Magnetic Reconnection in Solar Flares and CMEs

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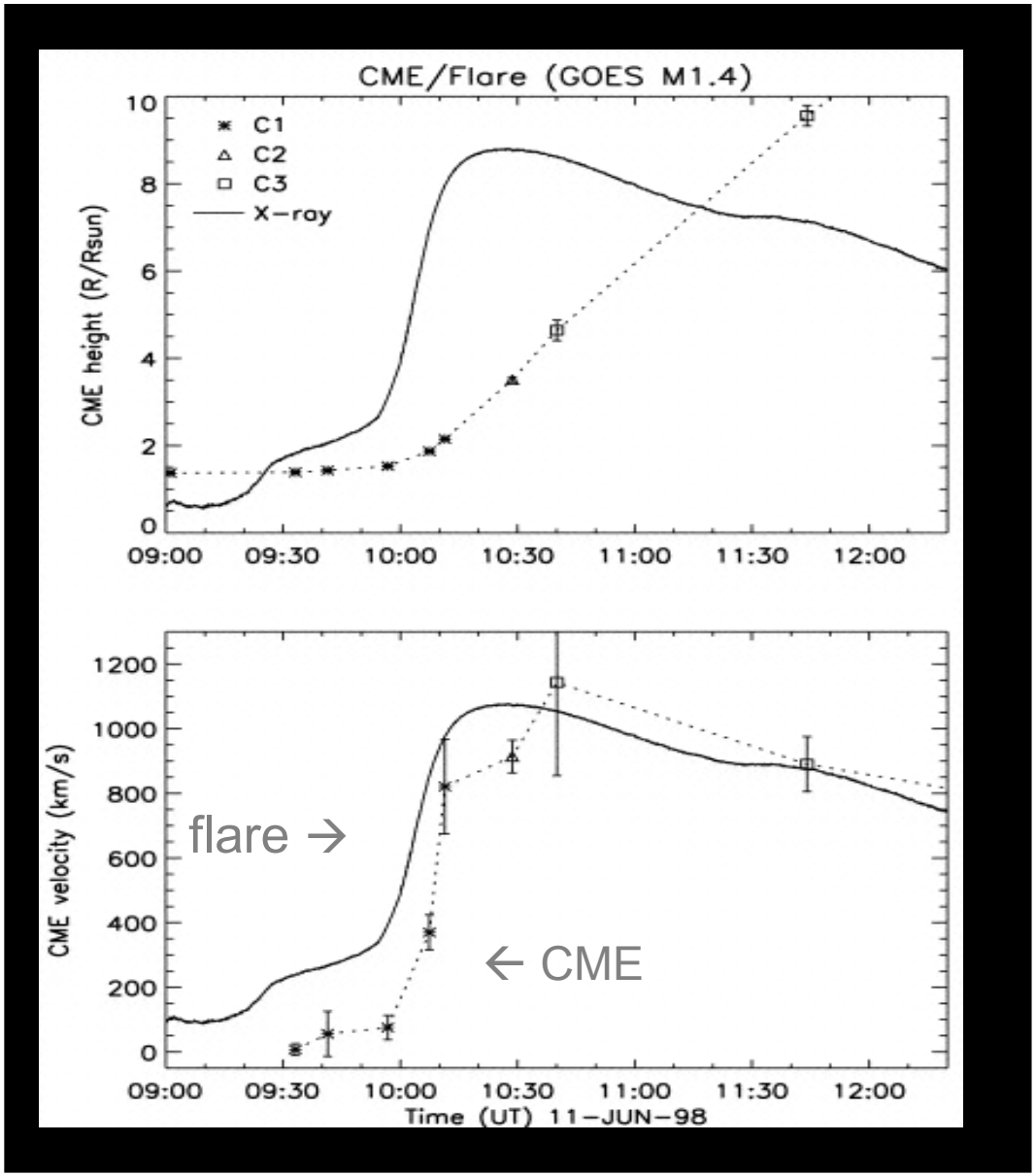
Solar Storms - Flares and Coronal Mass Ejections

Are flares and CMEs related by a common physical mechanism?

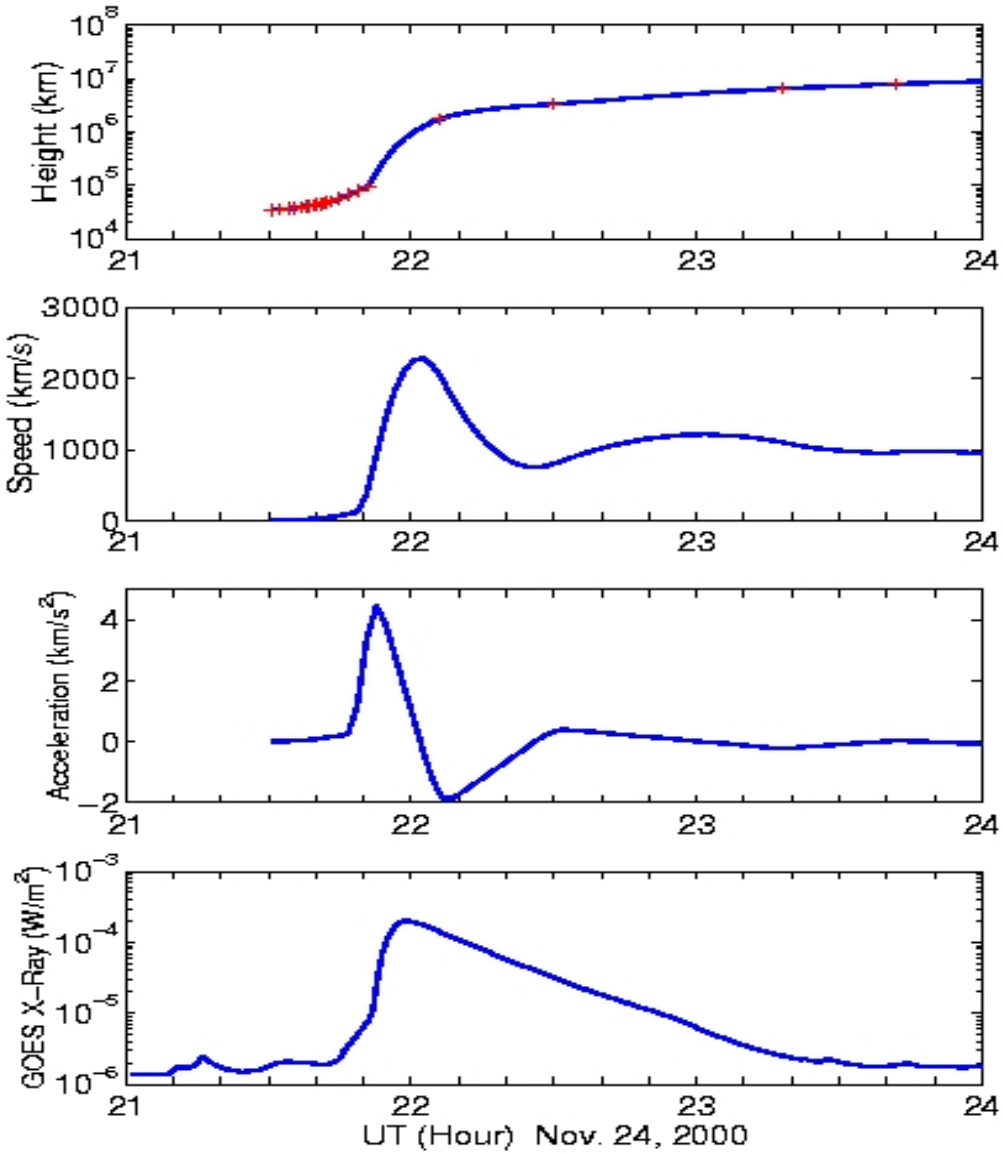
CME Motion and Flare X-Ray Emission



Fast acceleration of CMEs occurs in rising phase of flare soft X-ray emission

Zhang et al. 2001, Astrophysics J. Vol. 559 p 452

CMEs Are Accelerated During Flare Rise Phase



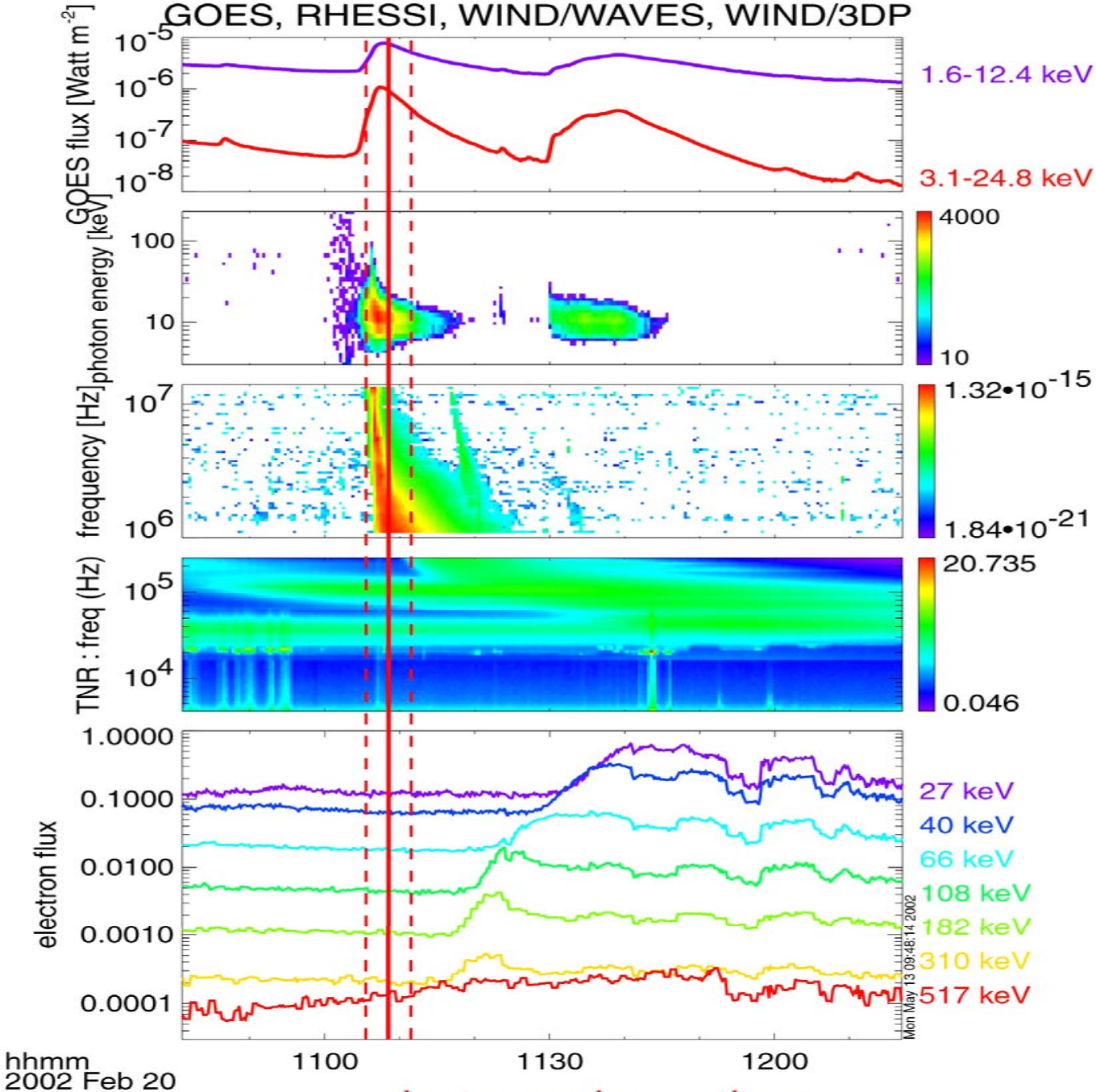
[Cheng *et al.*, ApJ, 2003]

Nov. 24, 2000
X1.8 flare event:

