Magnetic Reconnection in Space Plasmas

Lin-Ni Hau

et al.

Institute of Space Science

Department of Physics

National Central University, Taiwan R.O.C.

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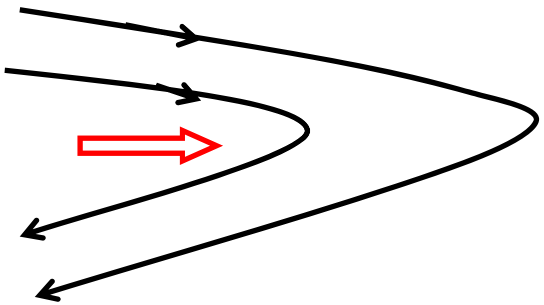
Contents

- ☆ Introduction
- ☆ Some highlights from recent works by others
- ☆ Some highlights of our efforts

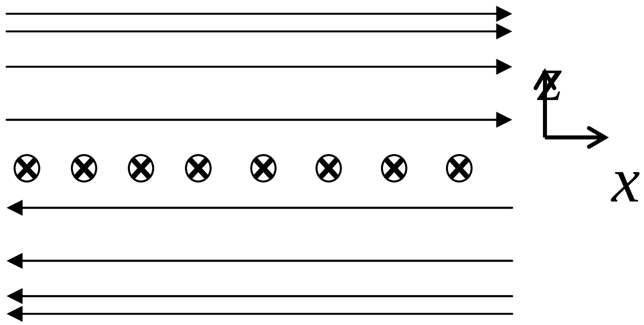
Plasma Universe

- Ionized gas in nature was first discovered in the Earth's ionosphere, then in the radiation belts, magnetosphere and interplanetary space etc.
- Solar system plasmas are mostly collisionless, nonthermal and spatially nonuniform involving various temporal and spatial scales.
- Solar system is a natural laboratory accessible to man-made spacecraft. Detailed and inter-comparisons between theory/simulation and in-situ observations can be made.
- 99% of the visible matter in the universe are in ionized state.

Generation and Dissipation of B

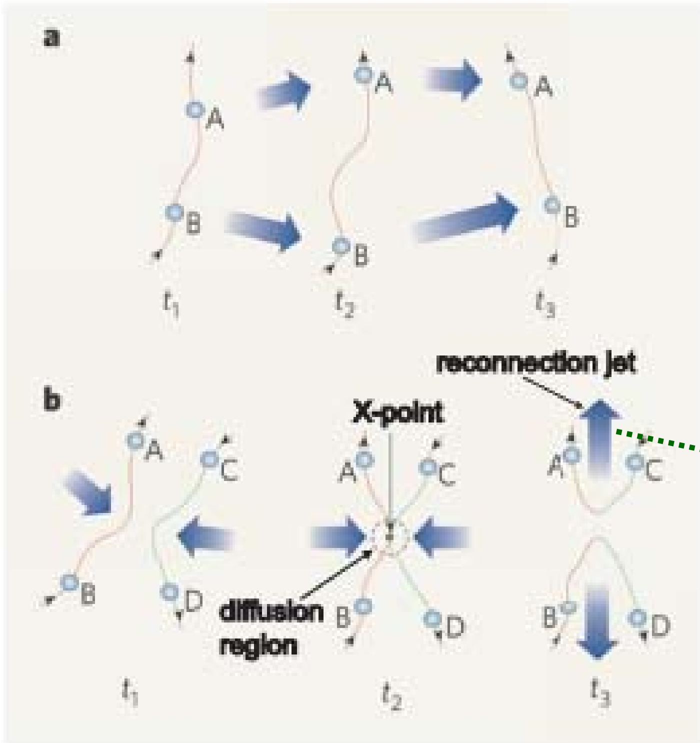


$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{u} \times \vec{B})$$



$$\frac{\partial \vec{B}}{\partial t} = \frac{\eta}{\mu_0} \nabla^2 \vec{B}$$

Magnetic Reconnection



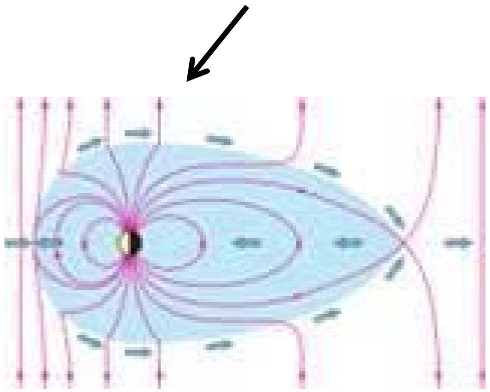
$$\vec{E} + \vec{u} \times \vec{B} \neq 0$$

$$\vec{j} \times \vec{B} \neq 0$$

Adapted from G. Paschmann (Nature, 2006)

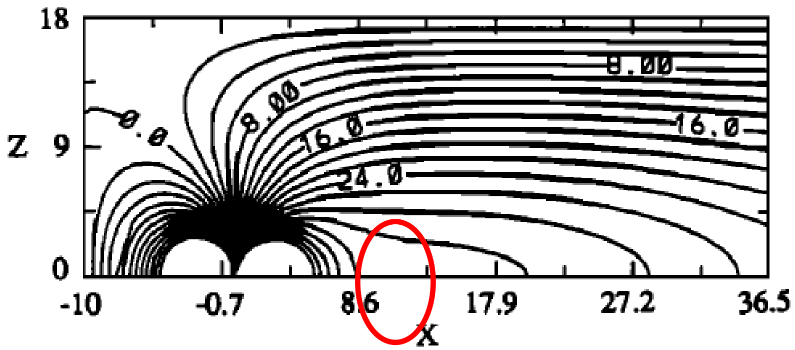
Open Magnetosphere

Open field lines



$\vec{E}$ °

Quantitative model

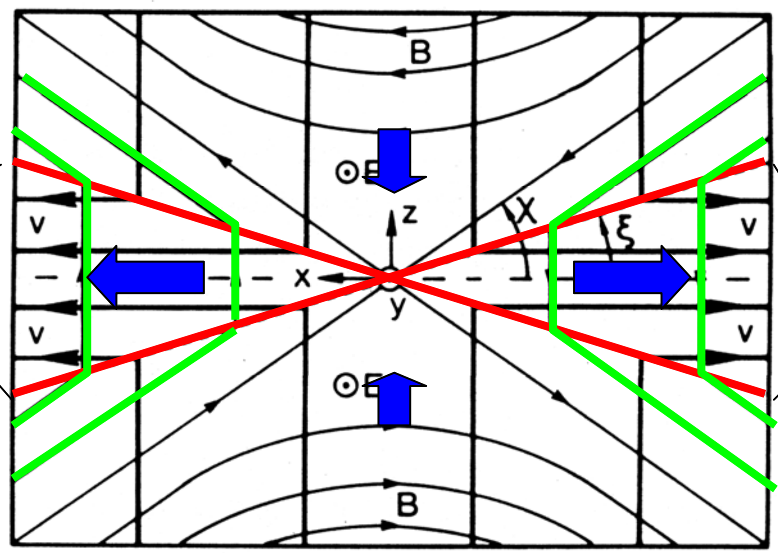


J. W. Dungey, PRL, 1961.

Hau et al, JGR, 1989, 1991.

