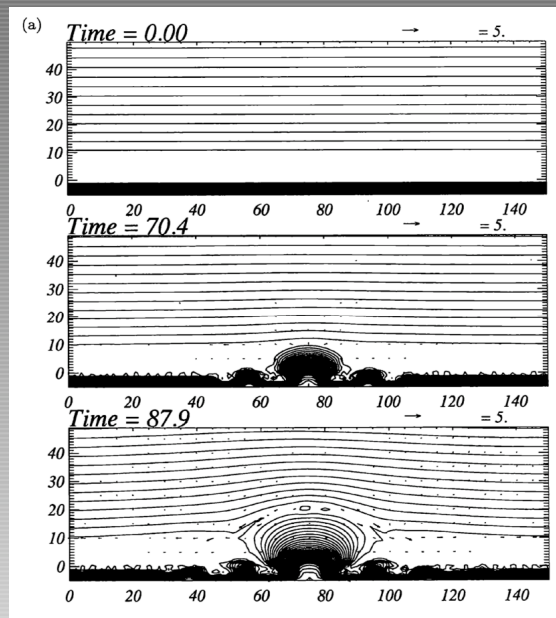
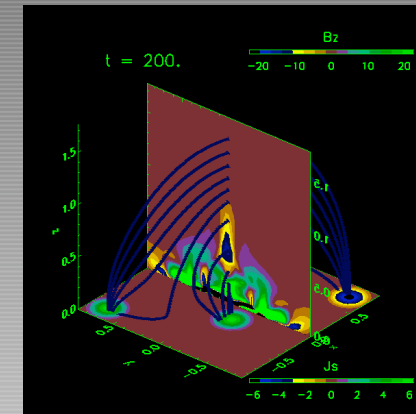
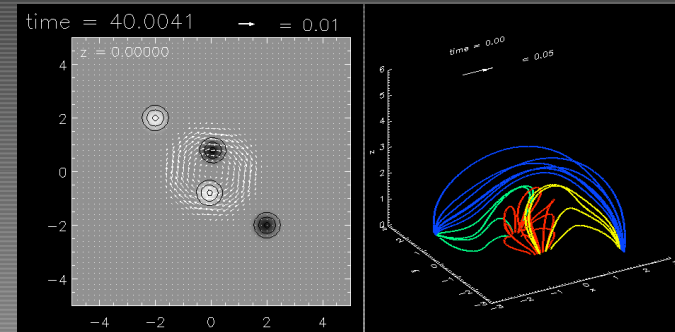


## *Interaction type* (current sheet formed in multiple flux domains)

When magnetic fields belonging to **different magnetic flux domains** interact with each other, a current sheet is formed around an **interface between them**.



Yokoyama & Shibata (1996)



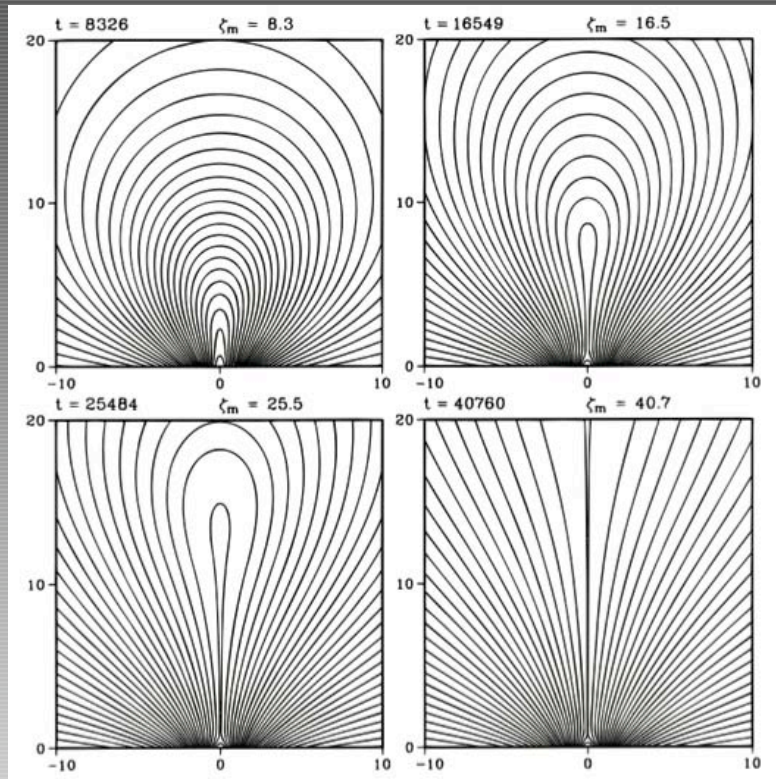
### 3D case

*Quadrupolar configuration with four flux domains*

([http://163.180.179.74/~magara/page31/Research\\_3DCS.html](http://163.180.179.74/~magara/page31/Research_3DCS.html))