1) CME acceleration occurs in low corona

2) CME acceleration peaks during flare rise phase

3) HXR emission occurs at peak CME acceleration

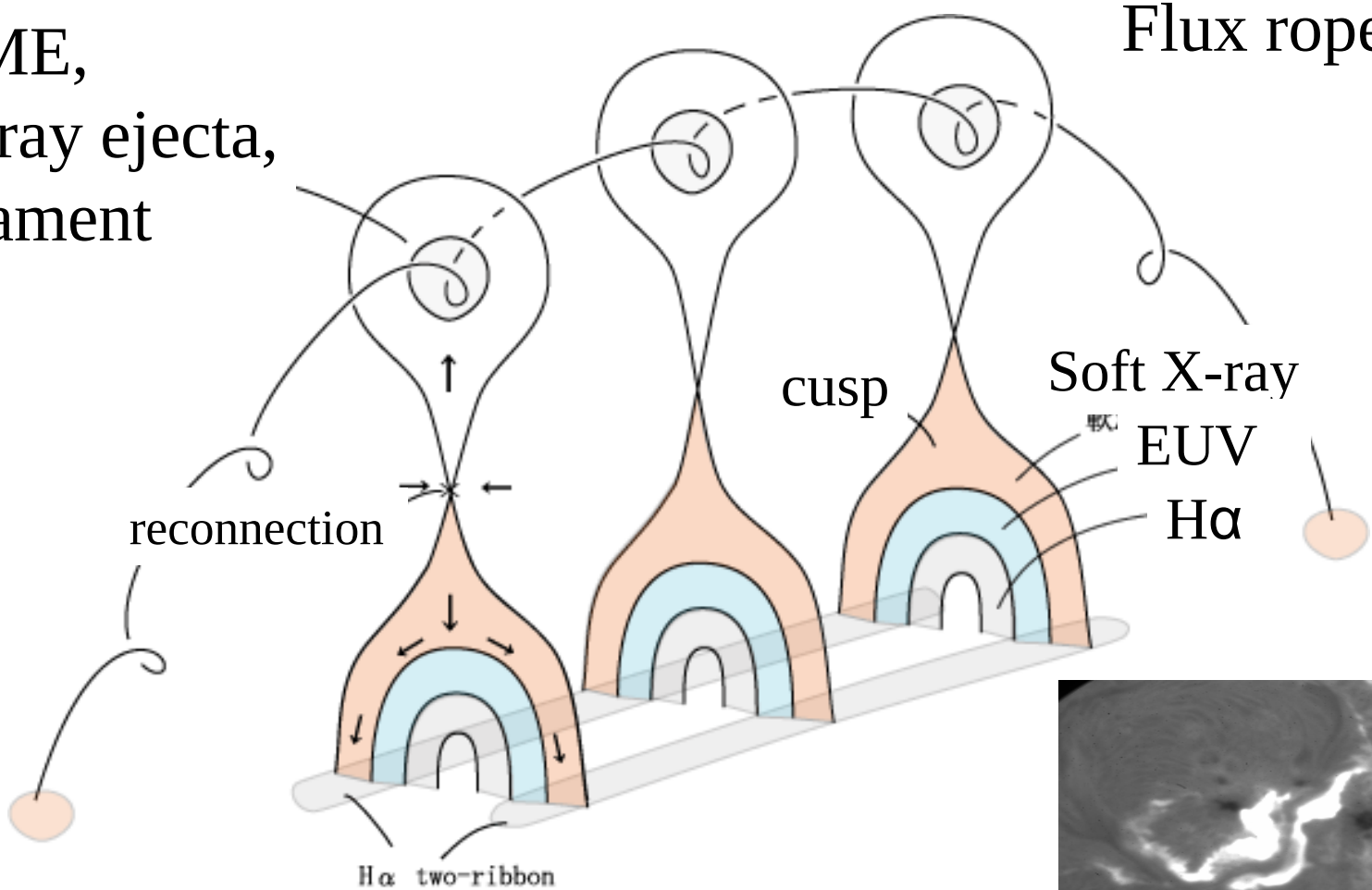


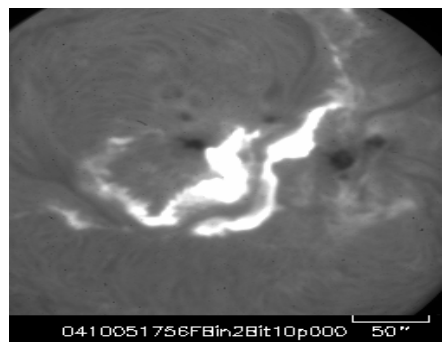
electron release time
near Sun derived

Physics Issues

- Is there a common physical mechanism underlying CME motion and flare emissions? ➔ magnetic reconnection
- What is the cause-effect relationship between magnetic reconnection and CME acceleration?
- Can electrons be accelerated by reconnection electric field to hard X-ray emitting energy of > 10 keV?

Magnetic Reconnection Model of CMEs and Flares

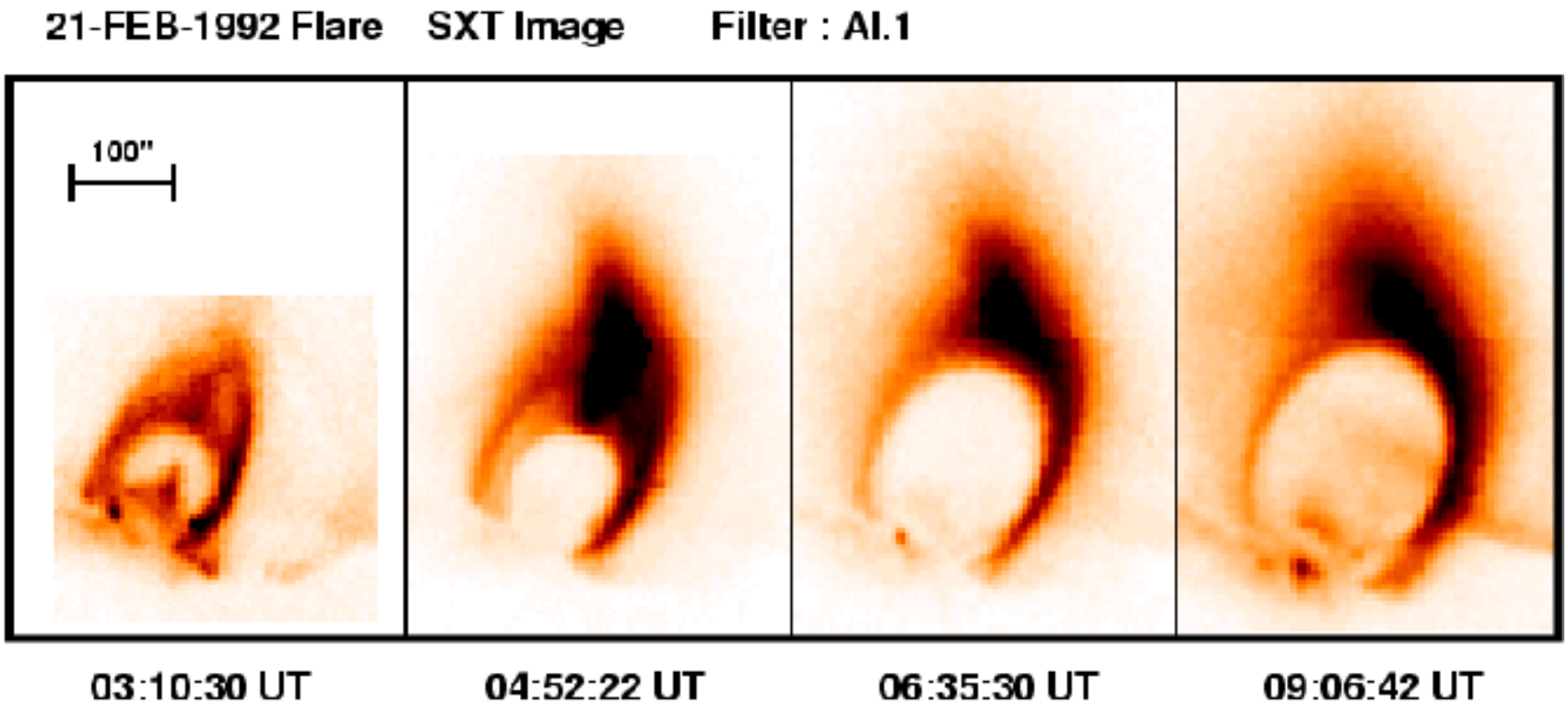




Shibata

LDE (long duration event) Flare

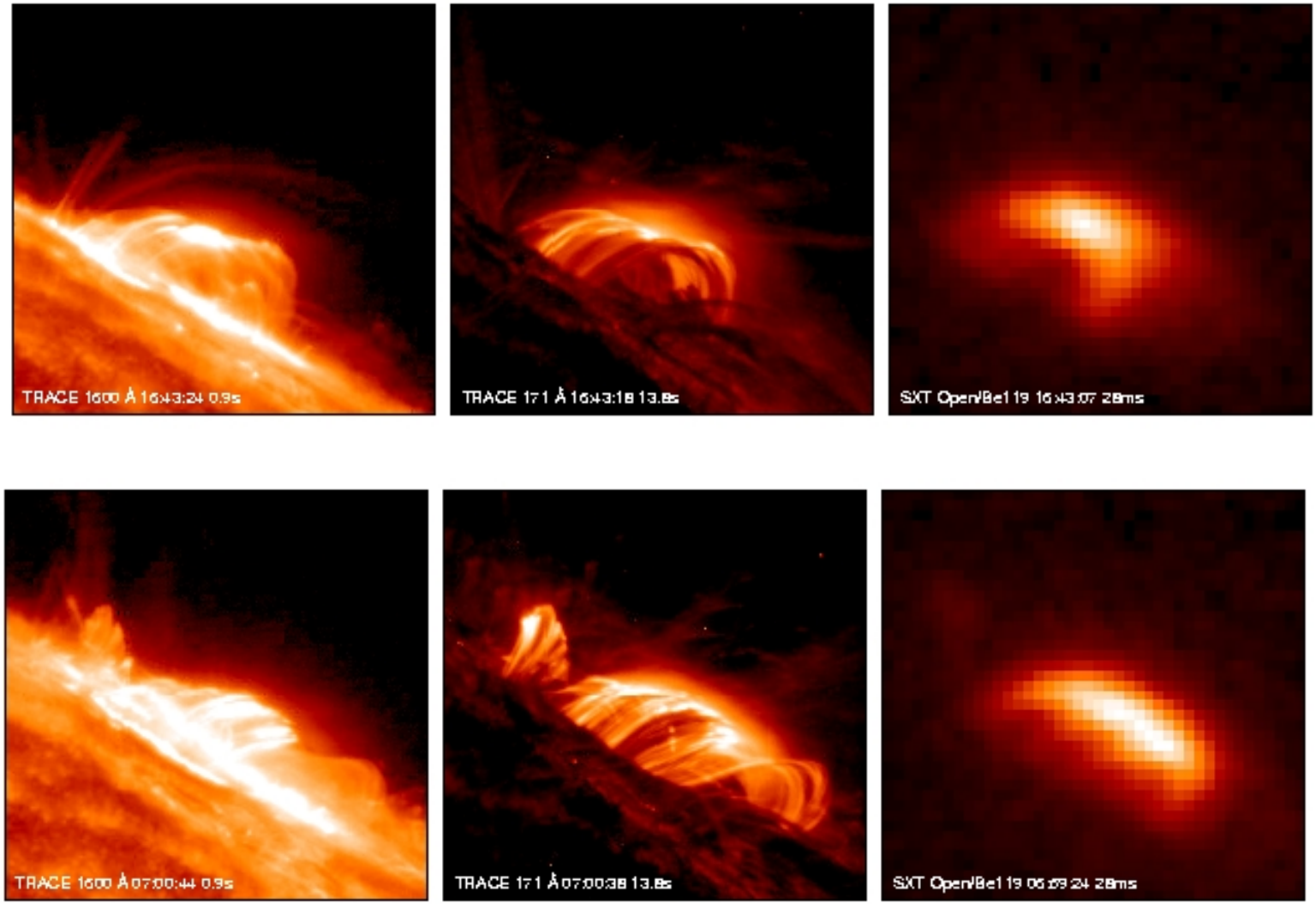
(Yokoh SXT, ~ 1 keV, Tsuneta et al. 1992)



