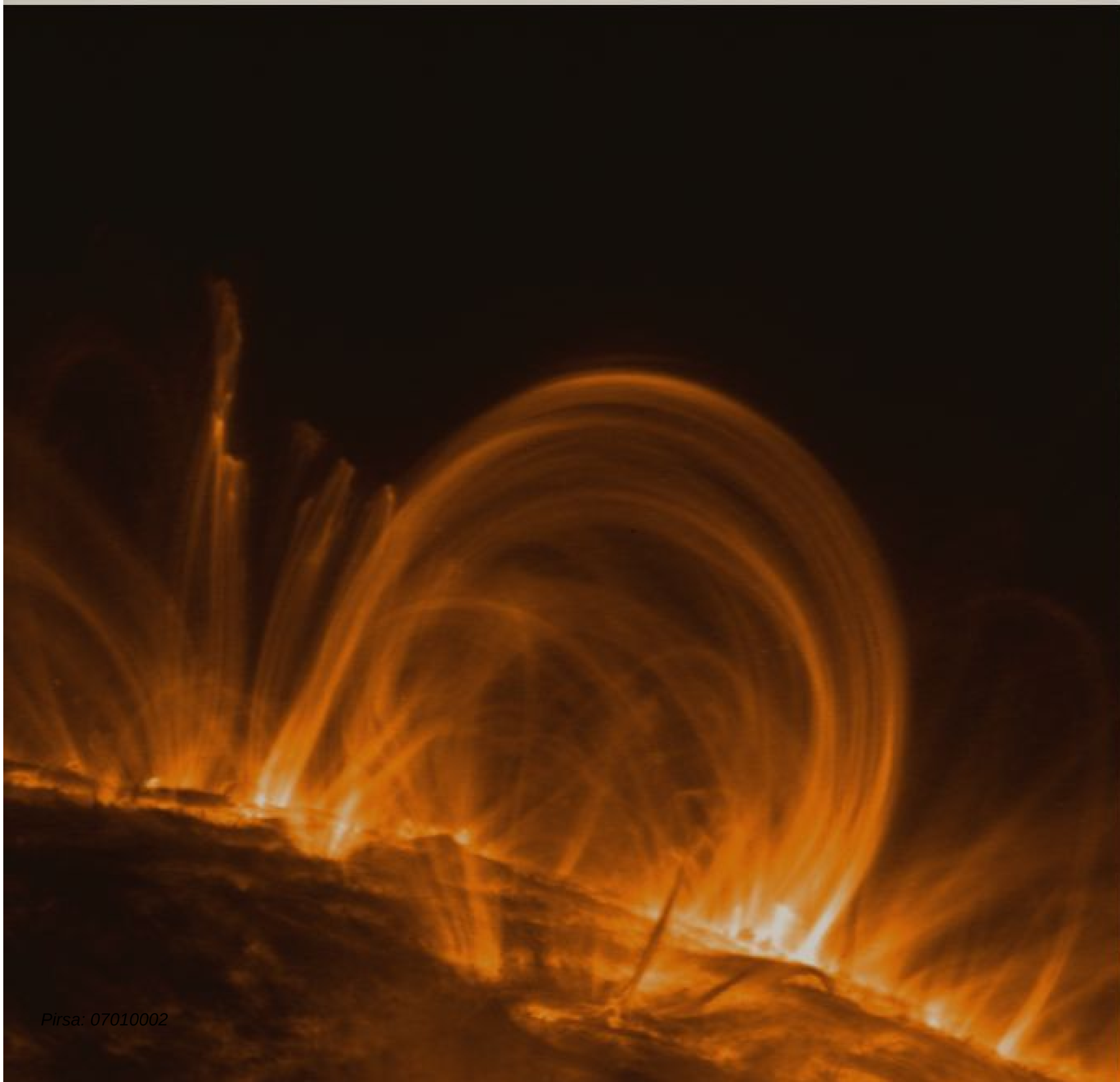
(R. Duncan, C. Thompson, C. Kouveliotou, 2003)

(Galaxy Clusters)

$B_{Inter} < 10^{-5}$Gauss

(1Gauss $= 10^{-4}$ Tesla)

Plasmas and Magnetic Fields



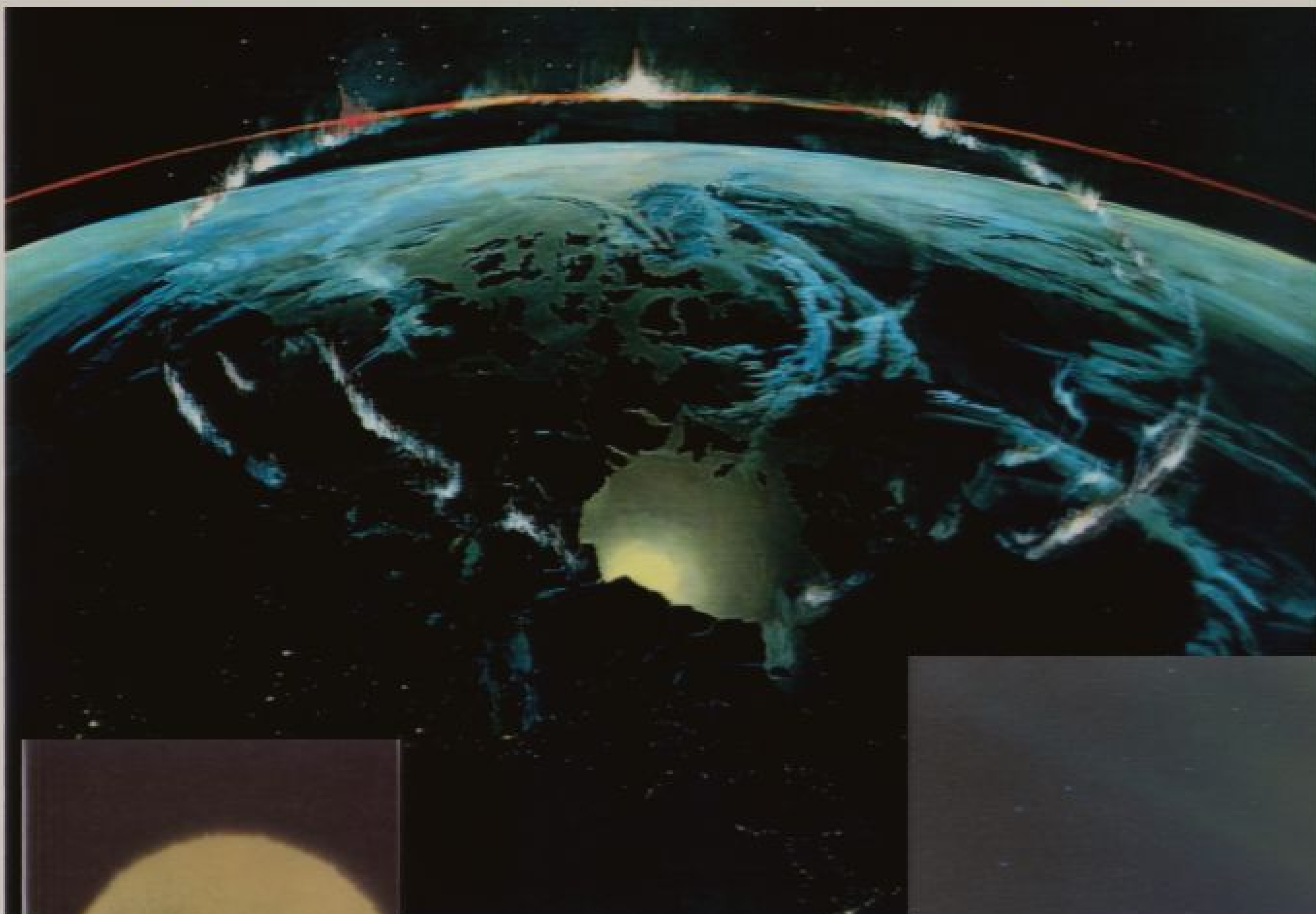
$B \sim 200G$

$T_e \sim 2.5x10^6K$

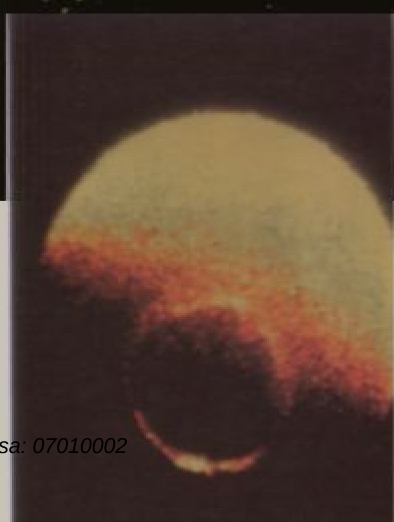
$N \sim 10^{10}cm^{-3}$

(TRACE Satellite Observations)

Plasmas and Magnetic Fields



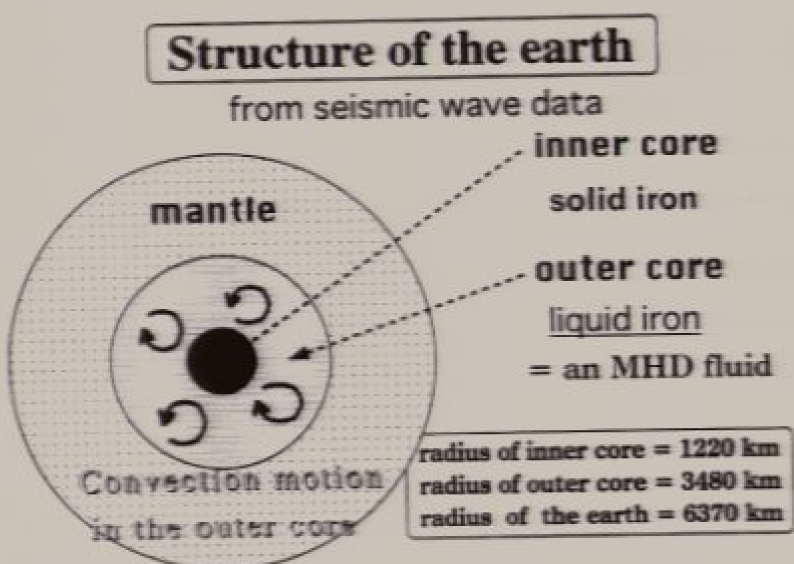
Aurora-Borealis

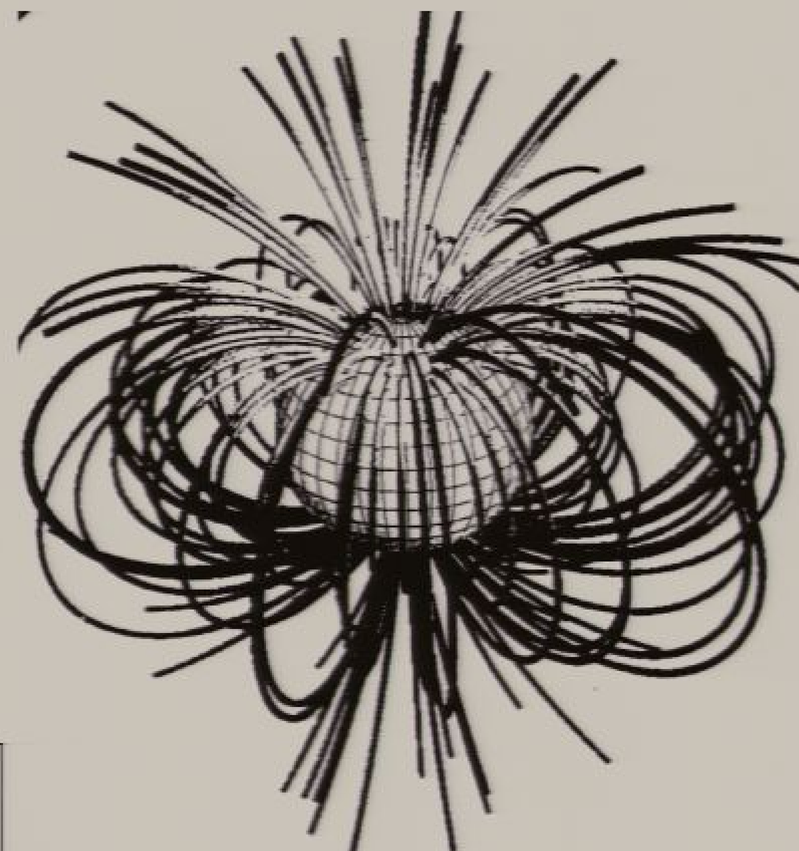


(DE-1 Satellite, 1989)

Magnetic Field Generation

Dynamo Mechanism





$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times (\vec{V} \times \vec{B})$$

Magnetic Field Generation

- Kinematic Dynamo – $\vec{V}$ is specified

  -flow fields may or may not be chaotic
  -chaotic flows can generate fast dynamos
  (Childress,'79, Arnol'd et al,'81, Galloway&Frisch,'86)

- Self-consistent Dynamo – $\vec{V}$ evolves from momentum eq.

  -can lead to saturation of magnetic field evolution which
  may involve magnetic reconnection

Magnetic Reconnection: Energy Conversion

Swirling Plasma Motion —**Dynamo**→ Magnetic Field Amplification

Plasma Flow, Heating and Particle Acceleration ←**Reconnection**— Magnetic Field Energy

Magnetic Reconnection: Definition

Magnetic reconnection is the process by which oppositely-directed components of field lines are broken and cross-connected, resulting in the destruction of magnetic flux and the topological rearrangement of magnetic fields.

These changes which occur on very small scales can cause a global readjustment of the field releasing magnetic energy on very large scales resulting in high speed flows, thermal heating and energetic particles.

Effects of Magnetic Reconnection

3 main characteristics of Magnetic Reconnection:

Magnetic topology changes (B)

Conversion of magnetic energy to heat and flows (V)

Acceleration of particles (E)

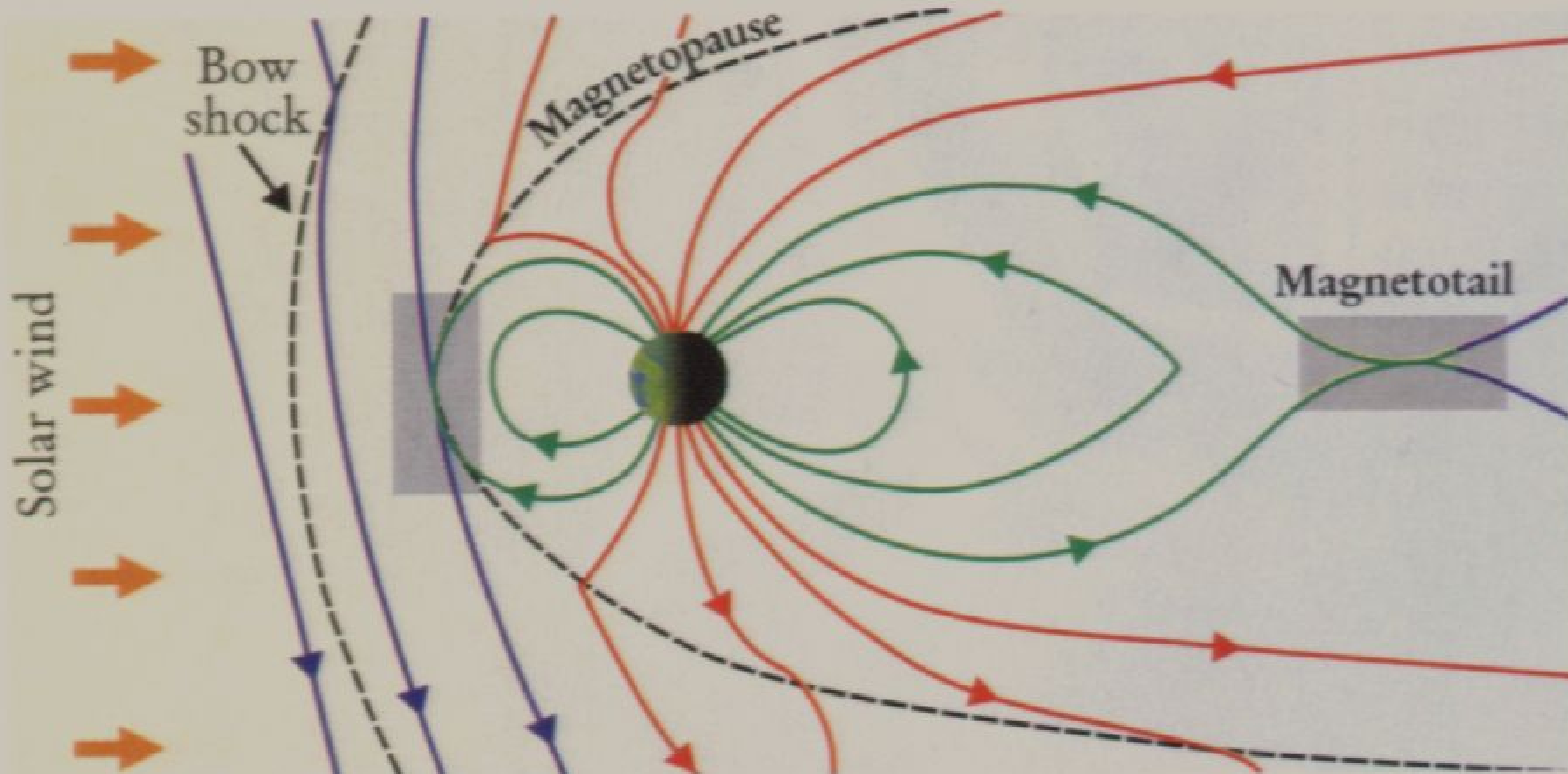
Magnetic Reconnection: Requirements

proper magnetic topology (oppositely-directed field components)

localization (dissipation and currents)

