ABSTRACT

SMALL AND LARGE-SCALE MAGNETIC FIELDS INVOLVED WITH SOLAR FLARES

by

Chang Liu

Solar flares are generally identified as an important source of disturbances that affect space weather, while many aspects of the basic flare process are still not well understood. The purpose of the present work has been to investigate the small and large-scale magnetic structures and their evolution associated with flares in the context of magnetic reconnection, based on which the goal of this dissertation is to further the understanding of the various properties of flares and related phenomena, including their origin, precursors, and evolution of morphology in solar atmosphere.

The research presented in this dissertation relied upon multiwavelength observations of flares from hard X-rays to radio wavelengths obtained from several ground- and space-based instruments. The studied topics in the flare core regions include microflares, flare-induced evolution of the photospheric magnetic field, and sigmoids. The large scale study includes remote brightenings, Moreton waves, type II and III radio bursts, and coronal mass ejections (CMEs). Statistical studies were carried out for microflares and the evolution of flare core fields. Large-scale activity was analyzed by examining two major eruptions, the 2003 October 29 X10 flare and the 2005 May 13 M8.0 flare.

The main findings in this dissertation are as follows: (1) results of X-ray spectral fitting indicate the nonthermal origin of X-ray emission at over $\sim$10 keV during the impulsive phase of microflares and the photon spectra of the microflares associated with type III bursts are generally harder than those without type III bursts; (2) white-light and magnetogram observations of $\delta$ sunspots reveal the rapid penumbral decay and central umbral/penumbral darkening associated with flares and suggest
that the flaring magnetic fields change from a highly inclined to a more vertical configuration. Moreover, these changes are irreversible; (3) in the 2003 October 29 X10 event, remote brightenings more than $2 \times 10^5$ km away from the main flare were ignited by hot particles transported along closed magnetic fields; meanwhile, this event was strong enough to indicate the common origin of the Moreton waves, the type II radio bursts and the CME; and (4) multiwavelength signatures were found to support the argument that the 2005 May 13 M8.0 flare originated from a characteristic sigmoidal active region following the tether-cutting flare model.

The major contribution of this dissertation is the discovery of new observational evidence to enlighten the future flare/CME modeling:

- Rapid change of δ spot structure associated with flares was found and the first flare scenario actually describing the flare effects on sunspots was proposed;

- The first well-observed ribbon-like hard X-ray emission in the RHESSI era was reported and explained as a natural outcome from the eruption of an EUV sigmoid.
SMALL AND LARGE-SCALE MAGNETIC FIELDS INVOLVED WITH SOLAR FLARES

by

Chang Liu

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SMALL AND LARGE-SCALE MAGNETIC FIELDS INVOLVED WITH SOLAR FLARES

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To my family,
for their endless love and encouragement
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CHAPTER 1

INTRODUCTION

In the solar system, the most energetic explosions that mankind knows so far are solar flares, which involve sudden particle acceleration, plasma heating, and bulk mass motion. Major solar flares release up to $10^{32} - 10^{33}$ ergs in $10^2 - 10^3$ s, while the liberated energy of many smaller flares (e.g., microflares) is only $\sim 10^{27}$ ergs, which reaches down to the limits of detectability of modern instruments. Nowadays, human activities are even more affected by the space weather, which is essentially related to the abrupt energy release from the Sun, i.e., in the form of solar flares and the often associated coronal mass ejections (CMEs) and solar energetic particles (SEPs) events. For example, streams of highly energetic particles stemming from them can present radiation hazards to astronauts, which is one of the major concerns in foreseeing manned missions to the moon and Mars. Therefore, understanding the physical process of impulsive energy release in solar flares and ultimately implementing the real-time space weather forecasting, are among the top priority goals across the solar research community. Nonetheless, many detailed physical process of the flare phenomenon have not yet been fully understood.

1.1 General Aspects of Solar Flares

Few phenomena have long stirred the interest of solar scientists more than solar flares. The first naked-eye solar flare was sighted by Chinese in 1,111 B.C.\textsuperscript{1}, and R. C. Carrington as well as R. Hodgson detected the first flare in white-light independently on 1859 September 1 (Carrington 1859; Hodgson 1859). Since not many flares release enough energy so as to be seen in the continuum, there were few records of flare

\textsuperscript{1}See http://solarb.msfc.nasa.gov/science/timeline/rise.html.
data for almost seven decades. An important turn in solar research history is the G. E. Hale’s invention of the spectroheliograph in 1892 (see e.g., Hale 1892), following which flares started to be observed in the optical emission line at 6562.8 Å (H\(\alpha\)) and were routinely recorded at this wavelength from ground observatories since the 1930s. They were hence referred to as “chromosphere eruptions” at that time. Since the mid-1970s, flares have been continuously registered in soft X-rays (1–8 Å), in addition to the classic H\(\alpha\) line observation. Nowadays, they have been observed throughout the electromagnetic spectrum with the advent of space-based observations, from \(\gamma\) rays at the shortest wavelengths to radio waves at the long-wavelength end. Flares are currently thought of as primarily a coronal phenomena rather than a chromospheric one. Thus, it is more rational to define flares as the process of sudden energy release in a restricted volume of the solar atmosphere.

With the flare phenomenon being investigated in multiple wavelengths, classification schemes particular to given wavelengths have been developed. Table 1.1 gives the two widely used classifications in H\(\alpha\) and soft X-ray wavelengths, which had come into common usage since about 1930 and 1970, respectively. Corresponding radio fluxes at 5 GHz are also listed. It is worth noticing the good correlation among levels in different wavelengths. In fact, this is an example of what has been known as the “Big Flare Syndrome” (Kahler 1982), which simply means that bigger flares are “brighter” at all wavelengths. Five standard terms, from very low to very high based on occurrence frequency of flares at different classes, are also used to describe the general level of solar activity.

Figure 1.1 shows the typical time profiles of flare multiwavelength emissions, although individual flares differ greatly in size and importance. In general, a flare can be roughly divided into three phases (see e.g., Kane 1974): precursor, impulsive phase, and gradual phase, as schematically illustrated at the bottom. The precursor is seen as a relatively small increase in softer radiation signifying a possible occurrence of
Table 1.1 Flare Classification Schemes

<table>
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<tr>
<th>Importance Class</th>
<th>Area(^a) ((10^{-6} , A_\odot))</th>
<th>Area(^b) ((\text{degree}^2))</th>
<th>Typical Duration</th>
<th>Percentage of All Flares</th>
<th>Radio flux at 5 GHz (sfu(^c))</th>
<th>Soft X-ray Classification</th>
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<tr>
<td>S</td>
<td>&lt;200</td>
<td>&lt;2.06</td>
<td>Several minutes</td>
<td>75</td>
<td>5</td>
<td>A</td>
</tr>
<tr>
<td>1</td>
<td>200–500</td>
<td>2.06–5.15</td>
<td>Tens of minutes</td>
<td>19</td>
<td>30</td>
<td>B</td>
</tr>
<tr>
<td>2</td>
<td>500–1200</td>
<td>5.15–12.4</td>
<td>An hour</td>
<td>5</td>
<td>300</td>
<td>C</td>
</tr>
<tr>
<td>3</td>
<td>1200–2400</td>
<td>12.4–24.7</td>
<td>≥An hour</td>
<td>&lt;1</td>
<td>3000</td>
<td>M</td>
</tr>
<tr>
<td>4</td>
<td>&gt;2400</td>
<td>&gt;24.7</td>
<td>≥An hour</td>
<td>&lt;1</td>
<td>30000</td>
<td>X</td>
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\(^a\) Corrected flare area at center of solar disk.

\(^b\) 1 degree\(^2\) = 1.476 \times 10^8 \, \text{km}^2\, \text{of solar surface}.

\(^c\) 1 sfu = 10\(^{-22}\) \, \text{W} \, \text{m}^{-2} = 10^4 \, \text{Jansky}.

Note. — Brightness suffixes of F (faint), N (normal), or B (brilliant) are often used in conjunction with the importance character of optical flare classification (for example, 2B). General level of solar activity, observed or expected within 24 hours, is also categorized by the following five standard terms:

- Very Low: Just < C-class X-ray events;
- Low: C-class X-ray events;
- Moderate: Isolated (1 to 4) M-class X-ray events;
- High: Several (≥ 5) M-class X-ray events, or isolated (1 to 4) M5 or greater X-ray events;
- Very High: Several (≥ 5) M5 or greater X-ray events.

the following impulsive phase within minutes. The impulsive phase is characterized by the obvious fast rise and decay in the harder radiation (e.g., hard X-rays and microwaves), which sometimes may have multiple spikes indicating several episodes of energy release. Meanwhile, the low-energy fluxes (e.g., soft X-rays and Hα) show a slow increase into the gradual phase, reach maximum after the peak of the impulsive phase, and then slowly decrease into the preflare level. Moreover, the time integral of the impulsive microwave bursts detected at centimeter wavelengths resembles the
rise to maximum in soft X-ray emissions. This relationship was reported by Neupert (1968) and is therefore known as the Neupert effect.

As for the spatial morphology of flares, they are roughly divided into two groups (Pallavicini et al. 1977) — small, short-lived, compact flares and usually big, long-duration two-ribbon flares. Physically, the real distinction between these two kinds of flares is not in the sense of size, but rather whether the flare is confined or not (ˇSvestka 1986). For a compact flare, its whole flaring life is probably confined in a relatively small loop in the lower corona. In contrast, a two-ribbon flare (see left panel in Figure 1.3 for an example) is usually associated with an erupting filament (which is therefore conventionally regarded as the flare trigger) and flare emission occurs in postflare arcades as well as at the feet of the arcades, thus leading to the formation of two bright ribbons on either side of the magnetic neutral line (see more related discussions in § 1.3.1). In some active regions, flares show a striking tendency to recur in nearly identical morphology and such events have been termed “homologous flares” (Waldmeier 1938, see § 3 for examples). Occasionally, a pair of flares occurs almost simultaneously or subsequently in different active regions. Their occurrence is not by chance, but result from certain physical connections (e.g., mass flow as identified in Wang et al. 2001). These flares are then called “sympathetic flares” (e.g., Pearce & Harrison 1990).

1.2 Multiwavelength Observation of Solar Flares

Because of the reasons stated in § 1, one of the most active research areas in solar physics is understanding the nature of energetically explosive flare events on the Sun. However, solar flares are complex phenomena and the released energy is transported through the entire flaring region, producing various flare signatures. The exhibition of these signatures and the relationship between them relies essentially on the form that the released energy presents, e.g., bulk heating of plasma in the flaring volume
and acceleration of charged particles from the main energy release site, thus different wavelength observations provide diagnostics of the flaring process in different aspects (c.f. Table 2.1). Through observations across the entire wavelength range with good spectral, spatial, and temporal resolution, one can study the complete physical processes in solar flares from the corona to the lower atmosphere. Over the last two decades, several multiwavelength studies of solar flares and related phenomena have been published (e.g., Alissandrakis et al. 1988; Holman et al. 1989; Wang et al. 1995; Nishio et al. 1997; Hanaoka 1997; Chiuderi-Drago et al. 1998; Kundu et al. 2001). These studies have helped to build a consistent and unified scenario of the flare phenomenon from different views.

1.2.1 Core Emissions

The heating process in the flare core region can be diagnosed through continuum and line emission in the soft X-rays, EUV/UV (e.g., 171, 195, and 1600 Å), and optical wavelengths (e.g., Hα), which reveals the flaring conditions in the corona, transition region, chromosphere, and the temperature minimum region. Quite often, the earliest obvious and detectable signature of an explosive flare event is the radiation in soft X-ray wavelengths with energies up to ∼10–20 keV. This is the reason that flare classification according to soft X-ray emission (see § 1.1) is long used and widely recognized, and modern space solar missions (see § 2.1) continuously monitor soft X-ray emission to provide indispensable information for flare research, such as the flare location, which is crucial for investigating the nature of any associated SEP event, and other quantitative information (e.g., flare magnitude), especially when there are no ground optical observations available. Soft X-ray emission reflects the abrupt heating of coronal plasma to temperatures of ∼10^7 K and contains a substantial fraction of the radiated energy in flares. It is well known that the observed soft X-ray spectrum can be fitted by a single temperature Maxwellian (although several
line emissions contaminate the soft X-ray continuum spectrum, e.g., the iron-line complex peaking at \( \sim 6.7 \) keV and the iron-nickel complex peaking at \( \sim 8.0 \) keV). By using the direction-integrated, non-relativistic Bethe-Heitler cross section formula (e.g., Jackson 1962), the soft X-ray spectrum \( I(\epsilon) \) observed at the orbit of the Earth can be written as (e.g., Tandberg-Hanssen & Emslie 1988)

\[
I_{\text{thermal}}(\epsilon) = \frac{D}{4\pi R^2} EM \frac{\epsilon}{\epsilon T^{1/2}} \exp(-\epsilon/kT) \quad \text{[photons cm}^{-2}\text{ s}^{-1}\text{ keV}^{-1}],
\]

(1.1)

where \( \epsilon \) is photon energy in units of keV, \( D = 5.7 \times 10^{-12} Z^2 \) cm \(^3\) s \(^{-1}\) K\(^{1/2}\) (for solar conditions, \( Z^2 \approx 1.4 \)), \( R = 1 \) AU, and EM is the volume emission measure of the source defined as

\[
EM = \int n_e^2 dV,
\]

(1.2)

where \( n_e \) is the electron density and \( V \) is the volume of the X-ray emitting plasma along the line of sight. Therefore, from the observed exponential-like soft X-ray spectrum, one can deduce the volume emission measure (therefore the density of the thermal plasma) and the temperature of the thermal bremsstrahlung source. Also, the thermal contribution to the flare energy budget can be evaluated as

\[
E_{th} = 3k_B T \sqrt{EMV},
\]

(1.3)

where \( k_B \) is the Boltzmann constant.

Meanwhile, it is now known that flares are actually very efficient particle accelerators. Through the electric fields associated with the varying magnetic fields that are characteristic for the flare-producing magnetically complex active regions, electrons and ions can be accelerated to energies up to 100 MeV. The accelerated 10–100 keV electrons appear to contain a significant portion of the energy released abruptly in the flare impulsive phase, which indicates that there is a close relationship between the electron acceleration and energy release process. Besides microwaves, the
hard X-ray continuum is the most direct signature of energetic electrons produced by flares, which carries intrinsic information about the electron acceleration during the flaring process that is unobtainable from emissions at any other wavelength. It is widely believed that interaction of beams of nonthermal electrons (e.g., the average energy of the electrons is much larger than the mean energy of the background source) with ambient solar plasma results in hard X-ray emission via nonthermal bremsstrahlung. For accelerated electrons precipitating into the dense chromosphere, the standard model for energy transport is the thick-target emission model proposed by Brown (1971). It is assumed in this model that nonthermal electrons undergo Coulomb collisions with dense ambient plasma and thus are immediately stopped, i.e., thermalized. In practice, considering the fact that the observed hard X-ray photon spectrum can normally be fitted by a straight line (on log–log axes), a power-law spectrum of injected source electrons is thus assumed as \( F(E) = AE^{-\delta} \) [electrons s\(^{-1}\) keV\(^{-1}\)]. Consequently, the hard X-ray spectrum \( I_{thick}(\epsilon) \) observed at the orbit of the Earth is also a power-law (see e.g., Tandberg-Hanssen & Emslie 1988), i.e., \( I_{thick}(\epsilon) = a\epsilon^{-\gamma} \), where \( a \) is almost a constant and \( \gamma = \delta - 1 \). For the case of thin-target emission model, which is applicable to nonthermal electrons ejected outward to the less dense corona, or trapped in low density coronal loop, the resultant hard X-ray spectrum is still a power-law with \( \gamma = \delta + 1 \).

From the fitting parameters of the observed photon spectrum of a thick target, the nonthermal contribution to the flare energy budget in the thick target approximation can be computed (Lin et al. 2001):

\[
E_{non-th} = 9.5 \times 10^{24} \gamma^2 (\gamma - 1) B(\gamma - \frac{1}{2}, \frac{3}{2}) A E_0^{-(\gamma - 1)} \Delta t \quad [\text{ergs}],
\]

where \( B(m, n) \) is the standard beta function, \( A \) is the normalization factor of the photon spectrum, \( E_0 \) is the energy cutoff, and \( \Delta t \) is the time interval.
1.2.2 Large-Scale Manifestations

Although the flare energy release seems localized, it can have widespread effects on the atmospheric plasma (relative to the flare core emissions discussed in § 1.2.1), since charged particles can be accelerated to high energies, and can spiral along the field lines of large-scale coronal loops. In addition, it is now known that coronal shock waves might be launched after large flares, which can even trigger another CME by disturbing a large interconnecting loop (Hudson & Warmuth 2004). Therefore, in contrast to solar flares that occur in relatively confined volumes inside an active region, large-scale activities — even large-scale magnetic restructuring processes — provide further information and thus complement the flaring scenario. In investigating these non-local flare phenomena, radio bursts can furnish important information on the physics involved. An overview of metric radio burst types is given in Figure 1.2, the classification of which is based on their morphology as they appear in dynamic radio spectra.

Type III Radio Bursts and Remote Flare Brightenings  The most rapid response to the particle acceleration phase during the flare are type III radio bursts,
which are intense bursts showing a rapid decrease in frequency with time (e.g., Kundu 1965) and generally appear with the onset of other impulsive phase signatures, such as hard X-ray bursts (e.g., Švestka 1976), and thus provide evidence of electron acceleration during the primary energy release. The conventional interpretation of type III radio bursts is mildly-relativistic electron beams with energy \( \sim 1–50 \text{ keV} \) traveling outward along open field lines at an appreciable fraction of the speed of light into ever less dense coronal regions, which generate strong Langmuir waves (plasma oscillations) that are scattered off ion-acoustic waves or other Langmuir waves to produce plasma radiation at either the fundamental (\( \omega_p \)) or second harmonic (\( 2\omega_p \)) of the plasma frequency that is given by

\[
\omega_p = 8.98 \times 10^3 \sqrt{n_e} \quad \text{[Hz]},
\]

(1.5)

where \( n_e \) is the electron density in \( \text{cm}^{-3} \). Note that these involve upward moving electrons, although the numbers are typically 4–5 orders of magnitude less than the number of electrons producing hard X-ray emissions. They may have been first accelerated on closed field lines and then drifted onto open field lines through a magnetic field curvature drift (Tandberg-Hanssen & Emslie 1988). Sometimes, reverse slope (RS) type III bursts are seen, in which the observed radiation drifts towards higher frequencies as time proceeds. These bursts presumably correspond to electron beams traveling downwards in the solar atmosphere, which, if moving along large-scale coronal loops, may even give birth to remote flare brightenings (see detailed discussions in \( \S \ 5 \)).

**Type II Radio Bursts and Moreton Waves** Outward propagating coronal shock waves, usually launched after many strong flares, are manifested in the radio wavelength by the well established type II radio bursts (see Nelson & Melrose 1985, for a review), which are due to plasma emission from electrons accelerated in shock
fronts and have a much lower frequency-drift rate (e.g., compared to type III radio bursts). In dynamic radio spectra, they can be identified as stripes of enhanced radio emission, usually with both fundamental and harmonic bands, slowly drifting from high (several hundred MHz) to low frequencies (∼20 MHz or less) within tens of minutes. Using a known (or assumed) coronal electron density profile, one can deduce the propagation speed of the driving shock wave by converting the frequency drift seen in the spectrogram to distance from the solar surface. By comparing several commonly used electron density models with actual measurements, Warmuth & Mann (2005) suggested that the one-fold Newkirk model (Newkirk 1961), which is given below, is a good representation for the inner corona:

\[ n_e = n_0 \times 10^{4.32R_s/R}, \]  

(1.6)

where \( R \) is the distance from the solar center, \( R_s \) is the solar radius, and \( n_0 = 4.2 \times 10^4 \text{ cm}^{-3} \). At a height of \( R = 1.8R_s \), switching to the Mann model (Mann et al. 1999) is preferred, which gives the same \( n_e \) as the Newkirk model at this height while it is more suited for the outer coronal and heliosphere. The Mann model is given by

\[ n_e = n_s \times \exp \left[ \frac{A}{R_s} \left( \frac{R_s}{R} - 1 \right) \right], \]  

(1.7)

where \( n_s = 5.14 \times 10^9 \text{ cm}^{-3} \) and \( A/R_s = 13.83 \).

Another signature of flare-associated shock waves seen in the chromosphere is Moreton waves (a.k.a. flare waves), which was named after the American solar astronomer Gail Moreton who first reported the phenomena in 1960 from the Lockheed Observatory (Moreton & Ramsey 1960). Moreton waves can be seen in H\( \alpha \), especially in the red wing of H\( \alpha \), because at the wave front, the mass motion is downward entering the chromosphere (Narukage et al. 2002). They appear as a moving diffuse arc propagating within a somewhat restricted solid angle at speeds of
∼500–1500 km s$^{-1}$, and are found to be often associated with metric type-II radio bursts (e.g., Kai 1970). Further discussions on Moreton waves are given in § 5.

However, the question of whether these coronal shocks are caused by flares or fast material ejecta is not straightforward and has been a subject of active research, considering the fact that flares and CMEs are usually inter-related phenomena within the overall eruptive process. Generally, coronal shock waves can be generated by two mechanisms (see e.g., Vršnak 2001). The first is the piston mechanism (Maxwell & Dryer 1982), in which the shock is ignited and driven into interplanetary space by an erupting filament or CME moving with a velocity higher than the local magnetosonic velocity. The second is the blast wave mechanism (Mann et al. 1995), in which the abrupt expansion of the flaring region (pressure pulse), resulting from the flare impulsive heating, generates a large-amplitude blast wave that subsequently transforms into the shock wave. Therefore, there is no a priori reason to exclude either of these mechanisms (see Cliver et al. 1999, for a review). Case studies were carried out for two major eruptions and are presented in §§ 5 and 6, respectively.

1.3 Solar Flare Models

Despite the fact that various manifestations in multiple wavelengths, whether in the core or on a large scale, as discussed in § 1.2, have been observed after the launch of solar flares, the origin of the flare phenomenon remains a mystery. It has long been thought and widely believed that the essential process behind solar flares is magnetic reconnection, i.e., the topological changes in the connectivity of field lines as a result of large-scale magnetic field restructuring in the constantly stressed coronal magnetic fields. It occurs when two oppositely directed field lines are pushed together, and is typically visualized as the subsequent formation of two new field lines. The process actually occurs in the central region where magnetic diffusion dominates, and results in a change of magnetic morphology, liberating the
free nonpotential energy and converting it into plasma heating, particle acceleration, and plasma motion. It is not intended to discuss the detailed reconnection mechanism in this dissertation, while it should be addressed that magnetic reconnection not only accounts for the enormous energy release in solar flares, but also provides the only explanation so far for many observational facts regarding solar flares, like the flare ribbon motions. Based on these facts, a number of flare models with different magnetic topology, but all involving magnetic reconnection in some form, have been put forward in the past half century and successfully explained certain aspects of the flare phenomenon. These different models all comprise the following common components: the driver mechanism that leads to the magnetic evolution, the loss of stability, and the subsequent magnetic reconnection process. This section covers the theoretical aspects of some well-established flare/CME models. Beginning from § 3 where the detailed research work is presented, comparison will be made whenever possible between the observations and the well accepted flare models, either to provide supporting evidence or to put forward new observational results, which is crucial for future flare/CME modeling.

1.3.1 The CSHKP Model

This is the classical 2D magnetic reconnection model for flares that is most widely accepted, following the ideas synthesized from Carmichael (1964), Sturrock (1966), Hirayama (1974), and Kopp & Pneuman (1976). It has been further elaborated by the modeling of Yohkoh observations (Tsuneta 1996, 1997; Shibata 1996a), and is able to nicely explain a lot of the observational features in multiple wavelengths.

The basic scenario proceeds in two essentially distinct phases as depicted in the right panel of Figure 1.3. During the first phase, the flare starts with a erupting prominence above the neutral line as the initial driver (Figure 1.3a). Field lines are then stretched by the prominence associated with a CME, to form a current
Figure 1.3  Left: The great “seahorse flare” of 1972 August 7 observed at Hα blue wing by the Big Bear Solar Observatory, showing the two-ribbon structure late in the event with bright Hα loops connecting the ribbons. Right: a classical flare model proposed by Hirayama (1974), which starts from a erupting prominence (a), triggers X-point reconnection beneath an erupting prominence (b), shown in sideview (b’), and leads to the formation of the two ribbon structure and the postflare loop prominence system (LPS; c).

sheet, which is then subjected to Sweet-Parker (Sweet 1958; Parker 1963) or Petschek (Petschek 1964) reconnection (Figure 1.3b). The region of the coronal X-point is thus assumed to be the location of major magnetic energy release causing local corona plasma heating and particle acceleration. Subsequently, the footpoints of the reconnecting field lines are heated by the resulting thermal conduction fronts and bombardment of nonthermal particles to produce various flare emissions (e.g., Hα and hard X-rays). Due to this impulsive heating, chromospheric plasma evaporates to fill flare loops with over-dense heated plasma emitting soft X-rays. During the much slower second phase (Figure 1.3c), successive reconnections take place higher and higher above the X-point, resulting in a growing shell of X-ray emission with a
cusp structure at the top (Klimchuk 1997). Meanwhile, the chromospheric ribbons (see Figure 1.3 left panel for an example), which are a series of footpoints of coronal arcade loops taking part in the reconnection, separate away from the central magnetic neutral line. Thus, the whole flare process largely rebuilds the original arcade from the core outward.