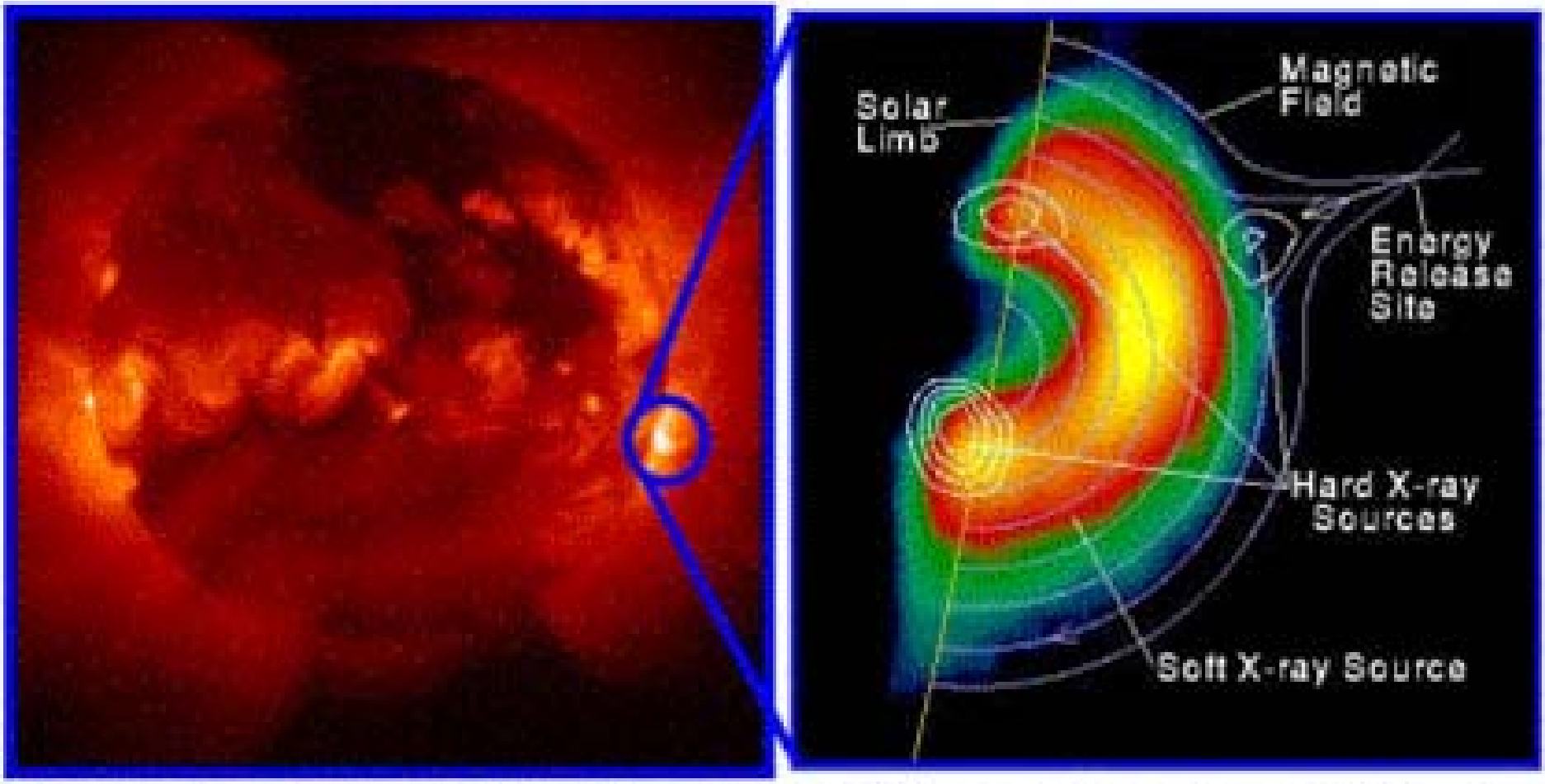
$T_e \sim 10^7$ K, $n_e \sim 10^{10}$ cm^{-3}

TRACE and Yohkoh SXT Images

(1998 Nov. 22 flare by H. Warren)



Outer loops have higher temperature



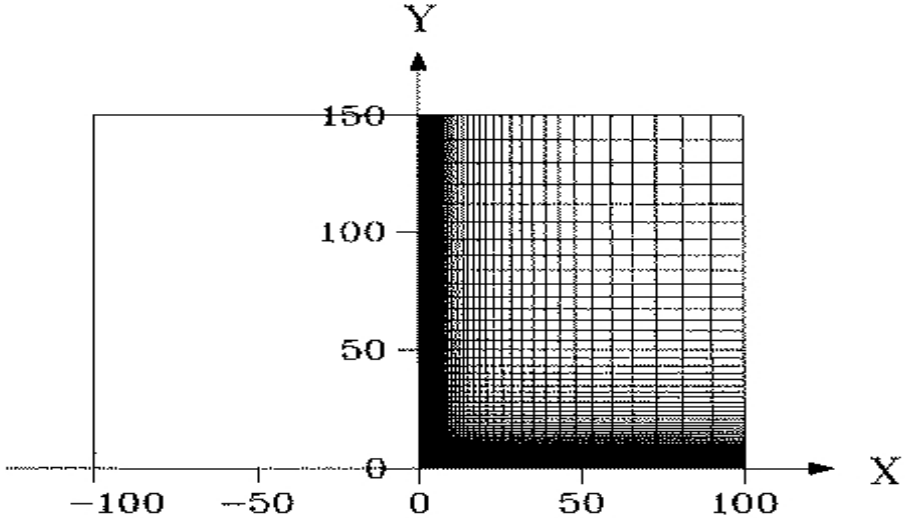
Yohkoh X-ray Image of a Solar Flare, Combined Image in Soft X-rays (left) and Soft X-rays with Hard X-ray Contours (right). Jan 13, 1992.

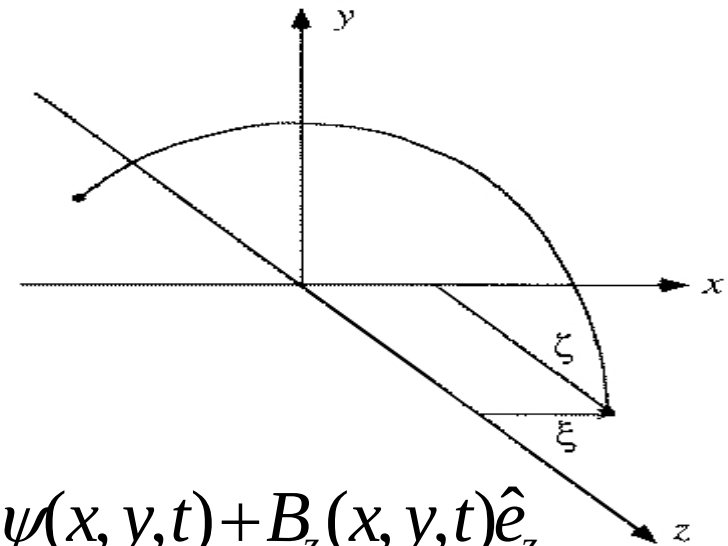
➔ Looptop HXR source suggests acceleration site is above SXR loop.

MHD Simulation of Arcade Field Reconnection

- Magnetic reconnection in thin current sheet is responsible for formation of flux rope and its upward acceleration.
- Reconnection rate depends on nonuniform anomalous resistivity (assumed as a function of current density) and overlying field.
- Simulation results provide understanding of correlation between observed flux rope acceleration and enhanced reconnection rate during flare rise phase.

Magnetic Reconnection in Arcade Field

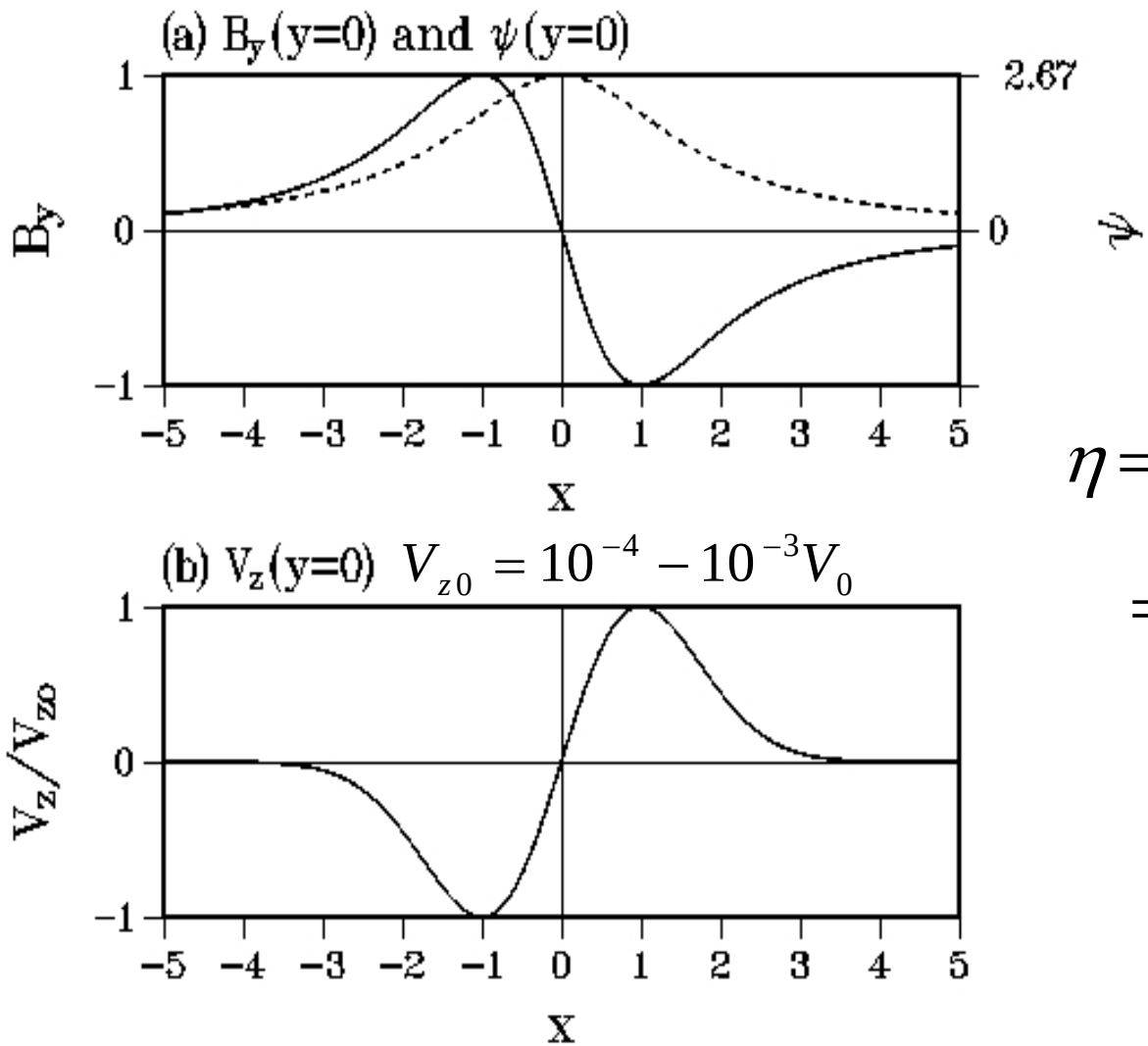




$$\vec{B} = \hat{e}_z \times \nabla\psi(x,y,t) + B_z(x,y,t)\hat{e}_z$$

- Increase of magnetic shear in arcade field (e.g., by shearing of field line footpoints near neutral line or flux emergence) causes current sheet formation.
- Magnetic reconnection creates flux rope and causes its acceleration.