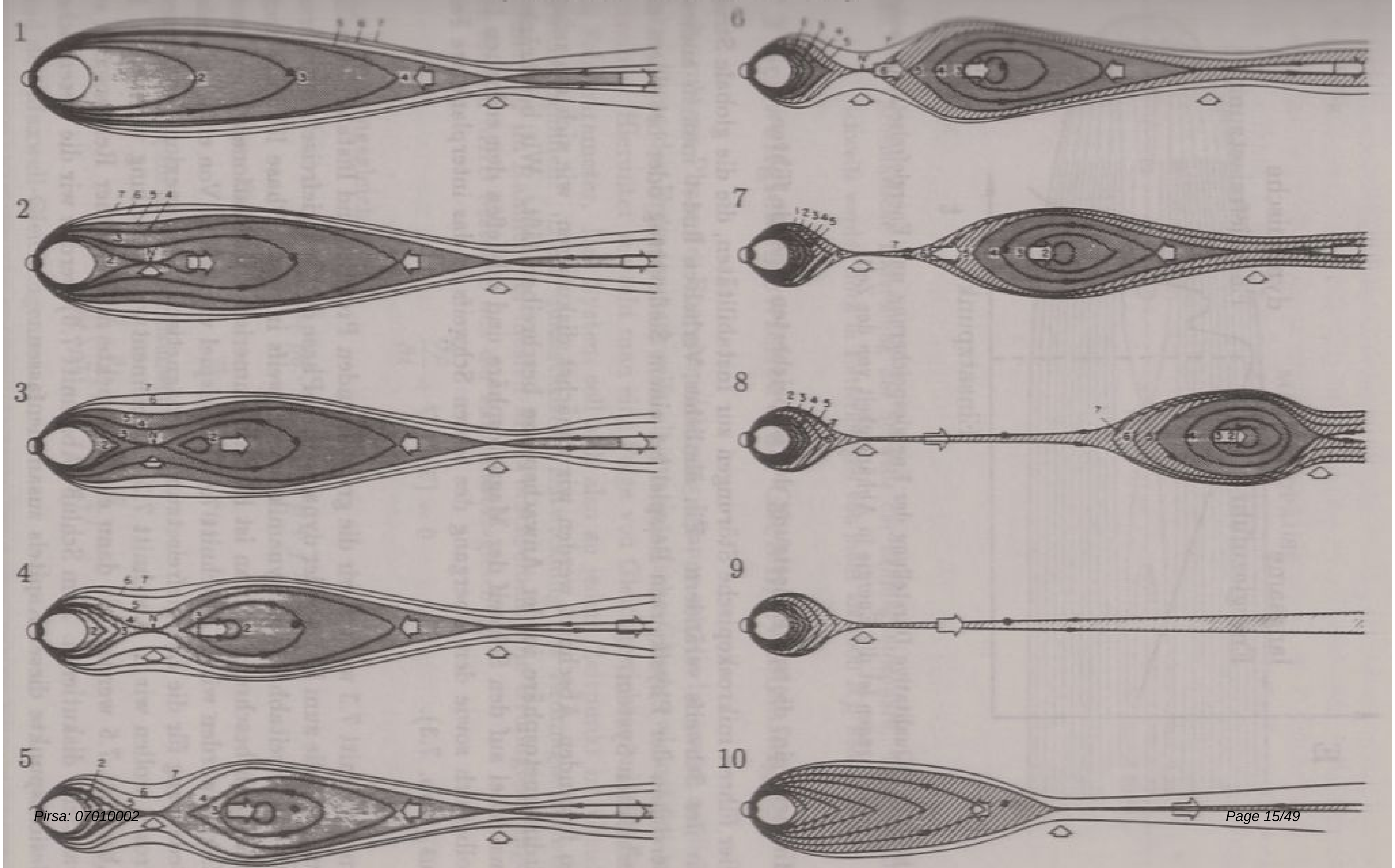
symmetry-breaking perturbation

Magnetic Reconnection in the Earth's Magnetosphere

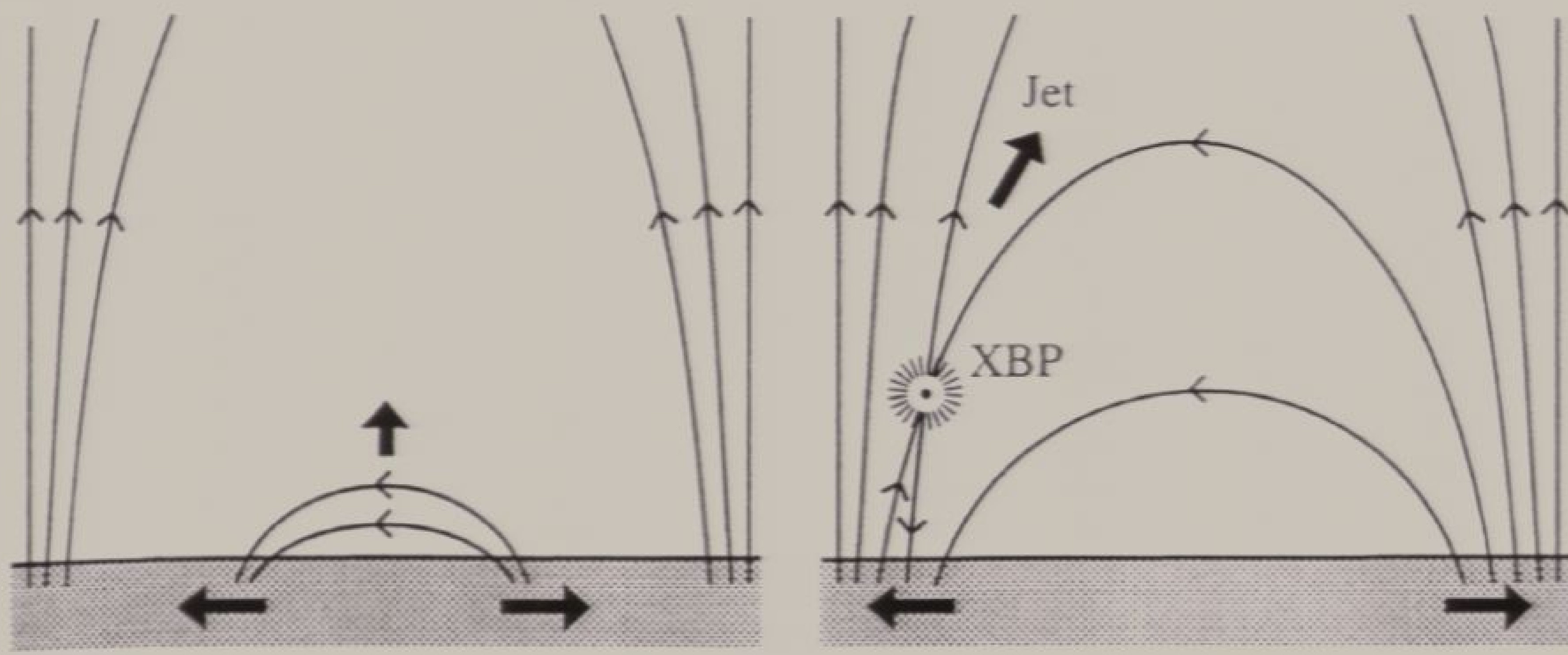


Magnetic Reconnection - Plasmoids

(Hones et al., 1979)

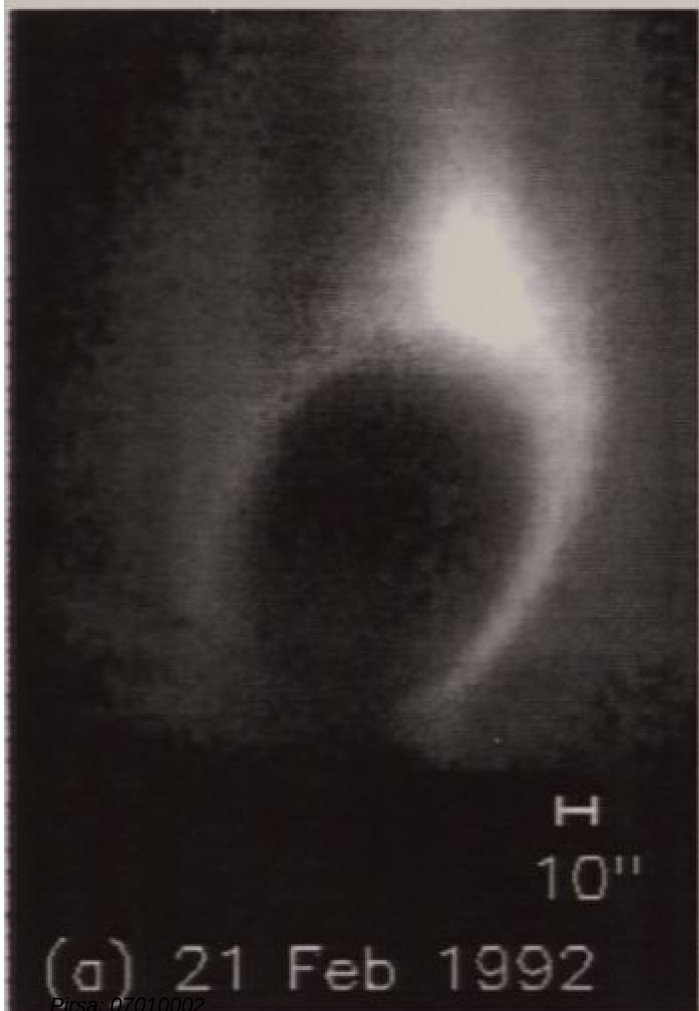


Magnetic Reconnection at the Solar Surface

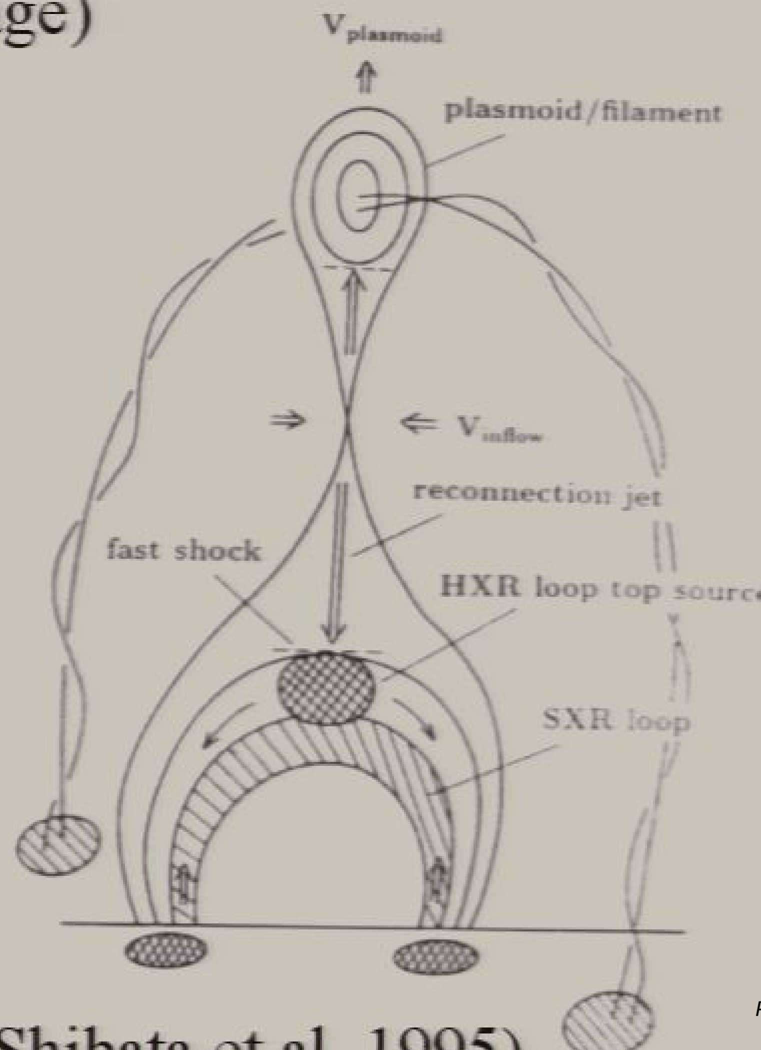


(Converging Flux Model, E.Priest et al., 1994)

Magnetic Reconnection and Solar Flares

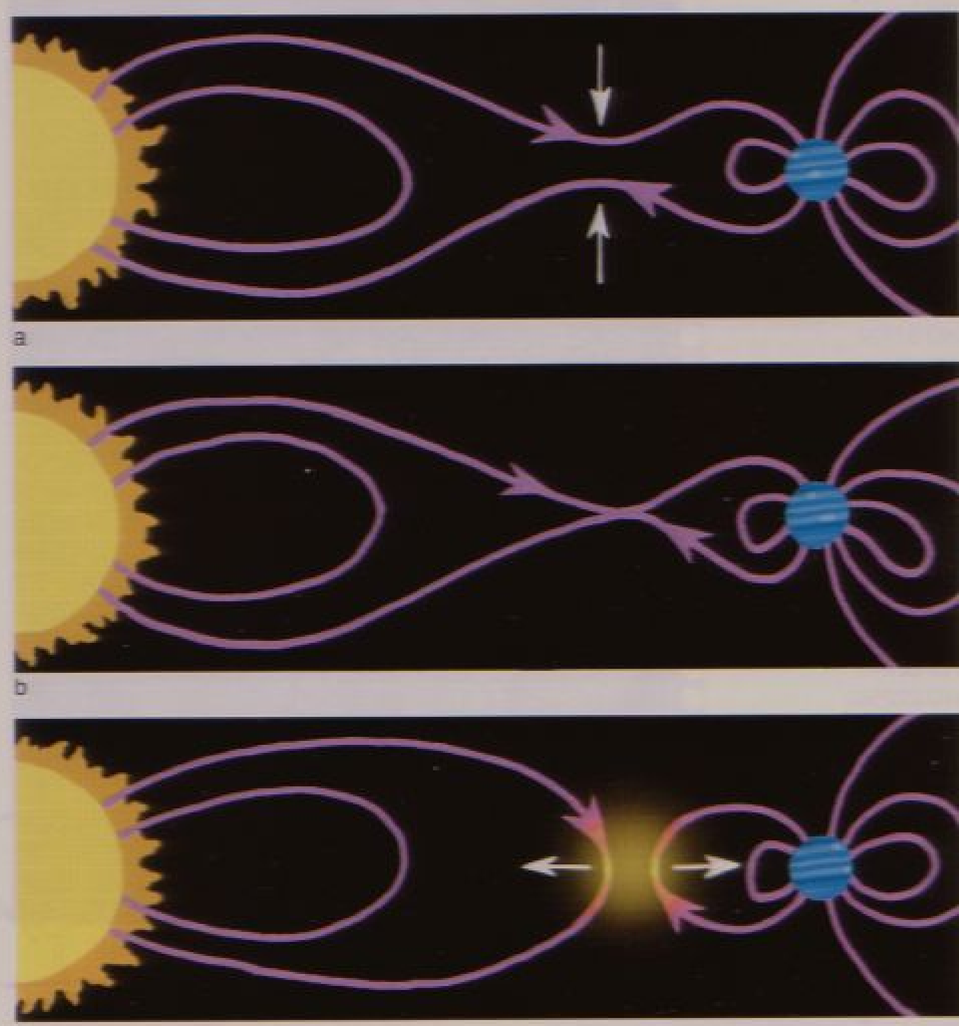


(X-Ray Image)
~1 keV



(Shibata et al, 1995)