In a two-dimensional configuration there is a simple relation between the rate of reconnection during the second phase, in terms of the electric field $E_{rec}$ in the reconnecting current sheet, and the apparent motion of the flare ribbons (Forbes & Priest 1984):

$$E_{rec} = B_n(X_r)V_r ,$$

(1.8)

where $V_r = \frac{\partial X_r}{\partial t}$ is the velocity of the outer edge of the ribbon and $B_n(X_r) = -\frac{\partial A_0}{\partial X_r}$ is the vertical magnetic field at the location $X_r$ ($A_0$ is the magnitude of the flux function at the separatrix). Thus, motions of the flare ribbons provide an indirect measure of electric field produced by reconnection in the corona. Relation (Equation 1.8) is independent of the precise form of the coronal magnetic field and flare model except for the assumptions that the configuration is two-dimensional, an X-line exists, and that the field lines are tied to a stationary photosphere (i.e., line-tied, or equivalently, their evolution timescale is much longer than the reconnection timescale). More generally, the reconnection rate in terms of the rate of photospheric magnetic flux change $\varphi_{rec}$ can be inferred as

$$\varphi_{rec} = \int E_{rec} dl = \frac{\partial}{\partial t} \left( \iint B_n dA \right) ,$$

(1.9)

where $dl$ is the length along reconnecting current sheet, $dA$ is the newly brightened flare ribbon area at each instant (Forbes & Lin 2000, and references therein), given that the magnetic flux is conserved from the photosphere to the corona and the photospheric magnetic fields are line-tied.
Thus, $E_{\text{rec}}$ and $\varphi_{\text{rec}}$ provide a model-independent measurement of the reconnection rate inside the corona reconnecting current sheet. Note that $E_{\text{rec}}$ reflects the reconnection rate per unit length along the current sheet with a two-dimensional assumption, while $\varphi_{\text{rec}}$ does not require the two-dimensional assumption, thus avoiding large uncertainties when evaluating the ribbon expansion velocities. In fact, the amount of total reconnection flux

$$\psi_{\text{rec}} = \int \varphi_{\text{rec}}(t) dt , \quad (1.10)$$

is an important physical parameter of the flux rope evolution (Qiu & Yurchyshyn 2005).

1.3.2 The Emerging Flux Model

It is well known that flares are more likely to occur in active regions with concentrated magnetic flux tubes, which emerge from the convection zone into the solar atmosphere presumably due to buoyancy instability (Zwaan 1987). The flare model proposed by Heyvaerts et al. (1977) describes the interaction of such new emerging flux with the existing overlying coronal field. However, this model requires the existence of a stable current sheet for a long period before the onset of the flare, which neither observation nor simulation could corroborate (Aschwanden 2005, and references therein). Therefore in principle this model can only apply to small flares (Priest & Forbes 2000). Later, based on the plasma jets that have been well observed with Yohkoh/SXT (e.g., Shibata et al. 1992), this model was further developed to explain the observations of $\text{H}\alpha/\beta$ surges and EUV/X-ray brightenings and jets (e.g., Zhang et al. 2000; Liu & Kurokawa 2004), which are evidence of reconnection outflow (Shibata et al. 1996b).
1.3.3 Flux Rope Catastrophic Model

Based on the fact that the coronal magnetic field can be described by the well-accepted force-free field theory (Priest 1984), Forbes & Priest (1995) developed a flare model, in which continuous converging flows serve as the driver mechanism and when the system of force-free magnetic field passes a critical point, a filament eruption is triggered. This fully analytically 2D model is able to produce reasonable amounts of energies favorable for flares and CMEs. One question, however, is whether the converging flows constitute a realistic driver, considering that the typically observed photospheric flows may be too slow or randomly oriented. Moreover, shear flows that are subject to tearing instability have been found to be important for flare initiation (e.g., Deng et al. 1993), which must involve a more complicated 3D configuration. Recently, Yang et al. (2004) and Deng et al. (2006) used a high-order adaptive optics system, frame selection, and speckle-masking image reconstruction technique and found specific evidence of strong shear flow up to 1.6 km s$^{-1}$ along the magnetic neutral line prior to the 2003 October 29 X10 flare. More important, the shear flows are in opposite directions on both sides of the magnetic neutral line. These flows might serve as the driver of the initial instability leading ultimately to the eruption.

1.3.4 The Magnetic Breakout Model

A leading theory for the initiation of a CME is the magnetic breakout model developed by Antiochos (1998) and Antiochos et al. (1999), in which magnetic reconnection occurs on top of the sheared arcade, which subsequently removes the unsheared field above the sheared core flux near the magnetic neutral line and therefore allows the field above the core flux to open up. The essential configuration of this model is the quadrupolar double arcades. Recent MHD simulations show that the evolution of the post-eruptive flare loop and chromospheric ribbon determined from the breakout model are in agreement with observations of long-duration flares (Lynch et al. 2004).
1.3.5 The Loop-Loop Model

Some flares clearly show an interaction between two flare loops, which can most simply be interpreted as the outcome of a quadrupolar reconnection process. The early theory of Gold & Hoyle (1960) involved two magnetic loops with parallel currents. The energy comes from the reconnection of their poloidal fields. This theory was one of the first to make use of the geometry of magnetic loops, which are now known to dominate flare structures.

The quadrupolar photospheric source model was first proposed by Uchida (1980), in which the initial configuration consists of two parallel arcades. As in the model proposed by Forbes & Priest (1995), the principal driver is converging flows that push the two arcades together. The upward expanding field resulting from the subsequent reconnection accelerates the filament, which is supported by the X-point above the middle neutral line, to become a CME. The field lines below the X-point form the postflare arcades. Another 2D quadrupolar reconnection model was proposed by Liu et al. (2005) to describe flare effects on sunspots, on which detailed discussions are given in § 4.

Moore et al. (2001) proposed an eruption model for sigmoidal bipoles. The reconnecting two field lines are antisymmetrically skewed on each side of the neutral line, giving the overall morphology of the active region a sigmoid shape. The arms of the sigmoid in the core region are highly sheared and are prone to reconnection. This reconnection mechanism is based on the many observations of coronal sigmoids observed in soft X-ray wavelengths and their transformation to flare arcades after the eruption. This model will be discussed in detail in § 6, where a conspicuous EUV sigmoid was observed before an M8.0 flare.

Most magnetic reconnection models for flares discussed so far make no direct reference to the large-scale current. In fact, there is strong evidence that large-scale currents play a central role in the energy release in solar flares (e.g., Gary &
A theoretical model for 3D quadrupolar reconnection was developed by Melrose (1997) in terms of two interacting current-carrying loops. The flare energy is the magnetic energy released when the two current-carrying flux loops reconnect to form two new current-carrying loops between the original four footpoints. A fundamental assumption in this model is the conservation of the large-scale currents that flow through coronal loops and close below the photosphere. A consequence of this assumption is that magnetic reconnection processes only redistribute the current paths, while the net current flowing into and out of the corona remains fixed. Aschwanden et al. (1999) adopted Melrose’s model to estimate the maximum transferable flare energy using the following equation:

$$\Delta E \approx 10^{29.63} \left( \frac{r_2}{10^9 \text{ cm}} \right) \left( \frac{I_2}{10^{11} \text{ A}} \right)^2 \text{ ergs},$$

(1.11)

where $r_2$ and $I_2$ are the radius and the current of the large-scale field line involved in the reconnection, which can both be estimated based on observations (e.g., coronal images and vector magnetograms).

According to Melrose’s model, some favorable configurations for energy releases are when a positive spot is near a negative spot (so that one of the final loops is very small) and when the two initial loops are at a large angle to each other. The most direct observational test for the model is a comparison of the energy available in the model with the energy actually released in a subsequent flare. Yurchyshyn et al. (2000) estimated the energy release in the 1998 November 5 M8.4 flare using Equation 1.11 and found it consistent with that obtained from the Yohkoh observations. To observe the large-scale currents, besides the handedness or helicity as a direct signature, another less direct way is through the magnetic shear at the photosphere. The model results in the formation of a shorter loop, which implies that the current path moves closer to the photosphere. Qualitatively, provided that the current is conserved,
### Table 1.2  Summary of Major Flare/CME Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Driver Mechanism</th>
<th>Specialty</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CSHKP model</strong></td>
<td>Rising filament or expanding coronal arch</td>
<td>Two-ribbon flare &amp; multiwavelength observational features</td>
</tr>
<tr>
<td><strong>Emerging flux model</strong></td>
<td>Photospheric flux emergence</td>
<td>Haα/β surges</td>
</tr>
<tr>
<td>(Heyvaerts et al. 1977, Shibata et al. 1996c)</td>
<td></td>
<td>EUV/X-ray brightening and jets</td>
</tr>
<tr>
<td><strong>Flux rope catastrophic model</strong> (Forbes &amp; Priest 1995)</td>
<td>Photospheric converging flows</td>
<td>Fully analytical for flares &amp; CMEs</td>
</tr>
<tr>
<td><strong>Magnetic breakout model</strong></td>
<td>Photospheric shear motion</td>
<td>Leading theory for CMEs</td>
</tr>
<tr>
<td>(Antiochos 1998)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Loop-loop model</strong></td>
<td>Converging flow</td>
<td>CMEs</td>
</tr>
<tr>
<td>2D case (Uchida 1980 Forbes &amp; Priest 1995)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2D case (Liu et al. 2005)</td>
<td>Converging motion</td>
<td>Sunspot’s changes</td>
</tr>
<tr>
<td>3D case (Moore et al. 2001)</td>
<td>Converging/shearing motion</td>
<td>Sigmoids</td>
</tr>
<tr>
<td>3D case (Melrose 1997)</td>
<td>Rapid rising of current loops</td>
<td>Relates the large-scale currents</td>
</tr>
</tbody>
</table>

*See § 4 for details.*

Formation of a shorter current-carrying flux loop from a larger one should increase the shear at the photosphere level. Such an increase has sometimes been observed (e.g., Wang & Tang 1993; Wang et al. 1994; Schmieder et al. 1994; Wang et al. 2002b; Liu et al. 2005) and is not expected in other models for flares (see more discussions in § 7.1.2). Alternatively, 3D quadrupolar reconnection in large flares could also be driven by emerging current loops, which are particularly suitable to explain two-ribbon flares (Mandrini et al. 1993).
1.3.6 Summary of Solar Flare Models

Magnetic reconnection plays a key role in the modern theory of solar flares. Many flare models make specific applications of reconnection in various forms to solve the problems of triggering, energy release, and related dynamical effects. Five important scenarios for flares have been revisited, with each one successful in explaining certain aspects of flare problems. In Table 1.2, different flare/CME models are sorted according to their driver mechanisms and specialties. In retrospect, there have been many variants of flare models since the 1940s, most of which were inspired by specific events. Although it is most likely that not all flares can be explained by a single model, efforts have also been made by Shibata (1998, 1999) on constructing a grand unified model of both larger flares (e.g., long-duration events) and smaller flares (e.g., microflares and soft X-ray jets), produced by fast magnetic reconnection driven by plasmoid ejection.

1.4 Scientific Goal and Dissertation Outline

Defined by the United States National Space Weather Program, the term “space weather” refers to conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health. Solar flares are certainly among the most explosive and energetic fast processes known in the solar system, and are usually identified as the source and core region of CMEs and SEP events, which are directly responsible for the space weather that affects Earth. While solar flares are complex magnetic phenomena involving broad manifestations in various scales, the scientific goal of this dissertation is therefore to understand the triggering and development of flares by investigating flare magnetic

See http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons/index.html for a grand archive of flare and CME cartoons illustrating different scenarios (compiled by Hugh S. Hudson).
structure and associated activities in both the flare core (e.g., microflares, evolution of flare core magnetic field, and sigmoids) and large scale (e.g., remote flare brightenings, Moreton waves, type II and III radio bursts, and CMEs) through multiwavelength observations. Both statistical and case studies have been carried out. Whenever possible, every aspect of the observational results is carefully compared with a few well-cited theoretical flare/CME models to provide a critical test of the models.

This dissertation is arranged as follows, with §§ 3 and 4 concentrate on the flare core region, and §§ 5 and 6 investigate large-scale flare activities.

**Chapter 2** contains a description of many ground- and space-based instruments from which the data were obtained and analyzed in this dissertation. Data co-alignment schemes are also explained.

**Chapter 3** contains analysis of 12 microflares using hard X-ray, Hα, and magnetogram observations. The relatively simple microflare events help to build the general magnetic configuration of solar flares.

**Chapter 4** contains analysis of rapid change of white-light structure and magnetic property of δ sunspot associated with seven major flares, from which the first model actually describing flare effects on sunspots is proposed.

**Chapter 5** contains a case study of the splendid 2003 October 29 X10 flare, in which several large-scale flare manifestations, such as remote brightenings, type II radio bursts, and the CME as well as the flare core dynamics are analyzed and compared.

**Chapter 6** contains a case study of the eruption from a rarely observed EUV sigmoidal active region on 2005 May 13, in which the first ribbon-like hard X-ray
emission in the RHESSI era is reported and explained under the context of tether-cutting flare model for sigmoids.

Chapter 7 contains a summary and discussion of this dissertation work. Future efforts are also outlined.
CHAPTER 2

DATA SOURCES

As pointed out by Miller et al. (1997), “Flares are unique in the astrophysical realm for the great diversity of diagnostic data that are available”. Ground observation of solar flares in optical wavelengths was carried out since the 1930s. However, due to absorption by the Earth’s atmosphere, only visible light, some infrared bands, and radio waves can reach the ground. In order to observe X-ray and γ-ray emissions effectively, the measurement has to be taken at a height > 30 km. For soft X-ray and UV radiation detection, the height must be at least 100 km. Such research, thus, needs high altitude balloon, rocket, and satellite as the observation platforms. Therefore, solar multiwavelength observation, especially in the high energy range, is a new and developing discipline with the coming of space era. Divided according to the band of solar electromagnetic radiation, Table 2.1 listed the multiwavelength observations used in this dissertation and their data sources. The following sections give further information regarding each observational instrument.

2.1 Space Observation

Recent launch of the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI; Lin et al. 2002) instrument on 2002 February 5 makes a unique contribution to the study of solar flares. RHESSI is the sixth NASA SMall EXplorer (SMEX) mission and it has unprecedented spatial, temporal and energy resolution, as well as continuous coverage over a wide energy range in hard X-rays and γ-rays. The primary scientific objective of RHESSI is to understand particle acceleration mechanism during the explosive energy release process of solar flares. Compared with the imaging system of high energy radiation implemented in past space instruments (e.g., the
### Table 2.1  Multiwavelength Observation of Solar Flares

<table>
<thead>
<tr>
<th>Band</th>
<th>Range</th>
<th>Energy (eV)</th>
<th>Data Range</th>
<th>Source of Emission or Excitation</th>
<th>Position</th>
<th>Data Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ-ray</td>
<td>$\lambda &lt; 2.5$ pm</td>
<td>$E &gt; 0.5 \times 10^6$</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Hard X-ray</td>
<td>$\lambda \in [0.0025, 0.1)$ nm</td>
<td>$E \in (12.4, 500 \times 10^3)$</td>
<td>12.4–100 keV</td>
<td>Nonthermal bremsstrahlung</td>
<td>Footpoints, Loop tops</td>
<td>RHESSI</td>
</tr>
<tr>
<td>Soft X-ray</td>
<td>$\lambda \in [0.1, 10)$ nm</td>
<td>$E \in (10.124, 12.4)$</td>
<td>1.6–12.4 keV</td>
<td>Thermal bremsstrahlung</td>
<td>Loop tops</td>
<td>RHESSI &amp; SXI</td>
</tr>
<tr>
<td>EUV</td>
<td>$\lambda \in [10, 150)$ nm</td>
<td>$E \in (8.24, 124)$</td>
<td>17.1, 19.5 nm</td>
<td>Excitation by accelerated $e$</td>
<td>Low corona</td>
<td>TRACE, EIT</td>
</tr>
<tr>
<td>UV</td>
<td>$\lambda \in [150, 300)$ nm</td>
<td>$E \in (4.13, 8.24)$</td>
<td>160 nm</td>
<td>$e$ precipitation, conduction</td>
<td>Upper chromosphere</td>
<td>TRACE</td>
</tr>
<tr>
<td>Visible</td>
<td>$\lambda \in [300, 750)$ nm</td>
<td>$E \in (1.65, 4.13)$</td>
<td>500, 656.3 nm</td>
<td>$e$ precipitation, conduction</td>
<td>Photosphere, chromosphere</td>
<td>TRACE, BBSO, OSPAN</td>
</tr>
<tr>
<td>Infrared</td>
<td>$\lambda \in [0.75, 1000)$ $\mu$m</td>
<td>$E \in (0.00124, 1.65)$</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Radio</td>
<td>$f \leq 300$ GHz</td>
<td>$E \leq 0.00124$</td>
<td>$\sim$1–18 GHz</td>
<td>Mainly gyrosynchrotron</td>
<td>Coronal loops</td>
<td>OVSA, Ondřejov</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\sim$18–800 MHz</td>
<td>Mainly plasma emission</td>
<td>low corona and above</td>
<td>Culgoora, Potsdam, GBSRBS</td>
</tr>
</tbody>
</table>

SXI: Solar X-ray Imager (Hill et al. 2005) on board the Geostationary Operational Environmental Satellite (GOES) 12 satellite.
TRACE: Transition Region and Coronal Explorer (Handy et al. 1999).
EIT: EUV Imaging Telescope (Delaboudinière et al. 1995) on board the Solar and Heliospheric Observatory (Domingo et al. 1995).
BBSO: Big Bear Solar Observatory (Zirin 1970).
Ondřejov: Ondřejov Radiospectrograph (Jiřička et al. 1993).
Culgoora: Culgoora Radiospectrograph (Presstage et al. 1994).

Solar Maximum Mission [SMM] spacecraft, the Hinotori satellite, and the YOHKOH [SOLAR-A] satellite), the unique features of RHESSI are the use of high purity germanium detectors and temporal modulation Fourier-transform imaging technique. Thus RHESSI is providing the first hard X-ray imaging spectroscopy, the first high-resolution spectroscopy of solar γ-ray lines, the first imaging above 100 keV, and the first imaging of solar γ-ray lines. RHESSI’s imaging spectroscopy over a 3-keV to 17-MeV energy range provides energy resolution of ~1 keV, spatial resolution as high as 2.3″, and temporal resolution as short as tens of milliseconds. These parameters are extremely suitable for studying electrons with energies >~10 keV that are believed to contain a significant portion of the energy released in solar flares (Lin et al. 1998). Because of its unique role and tremendous contributions, in August 2003, RHESSI received the NASA Senior Review Panel’s highest rating of any of the 14 Sun-Earth Connection (SEC) missions.

The Solar X-Ray Imager (SXI; Hill et al. 2005) on board the Geostationary Operational Environmental Satellite (GOES) 12 satellite was launched on 2001 July 23 and monitors the Sun’s X-rays for the early detection of solar flares, CMEs, and other phenomena that impact the geospace environment by providing routine, nearly uninterrupted, full-disk, soft X-ray images of the solar corona. The SXI’s 6–60 Å bandpass makes it sensitive to the coronal temperature range of \(10^6–10^7\) K (e.g., the peak sensitivity of open filter position and polyimide thin filter used in this dissertation is 3.4 MK and 3.8 MK, respectively). The observing time cadence is ~1–4 minutes, and the pixel resolution is 5″. The improved SXI on board GOES 13 satellite was launched on 2006 May 24 and obtained its first light on 2006 July 6. Meanwhile, GOES satellites continuously provide soft X-ray light curves at 0.5–4 Å and 1–8 Å channels.

The Transition Region and Coronal Explorer (TRACE; Handy et al. 1999) has been producing excellent data since it started taking data on 1998 April 1. It is a
powerful instrument linking dynamic phenomena from the chromosphere, through the transition region to the corona. Several observing bands cover a huge temperature range (e.g., 5000 Å white-light channel — $4 \times 10^3$ to $6.3 \times 10^3$ K, 1600 Å C I/Fe II channel — $4 \times 10^3$ to $1 \times 10^4$ K, 171 Å Fe IX/X channel — 0.2 to 2 MK, 195 Å Fe XII/XXIV channel — 0.5 to 2 MK, 284 Å Fe XV channel — 1.2 to 4 MK). TRACE data have a pixel resolution of 0.5$''$ and a cadence of seconds to minutes. TRACE usually covers a large field of view ($510'' \times 510''$) and a typical observing sequence consists of 1600 Å and 171 Å observations to cover both low and high temperatures.

Launched on 1995 December 2, the Solar and Heliospheric Observatory (SOHO; Domingo et al. 1995) is a space-based observatory, viewing and investigating the Sun from its deep core to the domain of the solar wind. The Michelson Doppler Imager (MDI; Scherrer et al. 1995) on board SOHO mainly obtains full-disk dopplergrams for the investigation of solar oscillations. In addition, MDI provides full-disk longitudinal magnetograms with a cadence of 1 minute and an image scale of $\sim 2''$ for a large number of observing days. Intensitygrams with $\sim 1$ hour cadence are also obtained. The EUV Imaging Telescope (EIT; Delaboudinière et al. 1995) on board SOHO provides sensitive temperature diagnostics in the range from $6 \times 10^4$ to $3 \times 10^6$ K (e.g., 171 Å and 195 Å channels used in this dissertation peak at 1.3 MK and 1.6 MK, respectively). The cadence of EIT image is about 15 minutes, with a pixel resolution of $\sim 2.6''$ (full-resolution mode) or $\sim 5.3''$ (half-resolution mode). The Large Angle and Spectrometric Coronagraph (LASCO; Brueckner et al. 1995) on board SOHO is a set of three coronagraph telescopes that record white-light images of the solar corona (i.e., C1 coronagraph — $\sim 1.1–3$ $R_\odot$, C2 coronagraph — $\sim 1.5–6$ $R_\odot$, and C3 coronagraph — $\sim 3.5–30$ $R_\odot$) and is the primary data source for tracking CMEs.

Future major space solar missions include the Solar Dynamic Observatory (SDO) and the newly launched Hinode (Solar-B), from which continuous series of
high-precision vector magnetograms, Dopplergrams, and filtergrams with sub-arcsec resolution are expected.

2.2 Ground-based Observation

Big Bear Solar Observatory (BBSO; Zirin 1970), one of two observatories in the United States capable of making the ground-based high-resolution observations to support the RHESSI mission, is well known for its high resolution Hα full-disk system, which uses a 2 K by 2 K 14-bit camera system, with a cadence of one minute. In addition, BBSO provides high resolution Hα observations with its 10-inch and 26-inch telescopes in the line centers and wings. The cadence is \(~10\) s and the spatial resolution is \(~0.5''\). Meanwhile, the recent improved new digital vector magnetograph (DVMG) system provides high-resolution (\(~0.6''\) per pixel) line-of-sight and vector magnetograms, which are crucial for studying the structure and evolution of magnetic fields in flaring active regions. BBSO is currently installing a new telescope that will offer a significant improvement in ground-based high angular resolution capabilities.

The Marshall Space Flight Center (MSFC) Vector Magnetograph Facility (West et al. 2002) also obtains vector magnetograms for certain observing days. The field-of-view of the instrument is \(7' \times 5'\) and the pixel resolution is \(1.28''\).

The Optical Solar Patrol Network (OSPA; Neidig et al. 1998), formerly known as the Improved Solar Observing Optical Network (ISOON), is an automated patrol telescope imaging the Sun in multiple wavelengths at rapid cadence. OSPAN acquires solar images at the Hα line and off-bands (once per minute), in continuum (once every ten minutes), and in line-of-sight magnetic fields with a pixel resolution of \(~1''\) (full disk mode) or \(~0.3''\) (high resolution mode).

Radio data were observed with multiple facilities. All the data are digitally recorded. The Owens Valley Solar Array (OVSA; Gary & Hurford 1990), the only solar dedicated radio observatory in the United States, provides high spatial,
temporal, and spectral resolution microwave observations of the solar atmosphere in the $\sim 1$–$18$ GHz frequency range. Radio dynamic spectra were also obtained from the Ondřejov Radiospectrograph (Jiřička et al. 1993) (0.8–4.5 GHz with 0.1 s time resolution), the Culgoora Radiospectrograph (Prestage et al. 1994) (18 MHz–1.8 GHz with 3 s time resolution), the Tremsdorf Solar Radio Observatory of the Astrophysical Institute (AI) Potsdam (Mann et al. 1992) swept-frequency spectrographs (40–90, 100–170, 200–400, and 400–800 MHz with 0.1 s time resolution), and the Green Bank Solar Radio Burst Spectrometer (GBSRBS; White et al. 2006) (18–70 MHz with 1 s time resolution).

2.3 Data Co-Alignment

Undoubtedly, data coordination among the multiwavelength observations is crucial for the science output while is a challenging task. Since different instrument has different accuracy of pointing, the rules/steps below were followed throughout this dissertation.

1. In order to have a spatial resolution of $2.3''$ (for the finest grid) and to precisely correlate with observations at other wavelengths, RHESSI implemented two precise aspect systems, the Solar Aspect System (SAS) and the Roll Angle System (RAS). The SAS yields sub-arc sec knowledge of the radial pointing with respect to the Sun center and the RAS provides precise knowledge on the roll angle of the rotating spacecraft ($\sim 15$ rpm). Thus the combined SAS/RAS aspect system allows correcting and interpolating the roll angles that provides a precision of $< 0.4''$ (pitch and yaw) and $< 1'$ (roll) (Fivian et al. 2002). No further pointing correction was applied to RHESSI data at the current stage.

2. SOHO also has very strict pointing requirements to support the helioseismology experiments, despite the fact that the roll angle is known to no better than $1^\circ$ that gives an error of up to $15''$ near the limb ($< 0.3''$ for RHESSI). Because of
its good pointing stability, SOHO was used as a reference of pointing information in order to facilitate the data co-alignment process.