Magnetic Field, Footpoint Motion, and Anomalous Nonuniform Resistivity



Nonuniform Anomalous Resistivity:

$$\eta = \eta_0 \left(\frac{J_z - J_c}{J_c}\right)^{\alpha} \text{ for } J_z > J_c$$

$$= 0 \qquad \text{for} \quad J_z < J_c$$

$\eta_0 = 10^{-6} - 10^{-5}$

$\alpha = 2$

$J_c = 1.5$

Anomalous Resistivity

$$\eta = \eta_0 \left(\frac{J_z - J_c}{J_c}\right)^{\alpha} \quad \text{for} \quad J_z > J_c$$

$$= 0 \qquad \text{for} \qquad J_z < J_c$$

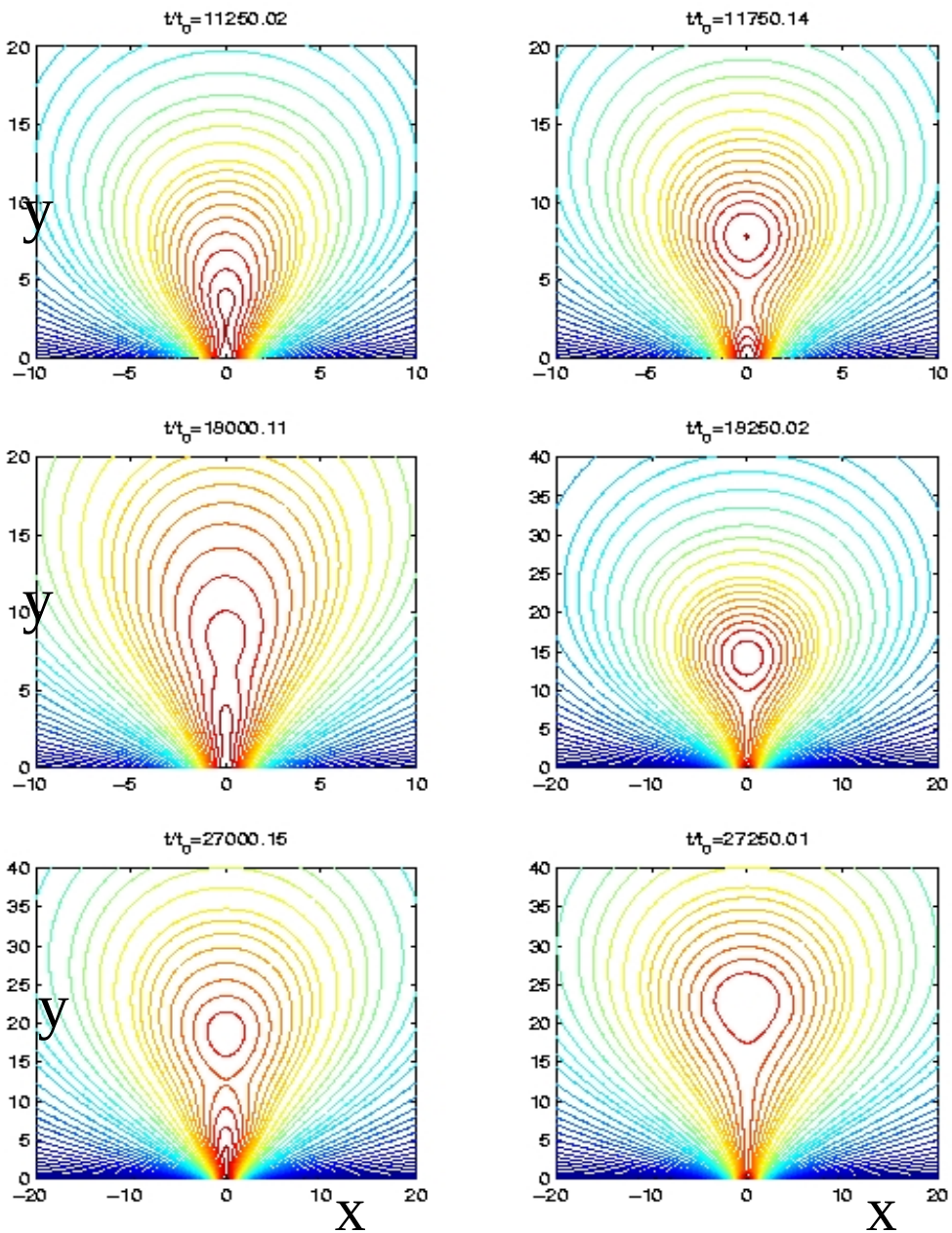
$\eta_0 = 10^{-6} - 10^{-5}$

$\alpha = 0 - 2$

$J_c = 1.5$

➔ Reconnection rate and CME acceleration depends on resistivity model.

Reconnection and Flux Ropes



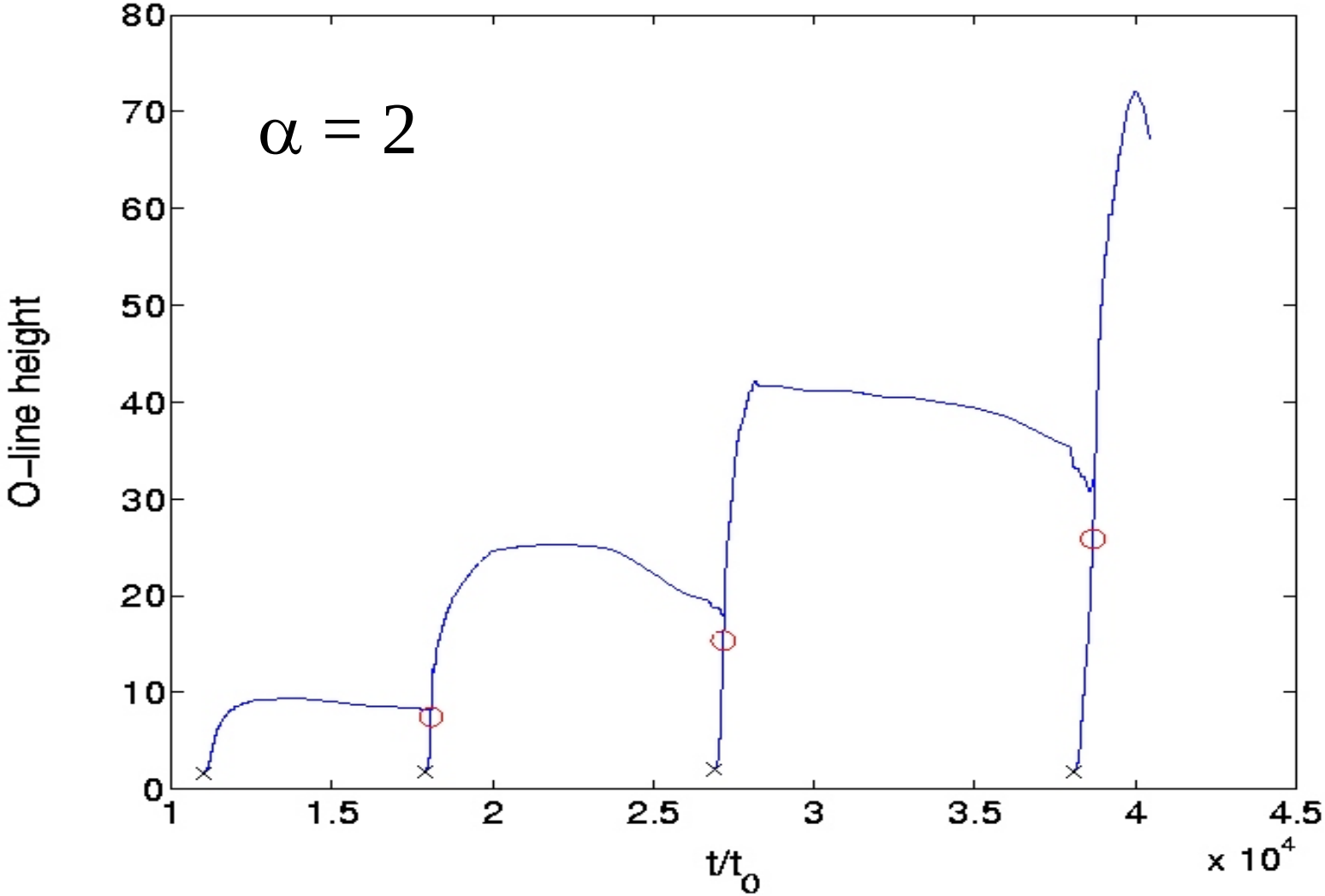
- Continuing increase of shear near neutral line forms CS, causes magnetic reconnection and creates flux ropes

- Reconnection rate depends on nonuniform anomalous resistivity model (α)