Magnetic Reconnection Model

Slow Shock



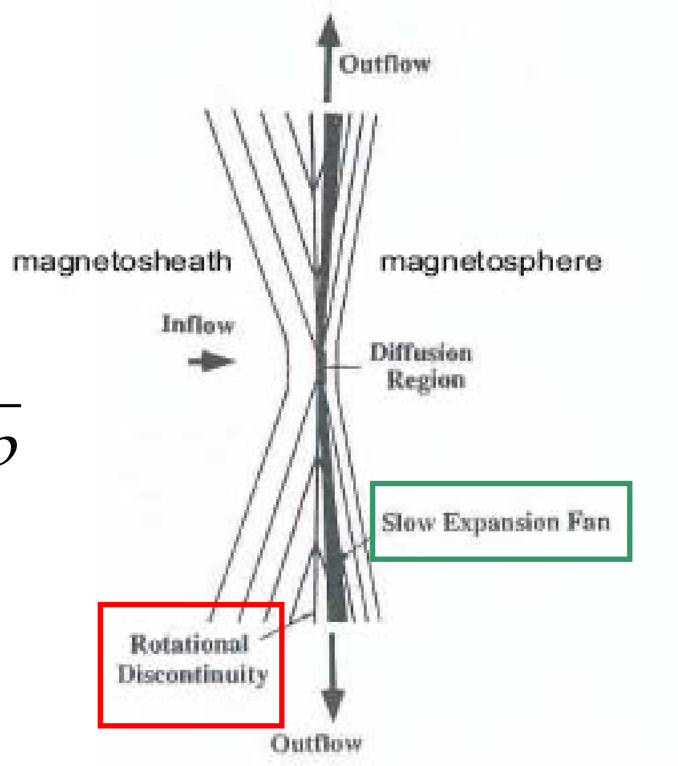
Slow Shock

$$u_o \sim B_i / \sqrt{\mu_o \rho}$$

Petschek, 1964.

Asymmetric Reconnection

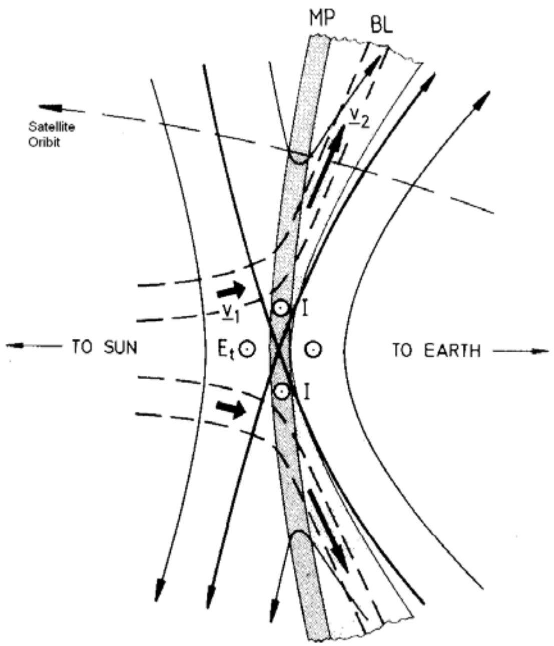
$$\Delta\vec{V} \sim \Delta\vec{B} / \sqrt{\mu_o \rho}$$

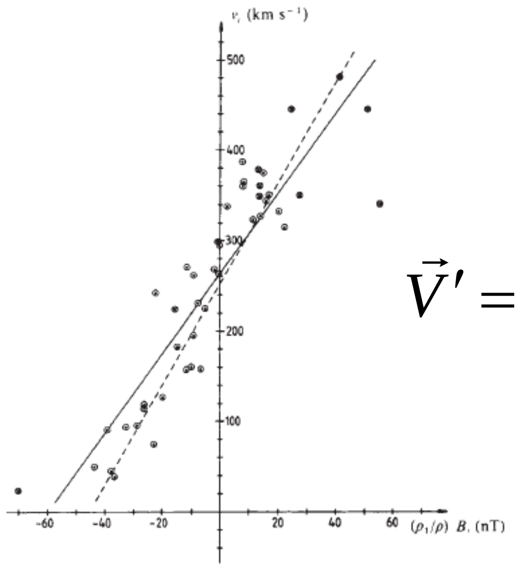


Levy et al., 1964.

(Adapted from Lee et al.)

First Evidence for Plasma Acceleration at Earth's Magnetopause

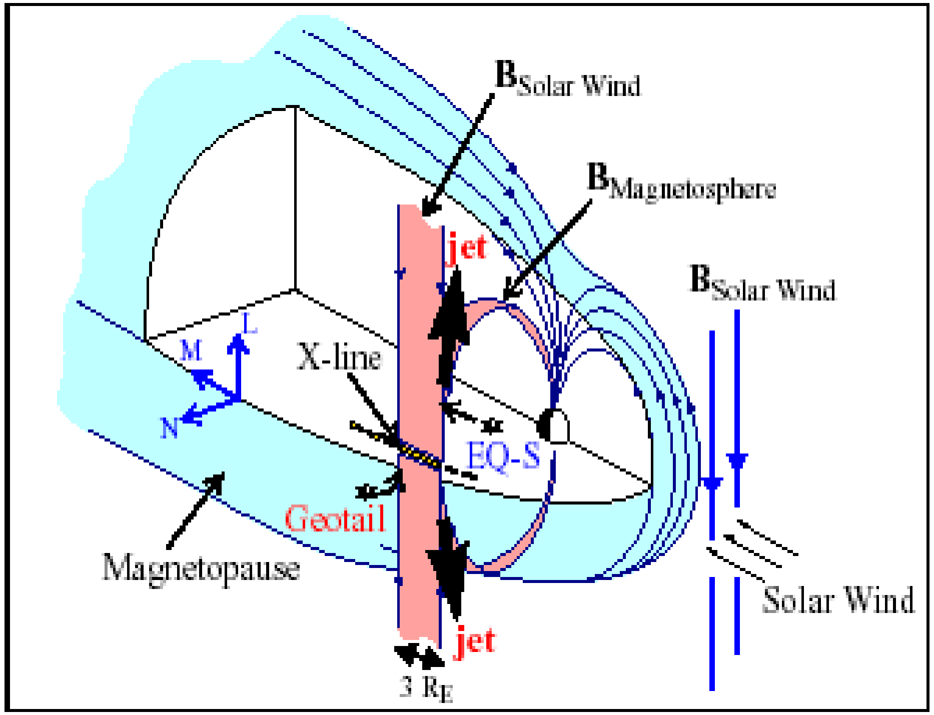




$$\vec{V}' = \vec{V}_A = \frac{\vec{B}}{\sqrt{\mu_0 \rho}}$$

Paschmann et al., Nature, 1979.

