Dynamics and Evolution of Solar Eruptive Prominences

by

Chunming Zhu

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy

Approved, Thesis Committee:

Dr. David Alexander, Chair
Professor of Physics and Astronomy

Dr. Frank Toffoletto
Professor of Physics and Astronomy

Dr. Fenglin Niu
Professor of Earth Science

Houston, Texas

April, 2014
Solar eruptive phenomena, including eruptive solar prominences/filaments, solar flares and Coronal Mass Ejections (CMEs), have severe impact on the Earth’s space environment and human activities: so-called Space Weather. The dynamics and evolution of the prominences/filaments are important for our understanding of the initiation processes that drive CMEs and lead to drastic energy release in the solar flares. This thesis focuses on recent progresses on the destabilization and subsequent eruption of the prominences/filaments, via three primary case studies that elucidate the most important activities occurring in the eruptive prominence: eruption of a bifurcated solar filament, interchange reconnection facilitating a filament eruption, and the interaction of two distinct filaments with subsequent production of solar flares.

In Chapter 2, we study a partial eruption of a bifurcated filament which exhibited clear and strong kinking motion of the filament axis (≈ 120° rotation). Seven mass transfer events are identified and are thought to also transfer magnetic flux from the lower to upper branch, leading to the generation of ideal instabilities, that subsequently triggered the eruption of the upper branch.

In Chapter 3, we present evidence of interchange reconnection driven by the interaction of an erupting filament with a nearby coronal hole that leads to the eruption
of this filament. Kinking motions in this filament serves to bring the magnetic field of its eastern leg in close contact with the unipolar magnetic field of the coronal hole where it drives the reconnection that governs the subsequent evolution of the filament and coronal hole boundary. The observed EUV brightenings and bi-directional flows in the contact layer formed by this interaction, along with the occurrence of type III radio bursts that are strongly related to escaping electrons along open fields, provide corroborative evidence for the occurrence of reconnection at this location. A consequence of this interaction was the development of a complex CME, that displayed both open and closed features: we believe this is the first time such a CME configuration has been observed directly in association with a filament eruption.

In Chapter 4, an interaction between two filaments, rarely reported before, is identified and studied. This complex interaction is responsible for the production of a hard x-ray coronal source as part of a C3.0 class solar flare. The observed hard x-ray coronal source occurring between the two filaments, driven by a convergence of the filaments, and a newly formed hot plasma layer, indicate that magnetic reconnection occurred between the magnetic fields associated with both filaments. The eruption of the filaments later led to the onset of a much larger solar flare, class M2.9, as expected from the standard flare model. It is interesting to note that both loop shrinkage and supra-arcade downflows (SADs) are present during this M2.9 flare.
I would express my great thanks to my advisor, Dr. David Alexander, for his insightful discussions and patient guidance over the years. I thank Dr. Lirong Tian, for her guidance on my research of rotating sunspots and magnetic helicity injection. I am grateful to Dr. Rui Liu, whose knowledge and discussions have enlightened me on the recent study of filament interactions. I would like to thank Dr. Xudong Sun, Dr. Stephen Bradshaw, Dr. Yuhong Fan, and Dr. Antoun Daou, for their thoughtful comments on my papers.

Great thanks to Dr. Frank Toffoletto, and Dr. Fenglin Niu, for their dedication as the committee members for this thesis.

I also thank the faculty, staff, and fellow students in our department of Physics and Astronomy at Rice University. Their stimulating suggestions and discussions, have helped me with the improvement of this thesis. Especially thanks to Umbe Cantu, Jingbo Liu, Jeffrey Reep, Wei Chen, Shuzhen Ye, Yi Chen, Jianda Wu, for their friendship and help over the years.

I would thank my wife Haixia Liu for the support and encouragement, and our lovely daughter Cindy Zhu, and my parents for their love.
## Contents

Abstract ..................................................... ii  
Acknowledgments ............................................. iv  
List of Illustrations ......................................... viii  
List of Tables ................................................ x  

1 Introduction .................................................. 1  
1.1 Solar Eruptive Phenomena ..................................... 1  
1.1.1 Solar Prominences .......................................... 3  
1.1.2 Solar Flares ................................................ 7  
1.1.3 Coronal Mass Ejections ..................................... 10  
1.1.4 Solar Eruptive Phenomena as a Single System ............ 10  
1.2 Kinking Prominences .......................................... 13  
1.2.1 Injections of Magnetic Energy and Helicity into the Solar  
Atmosphere ..................................................... 13  
1.2.2 Kinking Motions of Filaments .............................. 16  
1.3 Instruments and Data .......................................... 18  
1.3.1 SDO Spacecraft ............................................. 19  
1.3.2 STEREO Spacecraft ......................................... 20  
1.3.3 RHESSI Spacecraft .......................................... 21  
1.4 Outline of the Thesis ......................................... 22  

2 Eruption of a Bifurcated Solar Filament ....................... 24  
2.1 Introduction .................................................. 24  
2.2 Observations .................................................. 26
4.2.6 Transition to a M2.9 Flare and Field Line Shrinkage 65

4.3 Interpretation and Discussion ............................................ 69
  4.3.1 Filament-Filament Reconnection ................................... 69
  4.3.2 Field Line Shrinkage in the M Flare ................................. 71
  4.3.3 Proposed Physical Picture ............................................ 72

4.4 Conclusion ............................................................................. 74

5 Summary and Future work ..................................................... 75
  5.1 Summary .............................................................................. 75
  5.2 Future Work ......................................................................... 77
Illustrations

1.1 Space Weather. 2
1.2 Structures in the solar atmosphere. 3
1.3 Solar prominences/filaments. 4
1.4 Filament structures. 5
1.5 Chirality of prominences/filaments. 5
1.6 Magnetic reconnection. 8
1.7 Standard flare model. 9
1.8 A normal CME displaying a three-part structure. 11
1.9 Schematic diagram showing various features associated with a CME. 11
1.10 Simulation of a kinking filament in agreement with observation. 17
1.11 A hard x-ray coronal source at the projected crossing of both legs of a kinking filament. 18

2.1 Configuration of the filament at 9 May 2012 04:05 UT, 20 hours before eruption. 27
2.2 Observations of a filament eruption on 10 May 2012, in He II 304 Å. 29
2.3 Lightcurve in AIA 304 Å, filament displacement and rotation. 31
2.4 3D reconstruction using STEREO-A and SDO/AIA, showing the filament evolution viewed from three different perspectives. 32
2.5 Material transfers in the bifurcated filament. 38
2.6 Magnetic field evolution before and during the eruption. 39
2.7 Decay index calculation. 39
3.1 The solar filament with its ambient magnetic-field configuration before eruption. .................................................. 44
3.2 Evolution of the filament eruption, observed in SDO/AIA 304 Å. . . . 45
3.3 Normalized intensity profile in the EUV channels, and STEREO-A/WAVES radio observation. ........................................ 47
3.4 The reconstructed 3D configurations of the evolving filament from the STEREO-A and SDO EUV observations at four distinct times. . . . 48
3.5 Some “hook-like” features formed and became open when the filament approaching the coronal hole. .................................. 49
3.6 Inward and outward ejections in the contact layer. ......................... 50
3.7 The CME observed by STEREO-A/COR1. ................................ 51
3.8 The CME superimposed with the PFSS fields from each of the two observational viewpoints. ........................................... 53
3.9 Schematic drawing of the filament-CH interaction. ......................... 55

4.1 Configurations of the lower and upper filaments before eruption. .... 60
4.2 Evolution and interaction of the two filaments. ............................. 61
4.3 Production of two consecutive solar flares. ................................ 62
4.4 Converging motions of the upper filament and the erupting filament. . 63
4.5 A hot layer of plasma appeared at the interaction of two filaments. . 64
4.6 RHESSI X-ray observations overlaid on the EUV images from AIA 304 Å. .............................................................. 66
4.7 Tracking the dominating sources of the x-ray in the C3.0 flare. ......... 67
4.8 Observations of the magnetic loop shrinkage and descending dark voids in the M2.9 flare. ................................. 68
4.9 Proposed physical picture for the observed filament-filament interaction and production of solar flares. .................................. 73
# Tables

1.1 Types of filament eruptions. ............................................. 6
1.2 Estimates of the coronal energy sources. ............................. 13
1.3 SDO/AIA observation channels. ......................................... 19

2.1 Timeline for the filament eruption from 8 to 10 May 2012. ........ 30

3.1 Timeline for the filament eruption on 9 August 2012. ............... 54
Chapter 1

Introduction

This chapter presents a brief introduction to solar eruptive phenomena, in particular the solar prominence, the main focus of this thesis. In Section 1.1, the general features of solar eruptive phenomena are introduced. This is followed by an introduction to the injection of magnetic energy and helicity into the solar atmosphere, and its influence on the kinking motions of solar prominences. Some descriptions of the instruments and data that are used in our analysis are included in Section 1.3. The outline of this thesis is given in Section 1.4.

1.1 Solar Eruptive Phenomena

Solar materials, including the hot ionized gases (known as plasma) and magnetic fields are frequently observed to erupt away from the Sun. The major eruptions, consisting of eruptive solar prominences, solar flares and Coronal Mass Ejections (CMEs), can have severe impact on the Earth’s space environment and human activities (Fig. 1.1): this impact is known as space weather. These most prominent effects include:

- Spacecraft anomalies by radiation damage and spacecraft charging
- Harmful exposure of humans in space to photon and energetic particle radiation
- Perturbations to the geomagnetic field
• Disruption of navigation (such as the Global Positioning System) and communication systems
• Power grids blackout

Figure 1.1: Solar eruptive phenomena have severe impact on the space environment of the Earth. This graphic shows the Earth’s magnetosphere being impacted by energetic particles driven by a CME. Credit: SOHO (ESA & NASA).

The solar atmosphere is composed of three main regions (Fig. 1.2): the photosphere, the chromosphere, and the solar corona, differentiated by their temperature and density distributions. The photosphere, the visible surface of the Sun, is a thin layer of about 400 km thick (compare to the solar radius $R_\odot \sim 6.96 \times 10^5$ km). It has a temperature at approximately 5700 K and a density of $2 \times 10^{-4}$ kg/m$^{-3}$. The region directly above the photosphere is the chromosphere. It is a layer with typical thickness of around 2000 km, and temperature between 4400 K and 25000 K, increasing with height. The outermost layer is the solar corona, which is very hot (around one million K) and tenuous ($10^{-8}$ of the density in the photosphere). The corona
extends for several million km. Between the chromosphere and corona, there is a region called *transition region*, in which the temperature jumps drastically in about 100 km, bridging the temperature range from a few tens of thousands of degrees to the 1 million degree temperature of the corona.

The following gives a brief description of the solar eruptive phenomena that are observed to occur in the solar atmosphere.

![Diagram of the solar atmosphere](image)

**Figure 1.2**: The structures of solar atmosphere: the photosphere, chromosphere and corona. Only the lower corona is shown here. Credit: Smithsonian Astrophysical Observatory.

### 1.1.1 Solar Prominences

Solar prominences are usually observed as large arched features extending outward from the solar surface (left panel in Fig. 1.3). Their suspension in the hot and tenuous corona can persist for several solar rotations (a solar rotation is \( \sim 27 \) days). The prominence material is actually made up of typically a hundred times denser and
cooler plasma (almost completely hydrogen and helium) than the solar corona. The prominence plasma absorbs the radiation coming from below and scatters it in all directions. Thus they appear bright at the solar limb in emission, without a coronal background. On the other hand, when observed on solar disk, the radiation scattered by the filament is only a fraction of the chromospheric background, thus they display as dark, long and belt-like structures, in chromospheric and coronal lines (such as H$_\alpha$, $\lambda = 6563$ Å, and He II, $\lambda = 304$ Å). In this way, they are named solar filaments when viewed on the solar disk.

![Image of solar prominences and filaments](image)

**Figure 1.3**: Solar prominences (observed on limb, *i.e.*, edge of the Sun, in left panel) and filaments (observed on disk, in right panel). Prominences/filaments are comprised of cool and dense chromospheric plasma suspended by twisted magnetic flux tubes in the solar corona. Credit: SOHO (ESA & NASA).

A typical solar filament consists of a spine, barbs and two legs. The spine is used to describe the horizontal fine structure along the axis of the filament (Fig. 1.4). The lateral extensions (indicated by circles in Fig. 1.4) emanating from the spine, are the barbs, terminating in the chromosphere. Its two legs (also called “ends”) are the
outer ends that terminate in a single or multiple points on the solar surface. And the legs terminate in opposite polarities of magnetic field.

Figure 1.4: High resolution image of a filament observed in $H\alpha$. The barbs are marked by the circles. Filament structure. Credit: Dutch Open Telescope.

Figure 1.5: Chirality of prominences/filaments. When a prominence or filament is viewed from the positive polarity side (indicated by a plus sign), the axial fields in dextral/sinistral filament points to the right/left (thin arrows). Credit: GONG $H\alpha$ network.