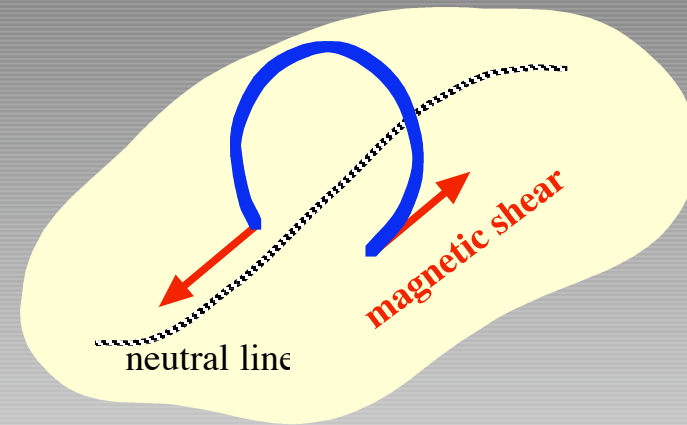
Longcope & Magara (2004)

## Stand-alone type (current sheet formed in a single flux domain)

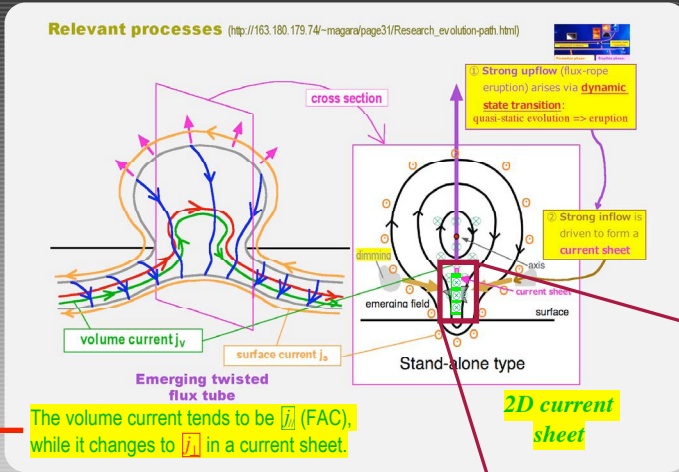


Choe and Lee (1996)

When **magnetic shear** increases in a **single magnetic flux domain**, a current sheet is formed **inside the domain**.



# 3D current sheet formed in an emerging twisted flux tube



## 3D current sheet

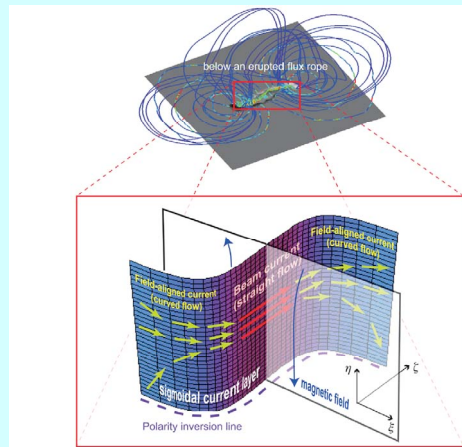
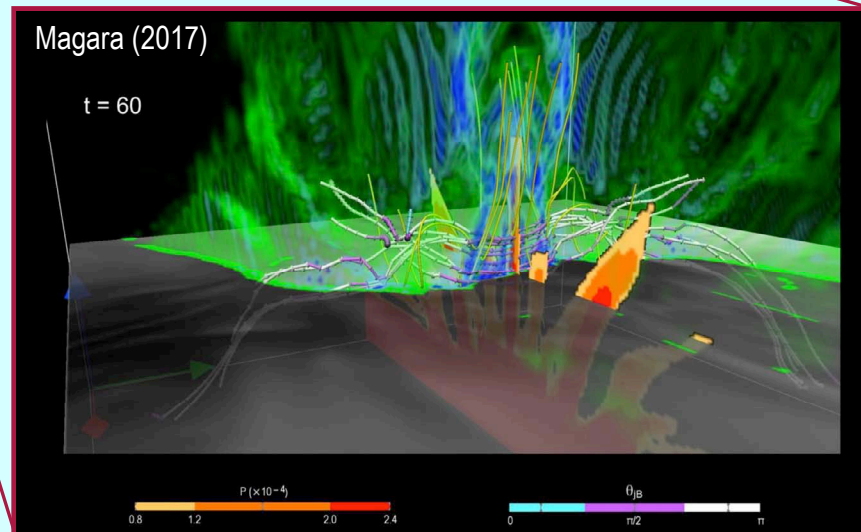


