JAXA/ISAS Oct. 01, 2015 Tokyo, Japan

Observations and Understanding of Solar Eruptions

Jie Zhang

GEORGE MASON UNIVERSITY

The Outline

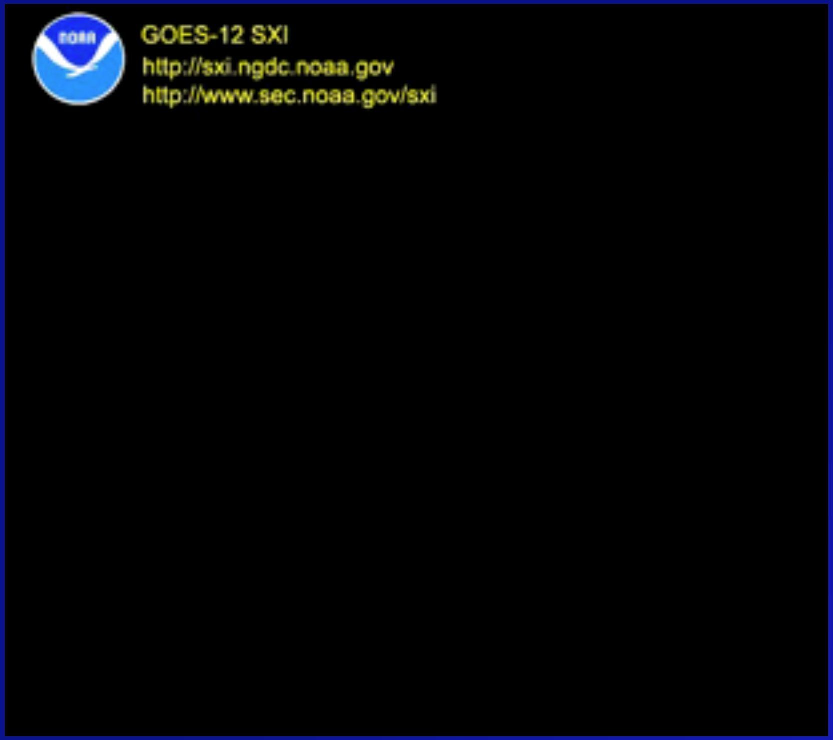
1. Flares/CMEs, Solar Eruptive Events (SEE), and two competing paradigms of models

2. Magnetic Flux Ropes (MFR): key test of models

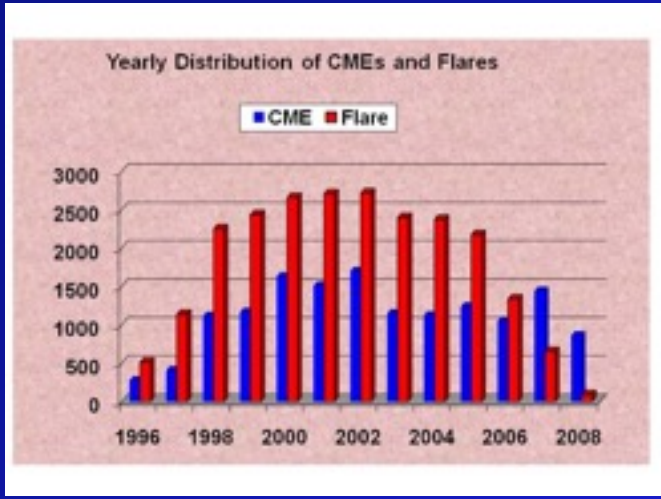
3. Conclusion and Discussions

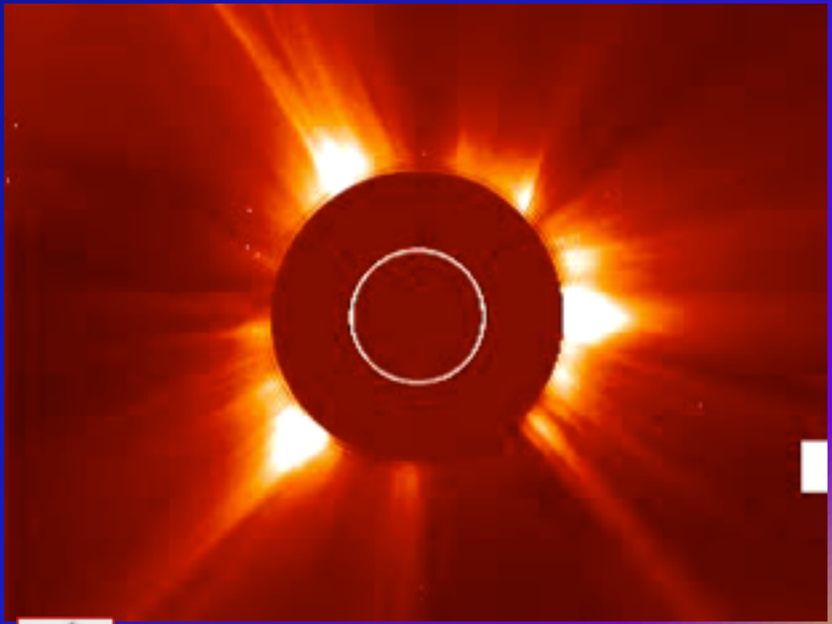
Flares and CMEs

Two types of energetic eruptions from the Sun



Flares (GOES/SXI)





CMEs (SOHO LASCO/C2)

Eruptive Flares

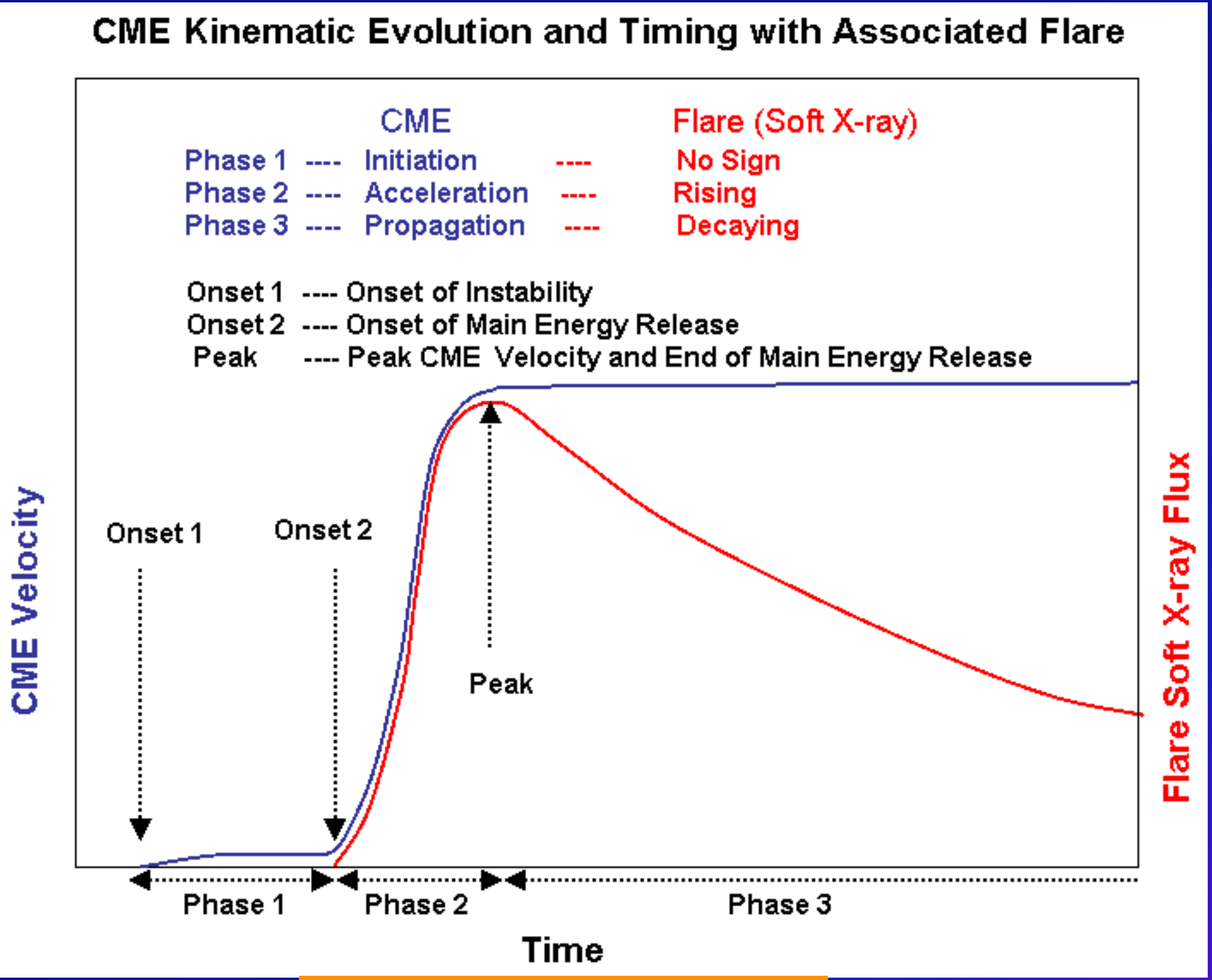
Flare	Eruptive (with CME)	Confined (no CME)
X-class	90%	10%
M-class	56%	44%
C-class (>C3.0)	30%	70%

(Andrew 2003; Yashiro et al. 2005; Wang & Zhang 2007)

In this talk, I will be focusing on eruptive flares, or solar eruptive event (SEE), i.e., a CME with an accompanying flare

Temporal Relationship

CME and flare are nearly synchronized in SEE



(Zhang & Dere 2006)

