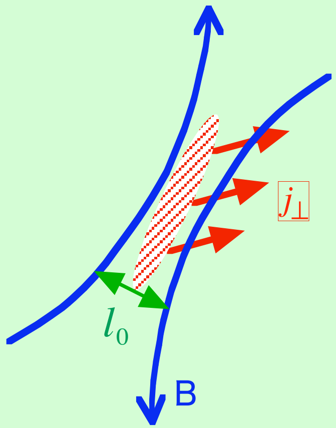
Energy release phase

main phase of a flare

A time scale problem...

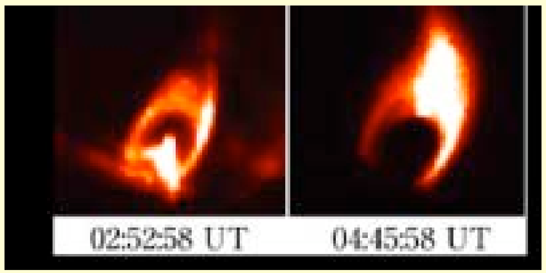
Time scale of energy release via diffusion (no flow)

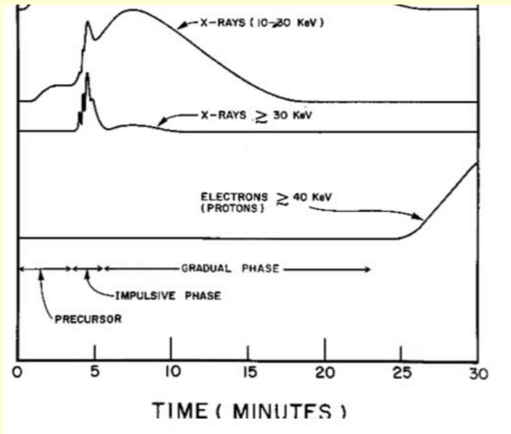
$$\tau_{diff} \sim \frac{l_0^2}{\eta_{diff}} \Rightarrow \frac{\left(10^9\ cm\right)^2}{10^4\ cm^2\ s^{-1}} \sim 10^{14}\ s$$



Huge gap!

Typical time scale of the main phase... $10^3\ s$





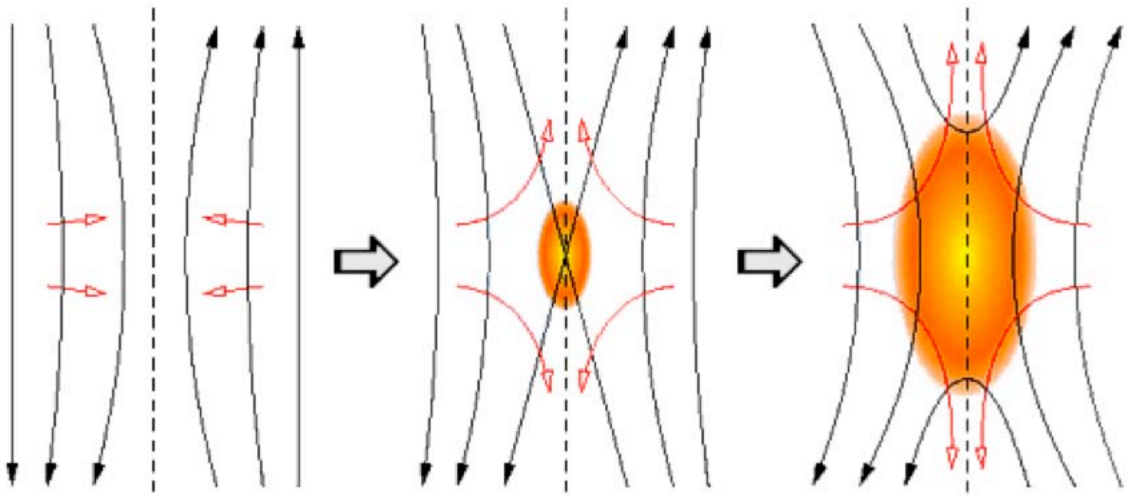
To explain the main phase of a flare, we need a mechanism for releasing free magnetic energy (i.e. dissipating cross-field electric current $j_{\perp}$) much faster than diffusion.