Fig. 14. Forward S-shaped sigmoidal current layer with beam current is schematically illustrated. (Color online)



Lorentz force  $j_{\perp} \times B$  is balanced by  $-\nabla P_{\text{tot}}$ . ( $j_{\perp}$ -based free magnetic energy is not converted to kinetic energy).



see also [http://163.180.179.74/~magara/seminars/flare-producing\\_current\\_system.pdf](http://163.180.179.74/~magara/seminars/flare-producing_current_system.pdf)

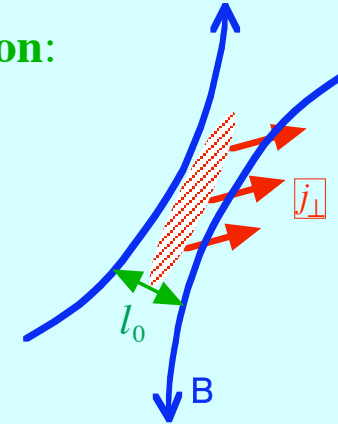
# Energy release phase

main phase of a flare

## A time scale problem...

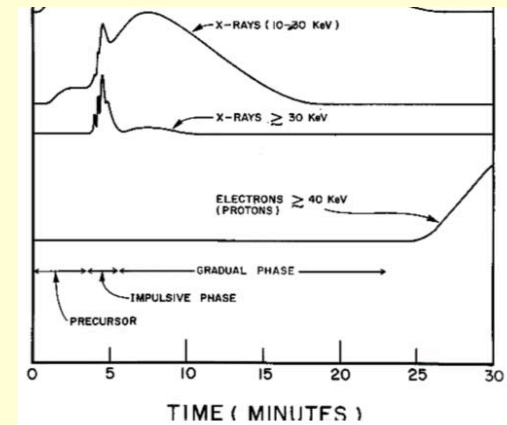
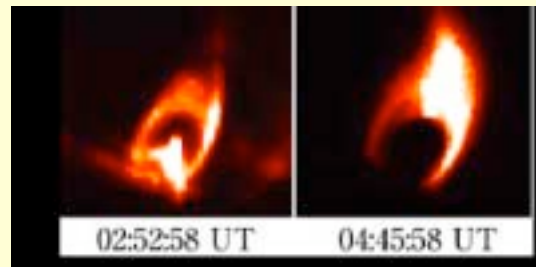
Time scale of releasing free magnetic energy via **diffusion**:

$$\tau_{diff} \sim \frac{l_0^2}{\eta_{diff}} \Rightarrow \frac{(10^9 \text{ cm})^2}{10^4 \text{ cm}^2 \text{ s}^{-1}} \sim 10^{14} \text{ s}$$