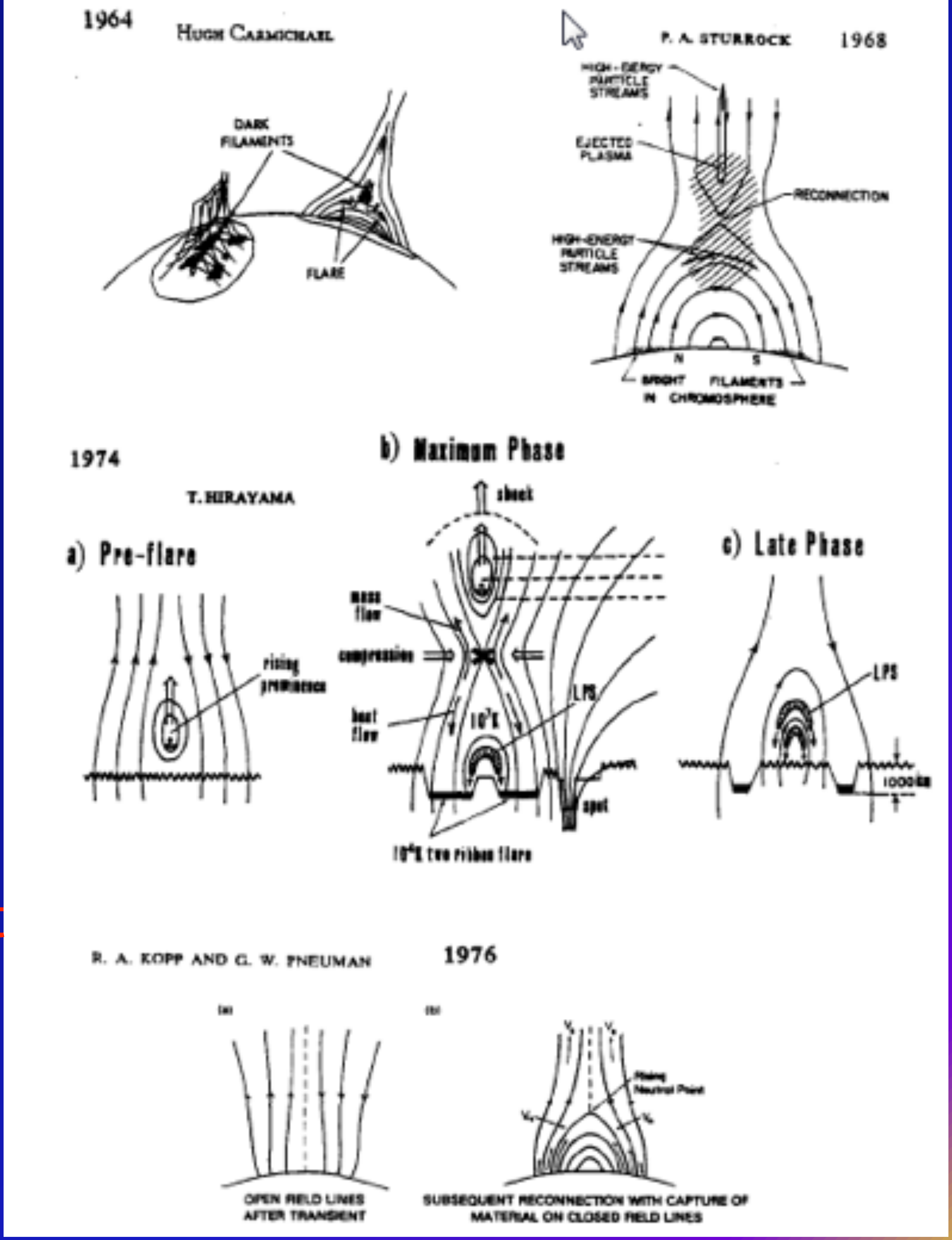
Also see earlier observational studies from Zhang et al. 2001; Gallagher et al. 2003; Temmer et al. 2008)

SEE Model: 1st Generation

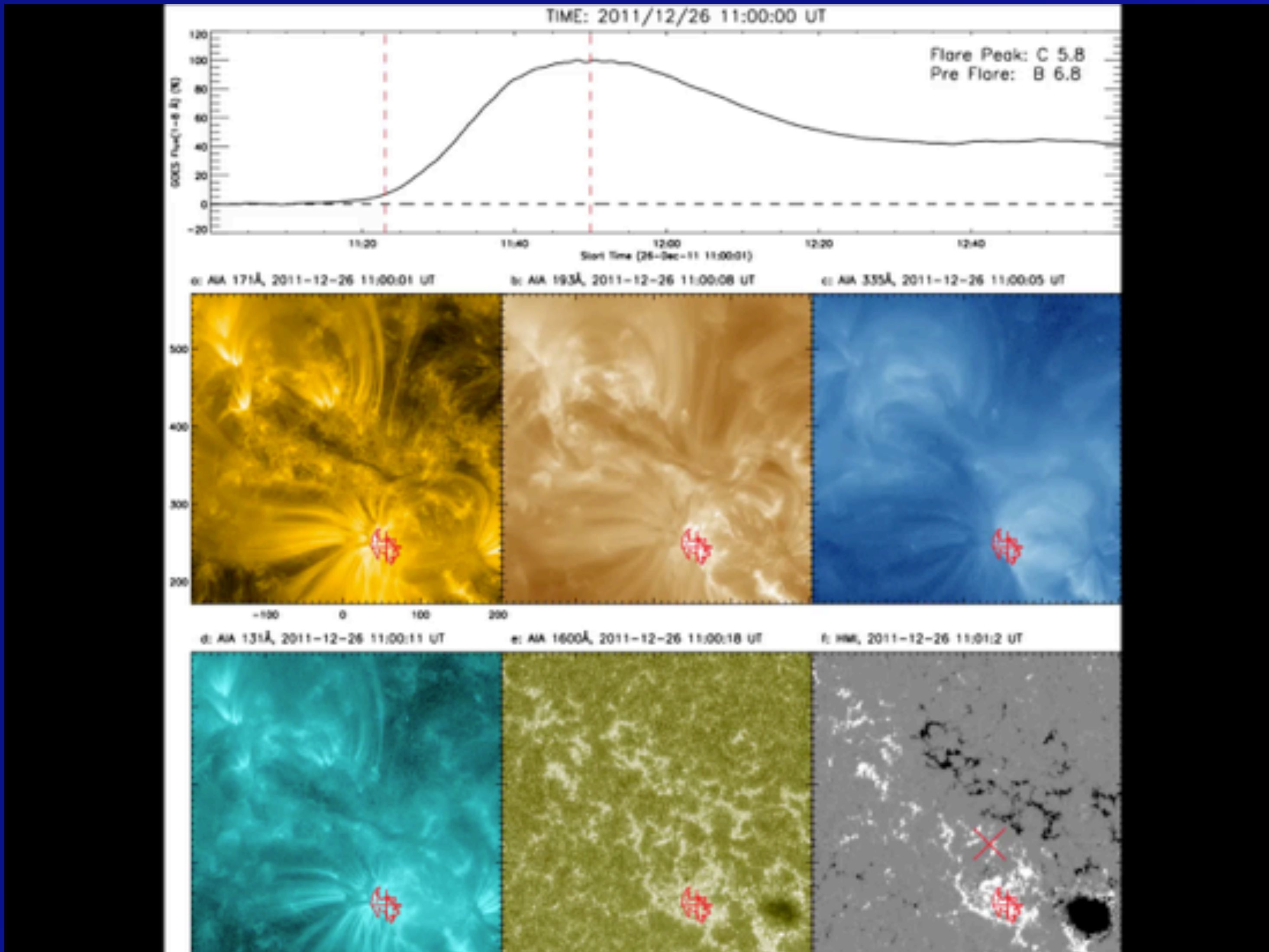
CSHKP Model has become a "standard"

(Svestka & Cliver 2002)

A bipolar magnetic field configuration with a dynamic current sheet that undergoes magnetic reconnection



Observations of a SEE



Show several SEE phenomena
(SDO AIA/HMI; X-ray)

SEE Model - 1st Generation

Successfully explain

1. Impulsive or fast energy release in solar flares (hard X-ray, gamma-ray, radio)
2. Expanding two ribbons, e.g, in Hα, UV
3. Post-flare loop arcade, e.g, in Hα, EUV
4. Long duration soft X-ray emission

SEE - G1 is centered on

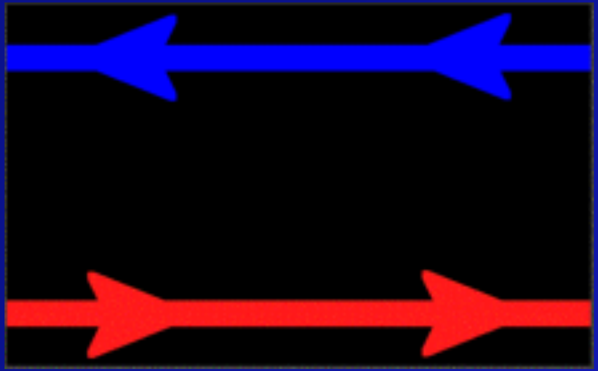
Fast magnetic reconnection that occurs in the vertical current sheet