3. Thus, full-disk Hα images were aligned with the full-disk SOHO/MDI magnetograms by limb fitting and matching plage areas. TRACE images were first calibrated using the standard procedures provided by the TRACE team. TRACE EUV and white-light images were further aligned with SOHO EUV images and SOHO/MDI intensitygrams by cross correlation, respectively. Similar technique was also used to register other ground-based observations (e.g., magnetograms) with SOHO. TRACE 1600 Å images were then aligned with TRACE white-light images relying on the common sunspot features.
CHAPTER 3

STUDIES OF MICROFLARES IN RHESSI HARD X-RAY, BBSO Hα, AND MDI MAGNETOGRAMS

As a starting point of investigating diverse signatures and magnetic properties of the flare phenomena, microflares with relatively simple magnetic configuration are explored first. A study of the morphology of 12 microflares jointly observed by RHESSI in the energy range from 3 to 15 keV and by BBSO at the Hα line is presented. They are A2–B3 events in GOES classification. From their time profiles, it is found that all of these microflares are seen in soft X-ray, hard X-ray, and Hα wavelengths, and their temporal evolution resembles that of large flares. Co-aligned hard X-ray, Hα and magnetic field observations show that the events all occurred in active regions and were located near magnetic neutral lines. In almost all of the events, the hard X-ray sources are elongated structures connecting two Hα bright kernels in opposite magnetic fields. These results suggest that, similar to large flares, the X-ray sources of the microflares represent emission from small magnetic loops and that the Hα bright kernels indicate emission at footpoints of these flare loops in the lower atmosphere. Among the 12 microflares, five events are included that are clearly associated with type III radio bursts as observed by the radio spectrometer on board Wind. Spectral fitting results indicate the nonthermal origin of the X-ray emission at over ∼10 keV during the impulsive phase of all the events, and the photon spectra of the microflares associated with type III bursts are generally harder than those without type III bursts. TRACE observations at EUV wavelengths are available for five events in the list, and in two of these, coincident EUV jets are clearly identified to be spatially associated with the microflares. Such findings suggest that some

1This chapter is based on the following paper:

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microflares are produced by magnetic reconnection, which results in closed compact loops and open field lines. Electrons accelerated during the flare escape along the open field lines to interplanetary space.

3.1 Introduction

Various kinds of small-scale dynamic structures are believed to be very important for understanding the detailed mechanisms of energy and mass transport in the Sun. Microflares are among the most interesting subjects. Hard X-ray microflares, tiny bursts with a few times $10^{26}$ to $\sim 10^{28}$ ergs carried by electrons with energy greater than 20 keV, were discovered with a balloon-borne instrument to occur at a rate of about 1 per 5 minutes near solar maximum (Lin et al. 1984). The transient release of energy in these hard X-ray events is basically nonthermal in character. Since then, there have been many attempts to identify similar events in different wavelengths. Hα counterparts of microflares were identified by Canfield & Metcalf (1987). They found that, at the times of hard X-ray microflare bursts, very small flares were observed in Hα with a size of several arcseconds in the vicinity of previous or subsequent flares of larger scales. Evidence for the existence of nonthermal electrons has been obtained from radio (Gary & Zirin 1988; Gopalswamy et al. 1994; White et al. 1995; Gary et al. 1997; Nindos et al. 1999) as well as from hard X-ray observations. Using data from Yohkoh Soft X-ray Telescope (SXT; Tsuneta et al. 1991) and Hard X-ray Telescope (HXT; Kosugi et al. 1991), Nitta (1997) found impulsive hard X-ray (14–23 keV) emission during the rise of soft X-rays in a large class of X-ray transient brightenings, or microflares, that occurred in an active region. Meanwhile, imaging observations at transition-region lines have been exploited to search for microflares in the UV and EUV wavelengths. Porter et al. (1987) determined that the UV brightenings in the quiet Sun observed in the C IV line by SMM were smaller than 6″, and the more long lived ones were coincident with soft X-ray microflares. Berghmans,
McKenzie, & Clette (2001) compared active region transient brightenings observed in very high cadence image sequences with the Yohkoh SXT, the SOHO/EIT, and TRACE, and found that the strongest EUV brightenings were counterparts of soft X-ray microflares.

With imaging observations, the magnetic properties of microflares have been extensively studied. Porter et al. (1987) found that the UV brightenings were located near neutral lines of the magnetic network and suggested that these events were microflares occurring in small magnetic loops, similar to microflares in active regions. Wang et al. (1999) studied 70 UV microflares in an active region observed at the C\text{IV} line by TRACE. They found two kinds of microflares: impulsive events with a lifetime of a few minutes that appeared to occur in a single magnetic polarity, and persistent events with a timescale of about half an hour or longer that were located across the magnetic neutral lines. Shimizu et al. (2002) studied magnetic and H\alpha signatures associated with soft X-ray microflares. Their results showed that most of the events were in the forms of multiple or single loop structures.

The RHESSI instrument provides uniquely high sensitivity in the energy range from $\sim$3 to 15 keV, together with $\sim$1 keV FWHM spectral resolution and simultaneous imaging down to 2.3′′. Moreover, when both RHESSI shutters (Lin et al. 2002) are out (i.e., open telescope mode), RHESSI observations from $\sim$3 to 15 keV are $\sim$14 to $\geq$130 times more sensitive than other instruments (Krucker et al. 2002) and thus can provide new information on low-level energy releases. The first RHESSI results on microflare imaging are presented by Krucker et al. (2002) and Benz & Grigis (2002). Meanwhile, BBSO provides high-resolution full-disk H\alpha observations in the line center with 1″ pixel resolution and 1 minute cadence. Thus, the combined BBSO/RHESSI microflare observations is unprecedented in studying the fine spatial and temporal structure and magnetic morphology of microflares with high resolution,
which will lead to a better understanding of energy transport process from the corona to the chromosphere.

For selected dates, when RHESSI is operating in open telescope mode, hard X-ray microflares in Hα are expected to be identified so as to study statistical and magnetic properties of microflares. Here the temporal characteristics of microflares in both hard X-ray and Hα are explored and this study concentrates on their morphology. When available, TRACE Fe xii 195 Å images are also used to understand the coronal environment of microflares.

3.2 Observations and Data Processing

In this chapter, a study on the morphology of microflares that were jointly observed by RHESSI in X-rays of ≥ 3 keV and by BBSO at the Hα line is presented. Microflares are selected from the RHESSI event list compiled by the RHESSI team with the following criteria: (1) events were observed when RHESSI was operating in open telescope mode; (2) they have relatively low peak flux, namely, less than 100 counts s\(^{-1}\) per detector in the 12–25 keV range; and (3) the incremental soft X-ray flux observed by GOES at 1–8 Å is below C1.0 level. With these criteria, a total of 800 microflare events are found from 2002 May to 2002 October, about a third of which were observed during the BBSO observing window. Here a set of 12 microflares that were jointly observed by RHESSI and BBSO are investigated. Note that the selection of the 12 events out of hundreds is not entirely random, because some events that are associated with type III bursts are included in order to investigate the morphologies and magnetic properties of type III–related microflares.

Standard RHESSI software and calibration procedures updated to 2003 early September were used to derive X-ray images. A full-disk image of each microflare was made with a resolution of 32″ to obtain the centroid position. Then, an image of each microflare around the flare position was reconstructed with ∼8.4″ resolution,
using RHESSI grids 3–9 (Hurford et al. 2002). Cleaned images are obtained with a cleaning beam of \( \sim 10'' \). Each image was made around the peak of the flare with \( \geq 60 \) s integration.

Photospheric magnetograms from MDI were also obtained to study the magnetic morphology of the microflares. The alignment between RHESSI X-ray images and MDI magnetograms was done by using the pointing information from the two instruments. Considering that the MDI roll angle is not known to better than 1\( ^\circ \), which gives an error of up to 15'' near the limb, the accuracy of alignment between RHESSI and MDI is estimated to be \( \sim 7'' \) on average for the present 12 events. The full-disk H\( \alpha \) images were then registered with the full-disk MDI magnetograms by limb fitting and matching plage areas. The accuracy of alignment between MDI magnetograms and BBSO H\( \alpha \) images is within 5''. As most microflares are compact sources in hard X-rays and H\( \alpha \) and in both wavelengths full-disk images were acquired, identification of microflares in these two wavelengths is straightforward. H\( \alpha \) movies were also obtained in order to confirm the brightenings coincident with the RHESSI bursts.

Spectral fits are performed to investigate the nonthermal properties in these microflares. The energy bin width is set to 1/3 keV, the standard finest binning\(^2\), and background is selected from the preflare and/or postflare data to be subtracted from the data taken during the flare.

### 3.3 Results

Table 3.1 lists the properties of the microflare events that were analyzed and presented in this study. For each of these events, soft X-ray and H\( \alpha \) counterparts were identified from their light curves, which exhibit emission peaks coincident with RHESSI bursts.

Table 3.1  Microflare Events

<table>
<thead>
<tr>
<th>No.</th>
<th>Date</th>
<th>AR</th>
<th>GOES level(^a)</th>
<th>Peak Time(^b) (UT)</th>
<th>Peak Count Rate(^b) (s(^{-1}) per detector)</th>
<th>Duration(^b) (s)</th>
<th>Power-law Index(^c) ((\gamma))</th>
<th>Type III</th>
<th>Jet(^d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1............</td>
<td>Jun 25</td>
<td>0008</td>
<td>A2.3</td>
<td>17:09:38</td>
<td>14</td>
<td>132</td>
<td>-3.3</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>2............</td>
<td>Jun 26</td>
<td>0008</td>
<td>B1.4</td>
<td>17:17:18</td>
<td>22</td>
<td>204</td>
<td>-4.5</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>3............</td>
<td>Jun 26</td>
<td>0008</td>
<td>B1.6</td>
<td>20:07:30</td>
<td>24</td>
<td>284</td>
<td>-4.2</td>
<td>faint(^e)</td>
<td>yes</td>
</tr>
<tr>
<td>4............</td>
<td>Jul 15</td>
<td>0030</td>
<td>A6.6</td>
<td>16:35:30</td>
<td>16</td>
<td>32</td>
<td>-4.5</td>
<td>storm(^f)</td>
<td>...</td>
</tr>
<tr>
<td>5............</td>
<td>Jul 15</td>
<td>0030</td>
<td>B2.1</td>
<td>18:01:54</td>
<td>20</td>
<td>348</td>
<td>-6.0</td>
<td>storm(^f)</td>
<td>...</td>
</tr>
<tr>
<td>6............</td>
<td>Jul 15</td>
<td>0030</td>
<td>A2.2</td>
<td>19:31:22</td>
<td>24</td>
<td>36</td>
<td>-4.1</td>
<td>storm(^f)</td>
<td>...</td>
</tr>
<tr>
<td>7............</td>
<td>May 08</td>
<td>9934</td>
<td>B1.1</td>
<td>17:46:38</td>
<td>30</td>
<td>84</td>
<td>-5.0</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>8............</td>
<td>May 10</td>
<td>9934</td>
<td>B2.1</td>
<td>17:07:10</td>
<td>18</td>
<td>340</td>
<td>-5.7</td>
<td>no(^g)</td>
<td>no</td>
</tr>
<tr>
<td>9............</td>
<td>Jun 16</td>
<td>9991</td>
<td>A8.1</td>
<td>21:06:30</td>
<td>15</td>
<td>108</td>
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<tr>
<td>10..........</td>
<td>Jun 30</td>
<td>0017</td>
<td>B3.1</td>
<td>22:12:50</td>
<td>52</td>
<td>340</td>
<td>-4.7</td>
<td>yes</td>
<td>...</td>
</tr>
<tr>
<td>11..........</td>
<td>Aug 19</td>
<td>0069</td>
<td>A7.6</td>
<td>20:32:34</td>
<td>52</td>
<td>(\sim) 120</td>
<td>-4.2</td>
<td>yes</td>
<td>...</td>
</tr>
<tr>
<td>12..........</td>
<td>Oct 22</td>
<td>0162</td>
<td>B3.0</td>
<td>21:19:22</td>
<td>32</td>
<td>224</td>
<td>-5.6</td>
<td>no</td>
<td>...</td>
</tr>
</tbody>
</table>

\(^a\) Refer to incremental flux by GOES at 1–8 Å.
\(^b\) From RHESSI flares list; refer to 12–25 keV energy range.
\(^c\) Spectral fits are performed at the peak of the microflares.
\(^d\) Jets are identified by making TRACE movies in 195 Å wavelength when data are available.
\(^e\) Starts at low frequencies (~1 MHz), slightly late relative to hard X-rays.
\(^f\) During the type III storm.
\(^g\) Small type III only in the decay of X-rays.
Figure 3.1  Event 2. Top: Light curve observed by GOES 10 in the 1–8 Å band (1.6–12.4 keV) of soft X-rays. Bottom: Light curves observed in Hα (top black line with diamonds) and X-rays at 3–8 keV (gray line) and 8–15 keV (bottom black line) by RHESSI with background subtracted. For a clearer representation, the 8–15 keV time profile is multiplied by a factor of 2. The vertical dashed lines show the integration time intervals for the RHESSI spectra shown in Figure 3.6.

They are A2–B3 class events by GOES classification, and the relative increase in Hα intensity is about 3%–5% above the preflare background. Although small, these events can be well observed by RHESSI at above 3 keV. Furthermore, five events in the present study are clearly associated with type III radio bursts.

Compared with large flares, these microflare events are short-lived, with a lifetime ranging from 30 s to 5 minutes in hard X-rays, as well as in Hα. Apart from this, the energy-dependent temporal evolution of the microflares is very similar
to large flares. As an example, Figure 3.1 shows the light curves of a typical microflare (event 2) observed in Hα at BBSO, soft X-rays at 1–8 Å by GOES, and X-rays at 3–8 and 8–15 keV by RHESSI. Note from previous studies (Krucker et al. 2002) that the 3–8 and 8–15 keV energy ranges roughly correspond to the thermal and nonthermal regimes, respectively. The figure shows that emissions at higher energies evolve more rapidly than those at lower energies. The hard X-rays arise during the rise of the soft X-rays and exhibit an impulsive rise and fast decay. The Hα emission mostly rises together with hard X-rays and decays more slowly, and the soft X-rays exhibit a smooth and slow evolution. These are general characteristics found for all of the microflares presented in this study and are often observed in large flares as well (e.g., Kurokawa, Takakura, & Ohki 1988). Some events exhibit multiple peaks in hard X-rays that are also observed in Hα suggesting several episodes of energy release at short timescales.

Figures 3.2 and 3.3 show the morphologies and magnetic properties of the 12 events. The X-ray images were obtained at two energy ranges, i.e., 3–8 and 8–15 keV, and were superposed on Hα images and magnetograms. For almost all events, the hard X-ray sources in the two energy ranges are clean elongated structures of 20″–30″ in size that overlap with each other. With the limited spatial resolution, it is difficult to distinguish fine structures at different energies. Sometimes, the sources appear nearly identical at both energy ranges (as in event 4). But sometimes (as in event 2; see also Figure 3.5), footpoints are observed at higher energies and an in-between loop structure at lower energies, which is consistent with the standard flare morphology. When comparing the hard X-ray sources with Hα images, it is seen that in all of the events, Hα images show two or more patches that brightened during the RHESSI bursts, and the hard X-ray structure usually connects two Hα bright patches. Furthermore, it is found that all of these events occurred in active regions near magnetic neutral lines, and the two Hα patches at the two ends of the X-ray
Figure 3.2 (1), (2), (3), (4), (5) and (6): 3–8 keV hard X-ray contours on SOHO/MDI magnetograms; (1a), (2a), (3a), (4a), (5a) and (6a): 8–15 keV hard X-ray contours on Hα images. The levels of RHESSI contours are 30%, 50%, 70%, and 90%. Event 6 does not show 30% level. The boxes indicate those Hα patches that brightened during the times of the microflares.
Figure 3.3  Same as Figure 3.2, but for events 7, 8, 9, 10, 11 and 12. Both the 3–8 and 8–15 keV energy channels are shown for event 8 at hard X-ray impulsive phase (8) and decay phase (8a).
source are usually located in opposite magnetic fields. This configuration suggests that these microflare events, like large flares, are looplike structures produced by magnetic reconnection at the neutral lines, with the X-ray source representing the flaring loop and the Hα brightenings reflecting the chromospheric emission at the footpoints of the flare loop.

It should be noted that a microflare is usually not a single isolated event. By examining the Hα movies with a large field of view, concurrent Hα brightenings were found in extended neighboring regions in single magnetic polarities for 6 out of 12 events. However, hard X-ray sources are only located in very confined structures crossing magnetic neutral lines.

Observations also indicate that microflares tend to recur in some active regions. Figure 3.2 shows a group of flares (events 1–3) occurring consecutively from June 25 to 26 at nearly the same location in NOAA AR 0008 and with like morphologies. These can be regarded as homologous flares. Events 4–6 on July 15 make another group of flares occurring close to each other in NOAA AR 0030. Such observations suggest that certain active regions may be more productive of microflares than other regions.

Among the 12 microflares studied in this study, five events are clearly associated with type III radio bursts, suggesting that, in these events, electrons escape the solar atmosphere along open field lines. Figure 3.4 shows an example of a microflare (event 2) and its associated type III burst. While most of the type III bursts start with the rise or peak of X-rays, a small type III is found in the decay of X-rays in event 8 in Figure 3.3. Simultaneously, a small hard X-ray bright point (in panel 8a) is found to appear just below the main source. This hard X-ray bright point does not show up in the rise and peak of hard X-rays (in panel 8). Although the Hα image is not good on this day because of the poor seeing, a small brightening is still detected from the time-lapse movie to be spatially associated with this small hard X-ray bright point.
Figure 3.4 GOES/RHESSI/Wind plots of event 2, which shows a good relation between X-ray bursts and type III radio burst.

and the type III burst. The three events in July took place during the type III storm, which makes it difficult to identify their association with type III bursts.

Furthermore, five events have the corresponding TRACE 195 Å observations, and jets are clearly identified from the time-lapse movie to accompany two of them (Table 3.1). Figure 3.5 shows the snapshot of the EUV jet in event 2 adjacent to the flare observed at X-ray, Hα and EUV wavelengths. These observations suggest the scenario that magnetic reconnection occurs between a set of open field lines and underlying bipolar structures. This forms a compact flare loop seen in X-rays and Hα
Figure 3.5  Event 2: 3–8 keV (gray) and 8–15 keV (black) hard X-ray contours on TRACE 195 Å image. The arrow points out the location of the associated jet.

and another set of open field lines along which both accelerated electrons and heated plasmas are ejected outward.

To explore the nonthermal properties of the microflares, their X-ray photon spectra observed by RHESSI are also fit using the SPEX software package. The spectral fitting is conducted in the energy range of 3–20 keV with the preflare and/or postflare background subtracted. In Figure 3.6, the result of spectral fitting is shown for event 2 as an example. Four short time ranges are analyzed, each spanning ~20 s, as shown in Figure 3.1. For the first two intervals taken at the rise and immediately after the peak (decay 1), the photon spectrum can be best fitted with a thermal component and a nonthermal component that has a power-law distribution
Figure 3.6  Spectra during the impulsive phase and the decay phases of the microflare event 2 (fitted time intervals shown in Figure 3.1). The rise and immediate decay phase (decay 1) are fitted with both a thermal contribution (dotted line) and a nonthermal component (dashed line), and the following decay (decay 2 and 3) with a thermal component only. The unit of EM is $10^{46}$ cm$^{-3}$. The power-law index is set to $-1.5$ below the cutoff energy, which is fitted to be $\sim 10$ keV. The bump at 6–7 keV is the iron-line feature. The shown curves give the range fitted; it does not fit the emission at $\sim 3$ keV well, and values above $\sim 20$ keV (for rise and decay 1) and $\sim 10$ keV (for decay 2 and 3) are dominated by noise.
The power-law index $\gamma$ of the photon spectrum is 4.7 and 4.9 for the two intervals, respectively, and the nonthermal contribution is an order of magnitude greater than the thermal contribution at energies over $\sim 10$ keV. These confirm the nonthermal origin of the X-ray emission at over $\sim 10$ keV during the impulsive phase. The spectra in the following two intervals during the decay phase are fitted with a thermal component only. Throughout the flare impulsive phase, the temperature from the fit is over 10 MK, and the EM is about $10^{46}$ cm$^{-3}$. Using the temperature and EM from the spectral fit and the size of the flare measured from the hard X-ray image, the thermal energy of this flare is estimated to be $\sim 10^{28}$ ergs.

Similar results of spectral fitting are obtained for other microflare events. Table 3.1 gives the power-law index of the photon spectrum for each of the 12 events during the peak of the 12–25 keV emission. The spectra of all of the 12 microflare events during the impulsive phase have a nonthermal component, i.e., the spectra cannot be well fitted using only a thermal model. The fitting shows that, at energies over 10 keV, the nonthermal component is predominant over the thermal contribution, and the power-law index of the nonthermal component ranges from 3 to 6. The preliminary fitting results further suggest that the spectra of the microflares associated with type III bursts are generally harder than those without type III bursts. In particular, the mean value of $\gamma$ is $4.0 \pm 0.6$ for the five events clearly associated with type III bursts and $5.4 \pm 0.4$ for the three events without type III bursts.

### 3.4 Conclusions of This Chapter

The recent successful launch and operation of the RHESSI satellite and the upgraded magnetograph system and Hα telescope at BBSO allow for the first time the detailed study of the locations, spectra, and magnetic properties of microflares with high resolution, which will advance the understanding of the energy transport process from the chromosphere to the corona. This chapter presents a study on the morphology
of 12 microflares that occurred between 2002 May and October. It is found that all of these small impulsive events are located near well-defined magnetic neutral lines in active regions. The X-ray sources are usually looplike structures connecting two Hα footpoints located in magnetic fields of opposite polarities. The spectral analysis shows that in these events X-rays over \( \sim 10 \) keV are emitted by nonthermal electrons. Moreover, five microflares presented in this study are clearly associated with type III radio bursts, indicating that in these events electrons escape along open field lines. These type III-associated microflares also seem to have a harder nonthermal hard X-ray spectra than other events. With available TRACE data, EUV jets were observed in some events to be spatially associated with the hard X-ray bursts. The findings of looplike hard X-ray sources, type III bursts, and EUV jets suggest a scenario of magnetic reconnection between open field lines and underlying bipolar structures.

One of the most interesting issues stemming from this study is the role of microflares in heating the corona. There are several aspects that can be addressed. First is the spatial distribution of microflares. Like large flares, all the microflares that have been mapped are located in active regions. This subject should be further investigated with more statistical significance. Second is the transport of mass and energy from the lower atmosphere to the corona. The present results show that the microflares closely resemble large flares and are most likely produced by magnetic reconnection in the low corona. A certain portion of these events may involve large-scale or open field lines along which mass and energy can be transported to the corona. To evaluate the efficiency of coronal heating by microflares, future studies should estimate the frequency of the events and compute the energy released in the microflares. Extended studies should also be made on whether there is a difference in the morphologies and magnetic properties between microflares associated with type III bursts and those without type III bursts.
CHAPTER 4

RAPID CHANGE OF $\delta$ SUNSPOT STRUCTURE ASSOCIATED WITH SEVEN MAJOR FLARES

It is generally accepted that the energy released in solar flares is stored in stressed magnetic fields. Thus it is rational to find that a large fraction of major flares occur in active regions that exhibit a $\delta$ configuration, which is the most magnetically complicated type of sunspot classification. The formation and disintegration of $\delta$ configurations is very important in understanding the evolution of photospheric magnetic fields, which are now known to be closely related to flare energetics. In this chapter\(^1\), the relationship between the change in $\delta$ spot structures and associated major flares is studied. A new observational result is presented that part of penumbral segments in the outer $\delta$ spot structure decay rapidly after major flares; meanwhile, the neighboring umbral cores and/or inner penumbral regions become darker. Using white-light observations from TRACE, the short-term evolution of $\delta$ spots associated with seven major flares is analyzed, including six X-class flares and one M-class flare. The rapid changes, which can be identified in the time profiles of white-light mean intensity are permanent, not transient, and thus are not a temporal result of flare emission. The co-aligned magnetic field observations obtained with MDI show substantial changes in the longitudinal magnetic field associated with the decaying penumbrae and darkened central areas. For two events for which vector magnetograms were available, it is found that the transverse field associated with the penumbral decay areas decreased while it increased in the central darkened regions. Both events also show an increase in the magnetic shear after the flares. For all

\(^1\)This chapter is based on the following paper:
the events, it is found that the locations of penumbral decay are related to flare emission and are connected by prominent TRACE postflare loops. To explain these observations, a reconnection picture is proposed in which the two components of a δ spot become strongly connected after the flare. The penumbral fields change from a highly inclined to a more vertical configuration, which leads to penumbral decay. The umbral core and inner penumbral region become darker as a result of increasing longitudinal and transverse magnetic field components.

4.1 Introduction

The scientific term δ sunspot was introduced by Künzel (1960) and is defined as umbrae of opposite polarity lying in a common penumbra. The δ spots have been known as the most active spot configuration. For over three decades, the morphological evolution of δ configurations and their strong connection to intensive flare activity have been widely studied by many authors (Zirin & Tanaka 1973; Tang 1983; Hagyard et al. 1984; Zirin & Liggett 1987; Zirin 1988; Tanaka 1991; Wang 1992; Tang & Wang 1993; Zirin & Wang 1993; Gaizauskas et al. 1994, 1998; Martínez Pillet et al. 1994; Schmieder et al. 1994; Shi & Wang 1994; Li et al. 1999; Sammis et al. 2000; Liu & Zhang 2001, 2002; Kurokawa et al. 2002). Using 18 years of observations at BBSO, Zirin & Liggett (1987) summarized the development of δ spots and classified them in three categories, concluding that δ groups are responsible for almost all great flares. Schmieder et al. (1994) made precise measurements of spot motions in active region AR 6659 during 1991 June to understand the fragmentation of the main δ spot group with time. They found that this fragmentation leads to a continuous restructuring of the magnetic field pattern, while rapid changes are evidenced because of fast new flux emergence. The first process leads to sheared field lines, and the second process triggers the release of the stored free magnetic energy.
At the same time, solar physicists have been studying flare-related changes in photospheric magnetic fields for nearly four decades (Severny 1964; Zvereva & Severny 1970; Moore et al. 1984; Kosovichev & Zharkova 1999, 2001; Wang & Tang 1993; Wang et al. 1994), which would provide crucial information as to how an active region stores and releases its energy. However, the role of photospheric magnetic fields is still far from being fully understood and is an area of ongoing research. Only recently have rapid and permanent changes of photospheric magnetic fields been observed to be associated with large solar flares (Kosovichev & Zharkova 2001; Spirock et al. 2002; Wang et al. 2002a,b, 2004b; Yurchyshyn et al. 2004). These studies show that high cadence ($\sim 1$ minute) and high spatial resolution ($\sim 1''$–$2''$) magnetic field observations reveal sudden flux changes associated with X-class and M-class flares.