Magnetic Reconnection in Other Solar Systems



(Rubenstein, 2000)

Magnetohydrodynamics (MHD)

Ideal MHD

magnetic field ‘frozen’ into the plasma which is assumed perfectly conducting

ideal Ohm’s law → $\vec{E} = -\vec{V} \times \vec{B}$

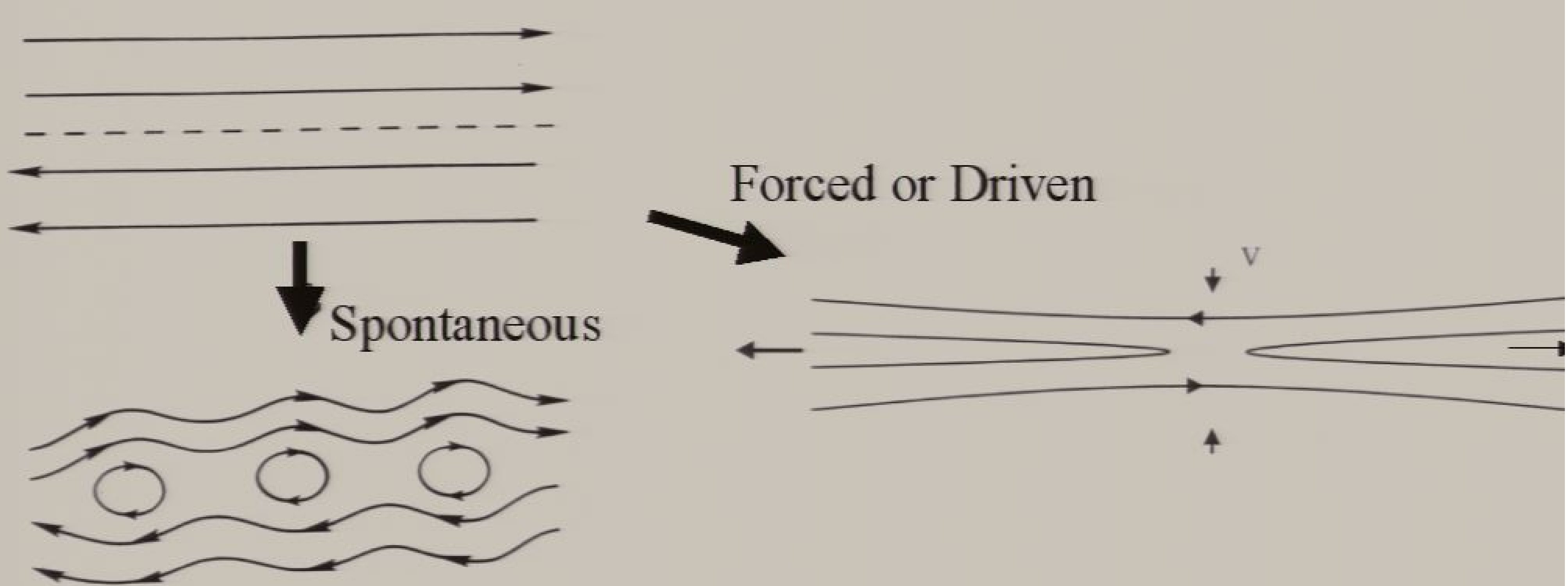
Non-ideal MHD

accounts for dissipation effects such as collisions, etc.

$$\vec{E} = -\vec{V} \times \vec{B} + \eta \vec{J} \quad + \text{other terms}$$

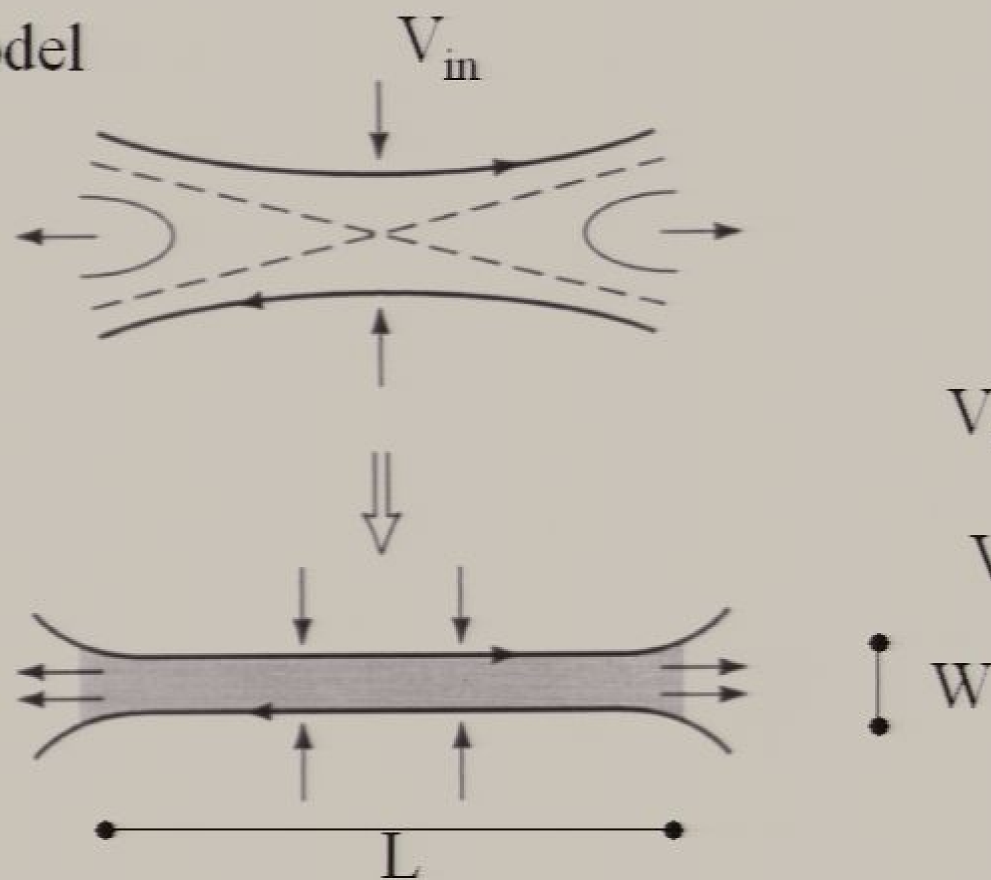
where $\eta = \frac{m_e \nu_{ei}}{e^2 n_e}$

Magnetic Reconnection: Spatial Structure



Reconnection Geometry I

Sweet-Parker Model
(1958, 1963)



$V_{in} = (W/L)V_{out}$

$V_{in} \sim S^{-1/2}\, V_A$

$S = \tau_{diff}/\tau_A$

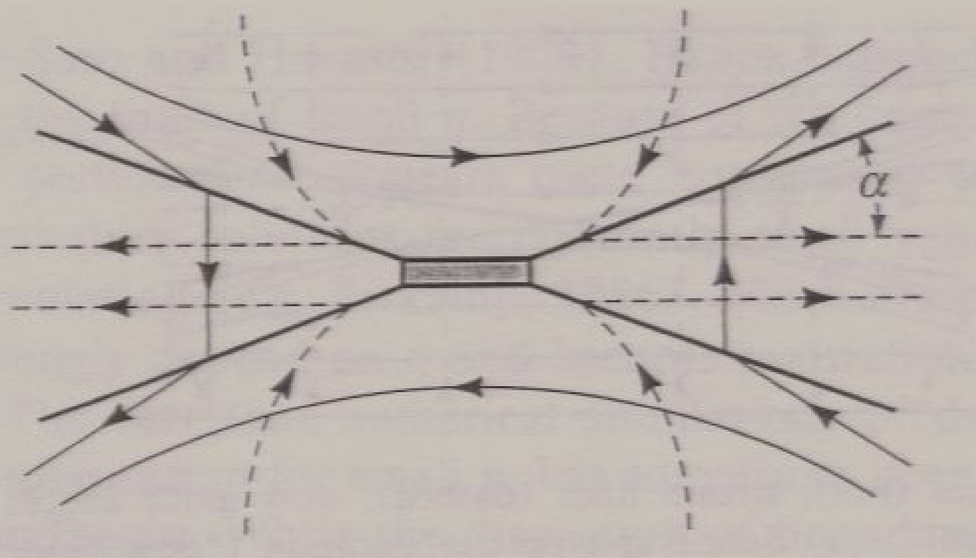
(Lundquist Number)

Reconnection Rate $\partial_t \psi = E = V_{in} B$

Typically $S \sim 10^8$ $V_A \sim 100\text{-}300$ km/s

Reconnection Geometry II

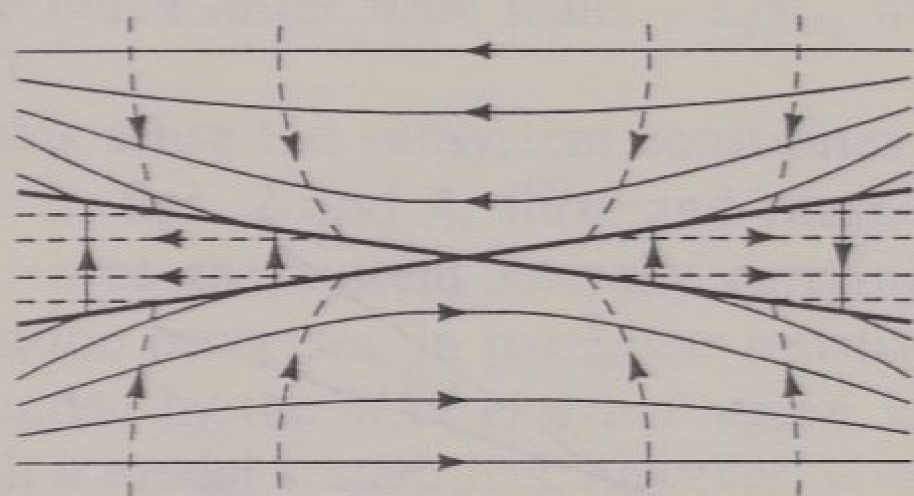
Petschek Model
(1964)



Features:

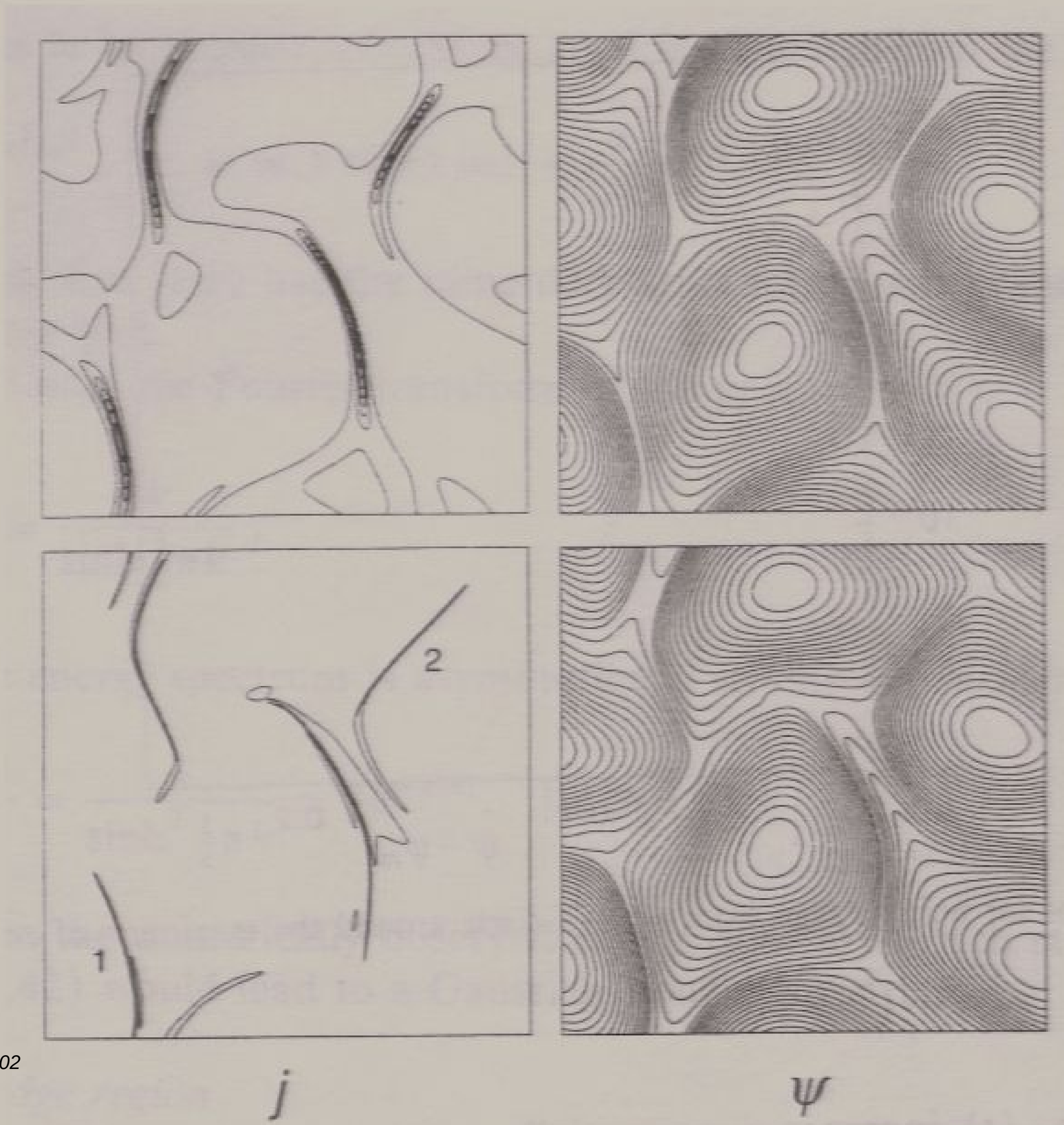
- **Much smaller diffusion region**
- **Shock structure**
- **Fast reconnection**

$$V_{in} \sim (\ln(S))^{-1} V_A$$



Current Sheet Formation

Initial magnetic flux:
$\Psi(x,y,t=0)=\cos(2x+2.3)+\cos(y+4.1)$



T=1.0

T=1.3

(2D MHD Simulations)
Biskmamp, 1993

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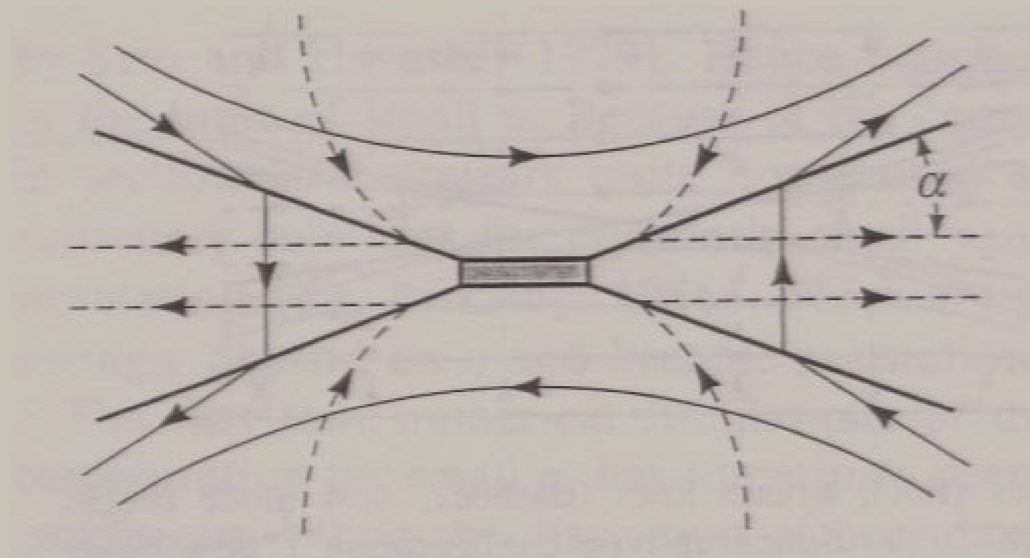