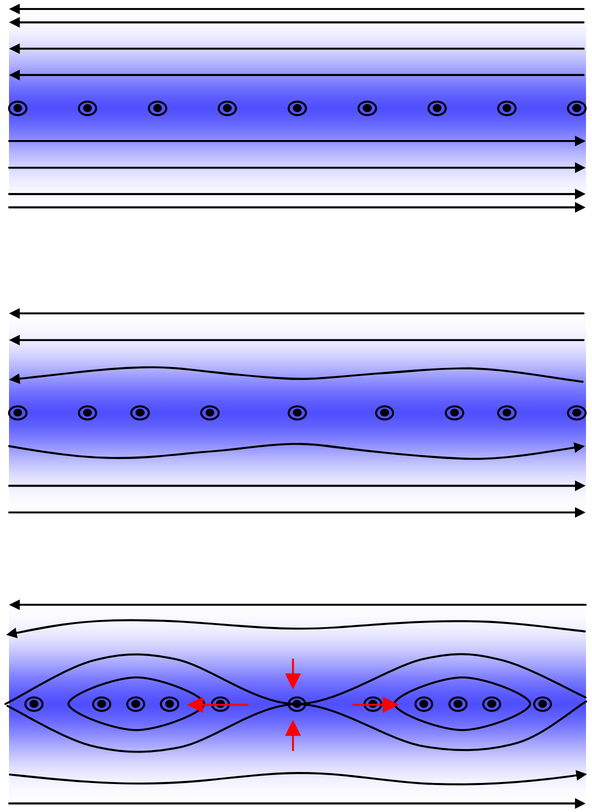
Reconnection Signature : Bipolar Jets



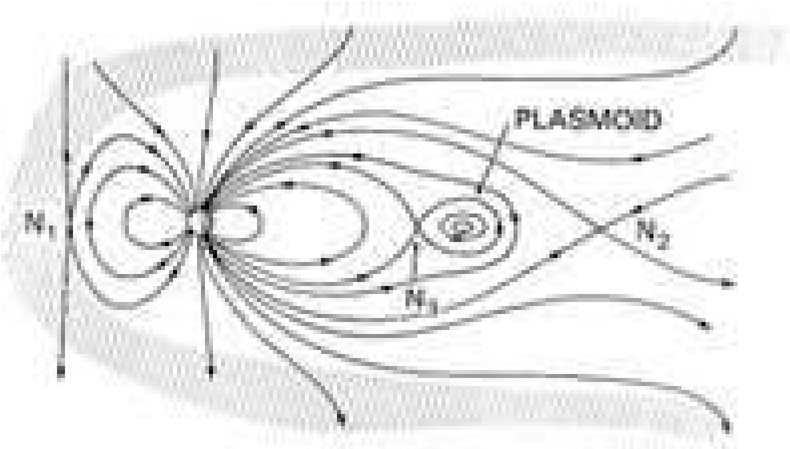
Phan et al., Nature 2001.

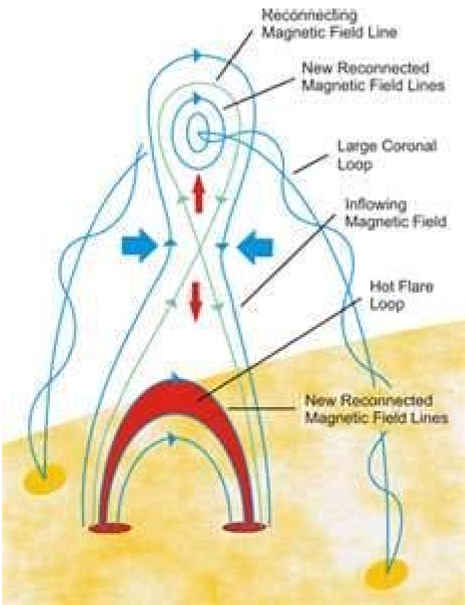
Stability of Thin Current Sheet

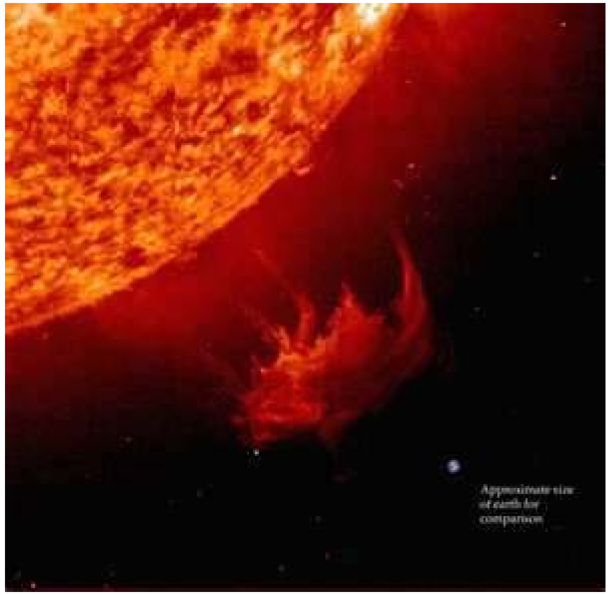
Tearing-mode Instability



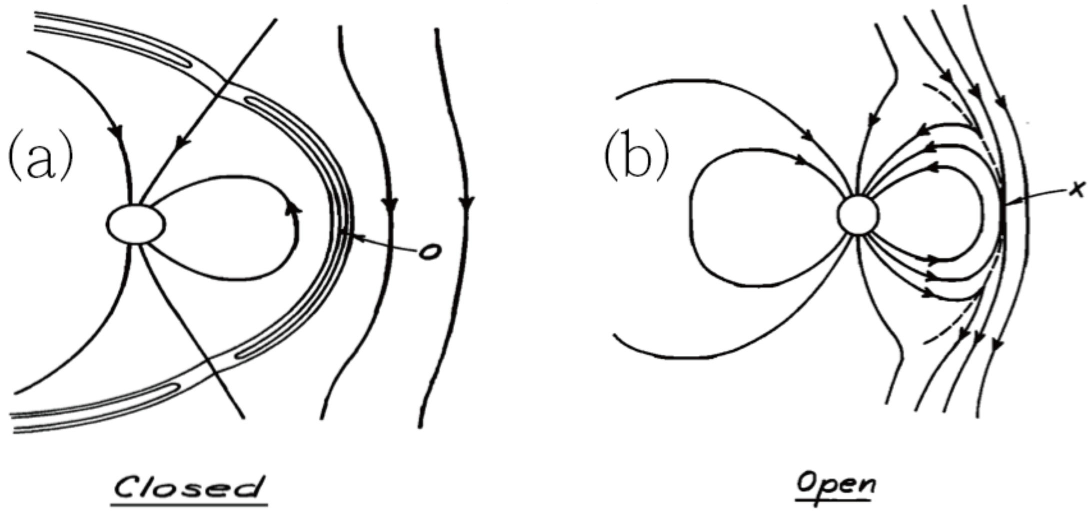
Furth et al., 1963.


PLASMOID
N1
N2
N3


Reconnecting
Magnetic Field Line
New Reconnected
Magnetic Field Lines
Large Coronal
Loop
Inflowing
Magnetic Field
Hot Flare
Loop
New Reconnected
Magnetic Field Lines


Approximate size
of earth for
comparison

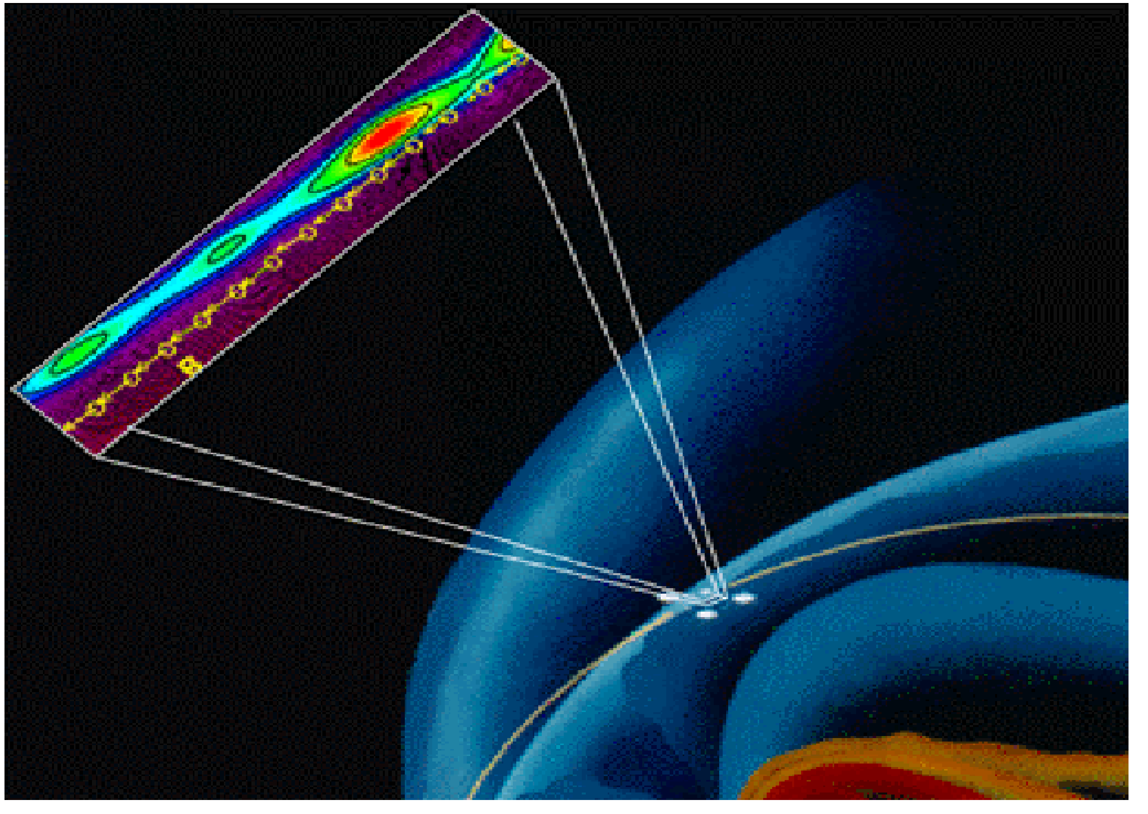
Closed vs. Open Models



Sonnerup and Cahill, 1967.