Other than doing polarization measurements of magnetograms, Deng et al. (2005) first tried a more straightforward approach focusing on changes of the white-light structure in flaring active regions. Since most great flares are associated with a $\delta$ configuration, they noticed that an entire $\delta$ spot region was undergoing rapid change when they studied the X2.3 flare in active region AR 9026 on 2000 June 6. In particular, two penumbral segments decayed rapidly right after the flare. Wang et al. (2004a) studied two more X-class flares that occurred in active region AR 10486 and found very similar penumbral decays. It is speculated that this phenomenon may not be restricted to specific active regions; thus, it is only natural to look for similar signatures associated with other flares. Note that the selection of the seven events in this study is not entirely random, because TRACE only has a partial view of the Sun, and its white-light observation is not available for every flare activity. In addition to the observational results, a reconnection picture for $\delta$ spots is proposed to interpret the findings. White-light difference images between postflare and preflare states are focused on to illustrate the penumbral decay and darkening of neighboring umbral cores and inner penumbral region, which will subsequently be related to flare
energetics. The evolution of $\delta$ spots that is presented in the present study is an impulsive change, which is closely related to major flares. Therefore, it is quite different when compared to the studies of long-term evolution of $\delta$ spots.

The data used in this study are introduced in § 4.2 and subsequently the penumbral decay associated with each event is described in § 4.3. For the X10 flare on 2003 October 29 and X5.3 flare on 2001 August 25, a more detailed analysis is given using vector magnetograms. In § 4.4 all the findings are summarized and a Sweet-Parker type (Sweet 1958; Parker 1963) reconnection picture for $\delta$ spots is proposed based on the observational results.

4.2 Observation and Data Processing

The key presented data are TRACE 5000 Å white-light images. Other data include TRACE Fe\textsc{i}x/x 171 Å and Fe\textsc{xii}/xxiv 195 Å images, full-disk magnetograms by SOHO/MDI, vector magnetograms obtained at MSFC and BBSO, and hard X-ray time profiles and images of RHESSI.

Standard TRACE calibration procedures were used to process the TRACE data. Since SOHO has very strict pointing requirements to support its helioseismology experiments, TRACE white-light images were further aligned with respect to SOHO/MDI intensitygrams. The penumbral decay associated with each event was then identified by carefully examining the morphological evolution of the flare active region. First, one white-light image near the peak time of the flare was chosen, and white-light images from well before to well after the flare were differentially rotated to that time using standard procedures in SolarSoftWare (SSW; Freeland & Handy 1998). Then movies were made using the co-aligned white-light images and were able to unambiguously trace the evolution of major spots. Meanwhile, SOHO/MDI offers high temporal resolution (1 minute) full-disk magnetogram data with $\sim$4\" spatial resolution. Combined with the corresponding TRACE white-light images
with 1″ spatial resolution and typical temporal resolution of 1.5–2.5 minutes, the magnetic polarity and position of a spot can be easily identified, and the time profiles of intensity and magnetic flux of a specific region can be calculated. TRACE also provides unprecedented observations of the outer solar atmosphere, thus enabling one to observe a corona that is extremely dynamic and full of flows and wave phenomena. The rapidly evolving loops generally outline the coronal magnetic field. Therefore, coronal images in TRACE 171 and 195 Å were tried to be used to study any change in the coronal environment between postflare and preflare states. It is understood that direct evidence for magnetic reconnection in flares may be difficult to find, despite the fact that it is thought to be the primary process behind flares. But since the reconnection appears to be (largely) completed by the time the postflare loop system are detected by TRACE (Schrijver et al. 1999), any obvious changes were carefully searched, especially for newly formed loops. A complete picture of the flare combined with the observational results in photosphere and chromosphere can then be deduced.

For the 2003 October 29 event, MSFC vector magnetograph data were used. The magnetograph is a filter-based instrument employing a tunable Zeiss birefringent filter with a 0.125 Å bandpass and an electro-optical modulator to obtain integrated Stokes profiles in the Fe i 5250 Å absorption line. The field of view of the instrument is 7′ × 5′ and the spatial resolution is 1.28″ pixel⁻¹. For the 2001 August 25 event, data from BBSO’s DVMG system were used, which typically covers an area of about 5′ × 5′ with ~0.6″ pixel resolution. The BBSO data reduction procedure is discussed in detail by Wang et al. (2002b).

To show the temporal evolution of the flares and understand the relationship between the rapid changes of magnetic fields and energy release sites, hard X-ray time profiles and images from RHESSI are used for the three events that occurred in 2003. Among the other four events, two have complete hard X-ray coverage by the Yohkoh HXT and have been studied in detail by other authors.
4.3 Results

For each event, it is started with an analysis of the difference image (postflare minus preflare state) in TRACE white-light, which was smoothed by a window of $10'' \times 10''$ in order to magnify the morphological changes by smoothing out the background pattern caused by granulation and 5 minute oscillation. Any bright feature in the difference image indicates a brightening in the postflare image, e.g., an area of decayed penumbra that fades into the granular background, whereas any dark feature corresponds to a darkening in the postflare image, e.g., the darkening of either an umbral core or an inner penumbral area. With the aid of difference images, the decaying and darkening regions in the time-lapse white-light movies can be identified and traced. Please note that the difference image sometimes may be affected by proper motions of features. Therefore, the time-lapse movies were ultimately relied on to pin down the exact location of the decaying (labeled “D” in figures) and darkening regions (labeled “E” in figures). Then time profiles of mean intensity were made for both the decaying and darkening areas. The mean intensity is defined as the average intensity of a certain area outlined by a box normalized to the photospheric intensity outside the sunspot in a quiet-Sun region. The evolution of the line-of-sight magnetic fields associated with these regions was also studied, by first creating movies using the corresponding MDI 1 minute cadence data and subsequently integrating the magnetic flux within each box. To link the temporal evolution of the flare, the hard X-ray time profile or the derivative of the soft X-ray light curve is further superposed onto the time profiles of the magnetic flux change.

Table 4.1 lists the seven flare events that were analyzed. For each of them, two penumbral decay regions and one central darkening region were located. Note that Deng et al. (2005) and Wang et al. (2004a) have discussed event 1 and events 1, 5, and 6, respectively. Here these studies are extended and other events are included to assemble a unified picture of penumbral decay. In addition to some
Table 4.1  Penumbral Decay Events

<table>
<thead>
<tr>
<th>Event No.</th>
<th>Date</th>
<th>Starting (UT)</th>
<th>Peak (UT)</th>
<th>Active Region</th>
<th>GOES Level</th>
<th>Location (deg)</th>
<th>D1 (%)</th>
<th>D2 (%)</th>
<th>$\Delta I_E$ (%)</th>
<th>D1 $(10^{19}$Mx)</th>
<th>D2 $(10^{19}$Mx)</th>
<th>$\Delta F_{E+}$ $(10^{19}$Mx)</th>
<th>$\Delta F_{E-}$ $(10^{19}$Mx)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1..........</td>
<td>2000 Jun 6</td>
<td>1458</td>
<td>1525</td>
<td>9026</td>
<td>X2.3</td>
<td>N33, E25</td>
<td>4.1</td>
<td>3.7</td>
<td>-5.3</td>
<td>-22±10</td>
<td>4.5±2</td>
<td>15±7</td>
<td></td>
</tr>
<tr>
<td>2..........</td>
<td>2001 Apr 6</td>
<td>1910</td>
<td>1921</td>
<td>9415</td>
<td>X5.6</td>
<td>S20, E31</td>
<td>4.6</td>
<td>3.4</td>
<td>-7.9</td>
<td>10±7</td>
<td>-16±8</td>
<td>~0a</td>
<td>~0a</td>
</tr>
<tr>
<td>3..........</td>
<td>2001 Apr 9</td>
<td>1520</td>
<td>1534</td>
<td>9415</td>
<td>M7.9</td>
<td>S21, W04</td>
<td>1.3</td>
<td>3.2</td>
<td>-3.1</td>
<td>~0a</td>
<td>-9.0±4</td>
<td>~0a</td>
<td>17±3</td>
</tr>
<tr>
<td>4..........</td>
<td>2001 Aug 25</td>
<td>1623</td>
<td>1645</td>
<td>9591</td>
<td>X5.3</td>
<td>S17, E34</td>
<td>6.6</td>
<td>5.2</td>
<td>-7.5</td>
<td>3.5±1</td>
<td>-17±3</td>
<td>-9.6±2</td>
<td>8.5±2</td>
</tr>
<tr>
<td>5..........</td>
<td>2003 Oct 28</td>
<td>0951</td>
<td>1110</td>
<td>10486</td>
<td>X17</td>
<td>S18, E20</td>
<td>6.1</td>
<td>6.2</td>
<td>-5.4</td>
<td>-9.0±7</td>
<td>6.9±2</td>
<td>-11±7</td>
<td>~0a</td>
</tr>
<tr>
<td>6..........</td>
<td>2003 Oct 29</td>
<td>2037</td>
<td>2049</td>
<td>10486</td>
<td>X10</td>
<td>S15, W02</td>
<td>6.3</td>
<td>4.6</td>
<td>-3.1</td>
<td>5.5±4</td>
<td>-7.7±2</td>
<td>49±7</td>
<td>-14±7</td>
</tr>
<tr>
<td>7..........</td>
<td>2003 Nov 2</td>
<td>1703</td>
<td>1725</td>
<td>10486</td>
<td>X8.3</td>
<td>S14, W56</td>
<td>5.4</td>
<td>5.0</td>
<td>-5.3</td>
<td>-25±3</td>
<td>3.6±0.8</td>
<td>-13±3</td>
<td>13±3</td>
</tr>
</tbody>
</table>

Note. — The results of changes of white-light intensity ($\Delta I$) and magnetic flux ($\Delta F$) are obtained by taking the difference between the average values of intensity/flux within 1–2 hours in the preflare and postflare states. The 1 $\sigma$ statistical error for white-light intensity is $\sim$0.5%, determined by calculating the fluctuation in the time profile of mean intensity in a quiet-Sun region. Since SOHO/MDI data have a noise level of no more than 20 G (Scherrer et al. 1995; Hagenaar 2001), 20 G $\times$ area is taken as a largest error to the magnetic flux.

- No reliable change is observed, either because the change is small or buried in the long term evolution of magnetic field.
general information about each event, it is provided in Table 4.1, the mean intensity changes $\Delta I_{D1,2}$ for the decaying areas D1 and D2 and $\Delta I_E$ for the central darkening region E, the amount of magnetic flux change $\Delta F_{D1,2}$ in the penumbral decay areas D1 and D2, and the magnetic flux changes $\Delta F_{E,+,-}$ for positive and negative polarities of the central darkening region E. Time profiles of mean intensity and magnetic flux are only presented for the 2003 October 29 event (Figure 4.2) and the results of the other events are summarized in Table 4.1. First, the three events that occurred in active region AR 10486 will be presented before discussing the remaining four events. Note that in all figures, image shift due to solar rotation was corrected. TRACE 1600 Å and EUV intensities are presented as negatives in order to optimize the visibility of flare structure.

4.3.1 2003 October 29 X10 Event

This X10 event was well covered by many space- and ground-based instruments. Along with other great flares in the active region AR 10486, it is being extensively scrutinized by the solar physics and space science community. Wang et al. (2004a) first reported the decayed penumbra associated with this event and the X17 event of 2003 October 28. After careful data alignment, another penumbral decay area for each of the events is found. Figure 4.1 compares the morphology between postflare and preflare states in both TRACE white-light and 195 Å for this X10 event. From the white-light difference image shown in Figure 4.1c, two penumbral decay areas D1 and D2 and the darkening central region E are identified. Figure 4.1d shows the white-light image at flare maximum with superposed RHESSI hard X-ray contours in the 50–100 keV channel obtained during the peak of the flare. It can be clearly seen that the two penumbral decay regions are cospatial with two flare kernels in white-light and hard X-rays. It is noticed that the much stronger eastern flare kernel is near the very prominent penumbral decay area D1, while the weaker western kernel
Figure 4.1 Comparison of preflare (a and e) and postflare (b and f) states for the X10 flare on 2003 October 29; (a and b) and (e and f) are TRACE white-light and 195 Å images, respectively, and (c) is the white-light difference image (the postflare image minus the preflare image). SOHO/MDI longitudinal magnetic field is superposed onto (a), showing the polarity of every spot clearly. The white/black contours represent positive/negative longitudinal magnetic fields, respectively. The magnetic contour levels are ±150, 300, and 1200 G. Panel (d) is the white-light image at flare maximum with superposed RHESSI 50–100 keV hard X-ray contours (levels are 20%, 40%, 70%, and 90% of the maximum counts) accumulated from 20:49:42 UT to 20:50:42 UT. The field-of-view of (a)–(d) is 180” × 180”; (e) and (f) have a larger field-of-view (250” × 250”) to show the complete coronal morphology, in which the large box encompasses the total areas of D1, D2, and E1, outlining the δ spot associated with the flare.

is near the less prominent area D2. Note that the positions of hard X-ray footpoints in Figure 4.1d are a snapshot at the flare peak time. The footpoint motions during the flare was studied in detail by Krucker et al. (2005, see also Figure 5.11). The two frames of TRACE 195 Å images, although with different exposure times, show that after the flare, strong postflare loops newly formed within the δ spot region, which is outlined by the large box in Figures 4.1e and 4.1f. In Figure 4.2 the
Figure 4.2 Top panel: Mean intensity of the penumbral decay areas D1 and D2 and the central darkening area E as a function of time on 2003 October 29. For a clearer representation, the data values of areas D2 and E are added 0.1 and 0.12, respectively. Middle and bottom panels: Evolution of absolute value of the longitudinal magnetic flux in each area. The curve of vertical spikes represents the RHESSI hard X-ray counts in the 50–100 keV range.

The intensity and magnetic evolution of these areas were analyzed. The error bars in the top panel are standard deviation determined for TRACE white-light images by calculating the fluctuation in the time profile of mean intensity in a quiet-Sun
region. An intensity of 1.0 represents the quiet-Sun intensity. Thus, a large value represents a smaller and/or lighter sunspot in the area. For the areas D1 and D2, it is obvious that their mean intensity increases very rapidly (6.3% and 4.6%, within \( \sim 30 \) minutes) after the flare, representing the rapid penumbral decay in these two regions. This change is monitored even longer after the flare (\( \sim 10 \) hours) and find that the decaying penumbrae remain unrestored. With similar results for other events that are discussed below, this means that the penumbral decay is not only rapid, but permanent, compared to the timescale of the flare itself. Moreover, the mean intensity for the central region E1 decreased rapidly and permanently by 3.1% after the flare, indicating that the feature is becoming darker. After a close inspection of the time-lapse movie, it is found that these darkening features actually include two kinds: one is the neighboring umbral core, and the other is the inner penumbra. However, in some events, only the inner penumbral region becomes darker after the flare. Figure 4.2 also shows substantial changes of longitudinal magnetic fields associated with the decaying and darkening areas. These changes are well related to the flare.

In Figure 4.3, the MSFC vector magnetograms before and after the flare are compared. The decrease in transverse field strength associated with the cusplike penumbral decay area D1 and the increase in the central region across the magnetic neutral line is obvious. In Figure 4.4 the MSFC data is further aligned with the TRACE pointing presented in Figure 4.1. It is found that the mean transverse field strength within areas D1 and D2 decreased by 173 and 56 G, respectively, and increased by 97 G in area E. For the small region across the magnetic neutral line (indicated by two white brackets in the panels \( e \) and \( f \)), the weighted mean magnetic shear angle increased by 10° after the flare (see also Figure 4.3, bottom panels). This shear angle is defined as the angular difference between the potential and the measured transverse fields, weighted by the measured transverse field strength. The
Figure 4.3  Top panels: MSFC vector magnetograms before and after the X10 flare on 2003 October 29 superposed onto the corresponding TRACE white-light images at 18:26 UT and 21:35 UT respectively. The white lines are the transverse fields with the length proportional to the field strength. The field-of-view is $185'' \times 185''$. Bottom panels: A magnified view of the flare site outlined by the boxes in the top panel. The black line is the magnetic neutral line where the flare is initiated.
Figure 4.4 MSFC intensity, transverse field, and longitudinal field images before and after the X10 flare on 2003 October 29. The three boxes are the same as in Figure 4.1. The white brackets in (e) and (f) indicate the length along the neutral line, where the weighted mean magnetic shear angle is calculated. High shear (70°–80°) and maximum shear (80°–90°) areas are denoted by closely spaced black and white plus signs, respectively.

mean inclination angle has no substantial change within area D2, but it increases by 12° within area D1. As it is discussed below, the study of vector magnetograms of 2001 August 25 event reveals similar results.

4.3.2 2003 November 2 X8.3 Event
This flare occurred when active region NOAA 10486 approached the west limb (S14°, W56°). Although the morphology of the whole region has changed dramatically, the flare is still related to the δ configuration in the eastern part of the whole sunspot group, which is identical to the location of the X10 flare on 2003 October 29. The difference image in Figure 4.5 shows two penumbral decay areas D1 and D2 and the
**Figure 4.5** Same as Figure 4.1, but for the X8.3 flare on 2003 November 2. The little black box in (d) indicates the position of a bright flare kernel in TRACE white-light. The RHESSI map was accumulated from 17:18:00 UT to 17:19:00 UT in the 50–100 keV energy range and the contour levels are 30%, 50%, 70%, and 90% of the maximum counts. The white-light contours in (e) and (f) outline the δ spot region related to the flare. The field-of-view is $150'' \times 150''$.

The central darkening region E, which is predominantly in the form of penumbra. TRACE white-light images have a data gap between 17:11 and 17:39 UT, and thus missed the flare peak around 17:25 UT. By examining the time-lapse movie, it is found that right before the data gap, there were discernible white-light flare kernels, which begin to glow. In Figure 4.5d a little black box is drawn around a white-light flare kernel, which is found to move across the penumbral decay area D1. The superposed RHESSI hard X-ray contours are also associated with the penumbral decay areas. Similar to the 2003 October 29 event, the stronger northern hard X-ray kernel is associated with the stronger penumbral decay area D1. The images in TRACE 195 Å show the evolution of the coronal loops, which can be observed more clearly for this near-limb event. It
Figure 4.6  X17 flare on 2003 October 28. All panels show similar images as in Figure 4.1, except that (d) is a TRACE 1600 Å image with superposed RHESSI 50–100 keV hard X-ray contours (levels are 30%, 50%, 70%, and 90% of the maximum counts) accumulated from 11:09:30 UT to 11:10:30 UT. The boxes in (e) and (f) represent the field-of-view in (a)–(d), which is 150″ × 150″. Note that the center of (d) has a 70″ shift to the west in order to show the complete flare morphology.

is found that early in the event (Figure 4.5e), loops were linking the northern spot to the area outside of the entire active region. After the reconnection (Figure 4.5f), new loops formed within the δ spot region, connecting the northern and southern spots.

4.3.3 2003 October 28 X17 Event

Although the cadence of TRACE white-light images is low (∼1 hour) for this flare, one is still able to find the decaying penumbra by comparing two white-light images, one before the flare (Figure 4.6a) and another well after the peak (Figure 4.6b). The difference image (Figure 4.6c) shows a strong penumbral decay area D1, while the decaying area D2 is not that obvious. The darkening region E includes both
the umbral core and inner penumbral regions. Since the white-light image at flare maximum is not available, a TRACE 1600 Å image is presented instead in Figure 4.6 and superpose RHESSI hard X-ray contours in the 50–100 keV range. Obviously, penumbral decay area D1 is related to a section of one of the two TRACE 1600 Å flare ribbons, while the less obvious penumbral decay area D2 is near one of the two hard X-ray sources but does not coincide with it. TRACE 195 Å images show a dramatic evolution of postflare loops (Figure 4.6f) over the δ configuration region that is related to the flare.

4.3.4 Reevaluation of the 2000 June 6 X2.3 Event

Deng et al. (2005) discussed this event in detail and found two penumbral areas that very obviously decayed right after the flare. Since this event is associated with filament eruption, they tried to interpret the penumbral decay phenomenon in the context of the magnetic breakout model (Antiochos et al. 1999) for CMEs and eruptive flares. The difference image, clearly showing the decaying and darkening regions, was later discussed by Wang et al. (2004a). By carefully examining the evolution in TRACE EUV images, it is found that the morphology of the coronal loops is substantially different between postflare and preflare states, and reconnection shown as orientation changes of coronal loops is very similar to the other six events in this study. Thus, this event also fits into a unified picture that is different from the breakout scenario and is discussed in the next section. Figure 4.7a shows the preflare state of the complicated active region NOAA 9026, which has a δ configuration. Two northern spots have positive magnetic polarity, and two southern spots have negative polarity. Figure 4.7f shows postflare loops that clearly connect the two sunspot regions on both sides of the neutral line and this connection extends to the penumbral decay regions D1 and D2, which are quite different from preflare state shown in Figure 4.7e. The white-light image near flare maximum is presented in Figure 4.7d, in which two
(b) 17:00 UT

Figure 4.7 X2.3 flare on 2000 June 6. All panels show similar images as in Figure 4.1, except that (e) and (f) are TRACE 171 Å images. The magnetic contour levels in (a) are ± 150, 300, 700, and 1400 G. The boxes in (e) and (f) represent the field-of-view in (a)–(d), which is 130″ × 130″.

white-light flare kernels (arrows) are discernible. These two white-light kernels are later found to separate, sweeping through the two penumbral decay areas D1 and D2. Unfortunately, there were no hard X-ray images available for this event.

Recent work reveals very similar penumbral decays associated with an X1.2 flare on 2000 June 7 in this active region (Chen et al. 2006). In contrast to these impulsive changes, Kurokawa et al. (2002) constructed a realistic model of a strongly twisted flux rope to explain the drastic evolution of this flare-productive active region in about 5 days. In particular, they reported the catastrophic decay of the central δ spot region from 10:00 UT of June 6 to 16:00 UT of June 7. Thus it is very meaningful to combine impulsive change and long-term evolution of δ configurations in the next study (e.g., Wang et al. 2005).
Figure 4.8  Same as Figure 4.7 except that (d) is a TRACE 1600 Å image near the flare maximum, but for the X5.6 flare on 2001 April 6. The boxes in (e) and (f) represent the field-of-view in (a)–(d), which is 160″ × 160″.

4.3.5 2001 April 6 X5.6 and April 9 M7.9 Events

These two flares occurred in the same active region (NOAA 9415) and were associated with the same δ spot. TRACE white-light observations covered both flares, with a short temporal data gap during the flare maximum. The difference images for both events (Figures 4.8c and 4.9c) show a similar ringlike structure: bright in the outer edge of the δ spot, indicating penumbral decay, and dark in the center, indicating the darkening umbral core and inner penumbra. Furthermore, the evolution in TRACE 171 Å images for both events clearly shows that after the flare, strong loops exist within the δ configuration, so that the two spots constituting the δ spot become strongly connected. Compared with the postflare state, this kind of connection is hardly seen in the preflare images. By studying Yohkoh SXT images, Yurchyshyn (2003) also reported this obvious connectivity change for the 2001 April 9 event. As
Figure 4.9  Same as Figure 4.8, but for the M7.9 flare on 2001 April 9. The boxes in (e) and (f) represent the field-of-view in (a)–(d), which is 130″ × 130″.

shown in Figures 4.8d and 4.9d, flare ribbons in TRACE 1600 Å were associated with the penumbral decay areas for both events. Yohkoh HXT observations were available for the April 6 event and were presented by Qiu et al. (2004a). They recognized three flare kernels in the HXT H channel (53–93 keV) and all three kernels were found inside the sunspot umbrae in the active region. The strongest of these flare kernels is located near the central darkening area E in the result.

4.3.6 2001 August 25 X5.3 Event

This white-light flare was discussed in detail by Metcalf et al. (2003), in which they found three flare kernels in the HXT M2 channel (33–53 keV). Two of the flare kernels are near the penumbral decay area D1 shown in Figure 4.10. Using BBSO data, Wang et al. (2002b) studied photospheric magnetic field changes associated
Figure 4.10  Same as Figure 4.7, but for the X5.3 flare on 2001 August 25. BBSO line-of-sight magnetogram contours at 16:13 UT are superimposed onto (a). Highlights in (a) and (b) are areas of decaying penumbra (D1 and D2) and darkening inner penumbra (E). The boxes in (e) and (f) represent the field-of-view in (a)–(d), which is $120'' \times 120''$.

with this flare and concentrated on the central region along the neutral line that is near the darkening area E in this study. As they pointed out, the central darkening region is predominantly in the form of penumbra. Besides this, the difference image in this study clearly shows two penumbral decay areas D1 and D2 in the outer $\delta$ spot structure. The BBSO vector magnetogram data were reexamined and it was found that the mean transverse field strength within the penumbral decay areas D1 and D2 decreased by $21 \pm 10$ and $36 \pm 6$ G, respectively, and increased by $113 \pm 21$ G in the central darkening area E. Although the changes of transverse field associated with the areas D1 and D2 are on the order of the sensitivity of the BBSO DVMG system, it is found that it is nonetheless statistically meaningful by plotting their time profiles. Moreover, the weighted mean magnetic shear angle within area E rapidly
increased by 10° after the flare. Note that in Figure 4.10a, the magnetic abnormality near area D1 (and some other locations as well) is due to very inclined magnetic field lines and the effects of projection. The time profile of MDI magnetograms shows that after the flare, the negative polarity within the area D1 increased, while the positive decreased. Taking into account the decreasing transverse field, it is deduced that the mean inclination angle within the area D1 becomes larger; i.e., the magnetic field turns more vertical. However, a significant change of the inclination angle within the area D2 is not found. Figure 4.10d shows the TRACE white-light image near flare maximum. It is found that the two white-light flare ribbons separate and sweep through the two penumbral decay regions. Again, the evolution in TRACE 171 Å images shows similar magnetic structures that connected the two spots after the flare.