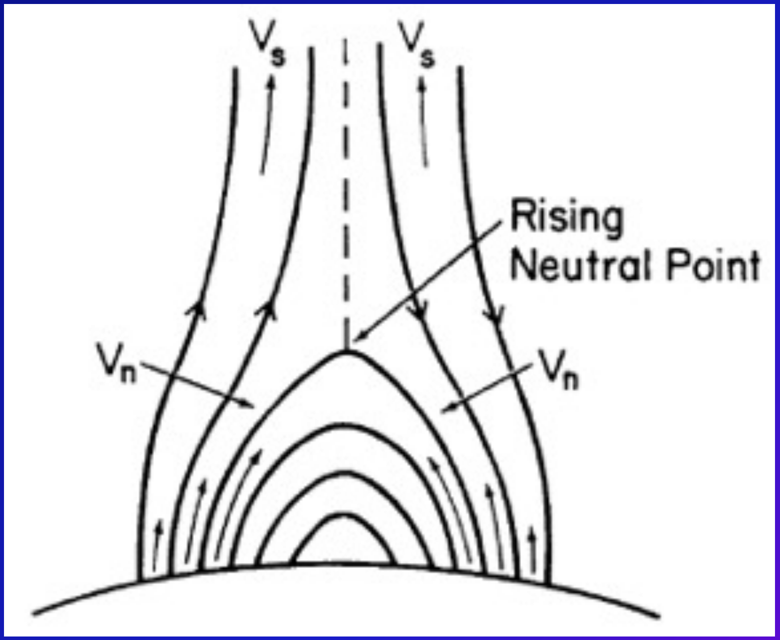
Reconnection for Flares

It is commonly believed that the physical mechanism of solar flares is magnetic reconnection

$$\frac{d\Phi}{dt} = V_i B_i = E = \eta j$$

(Sweet 1958; Parker 1957)





The successes of magnetic reconnection mechanism are

1. fast dissipation of magnetic energy
2. acceleration of non-thermal energetic particles

SEE Model: 2nd Generation

SEE Model G2 intends to identify:

1. Magnetic configuration prior to the eruption
2. What triggers the eruption

These issues are not explicitly addressed in G1 model.

There are two different paradigms of the 2nd generation models.

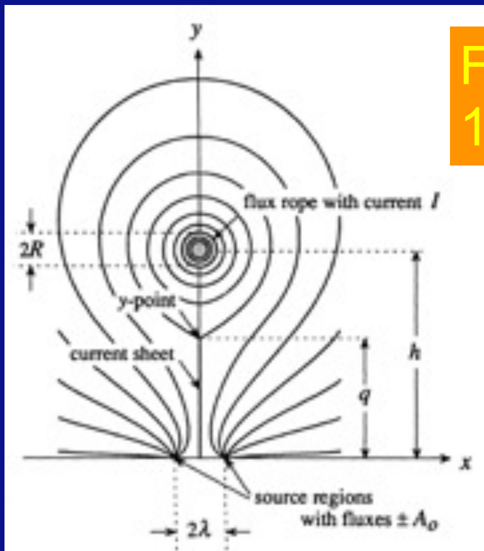
Paradigm 1: reconnection-triggering

This paradigm continues the 1st generation or "standard" models, identifying that magnetic reconnection is the trigger

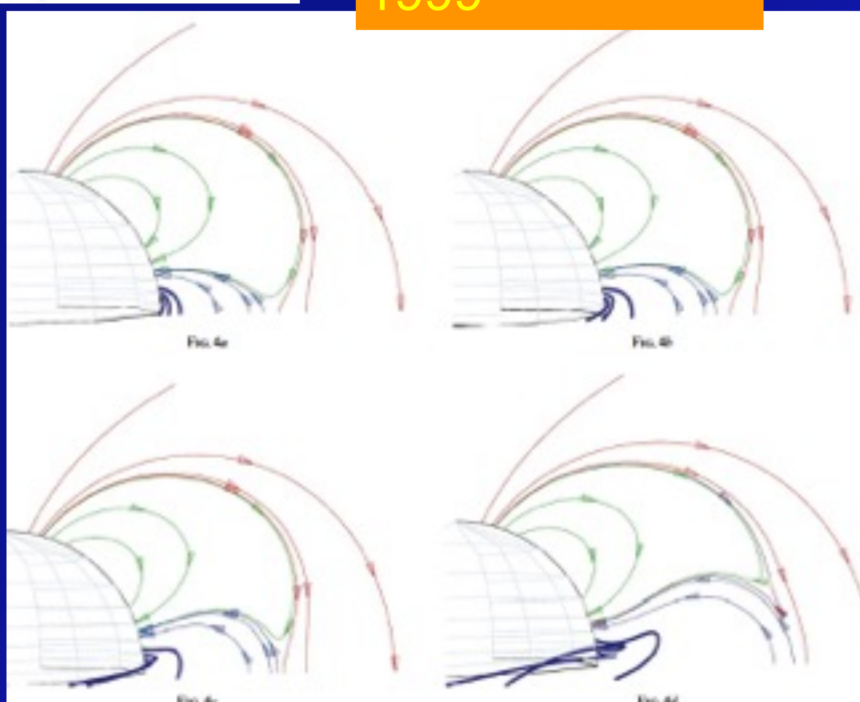
There are multiple variants

1. Catastrophe model (e.g., Forbes & Priest 1995): same B configuration in 2D
2. Breakout model (e.g., Antiochos et al. 1999): quadratic B configuration with a null
3. Tether-cutting model (e.g., Moore et al . 2001): sigmoid configuration in 3D

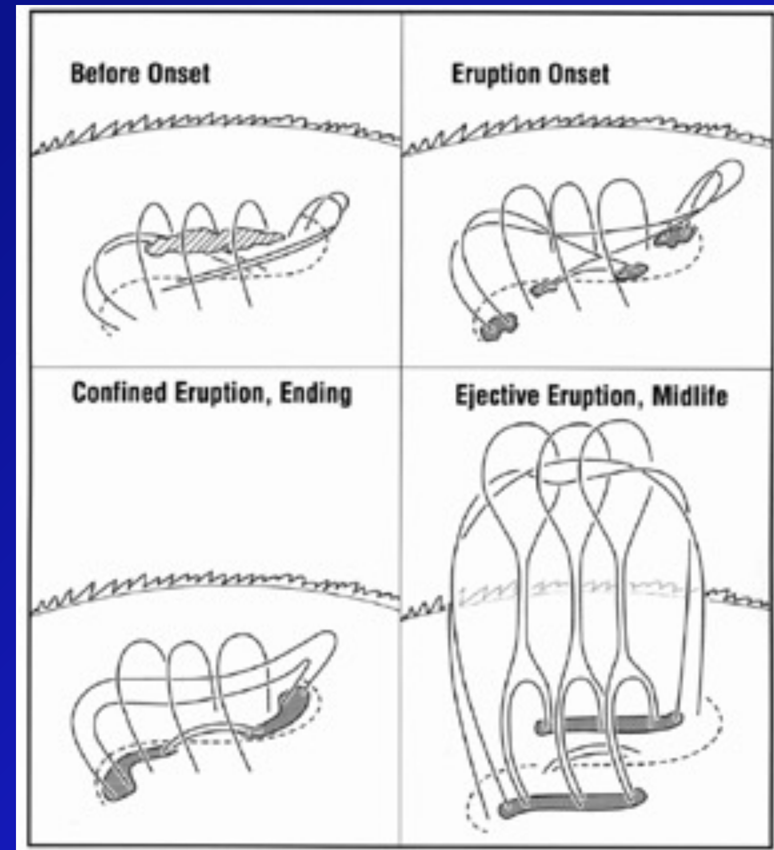
Reconnection-triggering Models



Forbes & Priest 1995



Antiochos et al. 1999



Moore et al. 2001

Paradigm 2: MFR-triggering

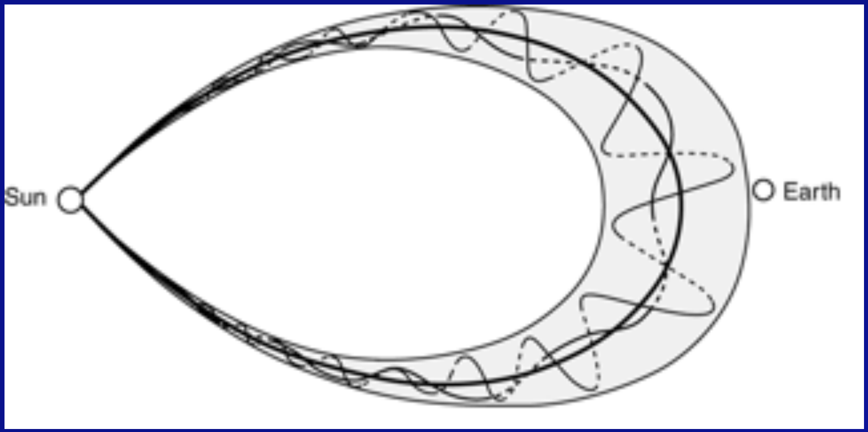
Magnetic flux rope (MFR) plays the essential role of

(1) Trigger the eruption (Initiation phase)

(2) Drive the eruption (main phase), possibly in conjunction with magnetic reconnection

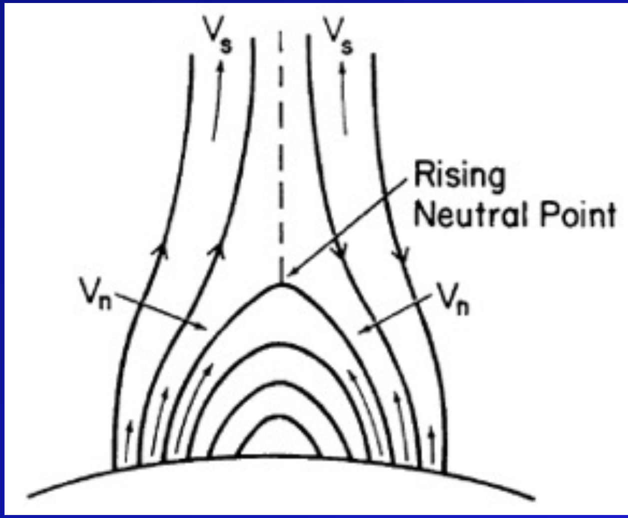
- Eruptive Flux Rope model (Chen 1989)
- Torus Instability model (Kliem & Török 2006)
- Partial Torus model (Olmeda & Zhang 2010)