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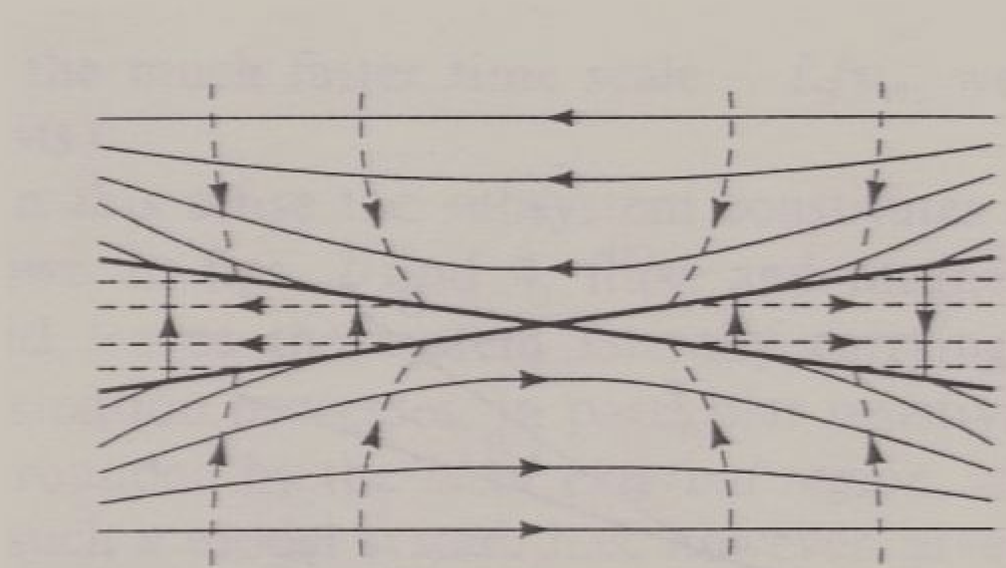

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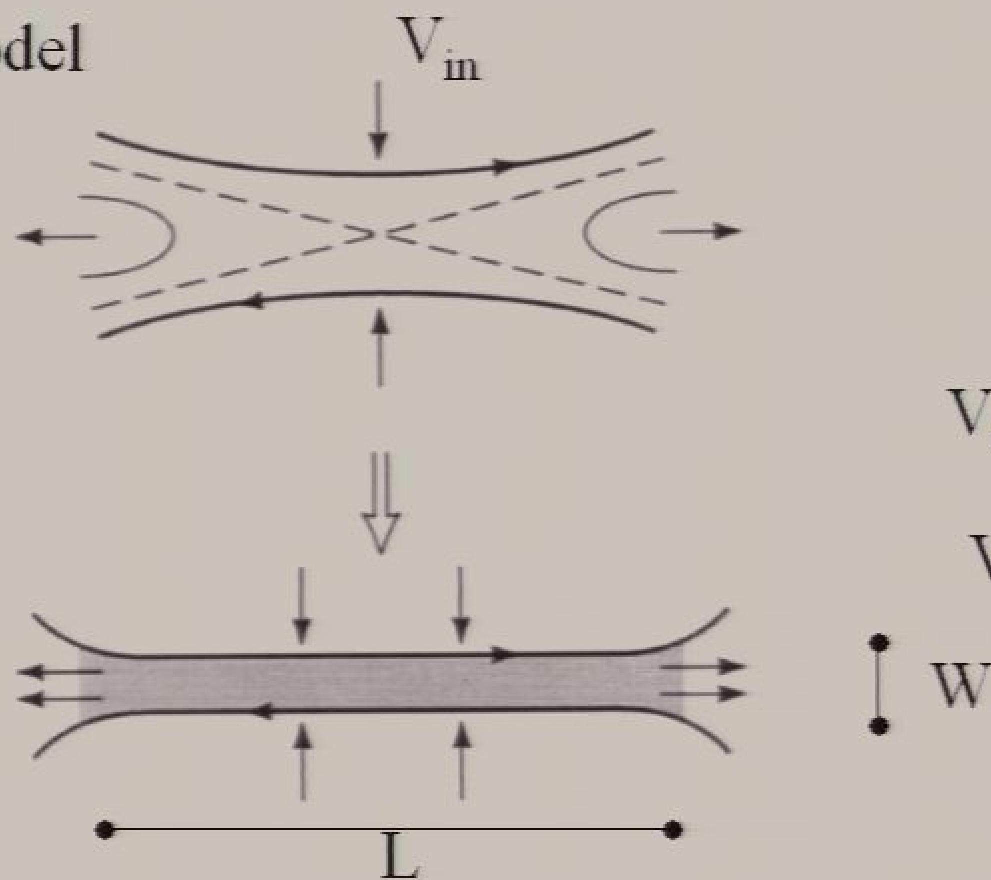

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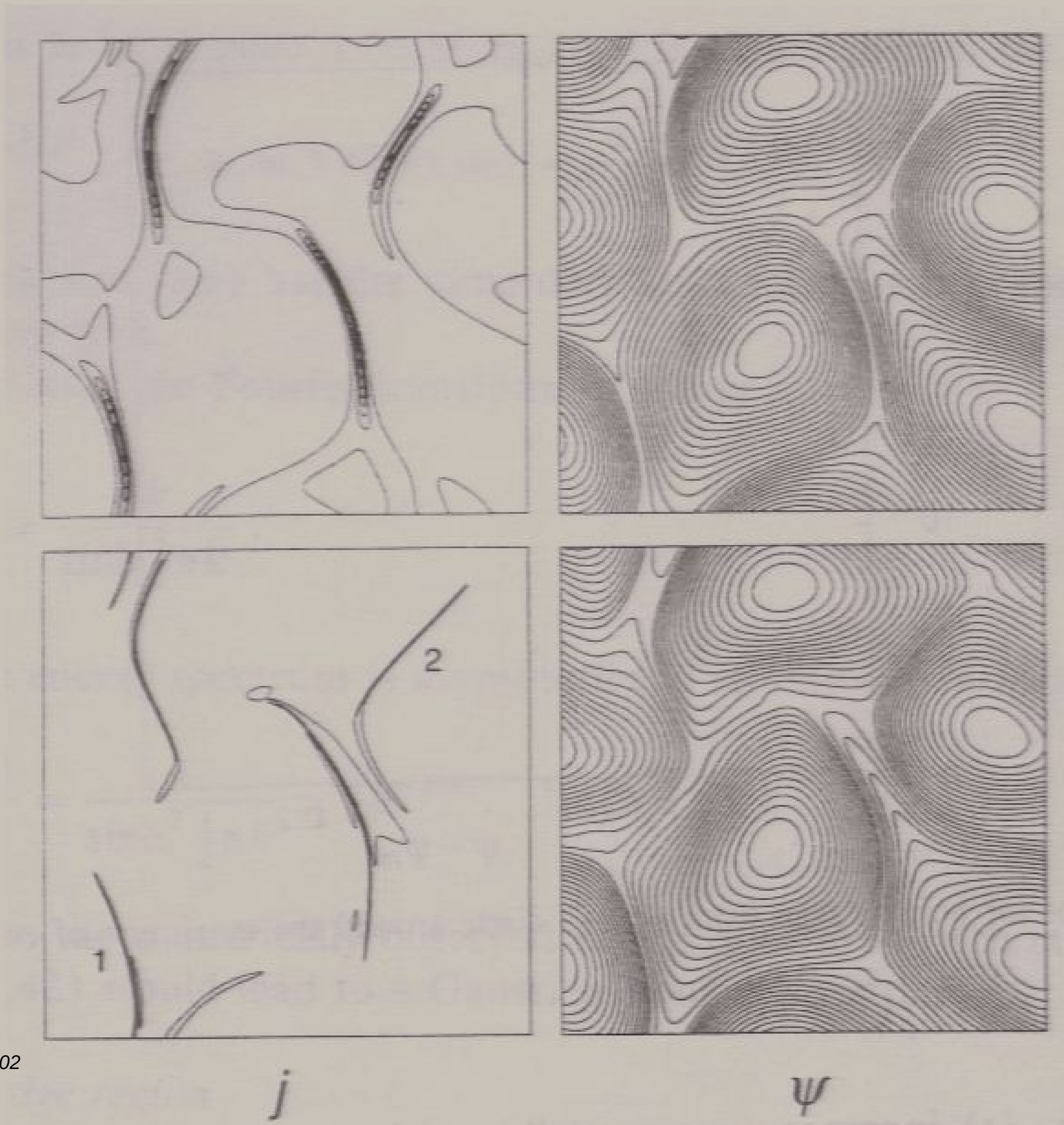

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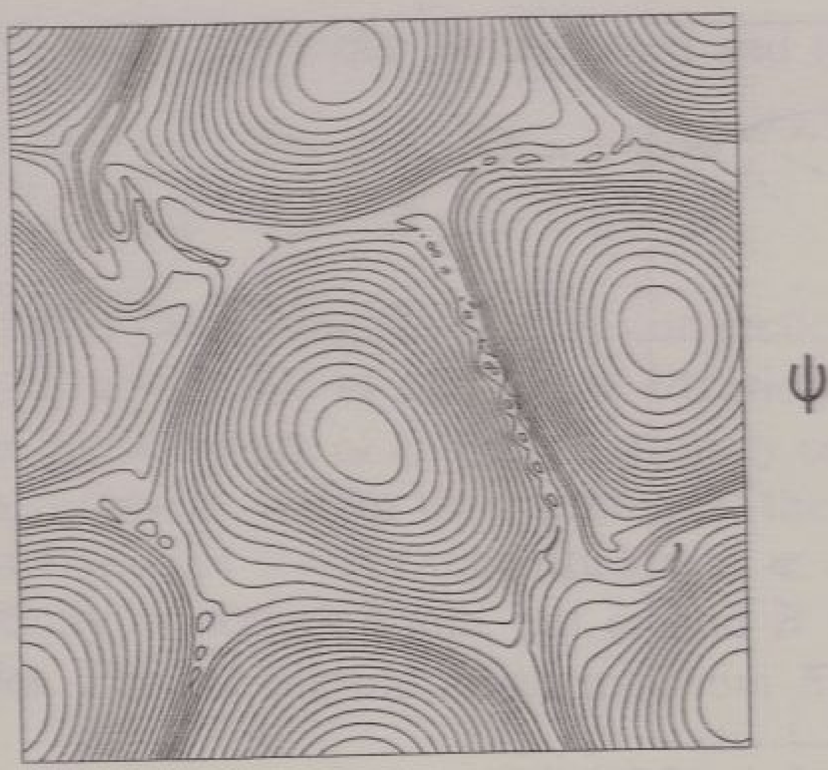
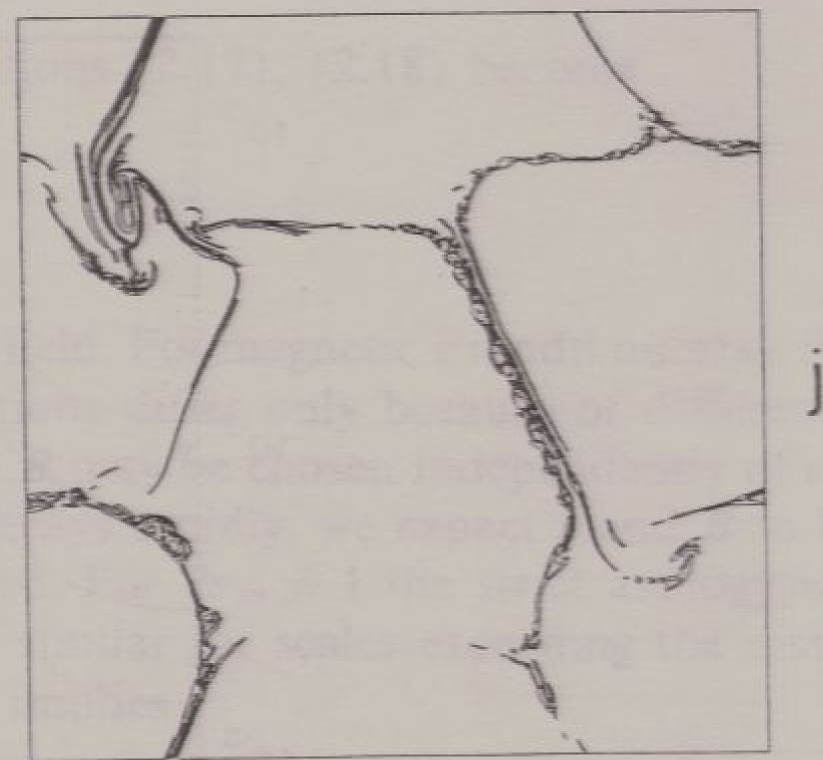
(2D MHD Simulations)
Biskmamp, 1993

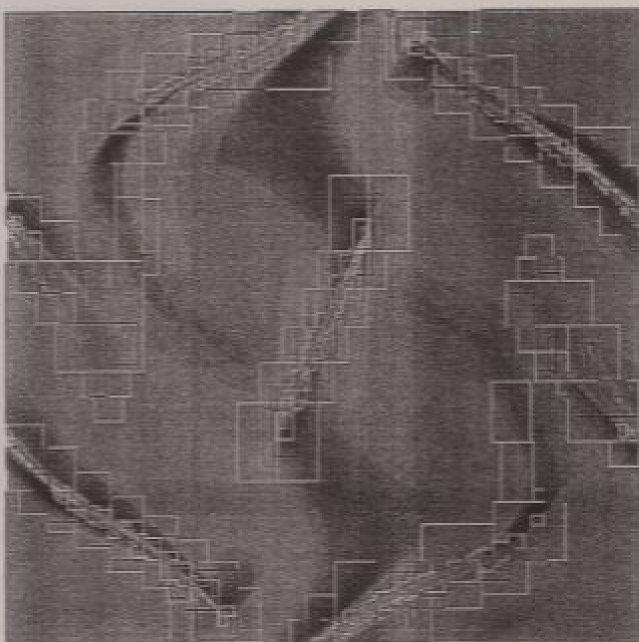




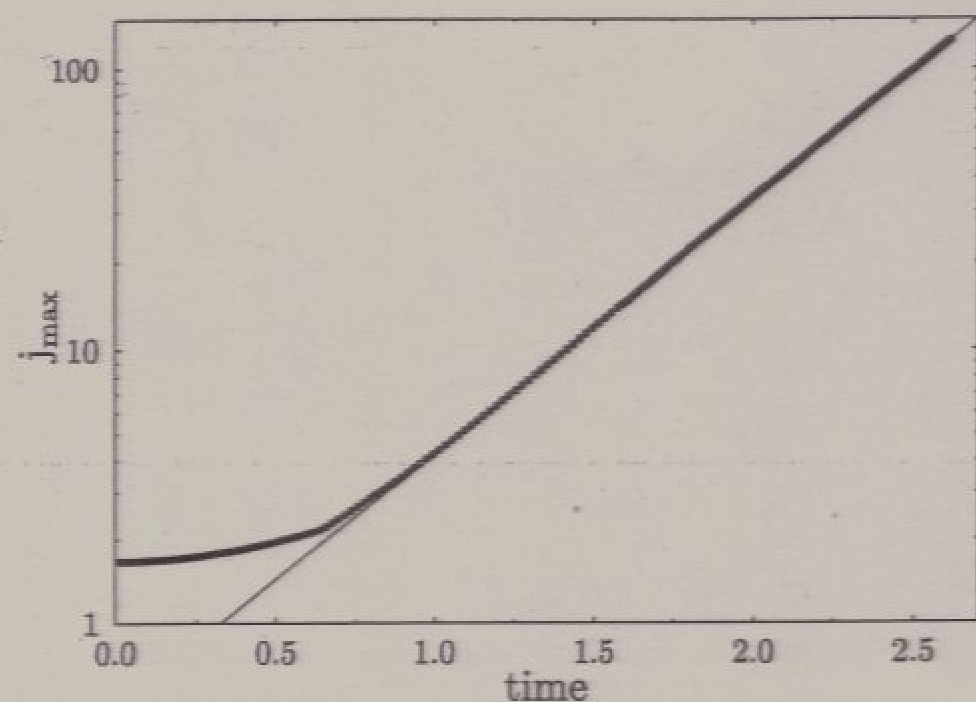
At later times: current filamentation and folding