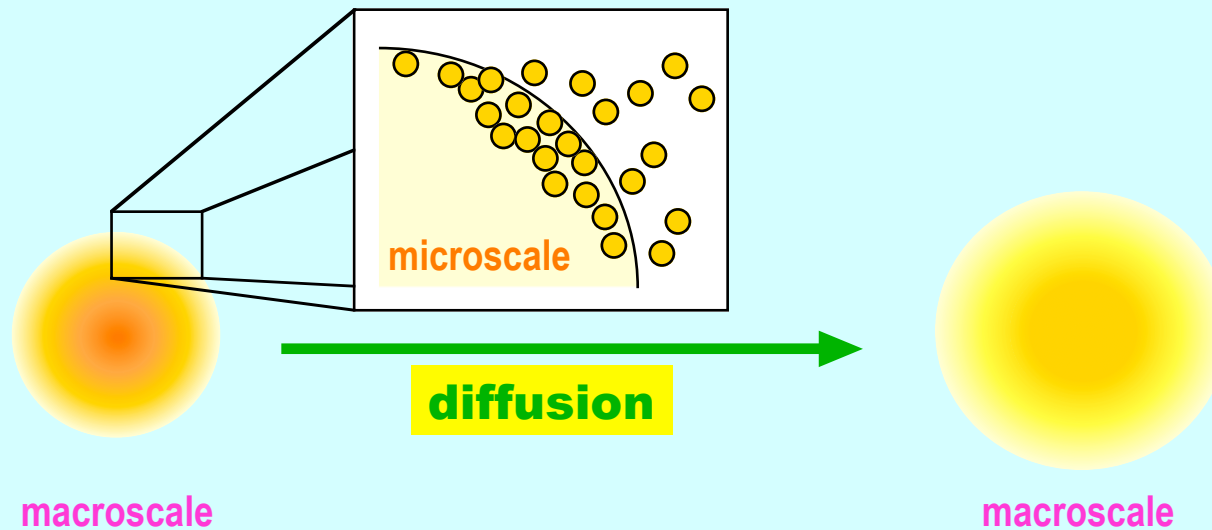
**Huge gap!**

Typical time scale of the **main phase**...  $10^3 \text{ s}$



# What is diffusion?

A **microscale process** ( $\leq$  kinetic approach) caused by **collision of particles**, which makes a **macroscale distribution** ( $\leq$  fluid approach) **smooth**.



**Diffusion** is characterized by **microscale evolution**:

$\Rightarrow$  **mean free path/inertial length  $l$**  & **collision time  $\tau_c$**

**dimension of diffusivity ( $\text{cm}^2/\text{s}$ )... velocity ( $\text{cm}/\text{s}$ ) x length ( $\text{cm}$ )**

$$v l = \frac{l}{\tau_c} l = \frac{l^2}{\tau_c}$$

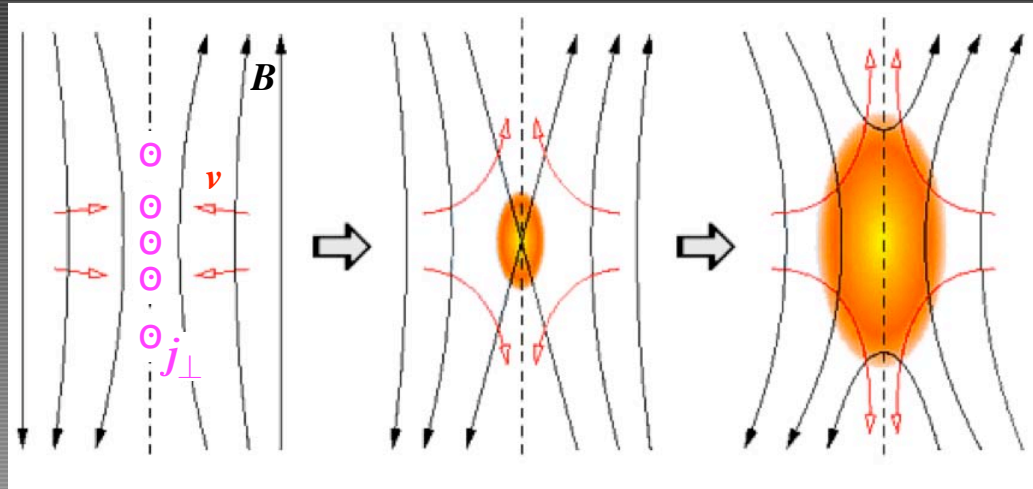
To solve the time scale problem, we need a process of releasing free magnetic energy (i.e., dissipating cross-field electric current  $j_{\perp}$ ) much faster than diffusion.



**Magnetic reconnection** could be the process.

# What is magnetic reconnection?

black arrows... *magnetic field*  
red arrows ... *flow*



**flow-coupled diffusion eq.**

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) - \nabla \times (\eta_{diff} \nabla \times \mathbf{B})$$