Flux Rope - Current Sheet



Magnetic Flux Rope - 3D

(Russell & Mulligan 2002)



Current Sheet - 2D

(Kopp & Pneuman 1976)

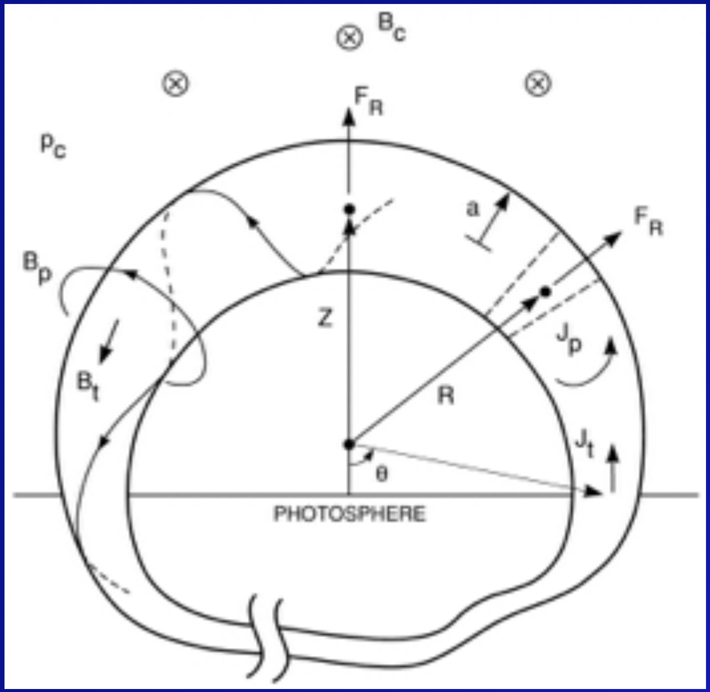
What is a flux rope?

- Magnetic field lines twist around a central axis
- At lease one full turn of twist from end to end
- Flux rope contains a current channel, which is 3D in nature

Magnetic Flux Rope

The physical mechanism: magnetic hoop force

- Flux rope eruption is driven by the Lorentz self-force (or hoop force, curvature force)



Chen (1989) and several follow-up studies

$$F_R = \frac{I_t}{C^2 R}\left[\ln\left(\frac{8R}{a}\right) + \frac{1}{2}\beta_p - \frac{1}{2}\frac{B_t^2}{B_{pa}} - 1 + \frac{\xi_i}{2} + 2\frac{R}{a}\frac{B_s}{B_{pa}}\right] + F_g + F_d$$

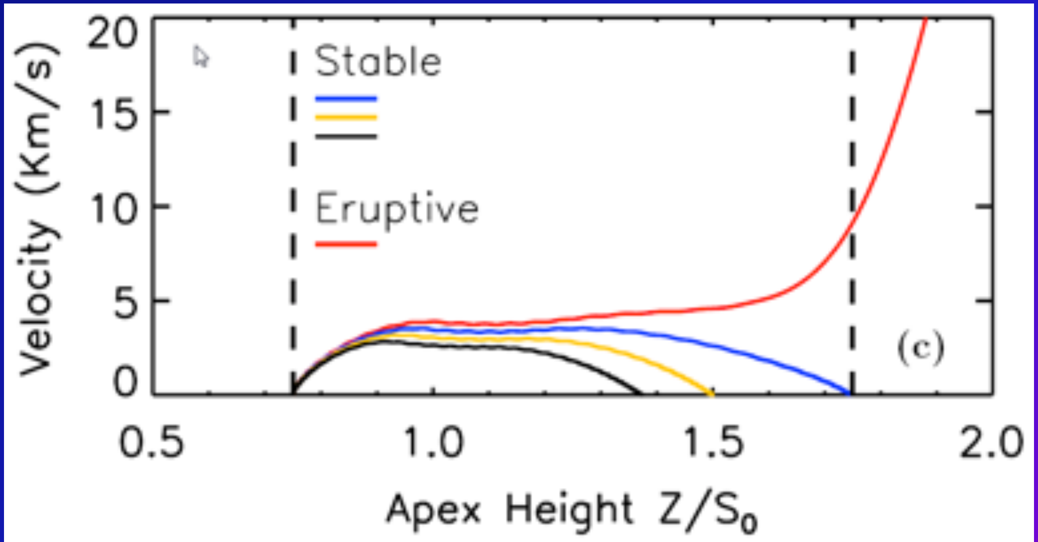
Magnetic Flux Rope

Torus Instability

- The instability specifies the condition at which the flux rope transits from the equilibrium state to the unstable state: critical gradient index (Kliem & Török 2006) (Olmedo & Zhang 2010); for numerical simulation, also see Fan & Gibson 2007; Aulanier et al. 2010)

$$\frac{d \ln B_s}{d \ln Z} \geq n_{critical}$$

$$n_{critical} \approx 1.5$$



(Olmedo & Zhang 2010)

The Outline

1. Flares/CMEs, SEE, and two competing paradigms of models

2. **Magnetic Flux Ropes: key test of models**

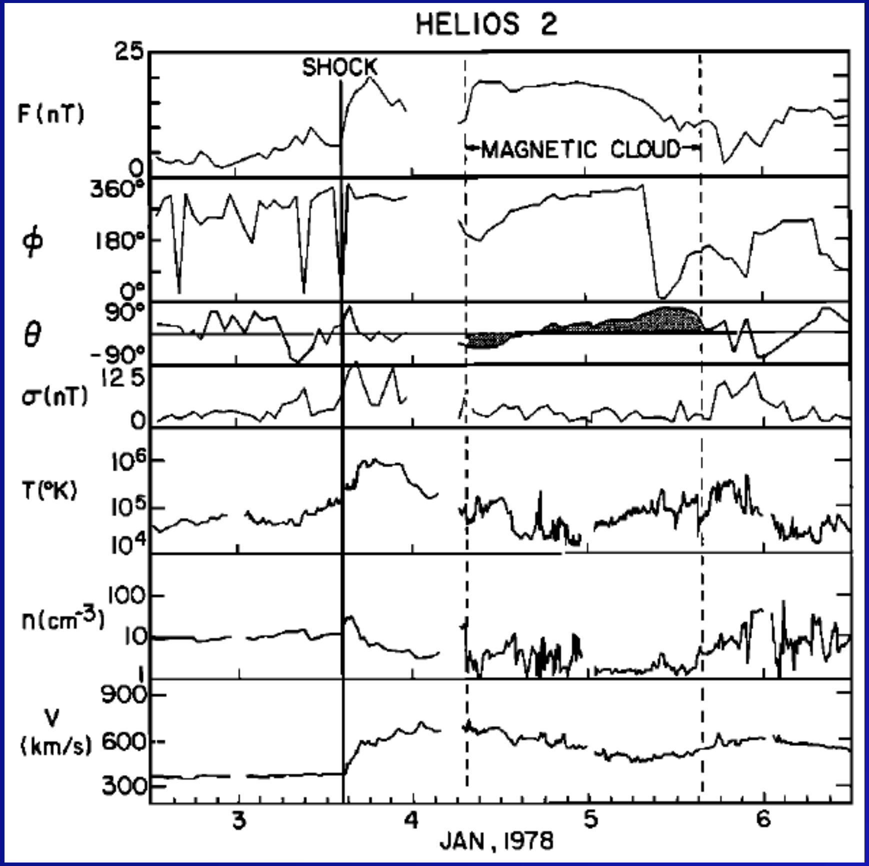
3. Conclusion and discussions

The Key Test

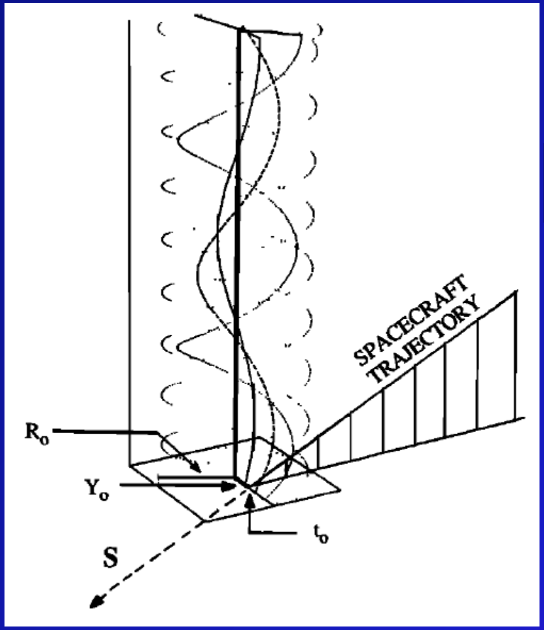
Does MFR exist prior to the eruption of a solar eruptive event? The key observational test

What is the role of MFR in eruption onset and eruption main phase?