The solar prominence is always situated long the *magnetic polarity inversion line*
(PIL), a neutral line separating the positive and negative polarities of the photospheric normal magnetic fields, with its two legs rooted in opposite polarities (see review by Martin, 1998). The orientation of their main axial magnetic field, is called the filament chirality, and comes in two forms: dextral or sinistral (Fig. 1.5). When the prominence or filament is viewed from the positive polarity side, the axial fields in a dextral/sinistral filament point to the right/left. The filament chirality exhibits a hemispheric preference pattern, with dextral/sinistral filaments dominating in the northern/southern hemispheres (Martin, 1998).

Table 1.1: Types of filament eruptions (Gilbert et al., 2007).

<table>
<thead>
<tr>
<th>Type of Eruption</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full</td>
<td>Bulk (≤90%) of filament mass and magnetic structure escape the Sun</td>
</tr>
</tbody>
</table>
| Partial          | a) Entire magnetic structure erupts with some or none of the filament mass (as a result of mass draining)  
|                  | b) Partial eruption of the magnetic structure with some or none of the filament mass (as a result of mass draining and/or settling) |
| Failed           | None of the filament mass nor magnetic structure escapes the Sun |

After a long time of relatively steady suspension in the solar corona, prominences are destabilized and observed to erupt upwards and outwards. These eruptions exhibit three types: full, partial or failed eruption (see definitions in Table 1.1; Gilbert et al., 2007). The full and partial eruptions result in the filament material and surrounding magnetic structure being ejected from the Sun, typically observed as a CME. The failed eruption, without filament mass nor magnetic structure escapes the Sun, producing no CME. Solar flares are usually associated with the eruptions in all three
1.1.2 Solar Flares

Solar flares are sudden brightenings in the solar atmosphere, releasing an amount of energy as high as $6 \times 10^{25}$ J over a timescale of minutes (for comparison, the total world annual energy consumption in year 2010 is $5 \times 10^{20}$ J. During solar flares, a large amount of plasma (including electron, protons, and ions) is strongly accelerated and heated. Solar flares also produce radiation spanning the entire electromagnetic spectrum, from radio waves to $\gamma$-rays. According to their peak flux (units: $W \, m^{-2}$) of soft x-ray emission within 1–8 Å as detected by the Geostationary Satellite system (GOES), solar flares are classified as A, B, C, M, or X, increasing by a factor of ten between two consecutive classes, and a linear scale within a same class. For example, an X1.0 flare is ten times stronger than an M1.0 flare, while an X2.0 flare is twice as powerful as an X1.0 flare.

It is generally accepted that the rapid release of the energy during solar flares is driven by magnetic reconnection. Magnetic reconnection is a dynamical process in which neighboring regions of magnetized plasma communicate with each other by reordering the magnetic field lines among topologically distinct domains (Priest and Forbes, 2000).

One basic model of magnetic reconnection, the so-called Petschek model (Petschek, 1964), is shown in Fig. 1.6. In this model, four magnetic domains are separated by two separatrices (two crossing dashed lines in Fig. 1.6), with a center part called the diffusion region (shaded) where the magnetic field may diffuse through the plasma. Magnetic field lines (and associated plasma) flow inward from above and below to the diffusion region, reconnect there, and newly connected fields spring outward to the
Figure 1.6: Magnetic reconnection (Petschek, 1964). Magnetic field lines flow inward from above and below to the diffusion region (shaded box at center), reconnect there, and newly connected fields spring outward horizontally. Four magnetic domains are separated by two separatrices (two crossing dashed lines).

left and right. As a result, the magnetic energy of the inflow is split up roughly in equal parts into both kinetic and thermal energy in the outflowing plasma (Forbes, 2000), leading to the acceleration and heating of particles in the plasma. It is suggested by the Petschek model that, in the solar corona, the typical outflow velocity (Alfvén speed) is around 1000 km/s, while the inflow speed is around 10–100 km/s.

Several models have been proposed to explain the observed solar flares. The most widely accepted flare model is the CSHKP model that evolved from a series of studies (Carmichael, 1964; Sturrock, 1966; Hirayama, 1974; and Kopp and Pneuman, 1976), also known as the standard flare model (Fig. 1.7). In this model, the solar prominence (dark shaded) is supported by the twisted magnetic flux tube (indicated by the arrowed circles in Fig. 1.7). When the prominence rises, it stretches the field lines (lines surrounding the flux tube and rooted at the photosphere), leading to the formation of a current sheet underneath. The anti-parallel magnetic fields
Figure 1.7: Standard flare model: Magnetic reconnection takes place at a current sheet (dark vertical line) beneath an erupting prominence (shaded region at the center). Credit: Martens and Kuin (1989).

associated with this current sheet reconnect at the diffusion region, which is assumed to be the location of major magnetic energy dissipation, heating and accelerating the local plasma. The downward accelerated particles and thermal conduction fronts then heat the dense chromosphere at the footpoints. Due to this impulsive heating, the chromospheric plasma ablates and fills the newly connected fields with heated plasma, which become the observed flare loops emitting soft x-ray emission ($T_e \sim 10^{-40}$ MK). Once these flare loops cool down, mostly by radiative losses and thermal conduction, they appear in the Extreme UltraViolet, or EUV ($T_e \sim 1-2$ MK), and other wavelengths at lower temperatures.
1.1.3 Coronal Mass Ejections

Coronal Mass Ejections (CMEs) are massive bursts of large-scale magnetized plasma from the Sun (Fig. 1.8). The velocities of CMEs range from $20 \text{ km/s}$ to $3200 \text{ km/s}$ with an average value of around $500 \text{ km/s}$ (Yashiro et al., 2004). The mass of a CME ranges between $1 \times 10^{11} - 4 \times 10^{13} \text{ kg}$, averaged at $3 \times 10^{12} \text{ kg}$ (Gopalswamy and Kundu, 1992; Hudson et al., 1996). CMEs are reported to be observed at $< 2/\text{day}$ near solar minimum to $\sim 8/\text{day}$ near the solar maximum (Robbrecht et al., 2009).

CMEs are usually observed in white-light coronagraph observations. They typically display the so-called three-part structure: a bright leading edge, a dark void (cavity) and a bright core (Fig. 1.8; Illing and Hundhausen, 1986). The bright core corresponds to the erupting prominence (House et al. (1981); Plunkett et al., 2000, also see Fig. 1.7). The leading edge is the coronal plasma that has piled up as a result of the erupting CME. The cavity is a region of lower plasma density, indicated by the white-light deficit.

1.1.4 Solar Eruptive Phenomena as a Single System

These large scale solar eruptive phenomena, including prominence eruptions, strong flare, and CMEs, are closely related to each other (e.g., Gilbert et al., 2000). It is widely accepted that they are different manifestations of a single process involving disruption and restructuring of the coronal magnetic field (e.g., Shibata et al., 1995).

The processes in this picture can be describe as follows (Fig. 1.9, see reviews of Forbes (2000)):

- A flux rope, carrying the prominence (dark shaded structure in Fig. 1.9), rises
Figure 1.8: A normal CME displaying a three-part structure, i.e., a frontal loop, a cavity, and a bright core. A white circle at the center marks the solar limb. This same CME was observed by LASCO C2 (left) and C3 (right). Credit: SOHO (ESA & NASA).

Figure 1.9: Schematic diagram showing various features associated with a CME (Forbes, 2000).
due to a specific initiation mechanism, *e.g.*, magnetic rearrangement or some instability.

- The rising flux rope stretches the closed magnetic field lines behind it, resulting in anti-parallel magnetic field lines approaching each other, driven by external magnetic pressure.

- A current sheet forms between the anti-parallel field lines, driving magnetic reconnection.

- This reconnection leads to release of the magnetic energy, producing a solar flare, as in the standard flare model (Fig. 1.7).

- The magnetic reconnection also removes the confinement for the flux rope, by cutting the line-tied magnetic field lines.

- With less confinement and a push by the upward outflow from the reconnection site, the flux rope keeps rising, ultimately being observed as a CME.
1.2 Kinking Prominences

1.2.1 Injections of Magnetic Energy and Helicity into the Solar Atmosphere

Solar eruptions involve energy conversion from magnetic energy to kinetic, gravitational and radiative energy. For a typical CME, its energy density ranges from $10^{-2} - 10 \text{ J m}^{-3}$ (Forbes, 2000). The typical energy density of possible energy sources is listed in Table 1.2. By comparing these values, we can see that the only possible source for energetic CMEs is magnetic energy.

Table 1.2: Estimates of the coronal energy sources (Forbes, 2000; Chen, 2011).

<table>
<thead>
<tr>
<th>Form of energy</th>
<th>Energy density ($\text{J m}^{-3}$)</th>
<th>Observed averaged value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic ($\frac{1}{2}m_pv^2$)</td>
<td>$8 \times 10^{-4}$</td>
<td>$n = 10^{15} \text{ m}^{-3}, v = 1 \text{ km s}^{-1}$</td>
</tr>
<tr>
<td>Thermal ($nkT$)</td>
<td>$1 \times 10^{-2}$</td>
<td>$T = 10^6 \text{ K}$</td>
</tr>
<tr>
<td>Gravitational ($nm_vgh$)</td>
<td>$5 \times 10^{-2}$</td>
<td>$h = 10^5 \text{ km}$</td>
</tr>
<tr>
<td>Magnetic ($B^2/2\mu_0$)</td>
<td>40</td>
<td>$B = 10^{-2} \text{ T}$</td>
</tr>
</tbody>
</table>

It is generally thought that the magnetic energy is transferred from the interior of the Sun through photosphere. The magnetic energy flux, also known as Poynting flux, $\left. \frac{dE}{dt} \right|_S$ out of a plane $S$, (see Kusano et al., 2002), is

$$ \left. \frac{dE}{dt} \right|_S = \frac{1}{\mu_0} \int_S \mathbf{E} \times \mathbf{B} \cdot \mathbf{n} \ dS $$  \hspace{1cm} (1.1)

In ideal MHD, Ohm’s law is given by

$$ \mathbf{E} + \mathbf{V} \times \mathbf{B} = 0 $$  \hspace{1cm} (1.2)
Thus, the Poynting flux can be described as,

\[
\frac{dE}{dt}\bigg|_s = \frac{1}{\mu_0} \int_S (B_t^2 V_n) \cdot n \ dS - \frac{1}{\mu_0} \int_S (V_t \cdot B_t) B_n \cdot n \ dS \quad (1.3)
\]

where the subscripts \( n \) and \( t \) indicate the normal and tangential component to \( S \), respectively. In the solar corona, the first term is generated by the vertical motion (or called emergence) of the magnetic field through the photosphere, and the latter is caused by the horizontal motions (shearing motion) at the photosphere.

With the emergence and shearing motion of the magnetic fields on the photosphere, another important physical parameter, known as Magnetic Helicity, is also injected into the solar atmosphere. Magnetic helicity measures how much a set of magnetic flux tubes are sheared and/or wounded around each other (e.g., Berger and Field, 1984). An important property of magnetic helicity is that it is approximately conserved in the presence of dissipative processes (Berger and Field, 1984). The conservation of magnetic helicity provides a constraint on the evolution of the magnetic field, making the helicity an important parameter used to explain a range of solar phenomena, like coronal heating, flares and CMEs.

The magnetic helicity was introduced as

\[
H = \int_V A \cdot B \ d^3x \quad (1.4)
\]

where \( A \) is the vector potential, \( B \) the magnetic field strength, \( B = \nabla \times A \) and the volume \( V \) is bounded by a magnetic surface with \( B_n = B \cdot \hat{n} = 0 \) (\( \hat{n} \) is the normal to the surface).

However, the boundary condition of \( B_n = 0 \) is not applicable for most regions of interest in solar physics, since, for example, most such regions are driven by magnetic flux that crosses the photosphere. As a result, Berger and Field (1984) introduced
the relative helicity, which can be written as (Finn and Antonsen, 1985)

\[ H = \int_V (\mathbf{A} \cdot \mathbf{B} - \mathbf{A}_p \cdot \mathbf{B}_p) \, d^3x \]  

(1.5)

Here, \( \mathbf{A}_p \) is the vector potential of a reference magnetic field, \( \mathbf{B}_p \) with \( \mathbf{B}_p = \nabla \times \mathbf{A}_p \). The requirement is \( \mathbf{A}_{p,t} = \mathbf{A}_t \), i.e., on the surface of the volume \( V \), the vector potentials \( \mathbf{A}_p \) and \( \mathbf{A} \) have the same tangential components.

According to Berger and Field (1984), the evolution of magnetic helicity though surface \( S \) is,

\[
\frac{dH}{dt} \bigg|_S = 2 \int_S (\mathbf{A}_p \times (\mathbf{v} \times \mathbf{B})) \cdot \mathbf{n} \, dS \\
= 2 \int_S (\mathbf{A}_p \cdot \mathbf{B}_t) v_n \, dS - 2 \int_S (\mathbf{A}_p \cdot \mathbf{v}_t) B_n \, dS
\]  

(1.6)

Similar to the energy injection, the first term indicates the helicity injection by emergence, and the second term for the injection by shearing motion.