First direct evidence for magnetic islands

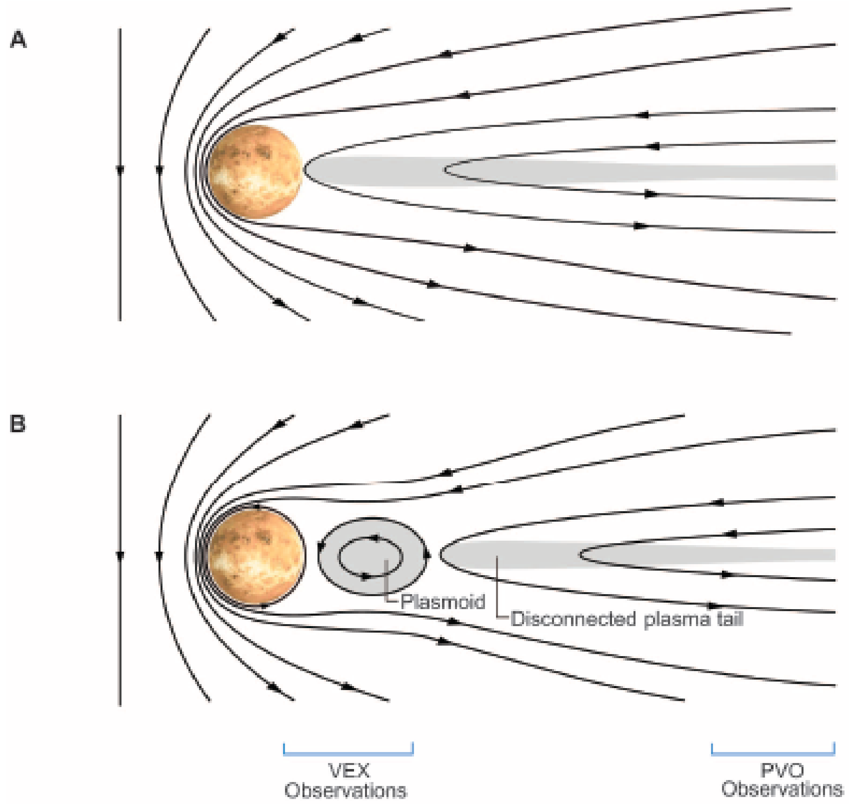
in space plasma environment



Hau and Sonnerup, JGR 1999.

Evidence for MR in Other Planets

- **Jupiter**
  e.g., Ge et al., 2010.
- **Saturn**
  e.g., Jackman et al., 2007.
- **Uranus**
  Richardson et al.
- **Mercury**
  Slavin et al., Science, 2009.
- **Mars**
  Eastwood et al.
- **Venus**
  Zhang et al., Science, 2012.



Venus Magnetotail

Plasma Models for Studying MR

MHD、Hall MHD 、Hybrid 、PIC 、Vlasov

Fluid aspect of field-line breaking :

$$\vec{E}+\vec{u}\times\vec{B}=\eta\vec{j}+\frac{m_i}{\rho e}\left(\vec{j}\times\vec{B}-\nabla\cdot\vec{p}_e\right)+\frac{m_e}{ne^2}\left[\frac{\partial\vec{j}}{\partial t}+\nabla\cdot\left(\vec{v}\vec{j}+\vec{j}\vec{v}\right)+\frac{e}{m_i}\nabla\cdot\vec{p}_i\right]$$

$$\frac{\partial\vec{B}}{\partial t}=\nabla\times(\vec{u}\times\vec{B})+\frac{\eta}{\mu_0}\nabla^2\vec{B}+\ldots\ldots$$

$$\frac{d}{dt}\left(\frac{p}{\rho^{5/3}}\right)=(\quad)\eta j^2+\ldots..$$

Reconnection Rate & Diffusion Region

- Hall current due to ion inertia is responsible for fast reconnection. Evidences for Hall current in reconnection region have been found.
- Electron physics is the core of diffusion region.
- Observations of electrostatic solitary wave/electron hole and turbulence in the reconnection region have been reported. (e.g., Eastwood et al., PRL, 2009)
- Current filamentation is the mechanism for breaking magnetic field-line during reconnection.

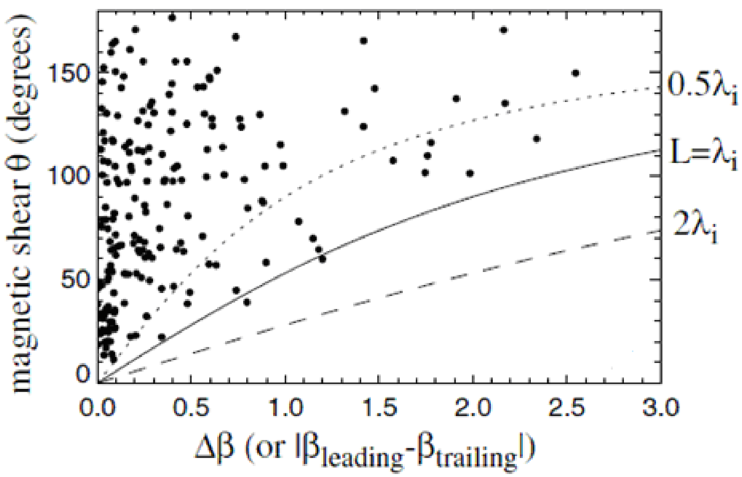
  (Che et al., Nature, 2011)

MR Dependence of Plasma Beta and Magnetic Shear Angle

Swisdak et al. (ApJ, 2010) :

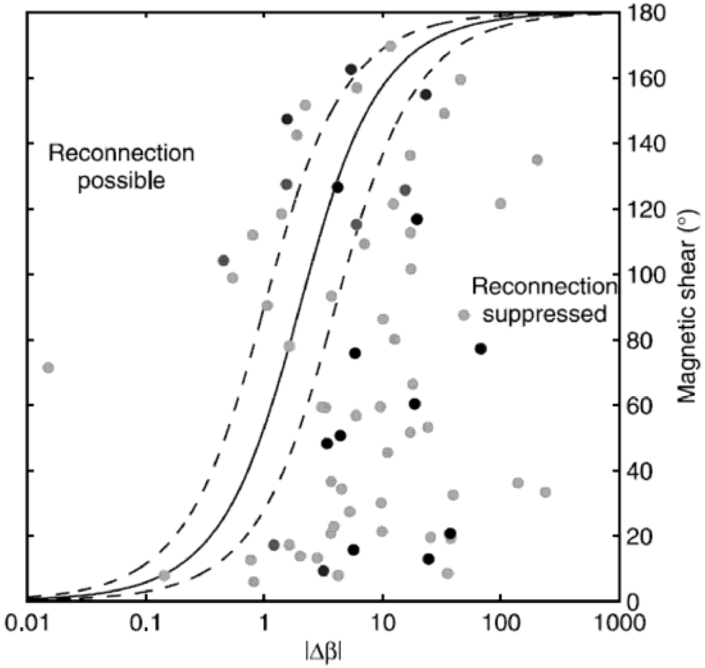
Reconnection is suppressed for $\Delta\beta > 2(L/\lambda_i)\tan(\theta/2)$

Solar Wind



Phan et al., ApJL, 2010.

