Solar Eruptive Events (SEE) and MFRs

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Questions

1. **Pre-eruption**: does an MFR exist prior to the onset of a SEE? .................

2. **Onset of eruption**: what triggers the onset of SEE?
   - Onset of the precursor phase
   - Onset of the impulsive phase
   - .................

3. **During the eruption**: what drivers the eruption that lasts from a few minutes to tens of minutes?
   - what is the role of MFR during the impulsive phase?
   - What is the role of magnetic reconnection during the impulsive phase?
   - .................
The Outline

1. Solar Eruptive Events (SEE) and their 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

<table>
<thead>
<tr>
<th>Flare</th>
<th>Eruptive (with CME)</th>
<th>Confined (no CME)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-class</td>
<td>90%</td>
<td>10%</td>
</tr>
<tr>
<td>M-class</td>
<td>56%</td>
<td>44%</td>
</tr>
<tr>
<td>C-class (&gt;C3.0)</td>
<td>30%</td>
<td>70%</td>
</tr>
</tbody>
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(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

Evolution of CME and flare are nearly synchronized in SEE

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

CME Kinematic Evolution and Timing with Associated Flare

- Phase 1: Initiator phase
- Phase 2: Impulsive phase or main phase
- Phase 3: Gradual phase

(Zhang & Dere 2006)
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 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): bipolar 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 (onset(s))
(2) Drive the eruption (main phase), likely in conjunction with magnetic reconnection

- Eruptive Flux Rope model (Chen 1989)
- Torus Instability model (Kliem & Török 2006)
- Partial Torus model (Olmeda & Zhang 2010)
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
- Most importantly, flux rope is intrinsically unstable
Magnetic Flux Rope

The physical mechanism: magnetic hoop force

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

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

Chen (1989) and several follow-up studies
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)

\[
\frac{d \ln B_s}{d \ln Z} \geq n_{\text{critical}}
\]

\[
n_{\text{critical}} \approx 1.5
\]

(Olmedo & Zhang 2010)
The Outline

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

2. Magnetic Flux Ropes: key test of the two paradigms of models

3. Conclusion and discussions
The Key Test

Does an MFR exist prior to the onset of a solar eruptive event? The key observational test
MFR - the discovery in ICMEs

\[ \nabla^2 B = -\alpha^2 B \]

Lundquist Solution
(Lepping et al. 1990)

Magnetic Cloud
(Burlaga et al. 1981)

(Russell & Mulligan 2002)
Magnetic Flux Rope - CME

(Dere et al. 1999)

(Chen et al. 2000)
Post-eruption

It is generally accepted by both paradigms of models that an MFR is fully formed post the eruption (following the main and gradual phase).

However, the issue is about before the eruption? Is an MFR or sheared arcade? What is the exact magnetic structure?
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:** 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), may be not (?)
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: also a strong evidence

- 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 onset of 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

Slow Rise Phase

Impulsive Acceleration Phase

Slice-Time Plot

a: Height-Time Plot

b: Velocity-Time Plot
Flux Rope - NLFFF Model

An MFR from NLFFF Extrapolation

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

Step 1: onset of the pre-cursor phase. The slow rising motion 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.
Step 2: Pre-cursor phase. 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 impulsive or main phase. The strengthening vertical current sheet reaches a critical point, at which a fast magnetic reconnection occurs. Fast magnetic reconnection causes tether cutting of overlying magnetic field, allowing fast acceleration and ultimately escape of the 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

1. Confined Flares (No CME)
2. Eruptive Flares (with CME)
3. Flareless CME (no flare)

Energized Magnetic Field

Current Sheet

Magnetic Reconnection

Ideal MHD Instability

Magnetic Flux Rope
End
Backup
Temporal Relationship

(Zhang et al. 2001) (Gallagher et al. 2003) (Temmer et al. 2008)