↓

Magnetic reconnection could be a mechanism that enables such fast energy release.

What is magnetic reconnection?

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



flow-coupled diffusion eq.

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

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

diffusion eq.

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

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

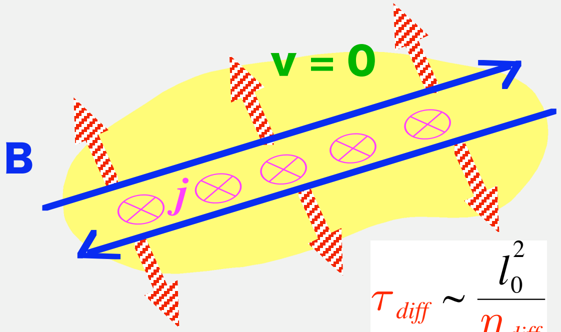
Difference between diffusion and reconnection...

• Diffusion

No flow (not dynamic process)

Magnetic field diffuses through a static plasma.

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



$$\tau_{diff} \sim \frac{l_0^2}{\eta_{diff}}$$

• Reconnection

Flow exists (dynamic process).

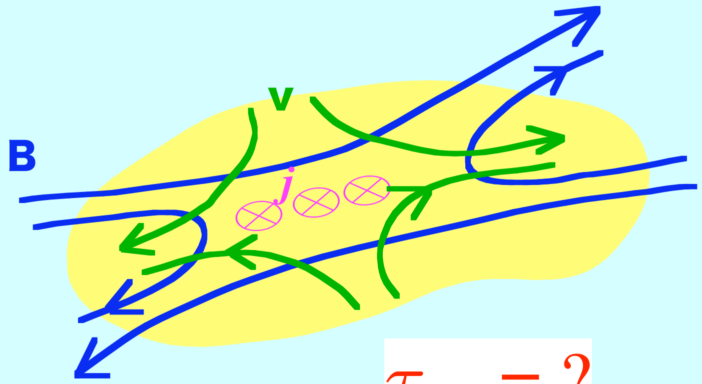
Magnetic field and flow interact with each other.

$$\frac{\partial \rho}{\partial t} + \nabla \bullet (\rho \boldsymbol{v}) = 0$$

$$\rho \left(\frac{\partial \boldsymbol{v}}{\partial t} + \boldsymbol{v} \bullet \nabla \boldsymbol{v} \right) = - \nabla p + \frac{1}{\mu_0} (\nabla \times \boldsymbol{B}) \times \boldsymbol{B}$$

$$\rho \frac{d}{dt} \left(\frac{1}{\gamma - 1} \frac{p}{\rho} \right) + p \nabla \bullet \boldsymbol{v} = \eta_{diff} \frac{|\nabla \times \boldsymbol{B}|^2}{\mu_0}$$

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



$$\tau_{rec} = ?$$

Speed of magnetic reconnection... characterized by **inflow speed**

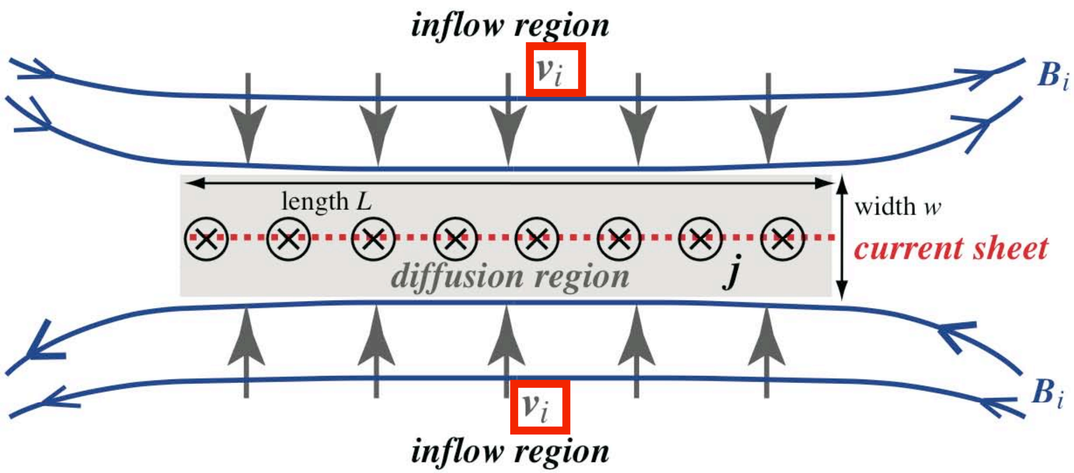


Figure 26: Magnetic reconnection in a current sheet.