Saturn's Magnetopause



Master et al., GRL, 2012.

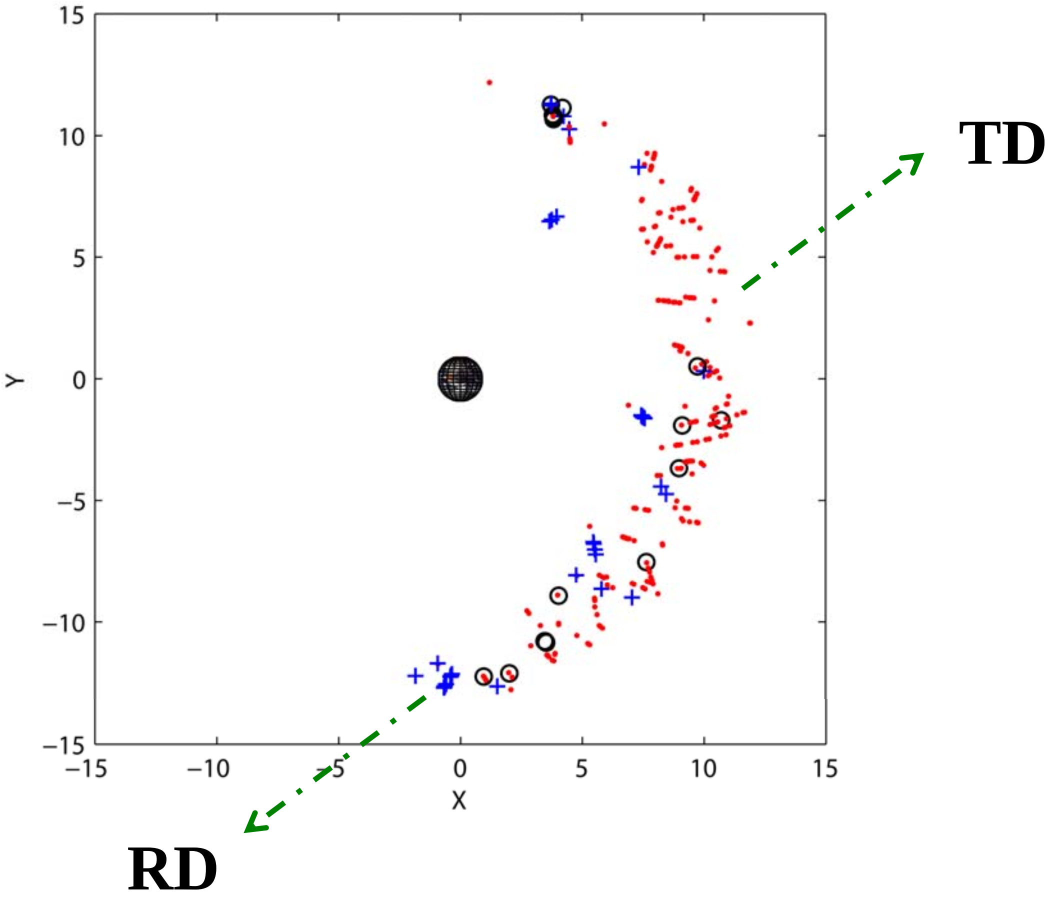
MR at Earth's Magnetopause

☆ **How often does MR occur ?**

☆ **Reconstruction of MR topology**

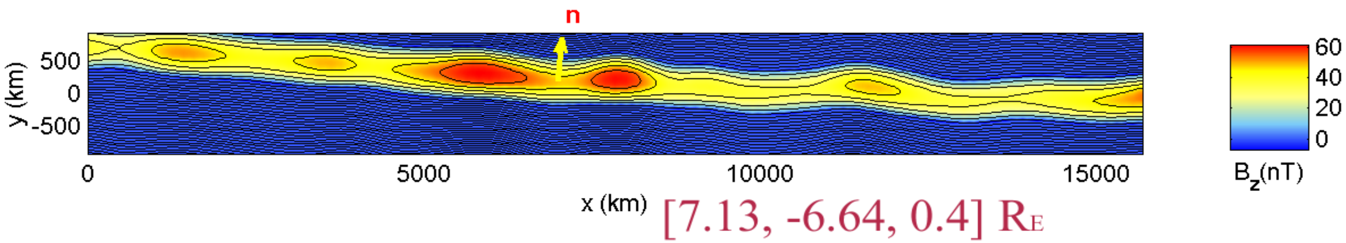
☆ **Some mechanisms for achieving fast reconnection**

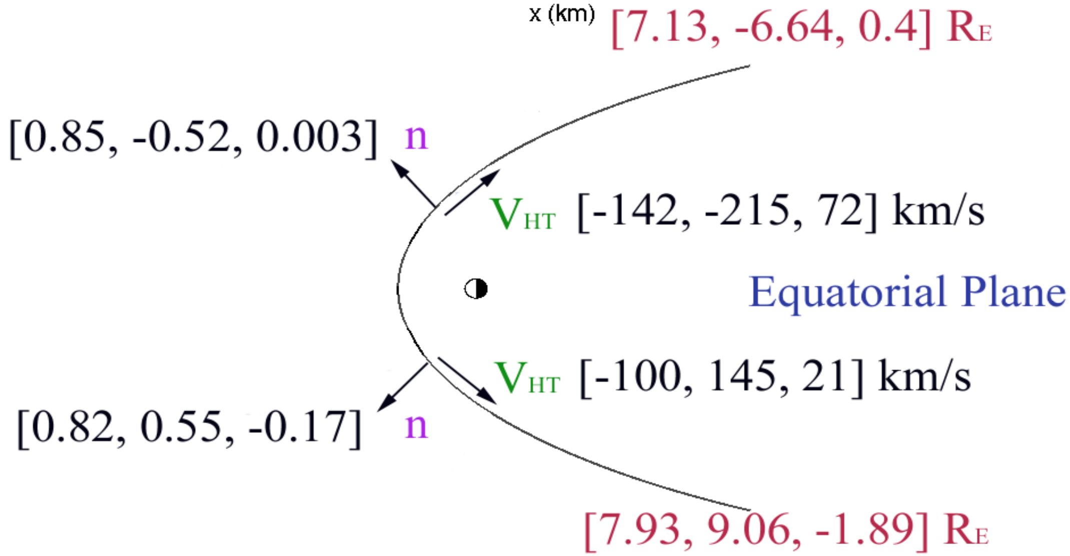
Spatial Distribution of 142 Crossings



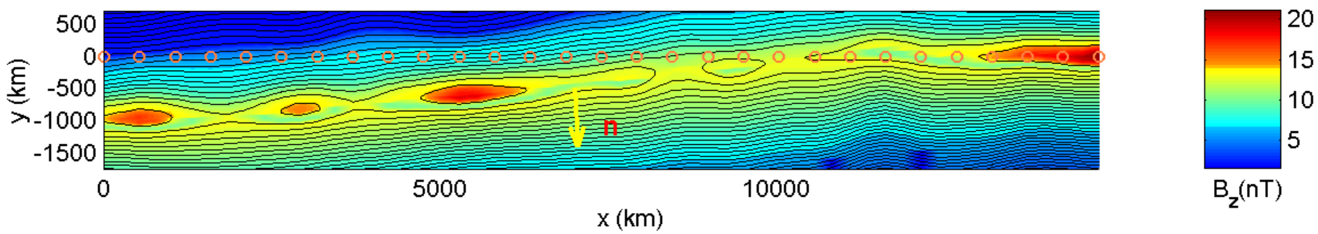
Chou and Hau, JGR, 2012.