- Merging of flux ropes further enhances reconnection rate

- Repetitive reconnection events -- homologous flares

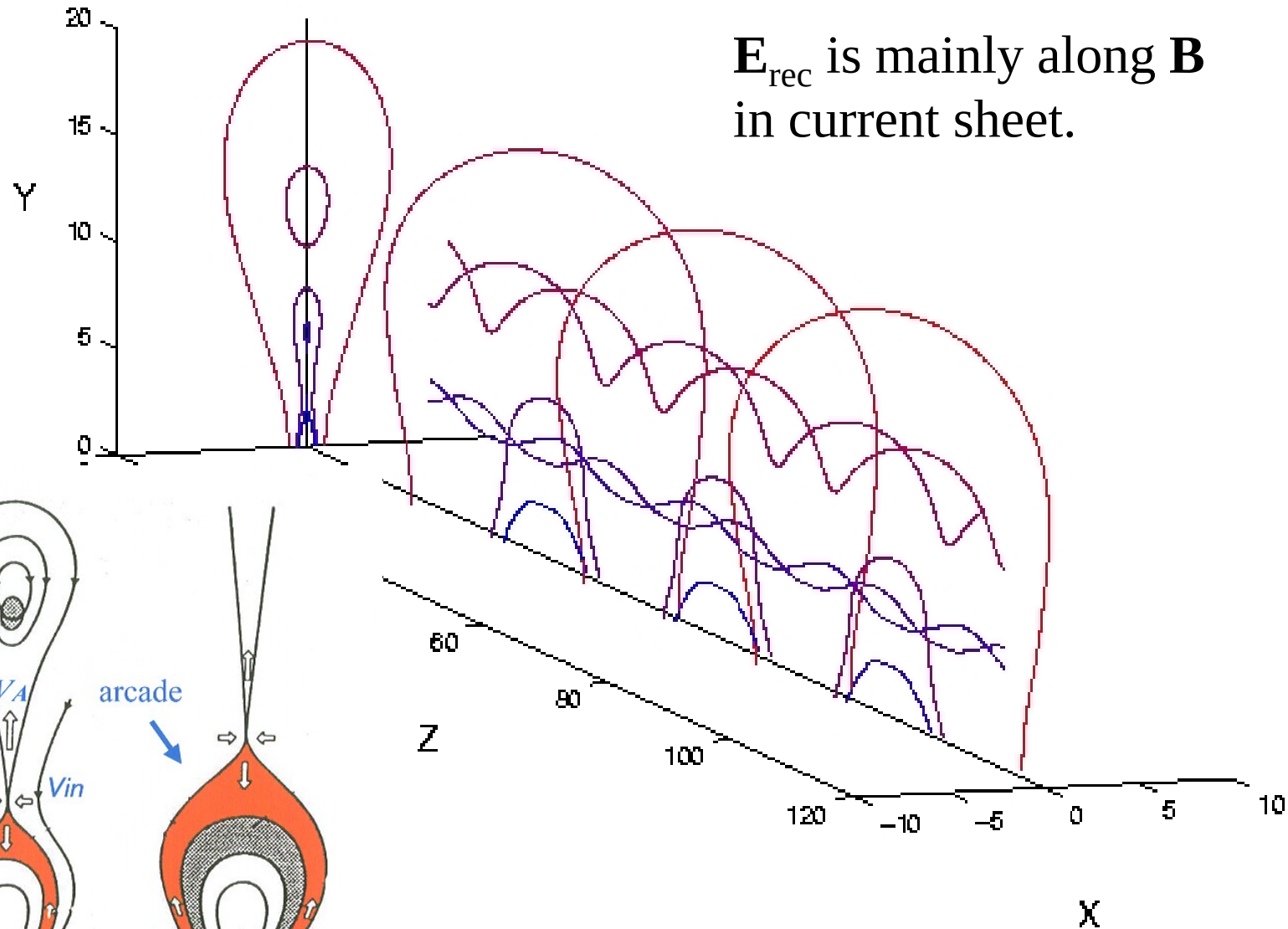
Flux Rope Motion

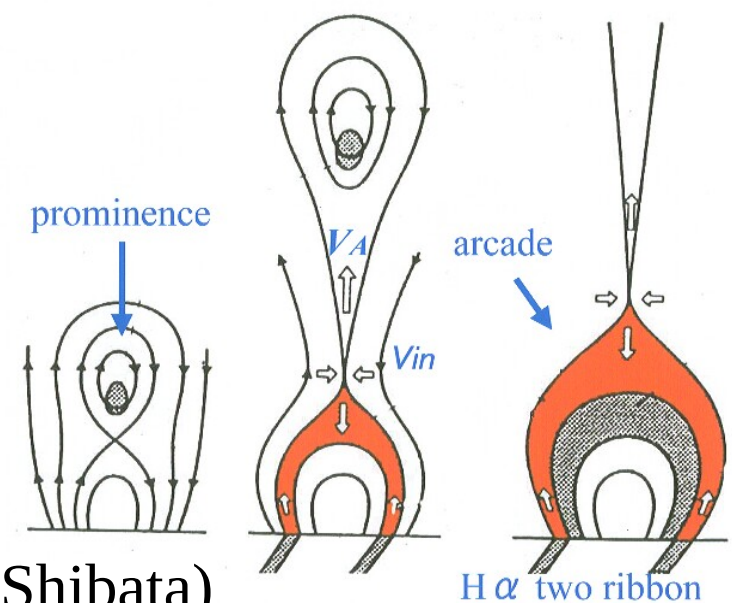


Similar behaviors for different α values

3D Field Structure

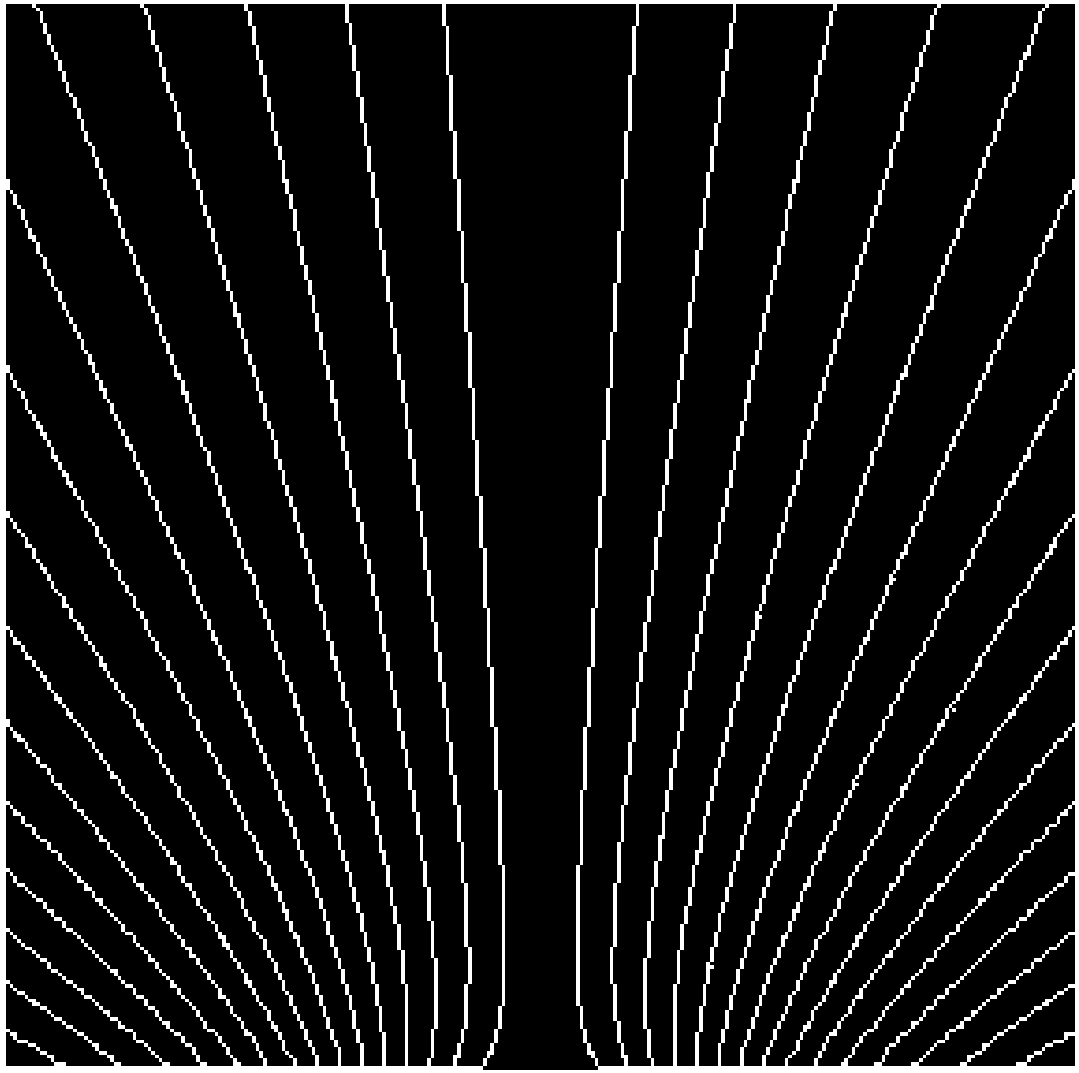
$\mathbf{E}_{rec}$ is mainly along **B** in current sheet.





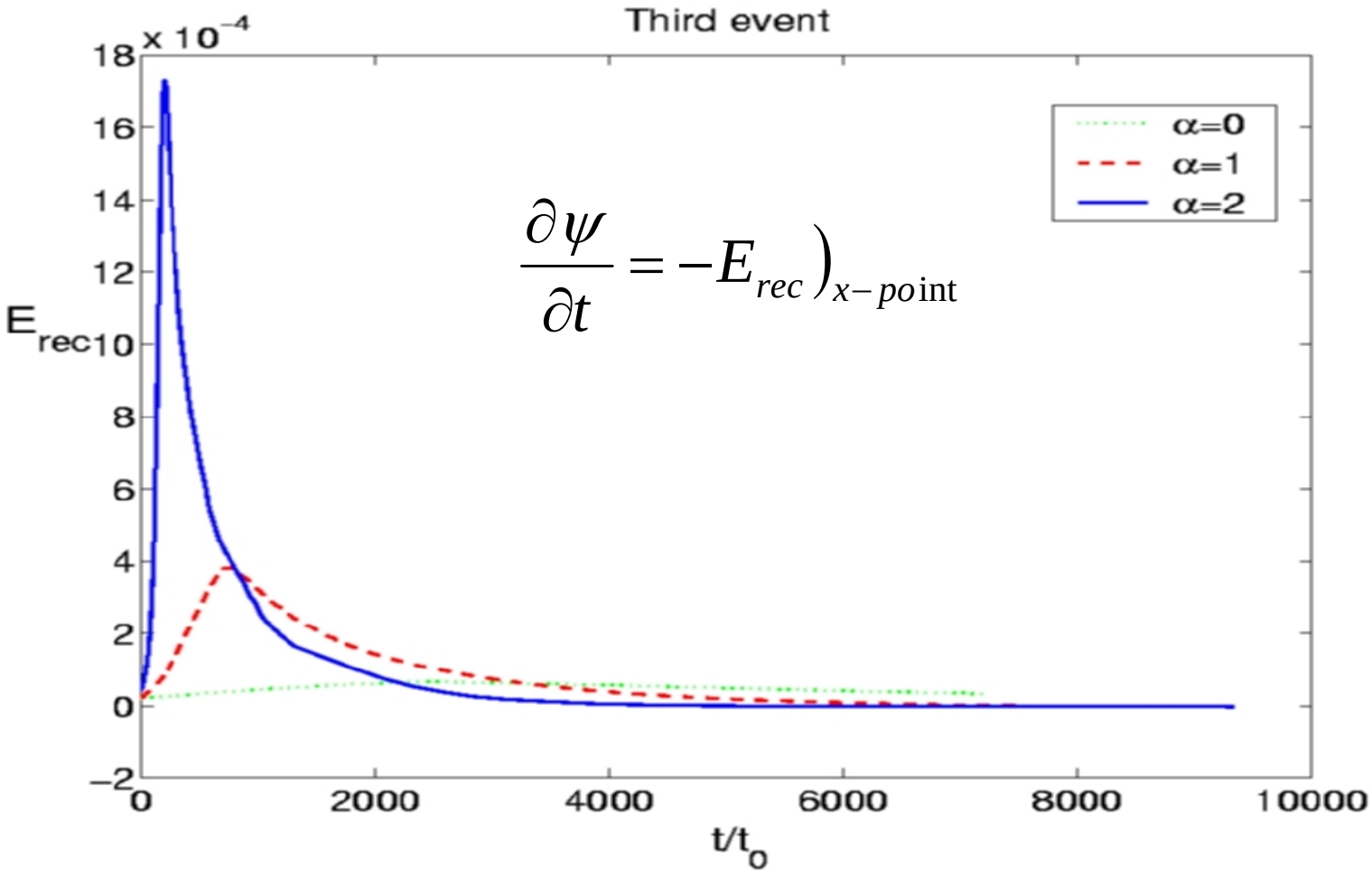
(Shibata)

Reconnection



T. Forbes

Reconnection Rate vs. Anomalous Resistivity



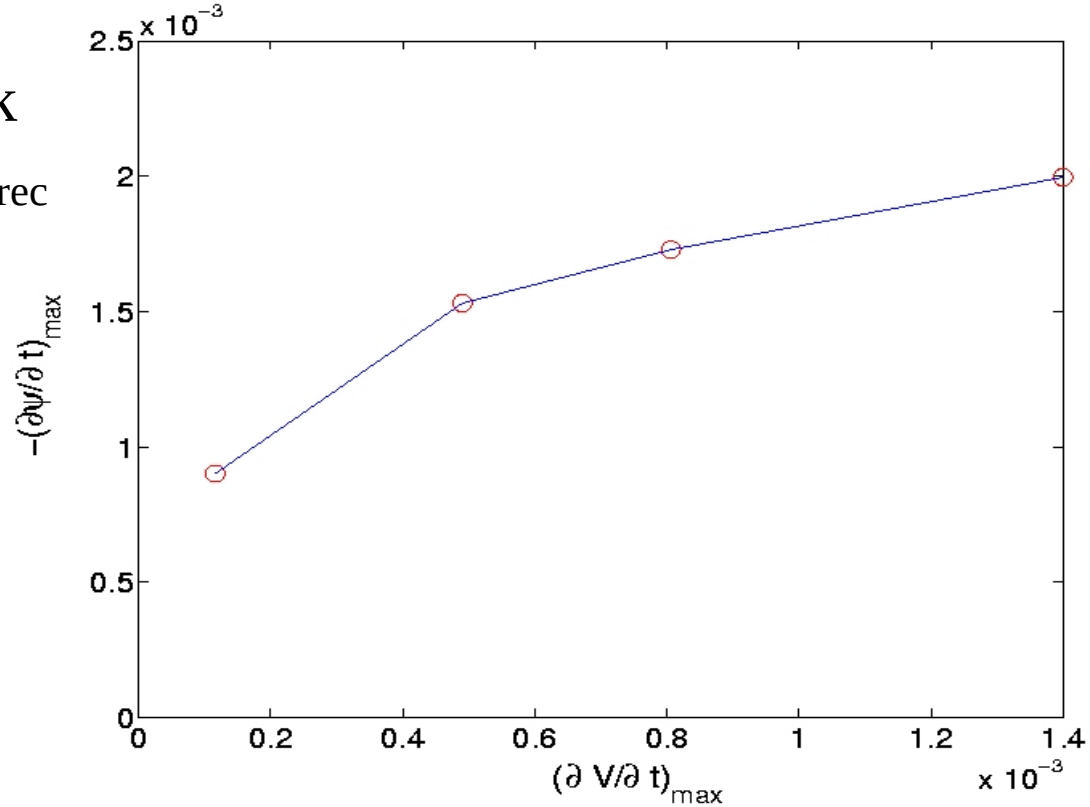
$$\frac{\partial \psi}{\partial t} = -E_{rec}\Big)_{x-point}$$

Impulsive E_{rec} accelerates particles along **B** in current sheet.

Maximum Reconnection Rate increases with Maximum Flux Rope Acceleration

$\eta_0 = 10^{-5}$, $\alpha = 2$, $J_c = 1.5$ (third reconnection event)

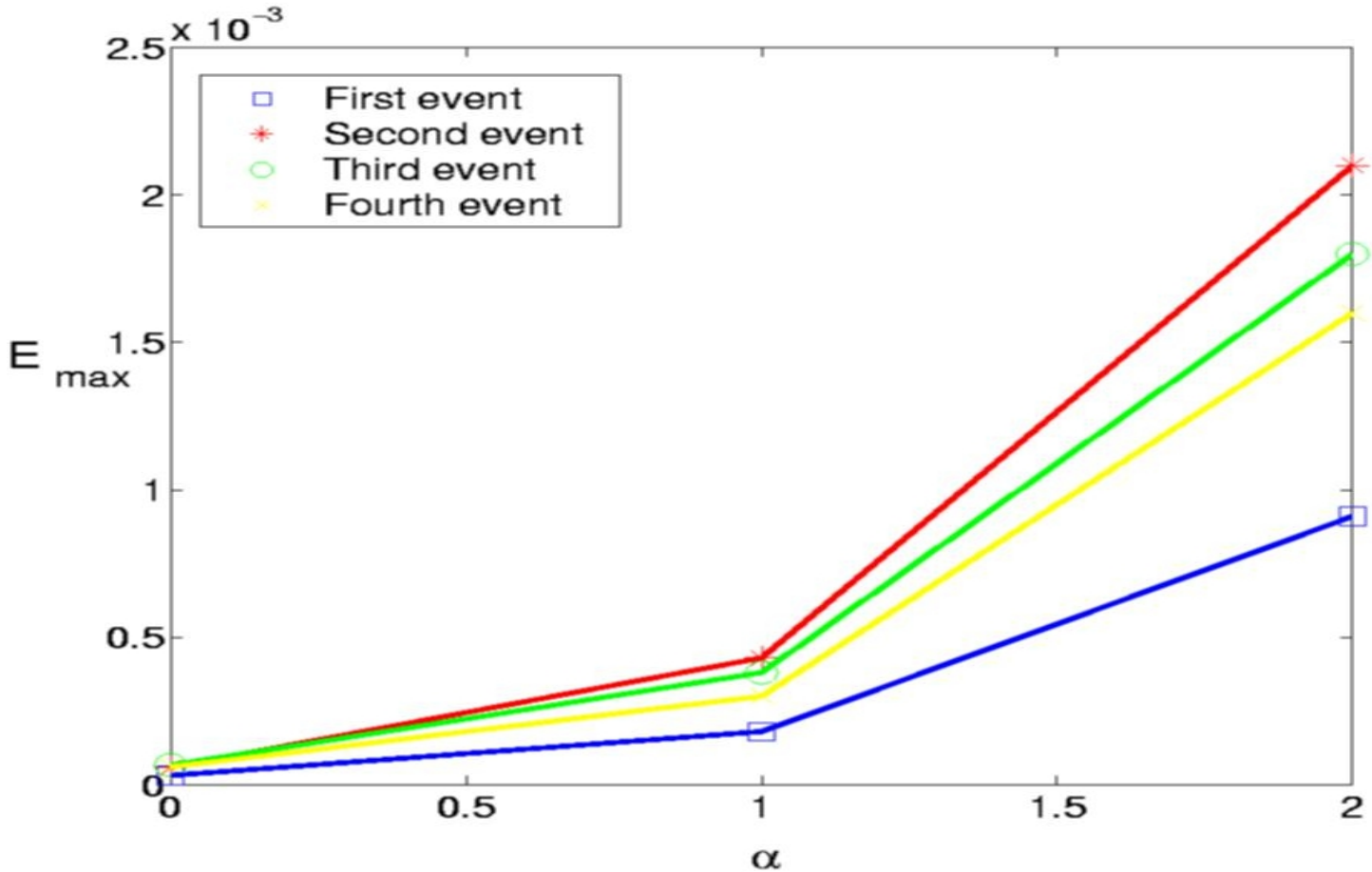
Peak E_{rec}



Peak acceleration

- Reconnection rate and flux rope acceleration decrease by about a factor of 10 for $\alpha = 0, 1$