Magnetic helicity tends to follow a common tendency called the hemispheric helicity rule (Pevtsov et al., 2008): solar magnetic fields in the northern (southern) hemisphere have a negative (positive) sign of helicity. Typically, about \( 70-80\% \) of active regions follow this hemispherical rule.

Nindos and Andrews (2004) found that the magnetic helicity in active regions that exhibits CMEs is much larger than those that produce just confined flares. Another interesting result is the asymmetry of helicity injection in emerging active regions (Tian and Alexander, 2009). They carried out a statistical study of 15 active regions and calculated the helicity injection into the leading and following polarities, separately. They found the amount of helicity injected into the leading polarity was several times (typically 3–10 times) larger than that into the following polarity. The authors suggested that this mainly resulted from the different speeds of emergence between the two polarities.
Sunspot rotation, in which the sunspot rotates about its center, contribute significantly to the magnetic helicity injection into the solar corona (Rust and Kumar, 1994; Low, 1996; Canfield et al., 1999; Kazachenko et al., 2009). Zhu et al. (2012) studied the rotational characteristics of 132 sunspots and found that a strong relationship exists between sunspot rotation and flux emergence in solar active regions.

1.2.2 Kinking Motions of Filaments

The magnetic helicity can generally be decomposed into two terms: twist and writhe, i.e., $H = H_{tw} + H_{wr}$. Twist is due to the magnetic field line twisting around the axis of the flux tube, while writhe originates from the twist of the axis of the flux tube itself. As the total helicity is conserved (Berger and Field, 1984), a decrease of the twist means increase of the writhe, i.e., twist is transformed into writhe, as seen in the process called kink instability.

For a straight cylinders with azimuthal ($B_\theta(r)$) and axial magnetic components ($B_z(r)$), and a length of $L$, the value of its twist is describe by (e.g., Berger and Field, 1984),

$$\Phi(r) = \frac{L B_\theta(r)}{r B_z(r)}$$  \hspace{1cm} (1.7)

The dense photosphere is considered as a line-tying boundary yielding standard boundary conditions ($\mathbf{v} = 0$) at both ends of the cylinder. With these simplifications, the instability of the cylindrically symmetric flux tube with uniform twist force free field was studied. The results show that the kink instability initiates when the twist of a uniform-twisted magnetic-flux tube ($\Phi$) exceeds a specific threshold value, e.g. $2.5\pi$, or 1.25 turns (Hood and Priest, 1979). Modern simulations with a force-free circular twisted flux tube (TD99 model; Titov and Démoulin, 1999) show that the kink instability occurs when the twist in the flux tube exceeds $3.5\pi$, or 1.75 turns.
Török and Kliem (2005) studied the evolution of the kink instability of a force free magnetic flux rope (i.e., twisted flux tube) that was anchored in the photosphere with TD99 model as the initial condition. And both the evolution of the helical shape (lower panels in Fig. 1.10) and the height-time trajectory were reproduced in very good agreement with the observed development of the failed filament eruption on 2002 May 27 (upper panels in Fig. 1.10, see also Ji et al., 2003, and Alexander et al., 2006), confirming that the kink instability of magnetic flux rope can be an initiation mechanism and driver of solar eruptions. They also concluded that the nature of the overlying field had a great effect on the types of eruption, i.e., a sufficiently steep
decrease will lead to a successful eruption (full or partial), otherwise a failed eruption would result. It is interesting that a hard x-ray coronal source was identified at the projected crossing of both legs of the kinking filament Fig. 1.11), implying ongoing magnetic reconnection in a current sheet at the crossing, due to the interaction of the two adjacent legs (Alexander et al., 2006).

Figure 1.11: A hard x-ray coronal source (indicated by S2) is identified at the projected crossing of both legs of a kinking filament (Alexander et al., 2006)

1.3 Instruments and Data

The data used in this thesis mainly comes from three spacecraft, including the Solar Dynamics Observatory (SDO), the Solar TERrestrial RElations Observatory spacecraft (STEREO), and high energy x-ray observations from the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI).
1.3.1 SDO Spacecraft

SDO is a NASA mission, the flagship of the Living With a Star (LWS) program. It was launched on February 11, 2010, to a circular geosynchronous orbit. It is considered as a succession to the Solar and Heliospheric Observatory (SOHO by ESA and NSA). SDO is composed of three instruments: the Atmospheric Imaging Assembly (AIA), the Helioseismic and Magnetic Imager (HMI), the Extreme Ultraviolet Variability Experiment (EVE).

The AIA (Lemen et al., 2012) takes full-disk images of the Sun in seven extreme-ultraviolet (EUV) channels and three UV to visible channels (Table 1.3), providing observations of the solar atmosphere in temperatures ranging from 5000 to 20 million K. The images are taken with high spatial and temporal resolutions, with a pixel scale of 0.6″ pixel$^{-1}$ ($\sim$ 436 km) and a cadence of 12 seconds.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Primary ion(s)</th>
<th>Region of atmosphere</th>
<th>log(T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4500 Å</td>
<td>continuum</td>
<td>photosphere</td>
<td>3.7</td>
</tr>
<tr>
<td>1700 Å</td>
<td>continuum</td>
<td>temperature minimum, photosphere</td>
<td>3.7</td>
</tr>
<tr>
<td>304 Å</td>
<td>He II</td>
<td>chromosphere, transition region</td>
<td>4.7</td>
</tr>
<tr>
<td>1600 Å</td>
<td>C IV+cont.</td>
<td>transition region, upper photosphere</td>
<td>5.0</td>
</tr>
<tr>
<td>171 Å</td>
<td>Fe IX</td>
<td>quiet corona, upper transition region</td>
<td>5.8</td>
</tr>
<tr>
<td>193 Å</td>
<td>Fe XII, XXIV</td>
<td>corona and hot flare plasma</td>
<td>6.2, 7.3</td>
</tr>
<tr>
<td>211 Å</td>
<td>Fe XIV</td>
<td>active-region corona</td>
<td>6.3</td>
</tr>
<tr>
<td>335 Å</td>
<td>Fe XVI</td>
<td>active-region corona</td>
<td>6.4</td>
</tr>
<tr>
<td>94 Å</td>
<td>Fe XVIII</td>
<td>flaring corona</td>
<td>6.8</td>
</tr>
<tr>
<td>131 Å</td>
<td>Fe VIII, XXI</td>
<td>transition region, flaring corona</td>
<td>5.6, 7.0</td>
</tr>
</tbody>
</table>
The HMI (Schou et al., 2012) provides full-disk measurements of photospheric magnetic fields with a pixel scale of 0.5″ pixel$^{-1}$ and a cadence of 45 seconds. It is also used to characterize the solar interior by providing oscillation data used for helioseismology studies.

The EVE (Woods et al., 2012) measures the Sun’s extreme ultraviolet irradiance from 0.1 to 105 nm with unprecedented spectral resolution (0.1 nm), and temporal cadence (10 seconds). The EUV is used to study the irradiance variations, which is thought to have significant impact on the atmospheric heating, satellite drag, etc, at the Earth.

### 1.3.2 STEREO Spacecraft

STEREO is also a solar observation mission operated by NASA. It has twin spacecraft that were launched on October 26, 2006, into orbits around the Sun, with one traveling further ahead (STEREO-A) and the other one falling behind (STEREO-B) the Earth in its orbit about the Sun. This enables stereoscopic imaging of the Sun and solar phenomena, like the eruption of prominences and CMEs. STEREO has four instrument packages, and we focus on the EUV and white-light observations from the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) and radio wave observations from STEREO/WAVES (SWAVES).

SECCHI has five telescopes (Howard et al., 2008): Extreme-Ultraviolet Imager (EUVI), two white-light coronagraphs (COR1 and COR2) and two heliospheric imagers (HI1 and HI2). The (EUVI) has four bandpasses (Fe IX 171 Å, Fe XII 195 Å, Fe XV 284 Å, and He II 304 Å), with spatial resolution of 1.6″ pixel$^{-1}$. It has a field of view (FOV) out to solar radii (1.7 $R_\odot$). The Field-of-View (FOV) of COR1
and COR2 are $1.4-4 \, R_\odot$ and $2.5-15 \, R_\odot$, respectively. HI1 and HI2 image the space between the Sun and Earth, to study the three-dimensional (3D) evolution of CMEs.

SWAVES (Bougeret et al., 2008) measures the three components of the fluctuating electric field from a fraction of a Hertz up to 16 MHz, plus a single frequency channel near 30 MHz. It can be used to study the radio emissions associated with energetic electrons and shock waves related to CMEs.

The combination of the images at the same wavelength from STEREO with or without SDO has been used to reconstruct the 3D structure of solar phenomena like prominences. A routine called SCC_MEASURE (developed by W. Thompson), which is available in the STEREO package of the Solar Software Library, has been widely utilized to locate the same feature in two images from different perspectives (e.g., Li et al., 2010; Thompson et al., 2012).

1.3.3 RHESSI Spacecraft

RHESSI (Lin et al., 2003) is a mission in NASA Small Explorer missions. It was launched on February 5, 2002. RHESSI is designed to explore the basic physics of particle acceleration and impulsive energy release in solar flares.

RHESSI provides imaging and spectroscopy from soft x-rays to $\gamma$-rays ranging from 3 keV to 17 MeV with energy resolution of $\sim$ 1 keV. Its spatial resolution is 2 arcseconds between 4–100 keV, 7 arcseconds to 400 keV and 36 arcseconds above 1 MeV. These measurements are obtained with a non-focusing, rotation modulation collimator imaging technique (Hurford et al., 2003).
1.4 Outline of the Thesis

Based on past observations from previous space missions and ground observatories, remarkable progresses have been made in our understanding of solar eruptive phenomena. However, there are still fundamental questions that remain open in this research area, such as:

- How does the eruptive filament initiate?
- How does the eruptive filament interact with nearby magnetic fields?
- What is the temporal/spatial relationship between the filament eruption and energy release?

To address these problems, a few tens of solar filament eruptions, focusing on kinking filaments and interactions of filaments, have been identified by us, with a number of specific case studies being developed that form the basis of this thesis. In Chapter 2, we present our study on a bifurcated filament which is consisted of two branches, with mass/flux transferring from the lower to higher branch, and discuss the role instabilities played in the initiation of the eruption. Chapter 3 presents an observation of interchange reconnection between a kinking solar filament and a nearby coronal hole, and how this interaction facilitates the eruption. In Chapter 4, we investigate a filament eruption involving filament-filament interaction, and the production of two consecutive solar flares. A conclusion is made and future work is discussed in Chapter 5.

Related publications are as follows,

5. Interaction Between Two Filaments During Eruption and Resulted Production of Solar Flares, C. Zhu, R. Liu, D. Alexander, X. Sun, to be submitted.


Chapter 2

Eruption of a Bifurcated Solar Filament

We study the partial eruption of a solar filament observed by the Solar Dynamics Observatory (SDO) and the Solar TErrestrial RElations Observatory-Ahead (STEREO-A) spacecraft on 9 May 2012. This filament was located in active region NOAA 11475, and consisted of two distinct branches, separated in height above the active region’s primary polarity-inversion line. For two days prior to the filament eruption, several threads of filament material were observed to connect the lower branch to the upper branch with evidence of a transfer of mass along them. The eruption commenced as a slow rise of the upper branch that began at 9 May 2012 23:40 UT, with the main eruption occurring half an hour later, producing a coronal mass ejection (CME). During the eruption, the upper branch was observed to rotate approximately 120 degrees in a counter-clockwise direction. We suggest that the mass transfer events also comprised a transfer of magnetic flux that led the upper branch of the filament to lose equilibrium as a result of a helical kink instability or torus instability.

2.1 Introduction

The inner core of coronal mass ejections (CMEs) is generally thought to be comprised of solar filament material (e.g. House et al., 1981). Thus, a detailed study of
filament eruptions is important for a clear understanding of CMEs, which, in turn, is important for the forecast of associated space weather events.

Several driver mechanisms have been proposed to explain observed filament eruptions; see Chen (2011) for a review. There are mechanisms that invoke some form of pre-eruption reconnection that facilitates the eruption of the previously confined core field, e.g., the tether-cutting model of Moore et al. (2001) or the magnetic breakout model of Antiochos et al. (1999). Others invoke ideal MHD instabilities, such as the helical kink instability (e.g., Liu and Alexander, 2009) and the torus instability (Kliem and Török, 2006; Schrijver et al., 2008). The helical kink instability initiates when the twist of a magnetic flux rope exceeds a specific threshold value, e.g., $2.5\pi$ (Hood and Priest, 1979) or $3.5\pi$ (Fan and Gibson, 2003, 2004; Török and Kliem, 2003). The critical condition for the torus instability is given by the decay index (Bateman, 1978):

$$n = -\frac{\text{d}(\log B_t)}{\text{d}(\log R)} > 1.5$$

(2.1)

where $B_t$ is the transverse component of the ambient magnetic field strength at some height $R$.