MFR - the discovery in ICMEs

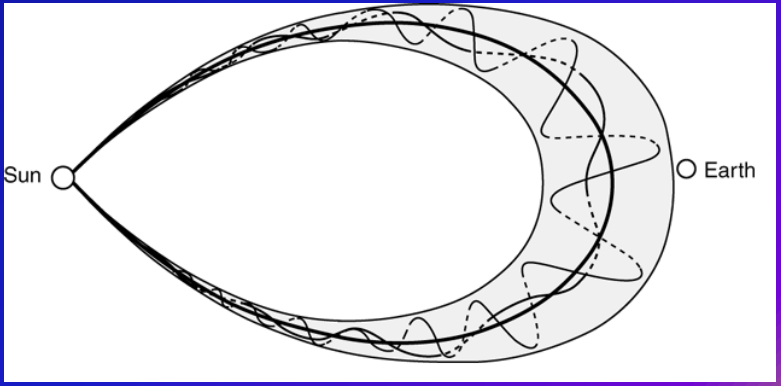


Magnetic Cloud
(Burlaga et al. 1981)



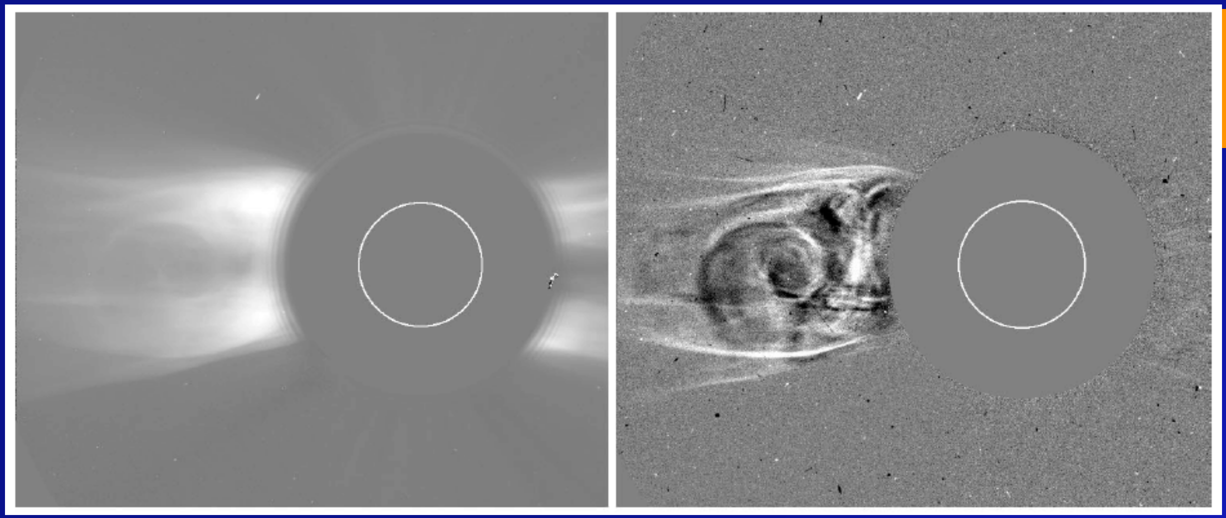
$$\nabla^2 B = -\alpha^2 B$$

Lundquist Solution
(Lepping et al. 1990)

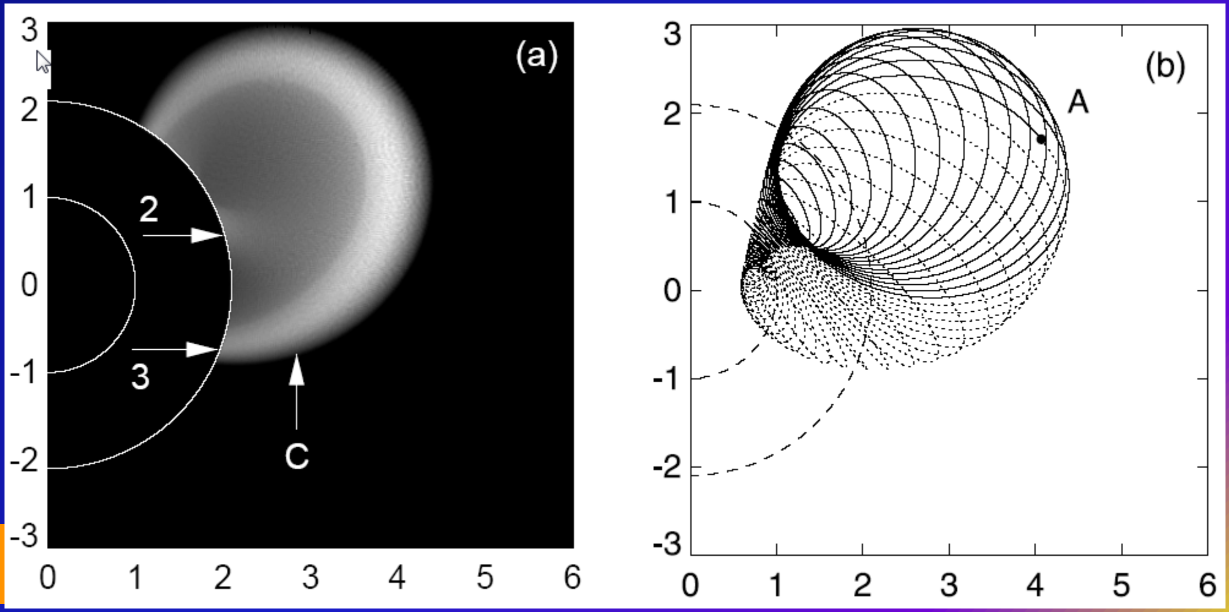


(Russell & Mulligan 2002)

Magnetic Flux Rope - CME



(Dere et al. 1999)



(Chen et al. 2000)

Post eruption MFR

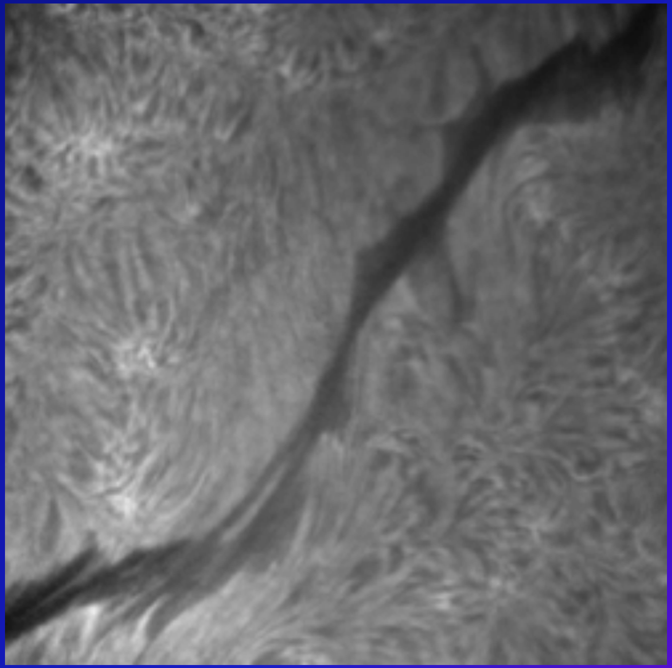
It is generally accepted by both paradigms of models that an MFR is formed post the eruption.

However, the issue is about before the eruption? Is an MFR or sheared arcade?

Is Filament an MFR?

Hα Filament

- Is filament a flux rope?
- Is filament a signature of the presence of the flux rope?



YES: (e.g., Rust & Kumar 1994; Gibson & Fan 2006; Kumar et al. 2011)

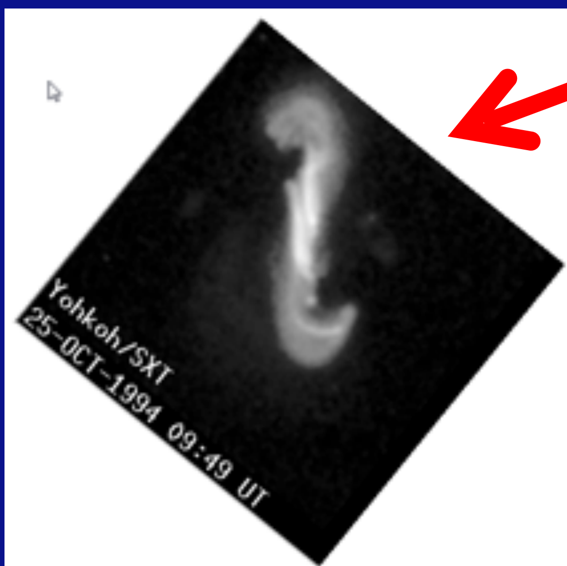
NO: dips in sheared arcade (e.g., Martin 1998; Antiochos et al. 1999)

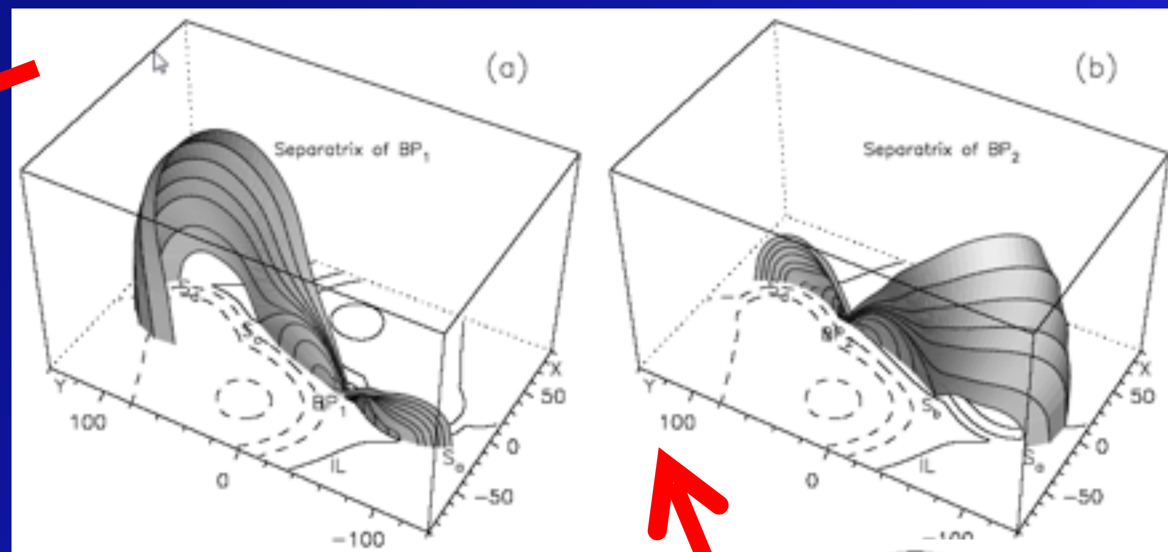
YES/NO: (Guo et al. 2010)

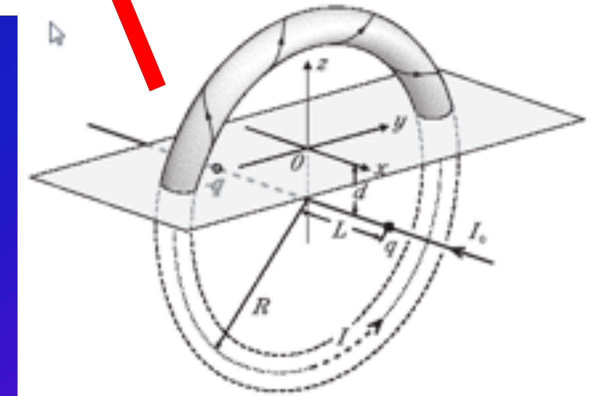
Coronal Cavity: Yes (e.g., Gibson et al. 2006)

Is Sigmoid an MFR?