4.4 Conclusions of This Chapter

Observations of rapid structural changes within seven δ spots have been presented, each associated with a major flare, by monitoring the evolution in TRACE white-light. The major findings are the following:

1. The time-lapse movies show that for each event, the δ spot appears to have shrunk after the major flare. Accordingly, it is found that part of the penumbral segments in the outer δ structure decayed and the neighboring umbral core and/or inner penumbral region near the magnetic neutral line darkened. Such short-term changes to the δ spot was not found when there was no major flare.

In contrast to previous studies of long-term evolution covering time periods of hours to days, the changes of the δ spot structure presented in this study are rapid and well associated with major flares. The difference images for all the seven events show a very similar pattern with a bright (decaying) region outside and a darkening in the center. Thus, it is argued that the changes observed in this study and others are real.
Figure 4.11 Scatter plot of the average intensity change of penumbral decay against GOES X-ray flux. The dashed line is a least-squares linear fit to all seven events with the correlation coefficient of 0.91. The error bars are standard deviation determined individually for each event by calculating the fluctuation in the time profile of mean intensity in a quiet-Sun region.

2. The increasing mean intensity in the penumbral decay areas and decreasing intensity of darkening regions are \(\sim 2\%-7\%\) above the quiet-Sun photospheric intensity. These changes are coincident with the impulsive hard X-ray emissions of the related major flares. More importantly, these changes are permanent, not transient. Figure 4.11 shows the scatter plot of the average intensity change of penumbral decay against GOES X-ray flux, from which the trend can clearly seen that the larger the flare size, the stronger the penumbral decay is.

The decayed and darkened features are best seen in the time-lapse TRACE white-light movies. The calculation of the mean intensity of these regions also show a clear increase or decrease, which coincide with the peak in the hard X-ray emission. A natural explanation of penumbral decay is that it could be associated with heating of the lower atmosphere due to the flare. However, such an explanation is argued
against mainly because that the decayed penumbra is not restored even several hours after each event (Wang et al. 2004a).

3. The locations of the penumbral decay are associated with flare emissions, albeit with distinct differences for each event. White-light flare kernels or ribbons are coincident with or sweep through the penumbral decay regions in the events 1, 4, 6, and 7. White-light observations at flare maximum were not available for the events 2 and 3; however, the decay regions in these two events are all near TRACE 1600 Å flare ribbons. RHESSI hard X-ray sources are associated with both penumbral decay regions in events 6 and 7. One of the decay regions in event 5 is near the hard X-ray source, while another is related to one of the two TRACE 1600 Å flare ribbons.

4. The postflare loops observed in TRACE EUV wavelengths “predominate” the \( \delta \) spot, suggesting that the two components of the \( \delta \) spot become strongly connected after reconnection. The nature of postflare loops in dynamic flares has been an interesting subject for quite a long time. The classical CSHKP model (see § 1.3.1) interprets the postflare loop systems as a result of the reconnection of magnetic field lines torn open by the flare event. According to this model, the magnetic configuration of the corona overlying the flare site contains many closed loops prior to the flare and this original configuration is restored through the reconnection after the flare. However, this can hardly explain the changes of photospheric features observed in this study. In a picture, which is presented next, the magnetic field geometry is altered drastically after the flare, which it is believed leads to the penumbral decay and central region darkening.

5. Vector magnetogram analysis of the 2003 October 29 and 2001 August 25 events both show that the transverse magnetic field decreases in the penumbral decay area, while it increases in the central darkening region, which directly supports the observational results of decayed and darkened penumbrae. Remarkably, the magnetic shear in both events shows an increase by 10° after the flares.
6. The longitudinal magnetic fields associated with the decaying and darkening regions also exhibit substantial changes after the flares. The interpretation proposed by Wang et al. (2004a) is further elaborated that the penumbral decay is due to changes in magnetic topology in the following way: the magnetic fields become more vertical after the flare and the umbrae become darker as a result of an enhancement of the longitudinal magnetic field. For the six events in this study, high-resolution, high-cadence line-of-sight magnetograms from MDI are used, and for the 2001 August 25 event, BBSO magnetograms are used. For each event, two penumbral decay regions were located, which are in opposing magnetic fields and one central darkened region near the magnetic neutral line. The changes of magnetic flux associated with the decaying and darkening regions were further calculated. From the results listed in Table 4.1, it can be seen that seven penumbral decay regions have a decreased longitudinal magnetic flux after the flare. It is believed this is because that the penumbral field turned more vertical and merged with the umbral field. For the other five penumbral decay regions with increasing longitudinal magnetic flux, it is speculated that the penumbral field turned more vertical but did not become sufficiently vertical to darken and become part of the umbral field. For the central darkening regions, the change of longitudinal magnetic flux is not conclusive. Since the central darkening regions usually include the sunspot umbra, one should recognize the limitation of filter-based magnetograph systems, which are not well suited for measurements of strong magnetic fields because of Zeeman saturation. Therefore, the conclusions are mainly based on white-light observations.

Based on the analysis of the seven events in the present study, a unified reconnection picture for the $\delta$ configuration is therefore put forward and a simplified cartoon for this picture is presented in Figure 4.12. This is the first flare scenario actually describing the flare effects on sunspots\(^2\). The gray and black lines stand for

\(^2\)See [http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons/thepages/Liu.html](http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons/thepages/Liu.html).
penumbral and umbral fields, respectively. Thus, the following three major points are made:

1. In the preflare configuration, a $\delta$ sunspot is the joining of two separate magnetic flux systems. A strong electric current may exist there because of the high field strength and large magnetic gradient.

2. The two spots become strongly connected after the flare, leading the penumbral fields to change from highly inclined in the preflare state to a more vertical configuration after the flare. This accounts for the penumbral decay.
3. The umbra becomes darker as a result of an enhanced longitudinal magnetic field. The strong connection between the two spots also leads to a substantial increase in the transverse field in the central δ spot region, which can explain the darkening of the inner penumbra. In events 4 and 6, where vector magnetogram data were available, such an enhancement of transverse fields after the flares is not found.

Note that, first, the preflare state in this picture is a simplified condition, because the two components of a δ spot may already have extra connection in the coronal that can support filament. But in either case, the TRACE EUV postflare images of all seven events clearly show that the direct connection between the two spots becomes much stronger after the flare. For the 2000 June 6 event, the associated filament may erupt outward first enabling the field lines of the two spots to connect. Second, other modifications can be applied to this picture. For example, the strong connection between the two components of the δ spot may result in the emergence of highly twisted flux tubes from beneath the surface, because relaxation of the surface makes flux emergence easier. This can add to the darkening of the central δ spot region and explain the increase of magnetic shear after the flare. Thus the present picture, with some appropriate adjustments, could be another explanation of the finding of rapid change of magnetic fields associated with six X-class flares (Wang et al. 2002b). Two events among them have been studied here. Third, although points 2 and 3 are mainly based on two events where vector magnetograms were available, the unified picture can explain all the other events that exhibit similar changes in morphology. Finally, observations also indicate that penumbral decay tends to recur in some active regions. Events 5, 6, and 7, occurring from 2003 October 28 to November 2 in NOAA AR 10486, all exhibit penumbral decay with similar properties. Events 2 and 3 on 2001 April 6 and 9 show another group of penumbral decay occurring at the same δ configuration in NOAA AR 9415.
CHAPTER 5

LARGE-SCALE ACTIVITIES ASSOCIATED WITH THE 2003 OCTOBER 29 X10 FLARE

In this chapter\(^1\), a multiwavelength study focusing on the large-scale activities associated with the 2003 October 29 X10 flare and a halo CME is presented. This event was strong enough to clearly show several large-scale activities, such as remote brightenings, Moreton waves at H\(\alpha\) off-bands, and type II radio bursts, which offers an excellent opportunity to clarify the relationship among them. The remote brightenings were found near two coronal holes more than \(2 \times 10^5\) km from the main flare in eastern and southern directions, respectively. Coronal dimmings were seen at the locus of the remote brightenings right after the flare at both EUV and soft X-ray wavelengths. The Moreton waves propagated both northeastward and southward, toward the aforementioned remote regions, at speeds of approximately 1100 and 1900 km s\(^{-1}\), respectively. The present analyses show that the Moreton waves, the type II radio bursts, and the CME started almost simultaneously, but were not cotemporal with the remote brightenings. The remote brightenings are rather consistent with the flare hard X-ray emissions within the active region, although they have much smaller scales. It is therefore concluded that the two remote brightening regions were magnetically connected to the flaring active region, and that the remote brightenings, as well as all other activities, were due to the interaction of an erupting flux rope at the core of the flare with magnetic field overlying the region. In this scenario, the large overlying loops should open to allow the flare activity underneath them, which points to a picture similar to the magnetic break-out process in such a large scale.

\(^1\)This chapter is based on the following paper:
Solar flares are local energy release phenomena in the scale of the flaring active region. It is believed, however, that an even larger scale magnetic field structure could be involved with the flare process, such as the scale of a CME. For this reason, it is critically important to bring the local energy release into a global context in the solar atmosphere. Observational signatures for the large-scale connectivity include remote brightening: radiation enhancement at Hα or soft X-rays found in regions distant from the flare site.

Remote brightening can be due to particles traveling from a flare core to the remote site along large-scale field lines. By studying two large flares in which Hα brightenings in remote quiet regions appeared simultaneously with RS type III radio bursts, Tang & Moore (1982) suggested that the remote Hα brightenings were initiated by direct heating of the chromosphere by RS burst electrons traveling along discrete magnetic loops connecting the main flare to remote sites. Similar Hα phenomena with cospatial microwave signature caused by fast electrons were also presented (Kundu et al. 1983; Nakajima et al. 1985; Hanaoka 1999). In this case, remote brightening can be an important tracer for a large-scale magnetic field connecting from the flare core to a distance place. Such a large loop itself is probably too tenuous to be directly observed but is important in restructuring of magnetic fields as a result of, for instance, interaction between the erupting flare loop in the core region and the overlying large-scale magnetic fields. Subsequent formation of coronal holes (dimmings) were also found above the remote brightening regions (Manoharan et al. 1996). Since the dimming is often interpreted as representing the loss of the coronal mass swept into the CME, such a large-scale structure consisting of the main flare site and remote brightening is a good indicator of the onset of a CME.

Alternatively, remote brightenings can be initiated by disturbances propagating outward from the flare site. The flare-associated global disturbances traveling
through the solar atmosphere have been detected by optical observations using $H\alpha$ filtergrams by Moreton & Ramsey (1960). Uchida (1974a,b) argued that Moreton waves are a chromospheric manifestation of the flare-produced fast-mode MHD shocks propagating in the corona, which can also excite type II radio bursts. However, an alternative driving mechanism for such shocks and the associated wave phenomena in the solar atmosphere has been proposed by Cliver et al. (2004). Moreton waves from explosive flares can cause progressive, short-lived, distant brightenings of weak plages and elements of the chromospheric network as the expanding blast wave passes over them (Švestka 1976; Riegler et al. 1982). Rust & Webb (1977) suggested on the basis of their analysis of Skylab X-ray data that remote $H\alpha$ brightenings can be caused by slow-mode shock waves seen in soft X-rays, which were further shown to be consistent with the spread of thermal conduction fronts along coronal magnetic loops (Rust et al. 1985). In this case, remote brightening may not directly reveal a large-scale magnetic structure connected to the flare core but is still important as an indicator of energy transport away from the flaring active region. Machado et al. (1988) concluded that all three energy transport processes — high-energy particles, shocks, and conduction fronts — play significant roles in the redistribution of flare energy.

More recently, Balasubramaniam et al. (2005) reported a phenomenon called sequential chromospheric brightenings (SCBs), observed to propagate away from the flare site. They attribute the SCBs to the sequential tearing away of a series of nested magnetic loops during the eruption of a CME. This presents another challenge in understanding the nature of remote brightenings.

In this study, the remote brightenings in $H\alpha$ and soft X-rays, together with Moreton waves, type II radio bursts, coronal dimmings, and a CME are studied, which were all observed during the 2003 October 29 X10 flare. The main goal is to clarify the relationship among these activities and eventually determine the large-scale magnetic structure. In § 5.2, the data used in this study are described. Analyses of
large-scale features in different wavelengths are presented in § 5.3 and a plausible reconnection scenario in § 5.4. Major results are summarized in § 5.5.

5.2 Observation

The 2003 October 29 flare was a very powerful, geo-effective event classified as 2B/X10.0. It occurred in the large superactive region NOAA 10486 (S15°, W02°), starting from 20:37 UT and reaching its maximum at 20:49 UT (according to GOES light curve). This event was well covered by many space- and ground-based instruments. The images in Hα were taken with the Air Force OSPAN. OSPAN is an automated patrol telescope that uses a tunable Fabry-Pérot filter system to image the Sun in multiple wavelengths at rapid cadence. Three full-disk images were used, in Hα center, Hα + 0.4 Å, and Hα − 0.4 Å. The time cadence of the images is 1 minute, and the pixel resolution is ∼1″ and ∼2″ for the Hα center and off-bands, respectively. Remote brightenings were observed in each of these lines. However, due to the cloudy weather on that day, the Hα data could not be completely flat-fielded and the data quality was degraded. Therefore, rather than following the usual approach of using the red wing images to probe the Moreton waves (e.g., Narukage et al. 2002), Hα red – blue wing subtraction images were made, which largely remove the image gradients. The result shows that there were indeed Moreton waves propagating both northeastward and southward right after the flash phase of the flare. It is noted that the image times of Hα − 0.4 Å and Hα + 0.4 Å are ∼3 s apart during the observed time interval. This difference in the observed times was negligible in this study, because only position difference in determining wave velocity is considered.

Remote brightenings were also observed in soft X-rays with the SXI on board the GOES 12 satellite. The SXI’s 0.6–6.0 nm bandpass makes it sensitive to the coronal temperature range of 10⁶–10⁷ K. In this study, images observed with the

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2Nathan Dalrymple 2005, private communication
open filter position were used. The observing time cadence is about 4 minutes, and
the pixel resolution is 5″.

Type II radio bursts associated with this event were recorded with the Culgoora
Radiospectrograph (Prestage et al. 1994). The instrument operates over a frequency
range from 18 MHz to 1.8 GHz and samples every 3 s. A CME was observed with
LASCO and the CME height-time data that are provided by the LASCO Web site
was used. Large-scale coronal dimmings are seen for this event in EUV images that
were observed with EIT. The observation in this study was made in a wavelength
range centered on 195 Å, comprising an Fe\textsubscript{XII} line emitted at $1.5 \times 10^6$ K at typical
coronal density. The EIT pixel resolution is 2.6″.

In order to explore the dynamics in the flare core region and understand the
relation between the large-scale activities and energy release sites, hard X-ray light
curves and images from RHESSI were used. Microwave emissions at 1.2–18.0 GHz
were also obtained from coordinated OVSA observations to investigate the nonthermal
properties of this event.

The magnetic field and white-light structure of the photosphere were observed
with MDI on board SOHO. For the data used in the current study, the cadence was
96 minutes and 6 hours for the magnetic and white-light data, respectively, with an
image scale of 2″. The soft X-ray light curve observed by GOES was also used to
track the timing of this flare.

5.3 Data Analysis

5.3.1 Remote Brightenings in H\textalpha and Soft X-Ray

The very complicated active region NOAA 10486 was about 15° south of the equator
and was just west of central meridian on 2003 October 29. Figures 5.1a and 5.1b
show the two extended remote brightenings (denoted as “RHBs”) observed in H\textalpha
that lay east and south of the X10 flare core (denoted as “F”), respectively. Note
Figure 5.1  
(a, b) Hα images from OSPAN showing the two extended remote Hα brightenings (RHBs; denoted by arrows) that started at different times, as well as the flare core (denoted as “F”). The eastern remote brightening (a) is in the shape of a letter L and the southern remote brightening (b) propagated southeast toward the limb.  
(c) 20 minute averaged MDI magnetogram centered at 20:49 UT.  
(d) EIT 195 Å image showing the two coronal holes (“CH”) near the remote brightenings.
Figure 5.2  Time sequence of OSPAN Hα images showing the dynamics of eastern remote brightening chain denoted in Figure 5.1a. Arrows with corresponding numbers indicate individual new brightening kernels as they began to glow. The field of view is $260'' \times 390''$.

that these two remote brightenings occurred at different times and exhibited different morphology. The arrows in Figure 5.1a point to the eastern remote brightening chain in the shape of a letter L, which comprises several discrete brightened patches with the earliest onset time at $\sim$20:41 UT. The brightening chain is more than $2 \times 10^5$ km away from the main flare site. Figure 5.1b shows the initial position of the southern remote brightening, which is more than $3 \times 10^5$ km away from the flare core and was initiated at $\sim$20:49 UT. The brightening site was then observed to move southeast toward the limb. To better show the weak magnetic field outside the active region especially near the polar area, 20 minute average around 20:49 UT on the MDI magnetograms was used and the result was presented in Figure 5.1c. It is obvious
Figure 5.3  Time sequence of OSPAN Hα images showing the dynamics of southern remote brightening that propagated southeast with its initial position indicated in Figure 5.1b. Arrows with corresponding letters indicate individual new brightening kernels as they began to glow. The field of view is 610″× 280″.

that the eastern remote brightening patches lie in the negative polarity region. For the southern remote brightening site that is near the south pole, the polarity is generally positive with many magnetic kernels clearly to be seen. From the EIT 195 Å image shown in Figure 5.1d, it can be seen that both the eastern and southern remote brightenings are located in the vicinity of coronal holes (marked “CH”). Since the magnetic field lines outside the coronal holes return to the surface, it is deduced that the remote brightenings are the footpoints of large-scale closed loops.

Figure 5.2 shows the evolution of the L-shaped eastern remote brightening in Hα. The remote bright chain first brightened in the end furthest away from the flare core (patches 1–4), then in the near ends (patches 5–7). At ~20:44 UT, more than 10 individually brightened patches can be seen. The time between onset and maximum brightness of the major kernels 1–4 is about 6 minutes. For the southern remote brightening shown in Figure 5.3, there are two brightening branches as indicated by letters a and b at 20:49 UT, respectively. The latter branch gradually faded away
Figure 5.4  Soft X-ray images from SXI using the open filter position. The left panel at ∼20:45 UT shows the eastern remote soft X-ray brightenings (RXBs) in the shape of a letter L (denoted by arrows). The right panel at ∼20:53 UT shows the position of the southern remote brightening patches similar to those seen in Hα. The white line represents the solar limb. The field of view is 1000" × 1000". West is to the right, and solar north is up.

after about 4 minutes, while the former one propagated southeast toward limb with successively activated bright patches (Figures 5.3c–5.3f).

Similar remote brightenings were also observed in soft X-rays. A time-lapse SXI movie shows that the southern remote brightening moved southeast toward the limb, identical to the motion observed in Hα. One frame at ∼20:53 UT is presented in the right panel in Figure 5.4. However, due to the lack of time resolution, there is only one frame that is at ∼20:45 UT showing the eastern remote brightening (Figure 5.4 left panel), but with almost the same morphology as seen in Hα (see Figure 5.1a).

The present remote brightenings with the SCBs reported by Balasubramaniam et al. (2005) was compared. They are similar in that small chromospheric features outside the flare core brightened in both events. Differences lie in their morphology. First, the SCBs successively brightened with distance from the flare, while the two extended remote brightening sites presented in this study were found more than
Figure 5.5  (a) Hα red − blue subtraction and (b) EIT 195 Å images. Overplotted are wave fronts (solid lines) and parts of great circles (dashed lines) along which the distances from the supposed origin of the Moreton waves were measured. Times (in UT) for the northern traveling wave fronts are 20:43, 20:44, 20:46, 20:47, and 20:53. For the southern traveling wave fronts, they are 20:43, 20:44, 20:45, and 20:46. The locations of the filaments that started to oscillate when the Moreton wave past over them are indicated by arrows. “CH” indicates the coronal hole region.

2 × 10^5 km away from the main flare with neighboring coronal holes. Second, the SCBs were initiated following an eruption, while the two remote brightenings in the present event have different timings and are associated with the two main stages of flare energy release, respectively (see § 5.3.3 below).

5.3.2 Moreton Waves and Type II Radio Bursts

The Moreton waves were traced by difference images of OSPAN Hα off-bands. Figure 5.5 shows the full-disk images of this event in Hα off-bands subtraction and EIT 195 Å with the overplotted locations of the wave fronts (solid lines), which were determined visually using the subtraction images. The northern Moreton wave first propagated northeastward, then changed its direction toward northwest, probably because it encountered the coronal hole region there (“CH”; also see Figure 5.1d).
Figure 5.6  Radio data for about 20:40–20:50 UT on 2003 October 29 observed with the Culgoora Radiospectrograph, showing the type II radio bursts from $\sim$20:42–20:50 UT. Dotted and dashed lines depict the fundamental and harmonic components of the type II emissions, respectively.

The southern Moreton wave propagated all the way to the south pole. The dashed lines are the paths of the Moreton waves, which are drawn as parts of great circles on solar surface taking into account the curvature of the Sun. Along each path, the photospheric distances of the fronts from the supposed origins that were determined considering the shape of the wave fronts and the evolution of the H\textsc{$\alpha$} flare was measured. Oscillations of several quiescent filaments in the northern hemisphere (Figure 5.5a, arrows) were also observed at about 20:53 UT, which indicates that the northern Moreton wave passed by them.

The type II radio bursts associated with this event are identified on the Culgoora radiospectrograph shown in Figure 5.6. The metric type II bursts began at $\sim$20:42 UT
with starting frequency $\sim$400 MHz and ended at $\sim$20:50 UT at $\sim$60 MHz. The fundamental and harmonic emissions are marked with dotted and dashed lines, respectively. Both components appear in two branches. The first branch drifted very fast until $\sim$20:43 UT, while the second branch drifted more slowly, lasting for about 5 minutes. To determine the speed of type II radio bursts, the frequency drift seen in the spectrograph is converted to distance from the photosphere under a coronal electron density model. Such conversion depends on the model and the one proposed by Newkirk (1961) is chosen as it has been shown to better represent the inner corona (e.g., Warmuth & Mann 2005). Using this admittedly rough approximation, the extrapolated speeds of the two branches of type II radio bursts are found to be $\sim$2000 and $\sim$900 km s$^{-1}$, respectively, with almost the same start time at $\sim$20:42 UT.

The time/distance diagram for the Morton waves, the type II radio bursts, and the CME are shown in Figure 5.7, together with overplotted light curves of GOES soft X-ray flux at the 1–8 Å channel and RHESSI 50–100 keV photons for comparison. The distances of the Moreton wave fronts are measured from the flare site along the great circles (see Figure 5.5). It is obvious that the southern and northeastern traveling Moreton waves are spatially correlated with the faster and slower branches of the type II radio bursts, respectively, with similar speeds (at $\sim$1900 and $\sim$1100 km s$^{-1}$, respectively) and start times ($\sim$20:42 UT), suggesting that these two phenomena are closely related. It is also interesting to point out that the northeastern traveling Moreton wave was “reflected” by the coronal hole region at $\sim$20:46 UT with subsequently reduced speed at $\sim$760 km s$^{-1}$. The corresponding type II radio burst was slightly slowed down to $\sim$800 km s$^{-1}$. It is thus inferred from these results that the Morton waves and the type II radio bursts are simultaneous with each other. On the other hand, Figure 5.7 shows that the timing of remote brightenings (denoted by asterisks) do not correlate with the Moreton waves. It is thus unlikely that the Moreton waves are the trigger of the remote brightenings.
Figure 5.7  Time evolutions of the distances of the type II radio bursts, the Moreton waves, and the CME, overplotted with GOES 10 soft X-ray flux at the 1–8 Å channel and RHESSI 50–100 keV photons binned into 4 s intervals. The vertical axis represents the distances from the flare site along the great circles (see Figure 5.5) for the Moreton waves, the distances from the photosphere calculated with the Newkirk’s coronal electron density model for the type II radio bursts, and the height of the CME by extrapolating a constant deceleration fit back to the flare site. Note that the CME leading edge was at 2.92 $R_\odot$ at the time of the first LASCO image at 20:54:05 UT. Asterisks denote the earliest onset time and corresponding distances from the flare site of remote brightenings. “Rs” represents the solar radius (695,800 km).

The EIT wave is another wavelike phenomenon in the solar corona (Thompson et al. 1998, 1999), and it is shown in Figure 5.8 the running differences of EIT images before and after the eruption. The detection of an EIT wave in these data is difficult because of the widespread emission (extended bright region) seen in Figure 5.8b, either characterized as a “global enhancement” or attributed to instrumental scattered light (Cliver et al. 2004, and references therein). It was thus found no clear signature of
Figure 5.8 SOHO/EIT 195 Å running-difference images. The sequence consists of EIT 195 Å images at (a) 20:33 UT, (b) 20:48 UT, (c) 21:13 UT, (d) 21:24 UT, with previous images subtracted from them. Widespread emission is seen in (b) as an oval structure. The coronal dimming regions A and B indicated by the arrows in (b) and (c), respectively, are also outlined in Figure 5.10 (see discussion in §5.3.4).

an EIT wave in this event. However, the dimming regions seen in Figures 5.8b and 5.8c are discussed in §5.3.4.

5.3.3 Timing of the Flare Emissions

In Figure 5.9, flare emissions at hard X-ray, microwave, and radio wavelengths in terms of their dynamic spectra are plotted. For comparison, the time profiles of flux of the major Hα remote brightening kernels are also overplotted (middle panel). All the dynamic spectra show that the flare consists of two major peaks: the first peak
Figure 5.9 Dynamic spectra in RHESSI hard X-ray (top), OVSA microwave (middle), and Culgoora radio (bottom) wavelengths. Overplotted in the middle panel, the filled/unfilled white and gray circles represent the time evolutions of intensity of the major remote brightening patches in the eastern site (kernels 1–4/5 in Figure 5.2) and southern site (kernels a/b in Figure 5.3), respectively. The black line is the light curve of western hard X-ray sources shown in Figure 5.11. The vertical dashed lines indicate the onset times of the eastern remote brightening kernels 1–4 (at 20:41 UT) and the southern remote brightening kernels (at 20:49 UT).

lying from about 20:40 to 20:49 UT and the second from about 20:49 to 21:00 UT. Note that the eastern remote brightening (white circles) coincides with the first phase of the flare, and the southern remote brightening (gray circles), with the second phase. The overplotted light curve (black line) of the western hard X-ray sources (see Figure 5.11 below) further shows that the onset time of the major eastern remote Hα brightening kernels 1–4 at 20:41 UT (first vertical dashed line) coincides with the first spike in hard X-ray and microwave. The peak times of eastern remote brightening kernels
are also correlated with the peak emissions in hard X-ray and microwave. Similar correlation is found for the southern remote brightening.