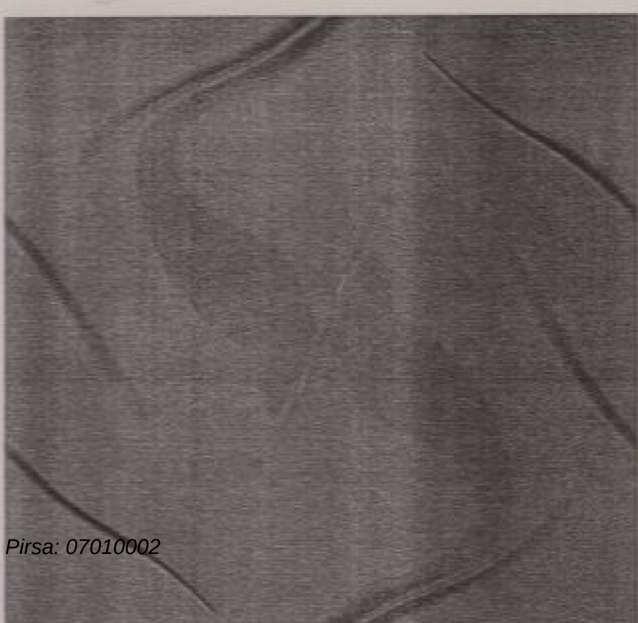
2D MHD simulations with Adaptive Mesh Refinement (AMR)

(Grauer, Marliani, Germaschewski, 1998)



Vorticity

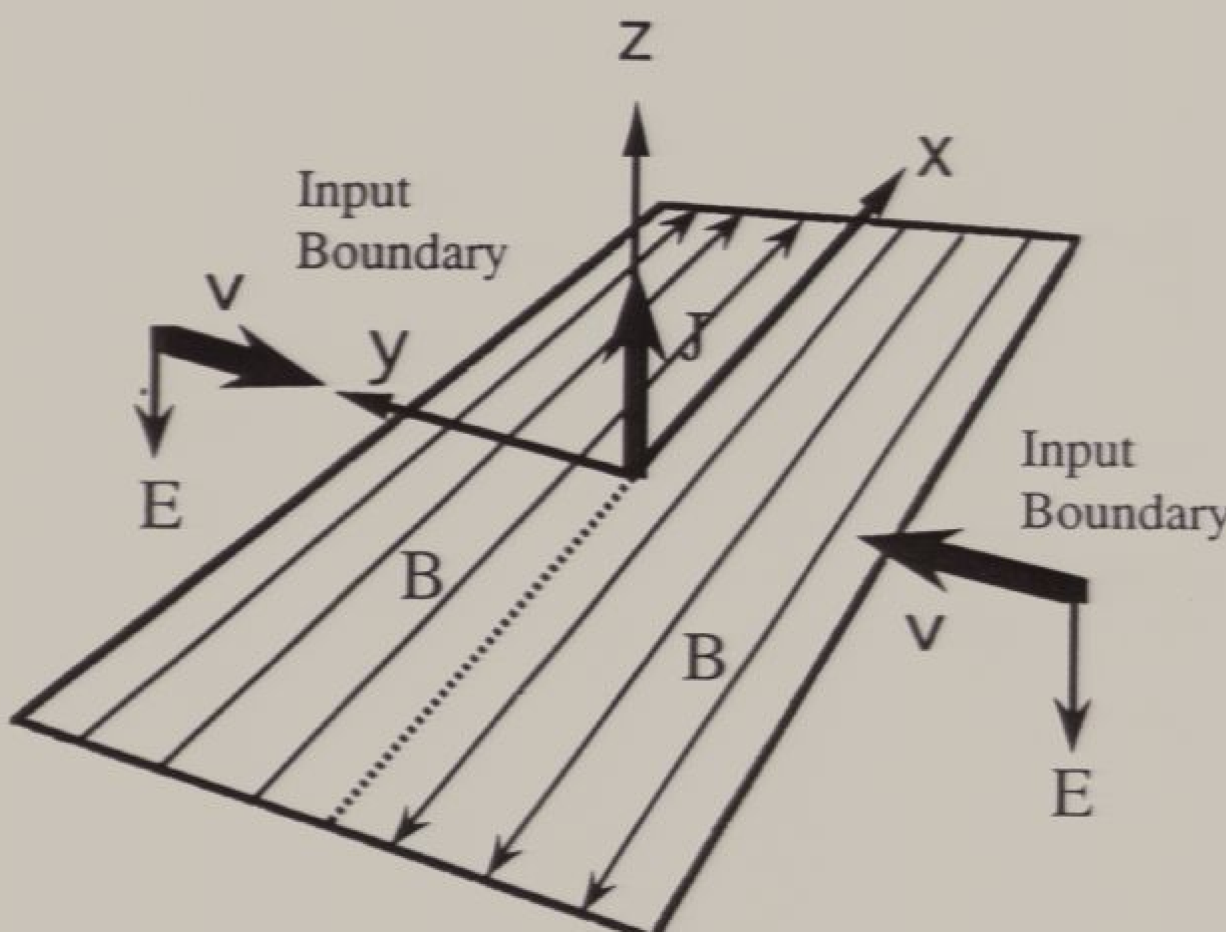




Current Density

-consistent with scalings
Sulem, Frisch et al., 1985

Neutral Sheet Configuration – Driven Magnetic Reconnection



Two-Fluid MHD Equations

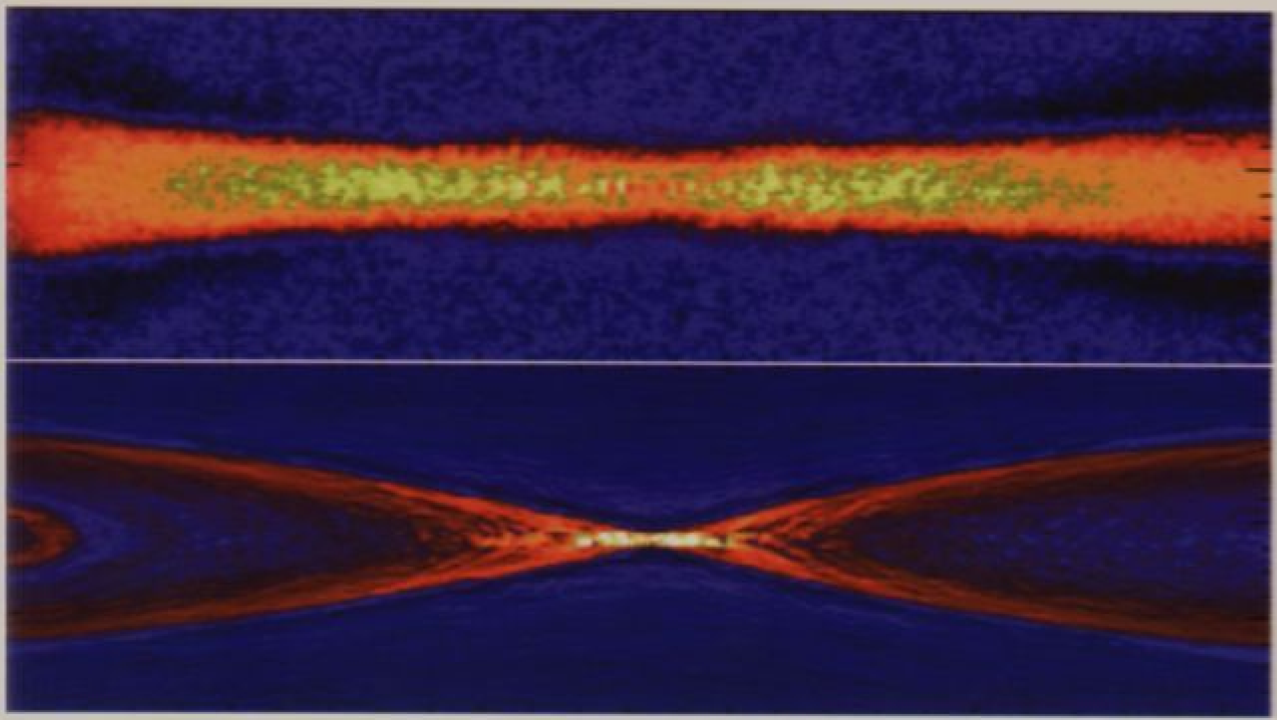
$$\frac{\partial n}{\partial t} + \nabla(nV) = 0$$

$$Mn\frac{dV}{dt} = -\nabla(P_e + P_i) + J \times B$$

$$\frac{\partial B}{\partial t} = -\nabla \times E \qquad J = (1/4\pi)\nabla \times B$$

$$\boxed{E = -V \times B + \eta J + \frac{J\times B - \nabla P}{en} + \frac{m_e}{e^2}\frac{dV_e}{dt}}$$

Two-Fluid MHD Simulations



J_i

J_e

Generalized Ohm's law:

$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = \eta \mathbf{J} + \frac{\mathbf{J} \times \mathbf{B} - \nabla p}{en} + \frac{m_e}{e^2} \frac{d\mathbf{V}_e}{dt}$$

Hall terms electron inertia

Result: Dual current sheet structure

(Drake et al. '91)

Kinetic Magnetic Reconnection

Macroscopic Dynamics

- Plasma mixing and diffusion
- MHD picture with classical electric resistivity

Microscopic Dynamics

- Particle inertia and finite orbit effects
- Decoupling of electron and ion motion at small scales
- Wave-particle interaction, binary collisions

Kinetic Simulation Equations

(1) Maxwell equations :

$$\frac{1}{c}\frac{\partial B_z}{\partial t} = -\frac{\partial E_y}{\partial x} + \frac{\partial E_x}{\partial y}, \quad \frac{1}{c}\frac{\partial A_z}{\partial t} = -E_z,$$

$$\frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} = \nabla \times \mathbf{B} - 4\pi\mathbf{j}, \quad \nabla \cdot \mathbf{E} = 4\pi\rho.$$

(2) Equations of motion :

$$\frac{d(\gamma_j \mathbf{v}_j)}{dt} = \frac{q_j}{m_j}\left[\mathbf{E} + \frac{\mathbf{v}_j}{c} \times \mathbf{B}\right], \quad \frac{d\mathbf{x}_j}{dt} = \mathbf{v}_j.$$

where

$$B_x = \partial A_z/\partial y, \quad B_y = -\partial A_z/\partial x,$$

$$\mathbf{j}(\mathbf{x}, \mathbf{t}) = \sum_{j=1}^{N} \frac{q_j \mathbf{v}_j(t)}{c} S(\mathbf{x} - \mathbf{x}_j(t)),$$

$$\rho(\mathbf{x}, t) = \sum_{j=1}^{N} q_j \, S(\mathbf{x} - \mathbf{x}_j(t)),$$

A_z : vector potential

γ_j : relativistic gamma factor

$S(x)$: form function of super-particle

Energy Exchange

1. Topological change of magnetic field :

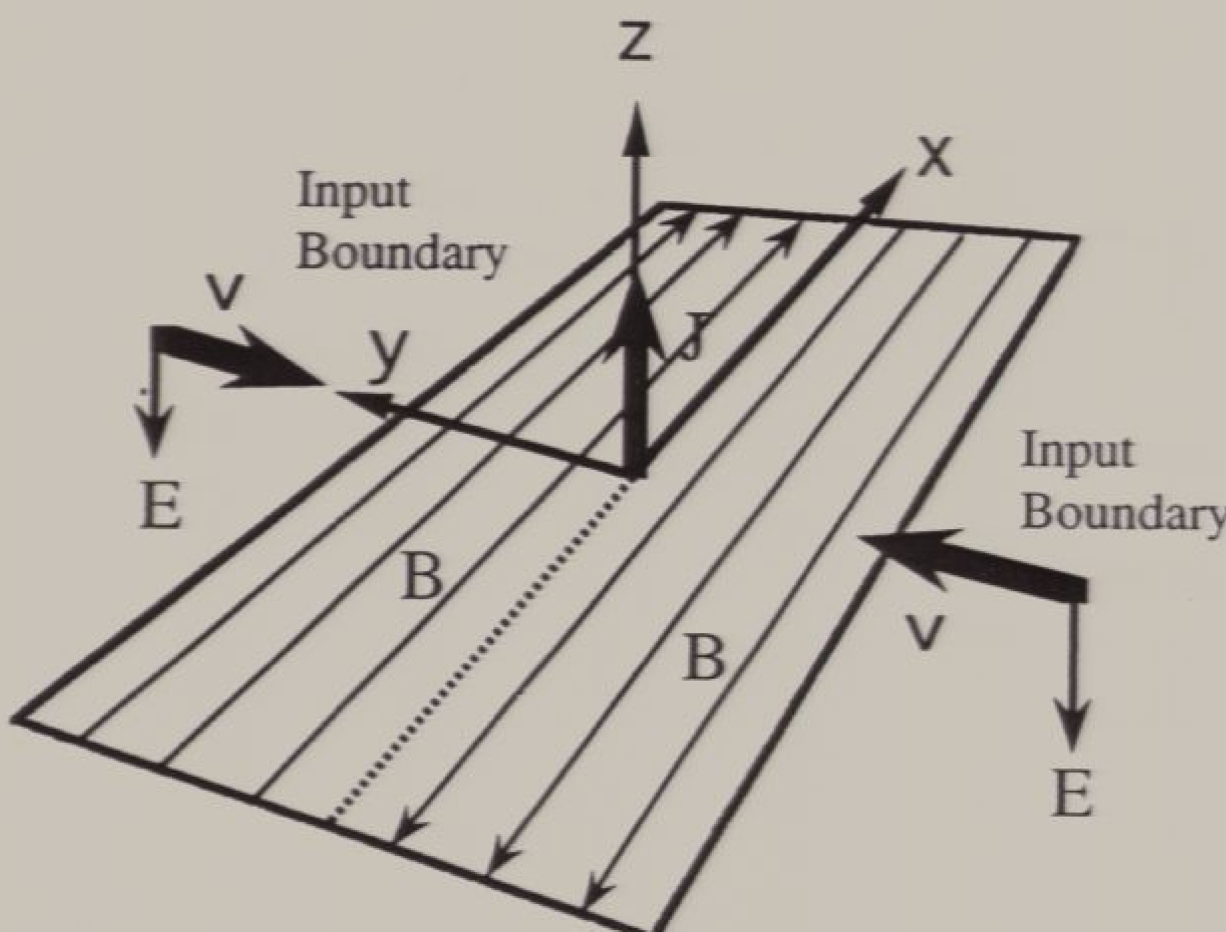
$$\frac{1}{c}\frac{\partial A_z}{\partial t} = -\underset{\sim}{E_z}$$

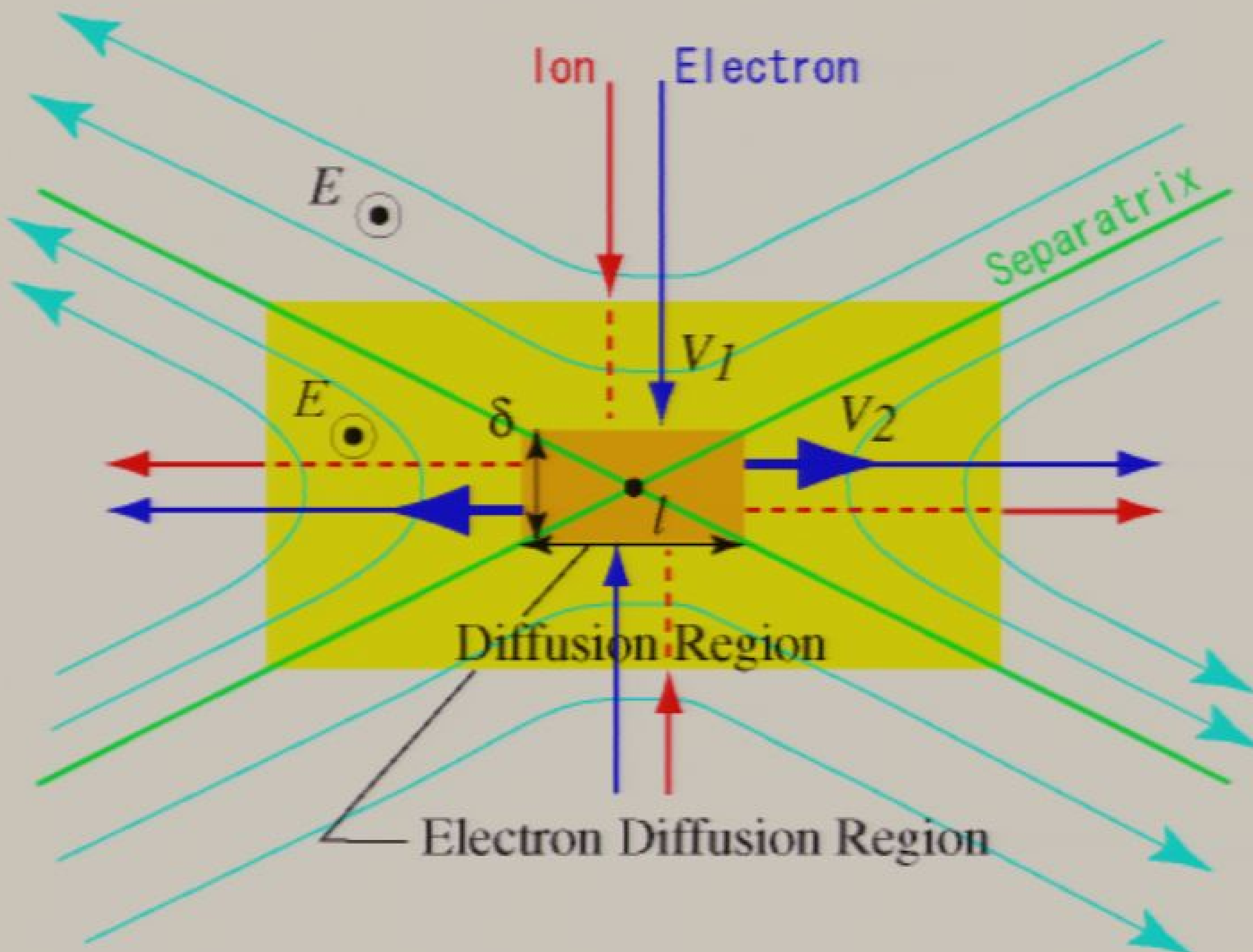
(2D, equilibrium current $\parallel$ z-axis)