In this chapter, we present observations of a partial filament eruption from active region AR 11475. The filament consists of two distinct branches, and mass was observed to transfer from the lower branch to the upper branch prior to the upper branch slowly rising and ultimately erupting. We analyze the observations in Section 2.2, follow with our interpretations on the driver mechanism for this partial filament eruption in Section 2.3, and present conclusions in Section 2.4.
2.2 Observations

2.2.1 Instruments and Data

The filament eruption, under investigation here, occurred from 9 May 2012 23:40 UT to 10 May 01:00 UT, but the evolution of the filament for the two days prior to eruption is also important and is included in the analysis described below. The primary data sources are the Atmospheric Imaging Assembly (AIA: Lemen et al., 2012) and Helioseismic and Magnetic Imager (HMI: Scherrer et al., 2012) on board the Solar Dynamics Observatory (SDO) and the Extreme-Ultraviolet Imager (EUVI: Wuelser et al., 2004) onboard the Solar Terrestrial Relations Observatory (STEREO). The EUV images from SDO/AIA are taken in seven bandpasses, with spatial resolution of 0.6′′ pixel\(^{-1}\) and temporal resolution of 12 seconds. In this chapter we restrict our considerations to observations in the He\(\text{II}\) 304 Å channel. STEREO consists of two identical spacecraft: STEREO-A (Ahead) and STEREO-B (Behind), near the ecliptic plane. EUVI onboard STEREO provides observations of chromosphere and lower corona in four bandpasses (Fe\(\text{IX}\) 171 Å, Fe\(\text{XII}\) 195 Å, Fe\(\text{XV}\) 284 Å, and He\(\text{II}\) 304 Å). During the event discussed in this chapter, the EUVI had a spatial resolution of 1.6′′ pixel\(^{-1}\) and a cadence of ten minutes in the 304 Å wavelength.

The filament was positioned between the two polarities of decaying active region AR 11475, located at W13N07 on the solar disk. This filament was inverse-S shaped, and consisted of two separate branches (Fig. 2.1a). The west branch was aligned with the polarity-inversion line (PIL, thick white line in Fig. 2.1b), while the east branch was projected onto the positive polarity region, indicating that the east branch lay at a higher altitude than the west branch. The double-decker filament studied by Liu et al. (2012) also showed a similar structure.
Figure 2.1: Configuration of the filament at 9 May 2012 04:05 UT, 20 hours before eruption. Left: Filament observation by SDO/AIA 304 Å, showing this filament is comprised of two branches. Right: SDO/AIA 304 Å observation overplotted with the line-of-sight magnetic field from SDO/HMI. White (black) contours denote positive (negative) polarities. The contour levels are 20, 60 and 140 Gauss. This filament is located above the polarity-inversion line region (PIL, thick white line) between polarities of AR 11475.

In order to determine the 3D orientation of the two branches and to confirm the assumption that the eastern branch lies at a higher altitude, we performed a 3D reconstruction using the static solar-rotation stereoscopy method of Aschwanden (2011). The filament was positioned behind the solar limbs of both STEREO-A and STEREO-B during the interval we are interested in, so that a direct three dimensional reconstruction, using a combination of STEREO and SDO data, was not possible for either branch prior to the eruption: as the eruption progressed, the increased height brought it into view of STEREO-A, allowing a more direct 3D reconstruction. The static solar-rotation stereoscopy approach enabled a determination of the altitude of the west branch of 28±5 Mm above the solar surface, while the east branch was located at an altitude of 37±3 Mm. Throughout the rest of the chapter, we will use lower and upper branches to stand for the west and east branches, respectively.
The northern (southern) footpoints of both the upper and lower branches are located in the positive (negative) polarity of AR 11475. According to the definition of filament chirality suggested by Martin (1998), both branches are dextral, and this is consistent with the prevailing hemispheric pattern of filament chirality.

2.2.2 Partial Filament Eruption

The upper branch of the filament showed a slow-rise phase early in the eruption followed by a fast-rise phase, consistent with most observed filament eruptions (Sterling and Moore, 2008). The slow rise began at 9 May 2012 23:40 UT, seen in STEREO-A (Fig. 2.2), before becoming eruptive at 10 May 00:20 UT, signifying the onset of the fast-rise phase. Meanwhile, the lower branch remained steady, showing no evident change. The eruption can therefore be classified as a partial filament eruption, as defined by Gilbert et al. (2007). During the eruption, the upper branch rose high enough to appear above the eastern edge of STEREO-A, while its footpoints remained occulted by the limb. We choose an East-West directed cut through the top of the upper branch (Fig. 2.2e) to determine the displacement of this branch as it erupts (cross symbols in Fig. 2.3).

As the upper branch rose and erupted, it also exhibited a counter-clockwise rotation as seen by SDO/AIA, which provided the observation from a vantage point of almost directly above this filament, due to its convenient position near disk center. The evolution of the rotation angle (triangles in Fig. 2.3) exhibited a similar profile to that of the filament displacement. The total rotation of this branch is about 120°, with the rotation ceasing at 10 May 00:50 UT after approximately 35 minutes of rapid rotation (\(~ 3.4° \text{ minute}^{-1}\)).

Due to projection effects, the filament displacements observed by STEREO-A
Figure 2.2: Observations of a filament eruption on 10 May 2012, in He II 304 Å. Top panels: Filament eruption and rotation observed by SDO/AIA 304 Å, from a viewpoint almost directly above this filament. The upper branch is highlighted by the dashed lines. Bottom panels: Side view of the filament eruption observed by STEREO-A, showing formation of an inverse-γ shaped structure due to the filament rotation. A cut through the data lying in the East-West direction, shown as white line in Panel (e), is chosen to determine the heights of the rising upper branch.

should be measurably smaller than the true heights. Since this filament eruption of the upper branch was observed by both SDO and STEREO-A, a 3D reconstruction can be performed to determine the true height evolution of the filament as it erupts. By choosing a series of EUV images from both perspectives at almost the same time, the spatial location of the upper branch was determined with the SolarSoft program of ssw_measure, created by W. Thompson (Li et al., 2010; Thompson et al., 2012). The evolution of this filament from three different perspectives are shown in Fig. 2.4, with a cadence of ten minutes. The heights of the filament top at each time, deduced from this 3D reconstruction, are shown in Fig. 2.3. For this eruption, the projected height is slightly lower than the 3D reconstruction result, mainly due to its location near the limb of STEREO-A and roughly radial eruption (Fig. 2.4). The largest
deviation of the projected heights from the true ones is around 10% at 00:55 UT.

The velocity of the upper branch during the eruption is estimated by a linear fit to the filament heights derived from the 3D reconstruction. In the slow-rise phase the average velocity is around 6.9 km s\(^{-1}\), while in the fast-rise phase it increases to approximately 97.6 km s\(^{-1}\).

Along with the slow rise and eruption, there is an observed brightening around the filament in SDO/AIA 304 Å. The evolution of the total intensity of the entire active region is integrated and shown in Fig. 2.4. The upper branch began to rise at around 23:40 UT, ten minutes before the brightening in AIA 304 Å. The observed filament rotation profile suggests that this partial filament eruption might be driven by ideal MHD instabilities (Kliem et al., 2012, although see Lynch et al., 2009). We investigate the possible role of a kink and/or torus instability in Section 2.3.

Table 2.1: Timeline for the filament eruption from 8 to 10 May 2012.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Time</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-eruption</td>
<td>8 May</td>
<td>Filament threads transfer events began at 08:10, 08:30, 10:10, 10:35, 13:45, 19:20, 19:30.</td>
</tr>
<tr>
<td></td>
<td>9 May</td>
<td>Filament threads transfer events began at 07:30, 22:30.</td>
</tr>
<tr>
<td>Eruption</td>
<td>9 May</td>
<td>The upper branch started to rise slowly.</td>
</tr>
<tr>
<td></td>
<td>9 May</td>
<td>Brightening observed to began in AIA 304 Å.</td>
</tr>
<tr>
<td></td>
<td>10 May</td>
<td>Partial filament eruption, filament rotation.</td>
</tr>
<tr>
<td></td>
<td>10 May</td>
<td>CME observed by STEREO-A/COR1* .</td>
</tr>
</tbody>
</table>

* cor1.gsfc.nasa.gov/catalog/cme/2012/html/201205100125a.html
2.2.3 Mass Transfer from the Lower Branch to the Upper Branch of the Filament

We consider the evolution of this filament over the two days preceding its eruption. During this time, some filament threads were observed to connect transiently the lower branch to the upper branch. These threads showed evidence of flowing material (West to East), indicating transfer of mass upwards into the upper branch. A similar phenomenon has been reported recently by Liu et al. (2012). The mass transfer
Figure 2.4: 3D reconstruction using STEREO-A and SDO/AIA, showing the filament eruption and rotation on 10 May 2012, viewed from three different perspectives (view from SDO, rotated to the north limb, and rotated to the west limb, respectively). The observation time is shown in the right panel with corresponding color. The grid spacing is five degrees.

Events are most readily evident using a stack plot approach. We select a slice through the filament in the East-West direction from a series of 304 Å images (Fig. 2.5a&c) showing the variation of this strip with time, and generate a stack plot (Fig. 2.5). A prime example of a transfer event is shown in Fig. 2.5c&d. The vertical dark feature in Fig. 2.1d is the lower branch of the filament. Part of this branch began to rise slowly at 13:20 UT and suddenly transferred to the left, stopping when it reached the upper branch. At this time, the upper branch was very faint, perhaps as a result of having very little material initially. The black curve in Fig. 2.5d is the total integral of intensity of 304 Å in the boxed region in Fig. 2.5c. As the mass transfer continued, it was associated with a brightening in AIA 304 Å, evident as an enhancement in the lightcurve. The observed brightening indicates plasma heating at the lower branch, causing the transition from absorption to emission in the transfer event. The transient nature of the connecting filament threads, the associated brightening in the lower branch, and subsequent destabilization and eruption of the upper branch suggests
that the mass transfer events were accompanied by an associated transfer of magnetic flux (see Liu et al., 2012).

From 08:00 UT to 14:00 UT on 8 May 2012, five clear transfer events were detected, as shown in Fig. 2.5a&b. There are also two additional events on 8 May 2012, and another two on 9 May 2012. Thus, in total, nine flux-transfer events were observed to occur during the two days preceding the filament eruption. All of these transferred mass went from the lower branch to the upper branch, i.e., in the upward direction. These events are listed in Table 2.1.

Furthermore, during these two days, there was ongoing magnetic cancellation that was observed to occur near the lower branch, as shown in the box in Fig. 2.6 (top panels). Two small positive polarities moved West toward the negative polarity and canceled at the PIL. The observed magnetic cancellation and subsequent brightenings seen in AIA 304 Å might suggest that magnetic reconnections were involved in the mass transfer process and subsequent heating of the filament. While we can determine long-term variations (∼two days) in the magnetic field, a direct correlation between an individual mass transfer event and any corresponding single event in the magnetic field is difficult to assess without a significantly more detailed study than is considered here.

2.3 Interpretation and Discussion

We observed a bifurcated solar filament that partially erupted on 9 May 2012. No significant magnetic field change was evident during the three hours prior to the filament eruption (see Fig. 2.6d&e), although some small-scale, weak magnetic field cancellation near the PIL is ongoing throughout the observational period. The weak field cancellation observed over the period of the eruption is insignificant when
compared to the magnetic field cancellation in the two days before 9 May 2012 (Top panels in Fig. 2.6). Furthermore, the major EUV brightening near the filament region was observed ten minutes after the rise of the upper branch. These observations suggest that this solar filament was initiated by ideal MHD instabilities rather than being driven by magnetic reconnection.

As it rose, the filament exhibited a rotation of about 120 degrees, indicating the possible role of the helical kink instability, in which rotation of the filament axis results from excessive twist in the filament magnetic field being transformed into writhe. However, it is possible that the observed filament rotation may also be driven by the Lorentz force that is generated by a rising magnetic flux rope in an ambient magnetic field (Isenberg and Forbes, 2007), although this mechanism is expected to be only able to provide a maximum rotation of 90 degrees. The observed rotation of 120 degrees suggests that a portion of twist of the flux rope has been converted into writhe, contributing some additional rotation, due to the relaxation of twist (Kliem et al., 2012), possibly by the helical kink instability.

If the ambient magnetic field above the filament decreases steeply enough, i.e., when the decay index (Equation 2.1) is greater than 1.5, the magnetic flux rope might become unstable due to the torus instability (Kliem and Török, 2006; Liu, 2008; Schrijver et al., 2008). In order to determine the threshold criteria of the torus instability for this filament eruption, the decay index of the overlying magnetic field is estimated from surface magnetic field observations coupled to the PFSS extrapolation model (e.g. Wang and Sheeley, 1992). A potential field assumption for the large-scale overlying field is expected to be sufficient for the analysis presented here (Xu et al., 2012; Kumar et al., 2012). The potential field is extrapolated from the SDO/HMI magnetogram of 10 May 2012 00:04 UT, near the onset of the eruption (Fig. 2.7).
The horizontal component of the extrapolated magnetic field strength is averaged over AR 11475 with heights from 0.1 to 0.6 $R_\odot$ (Right panel in Fig. 2.7). The decay index is obtained by a linear fitting to the inferred field, producing a value of 1.70, thereby exceeding the critical value of 1.50 (see Equation 2.1). Thus, a torus instability may be a possible initiation mechanism for this partial filament eruption.