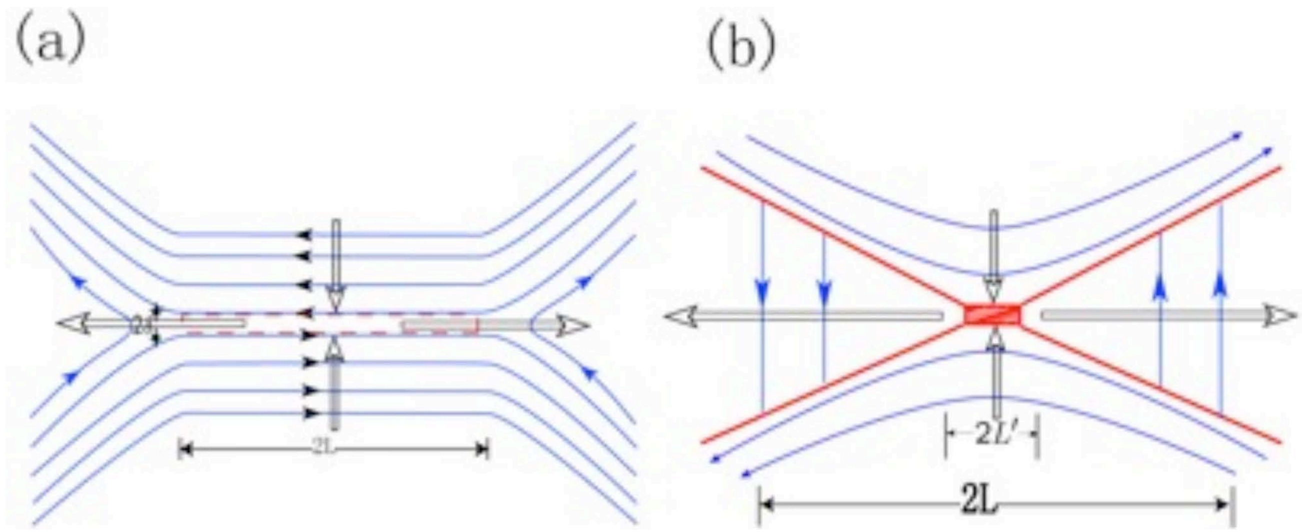
Shibata & Magara (2011)

Key parameter: $M_A \equiv \frac{v_{inflow}}{v_A}$

v_A: Alfvén speed in inflow region

Models of magnetic reconnection

The following two models assume different magnetic field configurations and flow patterns. Dependence of reconnection speed 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