$\mathbf{v} = \mathbf{0}, \eta_{diff}: \text{uniform}$

**diffusion eq.**

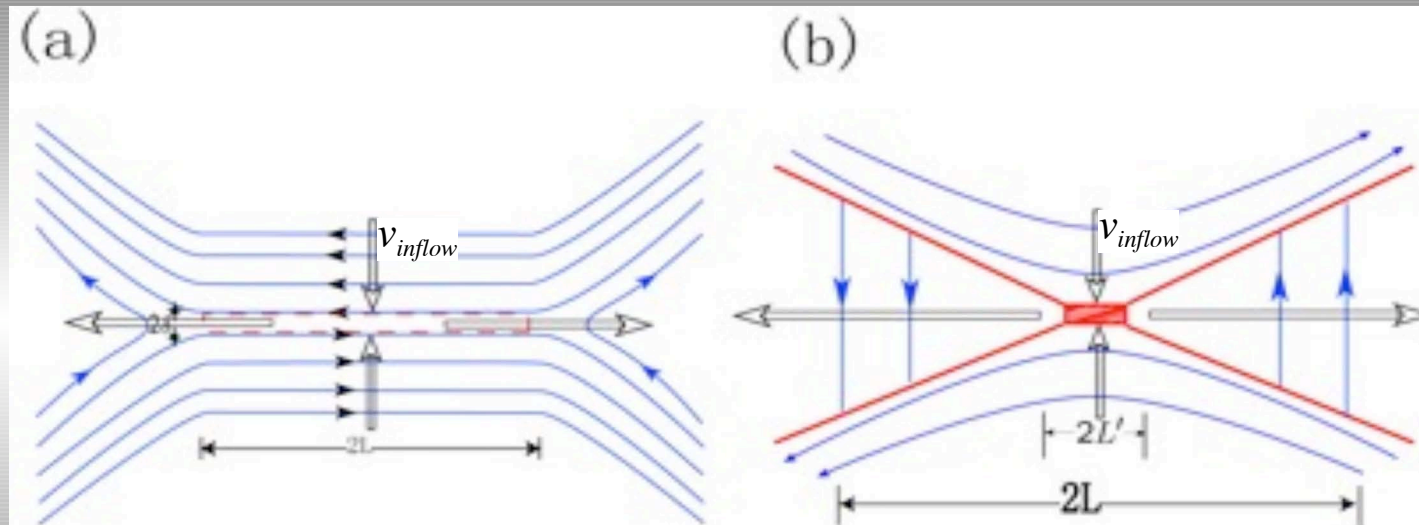
$$\frac{\partial \mathbf{B}}{\partial t} = \eta_{diff} \nabla^2 \mathbf{B}$$

It is **flow-coupled diffusion** by which  **$j_{\perp}$ -based** free magnetic energy is efficiently converted into thermal and kinetic energy.

# Models of magnetic reconnection

The following reconnection models assume **different magnetic field configurations**.

Dependence of *reconnection speed*  $M_A = \frac{v_{inflow}}{v_A}$  on **magnetic Reynolds number**  $R_m \equiv \frac{v_A L}{\eta_{diff}}$  is significantly different between them.