The transfer events were observed to occur from the lower branch to the upper branch over a period of two days in the build up to the filament eruption. During this period, magnetic cancellation was observed adjacent to the PIL that lay under the lower branch. Magnetic reconnection might be involved in these transfer processes, playing a role similar to that expected in tether-weakening (Moore and Roumeliotis, 1992; Sterling et al., 2007) or tether-cutting reconnection (Moore et al., 2001), releasing part of magnetic flux and material in the lower branch. The newly merged magnetic flux in the upper branch might serve to increase the twist until it become larger than the critical twist, leading to helical kink instability. Another possibility is that the increased pressure of the field in the upper branch caused it to rise locally to a location where the overlying field fall-off was steep enough for the torus instability to play a role in driving the eruption (Liu et al., 2012). One or both of the mechanisms would initiate the observed filament eruption.

### 2.4 Conclusions

In this chapter, we consider the partial eruption of a filament that had a two branch configuration. Both branches had dextral filament chirality. The upper branch rose slowly and erupted, resulting in a CME. The activation of the upper branch occurred ten minutes before a localized brightening was observed in 304 Å beginning at 23:50 UT on 9 May 2012 (Fig. 2.4). Furthermore, during the eruption, a large counter-
clockwise rotation of the filament axis was observed. These phenomena suggest that this filament eruption is driven by certain ideal MHD instabilities.

The observed filament rotation might result from two possible causes: Lorentz forces (Isenberg and Forbes, 2007) and relaxation of twist in the magnetic flux rope (e.g., Kliem et al., 2012). The relaxation of twist may contribute up to 40 degrees of rotation, while the Lorentz force mechanism provides for a maximum rotation of 90 degrees in the same direction only when a strong sheared magnetic field is present (Kliem et al., 2012). However, in this event, the premise of a strong sheared magnetic field is very difficult to maintain in a decayed and dispersed active region such as AR 11475. Therefore, it would suggest that the helical kink instability occurred with the twist of the filament flux rope being transferred into writhing motion and a large scale rotation. The helical kink instability is, therefore, a possible trigger mechanism for the observed filament eruption. To determine the individual contributions by each of these mechanisms, one could apply the parametric study of Kliem et al. (2012), where they compared the modelling results with varying twist of a flux rope and external shear field strength to the observed height and rotation profiles.

Another possible mechanism for the onset is the torus instability, which occurs when the magnetic field above the filament falls off steeply enough with height (Bateman, 1978; Kliem and Török, 2006). Based on SDO/HMI magnetogram data and an application of the PFSS extrapolation model, the estimated value of the decay index was 1.70, exceeding the critical value of 1.50 for torus instability initiation. Therefore, the torus instability might also be a candidate trigger mechanism for this filament eruption.

An important feature for this eruption is that several mass/flux transfer events were observed from the lower branch to the upper branch in the days preceding the
eventual eruption. These events might have enhanced the magnetic pressure in the upper branch, either increasing the twist or increasing its altitude to a region where the decay index was large enough so that the helical kink instability or torus instability was viable, respectively.

We have shown in this chapter that mass and flux transfer in multi-tier filament structures is an important contributor to the destabilization and subsequent eruption of the filament. We have also shown that ideal processes can play an important role in the evolution of the eruption and possibly dominate the early initiation of the eruption. How prevalent these processes are in the filament eruptions is the subject of an ongoing study.
Figure 2.5: Material transfers in the bifurcated filament. Top panels: AIA 304 Å observations of the filament in AR 11475. Bottom panels: stack plots generated from slices of the image series, marked by horizontal white lines in the top panels. Panel (b) spans 07:00 to 12:00 UT, panel (d) spans 13:00 to 15:00 UT, on May 8, 2012. Also shown are the lightcurves obtained from the integrated intensity in the box around the filament (black line profile). The enhancements (marked by black arrows) on the lightcurves, indicate the brightening in AIA 304 Å. These brightenings appeared together with transfers of filament material (marked by white arrows) from the lower branch to the upper branch.
Figure 2.6: Top panels: Magnetic field cancellation in the two days before filament eruption. The positive and negative polarities cancelled at the polarity-inversion line, as shown in the box region. Bottom panels: Magnetic field observations in three hours before and after the solar filament eruption.

Figure 2.7: Left panel: Potential-Field Source-Surface (PFSS) magnetic extrapolation of the active region AR 11475 at 10 May 2012 00:04 UT. Right panel: Variations of the average transverse magnetic field, inferred from the PFSS extrapolation, as a function of height from 0.1 to 0.6 $R_\odot$ above the photosphere. The solid line shows a linear fit to the data, indicating a decay index of 1.70.
Chapter 3

The Role of Interchange Reconnection in Facilitating Filament Eruptions

We study the interaction between an erupting solar filament and its nearby coronal hole, based on multi-viewpoint observations from SDO and STEREO. During the early evolution of the filament eruption there is a clockwise rotation of the filament which brings its Easternmost leg in contact with oppositely aligned field at the coronal hole boundary. The interaction between the two magnetic field systems is manifested as the development of a narrow contact layer in which we see enhanced EUV brightening and bi-directional flows, suggesting that the contact layer is a region of strong and ongoing magnetic reconnection. The CME resulting from this eruption is highly asymmetric with its southern portion opening up to the upper corona while the northern portion remains closed and connected to the Sun. We suggest that the erupting flux rope, that made up the filament, reconnected with the mixed open and closed fields at the coronal hole boundary, via the processes of “interchange reconnection” and closed-field disconnection, respectively, leading to the observed CME configuration.
3.1 Introduction

Solar filaments are relatively cool, dense plasma structures suspended in the solar corona that are generally located along the magnetic polarity-inversion line (PIL), with their ends located in regions of opposite polarity (Martin, 1998). Frequently, filaments erupt into the upper corona and can be observed as Coronal Mass Ejections (CMEs, see the review by Forbes (2000)).

It is occasionally reported that the magnetic field of the erupting filament reconnects with the ambient open field of a nearby coronal hole (CH), enabling the originally close field of the filament to become open. This process was defined as interchange reconnection (Gosling et al., 1995; Crooker et al., 2002). Crooker and Webb (2006) studied a magnetic cloud with open magnetic field observed at 1 AU and suggested that it resulted from the interchange reconnection between a CME flux rope and a nearby polar CH on the Sun. Baker et al. (2009) investigated a filament eruption from an active region which emerged into an equatorial CH, where one leg of this filament became open due to the process of the interchange reconnection.

In this paper we report an observation of a filament-CH interaction during a filament eruption. This filament showed kinking motion (Gilbert et al., 2007), in which one leg of the filament approached and then interacted with its nearby coronal hole boundary field. This interaction is responsible for several interesting features, including the formation of a flattened contact layer, bi-directional ejections within this layer, and a complex CME comprised of both open and closed structures. All of these features appear to be a result of the interaction between the filament and the coronal hole. This paper is organized as follows: in Section 3.2, we present the observations on the evolution of the filament eruption. In Section 3.3, we discuss these observations and present our interpretation. The conclusion appears in Section 3.4.
## 3.2 Observations

### 3.2.1 Instruments and Data

This filament eruption began on 9 August 2012 at 21:20 UT, observed by both the Solar Dynamics Observatory (SDO) and the Solar Terrestrial Relations Observatory Ahead spacecraft (STEREO-A).

The Atmospheric Imaging Assembly (AIA; Lemen et al., 2012) on board SDO takes full-disk images of the Sun in seven extreme-ultraviolet (EUV) channels and three UV to visible channels, with a pixel scale of 0.6′′ pixel$^{-1}$ and a cadence of 12 seconds. In this paper, we mainly focus on observations in the Fe $\text{IX}$ 171 Å, Fe $\text{XII}$, Fe $\text{xxiv}$ 193 Å, and He $\text{II}$ 304 Å channels. The Helioseismic and Magnetic Imager (HMI; Schou et al., 2012) on board SDO provides full-disk magnetograms with a pixel scale of 0.5′′ pixel$^{-1}$ and a cadence of 45 seconds. The Extreme-Ultraviolet Imager (EUVI; Wuelser et al., 2004) on board the STEREO has four bandpasses (Fe $\text{IX}$ 171 Å, Fe $\text{XII}$ 195 Å, Fe $\text{XV}$ 284 Å, and He $\text{II}$ 304 Å), with spatial resolution of 1.6′′ pixel$^{-1}$. During this eruption, the STEREO/EUVI had an image cadence of 5 minutes in the 195 Å filter and a 10 minutes cadence in the 304 Å.

At the time of this event, the separation angle between the SDO and STEREO was 122°. Observations from SDO/AIA 193 Å and the STEREO-A/EUVI 195 Å were used to provide a 3D reconstruction of the filament during its evolution. An associated CME was observed by the STEREO-A inner coronagraph, COR1, (field-of-view 1.4–4 $R_\odot$) starting at 21:45 UT. COR1 images have a cadence of 5 minutes.
3.2.2 The Filament and the Coronal Hole before Eruption

The filament under investigation here was located in active region (AR) 11538 (S23W49; Figure 3.1) in the Southern hemisphere associated with the PIL between the negative polarity incursion and preexisting ambient positive polarity. The filament was of “U” shape in projection with two clear legs as indicated in Figure 3.1a. Its eastern leg rooted in the negative polarity, and the western leg in the positive polarity. This configuration indicates that this filament had sinistral chirality (Martin, 1998), consistent with the prevailing hemispheric pattern of solar filaments.

A dark region in the EUV was observed to the south and west of this filament by SDO/AIA 193 Å (Figure 3.1b). The boundary of this dark region is obscured by EUV-bright foreground loops, making it difficult to determine its direct relationship to the surface magnetic field. However, a Potential-Field Source-Surface (PFSS) magnetic extrapolation (e.g., Schrijver and DeRosa, 2003) of the HMI data shows that this region corresponds well to the location of unipolar open fields (Figure 3.1c), indicating that it was a coronal hole.

3.2.3 Filament Eruption and its Rotation

The middle part of the filament (the base of the “U” shape) began to rise slowly at 9 August 2012 21:20 UT, with an associated brightening in the EUV being observed immediately to the southeast (Figure 3.2 and Movie A). This resulted in a burst of the AR-integrated EUV emission at 21:36 UT in all four wavelengths considered (Figure 3.2a). There are two other distinct bursts occurring at 21:48 UT and 21:57 UT, corresponding to two phases of the filament-CH interaction, described in Section 3.2.4. The eastern leg of the filament was observed to rotate towards the west until 21:51 UT when it apparently ran into the strong magnetic field at the coronal
Figure 3.1: The solar filament with its ambient magnetic-field configuration before eruption. (a) The solar filament in AIA 304 Å. (b) A coronal hole located in the south and west of the filament, in AIA 193 Å. (c) Magnetic field lines from the PFSS extrapolation, only open fields are shown here. (d) HMI Vector magnetogram: the strength of the normal field is denoted by the gray scale, while the blue (red) arrows shows the horizontal component of the field originating from the positive (negative) polarity. (e) The twisted fields derived from a Nonlinear Force-Free Field method (e.g., Sun et al., 2012), with the field strength indicated by the color scale.

hole boundary (CHB), shown in Figure 3.2c-d.

From the STEREO-A perspective, the filament appeared on the eastern limb (Figure 3.2g-i). The rise and expansion of the filament can be seen clearly, though the rotation is hard to determine from this viewpoint. The off-limb perspective allows us to readily determine the height of the filament and its evolution with time (plus signs in Figure 3.3b). The filament exhibits two distinct phases: an initial slow-rise followed by a rapid increase in height with time. The projected velocities were calculated by a linear fitting yielding a velocity of 4.3 km/s in the slow-rise phase
(21:20 - 21:34 UT) and 43.7 km s\(^{-1}\) after 21:34 UT, in the eruption phase.

Figure 3.2: Evolution of the filament eruption, observed in SDO/AIA 304 Å (the top and middle panels, and Movie A), and STEREO-A/SECCHI 195 Å (the lower panels, and Movie B). The rectangle in panel (d) denotes a cut along the contact layer to generate a stack plot in Figure 3.6a. A newly formed filament, resulting from reconnection at the filament-CHB, is indicated by a dashed curve in panel (f). A boxed region in (i) indicates the location where the filament is seen to “flatten”.

The EUV images from SDO and STEREO-A are used to reconstruct the spatial location of the filament in three dimensions, with the SolarSoft program of
SSW\_MEASURE (Thompson et al., 2012). The reconstructed three-dimensional (3D) configurations are shown in Figure 3.4. The filament had a clockwise-rotation of around 50° (Figure 3.4c) until it was apparently halted by an interaction with the field structures at the CHB. Filament rotation has been reported in several filament eruptions associated with twisted flux ropes, in which the twist of the flux rope transformed into the writhe (e.g., Török and Kliem, 2005; Liu et al., 2007; Zhu and Alexander, 2014).