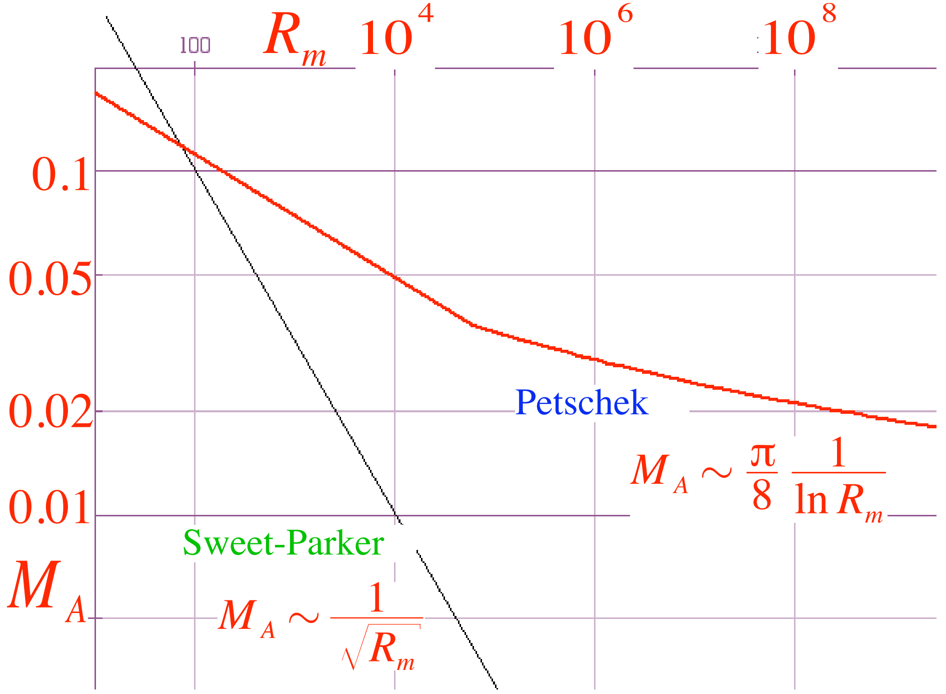
- **short diffusion region + slow MHD shocks**

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

When R_m is large, Petschek model is more suitable for a fast energy release than Sweet-Parker model.

Simple diffusion

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



In the solar corona, **Rm ～ 10^13**

→ **M_A ～ 0.01** (Petschek model)

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

From steady reconnection to non-steady reconnecton

Time profiles of radiative emissions during the main phase

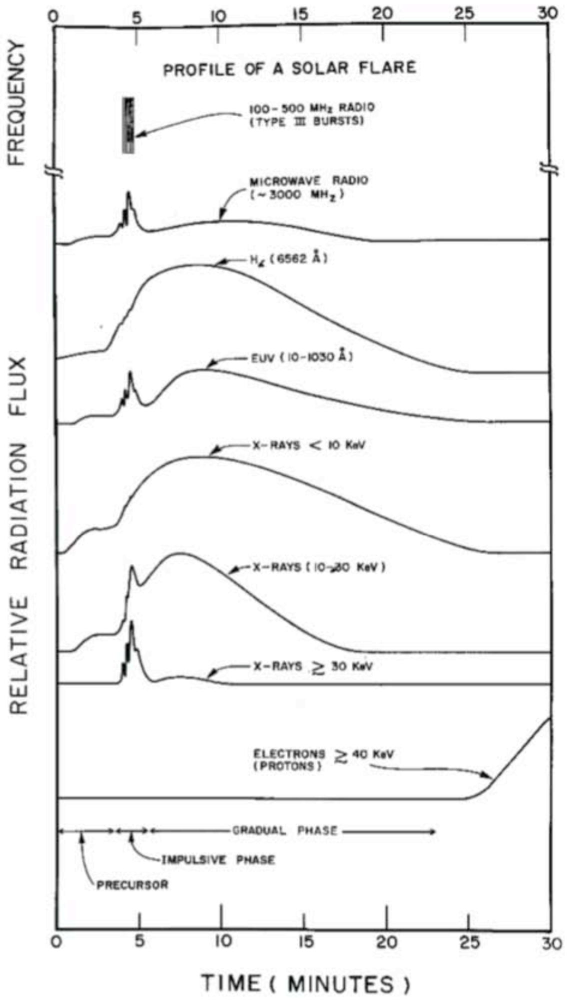
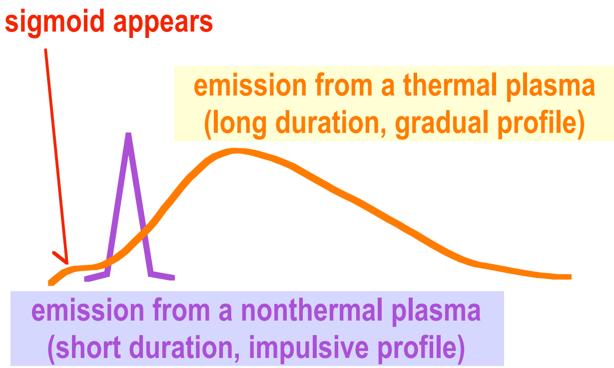
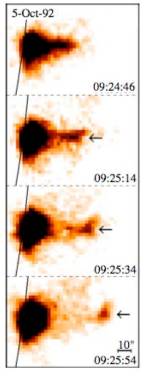