Twin TD events
at Dawn and Dusk Sides of Magnetopause

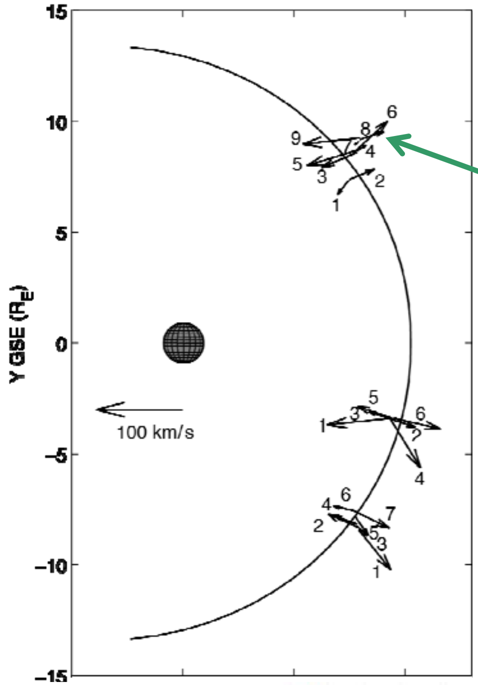


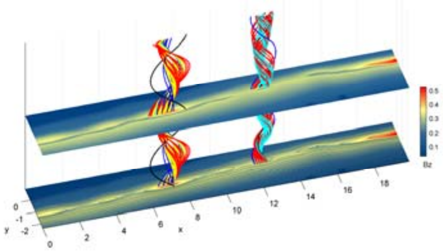


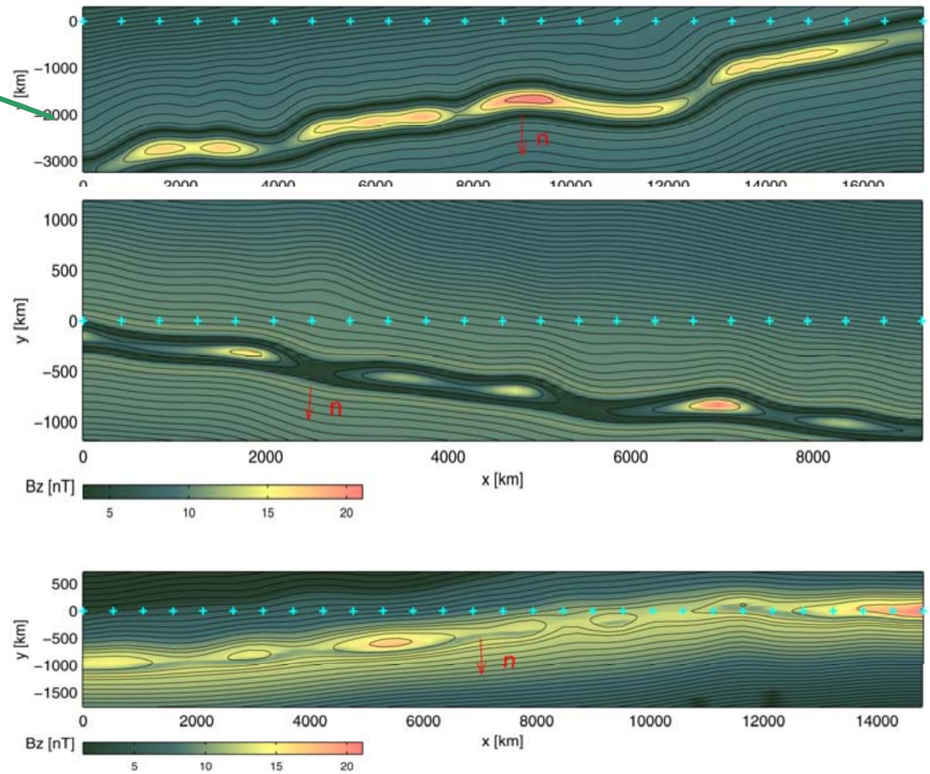
Teh and Hau, 2004; 2006.