- Stronger evidence. However, we could not observe its continuous transformation during the eruption: sigmoid->arcade.







(Titov & Demoulin 1999)

Also see Sterling & Hudson 1997; Canfield 1999; Gibson et al. 2006; McKenzie & Canfield 2008; Aulanier et al. 2010

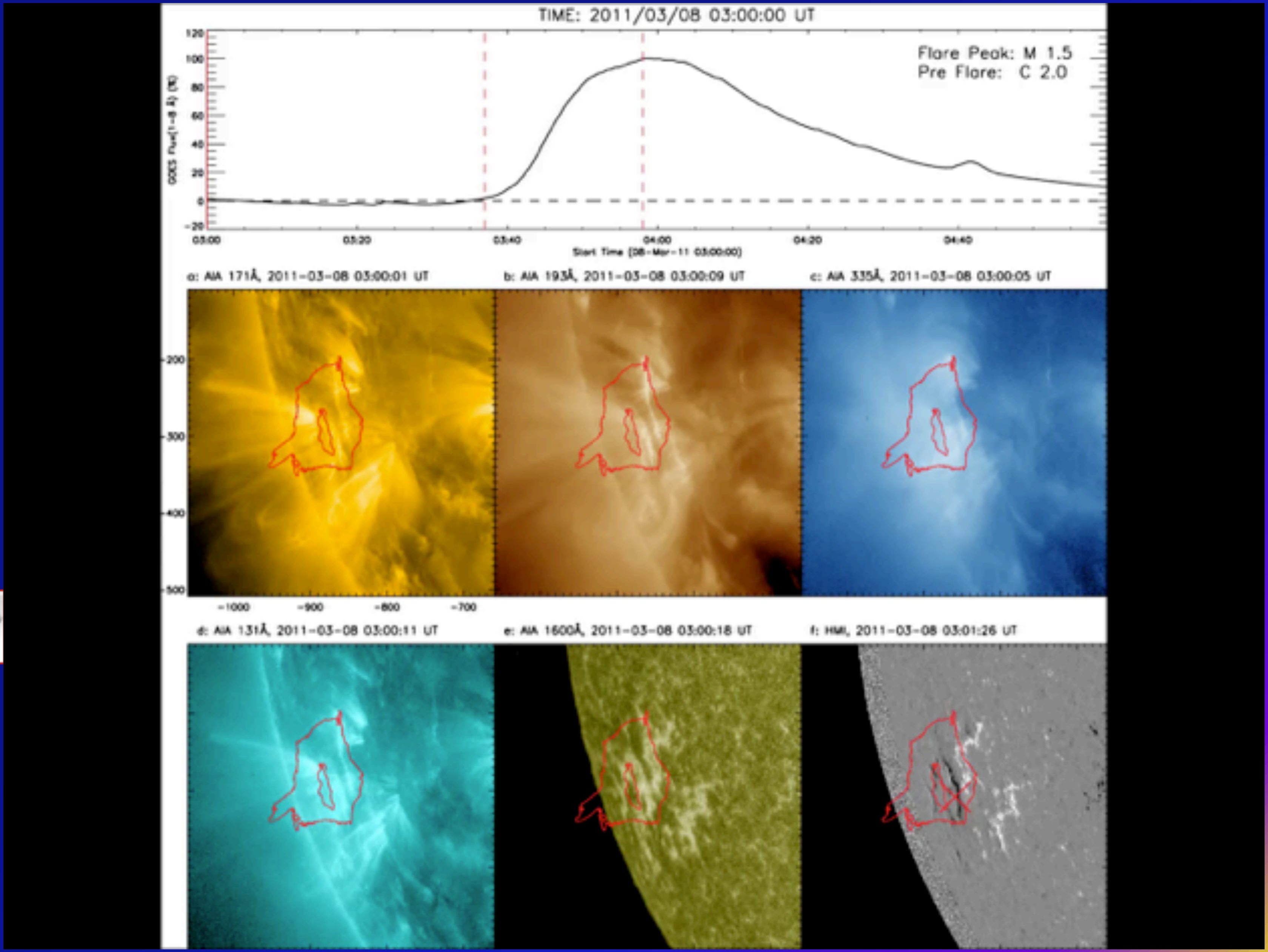
Is EUV Hot Channel an MFR?

EUV Hot Channel

- A single coherent structure with fixed footpoints
- Continuous transform from a sigmoid to a semi-circular loop
- Only appear in hot temperature (AIA 131Å, FeXX, ~10 MK)

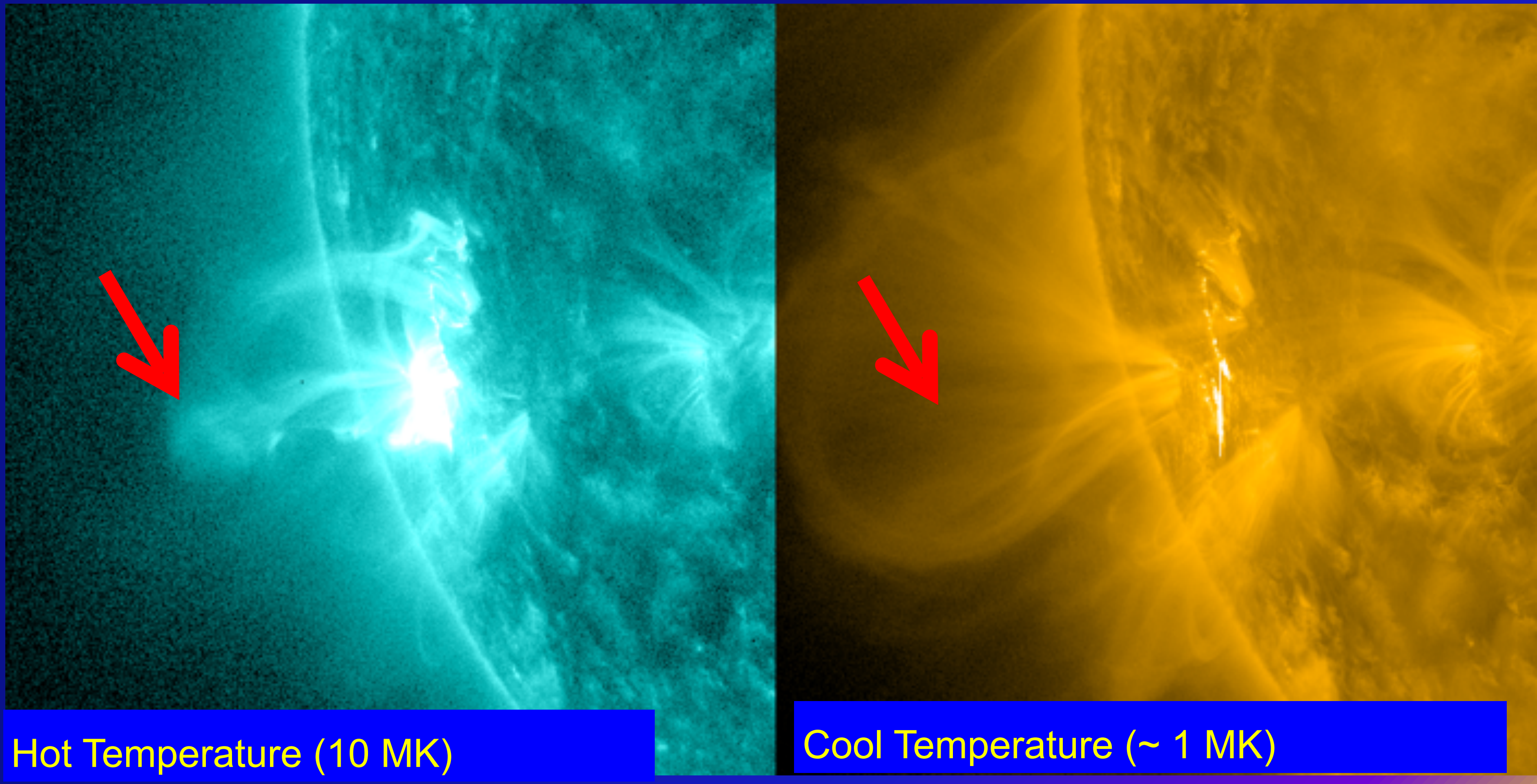
A strong evidence of the presence of flux rope before the eruption (Zhang, Cheng & Ding, Nature Communications, 2012)

Is EUV Hot Channel an MFR?