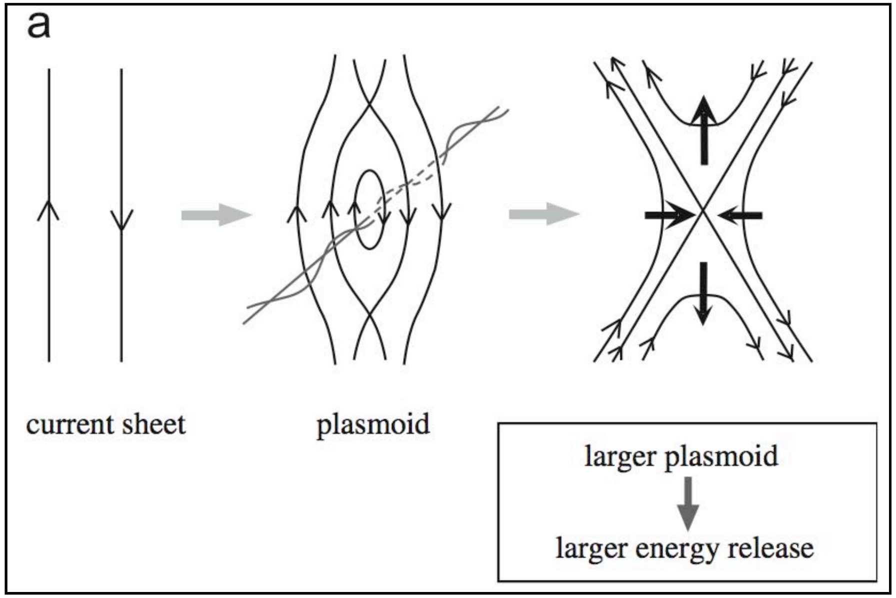
Figure 41: Typical time variation of emissions observed in various wavelengths during a flare (from Kane, 1974).

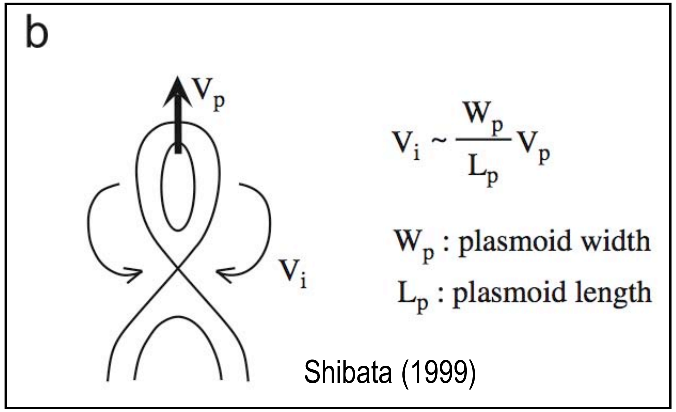


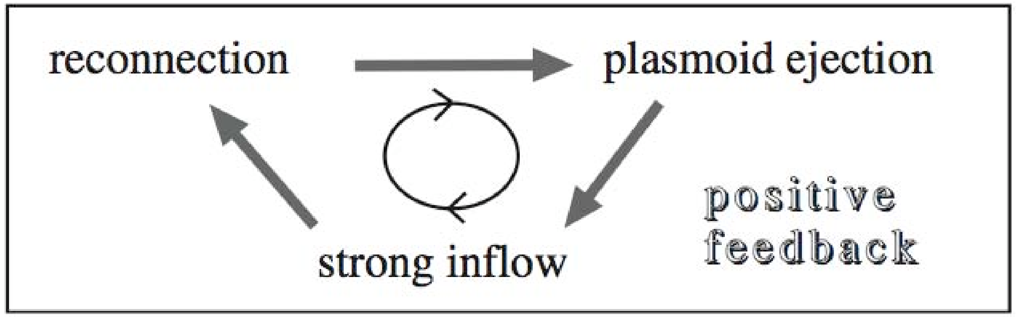
These time profiles suggest that **non-steady reconnection** proceeds during a flare.