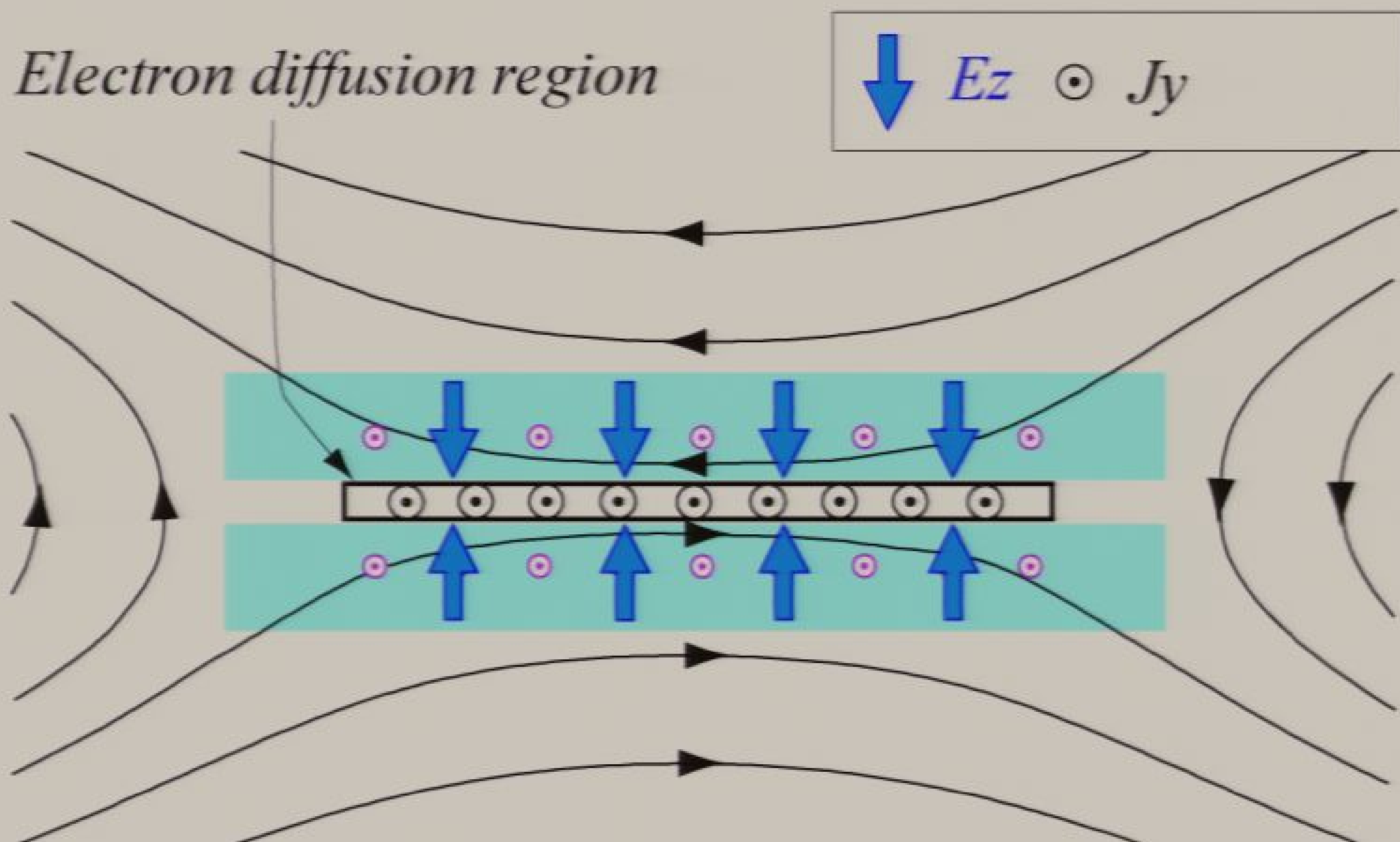
2. Energy Conversion between EM field and particles :

$$\frac{d}{dt}\int d^3x\{\frac{\mathbf{B}^2}{8\pi}+\frac{\mathbf{E}^2}{8\pi}\} = \int d^3x\{\nabla\cdot(\frac{\mathbf{B}\times\mathbf{E}}{4\pi})-\underset{\sim}{\mathbf{E}\cdot\mathbf{j}}$$

Neutral Sheet Configuration – Driven Magnetic Reconnection

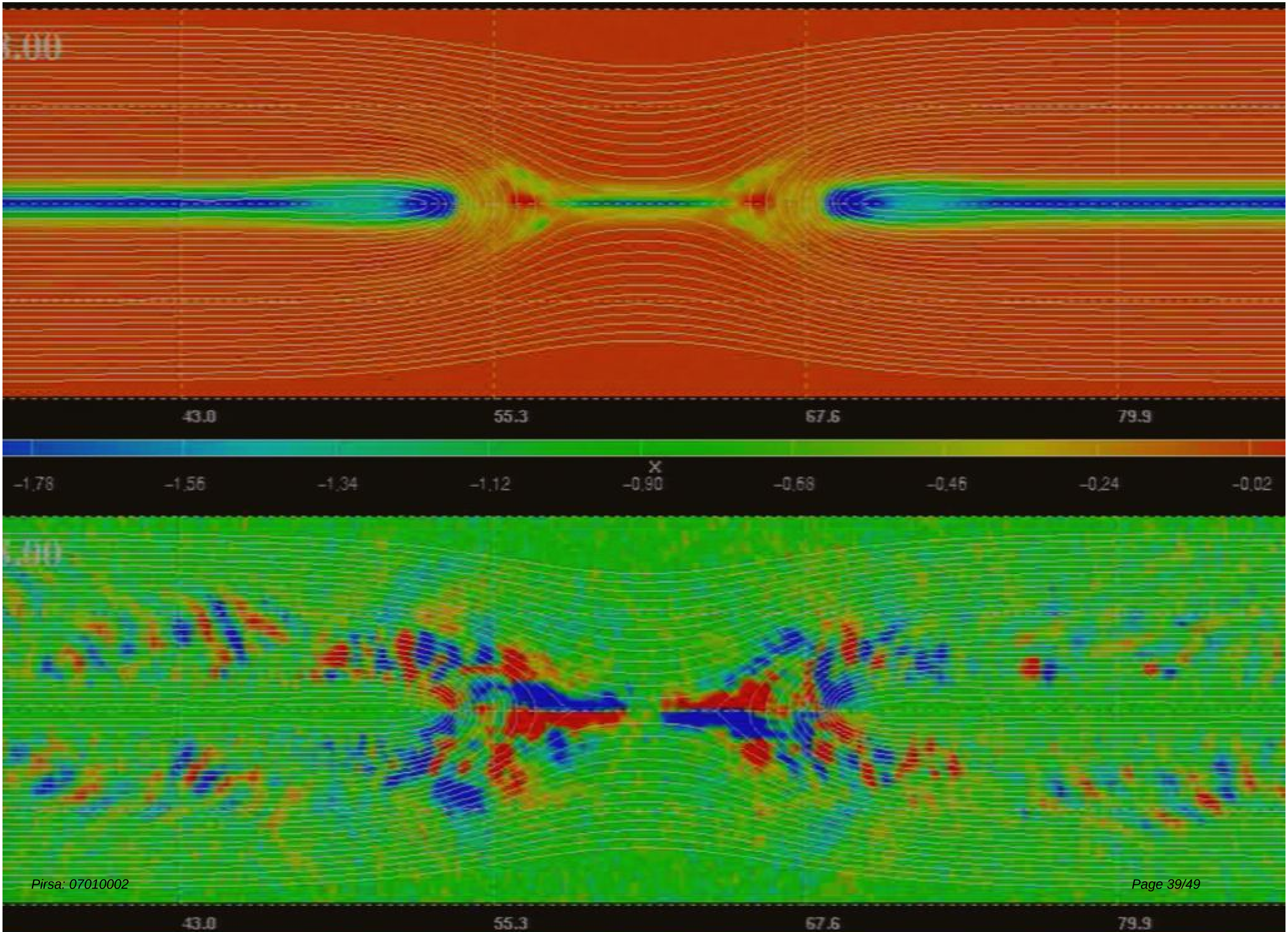



Ion
Electron
E
Separatrix
V1
E
δ
V2
l
Diffusion Region
Electron Diffusion Region



Electron diffusion region
Ez ⊙ Jy

.00
43.0
55.3
67.6
79.9
X
-1.78
-1.56
-1.34
-1.12
-0.90
-0.68
-0.46
-0.24
-0.02
.00
43.0
55.3
67.6
79.9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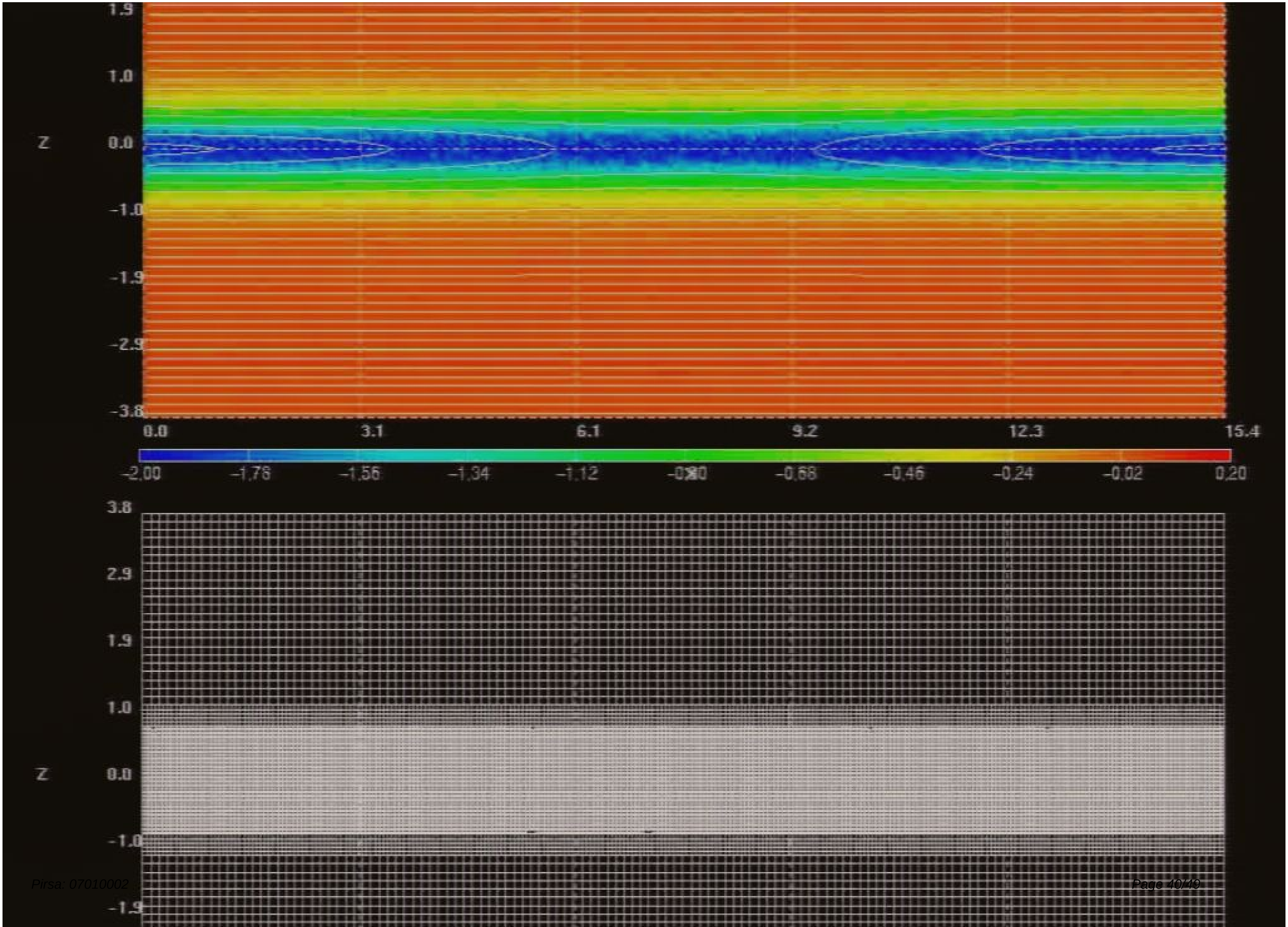
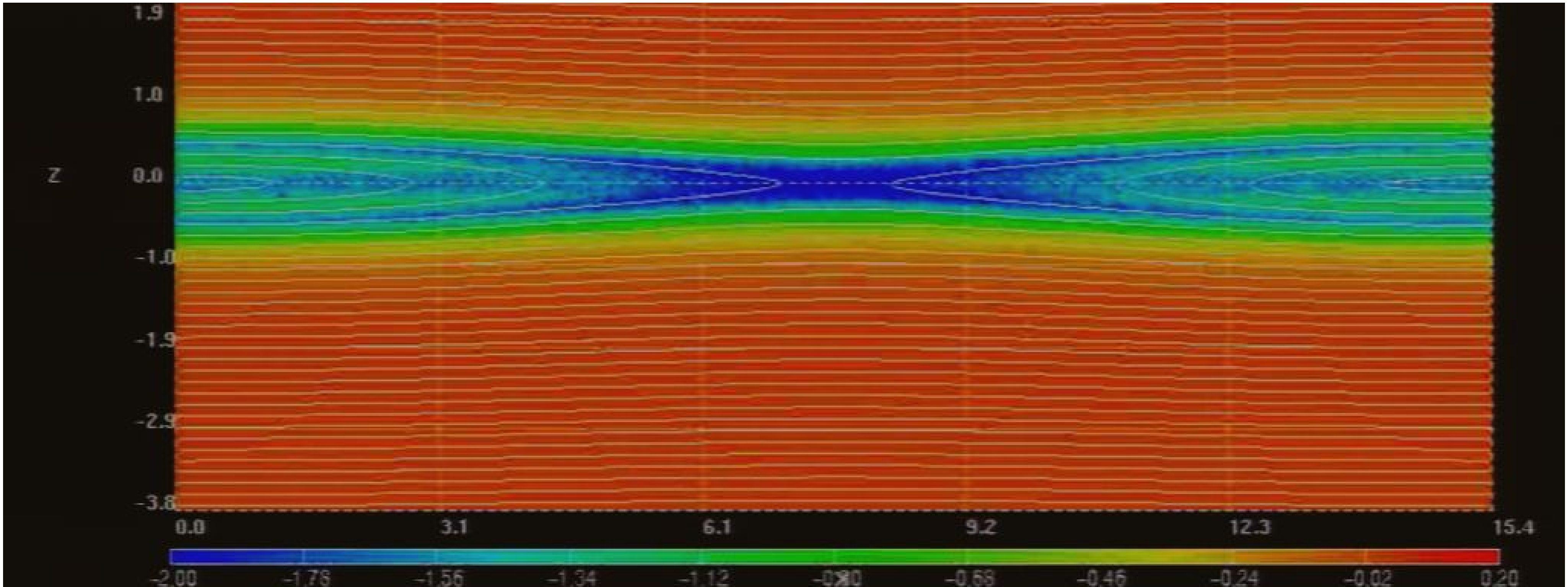
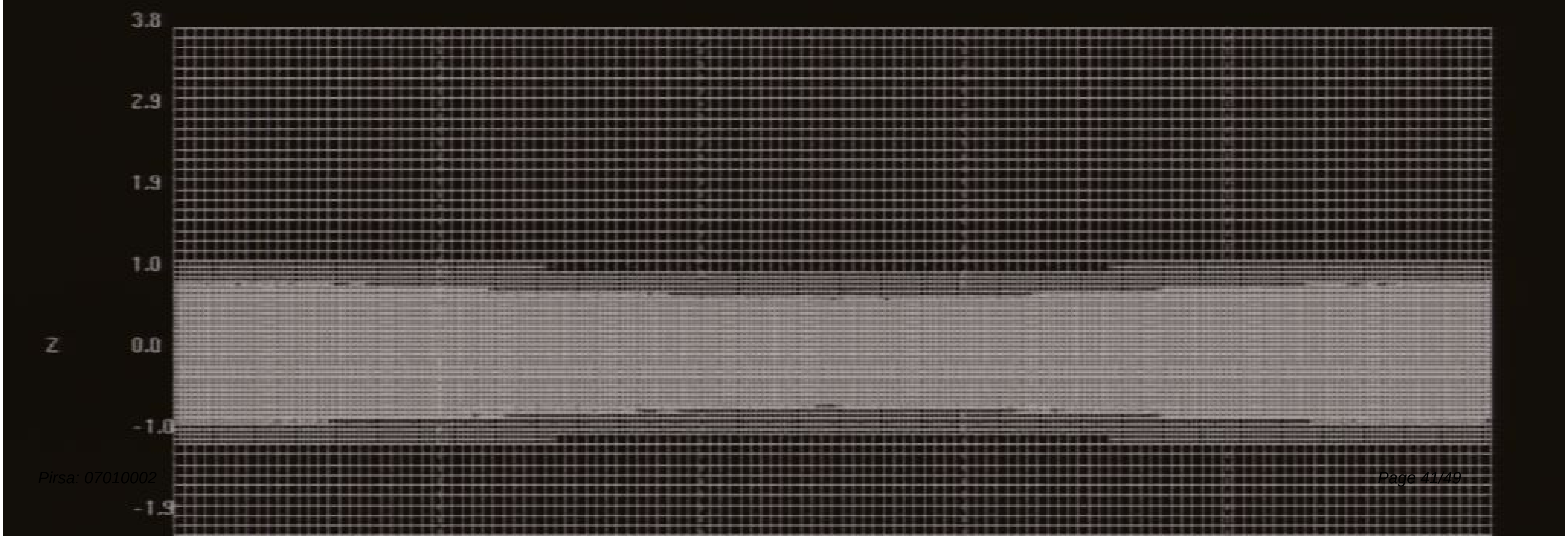