Multiple Crossings Event







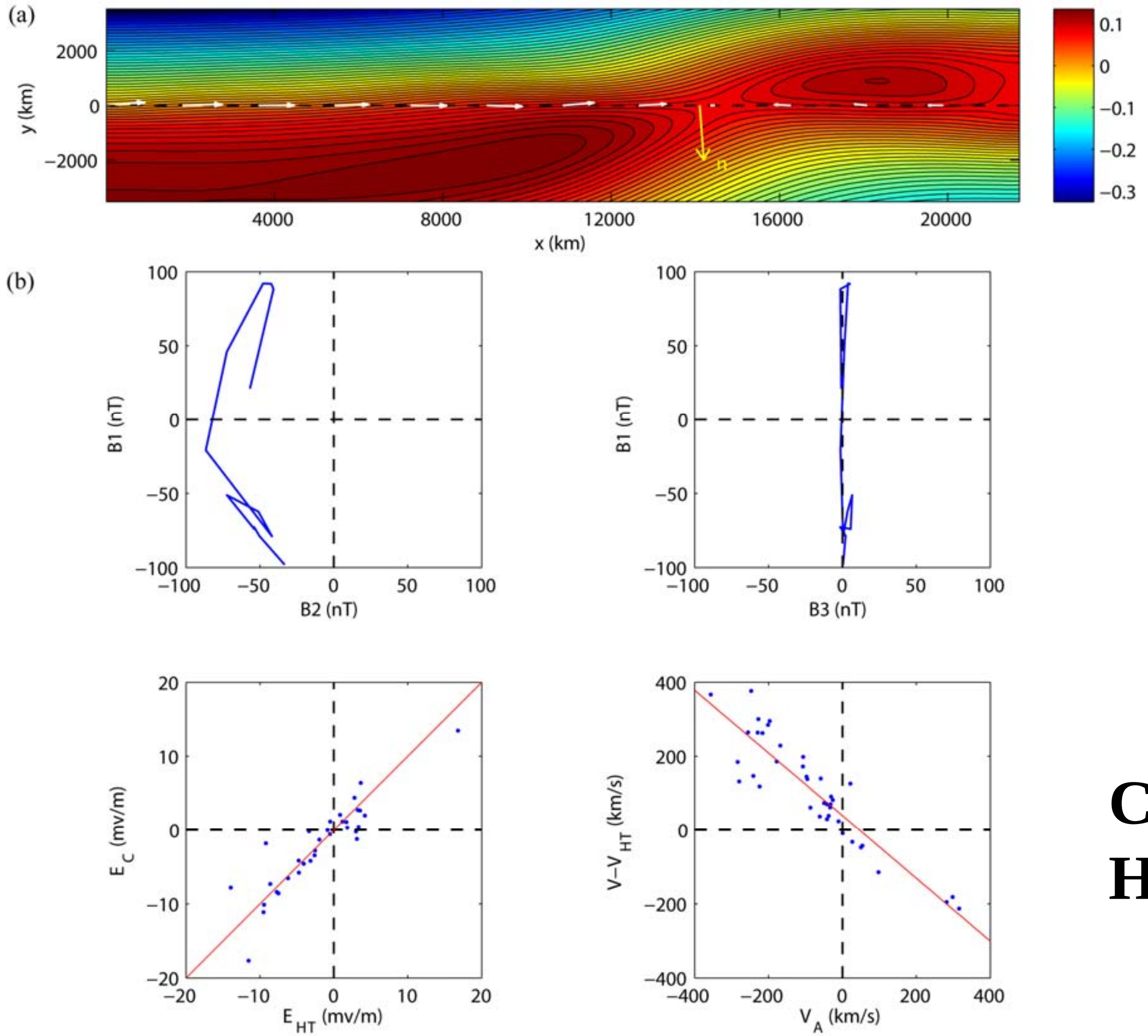
3

4

9

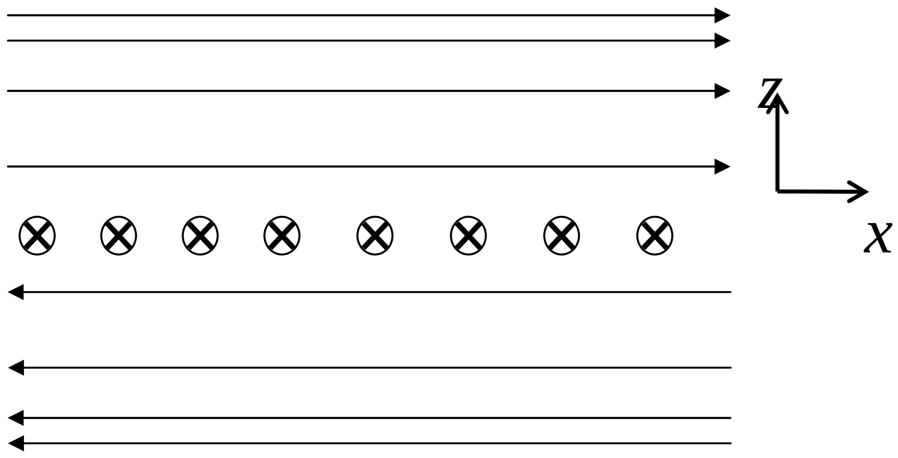
(Teh and Hau, JGR 2007)

RD Event – Tearing Instability?



Chou and Hau, 2012.

Harris Sheet Magnetic Field Model (Harris, 1962)

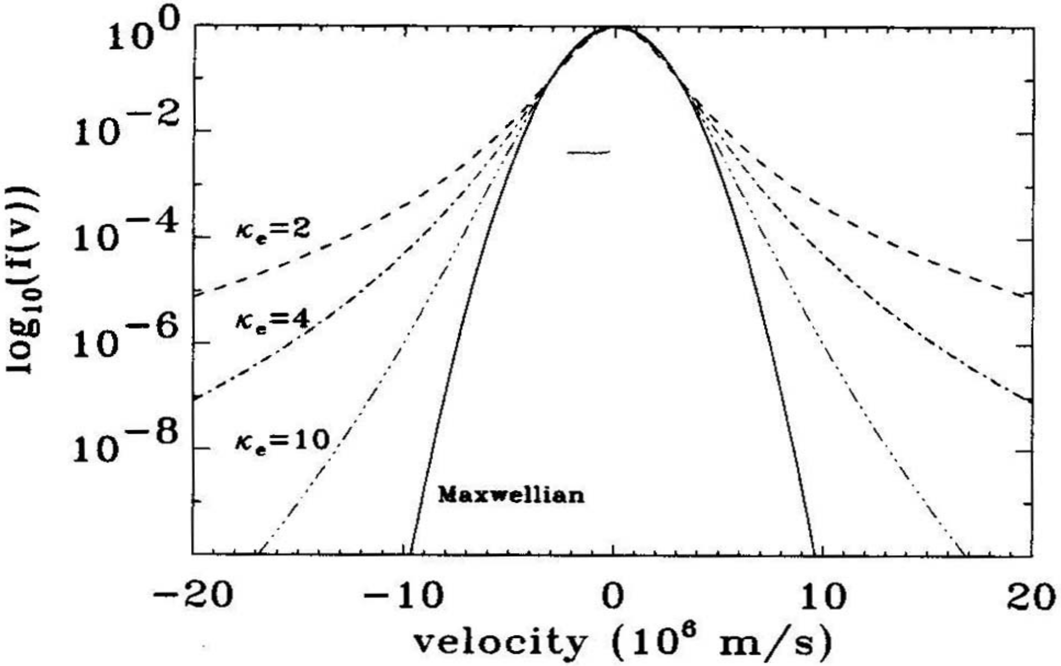


$$\vec{B} = B_o \tanh\left(z/h\right)\hat{x}$$

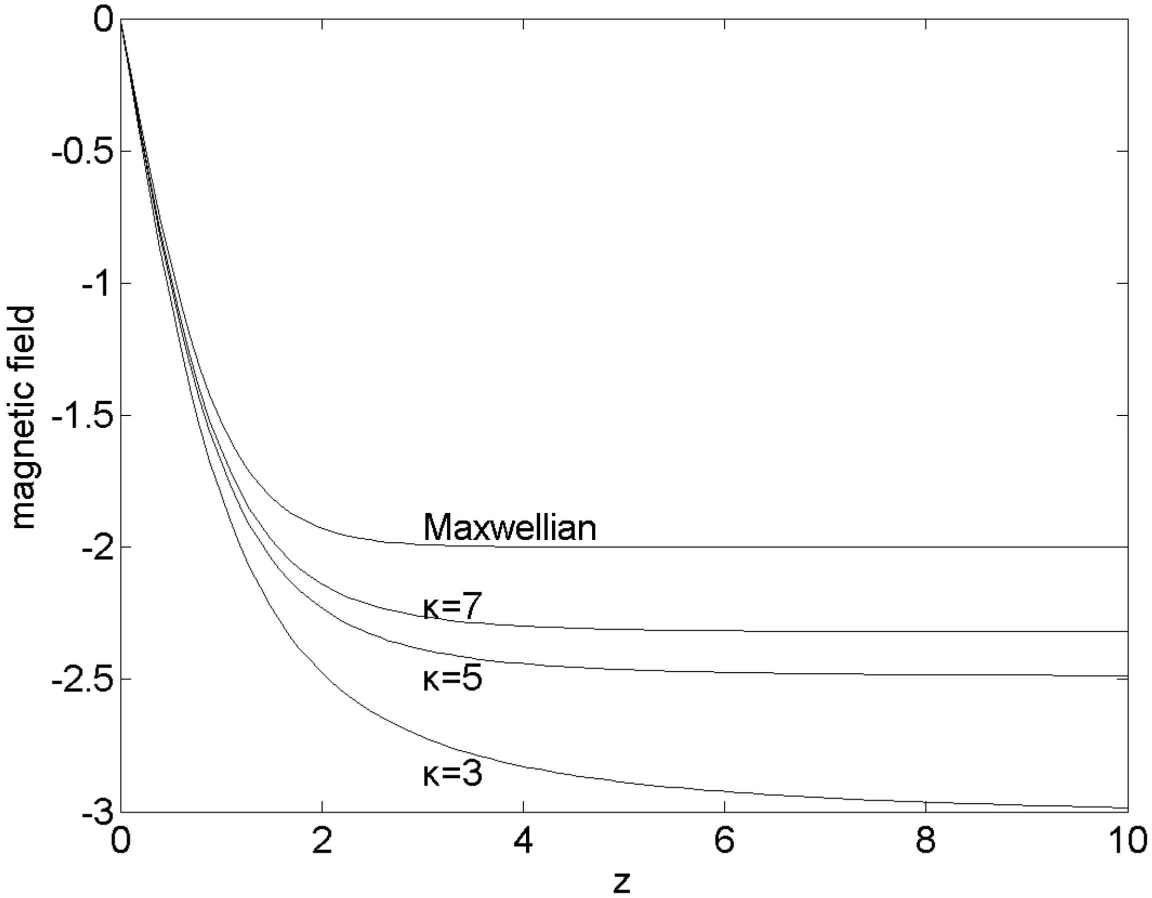
$$p = p_0 \,\mathrm{sech}^2(z/h)$$

Kappa Velocity Distribution

$$f^{\kappa}(\vec{v}) = \frac{n}{2\pi(\kappa v_{\kappa}^{2})^{3/2}} \frac{\Gamma(\kappa+1)}{\Gamma(\kappa-\frac{1}{2})\Gamma(\frac{3}{2})}(1+\frac{v^{2}}{\kappa v_{\kappa}^{2}})^{-(\kappa+1)}$$