### 3.2.4 Filament-CH Interaction

As the filament rose and rotated, some thin strands of material around the filament expanded westwards toward the coronal hole, as shown in the difference images of SDO/AIA 171 Å (Figure 3.5). Around 21:40 UT, some “hook-like” features formed with brightenings at their tips (Figure 3.5d-e and Movie A), and stretched towards the radial direction (Figure 3.5f). These structures are likely a result of the reconnection between the outermost parts of the magnetic flux around the filament and the magnetic field near the coronal hole.

The filament continued to rise and rotate until 21:50 UT when its interaction with the overlying magnetic field became more pronounced. As a result of this interaction, the filament structure in the contact region flattened and developed into a thin layer of filament material, as seen in the view from STEREO-A (Figure 3.2i). This contact layer was coincident with the CHB (Figure 3.4). At this location, the magnetic field in the core of the filament is toward the Sun, which is oppositely aligned to the field at the CHB. A significant brightening in the EUV was observed in this contact layer that lasted for about seven minutes until 21:57 UT. During this process, the layer became thinner as the brightening proceeded until this layer disconnected (Figure 3.2c-e).
Figure 3.3: (a) Normalized intensity profile in the EUV channels from SDO/AIA covering the whole active region. Three distinct bursts are marked with the arrows. The two horizontal solid lines denote the phases of the filament-CH interaction: R1 involving the outermost field of the filament, R2 involving the core field of the filament. (b) Heights of the evolving filament. Plus signs for the filament height above the limb in the view of STEREO/A observations, fitted linearly and shown in dashed lines. Triangles for the height derived from the 3D reconstruction. (c) STEREO-A/WAVES radio observation showing type III radio bursts associated with this event.

Throughout the period of the EUV brightening, bi-directional flows were observed in the contact layer. We determined the velocities of these ejections, by integrating the EUV emission from the SDO/AIA 171 Å images along a cut (Figure 3.2d) coincident with the thin contact layer. The stack-plot generated from these observations
Figure 3.4: The reconstructed 3D configurations of the evolving filament from the STEREO-A and SDO EUV observations at four distinct times (listed in panel (c)), and the ambient magnetic field of the background corona derived from the PFSS extrapolation. The open and closed fields are shown in green and black, respectively. The rotation of the filament as it rises is estimated to be 50°, clockwise, indicated on the figure by the two dashed lines in panel (c), from a viewpoint directly above the active region.

(Figure 3.6a) shows the presence of several moving features, in inward or outward directions. The projected velocities, from a linear fit, of the outward ejections range between 129 km s\(^{-1}\) and 174 km s\(^{-1}\), statistically faster than those of the inward ejections between 77 km s\(^{-1}\) and 129 km s\(^{-1}\) (Figure 3.6b), in agreement with previous observations (e.g., Liu et al., 2013). The observed difference might be a result of the higher density at lower altitudes, leading to stronger deceleration of the inward propagating material.

Assuming the ejected material streamed radially, the projected velocities of these ejections would be the component in the plane perpendicular to the line-of-sight direction. Based on the filament location, the radial velocities are estimated to be 1.3 times the projected velocities, measured from the SDO/AIA data. The “true” velocities of the ejections then range from \(\sim 100\) km s\(^{-1}\) to \(\sim 230\) km s\(^{-1}\).
Figure 3.5: Some "hook-like" features formed and became open when the filament approaching the coronal hole (see Movie A). Upper panels: images from AIA 304 Å. Lower panels: running difference of images from AIA 171 Å. The boundaries of the newly opened fields are indicated by dashed lines in panels (c) and (f).

The escaping electrons which stream along the open magnetic flux from the Sun are believed to invoke type III bursts (e.g., Krucker et al., 1999; Cane, 2003). Type III bursts were recorded by STEREO-A/WAVES for this event (Figure 3.3d), indicating the presence of accelerated electrons traveling outward along open magnetic field from the reconnection region. The type III bursts were detected as early as 21:36 UT, corresponding to the time at which the hook-like features in the filament were observed (Figure 3.5f-g), due to the interaction of the outermost part of the filament field with the open field of the CHB. Another relatively strong type III radio burst occurred at 21:54 UT, corresponding to the time of the observed brightening from the interaction between the core field of the filament and the coronal hole.
After the filament-CH interaction, the western leg of the filament became radial and the material in it erupted away, while the eastern leg formed new loops (see Figure 3.2f and Movie A).

Figure 3.6: (a) Stack plot of the cuts along the inward and outward ejections in AIA 171 Å (the location of the ejections is denoted by a rectangle in Figure 3.2d, with two arrows indicating the inward and outward directions), and (b) the inferred velocities of these ejections.

3.2.5 CME Observations by STEREO-A

A CME observed by STEREO-A/COR1 (Figure 3.7 and movie B) is identified to be associated with this filament eruption. This CME is comprised of two successive manifestations. The first manifestation was detected at around 21:45 UT (Figure 3.7a). It consisted of two distinct parts: one in the south which exhibited a narrow and extended structure, indicating open field, and a northern part that exhibited a loop-like structure, indicating closed field (Figure 3.7b). The second manifestation appeared at about 22:10 UT (Figure 3.7c), with similar structures to those seen in the event at 21:45 UT.

The southern ejection corresponds well to the open features at the CHB, observed
in the SECCHI 304 Å (Figure 3.7b-d). The northern ejection had two legs. The southernmost leg was extended towards the region near to the open field, \textit{i.e.,} the CHB; while the northern leg was extended back to the Sun.

![Figure 3.7: The CME observed by STEREO-A/COR1, superimposed with images of SECCHI 304 Å.](image)

### 3.3 Interpretation

Studies have shown that the twist can transform into writhe resulting in a rotation of the filament as the eruption proceeds (Kliem et al., 2012). The observed filament rotation (Section 3.2.3) is important for the filament-CH interaction discussed here because it served to bring the eastern leg in contact with the CHB region with the correct field orientation to lead to reconnection. We studied the structure of the magnetic field associated with this filament using a Nonlinear Force-Free Field (NLFFF)
extrapolation of the HMI vector magnetograms (Figure 3.1d; see Sun et al., 2012). We trace field lines starting at heights $\sim$10 Mm near the PIL and found twisted structure along major segments of the PIL (Figure 3.1e). This structure corresponds, at least partly, to the field configuration of the filament and may contribute to the observed filament rotation. We could not find a coherent structure spanning the whole PIL, i.e. the eastern and western part appear separated. This may be owing to the uncertainties in the field observation and modeling, since the region is away from disk center, and the field is relatively weak. Another possibility is that the helical structure associated with the filament formed before the eruption, when it was not force free.

In order to investigate the relationship between the observed CME structure and the magnetic-field configuration, the PFSS derived coronal fields were superimposed onto the observations from SDO/AIA and SOHO/LASCO C2, and from STEREO-A SECCHI and COR1, as shown in Figure 3.8. The field lines shown in each of the panels are the same but viewed from the corresponding vantage points. The box region shown in Figure 3.8b is the same one as in Figure 3.2i, indicating the region where the filament is seen to flatten, i.e., the contact layer. We see both closed and open magnetic fields at the contact layer, as shown in Figure 3.5 and Figure 3.8. The closed magnetic field originated from the positive polarity in the north and was connected to a negative polarity region at higher latitude. When the magnetic field of the filament reconnects with these open and closed fields, the filament material streams along the newly reconnected field structures, leading to the observed CME structure with both open and closed features (Figure 3.7 and Figure 3.8).

There are four types of reconnection proposed (Crooker et al., 2002), based on the interacting magnetic fields with open or closed configurations between (1) two open
field lines, (2) a closed field line on itself, (3) two distinct closed field lines (we call it “closed-field disconnection” here), and (4) open and closed field lines (i.e., interchange reconnection). This event, in which the fields of the filament reconnected with the mixed open and closed fields at the CHB, involves both interchange reconnection and closed-field disconnection.
Table 3.1: Timeline for the filament eruption on 9 August 2012.

<table>
<thead>
<tr>
<th>Time</th>
<th>Observation</th>
</tr>
</thead>
</table>
| 21:20    | Filament began to rise slowly  
                       Flaring started under the filament  
| 21:35-21:50 | Outermost filament expanded towards the CH and became open  
                       Type III radio bursts were observed  
| 21:50-21:57 | Brightening and bi-streaming flows observed at the contact layer  
                       The western leg of the filament becomes open  
                       Type III radio burst was detected  
| 21:45-22:40 | A CME was observed by STEREO/COR1  
                       The southern (northern) part exhibited open (closed) field feature  

3.4 Conclusion

In this study, we investigate the filament-CH interaction during a filament eruption on 9 August 2012, as listed in Table 3.1. This event involves interactions between the filament and both open and closed fields at the CHB. The reconnection between the filament and the open fields cause the western leg of the filament to open into the outer corona, which corresponds to the classic description of interchange reconnection described by Crooker et al. (2002), facilitating the filament eruption. Additionally, the closed-field disconnection between the filament and the closed fields transferred some filament material to newly formed loop structures that connected to the solar surface beyond the AR.

Overall, the multi-viewpoint observations have provided us with a great opportu-
Figure 3.9: Schematic drawing of the filament-CH interaction. The fields containing the filament material are shown in blue, with non-filament fields shown in black. The field direction is indicated by the arrows and is derived from the observed photospheric polarity distributions. The star region indicates where the inferred reconnection occurs.

nity to study this filament eruption in detail. During the eruption, the eastern leg rotated to come into contact with the CHB to form a flattened contact layer. Several features were observed in this contact layer, like brightening, bi-directional ejections and type III bursts. A CME, due to the filament-CH interaction, exhibited both closed and open features.
Chapter 4

Interaction Between Two Filaments During Eruption and Resulted Production of Solar Flares

We study a filament eruption involving filament-filament interaction on June 21, 2013, observed by SDO/AIA. Both filaments separated in height and were located above the same segment of a circular polarity inversion line (PIL) around a condensed leading sunspot in AR 11777. When the eruptive lower filament initiated, the upper one was observed to be descending toward it until both collided and interacted. A hard x-ray coronal source and a new hot plasma layer are identified at the interaction. This interaction produced a C3.0 flare, followed by a transition to a M2.9 flare. A post-flare loop arcade of a “C” shape formed in the M2.9 flare, during which we identify and investigate both magnetic loop shrinkage and a descending dark void.

4.1 Introduction

Solar filaments are relatively cool and dense plasma suspended by dips of sheared or twisted magnetic structures in solar corona. They can persist steadily for several solar rotations, until finally erupted away. The solar filament eruptions are usually observed to be associated with solar flares and Coronal Mass Ejections (CMEs) (review by Forbes, 2000).

It has been reported that the interaction between filaments of same chirality at
their neighboring endpoints resulted in their merging into a longer filament (Schmieder et al., 2004; Bone et al., 2009). The newly formed longer filament by this so-called “head-to-tail” linkage is thought to be steady until further magnetic cancellation at the footpoints (Martens and Zwaan, 2001; DeVore et al., 2005).

The collisions and interactions between bodies of filaments are also studied by simulations and observations. Linton et al. (2001) developed a series of MHD simulations on interactions of twisted flux tubes under convective zone conditions. Based on this study, four types of interaction were proposed: (1) bounce, (2) merge, (3) slingshot and (4) tunnel. Kumar et al. (2010) reported the collision of the central segments of two filaments and a following separation of newly formed stable filaments with exchanged footpoints, corresponding to the slingshot reconnection (Linton et al., 2001; Linton, 2006; Török et al., 2011). A M1.4 flare was also reported during this process, but not directly related to the filament interactions (Chandra et al., 2011). Jiang et al. (2013) investigated a similar event suggesting a partial slingshot reconnection between a small filament and a nearby larger and thicker filament, while no flaring was observed. Alexander et al. (2006) studied an eruption of a kinking filament and identified a hard x-ray coronal source at the projected crossing of the writhed filament, which could be treated to be generated by the interaction of two converging flux tubes (two legs of the same filament here). However, observations on the interactions between filaments are still very rare. And the relationship between the interaction and flare production remains unclear.

In this study, we present an observation on an interaction between two filaments and the associated flares, on June 21, 2013. This report is organized as follows: in Section 4.2, we describe the observations on the interaction of both filaments and the resulted solar flares. Our interpretation is presented in Section 4.3. The conclusion
appears in Section 4.4.

4.2 Observations

4.2.1 Instruments and Data

The filaments under study were located in AR 11777 (E71S16, Fig. 4.1), appearing near the western limb on June 21, 2013, from the view the Solar Dynamics Observatory (SDO) orbiting around the Earth. The Atmospheric Imaging Assembly (AIA; Lemen et al., 2012) on board SDO takes full-disk images of the Sun in seven extreme-ultraviolet (EUV) channels (logT ranges 5.6∼7.3) and three UV to visible channels (logT ranges 3.7∼5.0), with a pixel scale of 0.6″ pixel$^{-1}$ and a cadence of 12 seconds. The Helioseismic and Magnetic Imager (HMI; Schou et al., 2012) on board SDO provides full-disk magnetograms with a pixel scale of 0.5″ pixel$^{-1}$ and a cadence of 45 seconds.