Therefore, the remote brightenings are rather well related to the flare core emissions. This finding suggests that the remote brightenings may be due to direct chromospheric heating by the flare-accelerated electrons traveling along the large-scale magnetic loops connecting the flare core to the remote patches. Furthermore, the remote brightenings in the eastern and southern sites are associated with the first and second energy release process in the main flare, respectively.

The two phases shown in the radiospectrograph (bottom panel) are clearly characterized by the type II emissions and the radio pulsations (indicated by arrows), respectively. Since the radio pulsations can be regarded as a signature of dynamic magnetic reconnection (e.g., Kliem et al. 2000), the finding of association of type II emissions and radio pulsations with two distinct flaring phases bolster the argument of this eruption as two different processes (see discussion in § 5.4 below). Detailed study of the radio pulsation structure is beyond the scope of this study.

5.3.4 Coronal Dimming and CMEs

Coronal dimmings were found associated with this event in both EIT and SXI images. The top row of Figure 5.10 shows EIT 195 Å images before the flare (19:39 UT) and after the flare (21:48 UT) and the difference between two. The middle row shows preflare and postflare and the difference between the SXI images. Note that the soft X-ray image about 3 hours after the flare is chosen as postflare image in order to avoid the scattered light in the telescope right after the flash phase of the flare (see Figure 5.4). Care was also taken to differentially rotate all frames to 20:30 UT before subtraction. Two very similar dimming regions in EUV and soft X-ray are found and marked by “A” and “B” in the difference images. It is clearly visible that the two coronal dimmings are well associated with the two remote Hα brightenings,
Figure 5.10  Top row: Pre- and postflare EIT 195 Å images and the difference, showing the EUV dimming associated with the 2003 October 29 flare/CME. Two dimming regions are outlined by boxes A and B. Middle row: Pre- and postflare SXI soft X-ray images and the difference, showing the similar dimming regions as EUV. “F” denotes the flare core region. Bottom row: MDI magnetogram (left), Hα difference image showing the eastern remote brightening (middle), and Hα difference image showing the southern remote brightening (right). The field of view is $1200'' \times 1200''$. 
respectively, shown in the bottom middle and right panels. The bottom left panel shows a MDI magnetogram at 20:30 UT for comparison and it can be seen that the two H\alpha remote brightenings are located in opposite polarity magnetic fields. On the basis of Figures 5.8 and 5.10, the following is noted. First, Figures 5.8b and 5.8c shows that the eastern A and southern B dimming regions formed at different times, approximately following the occurrence of eastern and southern remote brightenings, respectively. The fact that the dimmings occurred at two different times supports the previous conclusion that two distinct energy release processes were involved with this eruption and each caused large-scale disturbances in the solar atmosphere. Second, the locus of these dimming regions are well aligned with those of the remote brightenings, suggesting that the remote brightenings occurred in the regions that eventually became evacuated to form extensions of the pre-existing coronal holes that they border. Since dimmings are considered as due to the loss of the coronal mass swept into CMEs along open field lines (e.g., Pohjolainen et al. 2005), the coronal dimmings found associated with the remote brightenings in this event may imply the opening of large-scale magnetic loops that were linking the remote brightening regions to the flare core as deduced in § 5.3.3.

A halo CME associated with this event was observed. It was first seen in C2 at 20:54:05 UT as a bright loop front over the south pole extending to \( \sim 2.9 \, R_\odot \). The CME height-time data provided by the LASCO Web site was used to find the average speed of the leading edge to be about 2029 km s\(^{-1}\). This speed is very similar to that of the faster branch of the type II radio burst and the southern traveling Moreton wave, implying their common origin. The height-time data back to the flare site was also extrapolated assuming a constant deceleration to find the CME starting at \( \sim 20:42 \) UT (see Figure 5.7), which is very close to the onsets of Moreton waves and the type II radio bursts. It can thus be concluded that the Moreton waves, the type
Figure 5.11 Temporal evolution of 50–100 keV hard X-ray source is superposed onto a MDI magnetogram (20:50 UT). Each cleaned RHESSI image is integrated over 20 s (5 spacecraft spin periods) with 9.4” FWHM resolution (using grids 3–7). Contour levels are 90%, 94%, and 98% of the maximum counts of each source illustrating its centroid position. The changing color of the contours represents times from 20:40:30 to 20:56:10 UT. The eastern (E) and western (W1) sources show clear separation motion after about 20:49 UT.

II radio bursts, and the CME are concurrent in this event. Close timing of Moreton wave, type II radio burst, and CME was also reported by Eto et al. (2002).

5.3.5 Flare Footpoint Motions

It is shown, in Figure 5.11, the RHESSI 50–100 keV hard X-ray source motions overplotted onto the MDI magnetogram. The kinematic morphology of the hard X-ray footpoints can be categorized into two phases. First, before about 20:49 UT, the hard X-ray emission is very complex and the footpoint motion is not clear. Two separate sources are seen in the western side at the beginning, while the source labeled
W2 disappeared around 20:43 UT. As it is discussed in §§ 5.3.1 and 5.3.3, the remote brightening kernels 1–4 lie farther away from the flare core but brightened earlier than those closer ones. A similar disjointed time-distance sequence of remote brightenings was also reported by Tang & Moore (1982). The eastern remote brightening kernels are also temporally associated with the western hard X-ray sources. These facts actually rule out the possibility of a shock wave propagating away from the flare site as the exciting agent of remote brightening, while favoring direct heating of the chromosphere by hot electrons traveling along large-scale loops. Second, the standard motion of hard X-ray footpoints as well as ribbons seen in Hα and UV wavelengths, i.e., separating away from the magnetic neutral line, is clearly seen during the second energy release process of the flare after about 20:49 UT. The eastern hard X-ray source moves obviously about 25″ toward the east, and the western source about 15″ toward the west. Interestingly, the southern remote brightening kernels also exhibit motion toward the east (see § 5.3.1), the same direction and during the same period as the eastern hard X-ray source. It is therefore presumed that the small-scale motion (less than 50″) of flare footpoints in the core region could represent a “mapping” of the large-scale restructuring, manifested as remote brightenings.

It is thus believed that the hard X-ray footpoint motions showing distinct behaviors in two phases is an important clue to the three-dimensional magnetic reconnection. According to the standard two-dimensional reconnection model (Priest & Forbes 2002), the progressive footpoint motion indicates magnetic reconnection in the coronal X-point. In the first stage (before ∼20:49 UT), however, such systematic hard X-ray footpoint motion is not seen, probably owing to the three-dimensional structure of the large-scale magnetic field that is not taken into account by the model. It is in the second stage (after ∼20:49 UT) that the progressive footpoint separation as predicted by the standard model can be seen. Krucker et al. (2005) carried out a detailed analysis of this footpoint motion to find a good correlation
between the electron energy and the magnetic energy release in the second stage. It therefore implies that the three-dimensional magnetic field evolves into a configuration resembling the standard two-dimensional reconnection model, perhaps as a result of the large-scale loop interaction in the first stage.

5.4 Speculation on the Large-scale Magnetic Fields
Since the present analysis suggests the presence of large-scale magnetic connections, it is considered appropriate to specify such a magnetic structure and its evolution during the flare. The present speculation here is mainly based on the magnetic polarity. In Figure 5.12a, the magnetic field configuration in the preflare state is plotted. The eastern remote brightening region has negative magnetic polarity and it should be connected to the positive polarity in the flare active region (black line). The southern remote brightening region has positive polarity and therefore connects to the negative polarity of the flare core (white line). Finally, the connectivity around the neutral line inside the active region (gray line) can be assumed. Under this configuration, it is the gray and black lines that can, on interaction, lead to the first phase of the flare emissions and the remote brightening in the east altogether.

The second phase is characterized by the hard X-ray footpoint as well as Hα/UV ribbon separation from the magnetic neutral line and the southern remote brightening. As discussed in § 5.3.5, this progressive motion could fit into the standard reconnection model. Figure 5.12b shows such magnetic configuration. As the reconnection point rises higher, the footpoints move farther away from the magnetic neutral line. Some portion of the hot particles precipitating along the recently reconnected field lines (thick gray line) can also drift to the ambient field lines that are connected to the southern remote brightening region (i.e., transported from the thick gray line to the white line; Lau & Ramaty 1995). As a result, the southern brightening occurred during the second phase of the flare.
Figure 5.12 Schematic picture showing the preflare (a) and postflare (b) magnetic configuration. See text for detailed explanation. (c) Preflare magnetogram obtained by MDI, superposed with the 3-day time profiles from October 28 00 UT of the measured absolute magnetic flux within the positive and negative polarity region P and N (as denoted by the boxes), respectively, where the October 29 X10 flare (denoted by the curve of vertical spike that represents the light curve of RHESSI 50–100 keV photons) occurred. The values for the Y-axis give the magnetic flux in $10^{21}$ Mx. (d,e) MDI white-light intensitygrams showing the rotational motion of spots F1 and F2 during about 4 days period before the flare. The fields of view of (a, b) and (c–e) is $780'' \times 780''$ and $290'' \times 290''$, respectively.
The pre- and postflare configurations shown in Figures 5.12a and 5.12b may explain the flare activities associated with the first and second phases, respectively. One issue, however, is that the magnetic evolution from the preflare to the postflare state requires that the overlying field (black line) should open, which becomes CME, in order to allow the inner loop system (gray line) to grow outward. This opening can be realized by reconnection of the black line and the gray line, but whether or not such reconnection is physically possible becomes another issue. Although this question is beyond the scope of this study, some characteristics in the long-term evolution of this active region that could be related to the triggering of such reconnection are reported as follows. First, it is found that magnetic flux emergence occurred in the flaring part of the active region (gray line). Examination of the MDI magnetograms from October 28 to 31 shows that the positive and negative flux within regions P and N increased by about $1.9 \times 10^{21}$ and $0.7 \times 10^{21}$ Mx, respectively (Figure 5.12c). A previous study also reveals that the magnetic shear along the flaring neutral line increased after this event (Liu et al. 2005). The apparent shear increase is interpreted as due to emergence of sheared magnetic fields, which can help to trigger the reconnection of the active region fields (gray line) with the overlying fields (black line) (Feynman & Martin 1995). Second, the evolution in MDI white light (Figures 5.12d and 5.12e) shows that the spots F1 and F2 had counterclockwise rotation by about $180^\circ$ during about 4 days period before the flare. Such rotation of sunspot will twist the active region fields (gray line), making them more prone to erupt (Sturrock et al. 2001). The twisted field lines can also have a larger tilt angle with respect to the overlying field to enhance the probability of reconnection. Finally, the reconnection in such a case will occur in a way to unwind the magnetic twist, i.e., reverse the rotation. It may then be expected that the Moreton waves and the type II radio bursts would be generated with a wide directivity toward the east and south regions, in agreement with the above observation (see Figure 5.5).
5.5 Conclusions of This Chapter

The large-scale activities associated with the 2003 October 29 flare are studied. The initial motivation of this study was the mechanism for the remote brightenings associated with this flare, but it also led to the study of the relationship between CME, Moreton waves, and type II bursts. Results of this study can be summarized as follows:

1. The timing of the Hα remote brightenings against the Moreton waves and the type II radio bursts have been checked. In the present results, the Moreton waves and the type II radio bursts are simultaneous but do not coincide with the remote brightenings; thus, they cannot be the trigger mechanism for the remote brightenings in this event.

2. The remote brightenings are closely related to the flare core emissions in time and morphology. It is therefore considered that the direct heating by hot particles transported along closed magnetic fields is more appealing as the mechanism for the remote brightenings. This result suggests the presence of large-scale connections between the remote brightenings and the flare core.

3. The timing analysis revealed that the CME, the Moreton waves, and the type II radio bursts could have occurred simultaneously. This may suggest that a CME could be a viable driver for the Moreton waves as well as type II radio bursts (Cliver et al. 2004).

4. The magnetic reconnection has to occur in two distinct stages in order to explain both light curves and morphological changes in the flare core and the remote brightening regions. In the first stage, a flux rope in the active region interacts with the overlying field to cause the first flare emission phase and the eastern remote brightening. In the second stage, the flux rope erupts and reconnects to cause continuous hard X-ray footpoints separation and the southern remote brightening.
5. Coronal dimmings were found at the locus of the two remote brightening regions, respectively. This is taken as another piece of evidence for the idea that this remote brightenings are due to magnetic reconnection rather than traveling disturbances.

6. From the long-term evolution of the active region, it is suggested that the emergence of sheared magnetic fields and the accumulation of magnetic twist due to sunspot rotation could trigger the first stage reconnection, which is responsible for most of the large-scale activities including the Moreton waves, type II radio bursts, CME, the eastern remote brightening, as well as the flare core emissions.

In the sense that the inferred scenario requires a removal of overlying field to allow the flare activity underneath, it favors a reconnection picture analogous to the magnetic break-out model (Antiochos 1998; Antiochos et al. 1999). A distinctive feature of this event, however, is that the two types of reconnection, one leading to the removal of the overlying field and the other associated with the flare ribbon motion, are well separated in time, perhaps owing to the large dimension of its magnetic configuration. It thus proposed that the remote brightenings and the flare emissions in this event could be a good example for clarifying the CME and flare processes in the magnetic break-out model.
In this chapter\textsuperscript{1}, a multiwavelength study of the eruption on 2005 May 13 that produced an M8.0 flare and a fast halo CME is presented. As an interesting property, the source active region NOAA 10759 appeared in a conspicuous sigmoid shape in TRACE 171 Å. Although such type of sigmoid has been well known in the soft X-ray community as a special magnetic structure prone to magnetic eruptions, this is perhaps the first case of high resolution observation at EUV wavelength. Following the event, the EUV sigmoid structure changed to an arcade structure. Another noteworthy property was that the hard X-ray emission source evolved from a confined footpoint structure to an elongated shape almost coinciding with the UV flare ribbons. This can be linked with the change of the sigmoid structure to an arcade structure after the eruption. Information on the eruption itself is obtained primarily from the radio dynamic spectra. First, radio disturbances known as type II precursors were found at the time of expansion of the two magnetic elbows of the sigmoid, which must be related to the beginning of the ejective eruption. Second, around the flare maximum, drifting pulsating structures (DPS) as well as typical type II and III radio bursts were found, which implies the ejecting plasmoid and subsequent blow-out of the envelope field and particle acceleration. Eventually the eruption picture drawn in this observation is quite similar to the standard bipolar eruptive flare model elaborated by Moore et al. (2001), in which the eruption starts in the

\textsuperscript{1}This chapter is based on the following papers:
core of a sigmoid and proceeds outward with the rising plasmoid via the runaway tether-cutting reconnection to produce a CME.

6.1 Introduction

Magnetic configurations that are favorable for eruption have been of recent interest in relation to space weather. One of the strongest candidates is the so-called sigmoid, an S-shaped magnetic field structure as seen in soft X-rays. It was first investigated by Rust & Kumar (1996) who found that many large soft X-ray brightenings associated with Hα filament eruptions and CMEs had sigmoidal shape. Several authors claimed that when active regions are in the sigmoid configuration, a higher probability of eruption to produce flares and associated CMEs is generally expected (Hudson et al. 1998; Canfield et al. 1999; Glover et al. 2000), and thus a sigmoid is an important precursor of a CME (Canfield et al. 2000). It was also found that a sigmoid often changes, after the eruption, to an arcade of loops, a process termed “sigmoid-to-arcade” evolution (Sterling et al. 2000). A qualitative model involving the sigmoid as pre-eruption configuration has been proposed by Moore et al. (2001), in which a magnetic explosion is unleashed by internal tether-cutting reconnection in the middle of the sigmoid. The sigmoid is now regarded as an important signature in space weather forecasts (Rust et al. 2005).

To date, active region sigmoids have primarily been observed using the Yohkoh SXT, implying that they are at temperatures of 2 MK and higher. It is, however, found that the active region NOAA 10759 (N12, E11) on 2005 May 13 appears in a sigmoid shape not only in soft X-rays but also in the EUV wavelength 171 Å of TRACE. The observation of sigmoid in EUV means that this structure can be seen at a wider range of temperatures down to 1 MK, and in fact, the structure is more clearly visible thanks to the higher spatial resolution (0.5″ per pixel) of TRACE. This sigmoid active region spawned a major Sun-to-Earth event with a flare classified as
2B/M8.0, an associated fast halo CME, and an intense geomagnetic storm on 2005 May 15.

Yurchyshyn et al. (2006) presented detailed description and analysis of the May 13, 2005 eruption, the corresponding CME and intense geomagnetic storm observed near the Earth on May 15, 2005. This multiwavelength study indicated that persistent converging and shearing motions near the main neutral line could lead to the formation of sigmoidal core fields (van Ballegooijen & Martens 1989; Linker et al. 2005; Welsch 2006). They further argue that those core fields eventually erupted according to the reconnection model (Moore & Labonte 1980). The in-situ formed erupting loop was observed as a magnetic cloud (MC) when it encountered the Earth. The erupting flux rope (EFR) model (Chen & Garren 1993; Chen 1996; Krall et al. 2000) was able to produce both a model halo CME and the interplanetary CME (ICME), thus providing a good global match to the overall timing and components of the magnetic field in the MC observed on May 15 2005. The orientation of the model ICME and the sense of the twist, inferred from the EFR model, agree well with the orientation and the magnetic helicity found in the source active region.

The present study further extends this comprehensive analysis of the 2005 May 13 event and focuses on the eruption processes of the EUV sigmoid. The results are compared with the bipolar eruption model proposed by Moore & Labonte (1980) and further elaborated by Moore et al. in 2001 (hereafter, Moore’s model) as a guide for interpretation. The plan of this chapter is as follows: § 6.2 summarizes the data sets used in this study. In § 6.3, the main results of the multiwavelength data analysis are described, and a summary is given in § 6.4.

### 6.2 Observational Data

A long duration event (LDE) flare started at 16:13 UT on 2005 May 13, reached its maximum at 16:57 UT, and ended at 17:28 UT (in terms of soft X-ray emission
measured by GOES). The event was well covered by many space- and ground-based instruments. Details of the flare loop structure are obtained from the TRACE 171 Å channel, SXI, and EIT. SXI images for this event were made with the polyimide thin filter sensitive to the coronal temperature at 3.8 MK and corrected for the instrument point-spread function. The observing time cadence ranges from 1–4 minutes and the pixel resolution is 5″. The EIT 195 Å images have 5.26″ pixel resolution and ~15 minutes cadence and represent an Fe XII line formed at a temperature around 1.5 MK.

LASCO observed a full-halo CME associated with this event. Due to the failure of the LASCO/EIT Electronics Box (LEB), unfortunately, only one C2 and one C3 full-frame images showing the halo CME were recorded. By combining three other C3 partial frames, the CME development can be followed in the southwest direction.

Radio observations for this event were obtained at OVSA, the Ondřejov radiospectrograph, the Tremsdorf Solar Radio Observatory of AIP Potsdam, and GBSRBS. All the data are digitally recorded. The Ondřejov data covered the whole event at 0.8–2.0 GHz and only the early phase at 2.0–4.5 GHz with 0.1 s time resolution. The AIP Potsdam instrument consists of swept-frequency spectrographs in the ranges 40–90, 100–170, 200–400, and 400–800 MHz, with a sweep rate of 10 s\(^{-1}\). There are, however, data gaps in 100–170 and 400–800 MHz ranges. The GBSRBS data used in this study were obtained with its low frequency system composed of a stand-alone active dipole that operates at approximately 20–70 MHz with 1 s sampling cadence. These radio data are used to infer the dynamics of the ejecta.

TRACE UV images provide a unique opportunity to observe transition region and chromospheric emission at high temporal and spatial resolution. The TRACE 1600 Å channel covered this event with a highest cadence of 3 s during some intervals and 0.5″ pixel resolution, which is used to study the flare ribbon motion in this event. Flare emission observed in the 1600 Å band comes predominantly from the upper
chromosphere and transition region and is thought to be produced by a mixture of particle precipitation and thermal conduction (see, e.g., Warren & Warshall 2001). Hard X-ray images were also obtained from RHESSI to further explore the energy release in this event. The photospheric magnetic field of the active region was measured with MDI.

6.3 Results
In this section, significant observational features found in all data sets are described. In specific, the sigmoid structure and its evolution observed at EUV and soft X-rays, CME and associated coronal dimmings in white-light and EUV, eruption signatures in radio dynamic spectra, and finally ribbon motions in UV and hard X-rays are presented. The results are interpreted whenever a plausible theoretical model for the observations is available.

6.3.1 Sigmoid in EUV Images
It is shown, in Figure 6.1, TRACE 171 Å images taken just before the event (16:08 UT) and in the postflare state (20:43 UT). The superposed contours are longitudinal fields measured with the MDI magnetogram. It can be seen that this is a bipolar active region consisting of a main round sunspot at the leading side with the positive magnetic polarity and a trailing part of negative polarity. The preflare EUV image (left panel) clearly shows many conspicuous inverse S-shaped sigmoidal loops at a better resolution (0.5") than previously observed sigmoids with the SXT (2.45" per pixel in full-resolution mode). After the eruption, the sigmoidal field changed to loops of an arcade (right panel), thus exhibiting the sigmoid-to-arcade evolution (Sterling et al. 2000). Following the nomenclature in the Moore’s model, the two oppositely curved magnetic elbows are denoted as “A” and “C”, each of which links one polarity to the other (for details on the magnetic configuration see Yurchyshyn et al. 2006).
Figure 6.1 Pre- and postflare images from TRACE 171 Å channel showing the sigmoid-to-arcade evolution of the coronal magnetic field in the 2005 May 13 M8.0 event. “A” and “C” denote the magnetic elbows and “B”, envelope loops, following the nomenclature used by Moore et al. (2001). MDI longitudinal magnetic field is superimposed with the red and yellow contours representing positive and negative fields, respectively. The contour levels are ± 50 G. The field of view is 384″ × 384″.

They loop out on opposite ends of the neutral line to form a typical sigmoid. In the middle of the active region, they are highly sheared along the magnetic neutral line. The envelope field (denoted as “B”) is less sheared and extends outward, possibly overarching the sheared core field. Since the active region is located very close to the disk center, the images in this figure serve as a top view of the preflare configuration, and they coincide with those depicted in the Moore’s model (see Figure 1 of Moore et al. 2001). In TRACE images, this sigmoid shape could be seen even four hours before the flare/CME (c.f. Figure 6 of Yurchyshyn et al. 2006) and the two elbows, gradually build up as nearing the flare time. A similar evolution of the sigmoid can also be seen in the EIT 195 Å images, at a lower spatial resolution.
6.3.2 Sigmoid in Soft X-Ray Images

The sigmoid structure was also checked with the soft X-ray images from SXI. While TRACE 171 Å channel has a data gap around the flare impulsive phase, the SXI data covered this period and showed important changes of the sigmoid morphology that was missed by TRACE. Figure 6.2 shows the time sequence of SXI images across the flaring interval in the upper three rows and the running difference images in the lower three rows. The sigmoid evolution in three distinct stages is described as follows:

1. Flare core brightening phase (∼16:18–16:27 UT, first row): the flare core is gradually brightened at the event onset. This is more clearly visible in the difference images. This core brightening indicates that the very start of the eruption begins with the internal reconnection among the sheared field in the middle of the sigmoid.

2. Loop expansion phase (∼16:30–16:39 UT, second row): two magnetic elbows lying northeast and southwest of the active region begins to slowly expand outward. This is more discernible in the difference images and best seen in a time-lapse movie. From 16:31 to 16:38 UT, the southwestern elbow showed an obvious outward expansion, with the outermost fronts outlined (see Figure 6.2). The expansion motion of the sigmoid elbows was also observed in the events studied by Moore et al. (2001) and interpreted as the beginning of ejective eruption.

3. Explosive phase (after ∼16:43 UT): the large-scale loops in both northeast and southwest direction were abruptly ejected outward, simultaneous with the sudden enhancement of the flare core emission. This is also evident from the difference images. In this stage, the envelope fields of the bipole appeared to be blown by the twisted flux rope as a result of the reconnection among the sigmoidal field. Afterward they are gradually re-closed to form and sustain a long-duration bright arcade. This leads to the sigmoid-to-arcade evolution.
Figure 6.2  Time sequence of SXI soft X-ray images (upper three rows) showing the evolution of the sigmoid that exhibits three stages (see discussion in § 6.3.2). Lower three rows are the running difference images. The outermost fronts of the southwest elbow are outlined to show its expansion, with crosses denoting the measured positions at $\sim 238^\circ$. The field of view is $700'' \times 700''$. West is to the right and solar north is up.

6.3.3 Filament, CME, and Coronal Dimming

There was an inverse S-shaped chromospheric filament running along the magnetic neutral line, which is associated with the preflare EUV sigmoid. It showed disturbance and briefly disappeared from the field of view during the flare impulsive phase. However, it was undisturbed and re-appeared afterward (see Figure 3 of Qiu &
Figure 6.3 LASCO images showing the evolution of the halo CME associated with the 2005 May 13 M8.0 flare. The preflare C2 image at 16:52 UT shows several streamer structure with the strongest one lying in the southwest. 17:22 UT C2 and 17:42 UT C3 are full-frame images, while C3 images at 17:30, 17:40, and 17:50 UT are partial-frame. The evolution of the outermost part of the CME diffuse front (CME leading edge) and the CME flank (where the CME interacts with the southwestern streamer and the intensity gradient is maximum) are both measured (marked by arrows), at measured position angles (MPA) of ∼180° and ∼238°, respectively. The top middle panel is the SOHO/EIT 195 Å difference image showing the twin dimmings after the launch of the CME.

Yurchyshyn (2005). In fact, it has been found that although the sigmoid-to-arcade transformation indicates catastrophic perturbation in the corona, the active region filament lying below the sigmoid often shows no significant changes through the eruption and can be interpreted as partial eruption only (Pevtsov 2002).