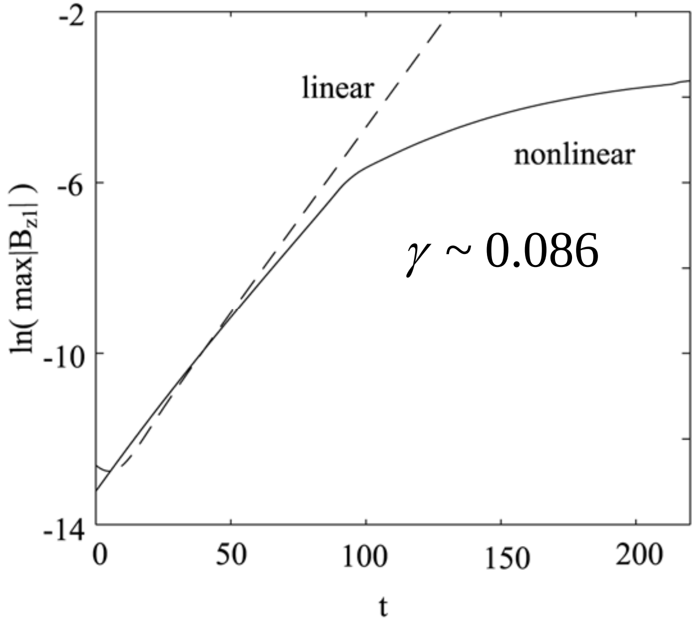
Generalized Harris Sheet Equilibrium Solutions



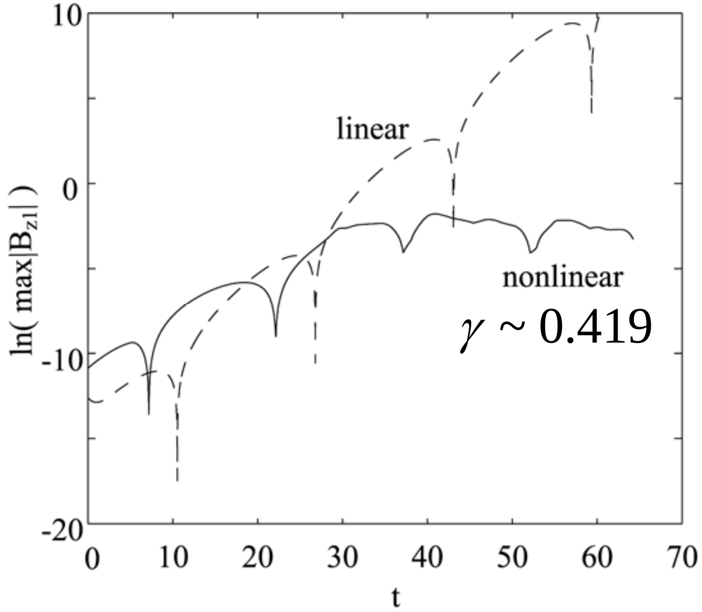
Fu and Hau, Hau and Fu, PoP 2005; 2007.

Growth Rate of Tearing Instability

$p_{\perp}/p_{\parallel} = 1.1$

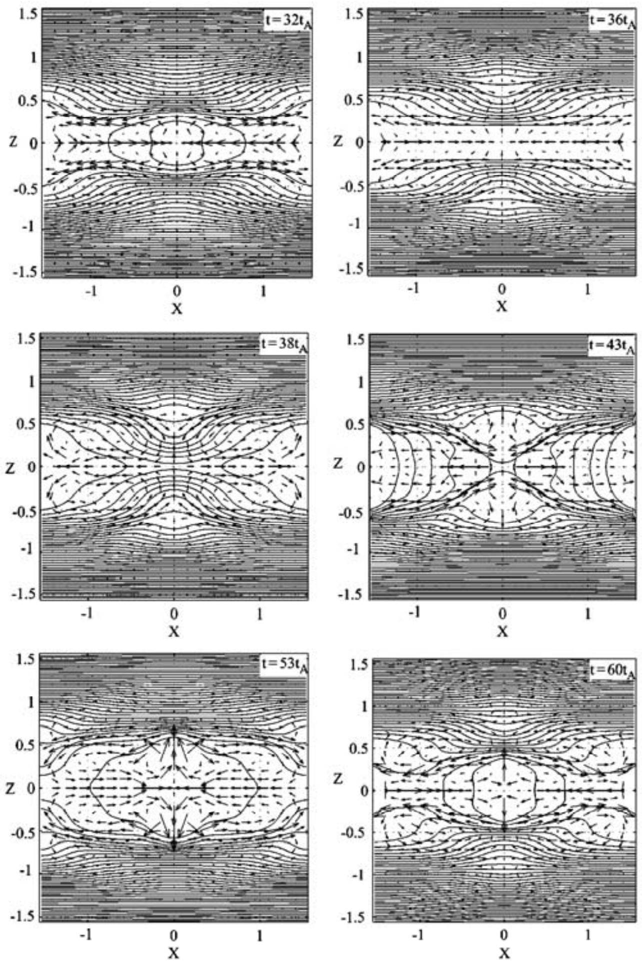


$p_{\perp}/p_{\parallel} = 1.25$



Chiou and Hau, 2002; 2003; 2004.

Oscillatory Tearing Instability



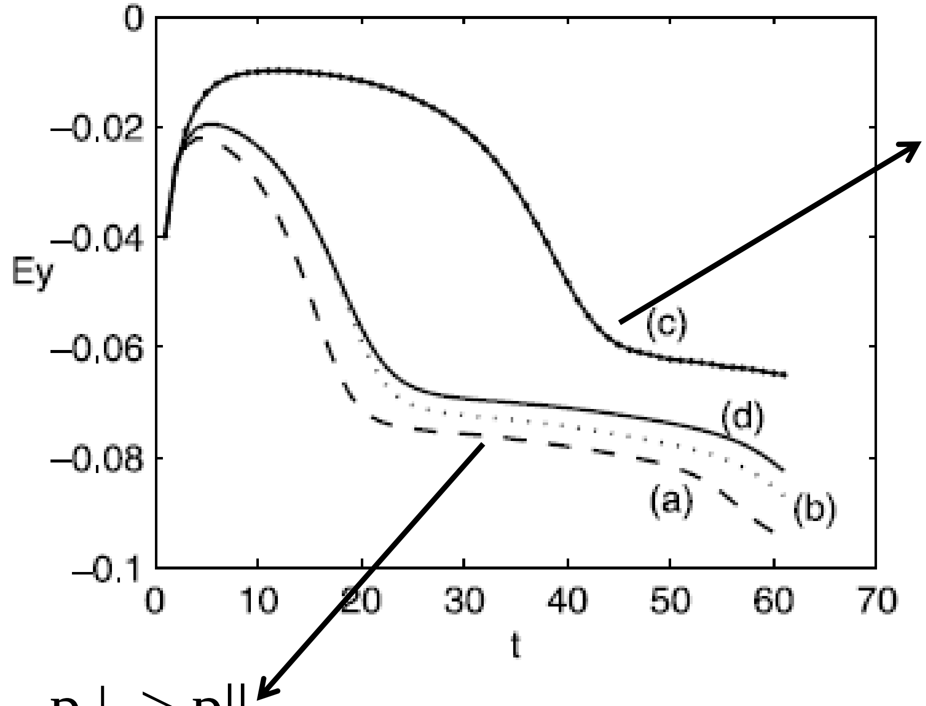
X-line and O-line may take place alternatively.

Plasma flow may reach the Alfven speed.

Turbulent reconnection

Chiou and Hau, 2002; 2003; 2004.

Reconnection Rate in Anisotropic Plasmas



p|| >> p⊥

p⊥ > p||

Hung, Hau and Hoshino, GRL, 2011.

ISSS-11

- The 11th International
- School/Symposium for
- Space Simulations will
- be held in Taiwan on
- July 21-27, 2013.
- Isss11.ncu.edu.tw