Reconnection Rate vs. Anomalous Resistivity



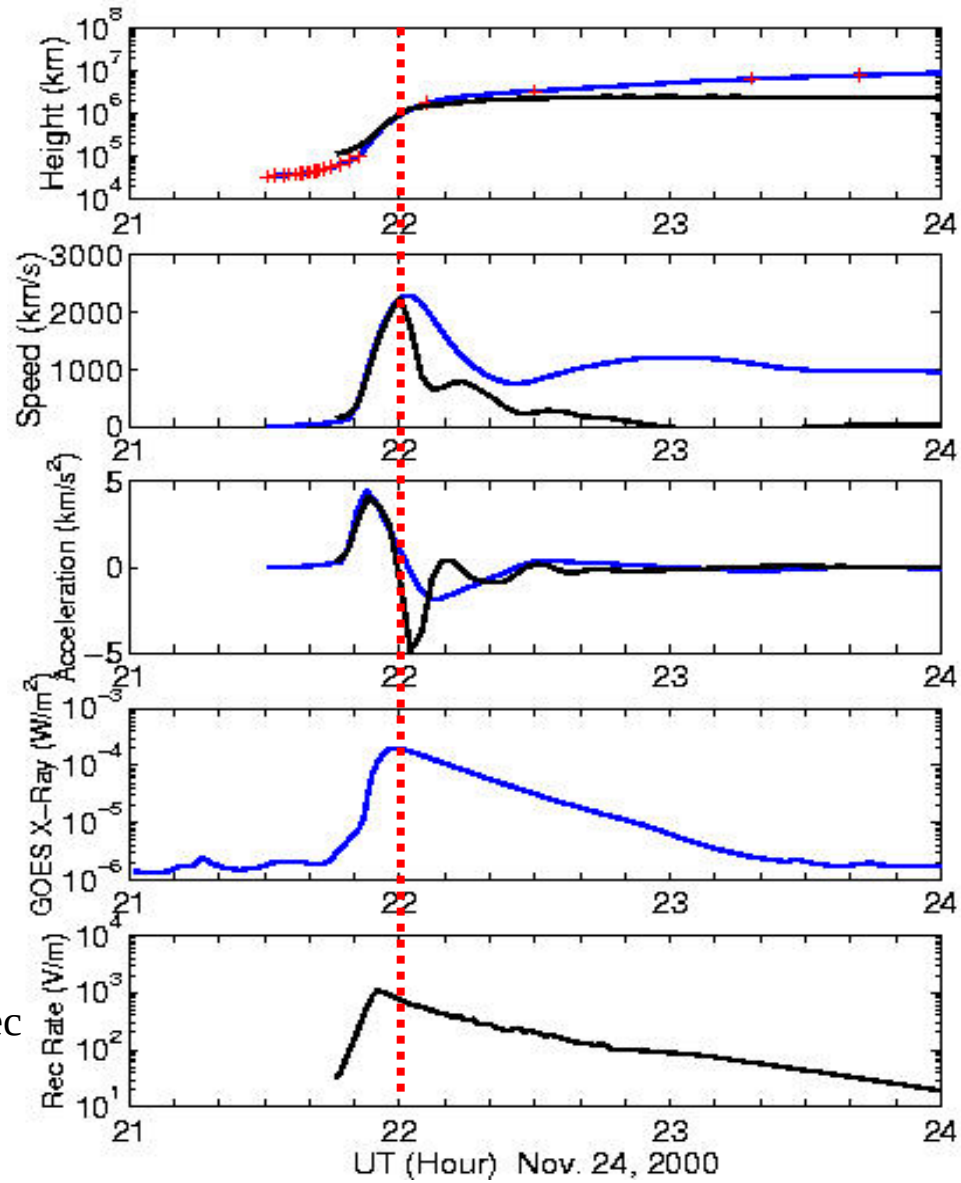
$\eta_0 = 10^{-5}$
$J_c = 1.5$

- Each event has different overlying field configuration.
- Reconnection rate and flux rope acceleration depend on both anomalous resistivity and overlying field.

Comparison Between Observation and Model

Nov. 24, 2000 X1.8 flare event

[Cheng, *et al.*, ApJ, 2003]



E_{rec}

- $\alpha = 2$ (third event)
- Good agreement between observation (blue curves) and model results (black curves) during flux rope acceleration phase.
- Impulsive HXR emission at peak CME acceleration and peak reconnection E-field.

Model Parameters :

$B_0 = 300\ G,\ n_0 = 10^9\ cm^{-3}$

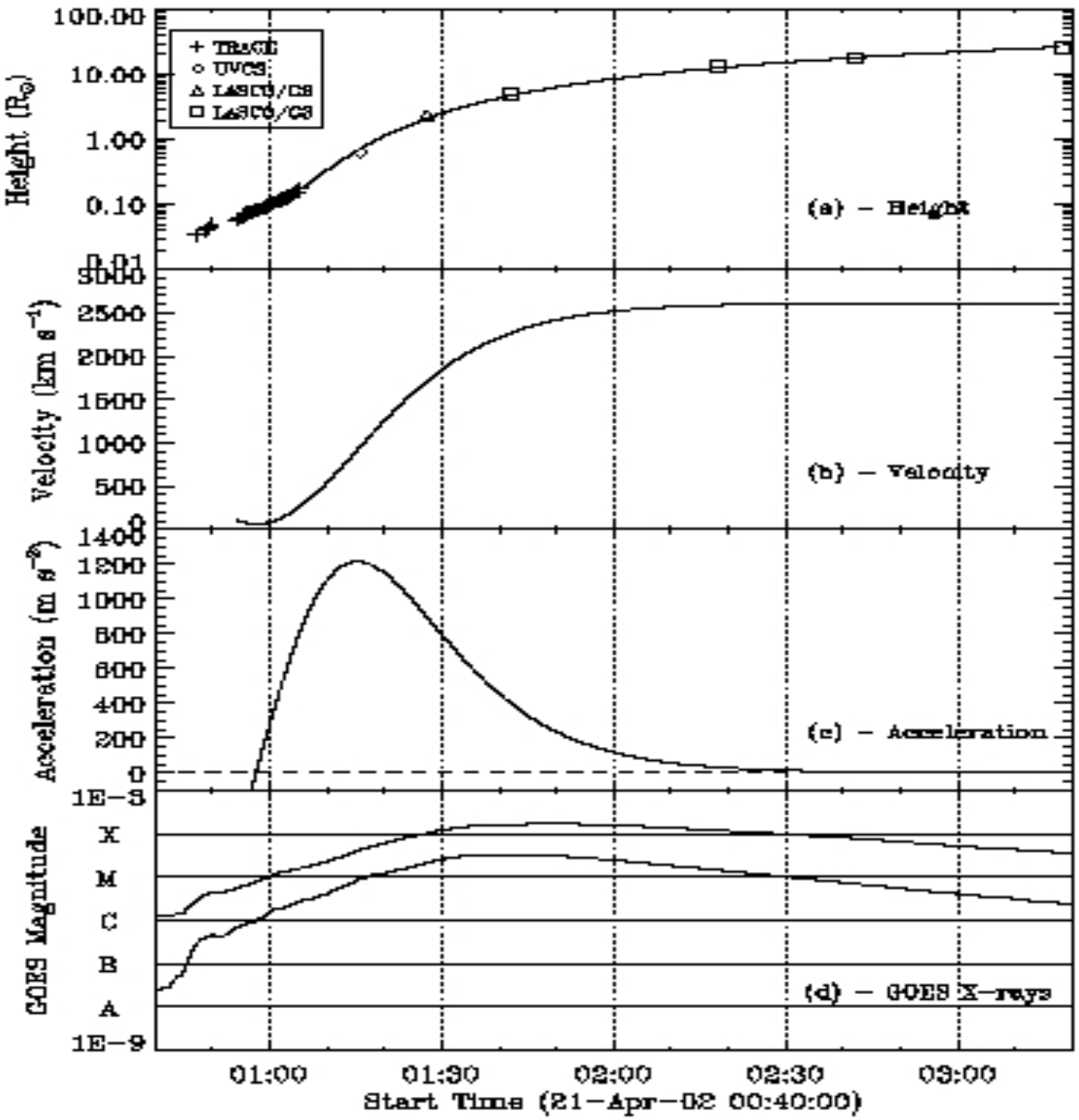
$L_0 = 6 \times 10^4\ km$

$V_0 = 2 \times 10^4\ km/s$

$t_0 = 3$ sec

Max. $E_{rec} = 1000\ V/m$

CMEs Are Accelerated During Flare Rise Phase



Gallagher *et al.*, ApJ, 2003

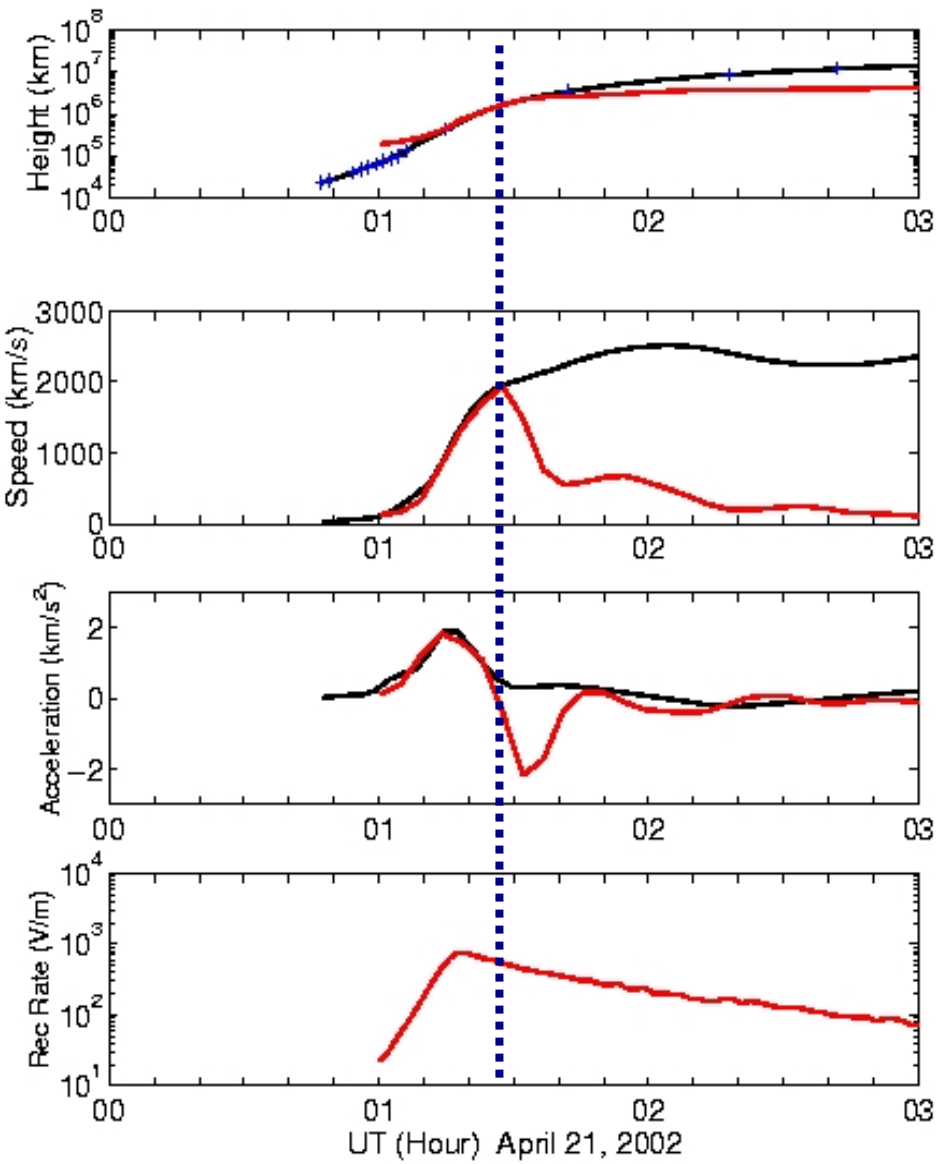
April 21, 2002
X1.5 flare event

CME acceleration peaks during flare rise phase

Comparison with Gallagher's Observation

April 21, 2002 X1.5 flare event

[Gallagher, *et al.*, ApJL, 2003]



- $\alpha = 2$ (third event)
- Good agreement between observation (black curves) and model results (red curves) during flux rope acceleration phase.
- Impulsive HXR emission at peak CME acceleration and peak reconnection E-field.