Figure 6.3 shows the development of the full-halo CME associated with this eruption. The CME was first seen in C2 at 17:22 UT already halfway across the C2 field of view and completely surrounding the C2 occulter. The C3 image taken at 17:42 UT also shows a very symmetric and bright halo (see Figure 8 of Yurchyshyn et al. 2006). There are three C3 partial frames at 17:30, 17:40, and 17:50 UT available,
which were combined to measure the CME propagation (marked with arrows). The outermost part of the CME diffuse front (CME leading edge) was measured at a position angle of $\sim 180^\circ$, and the CME flank where it interacted with the southwestern streamer and the intensity gradient is maximum was measured at a position angle of $\sim 238^\circ$. The average speed of the CME leading edge and flank are $\sim 1600 \text{ km s}^{-1}$ and $\sim 1100 \text{ km s}^{-1}$, respectively. The LASCO Web site reports the speed of this CME to be $\sim 1689 \text{ km s}^{-1}$ at the position angle of $2^\circ$, which is very similar to the above mentioned result of that of the southern diffuse front and might be the speed of the northern diffuse front that can also be seen. It should be remarked, however, that the LASCO Web site only measures two frames and one of them, the C3 image at 17:12 UT, barely shows the CME.

A coronal dimming, an important signature of CMEs (see, e.g., Thompson et al. 2000), was also looked for using EIT 195 Å images. The difference image between just before and after the flare impulsive phase at 16:37 and 16:57 UT, respectively, is shown in the middle upper panel in Figure 6.3. Two regions of strong dimmings were found that lie on opposite ends of the neutral line, extending toward northeast and southwest. This kind of so-called twin dimmings has been only occasionally observed in EIT (see, e.g., Thompson et al. 1998). In this case, the twin dimmings were not transient, but sustained after the eruption, as one can tell by comparing all the other postflare EIT images (17:07, 17:27, and 17:37 UT) with the preflare image. By 22:57 UT (EIT 195 Å data has a gap between 17:37 and 22:57 UT), the southwestern dimming region already developed into an elongated trans-equatorial coronal hole.

\subsection{Radio Bursts}

It has been well known that Type II radio bursts are the manifestation of shock waves in the solar corona, usually associated with either large flares and/or fast CMEs
(Nelson & Melrose 1985). It is shown, in Figure 6.4, the GBSRBS radio spectra along with the X-ray light curves for this event, in which a fast decametric type II burst is clearly seen with the fundamental and harmonic emissions marked with dotted lines (bottom panel). The type II burst began at $\sim$16:41:30 UT with starting frequency $\sim$50 MHz (harmonic lane) and was immediately preceded by a type III radio burst, which is conventionally interpreted as accelerated electrons escaping along open field lines. The occurrence of the type II and type III radio bursts are almost simultaneous with the peak of RHESSI 25–100 keV hard X-ray emissions at $\sim$16:42 UT (second panel). The harmonic lane of the type II burst and the type III burst were also recorded by the dynamic spectrum from Potsdam in the 40–90 MHz band. In order to determine the speed of type II radio burst, it is needed to convert the frequency drift seen in the spectrograph to the trajectory of the type II source using a coronal electron density model. It has been suggested that the one-fold Newkirk model (Newkirk 1961) well represents the density in the inner corona and that at coronal heights greater than 1.8 $R_\odot$, switching to the Mann model (Mann et al. 1999) is preferred (Warmuth & Mann 2005, see § 1.2.2 for details). This suggestion is followed and the speed of the type II radio burst is estimated to be $\sim$1200 km s$^{-1}$. The formation height of the metric type II precursor (see below) in this event is estimated to be $\sim$0.9–1.7 $\times$ 10$^5$ km (see Figure 6.8).

A remarkable feature at the very beginning of the flare is the radio bursts in the $\sim$200–300 MHz frequency range at 16:33:30–16:34:30 UT as detected in the Potsdam radiospectrogram (Figure 6.4, fourth panel). These fast drift bursts or pulsations are the new type of radio emission, called type II precursor (Klassen et al. 1999). In this event they are concurrent with the earliest energy release at $\sim$16:32–16:35 UT traced here by the temporal derivative of the soft X-ray light curve (gray curve in top row) and also by the onset of the soft X-ray loop expansion. Meanwhile, the broadband pulsations appeared at 16:32:40–16:36:30 UT in the high frequency range
Figure 6.4  Top panel: Time evolution of the GOES X-ray fluxes and the time derivative of the 1.6 keV band. Second panel: RHESSI photon rates binned into 4 s intervals. The 25–50 and 50–100 keV rates are placed arbitrarily. The time intervals a–f divided by the vertical lines are for RHESSI images shown in Figures 6.7 and 6.8. The attenuator status for RHESSI switched between A1 and A3 during the observation period. “N” and “S” denote the time period of RHESSI night and south Atlantic anomaly, respectively. Third to bottom panels: Radio spectrum observed by Ondrejov, Potsdam, and GBSRBS, respectively. Note the broadband DPS at 16:58–17:12 UT in the 1.0–2.0 GHz range and the metric type II precursor around 16:34 UT in the 200–300 MHz range. Fundamental (“F”) and harmonic (“H”) components of the type II emissions detected by GBSRBS are depicted by the dotted lines.
Figure 6.5  Detailed view of observations by the Ondřejov radiospectrograph. Top panel: The 2.0–4.5 GHz radio spectrum observed at the very beginning of the 2005 May 13 flare. It shows broadband pulsations in which high-frequency boundary drifts towards lower frequencies. Middle panel: The 0.8–2.0 GHz radio spectrum shows the narrowband DPSs, indicating the plasmoid ejection in the impulsive flare phase. See also the reverse drift bursts at 16:37:47–16:37:57 UT in the 1.4–1.8 GHz range. Bottom panel: An enlargement of the drifting pulsation structure observed in the postflare phase. See also the fiber bursts at 16:59:30–17:00:10 UT in the frequency range of 1.4–2.0 GHz.

of 2.0–4.5 GHz of the Ondřejov radiospectrograph (Figure 6.5, top panel). As can be seen here the high-frequency boundary of these pulsations drifts towards lower frequencies. These pulsations might be caused by a series of fast electrons beams, which drift so fast that cannot be distinguished. In the 0.8–2.0 GHz range (not shown) these bursts were associated with weak 0.8–2.0 GHz broadband continuum on
which the bright narrowband continuum (1.3–1.5 GHz, 16:33:30–16:33:50 UT), zebra pattern (1.6–1.8 GHz, 16:33:00–16:33:41 UT; Zhelezniakov & Zlotnik 1975; Bárta & Karlický 2006), and narrowband dm-spikes (0.8–1.2 GHz, 16:33:30–16:34:00 UT) were superimposed. All these radio bursts are considered to be the high-frequency precursors of the type II radio burst observed in decametric range.

At 16:37:15–16:41:00 UT in the 0.8–1.4 GHz range two weak narrowband drifting pulsating structures (DPS) were observed (Figure 6.5, middle panel). Their frequency drift rate was about $\sim -2.5 \text{ MHz s}^{-1}$. See also the reverse drift bursts at 16:37:47–16:37:57 UT in the 1.4–1.8 GHz range. These DPSs were observed during the rapid rising phase of the hard X-ray emission, therefore they may represent the radio emission from ejected plasmoids formed during the flare reconnection process as proposed by Kliem et al. (2000) and Karlický (2004).

Finally, in the postflare phase, at 16:58–17:12 UT in the 1.0–2.0 GHz range the broadband DPS was observed (Figure 6.4 third panel and Figure 6.5 bottom panel). The emission frequency drifts at a rate $\sim -1.2 \text{ MHz s}^{-1}$. It consists of several strong pulses with the characteristic period of about 90 s, which might indicate oscillation of the postflare loops. The fiber bursts were also recognized (see Figure 6.5 bottom panel; Aurass & Kliem 1992). Since this drifting pulsating structure is observed after the hard X-ray maximum, it can be associated with the postflare growing loop system (Švestka et al. 1987). Namely, this radio emission is probably generated by plasma emission processes at the top of this growing postflare loop system while there is still slow reconnection above the postflare loops to inject the radio emitting particles (see e.g., Akimov et al. 1996). The radio drift towards lower frequencies is then explicable in terms of the decrease of the electron density at the top of this loop with time. The termination shock may also present at the top of this loop system and contribute to the radio emission as proposed by Aurass & Mann (2004).
Figure 6.6  Separation of flare ribbons from 16:30 to 17:00 UT observed in TRACE 1600 Å (color-coded areas). The gray background is a preflare TRACE 171 Å image at 16:08 UT showing the sigmoidal field. The white dashed line is the magnetic neutral line.

6.3.5 UV Ribbon Motion

Recently many studies were made to use flare ribbon separation motion as a clue to the magnetic reconnection in corona (Saba et al. 2006, and references therein). In that approach, the change rate of the magnetic flux in the chromospheric ribbon area, \( R = \frac{d\Phi}{dt} \), is measured and then regarded as equivalent to the rate at which magnetic flux brought into the magnetic reconnection region in the corona (Priest & Forbes 2002). In this event the flare ribbon motion is clearly seen in TRACE 1600 Å images, and the ribbon area was measured in every 15 s while the original TRACE
data have 3 s cadence with some time gaps. The successive flare ribbon position was registered onto the co-aligned magnetogram and followed the intensity-based binary masks method presented by Saba et al. (2006) to determine $R$. The separation motion of the flare ribbon from 16:30–17:00 UT is shown as color-coded areas in Figure 6.6 and plot the resulting $R$ in both the positive and negative magnetic fields as a function of time in Figure 6.10 (middle panel). In the present result the flux change in two polarities are well balanced and the peak of the magnetic reconnection rate reaches $\sim 5.1 \times 10^{18}$ Mx s$^{-1}$. The total amount of magnetic flux participating in the reconnection is $\sim 3.4 \times 10^{21}$ Mx. It is noted that this value is about two times smaller than that reported by Qiu & Yurchyshyn (2005), in which 1 minute cadence Hα images were used. The difference is attributed mainly to the higher cadence TRACE UV data near the flare peak time used in the present study. It is also found that the magnetic flux reconnection rate is temporally correlated with both the hard X-ray light curves and the time derivative of the soft X-ray light curves, the signatures of nonthermal flare emissions. This coincidence is theoretically expected under the standard magnetic reconnection in bipolar magnetic structure (Priest & Forbes 2002) and also observationally confirmed in several previous studies (Qiu et al. 2004c).

6.3.6 The Ribbon-Like Hard X-ray Emission

**Introduction** Theoretical aspects of flare ribbon morphology is reviewed first as follows. The “ribbon” structures of solar flares have long been observed at Hα and EUV/UV wavelengths. A ribbon in one magnetic polarity region is paired with a ribbon in the other magnetic polarity region and both run parallel to the magnetic neutral line lying between them. Such a configuration has been regarded as evidence for the classical 2D reconnection model called the CSHKP model, in which magnetic reconnection occurs at a coronal X-point and energy release along the field lines produces bright flare emissions at the two footpoints in the lower atmosphere
connected to the X-point. A series of footpoints along a coronal arcade of loops will form two ribbons, and the ribbons should separate from each other as successive reconnections occur in the higher corona above the arcades. Even though the actual flare process may take place in a more complicated 3D structure, the observations of two-ribbon flares, at least, show the general applicability of the CSHKP model (Lin et al. 2003).

In many events, hard X-ray emissions are found as single or double compact sources near magnetic neutral lines and considered as coming from footpoints of flaring loops (Ohki et al. 1983; Sakao et al. 1996). Although there are found loop-top hard X-ray sources as well (Masuda et al. 1995), the trend of footpoint hard X-ray emissions is stronger with increasing photon energy. The footpoint emission of hard X-rays is generally understood as thick target bremsstrahlung radiation of high energy particles accelerated in the corona and precipitating into the chromosphere along the magnetic loops (Dennis 1988). This means that hard X-rays, EUV/UV, and Hα commonly represent the chromospheric response to the energy input from the corona during flares. Nevertheless hard X-rays sources usually appear in point-like compact regions within the Hα/UV ribbons. This distinction between the flare emission morphology at softer wavelengths and that of hard X-ray sources has been recognized as a yet unsolved problem and is a subject of active research. For example, as early as the in the era of balloon-borne X-ray detection, Takakura et al. (1971) compared the Hα source and hard X-ray source in the 1969 September 27 flare. They found that the hard X-ray source was located on the line passing through the center of the flare region, and the size of the source was much smaller than that of the Hα flare region. One explanation to this myth was proposed by Asai et al. (2002), who found hard X-ray kernels being confined to stronger-field parts of the ribbons. Asai et al.’s explanation is based on the standard magnetic reconnection model, in which the magnetic energy release is proportional to the local field strength. This, however,
means that the confined hard X-ray source only represents an enhancement in energy release rate according to the magnetic field contrast, and thus more of the ribbon in hard X-rays should be seen, given sufficient dynamic range of the hard X-ray observations.

In retrospect, only a single event of ribbon-like hard X-rays has been reported. It was the 2000 July 14 X5.7 flare observed with the Yohkoh HXT and the hard X-ray ribbons were found in both the M2- (33–53 keV) and H-bands (53–93 keV) (Masuda et al. 2001). However, the most of the flare rising phase was not observed due to an HXT data gap. It was also not shown whether those hard X-ray ribbons coincided with ribbons at other wavelengths.

Observation  RHESSI has an almost complete coverage of the impulsive phase of this event\textsuperscript{2}. Figure 6.4 second panel shows the RHESSI hard X-ray lightcurves at three energy channels along with the time intervals chosen for imaging (a–f). For high image quality, a one-minute time interval was chosen. RHESSI images were reconstructed with the CLEAN algorithm using grids 1–9, which gives ∼5.9" FWHM resolution. The natural weighting scheme was used, in which counts from all detectors are given equal weight, to have a better sensitivity for the detection of isolated compact sources and extended sources (Hurford et al. 2002, also see Veronig et al. 2006). Imaging in the time period between intervals e and f was avoided, within which change of the RHESSI attenuator from A1 to A3 occurred. No pulse pile-up of lower energy photons is evident in the obtained RHESSI hard X-ray images. Alignment between RHESSI and TRACE was done in two steps. First, by matching the main sunspot feature it was found that the shift between TRACE 1600 Å and white-light bands for this event are negligible. The TRACE white-light channel was then aligned with an MDI intensitygram via cross-correlation and the offset found

\textsuperscript{2}See a brief report in the RHESSI Science Nuggets at http://sprg.ssl.berkeley.edu/~tohban/nuggets/?page=article&article_id=40
Figure 6.7 A time sequence of RHESSI 25–50 keV hard X-ray images integrated in the one-minute time intervals a–f (denoted in Figure 6.4 second panel). Each RHESSI image was reconstructed with the CLEAN algorithm using grids 1–9 with the natural weighting scheme (giving \( \sim 5.9'' \) FWHM resolution). The peak flux in each image is labeled and the green contours show flux at levels of 0.1, 0.115, and 0.13 photons cm\(^{-2}\) s\(^{-1}\) arcsec\(^{-2}\). Panel f also shows RHESSI 6–12 keV image with yellow contours at levels of 50%, 70%, and 90% of its maximum flux. The white contours outline the TRACE 1600 Å ribbons taken near the center of each RHESSI time interval.

was applied to the TRACE 1600 Å images. Considering that the MDI roll angle can be known no better than 1°, the accuracy of alignment between RHESSI and TRACE 1600 Å band is estimated to be \( \sim 5'' \) at maximum.

Figure 6.7 shows the RHESSI 25–50 keV maps superposed with contours at fixed photon flux levels and those outlining TRACE UV ribbons. Until the flare maximum (intervals a, b, and c), hard X-ray emissions appear as point-like compact sources, which are located within the flare ribbons. At the flare maximum time, there are four hard X-ray sources and the average magnetic field strengths of flare ribbons
Figure 6.8  Same as Figure 6.7, but the RHESSI 50–100 keV hard X-ray images are shown. The green contours show flux at levels of 0.018, 0.02, and 0.022 photons cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$.

associated with hard X-ray emission kernels (\(\gtrsim 50\%\) of the maximum) are about two to three times larger than that of the other parts of the ribbons. This result is in agreement with the suggestion by Asai et al. (2002) that the hard X-ray emissions are concentrated on the parts of ribbons with stronger magnetic fields.

After the flare maximum (intervals \(d\), \(e\), and \(f\)), the hard X-ray sources, however, become elongated to form a ribbon structure. This footpoint-to-ribbon evolution of hard X-ray emissions is more evident for the much stronger eastern hard X-ray sources. Several kernels can be seen within the ribbon during the time interval \(e\). At the time interval \(f\), significant hard X-ray emission (although with a much lower flux level compared with peak time) is found along the entire section of each ribbon. Note that the hard X-ray distribution at this time is no longer concentrated to the
Figure 6.9  Pre- and postflare images from TRACE 171 Å channel showing the sigmoid-to-arcade evolution of the coronal magnetic field. “A” and “C” denote the magnetic elbows and “B”, envelope loops, following the nomenclature used by Moore et al. (2001). SOHO/MDI longitudinal magnetic field is superimposed with the yellow and green contours representing positive and negative fields, respectively. The contour levels are \( \pm 50 \) G. Same RHESSI contours as Figure 6.7c are overplotted onto the preflare TRACE image. RHESSI image Figure 6.7f is overplotted onto the postflare TRACE image with contour levels 40%, 60%, and 80% of the maximum. The field of view is 384" × 384".

strongest magnetic field regions, unlike the above mentioned suggestion by Asai et al. (2002).

A nearly identical trend is found at higher energies (50–100 keV) as shown in Figure 6.8, although the image quality is not as good as that of 25–50 keV images due to significantly lower photon counts. At lower energies (6–12 keV), X-ray sources lie between the ribbons presumably near the tops of the loops joining them (see Figure 6.7f). Therefore this ribbon-like structure is not a phenomenon limited to low energy thermal particles, but extends to nonthermal high-energy electrons.

It is also noted, within the accuracy of the alignment, that the hard X-ray sources tend to lie at the evolving edge of UV ribbons that were expanding to the southeast and northwest directions. This indicates that the hard X-ray sources are
due to the electrons precipitating along the most recently reconnected field lines. One may ask whether the hard X-ray sources move with and/or along the UV ribbons. Although the hard X-ray sources could not be traced in detail because of the limited time range of good count statistics for RHESSI imaging, the location of the hard X-ray ribbons remains consistent with the UV ribbons in all the six time intervals covering 6 minutes. Image quality would have been degraded if shorter time intervals for imaging was used.

The hard X-ray sources are further superimposed onto the pre- and postflare TRACE images in Figure 6.9. The footpoint-like hard X-ray sources are clearly seen at the foots of thepreflare sigmoid while the hard X-ray ribbon lies along one side of the postflare TRACE arcade.

**Interpretation** To understand why the hard X-ray ribbon structure appears so prominently in this specific event, the special sigmoidal magnetic structure of this active region is recalled and a speculation on the flaring scenario based on the Moore’s model is offered as follows. In Figure 6.11, a schematic plot of the magnetic field configuration and its evolution in the model is reproduced. First, reconnection begins between the two elbows in the middle of the sigmoid (Figure 6.11a), and later less sheared field lines from the outer sigmoid core progressively reconnect to each other. Hard X-ray sources should be largely footpoint-like at this stage lying at the footpoints of the sigmoidal loops (sources 1–4 in Figure 6.11a), which corresponds to the hard X-ray morphology in Figure 6.7c and Figure 6.9 left panel. Second, at the flare maximum, the envelope is blown out, along with the twisted flux rope inside it, after which the opened legs of the envelope will continue to reconnect (Figure 6.11b). In this stage, it is presumed that the electrons are accelerated either in the whole magnetic arcade in the corona, or in local corona area and then fan out throughout the arcade to bombard the dense chromosphere. This leads to the ribbon-like hard
X-ray emissions as shown in Figure 6.7d–f and Figure 6.9 right panel. On this basis, it is speculated that this footpoint-to-ribbon transformation of the hard X-ray source morphology is a natural outcome of the sigmoid-to-arcade evolution of the magnetic field configuration.

Another question that follows is why, then, such ribbon-like hard X-ray sources have not been reported in other events involved with the sigmoid structure as well. First, as pointed out by Asai et al. (2002), the limited sensitivity of the instrument can result in picking up stronger X-ray emission sources only. The previous hard X-ray imager, Yohkoh HXT, had a good dynamic range of ∼10, but the current instrument, RHESSI, has even a higher dynamic range of ∼20 (Hurford et al. 2002). Second, it is wondered whether an unusual property of this active region has something to do with the visibility of the hard X-ray ribbons. Although numerous preflare sigmoids have been observed at soft X-ray temperatures > 1.5 MK (e.g., Sterling et al. 2000), it is the first time to find a sigmoid at the EUV temperature (∼1 MK). It is a speculation that the relatively low temperature of this sigmoidal active region might be related to the formation of the hard X-ray ribbons. For instance, the chromosphere of this active region was less pre-heated before the flare compared with other soft X-ray sigmoids and could therefore yield a better contrast in hard X-ray emission when bombarded by the high energy electrons from the corona. Finally, note that the sigmoid-to-arcade transformation has been discussed only recently, specifically after Sterling et al. (2000). Only a few papers have been published on the sigmoidal active regions without focus on its association with hard X-ray morphology, except Masuda et al. (2001).

6.3.7 Evolution of Flux Rope
The flux rope motion in relation to the CME dynamics is finally wished to be determined. Since this is a disk event, the height of the flux rope directly could
not be measured. The horizontal motion of the expanding elbows is used instead as a proxy for the height of the ascending flux rope assuming a cylindrical symmetry. The projected distance of the soft X-ray loop front is measured from the expanding southwestern elbow depicted in Figure 6.2 (crosses) and the center of the sigmoid and is fitted assuming a constant acceleration. The heights of the decametric type II burst and the metric type II precursor are estimated using Mann’s and Newkirk’s coronal electron density models, respectively. The best-fits of height-time data of the southern CME leading edge (at 180°) and flank (at 238°) were extrapolated back to the flare site assuming a constant velocity and a constant deceleration, respectively. The heights of the expanding soft X-ray loop, the type II radio burst and precursor, and the CME determined in these ways are shown in Figure 6.10 (bottom panel), in comparison with the time profile of the magnetic reconnection (middle panel), the light curves of GOES soft X-ray flux at the 1–8 Å channel, its time derivative, and RHESSI 50-100 keV photon rates (top panel). Three things are noted as follows:

First, the radio and soft-X ray data of this event show that the formation height of the metric type II precursor is similar to that of the concurrent initial rising of the flux rope after reconnection (see Figure 6.10 bottom panel). It is thus likely that the type II precursor emission observed in this event is driven by the moving X-ray loops, and therefore is a signature for the onset of shock formation in the low corona (see Dauphin et al. 2006, and references therein). It is however remarked that the X-ray loop in this event moved at \( \sim 250 \text{ km s}^{-1} \), which might not be high enough to generate the shock in the low corona (\( \sim 10^5 \text{ km} \)). But this velocity might be underestimated since only the projected distances could be measured. As a comparison, type II emission are reported to be usually associated with rapidly rising X-ray structure (e.g., Gopalswamy et al. 1997; Klein et al. 1999; Dauphin et al. 2006).

Second, the decametric type II burst has the similar velocity and height-time evolution as that of the southwestern CME flank, where it interacts with a strong
Figure 6.10  Top panel: Flare light curves of GOES 1–8 Å channel, its time derivative (black line), and RHESSI 50–100 keV photon rates binned into 4 s intervals. Middle panel: Magnetic reconnection rate derived in positive and negative magnetic fields. Bottom panel: Time evolutions of the distances of the expanding soft X-ray loop, the type II radio burst, and the CME. The vertical axis represents the projected distances from the center of the sigmoid for the expanding soft X-ray loop, the distances from the photosphere calculated with the Mann’s and Newkirk’s coronal electron density model for the type II burst and type II precursor, respectively, and the heights of the CME front and flank by extrapolating a constant velocity and constant deceleration best-fit, respectively, back to the flare site. The size of symbol for the metric type II precursor denotes its range of appearance time and formation height. Note that the CME leading edge was at $\sim 5.2 \, R_\odot$ at the time of the first LASCO C2 image at 17:22 UT. “Rs” represents the solar radius.
streamer structure, instead of that of the southern diffuse front that might be the CME leading edge. Density enhancement in the helmet streamer compared to the diffusion front forms a low Alfvénic region as favorable for the generation of the type II burst. Therefore, this suggests that the type II radio emission in this event originated when the CME interacted with the dense coronal streamer, as has been previously reported (e.g., van der Holst et al. 2002; Reiner et al. 2003; Mancuso & Raymond 2004; Cho et al. 2007).

Third, at the flare peak (∼16:42 UT), the maximum of the magnetic reconnection rate and the sudden increase of height of flux rope are seen together. It is not sure whether or not there was a true acceleration of the flux rope due to the lack of direct measurement of the height at this time. As a comparison, Qiu et al. (2004c) found that a maximum acceleration occurs at the time of maximum magnetic reconnection rate derived from the ribbon expansion, and claimed that the flux rope motion is affected by the magnetic field reconnection. As a support to this view, there have a couple of radio signatures. First, the DPS in the 0.8–1.4 GHz range suggests the ejection of the plasmoids (Karlický 2004). Second, the type III radio burst immediately preceding a decametric type II burst implies that the flux rope blew the envelope field in the upper corona, and finally escaped to become the CME.

### 6.4 Conclusions of This Chapter

In this study, a set of multiwavelength data of the eruption occurred on 2005 May 13 have been presented. The following summarizes and highlights the noteworthy properties found in this study and clarify how they agree to the Moore’s model with illustrations shown in Figure 6.11.