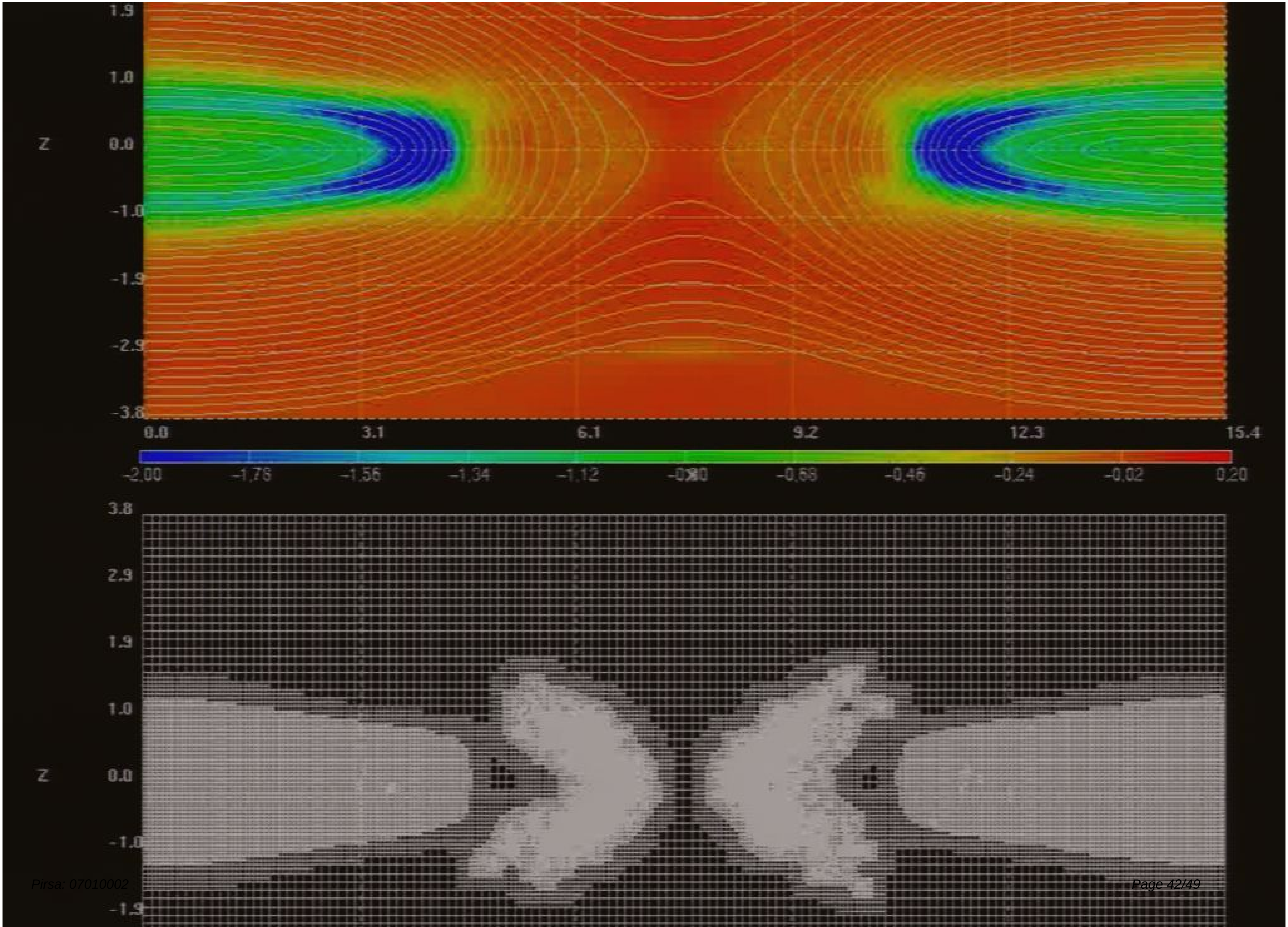
1.9
1.0
Z
0.0
-1.0
-1.9
-2.9
-3.8
0.0
3.1
6.1
9.2
12.3
15.4
-2.00
-1.78
-1.56
-1.34
-1.12
-0.68
-0.46
-0.24
-0.02
0.20
3.8
2.9
1.9
1.0
Z
0.0
-1.0
-1.9



1.9
1.0
Z
0.0
-1.0
-1.9
-2.9
-3.8
0.0
3.1
6.1
9.2
12.3
15.4
-2.00
-1.78
-1.56
-1.34
-1.12
-0.68
-0.46
-0.24
-0.02
0.20



3.8
2.9
1.9
1.0
Z
0.0
-1.0
-1.9


1.9
1.0
Z
0.0
-1.0
-1.9
-2.9
-3.8
0.0
3.1
6.1
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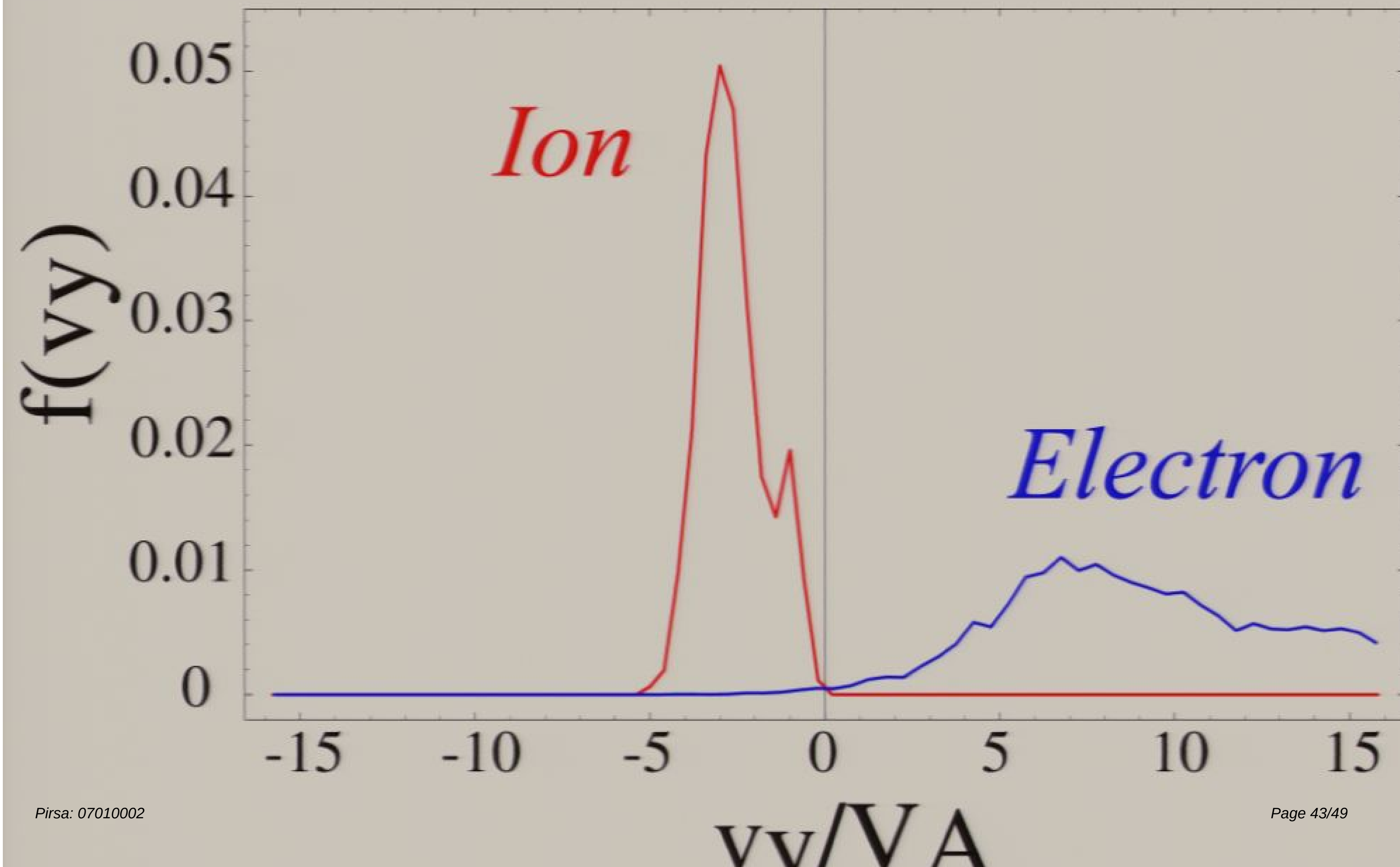
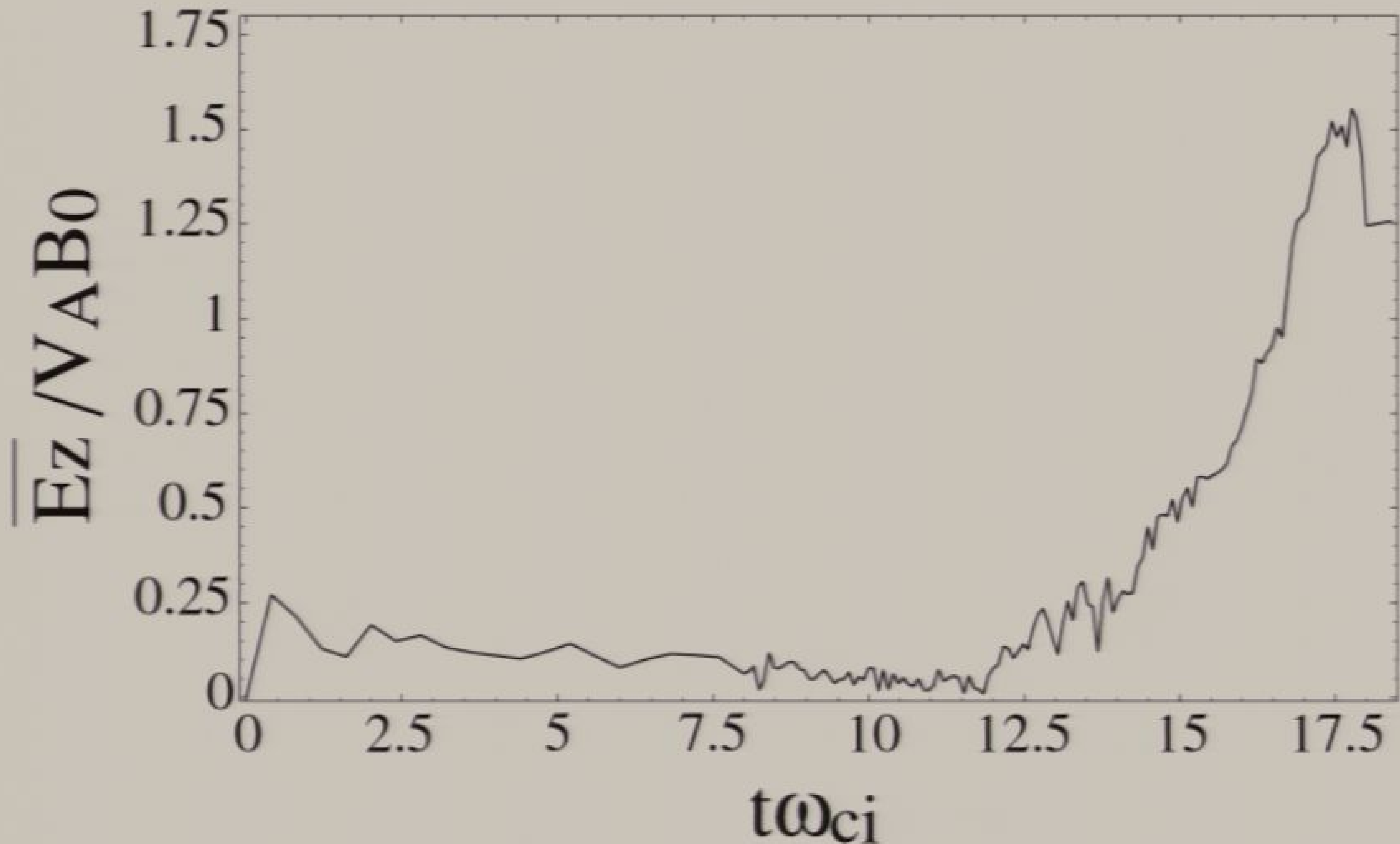
-0.46
-0.24
-0.02
0.20
3.8
2.9
1.9
1.0
Z
0.0
-1.0
-1.9

Distribution Functions - Nonthermal

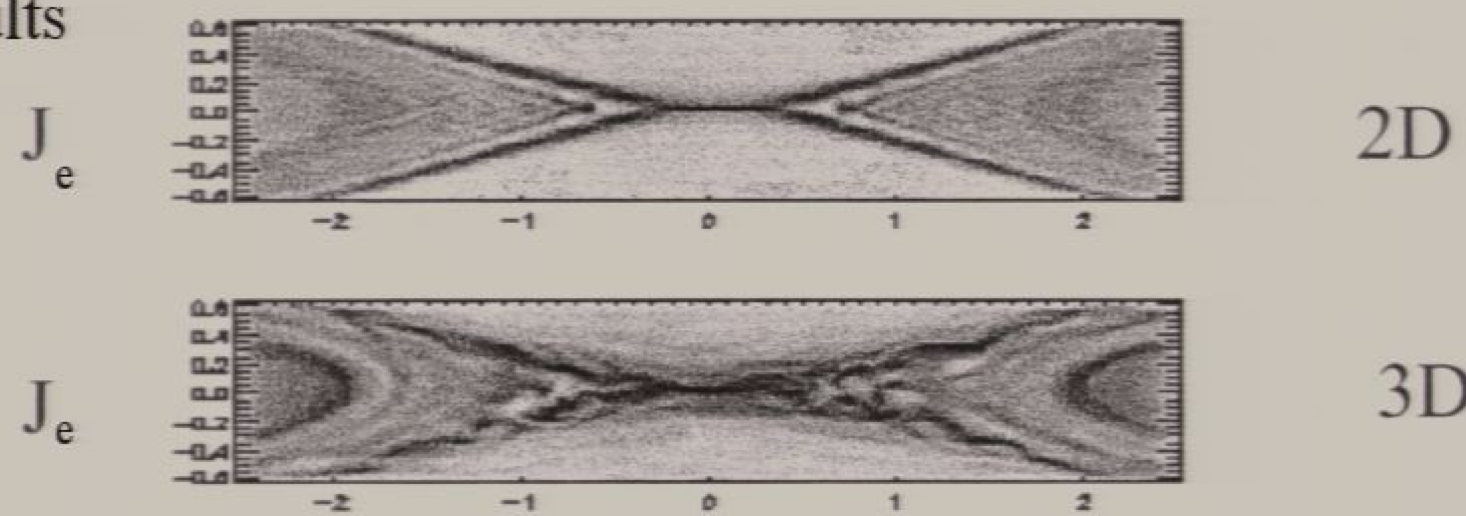


Kinetic Magnetic Reconnection



Other Important Effects in Kinetic Magnetic Reconnection

2-Fluid MHD Results
(Drake et al., '91)