4.2.2 Configuration

AR 11777 has a strong and compact negative polarity, surrounded by dispersed positive polarities. As a result, the polarity-inversion-line (PIL) is circular around the negative polarity, and separated into two segments (Fig. 4.1a): a north-eastern part where the interacting and erupting filaments located above, and the other south-western part where a long filament was located but remained steady and survived the eruption.

Among the two interacting filaments, one is much longer and higher up in solar corona, compared to the other lower filament (Fig. 4.1b). The upper filament has an elbow shape, with its northern footpoint located in the compact negative polarity
and southern footpoint in the southeastern positive polarity. The shorter and lower filament has a similar configuration, with northern (southern) footpoint in negative (positive) magnetic polarity. And both filaments are located above the same PIL, with positive (negative) polarities in the east and north (west and south). This configuration indicates that both filaments have sinistral chirality (Martin, 1998), consistent with the prevailing hemispheric preference of solar filaments. At around 23:40 UT on June 20, 2013, three hours before the filament eruption, a barb structure (dotted lines in Fig. 4.1b) became separated from the upper filament and formed a loop above. In this report, we treat it as a component of the upper filament, i.e., when we refer to “upper filament”, we mean both of the upper filament (dashed line in Fig. 4.1b) and the barb structure, if we do not talk about them separately.

The eruptive lower filament began to rise at around 02:20 UT, June 21, 2013. The evolution of this filament eruption is displayed in Fig. 4.2a-d and Movie 1. A slit is chosen along the East-West direction (dashed line in Fig. 4.2b) from a series of 304 Å images to generate a height-time stack plot as shown in Fig. 4.2e, in which the height of the lower filament is tracked by a blue dashed curve. With a time derivative of this height-time evolution, its velocity is determined and observed to display four phases (red curve in Fig. 4.3b): 1) a slow-rise phase ranging from 02:20-02:30 UT, below 10 km s$^{-1}$, 2) a short fast-rise phase, from 02:30-02:34 UT, with velocity accelerating from 10 km s$^{-1}$ to 90 km s$^{-1}$, 3) a relatively steady velocity of $\sim$100 km s$^{-1}$, between 02:34-02:45 UT, and 4) a second fast-rise phase starting from 02:45 UT, with velocity increased to 450 km s$^{-1}$ till 02:53 UT.

A compression front, is formed at around 02:44 UT with a projected distance of 110 arcseconds ($\sim$80 Mm) ahead of the erupting and expanding filaments (Fig. 4.2e). This front is clearly seen in AIA 171 Å (T $\sim$ 1 MK). The height-time evolution
Figure 4.1: Configurations of the lower and upper filaments before eruption, observed in SDO/AIA 304 Å. Left panel: AIA 304 Å image superimposed with contours of normal magnetic field strength from SDO/HMI. The positive/negative polarities are denoted by green/black contours respectively, in levels of [-1200, -300, 300, 1200] Gauss. Right panel: Sharpened 304 Å image clearly showing the structures. The dashed line denotes the upper filament, the dotted line for a barb structure which separated from the upper filament around three hours before. The locations of two smaller and lower filaments are indicated by white arrows. And only the northern one erupted later.

Information in Fig. 4.2e is generated in AIA 171 Å and overlaid on the stack plot to show its relative position. The derived velocity is displayed in Fig. 4.3b. This velocity is slightly lower than the erupting filament, indicating that it is actually driven by the eruption and expansion of the filament, similar to the formation of a compression front studied by Zhang et al. (2012).

There were two solar flares observed to be associated with this filament eruption, as seen in Fig. 4.3a, a flare of C3.0 class followed by a transition to the other M2.9 flare. In the following parts of this section, we investigate the evolution of this eruption and its relation to the production of both flares, respectively.
Figure 4.2: Evolution and interaction of the two filaments. Left Panels: The eruptive lower filament pushed up the upper one and both erupted away. Right Panels: The height-time stack-plot along a cut denoted by the dashed line in Fig.2 b. The dashed lines, in colors of blue (purple, green, and light green) are used to denote the trajectories of the lower filament (upper filament, barb structure, and compression front) respectively. The x-ray observation from Fermi/GBM is indicated by black curve.

### 4.2.3 Converging Motion

As the lower filament rose up, the upper filament and its barb structure were observed to be moving sunward, \textit{i.e.}, both filaments converging toward each other (Fig. 4.4a&cb). With the same method in Fig. 4.2, the motions of these structures are determined by tracking the moving features in the generated stack plot (Fig. 4.4b), with the velocities shown in Fig. 4.4c. The velocity of the lower filament kept on increasing until 02:34 UT, covering the first slow-rise phase and the following short fast-rise phase. During this interval, the upper filament and the barb moves downward
with final velocities of 10 and 25 km s\(^{-1}\) respectively before collision with the rising lower filament.

### 4.2.4 A Newly Formed Hot Layer

Before the eruption, the upper filament, which appeared in AIA 304 Å, was hardly identifiable in the hot channel of AIA 131 Å (T\(\sim\)10 MK). When both filaments collided with each other, a hot layer of plasma wrapping around the upper filament, appeared at 02:33 UT, as seen in AIA 131 Å (Fig. 4.5d, and movie 2). The observation in AIA 1600 Å for the transition region and upper photosphere shows an extended ribbon, which is composed of the footpoints of numerous hot loops in this layer. Meanwhile, all four footpoints are observed to be brightening, as observed by AIA 1600 Å with a contour at 1000 DN s\(^{-1}\) (blue contours in Fig. 4.5b).
Figure 4.4: Converging motions of the upper filament (barb structure) and the erupting filament. Panel a: AIA 304 Å image just before eruption. A cut is chosen to generate the height-time stack plot in Panel b. Three horizontal lines, corresponding to the barb structure, the upper filament and the lower filament in Panels a & b, respectively from top to bottom. Panel b: same description as for Fig. 4.2e. Panel c: the velocities (absolute values here) of these three structures, with same color system in Fig. 4.2e.

4.2.5 Production of a C3.0 Flare

Another direct result of the interaction between two filaments is the C3.0 solar flare. A hard x-ray burst initiated at 02:32 UT and lasted for about 7 minutes (Fig. 4.3a), corresponding to the impulsive phase of this flare. Three times were chosen to study the spatial evolution of the x-ray sources (denoted by three dashed lines in Fig. 4.3a, corresponding to the early, middle and late intervals of the burst, respectively). The results are displayed in Fig. 4.6a-c. At 02:33 UT (Fig. 4.6a), two main sources are identified: one in the northwest corresponds to the northern footpoint of the lower filament, and a second one between both filaments, i.e., a coronal x-ray source in both soft (<12 keV) and hard (>12 keV) x-rays. There is another small hard x-ray source at the southern footpoint of the upper filament,
Figure 4.5: A hot layer of plasma appeared at the interaction of two filaments. The images shown here are after a 90° clockwise rotation. Top panels: observations from AIA 304 Å, with contours of AIA 1600 Å at 400 DN s\(^{-1}\) (in green) and 1000 DN s\(^{-1}\) (in blue) in panel (b). Panel (c): AIA 131 Å image (T \(\sim\) 10 MK) before eruption, showing that the upper filament was cool and did not present in this channel. Panel (d): running difference of AIA 131 Å images when both filaments collide, the enhancement corresponds to the newly formed plasma warp.

as seen in Fig. 4.6a. However, there were no strong enough x-ray emissions at the southern footpoint of the lower filament and northern footpoint of the upper filament, indicating that this flare is asymmetric. Beginning at 02:34 UT (Fig. 4.6b), the previous footpoint source started to dominate in the emission of x-rays. At 02:38 UT (Fig. 4.6c), a hard x-ray source at the southern footpoint of the upper filament became identifiable once again, probably due to the decaying emission at the dominating northern footpoint of the lower filament.
During the C flare, the spatial evolution of the dominant x-ray source is studied, as shown in Fig. 4.7. Ten intervals with 32-seconds cadence (beginning of each cadence is denoted by a dashed line), from 02:32 to 02:39 UT, are used to reconstruct the x-ray images. Contours at 95% level of the maximum value at each time are overlaid on the AIA 304 Å image. For the soft x-ray evolution in Fig. 4.7b, the coronal source dominated for the first two intervals, and it ascended slightly, probably due to the rising of the interaction region driven by the erupting lower filament. Then the northern footpoint source of the lower filament became prevalent for about 2 minutes. After that, its southern footpoint dominated at the later time. The dominant source of the hard x-ray displays similar behavior as the soft x-ray (Fig. 4.7c), except the later part when the hard x-ray observation becomes unreliable due to this relatively short time cadence and not any included here. It is remarkable to note that, when comparing the first two prevailing coronal sources in both soft and hard x-ray at the same time, the hard x-ray source appeared a bit higher than the soft x-ray source.

4.2.6 Transition to a M2.9 Flare and Field Line Shrinkage

A M2.9 solar flare began at around 02:45 UT, five minutes after the previous C3.0 flare (Fig. 4.3a), and lasted more than 3 hours till 06:00 UT (not shown here). Based on the Hard x-ray observation from Fermi/GBM, the impulsive phase of this M flare started at 02:52 UT. We looked into the RHESSI images for the X-ray sources at earlier and later parts of this impulsive phase (Fig. 4.6d-e, the timing is indicated by dot-dashed lines in Fig. 4.3a), while its middle portion (03:05-03:25 UT) was not covered due to RHESSI night. The locations for the Hard x-ray source of 25-50 keV are at the northern footpoint of the lower filament in all three times. The sources for x-ray of 6-12 and 12-25 keV are above that footpoint. And these relatively lower
energy source are slightly moving southward and upward, compared with the locations of earlier ones.

*Field Line shrinkage* (or *loop retraction*) were observed during this M flare. For instance, two locations are identified at 03:28 UT, one in the north and the other in the south (covered by two boxes in Fig. 4.8a). In both regions, the loops are observed to retract toward the post-flare loops and stop there. A cusp-shaped structure also presented in the northern loop retraction region, with its top curved southward, denoted by dashed line in Fig. 4.8a (or see Movie 2). The velocity of the retracting loops is shown with a stack plot along a cut in the East-West direction (along the arrow...
Figure 4.7: Tracking the dominating sources of the x-ray production in the C3.0 flare. Upper panel: x-ray observation from Fermi/GBM. Lower left panel: contour levels of 95% of the maximum value from RHESSI observation in 6.0-12.0 keV, changing with time (indicated in upper panel by dashed lines respectively). Same as Lower left panel, but in 12.0-25.0 keV. The spine of the lower erupting filament is indicated by the dashed curve.

in Fig. 4.8a, with the arrow indicating the direction of motion). In the generated distance-time stack plot in Fig. 4.8b, two moving features are obtained and denoted by the dashed lines, corresponding two retracting loops. The earlier retraction can be tracked to 35 arcseconds further to the east than the later one. This difference might be caused by varying emissions due to variant densities and temperatures in the loops. The velocities of both loops (Fig. 4.8b) were observed to be decreasing as they were moving toward the post-flare loops, changing from a few hundreds km/s until it stopped.
Figure 4.8: Observations of the magnetic loop shrinkage (upper panels) and descending dark voids (lower panels) in the M2.9 flare. Panel a: running difference of AIA 131 Å images. Two locations with loop shrinkage are identified, denoted in two boxes. A cut along the arrow in the top box is chosen to generate a height-time stack plot as in Panel b. The direction of the arrow indicates that the loop was relaxing to the post-flare arcade. A cusp-shaped structure is identified and denoted by the dashed curve. Panel b: Trajectories of two retracting loops, indicated by two dashed lines. The derived velocities are shown in Fig. 4.3b. Lower panels: observation of a descending dark void. Same as in upper panels. Movie 2 is supplemented to better show these features.
It is also interesting to note that a lot of tadpole-like dark voids traveling downward successively in this flare. These tadpole-like voids are also called supra-arcade downflows (SADs; e.g., McKenzie and Hudson, 1999; Liu, 2013). The box region in Fig. 4.8c shows one example of these SADs. It was located above the central part of the post-flare loops, which is different from the locations where the field line shrinkage observed. With the same method in the study of loop retraction, the trajectory of this SAD is extracted from the generated stack plot (Fig. 4.8d). And its derived velocity is shown in Fig. 4.3b. It descended with an initial velocity of 280 km/s at 03:57 UT until stopped at the post-flare loop region ten minutes later. The SADs were still observable by the end of this flare, at 06:00 UT.

4.3 Interpretation and Discussion

4.3.1 Filament-Filament Reconnection

There are three indicators for that reconnection was going on between both the lower and upper filament: 1) converging motion before interaction, 2) a coronal hard x-ray source between both contacting filaments, 3) a newly formed hot plasma layer.