1. A characteristic feature of this event was the EUV sigmoid structure. The preflare sigmoid in this event had been unambiguously observed in images taken with 1 MK TRACE 171 Å Fe IX/X channel, 1.5 MK EIT 195 Å Fe XII channel, and
Figure 6.11  Schematic picture interpreting the present multiwavelength observations, based on the eruptive model for sigmoidal bipoles proposed by Moore & Labonte (1980) and elaborated in Moore et al. (2001). Four hard X-ray sources 1–4 are at the foots of the sigmoidal loops in a (c.f. Figure 6.7c and Figure 6.9 left panel). The thick gray lines denote envelope fields. See detailed discussions in §§§ 6.3.6, 6.3.7, and 6.4.
3.8 MK SXI polyimide thin filter position, thus confirming the structure visible in a wider temperature range than previously known (> 1.5 MK, see Sterling et al. 2000). The high resolution preflare TRACE image clearly reveals not only the overall sigmoid shape, but also the highly sheared field in the core and the envelope coronal magnetic field. This structure is schematically drawn in Figure 6.11a.

2. The subsequent evolution of the sigmoidal active region up to the flare maximum as seen at EUV and Soft X-rays is in good agreement with the Moore’s model. In specific, the initial flare brightening occurred in the middle of the sigmoid seems to signify the beginning of tether-cutting reconnection at the sigmoid core (Figure 6.11a). Later expansion of the two elbows of the sigmoid indicates the ongoing ejective eruption. Finally, the envelope field is blown out by the eruption of the flux rope (Figure 6.11b), which leads to the long-lived postflare reconnection and flare arcades.

3. The filament was not disrupted during this event, which implied that filament is not the trigger thus not essential for this kind of reconnection between sigmoidal loops. This further suggests that the tether-cutting reconnection occurs above the filament and the resulting loops below the X-point actually protects the filament from disruption (Pevtsov 2002).

4. The exceptional long-lived twin dimmings seen in this event, when placed within the context of the Moore’s model, can be naturally explained by the eruption of the two magnetic elbows extending northeast and southwest of the active region (Figure 6.11b).

5. A special feature found in the RHESSI images is the morphological change of hard X-ray emissions from the typical point-like compact sources (Figure 6.11a, c.f. Figure 6.7a–c) to the elongated ribbon source (Figure 6.11b, c.f. Figure 6.7d–f). It is suggested that this footpoint-to-ribbon transformation of the hard X-ray
source is another signature of the sigmoid-to-arcade evolution of the magnetic field configuration.

6. For this event there have a rich collection of radio emission features, including the type II precursors, DPS, and type II and III bursts. The event can thus be interpreted as follows: the type II precursors found in the metric to microwave wavelengths are due to a low coronal shock driven by the rising flux rope seen at soft X-rays (Dauphin et al. 2006, and references therein). The similar timing suggests that the decametric type II emission in this event occurred when the CME interacted with the dense coronal streamer, a favorite condition for the shock formation. Following Karlický (2004), the DPS in the 0.8–1.4 GHz is associated with the ejection of the plasmoids around the flare maximum, and another broadband DPS in the 1.0–2.0 GHz range with the growing postflare arcades.
This dissertation work is supported in part by a grant from the NSF’s Solar, Heliospheric, and INterplanetary Environment (SHINE) program. One of the fundamental questions in the SHINE objective is to understand solar properties of flare/CMEs and related phenomena, including their ultimate origin, precursors, and near-Sun evolution. The research presented was focused on this problem, by investigating the core and large-scale magnetic structures and their evolution associated with flare/CMEs through multiscale (from microflares to major solar eruptions) and multiwavelength (from hard X-rays to radio) observations. In the following, the key results of the presented observational studies are summarized. Subsequently, related discussions on each aspect are made to further the understanding of the physics involved and shed light on the direction of future research.

7.1 Flare Core Region

7.1.1 Microflares
Most of the solar flare events investigated in this dissertation occurred between 2000 and 2005, the declining phase of solar cycle 23. One of the most exciting events for the solar research community during this period was the launch of RHESSI, a powerful tool for studying electron acceleration in solar flares. By inserting a thin shutter (A1) or a thick shutter (A3) automatically in front of the detectors to absorb the low energy photons, RHESSI is able to avoid saturation when large flares occur. On the other hand, when both shutters are out (A0), RHESSI provides uniquely high sensitivity in the energy range from $\sim 3$–$15$ keV compared with previous solar hard X-ray instruments (see Liu et al. 2004, and references therein). Therefore, for the first
time, a detailed study of the locations, spectra, and magnetic properties of microflares with high resolution was carried out by combining RHESSI X-rays, BBSO Hα, and MDI magnetogram observations. 12 microflare events were presented in Liu et al. (2004), and the major conclusions are as follows:

- **All these microflares have detectable signatures in hard X-ray, soft X-ray, and Hα with temporal evolution resembling that of large flares;**

- **The studied X-ray class A2–B3 flare events all occurred in active regions with locus near magnetic neutral lines. Homologous microflares are also found in certain active regions;**

- **Spectral fitting results suggest the presence of nonthermal hard X-ray emissions down to \( \sim 10 \) keV during the impulsive phase of microflares. The photon spectra of microflares associated with type III radio bursts are generally harder than those without type III bursts at the flare peak time, indicating that a larger portion of electrons was accelerated to higher energy regime;**

- **The elongated X-ray sources, which represent emission from small magnetic loops, are found to connect two Hα bright kernels, which indicate emission at footpoints of these loops in the lower atmosphere. In one event (2002 June 26 B1.4 flare), RHESSI further resolved two nonthermal footpoint-like emissions with thermal sources in-between;**

- **Co-temporal and co-spatial EUV jets are identified for the type III-associated B1.4 event. This suggests that open field lines, which resulted from magnetic reconnection, provided a pathway along which both accelerated electrons and heated plasma were ejected outward.**

The above argument of morphology of Hα and hard X-ray emissions produced in microflares, as well as recurrent microflare activity, were reasserted by Jain et al. (2006) utilizing observations from SOlar X-ray Spectrometer (SOXS) mission on board an Indian satellite. The distribution of microflare events with respect to the flux, the solar activity, and active regions was statistically studied by Qiu et al. (2004b). Nonthermal properties of microflares are further confirmed through spectral analysis of X-rays as well as microwaves (Qiu et al. 2004b; Maltagliati et al. 2006).

One thing, however, is that the definition of microflare is not based on physics, and thus the division between flares and microflares is arbitrary. In the present
Figure 7.1  Demodulated RHESSI hard X-ray light curves at different energy ranges during the rising phase of the 2002 March 17 M4.0 flare. The vertical dotted lines denote those pronounced spikes. Inset frame show magnified view of a short time period where several spikes can be identified. (reproduced according to Qiu et al. 2005, private communication)

study (see § 3), flares with GOES soft X-ray class $\leq$ C1.0 are defined as microflares. This criterion was then also followed by other studies (e.g., Jain et al. 2006). These flares are small in the sense of low soft X-ray emission output and usually last for minutes. On the other hand, some flares display short timescales, which could indicate that flare energy release is fragmented. Termed “elementary bursts” (de Jager & de Jonge 1978), such flare temporal components could have rise and decay time as short as 1.2 s. Using recently developed demodulation code (Qiu et al. 2005, private communication), RHESSI was able to resolve hard X-ray spikes with fine temporal structures of $\leq$ 1 s up to 100 keV photon energy (see Figure 7.1 for an example). It is thus scientifically interesting to explore these “microflare”-like features in larger flares by combining multiwavelength observations with high cadence and high resolution to further the understanding of flare energy release in detail.
7.1.2 Rapid Evolution of Magnetic Fields

Very recently, the new observational phenomenon of rapid changes of sunspot structure associated with a substantial fraction of flares was discovered by the BBSO group (Wang et al. 2004a; Deng et al. 2005; Liu et al. 2005; Chen et al. 2006). In particular, Liu et al. (2005) studied the relationship between the change in $\delta$ spot structures and associated major flares for seven events. The results are quite consistent for all the events:

- **Penumbral segments in the outer $\delta$-spot structure decay rapidly after major flares, and meanwhile, the neighboring umbral cores and/or inner penumbral regions become darker. The rapid changes, which can be identified in the time profiles of white-light mean intensity, are permanent, not transient, and thus are not due to flare emission;**

- **The co-aligned magnetic field observations show substantial changes in the longitudinal magnetic field associated with the decaying penumbral areas and darkened central areas. For two events for which vector magnetograms were available, it is found that the transverse field associated with the penumbral decay areas decreased while it increased at the flare neutral lines. Both events also show an increase in the photospheric magnetic shear after the flares;**

- **For all the events, the locations of penumbral decay are found to be related to flare emission and are connected by prominent TRACE postflare loops.**

Before this study, solar flare physicists focused mainly on the long term evolution of $\delta$ sunspots structure in terms of days. This study shows that the rapid penumbral decay is a real physical process due to a permanent change of the penumbral field lines to a more vertical state after reconnection, thus is closely associated with the flaring process within hours. Wang et al. (2005) reevaluated the Bastille Day flare on 2000 July 14 and found very similar penumbral decays. They provided further solid physical evidence to support those real changes, e.g., decrease of Evershed velocity in the penumbral decay areas and formation of a new electric current system near the flare neutral line.

Motivated by these studies, Chen et al. (2006) investigated 403 events from 1998 May 9 to 2004 Jul 17, including 40 X-class, 174 M-class, and 189 C-class flares.
Figure 7.2 Mean penumbral decay index, which is defined as contrast change integrated over the decayed area, as a function of GOES X-ray flux. Obviously, larger flares show much larger detected structure changes. (Chen, W., Liu, C., Song, H., et al. 2006)

Their main result, as shown in Figure 7.2, suggests that the phenomenon of sunspot change associated with flares is more notable for larger events. In retrospect, it is worth mentioning that a brief note was published by Howard (1963) claiming that the sunspot penumbrae might shrink after flares.

To explain these observations, the first reconnection picture actually describing the flare effects on sunspots was proposed\(^1\), in which the two components of a $\delta$ spot become strongly connected after the flare. In the outer border of the $\delta$-structure, the penumbral fields change from a highly inclined to a more vertical configuration, which leads to penumbral decay. The umbral core and inner penumbral region close to a neutral line become darker as a result of increased field strength there, mainly in the form of transverse fields.

\(^1\)See http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons/thepages/Liu.html.
The increase of magnetic shear near flaring neutral lines after flares is contradictory to the conventional thinking that the magnetic shear should decrease following the release of nonpotential magnetic energy. Based on the study of short-term evolution of magnetic fields associated with five flares in δ sunspots, Wang (2006) suggests the following explanation: it is true that the shear of the whole active region, signified by the separation of mean positions of the two magnetic polarities, relaxes after flares reflecting the overall energy release; however, the shear increase near the neutral line is a localized phenomenon, reflecting magnetic connectivity for a small area, and therefore does not necessarily contradict the expectation of an overall decrease of the stored magnetic energy of the active region. Indeed, in the reconnection model proposed by Melrose (1997) involving current-carrying loops, some current will be able to be measured near the photosphere due to the low and small loop that resulted from the reconnection, and therefore, an increase of the magnetic shear near the flaring neutral lines may be detected. An alternative way to explain this is that, after reconnection, there is new flux emergence due to the relaxation of the fields above the photosphere and the newly emerged flux is more strongly sheared.

It is anticipated that the next generation of high cadence, high resolution, and high precision polarimetry data from BBSO imaging magnetograph systems, as well as the newly launched Hinode and future SDO missions, will provide better sensitivity to more accurately measure photospheric magnetic field evolution.

7.1.3 Sigmoids

“One of the best shows in 15 years!” This is the comment from astronomy enthusiasts about the Northern Lights (auroras) that rippled across much of the United States on the weekend of 2005 May 14 and was discernible as far south as in California and
Arizona\textsuperscript{2}, following a major Sun-to-Earth eruption classified as M8.0 on 2005 May 13. This eruption stirred equally strong interest for flare researchers because the source active region NOAA 10759 appeared in a strikingly sigmoid shape at TRACE 171 Å channel just before the flare/CME. A detailed multiwavelength study of the eruption of this EUV sigmoid was presented by Liu et al. (2006b,c) and the major findings in the flare core region are as follows:

- In this event, the first sigmoid observed with high resolution (0.5\arcsec per pixel) and at an EUV wavelength (TRACE 171 Å) was reported. Compared with the numerous previously studied sigmoids, which were predominantly observed with the Yohkoh SXT at soft X-ray wavelengths with a highest resolution of 2.45\arcsec per pixel, the TRACE image clearly shows not only the overall sigmoid shape of the preflare coronal magnetic field structure, but also the highly sheared magnetic fields near the flaring neutral line. Moreover, this EUV sigmoid (\sim 1 MK) was visible in a lower temperature range than previously known for soft X-ray sigmoids (> 1.5 MK). After the flare, the sigmoid changed to a giant arcade structure as expected;

- Although an inverse S-shaped filament was observed before the event, which is presumably a chromospheric manifestation of the overall sigmoidal preflare magnetic field structure, it did not disrupt after the eruption (see Pevtsov 2002, for a statistical study). This challenges the classic flare models, in which filaments are usually regarded as the trigger of the ultimate eruption;

- The RHESSI hard X-ray sources imaged in a wide energy range, from 25–100 keV, show a footpoint-to-ribbon transformation from before to after the flare peak. In the flare decay phase, hard X-ray sources occupy most of the flare UV ribbons. This is the first well-observed hard X-ray ribbon structure since the launch of RHESSI in 2002\textsuperscript{3}.

Based on the tether-cutting flare model for eruptive bipoles proposed by Moore et al. (2001), a tentative flaring scenario was put forward, which naturally links the unusual sigmoidal active region with the appearance of the rarely observed ribbon-like hard X-ray sources. At the early phase of the eruption, tether-cutting reconnection occurs in the sigmoid core region where the magnetic fields are highly sheared.

\textsuperscript{2}See http://spaceweather.com/aurora/gallery_01may05_page2.htm.
\textsuperscript{3}See a brief report in the RHESSI Science Nuggets at http://sprg.ssl.berkeley.edu/~tohban/nuggets/?page=article&amp;article_id=40.
The hard X-ray emission appear as footpoint-like sources located at the foot of the sigmoidal loops. Later on, the reconnection between the sigmoidal loops result in a small loop below the coronal X-point and a large twisted flux loop above. The small loop actually protects the filament from disruption, while the large twisted flux loop erupts outward and blows away the envelope fields, following which reconnection occurs between the opened legs of the envelope fields. At this stage, the electrons are presumed to be accelerated in the whole coronal arcade, or in the local corona area then fan out through the arcade to bombard the dense chromosphere, leading to the ribbon-like hard X-ray emissions.

Moreover, the undisturbed filament indicates that filament eruption is not a prerequisite for certain types of reconnection, e.g., the tether-cutting reconnection between the sigmoidal loops.

It is certainly of great importance to find out how the sigmoid involved in this event formed. Using the BBSO line-of-sight magnetograms covering the period from 15:43–19:44 UT, Yurchyshyn et al. (2006) produced the averaged flow maps by local correlation tracking technique (November & Simon 1988) showing the long-term evolution of the photospheric magnetic fields (see Figure 7.3). Converging and shearing motions can be seen along two different converging lines CLN and CLS, where oppositely directed flows, associated with the negative polarity fields and the main sunspot, merge. The authors speculate that these converging and shearing flows could, according to the cancellation model (van Ballegooijen & Martens 1989), lead to formation of the two systems of independent magnetic loops, i.e., the sigmoidal core fields, and to the build up of free magnetic energy in the coronal field (Welsch 2006). Figure 7.4 shows TRACE 171 Å images up to about three hours before the event, which exhibit such gradually formation and strengthening of the sigmoidal loops, presumably due to the mechanism mentioned above.
**Figure 7.3** Averaged horizontal plasma flow map calculated from 107 BBSO line-of-sight magnetograms recorded between 15:43 and 19:44 UT on 2005 May 13. The maximum velocity in the sunspot moat lying just north of the main sunspot reaches \(\sim 1\, \text{km s}^{-1}\) with r.m.s. = 300 m s \(^{-1}\). Nf1, Nf2, Pf1, Pf2 denotes the locations of the nonthermal hard X-ray footpoint sources at the foots of the sigmoidal loops (see, e.g., Figure 6.9 left panel). Lines CLN and CLS mark the area of converging horizontal flows, and the diamond indicates the stagnation point in the flow pattern. (Yurchyshyn, V., Liu, C., Abramenko, V. & Krall, J. 2006)

**Figure 7.4** Three TRACE 171 Å images showing the building up of the sigmoid responsible for the 2005 May 13 M8.0 flare/CME at \(\sim 17\, \text{UT}\).
It should be further emphasized that statistically, active regions with a sigmoidal shape are more likely to erupt and cause CMEs (see § 6.1), thus automatic feature recognition technique has been developed to use the appearance of sigmoid shape to implement CME forecasting (Rust et al. 2005). In a physical point of view, the overall shape of fields in an active region with strong electric currents flowing is theoretically sigmoidal (Amari et al. 2000), thus the presence of sigmoid indicates that free magnetic energy is being stored in the coronal magnetic fields available for flare/CMEs eruptions. In principle, the well-accepted force-free field, i.e., \( \nabla \times B = \alpha B \), is a good approximation to describe coronal magnetic field (Priest 1984). Practically, Pevtsov et al. (1997) gave a two-dimensional linear force-free field solution to parameterize the shape of sigmoids, i.e., \( \alpha = (\pi L) \sin \gamma \), in which \( L \) is the length of line connecting endpoints of sigmoidal loops, and \( \gamma \) is the acute angle between this line and a tangent to the central sigmoidal loops. The authors found a good correlation between coronal \( \alpha \) value derived in this way and the photospheric \( \alpha \) determined from vector magnetograms, implying the current responsible for the coronal sigmoid shape has its subphotospheric origin. In regard of simulation, Kliem et al. (2004) demonstrated how the sigmoids form and concluded that the vertical current sheet below the erupting twisted flux rope due to kink instability is a central element of the standard flare model.

7.2 On the Large-Scale

7.2.1 The 2003 October 29 X10 Event

Since 2002, the frequency of X-flares during the solar cycle 23 has headed toward minimum\(^4\). Besides the notably intense solar activities around 2000 July and 2001 April, there was little bang that can excite space weather forecasters. However, the dramatic activities on the Sun during 2003 October/November changed the story,

\(^4\)See Figure 2 of a Science@NASA report at http://science.nasa.gov/headlines/y2005/05may_solarmyth.htm.
highlighted with the X28 limb event on 2003 November 4 that would rank as the largest X-ray flare since solar soft X-ray data became available in the mid 1970s. Most of the major eruptions stemmed from the active region NOAA 10486, one of the largest sunspot groups of the current solar cycle. When it rotated to near the disk center on 2003 October 29, it spawned an X10 flare, which was so strong that caused remarkable disturbances in the solar atmosphere as well as interplanetary space. Liu et al. (2006a) combined multiwavelength data sets obtained from various observational facilities to show many well-exhibited large-scale postflare phenomena seen in this event. The major conclusions are as follows:

- **Two extended remote brightenings and coronal dimmings were observed at Hα and EUV wavelengths, respectively, which are more than \( 2 \times 10^5 \) km away from the main flare site. These remote Hα brightenings are located on the edge of coronal holes that showed dimming after the flare. Because of their synchronism with the main flare emissions observed at hard X-ray and microwave wavelengths, it is suggested that the remote Hα brightenings represent heating of the chromosphere by the flare-accelerated electrons traveling along the large-scale magnetic loops connecting the flare core to the remote patches;**

- **The timing analysis suggests that the CME (\( \sim 2029 \) km s\(^{-1}\)) could be a viable driver for the Moreton waves (\( \sim 1900 \) km s\(^{-1}\)) and type II radio bursts (\( \sim 2000 \) km s\(^{-1}\)), which were all launched at about 20:42 UT;**

- **Long-term evolution of the active region suggests that the first stage magnetic reconnection could have happened between the emerging sheared and twisted magnetic fields with the overlying large-scale fields, which is responsible for most of the large-scale activities. In the distinct second stage, regular separation motion of the hard X-ray footpoints are found, indicating the successive reconnection after the eruption of flux rope. In the sense that this two stage reconnection scenario requires a removal of overlying field to allow the standard type flare activity underneath, it favors a reconnection picture analogous to the magnetic breakout model.**

The aforementioned scenario requires that there are large-scale magnetic loops connecting the flare core to the remote brightening sites (see Figure 5.12a). However, such loops can hardly be seen in the coronal images, possibly due to the unfavorable temperature and emission measure. It is nonetheless meaningful to note that the
Figure 7.5  Comparison of the current helicity density $h_c$ map and the RHESSI hard X-ray observation of the 2003 October 29 X10 flare. In (a), the solid and dashed black contours represent the upward ($h_c > 0$) and downward ($h_c < 0$) components of the current helicity density at 06:29:27 on 2003 October 29, respectively, with levels of $\pm 2, 8, 20, 40 \times 10^{-2} \, \text{G}^2 \, \text{m}^{-1}$. In (b), white contours of the hard X-ray (50–100 keV) emissions near the peak of the X10 flare are superposed on (a), with levels of 10%, 20%, 40%, 70%, and 90% of the maximum. The cleaned RHESSI image is constructed from the time period 20:45:30–20:46:30 UT using grids 3–9. The correlation between the two hard X-ray footpoints and the counterhelical islands (B and C) is obvious. (Liu, Y., Kurokawa, H., Liu, C., et al. 2006)

reconstructed coronal magnetic field using the potential field source surface model (PFSS) shows such large-scale loop structure connecting the active region flare core to the eastern remote brightening site\(^5\).

In the sense of large-scale study, the overall evolution of the non-potentiality of the flaring active region is an important topic. For this purpose, the vertical

\(^5\text{See a result at http://cdaw.gsfc.nasa.gov/geomag_cdaw/data/cdaw1/nitta/pfss/pfss_20031029_18.gif}\)
electric current density $J_z = \frac{1}{\mu_0} (\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y})$ and the further derived current helicity density $h_c = (\nabla \times B)_z \cdot B_z = \mu_0 (J_z B_z)$ based on photospheric vector magnetic field observations provide a way to quantitatively describe the degree of non-potentiality of active regions. Liu, Kurokawa, & Liu (2006) analyzed vector magnetograms taken at Huairou Solar Observing Station (HSOS) and Mees Solar Observatory (MSO), which reveal that the super active region NOAA 10486 was a complex region containing current helicity flux of opposite signs. Based on a comparison of two days of deduced current helicity density data, pronounced changes were noticed that were associated with the occurrence of the X10 flare. The average current helicity density (negative) of the main sunspot, the helicity densities of ambient counterhelical patches (positive), and the helicity of the whole sunspot group decreased significantly by about 50% after the flare. This result strongly suggests that the X10 flare on 2003 October 29 was resulted from reconnection between the counterhelical fluxes which led to the effective canceling of opposite helical fields. Furthermore, the cores of the two hard X-ray footpoints are adjacent to the positions of two counterhelical patches which disappeared after the flare, as shown in Figure 7.5. It is therefore interesting to investigate in the future whether the emerging magnetic flux in the flare core region has an opposite helicity sign with the overlying large-scale field in this event.

7.2.2 The 2005 May 13 M8.0 Event

For this event, large-scale evolution was evaluated under the context of tether-cutting flare model as follows (Liu et al. 2006c):

- **Ejective eruption occurred after the initial flare brightening at the sigmoid core region due to tether-cutting reconnection, and the subsequent expanding soft X-ray loops could have driven a shock in the low corona, which was manifested as the type II precursors found in a wide frequency range;**

- **Near the flare maximum, a twisted flux rope (plasmoid) was abruptly ejected outward, which drove the decametric type II emission in the high corona and became the CME;**
• *The timing analysis suggests that the decametric type II emission in this event occurred in the region where the CME interacted with the dense coronal streamer, a favorite condition for the shock formation;*

• *The exceptional twin dimmings after the launch of the CME could be explained as due to the loss of corona mass after the eruption of the sigmoidal loops in the northeast and southwest directions.*

It should be noted that as being emphasized in the model of Moore et al. (2001, c.f. Figure 6.11), sheared sigmoid core field and envelope fields above are actually not in separate domains. Such drawing of sheared core and envelope fields are completely arbitrary only to match the observed configurations. Thus, the mentioned tether-cutting reconnection begins from the sheared core field, then the continuous larger scale and less sheared fields come to reconnect. The outcome of this reconnection process will be one large-scale magnetic system directly connecting the leading and following part of the active region. In another word, the erupting flux loop (CME) should be rooted in the leading positive and following negative fields. Yurchyshyn et al. (2006) claimed that this in-situ formed erupting loop was subsequently observed as a MC when it encountered the Earth. The authors were further able to use the EFR model to produce both a model halo CME and ICME which provides a good match to the overall timing and components of the magnetic field in the MC observed on May 15 2005. Also, the magnetic properties of the model ICME (e.g., orientation, twist) agree with those of the source active region.

With the combined studies of the flare manifestations in the core region as well as in the large scale, the 2005 May 13 event thus provides a good example of investigating major solar eruption from its source region all the way to the magnetosphere, which is crucial to unearth the physics behind the observed various disturbances in all scales, hence helpful to advance the space weather forecasting.
7.2.3 Foreseeing the Future Work

As a concluding remark to this dissertation, the direction of future efforts are outlined below:

- **With existing and improved vector magnetograms at BBSO, and with newly launched Hinode and SDO after 2008, more quantitative studies of rapid changes of magnetic fields associated with the core region of flares and CMEs should be made.** These studies include analysis of spectroscopic properties of changing sunspot structure and 3-D extrapolation of magnetic field structure before and after the eruptive events. In addition, flow fields (shear flow and converging flow) should be studied. These will provide a key to understand the possible triggering of flare/CMEs and subsequent restructuring of magnetic fields;

- **Studies should be extended to include much extended areas (consider the entire solar disk), so one will have a much larger scale views of flare/CMEs. Several aspects of the large-scale signature of eruptions, including Hα remote brightenings, remote filament activations, Moreton waves, type II radio bursts, and large-scale coronal dimmings should be integrated to map out the initiation and subsequent disturbances of the flare/CME eruptions;**

- **Various aspects of the observational results should be carefully compared with the generally accepted flare/CME models to further the understanding of the physics behind the complicated solar eruption phenomena.**
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