3D effects important for current sheet stability

Other Important Effects in Kinetic Magnetic Reconnection

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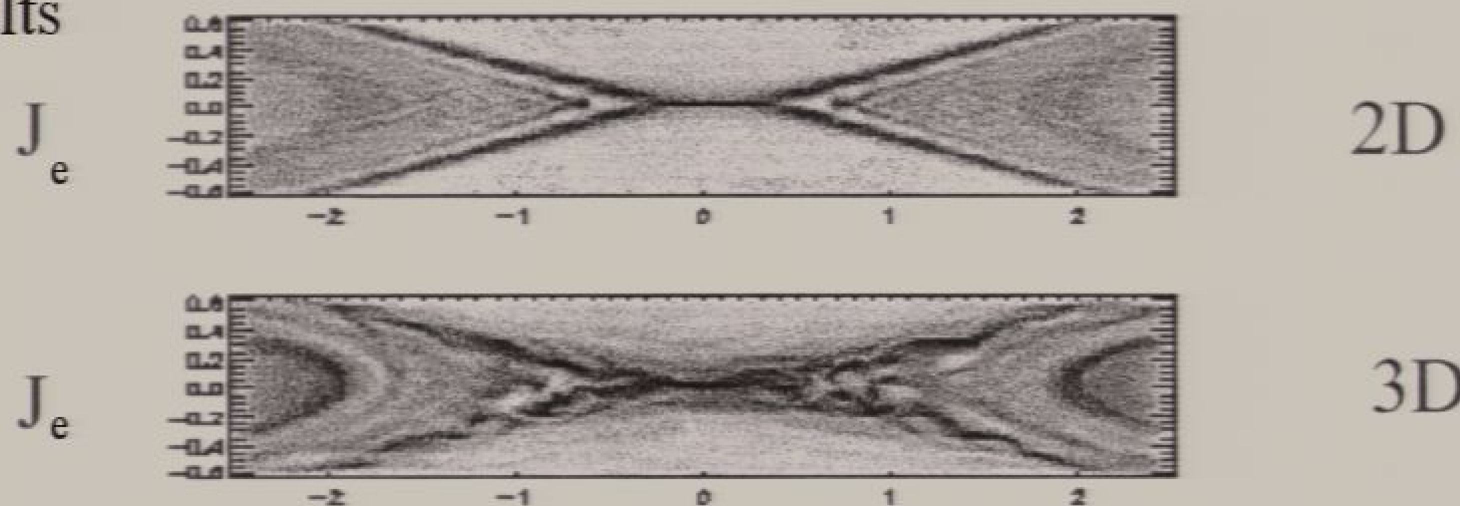
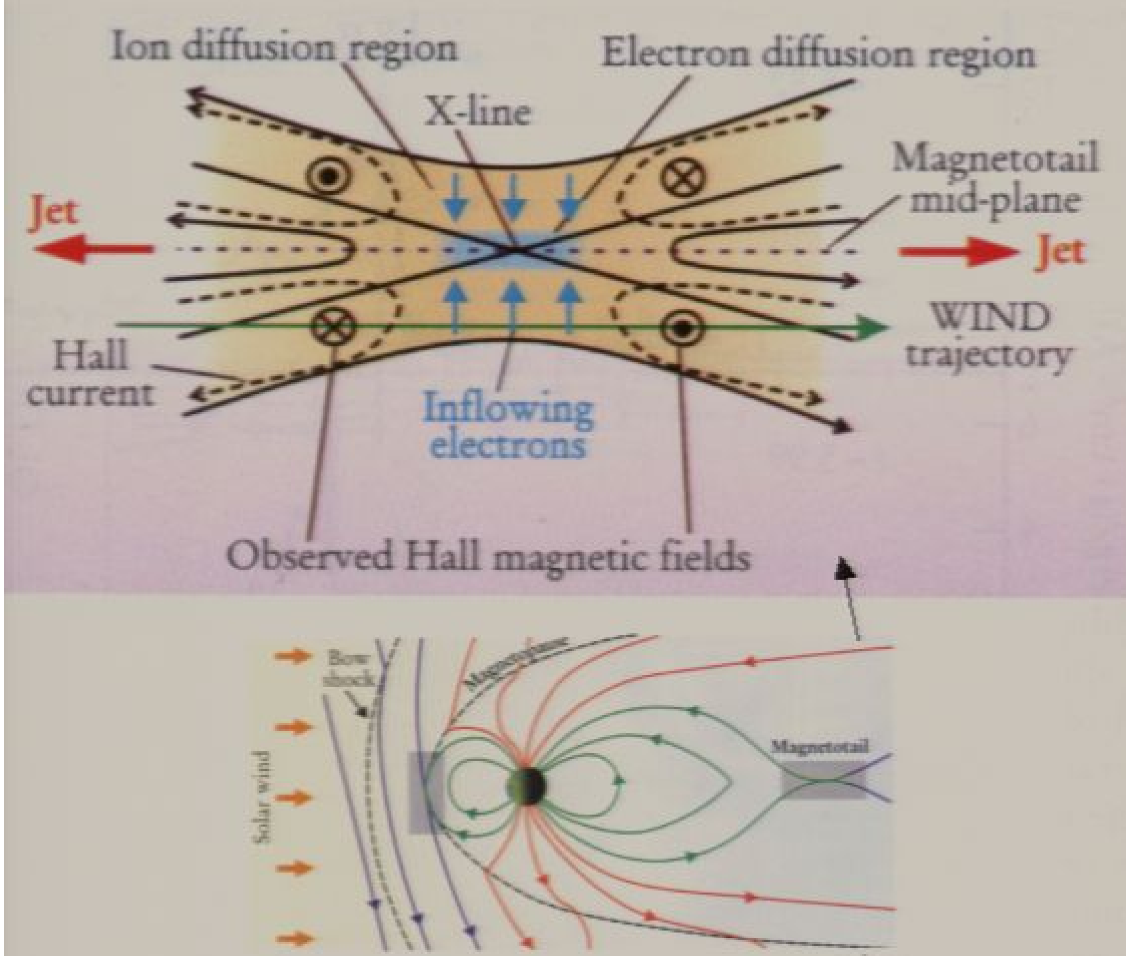
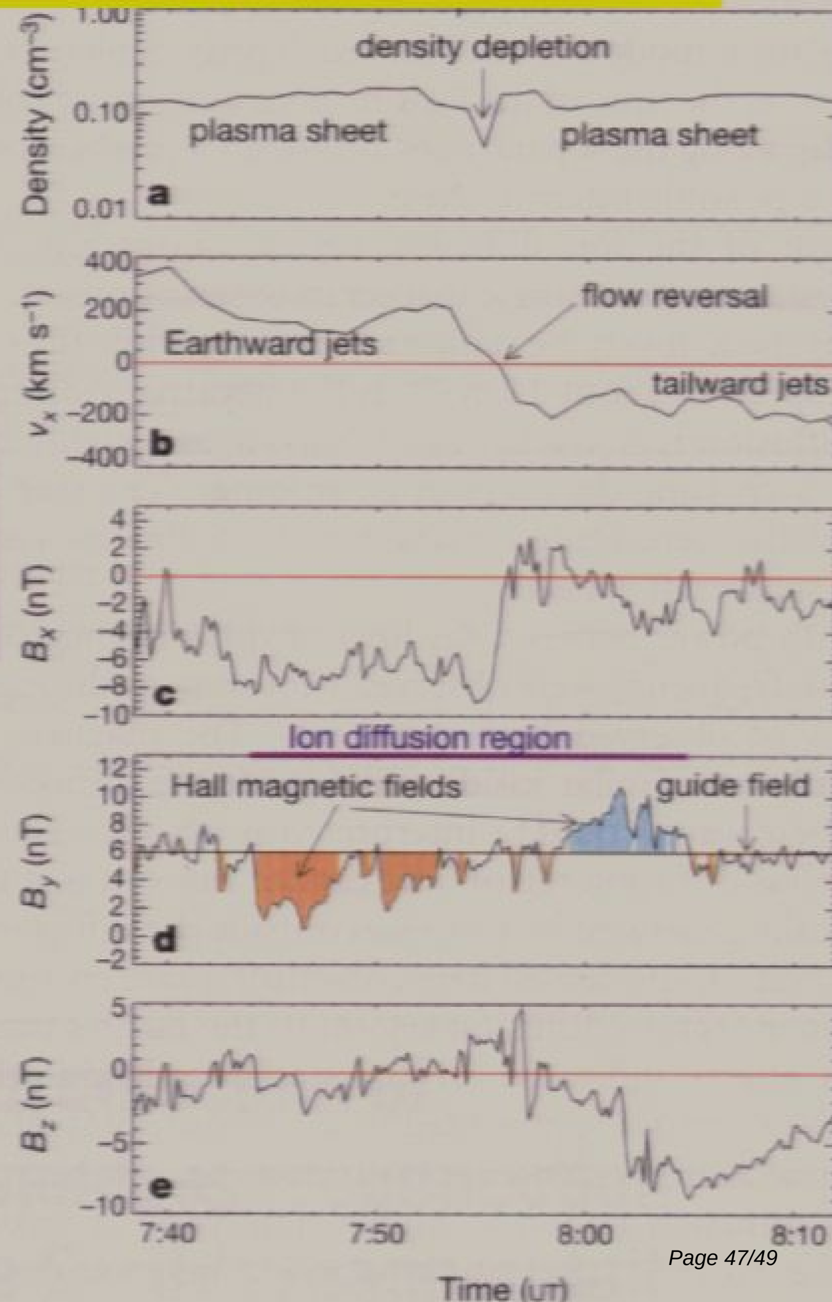


3D effects important for current sheet stability

Observations in Space





WIND Spacecraft Observation
(April, 1999)

Ref. M. Oieroset, et al.,

Laboratory Connections

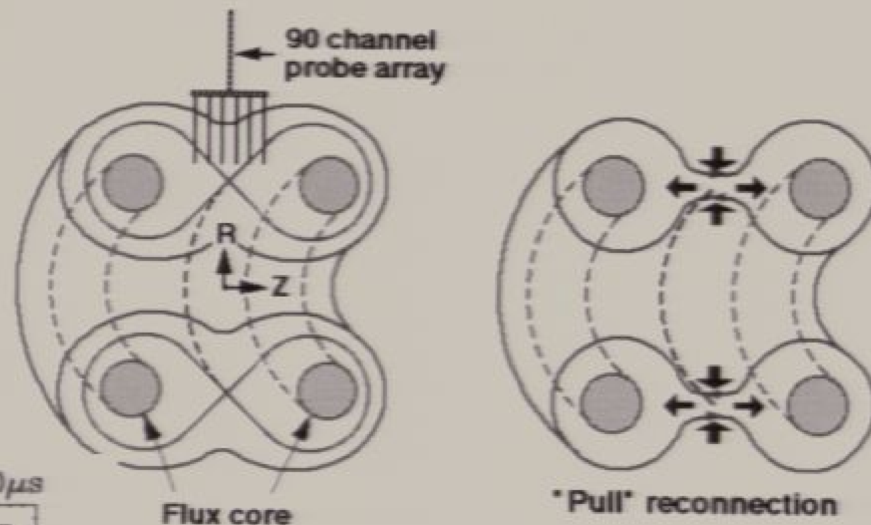
Magnetic Reconnection Experiment (MRX)

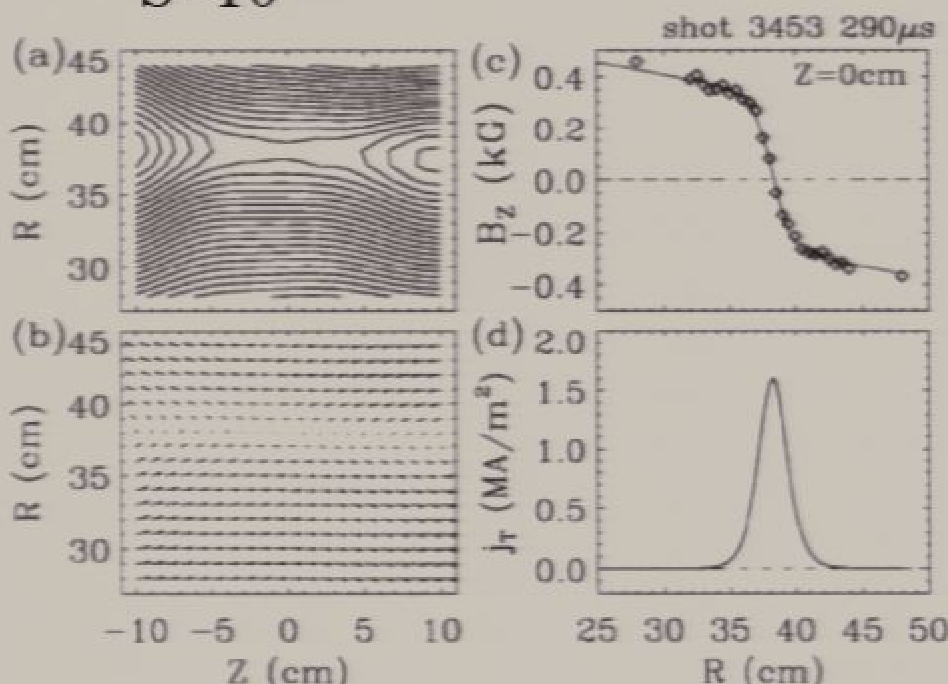
Princeton Plasma Physics Lab. (PPPL)

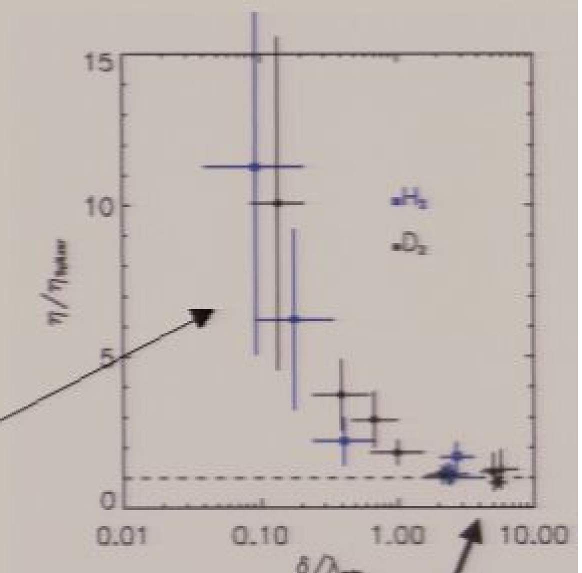
(Trinchouk et al., PRL, 2001)

$B < 2kG$, $T \sim 5\text{-}20eV$, $n \sim 10^{20}/m^3$

$S \sim 10^3$







Anomalous resistivity observed – wave turbulence?

Summary and Current Topics

1) MHD picture with classical electric resistivity gives magnetic reconnection rates which are too slow and inconsistent with observations

2) Fast reconnection rates possible by describing the layer kinetically which leads to decoupling of the electron and ion motion

3) Fast flows, plasma heating and acceleration observed in kinetic simulations

4) 3D effects and wave-particle interactions important → a possible source of anomalous restivity. Requires a 'first principles model'

5) Coupling of local scale reconnection physics to global MHD behavior is an active research area

6) Connections to multi-satellite observations and laboratory experiments needed to get complete picture of 3D structure

7) Scaling to large scale astrophysical systems not well understood