Model Parameters :

$B_0 = 250\ G,\ n_0 = 10^9\ cm^{-3}$

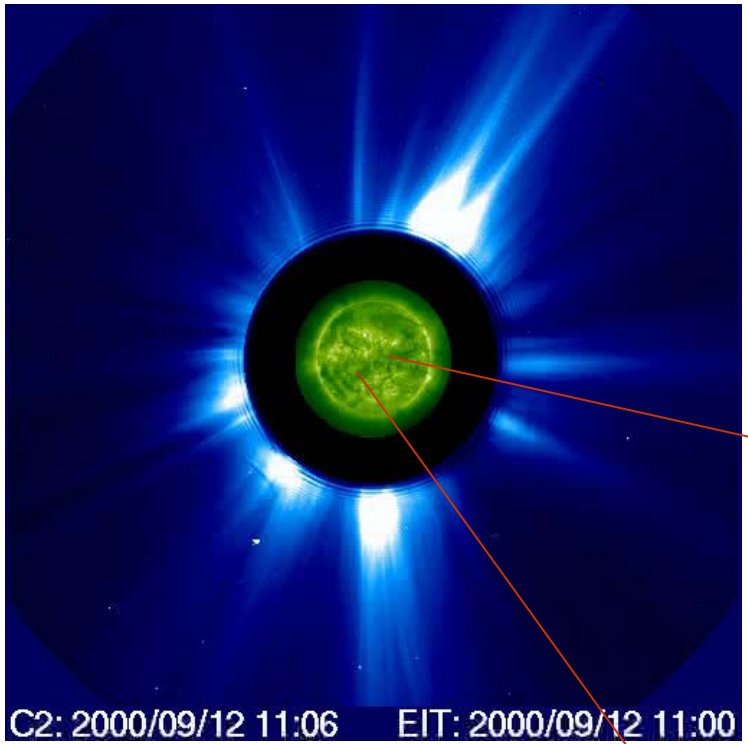
$L_0 = 10^5\ km$

$V_0 = 1.72 \times 10^4\ km/s$

$t_0 = 5.8$ sec

Max. $E_{rec} \approx 900\ V/m$

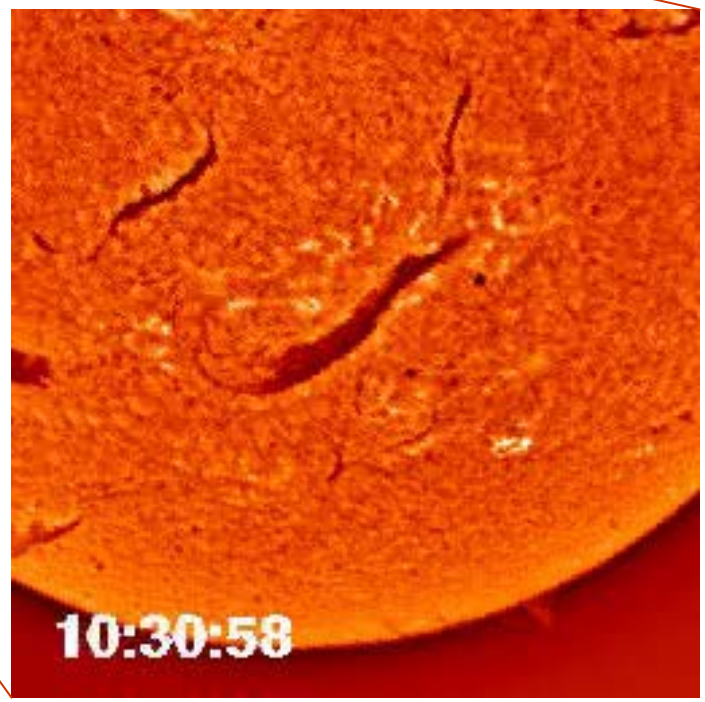
2000 September 12



← Coronal Mass Ejection

(from http://cdaw.gsfc.nasa.gov/)

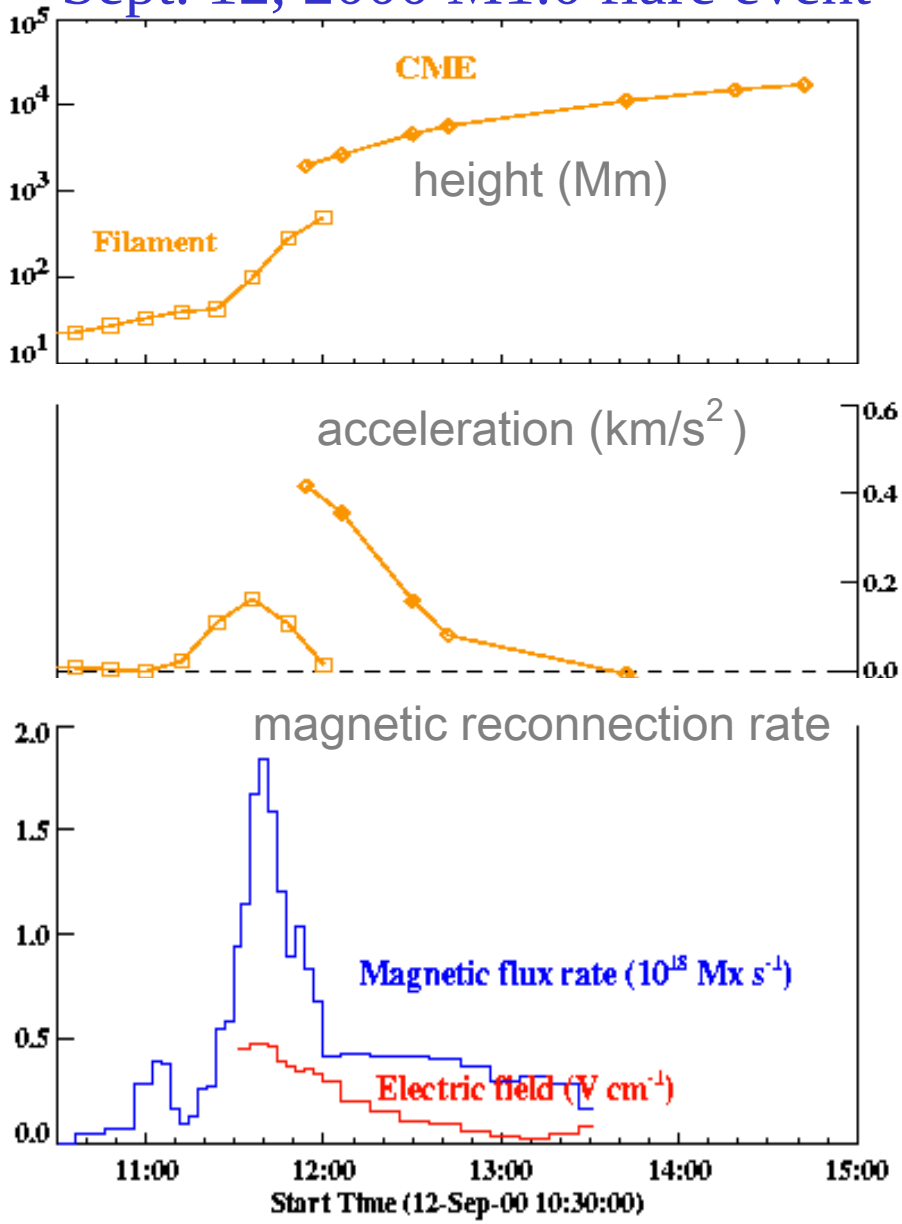
Filament eruption



Flare emission on the solar surface (with two separating ribbons) rises during CME acceleration phase

Reconnection Rate vs. CME Acceleration

Sept. 12, 2000 M1.0 flare event

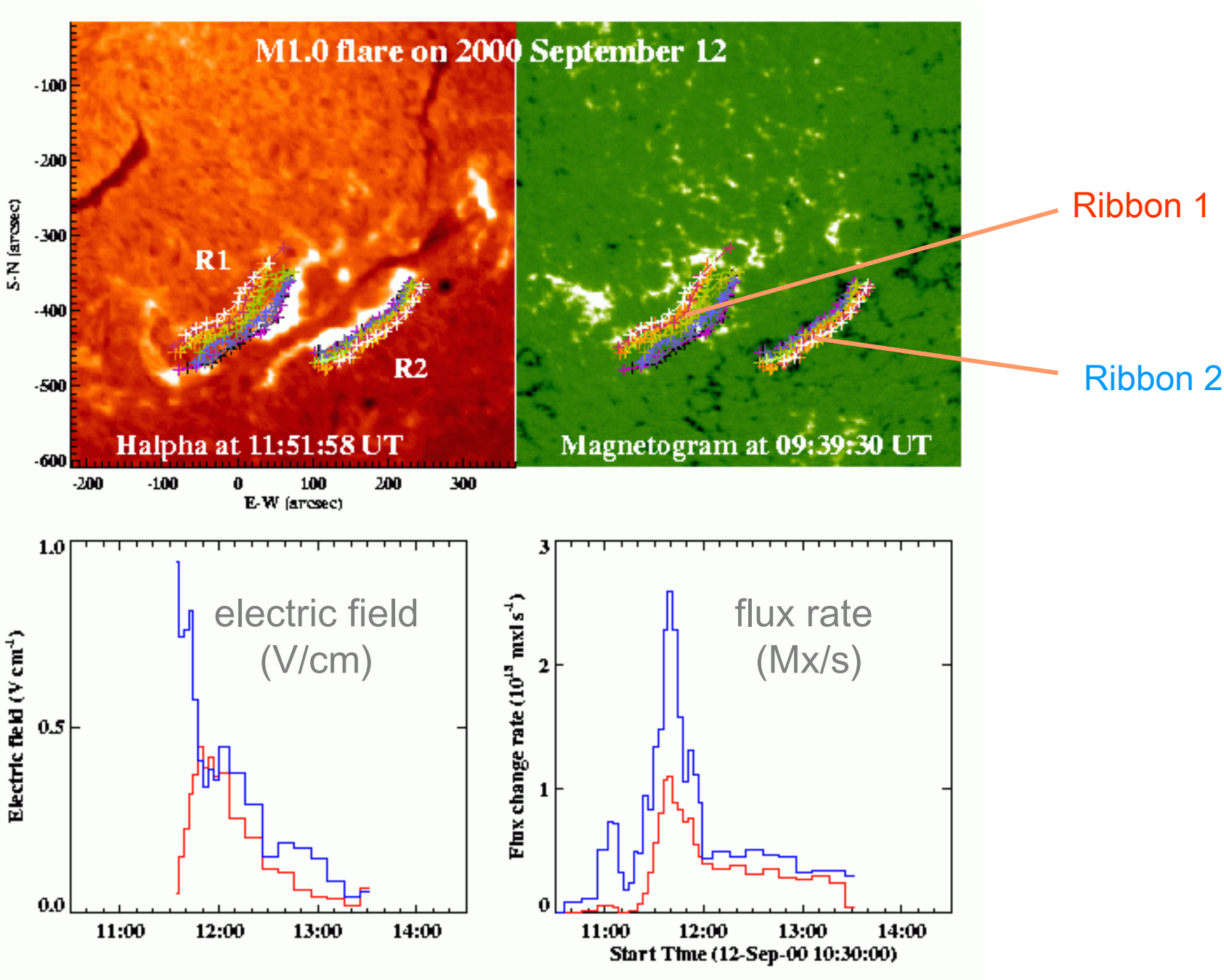


Qiu, et al., ApJ, 2004

- Peak reconnection rate and acceleration:

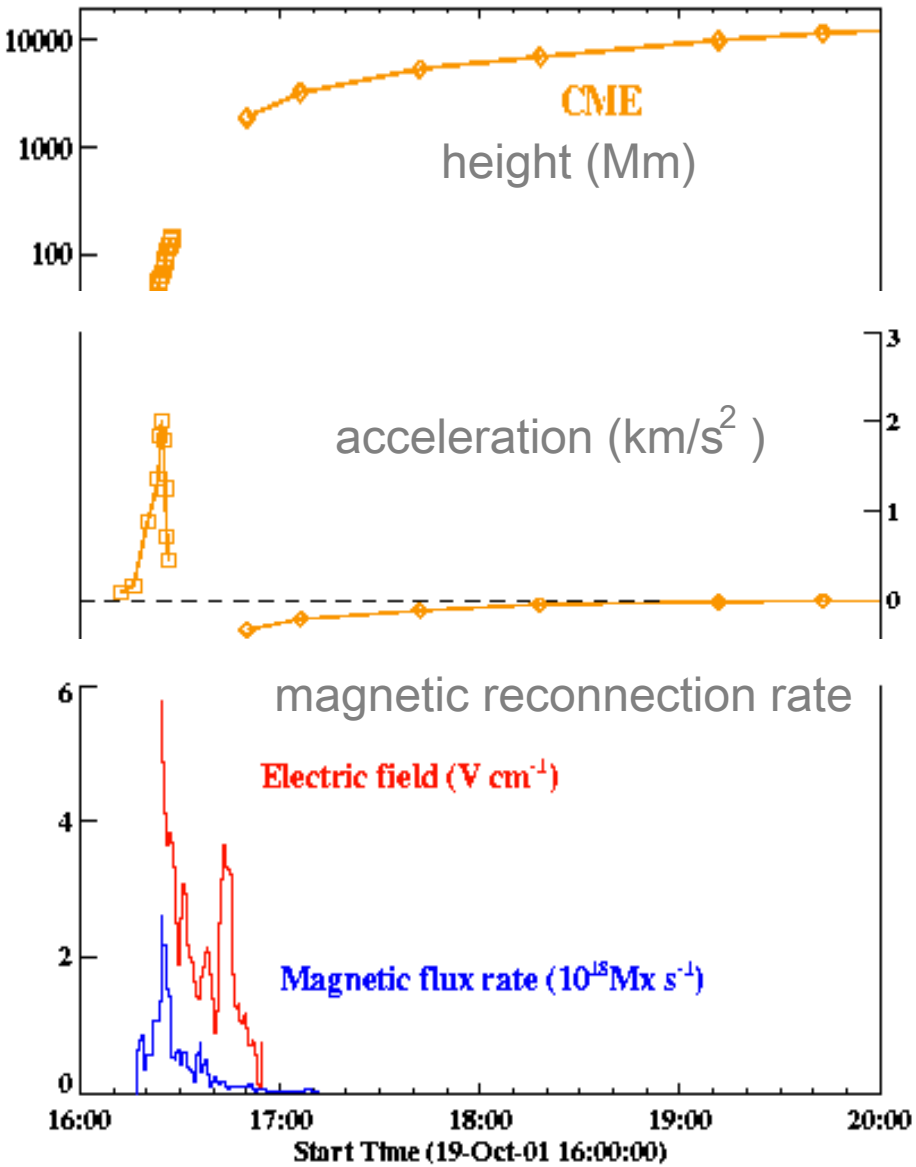
$E_{rec} \sim 50$ V/m
$a \sim 0.4$ km/s^2

CME heights taken from http://cdaw.gsfc.nasa.gov/CME_list/


M1.0 flare on 2000 September 12
R1
R2
Halpha at 11:51:58 UT
Magnetogram at 09:39:30 UT
S-N (arcsec)
E-W (arcsec)
Ribbon 1
Ribbon 2
electric field
(V/cm)
Electric field (V cm^{-1})
flux rate
(Mx/s)
Flux change rate (10^{13} mxl s^{-1})
Start Time (12-Sep-00 10:30:00)

Reconnection Rate vs. CME Acceleration

Oct. 19, 2001 X1.6 flare event



Qiu, et al., ApJ, 2004

- CME acceleration, reconnection rate (electric field), flare non-thermal emissions are temporally correlated, all reach their peak values during SXR emission rise phase

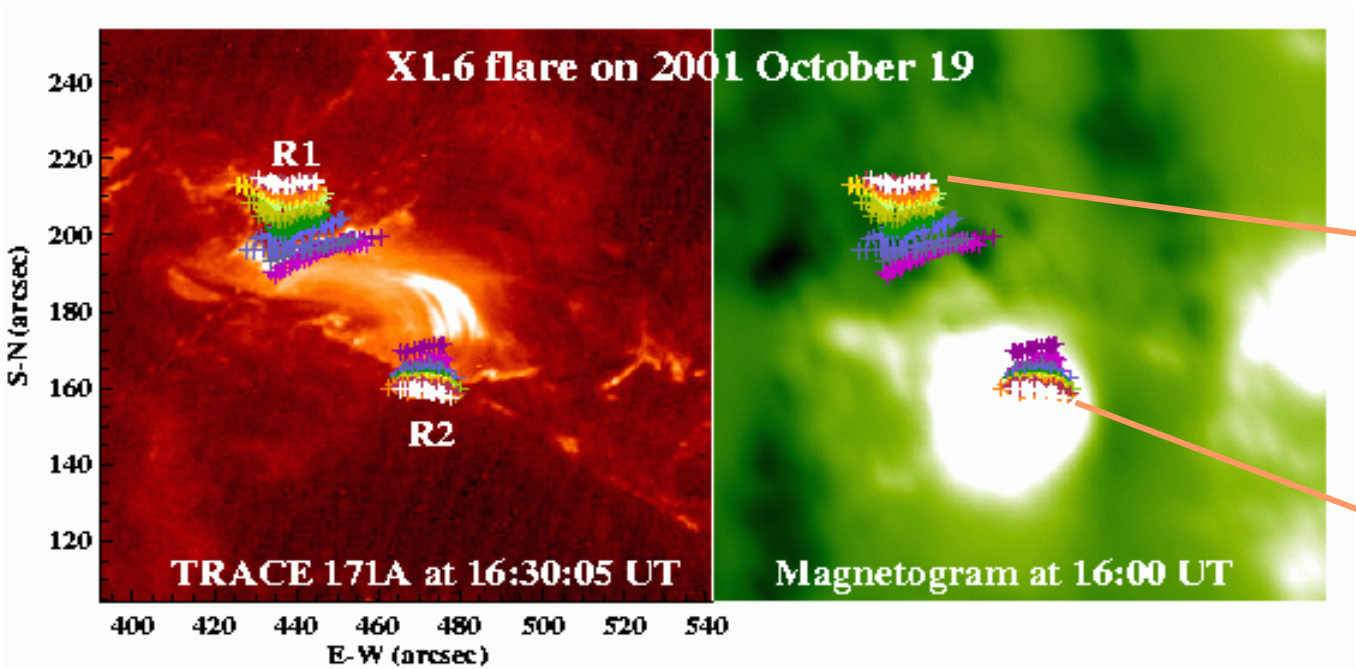
- Peak reconnection rate and acceleration:

$$E_{rec} \sim 580 \text{ V/m}$$
$$a \sim 2.5 \text{ km/s}^2$$

CME heights taken from

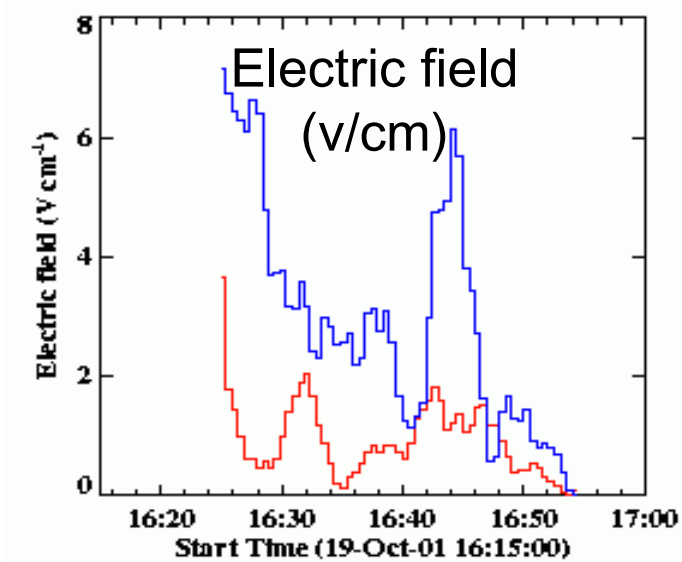
http://cdaw.gsfc.nasa.gov/CME_list/

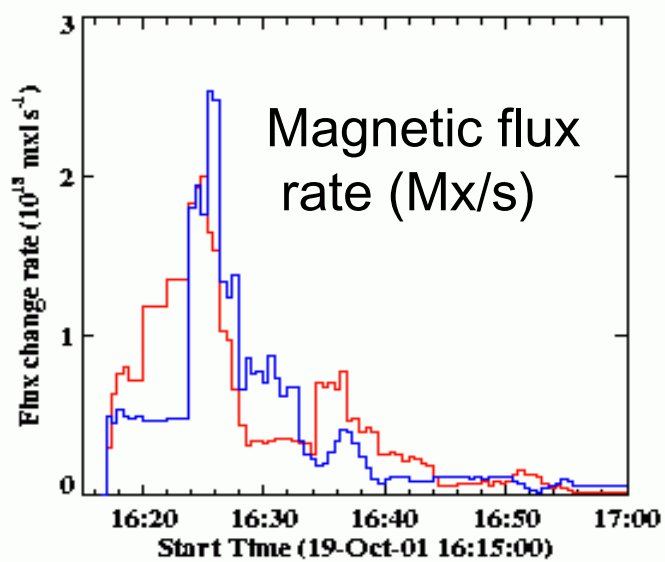
Magnetic Reconnection Rate in Flares



Ribbon 1

Ribbon 2





Acceleration $\propto$ Reconnection Rate

Event (magnitude)	2000/09/12 (M1.0)	2001/10/19 (X1.6)
Max CME acceleration (km/s^2)	0.2 - 0.4	2.
Duration of acceleration (min)	> 120	< 40
Mean and Max. velocity (km/s)	1550 & 1700	900 & 1450
Max. magnetic field (Gauss)	200	1200
Max. electric field (V/m)	50	580
Duration of reconnection (min)	> 120	~ 30

Physics of Anomalous Resistivity

- MHD simulations employ “phenomenological” anomalous resistivity (assumed as a function of current density).
- Simulation results (for $\alpha = 2$) provide good agreement with X-class flare observations.
- It is impractical, if not impossible, to simulate current sheet magnetic reconnection physics in global solar corona scale by self-consistent kinetic models.
- Can simulation results provide insights on kinetic physics in reconnecting current sheet?

How Are Electrons Accelerated to X-Ray Flare Emission Energy?

- Particles are accelerated in current sheet by magnetic field-aligned electric field ($E_{||}$)
- For $E_{||}$ = 1000 V/m, electrons are accelerated to 1 MeV in a field-aligned distance of 1 km in 10^{-5} s
- Particle motion in evolving current sheet and arcade field must be considered:
  - ExB drift ($V_E \sim 10^2$ - 10^3 km/s)
  - magnetic trapping
  - magnetic (gradient B and curvature) drift
  - particle collisions

➔ Need kinetic calculations with simulated fields!

Summary and Discussion

- MHD simulations employing model anomalous resistivity have provided physical understanding of observed correlation between flux rope acceleration and enhanced reconnection rate during flare rise phase.
- To further understanding we propose to pursue the following tasks:

1. 3D Resistive MHD Simulations with more realistic arcade field and nonuniform anomalous resistivity in reconnecting current sheet.
2. Test Particle Simulations of particle acceleration during flare impulsive phase based on dynamical electric and magnetic fields obtained from MHD simulations → a first step toward understanding of particle acceleration in evolving global (**E**,**B**) fields.