Plasmoid ejection may play a key role in non-steady reconnection...



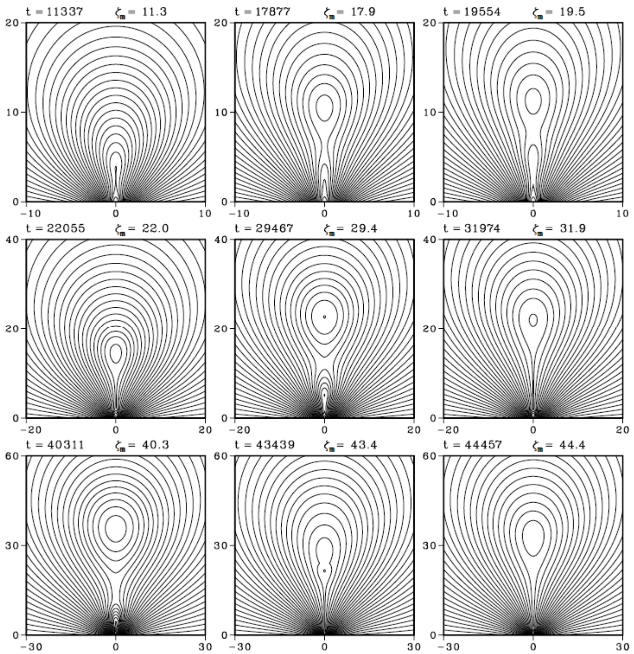






Multiple ejection of plasmoids

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



Choe & Cheng (2000)