## Sweet-Parker model

**long** diffusion region

$$M_A \sim \frac{1}{\sqrt{R_m}}$$

## Petschek model

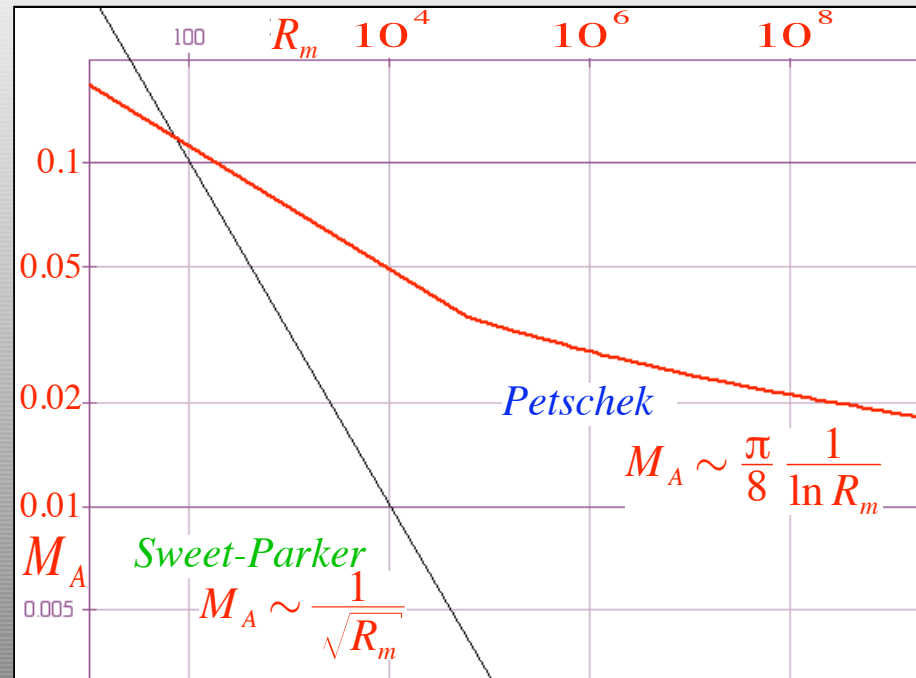
**short** diffusion region

$$M_A \sim \frac{\pi}{8} \frac{1}{\ln R_m}$$

When  $R_m$  is large, *Petschek model* is more suitable for rapid energy release than *Sweet-Parker model*.

Simple diffusion

$$M_A \sim \frac{1}{R_m}$$

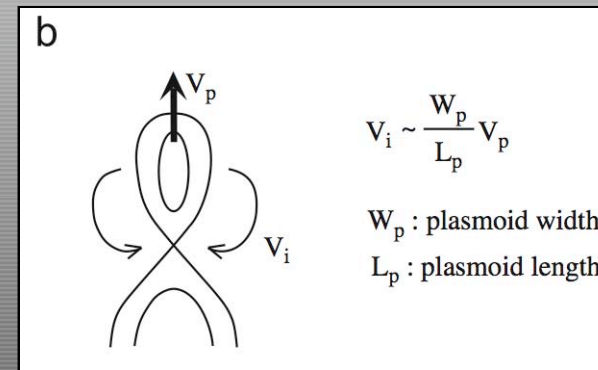
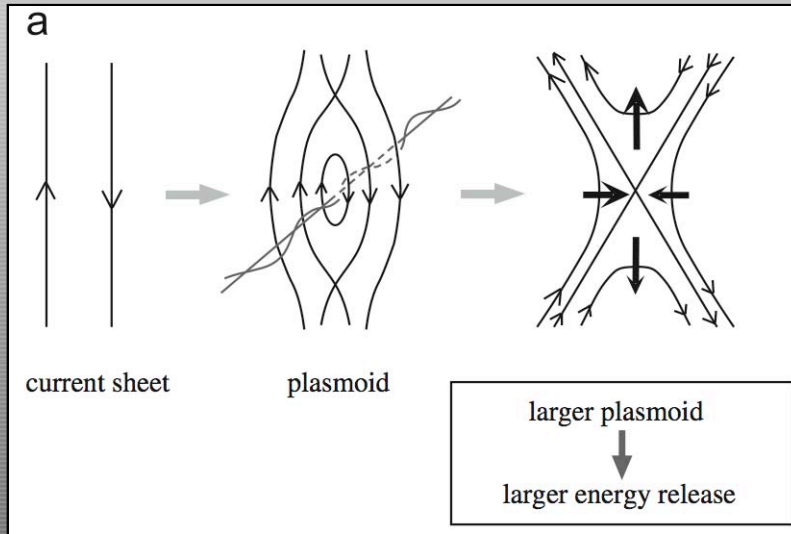
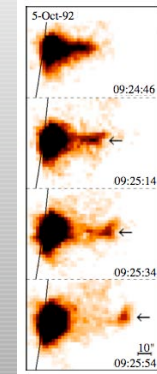


In the solar corona,  $R_m \sim 10^{13}$

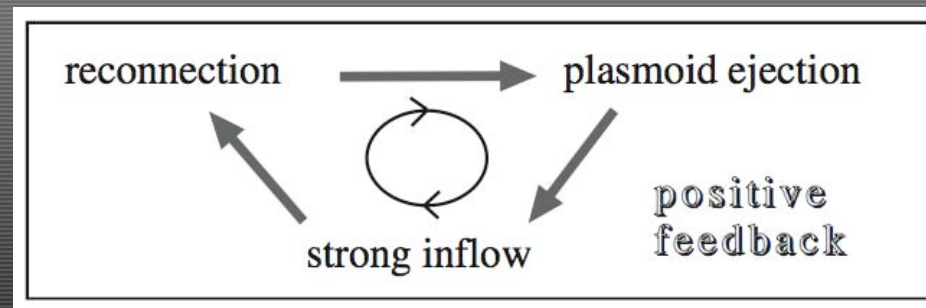
→  $M_A \sim 0.01$  (*Petschek model*)

This can explain the time scale of a flare ( $t^{\text{Petschek}} \sim \frac{L}{M_A v_A} = \frac{10000 \text{ (km)}}{0.01 \times 1000 \text{ (km/s)}} = 1000 \text{ (sec)}$ ).