A converging motion of two filaments was reported by Kumar et al. (2010) by showing that they are approaching each other with a speed of \sim 10 \text{ km/s}. This value corresponds to the theoretical study by Petschek (1964), which involves an inflow speed of around 10 \text{ km/s} as an initial condition for Petschek-type reconnection. Here in our study, just before contact of both filaments, the upper filament descending at \sim 10 \text{ km/s}, and the barb structure with a velocity of \sim 25 \text{ km/s}. The eruptive lower filament rose up faster with \sim 40 \text{ km/s}, but is still comparable. Basically, the velocities of the converging motion is consistent with the previous studies.
However, compared with previous observations, the driving mechanisms for the converging motion can be different. In the study of Kumar et al. (2010), the approaching filament is thought to be driven by slow photospheric motions. The filament-filament interaction reported by Jiang et al. (2013) is initiated by a eruptive one among them. In this event, the lower filament is eruptive, similar to the one in Jiang et al. (2013). While the descending motion of upper filament and the barb structure should be explained by a different mechanism. A possible candidate is the $\mathbf{J} \times \mathbf{B}$ force. As the solar filament is thought to be supported by a twisted magnetic flux tube, it can be treated as a system that carry current along the main axis of the filament. The lower and upper filaments, with same sign of twists, are systems carries the parallel currents. Thus both systems would be attract each other by the $\mathbf{J} \times \mathbf{B}$ force, leading to the observed converging motion.

A hard x-ray source is identifiable at the interaction interface between both filaments, as seen in Fig. 4.6a and Fig. 4.7c. During the first minute of the impulsive phase in the C3.0 flare, this coronal source dominated in the x-ray production. And the centroid of the dominating x-ray source is slightly higher in 12-25 keV than that in 6-12 keV. Similar observations on the separation of centroids in varying energies have been reported (e.g., Sui and Holman, 2003; Liu et al., 2008). Liu et al. (2008) interpreted this separation is due to higher levels of turbulence near the reconnection than locations of further away. These observations suggest that a reconnection site appeared right above the hard x-ray coronal source at the interaction.

The new hot layer of plasma is consisted of numerous hot loops. A large number of the footpoints of these hot loops rooted at the elongated brightening ribbon. And at the same time, all four footpoints are also found to be brightening in AIA 1600 Å. Based on these observations, we suspect that this hot layer is a quasi-separatrix layer
(Demoulin et al., 1996) that wraps around the upper filament, separating its twisted magnetic fields from the outer fields. As the two filaments interact with each other, accelerated electrons can stream along the loops in this layer, deposited energy into the footpoints of these loops and cause the brightenings at those regions.

Both of the upper and lower filaments have sinistral chirality. And they originated from the same segment of PIL of AR 11777, indicating a small contact angle. In the simulation of Linton et al. (2001), this configuration would result in merging of both filaments after interaction. In our study, there are no evident signatures for the other types of interaction (i.e., bounce, tunnel and slingshot). And the lower eruptive filament reconnects with the upper and also pushed it up until both finally erupted away. From this point of view, both filaments are supposed to be merged together, at least partially, and formed a complicated structure with four footpoints.

4.3.2 Field Line Shrinkage in the M Flare

Both of the field shrinkage and the SADs are generally thought to be the same manifestation as a consequence of the newly reconnected evacuating flux tubes retracting from the reconnection site (e.g., McKenzie and Hudson, 1999). The difference between them, i.e., appearing as a retracting loop or a sunward dark void, is interpreted as a result of viewing from varying viewpoints (Fig.2 in Savage and McKenzie, 2011): when the retracting flux tube viewed along a line-of sight tangential/perpendicular to its axis, it appears as SAD/shrinkage. Here we adopt side-on/face-on for both viewing direction, respectively. Warren et al. (2011) demonstrated this speculation with both STEREO and SDO observations. In our study, the post-flare loop arcade appears as in “C” shape (see Fig. 4.8c), with one side rooted in the compact negative sunspot in AR 11777, and the other side in the dispersed trailing positive polarities.
Due to this special shape of this arcade, our views toward the loops in it are actually changing from face-on at the southern part to side-on at the middle part, becoming face-on again to the northern part of this arcade. Our observation show that the field line shrinkage is mainly identified at the northern and southern parts, while the SADs found above the middle part. This result corresponds well to with the expectation. Warren et al. (2011) also reported a similar result in a Γ-shaped post-flare loop arcade, though the configuration here in our study is more complicated. The initial velocities of the investigated two loop shrinkage and one SAD are 350, 140 and 280 km/s, respectively. These values are typical, compared with the previous studies (e.g., Savage and McKenzie, 2011).

The C-shaped post-flare loop arcade stays above the region corresponding to northeastern segment of the circular PIL, where the upper filament located above before eruption (Fig. 4.1). The observation of loop shrinkage and SADs here is an important evidence for the magnetic fields reconnecting high above the post-flare loop arcade. We suggest that the process for this M2.9 flare follows the standard flare model, i.e., magnetic reconnection occurs at the stretched current sheet beneath the erupting upper filament.

### 4.3.3 Proposed Physical Picture

Both interacting filaments, driven by converging motions, reconnected at the quasi-separatrix layer that wrapped around the upper filament, and produced the observed a coronal hard x-ray source in between and a hot plasma layer. During the interaction and eruption, a C3.0 flare is produced, followed by a transition to another M2.9 flare. We suggest that the production of this M2.9 flare follows the standard flare model. A physical picture is proposed for this event, as shown in Fig. 4.9.
1) Before the eruption, both the upper and lower filaments were located above the same segment of the PIL. And the upper filament was confined by above magnetic loops (Fig. 4.9a, only one field loop shown in dark as an example for simplification).

2) The erupting filament and the converging upper filament collided and reconnected at the quasi-separatrix layer, producing a coronal hard x-ray source in between and a hot plasma layer. Due to this interaction, both filaments merged at the center (at least partially), and formed a complicated structure with four footpoints (Fig. 4.9b).

3) The above magnetic loop became extended due to the stretching of the upper filament, forming a vertical current sheet underneath it (Fig. 4.9 c to d).
4) The legs of the magnetic loops beside the vertical current sheet reconnected there, following a standard flare model, producing the observed M2.9 flare (Fig. 4.9d). The retracting flux tubes form the reconnection site are either observed as loop shrinkage from the face-on view, or SADs from the side-on view, related to their configurations to the line-of-sight direction.

4.4 Conclusion

We have studied the evolution of a filament eruption event involving filament-filament interaction on Jun 21, 2013. Based on the observations of hard x-ray coronal source in between, the converging motion and a newly formed hot plasma layer, we conclude that a C3.0 flare was successfully generated by this filament-filament interaction. And due to this interaction, both filaments, with the same sign of chirality and contact at a small angle, is thought to merge together into a complicated structure with four footpoints, and erupted away.

A successive M2.9 flare was produced due to the eruption of the upper filament following the picture of the standard flare model. The post-flare loop arcade was of a special “C” shape, enabling us observing the loops with co-existing face-on or side-on views. As a result, both loop shrinkage and SADs are identifiable in this event.
Chapter 5

Summary and Future work

5.1 Summary

This work explores the dynamics and evolution of solar eruptive prominences (filaments), with multi-wavelength observations from SDO and STEREO and supporting observations from a number of other ground and space based solar observatories. Our study covers three primary classes of event: eruption of a bifurcated solar filament, interchange reconnection between a kinking filament and a nearby coronal hole, and the interaction of two filaments with production of solar flares. The main results are summarized here.

In the case of the evolution of the bifurcated filament, the observed mass/flux transfers between the lower and upper branches seemingly play an important role in the eventual eruption of the filament. Seven mass/flux transfers (from the lower to the higher branch) are identified and are thought to have contributed to an increase in the magnetic flux of the upper branch, supplied from the lower branch, which leads to the development of an ideal instability. Two possibilities were identified given the observed evolution and the ambient conditions, namely the kink and the torus instabilities. The partial eruption of this bifurcated filament exhibited clear kinking motion ($\sim 120^\circ$ rotation). How prevalent these processes are in the filament eruptions needs further investigation, though we do note that similar behaviors appear during hours before the eruption of the interacting filaments on June 21, 2013.
In the interchange reconnection study, where we explore the interaction between an erupting filament and nearby coronal hole magnetic field. We found that once more kinking motions played a crucial role in the eventual eruption of this prominence. A kinking motion of this filament (∼ 50° rotation prior to the filament impacting the coronal hole) served to orient the eastern leg, with oppositely directed field to that of the coronal hole, in such a way to drive reconnection with the unipolar field of the hole. The associated EUV brightenings and bi-directional flows in a newly formed contact layer, and the occurrence of type III radio bursts that are strongly related to escaping electrons along open field lines, provided further evidence for the occurrence of a reconnection in the contact layer. A further consequence of this interaction was the development of a complex CME, that exhibited both open and closed features, in agreement with the expected result of an interchange reconnection.

Finally we discussed the dynamic interaction between two filaments, a phenomenon that has rarely been observed before. A number of energetic phenomena are observed to occur as this interaction proceeds including the creation of a hard x-ray source in the solar corona as part of a C3.0 class flare, the transition to another flare event (class M2.9). Both filaments were separated in height above the same segment of a circular Polarity Inversion Line (PIL), and had the same sign of chirality. During the interaction, converging motions brought the two filaments into contact, resulting in the observed hard x-ray coronal source, and a newly formed hot plasma layer, indicating that the reconnection occurred between the magnetic fields associated with each filament. The large M2.9 flare resulted from the eruption of both filaments, and followed a pattern expected from the standard model of solar flares. It is also interesting to note that both loop shrinkage and SADs were present in this flare, with loop shrinkage at the ends of a “C” shaped post-flare arcade, and SADs at the
central portion, confirming the expectations in previous studies that loop shrinkage and SADs are actually the same phenomenon but viewed from different perspectives (e.g., McKenzie and Hudson, 1999).

These results bring new insights in our understanding of the destabilization and evolution of the eruptive prominences/filaments and the respective roles played by ideal instabilities and magnetic reconnection in directing the dynamic evolution. However, there are still many questions that need to be addressed in the future if we are to fully discern the physics of these complex events. For example, although we found that the eruption of a bifurcated filament might be triggered by ideal instabilities brought about by the transfer of flux within the bifurcated structure, we do not know how these transfers were initiated. Similarly, the other two studies, while providing new information on the drivers of filament eruptions and how the ambient coronal environment around them modifies their evolution, raise a number of questions about the nature and scope of the initiation mechanisms. Some of these outstanding issues and questions provided the basis for future research.

5.2 Future Work

Based on the work of this thesis, we propose future studies that will further expand our knowledge and understanding of the processes that drive solar eruptive prominences/filaments.

(1) Trigger mechanisms of solar filament eruptions

Currently, we have identified ∼15 solar filament eruptions that exhibit evident and substantial rotations during their eruptions, indicating possible evidence for the participation of the kink instability. A follow-up study on the initiation and evolution of these eruptions, could be carried out by measuring the height-time trajectory (for
dynamics) and the rotation (quantifying the kinking motions). In particular, with the help of the observations from multiple viewpoints (STEREO and SDO) and the 3D reconstruction method (Thompson et al., 2012), the “true” values (compared to the projected measurements) of the heights and rotations can be determined. Furthermore, the nature of these eruptions (full, failed and partial), and how its relationship to the kinking motion and ambient magnetic field environment (e.g., decay index) will also be addressed.

(2) The Influencing Factors in Filament-Filament Interactions

Numerical simulations have been used to study the collision and reconnection of twisted flux tubes (e.g., Linton et al., 2001, 2006). They demonstrated that both the chirality and the contact angle (angle between their axes) are important parameters in determining the type of the interaction (i.e., bounce, merge, slingshot and tunnel) and the efficiency of the resulting energy release, though kink effects were suppressed in their model for simplicity. No flaring has yet been identified to be directly related to the slingshot type interactions (Kumar et al., 2010; Chandra et al., 2011; Jiang et al., 2013). However, our study shows that a merging interaction produced a C3.0 flare providing tantalizing observational evidence for Linton-like events on the Sun. Further detailed multiwavelength studies are needed to address the associated physical processes and the dynamics of the energy release.

(3) Filament Eruptions and their Interaction with Ambient Magnetic Fields

The interchange reconnection, a reconnection that occurs between closed and open magnetic fields, is thought to be an effective way of reducing the total magnetic flux in the heliosphere and thus avoiding the so-called “magnetic field magnitude catastrophe” (Gosling et al., 1995). It has been also used to explain the existence
of open fields of an interplanetary CMEs (ICMEs) observed near the Earth (Crooker and Horbury, 2006). A detailed 3D multiwavelength study on this topic will shed light on the physical processes leading to the opening of the flux rope associated with the solar filament. What roles kinking motions play in the interaction, and how the twist in the flux tube transfers along the open field, still remain unclear. This topic is crucial for our understanding of the Sun-Earth Connection (e.g., Baker et al., 2009; Crooker et al., 2002, 2006).
Bibliography


RP Lin, BR Dennis, GJ Hurford, DM Smith, A Zehnder, PR Harvey, DW Curtis, D Pankow, P Turin, M Bester, et al. The reuven ramaty high-energy solar spec-


Wei Liu, Qingrong Chen, and Vahé Petrosian. Plasmoid ejections and loop contrac-