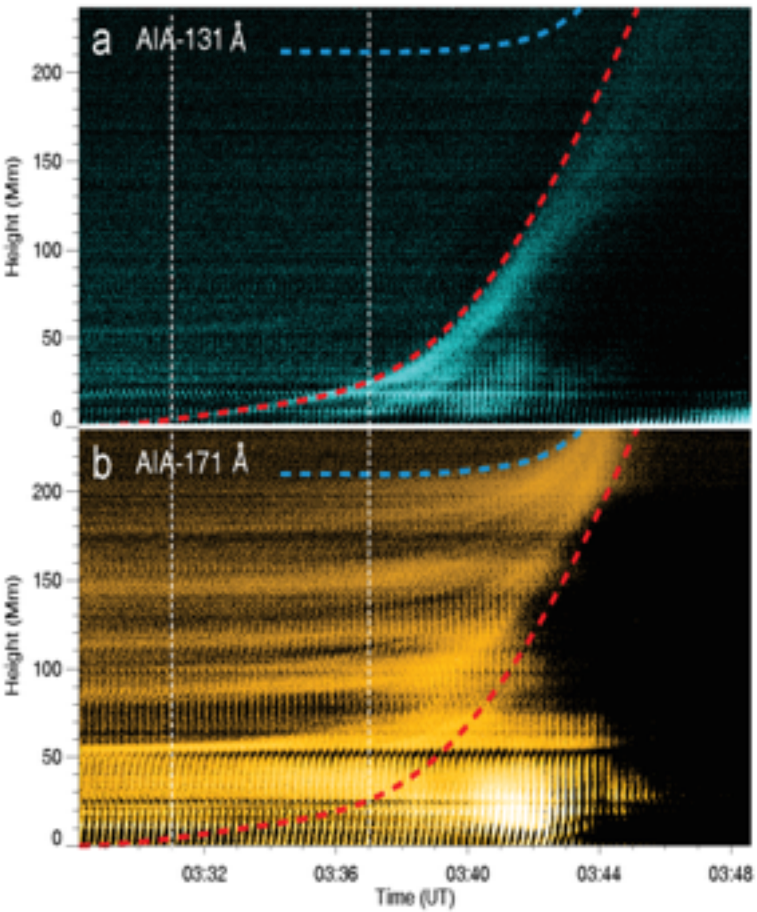
EUV Hot Channel

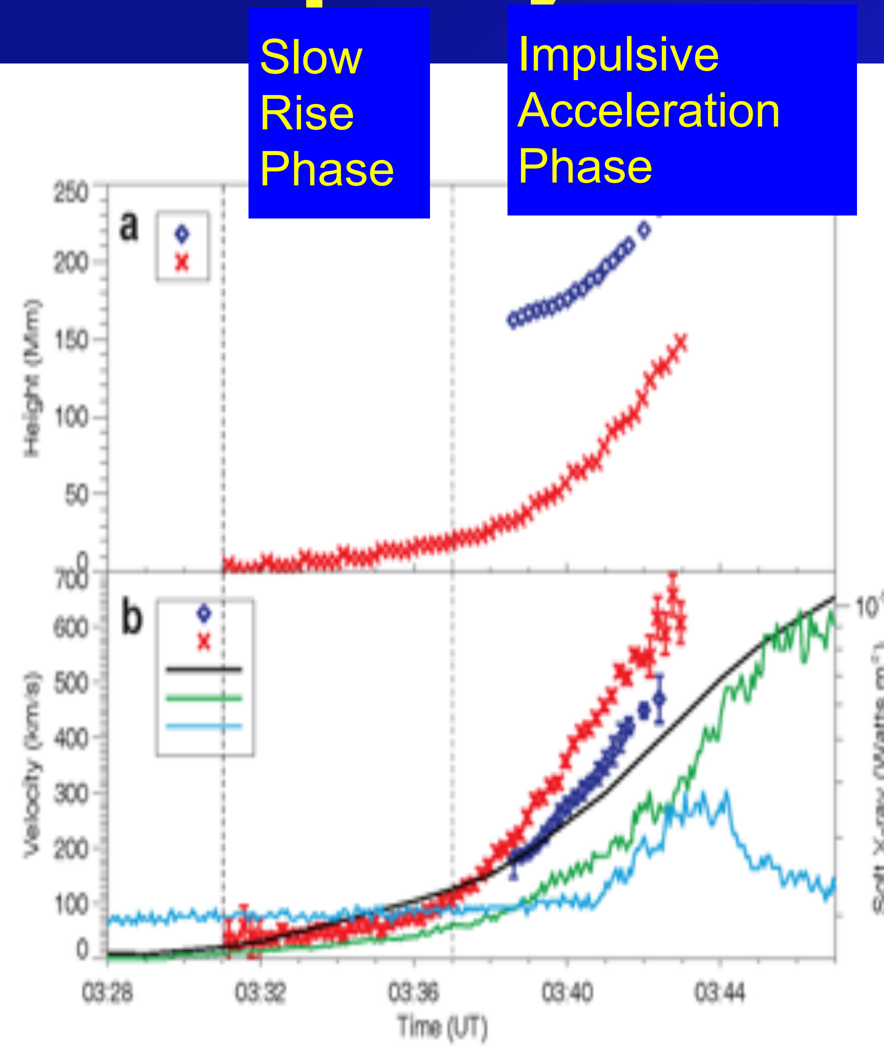
The best evidence of MFR



(Zhang, Cheng & Ding, Nature Communications, 2012)
Also see (Cheng et al., ApJ Lett., 2011)

Kinematic Property





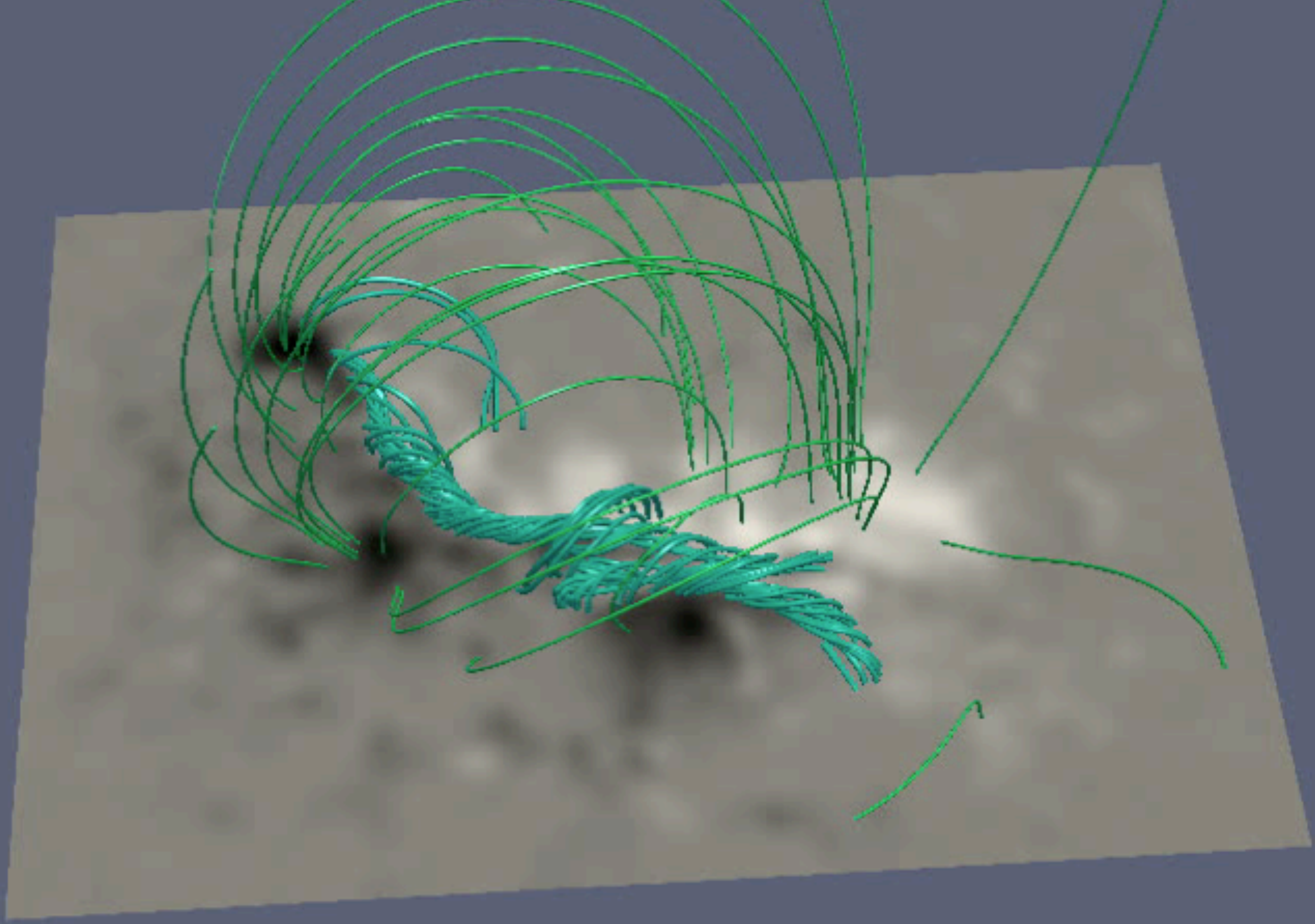
Slice-Time Plot

a: Height-Time Plot
b: Velocity-Time Plot

EUV Hot Channel - Side View

Side View

2013 May 22 Flux Rope Eruption (SDO/AIA 131 A)



An MFR from NLFFF Extrapolation

AR 11429, March 7, 2012. Super-active active region

Discussions

Step 1: onset of slow rising motion. The slow rising onset is caused by the ideal MHD instability of a pre-existing magnetic flux rope. The onset of the slow rise is likely to be caused by the torus instability, that is, the initial MFR rise is driven by Lorentz self-force. But the rising motion is restrained by the overlying B field, thus slow.