***Plasmoid ejection may play a key role in non-steady energy release...***

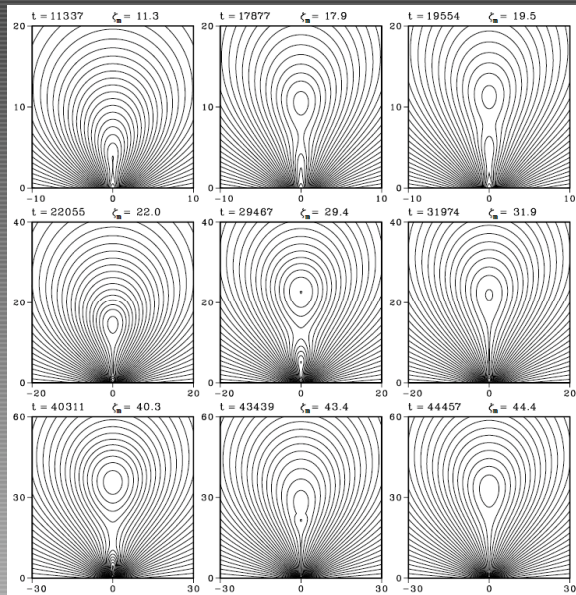


Shibata (1999)



# Multiple plasmoid ejection

multiple plasmoid ejection => a series of non-steady energy releases => intermittent emissions



Choe & Cheng (2000)

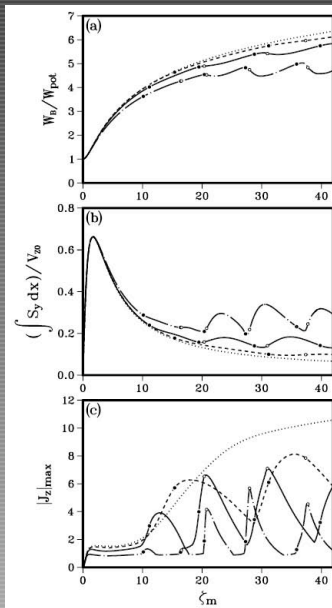
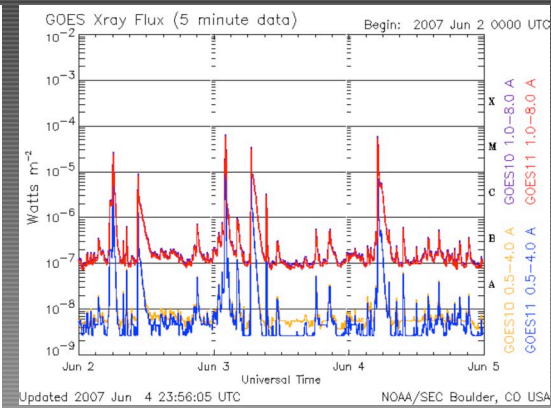


FIG. 5.—Evolution of (a) magnetic energy in units of the potential field energy; (b) Poynting flux through the bottom boundary divided by  $V_{\text{pot}}$ ; and (c) maximum magnitude of the current density in the current sheet under the magnetic island for all subcases of Case I. All the quantities are plotted as a function of  $z_m$ , which is the plasma displacement at  $x = \pm 1$ . In all three figures, the solid lines represent Case 1A, in which  $V_{\text{pot}} = 10^{-3} v_0$  and  $\eta = 10^{-2}$ ; the chain-dotted lines represent Case 1B, in which  $V_{\text{pot}} = 10^{-2} v_0$  and  $\eta = 5 \times 10^{-5}$ ; and the dashed lines represent Case 1C, in which  $V_{\text{pot}} = 5 \times 10^{-3} v_0$  and  $\eta = 10^{-5}$ . The dotted lines are for the ideal MHD case (Case 1D), in which  $V_{\text{pot}} = 10^{-3} v_0$  and  $\eta = 0$ . Filled circles denote the initiation of a new reconnection event in the underlying arcade and the open circles indicate the completion of the island merging.



Updated 2007 Jun 4 23:56:05 UTC NOAA/SEC Boulder, CO USA

# Post-flare phase

transport of released energy to lower atmosphere

and

responses from the atmosphere to it