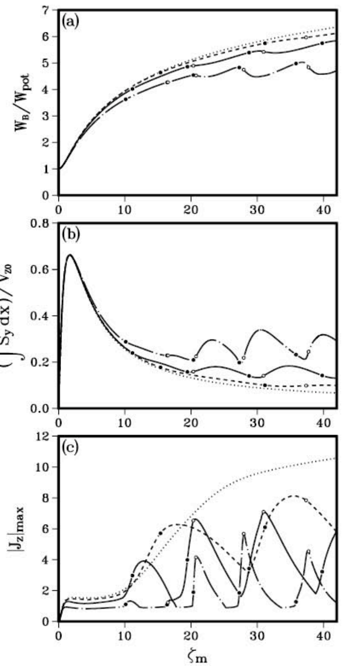
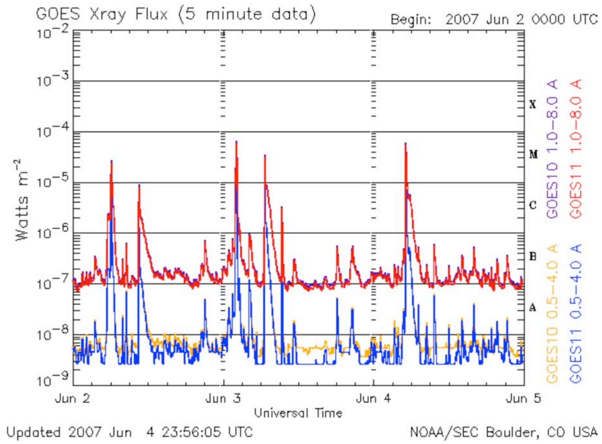
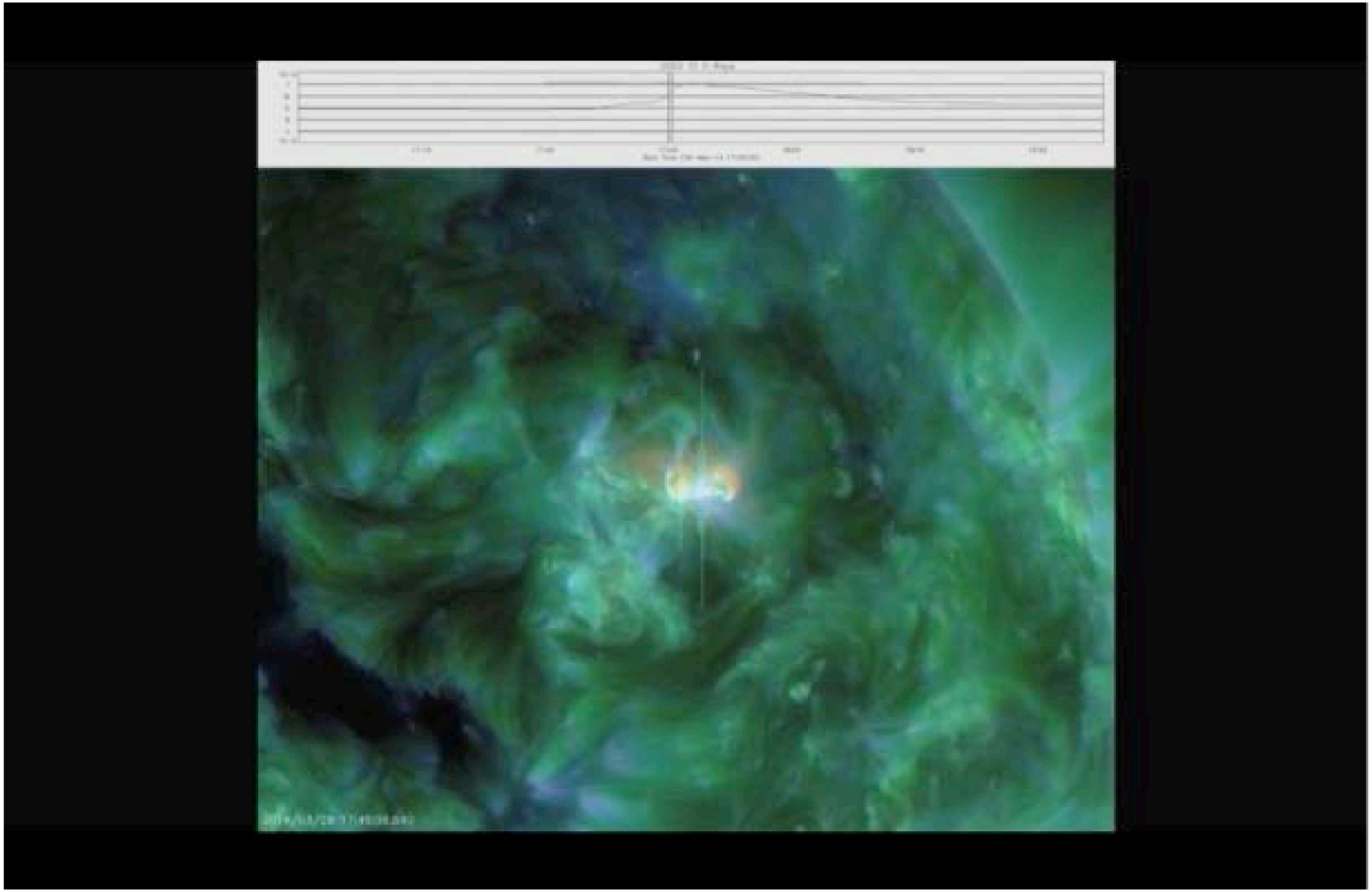


FIG. 5.—Evolution of (a) magnetic energy in units of the potential field energy; (b) Poynting flux through the bottom boundary divided by V_{z0}; and (c) maximum magnitude of the current density in the current sheet under the magnetic island for all subcases of Case 1. All the quantities are plotted as a function of ζ_m, which is the plasma displacement at $x = \pm 1$. In all three figures, the solid lines represent Case 1A, in which $V_{z0} = 10^{-3}\, v_0$ and $\eta = 10^{-5}$; the chain-dotted lines represent Case 1B, in which $V_{z0} = 10^{-3}\, v_0$ and $\eta = 5 \times 10^{-5}$; and the dashed lines represent Case 1C, in which $V_{z0} = 5 \times 10^{-3}\, v_0$ and $\eta = 10^{-5}$. The dotted lines are for the ideal MHD case (Case 1D), in which $V_{z0} = 10^{-3}\, v_0$ 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.



An X-class flare accompanying a CME (29 March, 2014)



A sigmoid appeared during the preflare phase.