Discussions

Step 2: Continuing the Slow Rising Motion. The ideal MHD instability drives the slow rising motion of the MFR. This rising MFR stretches the surrounding and underlying magnetic field, forming and strengthening the current sheet underneath the flux rope.

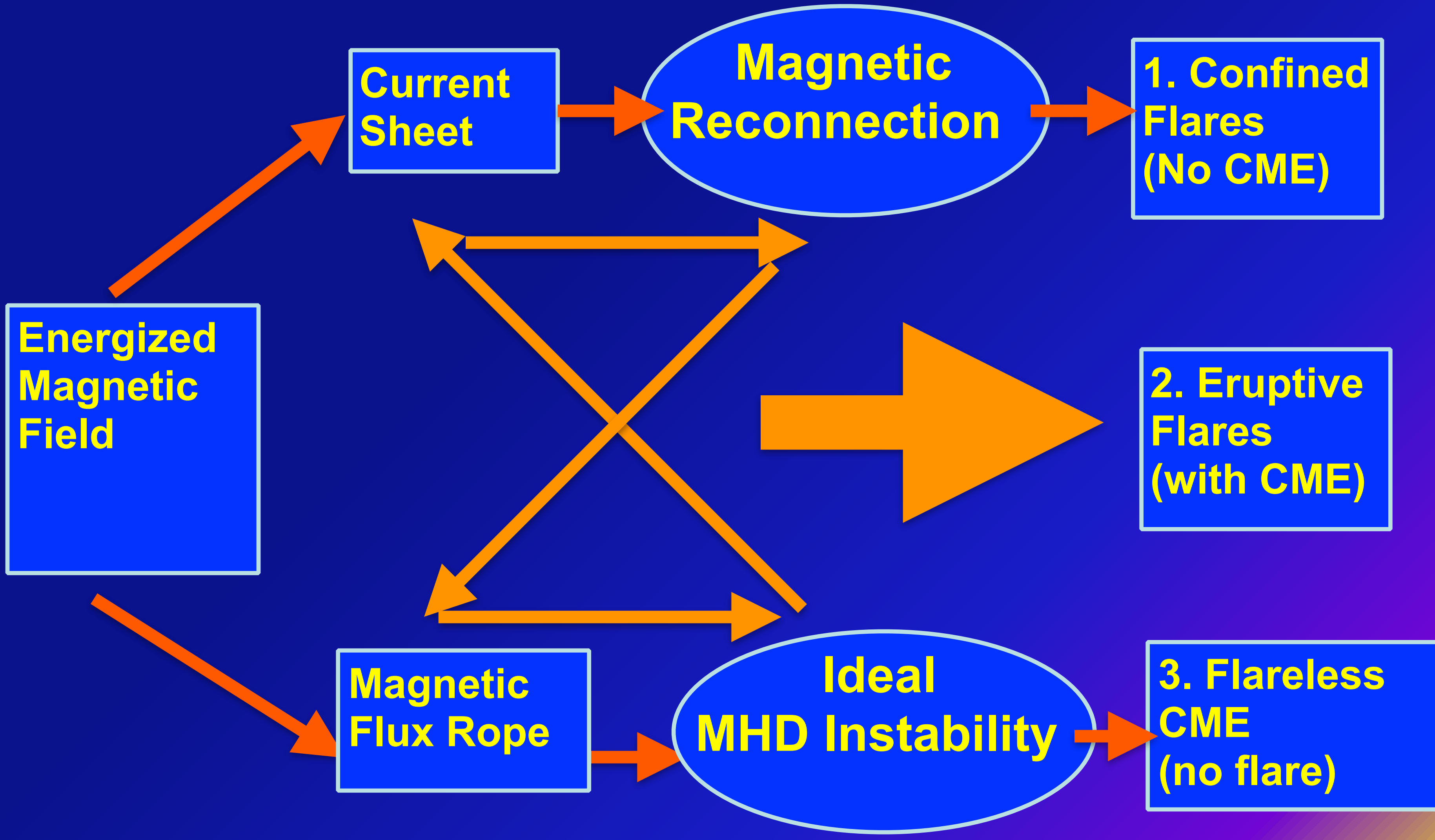
Discussions

Step 3: Onset of the fast Acceleration as well as the flare. The strengthening vertical current sheet reaches a critical point, at which a fast magnetic reconnection occurs. Fast magnetic reconnection causes tether cutting of restraining of overlying magnetic field, allowing fast acceleration of MFR

Discussions

Step 4: the Main Phase. Fast magnetic reconnection in the vertical current sheet adds poloidal magnetic flux into the MFR, making the acceleration even fast. The fast acceleration of MFR further enhances the current sheet, thus strengthens magnetic reconnection. It is likely that magnetic reconnection in the current sheet and torus instability in the MFR re-enforce one another through a **positive feed-back process,** resulting in **nearly synchronized** CME-flare evolution during the main energy release phase.

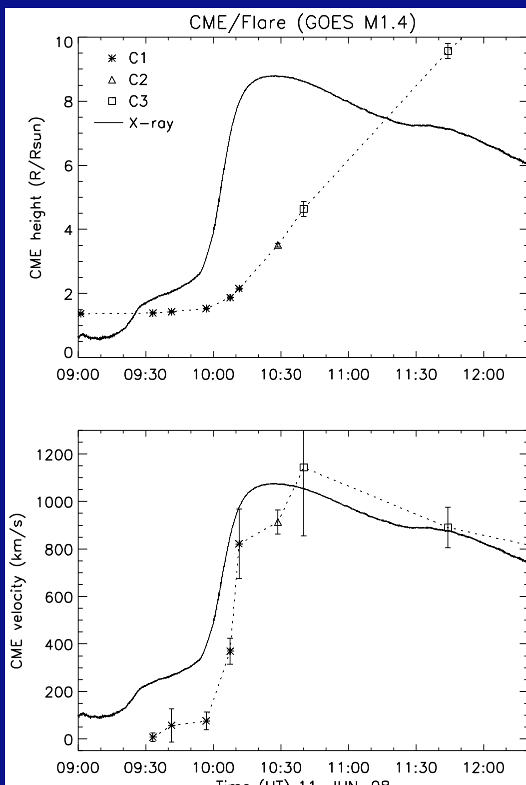
A Unified Scheme for All Types of Solar Events



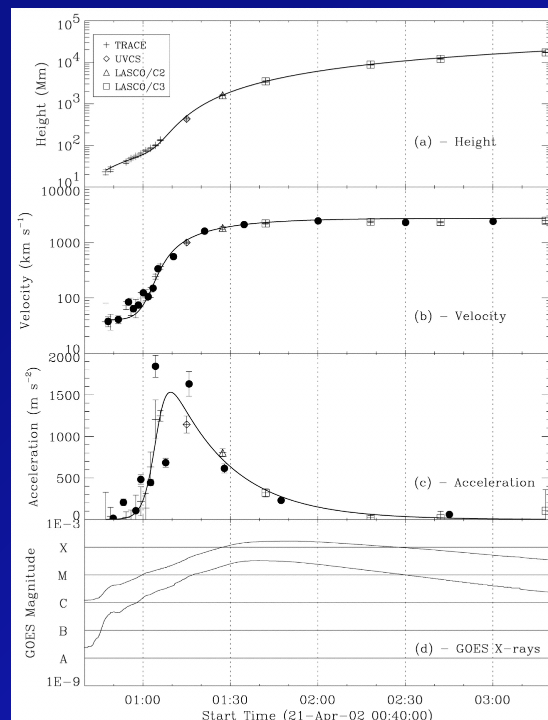
End

Backup

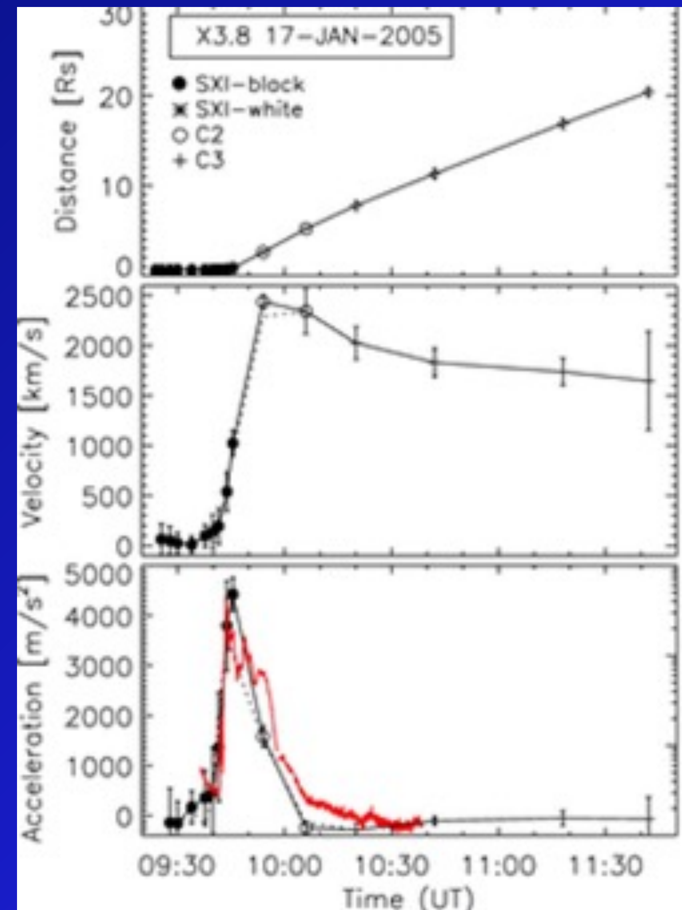
Temporal Relationship



(Zhang et al. 2001)



(Gallagher et al. 2003)



(Temmer et al. 2008)