Structure and evolution of magnetic fields associated with solar eruptions

Haimin Wang and Chang Liu

Space Weather Research Laboratory and Big Bear Solar Observatory, New Jersey Institute of Technology, University Heights, Newark, NJ 07102-1982, USA; haimin.wang@njit.edu

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Abstract This paper reviews the studies of solar photospheric magnetic field evolution in active regions and its relationship to solar flares. It is divided into two topics, the magnetic structure and evolution leading to solar eruptions and rapid changes in the photospheric magnetic field associated with eruptions. For the first topic, we describe the magnetic complexity, new flux emergence, flux cancelation, shear motions, sunspot rotation and magnetic helicity injection, which may all contribute to the storage and buildup of energy that trigger solar eruptions. For the second topic, we concentrate on the observations of rapid and irreversible changes of the photospheric magnetic field associated with flares, and the implication on the restructuring of the three-dimensional magnetic field. In particular, we emphasize the recent advances in observations of the photospheric magnetic field, as state-of-the-art observing facilities (such as Hinode and Solar Dynamics Observatory) have become available. The linkages between observations, theories and future prospectives in this research area are also discussed.

Key words: Sun: flares — Sun: magnetic fields

1 MAGNETIC STRUCTURE AND EVOLUTION LEADING TO SOLAR ERUPTIONS

One of the greatest scientific discoveries in the last century is the existence of magnetic fields in sunspots (Hale 1908). Following this discovery, the detailed structure and polarities of magnetic fields in solar active regions (ARs) have been extensively investigated (e.g., Richardson 1948). On a large scale, the magnetic field and its evolution play a crucial role in the generation of the solar activity cycle. In the short term, the level of complexity of the magnetic field can be linked to the productivity of solar flares. It is generally believed that the magnetic field provides energy for solar energetic events, namely, flares and coronal mass ejections (CMEs). Although the details of energy storage and release have not yet been fully understood, from an observational point of view, the frequency and intensity of activities observed in the solar corona correlate well with the size and complexity of the host ARs. Furthermore, the evolution of the photospheric magnetic field is coupled to the surface flow field, which provides important information about energy build-up and conditions for triggering flares. In recent years, there have been significant advances in the study of magnetic structure and evolution, owing to the availability of state-of-the-art observations and the development of advanced data analysis and modeling tools. In this section, we review the current
understanding of both static and dynamic pre-flare conditions. Clearly, the related studies not only reveal the physical mechanisms associated with triggering flares, but also enhance our ability to forecast solar eruptions, which are the source of the geomagnetic and particle effects in the near-Earth environment. Therefore, these studies are an important part of space weather research.

1.1 Static Pre-flare Condition

Significant attention was paid to the classification of magnetic complexity of sunspots even in early years. One of the most widely used classification schemes is the Mount Wilson classification system (Hale & Nicholson 1938), in which sunspots are categorized into α, β, γ and δ configurations which have increasing magnetic complexity. The α and β sunspots have a simple unipolar and bipolar structure, respectively, and these two classes of sunspots have a relatively small chance of producing flares. γ sunspots have mixed polarities, while δ sunspots are the most complicated, with two umbrae of opposite polarities sharing a common penumbra. Most ARs can exhibit properties that are combinations of these classifications due to the existence of different activity centers. Kübel (1960) was the first to link flare productivity to δ sunspots. A more significant correlation between δ sunspots and the production of major flares was revealed by Zirin & Liggett (1987), in which 18 years of data from Big Bear Solar Observatory (BBSO) were analyzed to study the development of δ sunspots and their association with flares. In particular, the authors introduced the term “island δ sunspot,” which is a compact, elongated δ sunspot that could be the core of the most flare productive ARs. For example, Wang et al. (1991) studied the well-known AR 5395 that appeared in March 1989, which produced a number of large flares and caused significant space weather effects.

Figure 1 shows the BBSO D3 and magnetograph observations of this AR that were taken on 1989 March 10. The dominant polarity of this AR is positive, but many small negative umbrae surround the central positive umbra, forming an extended magnetic polarity inversion line (PIL). Multiple flares were observed to occur in different sections of this PIL.

Other sunspot classifications are also used to describe the size and complexity of ARs related to flare productivity, and therefore have received attention for their usefulness in terms of solar flare prediction. For example, McIntosh (1990) introduced the “McIntosh” sunspot classification system, which is modified from the earlier Zurich classification system (Kiepenheuer 1953). It includes 60 distinct types of sunspot groups, and has been incorporated into an expert system that predicts flares (e.g., Gallagher et al. 2002; Bloomfield et al. 2012). The McIntosh classification system is currently used by the Space Weather Prediction Center of NOAA.

Before the availability of vector magnetic field data, line-of-sight (LOS) magnetograms alone were used extensively to study solar magnetic fields. One way to analyze the non-potentiality of ARs based on the LOS magnetic field observation is to carry out potential field extrapolations, and compare the structure of the derived three-dimensional (3D) magnetic field with that of the observed coronal loops. Schrijver et al. (2005) classified ARs into flare-active and flare-quiet regions based on a comparison of extrapolated fields with coronal loops observed by the TRACE satellite. They found that in ARs with non-potential coronae, flares occur 2.4 times more frequently and their average peak brightness in X-ray is 3.3 times higher than those flares in near-potential regions.

Besides sunspot classifications based on LOS magnetograms, vector magnetograph observations can produce important and useful magnetic parameters for characterizing the non-potentiality of ARs. Several ground-based observatories provided valuable vector magnetograms before such data from space observations became available in recent years. These facilities include BBSO, Marshall Space Flight Center, Huairou Solar Observing Station, administered by National Astronomical Observatories, Chinese Academy of Sciences, and Mees Solar Observatory, administered by the University of Hawaii. Wang et al. (1996) used vector data from Huairou and demonstrated how the vertical current can be used as a proxy for non-potentiality. The authors found that flare activity in AR 6233 was closely associated with vertical electric currents. In an effort to identify an indicator
of activity, numerous photospheric magnetic properties have been explored (e.g., Schrijver 2007; Jing et al. 2006; Song et al. 2009; Welsch et al. 2009). A number of magnetic parameters have been used to predict solar flares, such as surface magnetic free energy (Wang et al. 1996; Leka & Barnes 2003a,b; Falconer et al. 2006), unsigned magnetic fluxes averaged in different ways (Schrijver 2007; Barnes & Leka 2006; Georgoulis & Rust 2007; Jing et al. 2006), magnetic shear and magnetic gradient (Hagyard et al. 1984; Song et al. 2009; Falconer 2001; Falconer et al. 2003; Chen & Wang 2012; Li & Zhu 2013), and magnetic energy dissipation (Abramenko 2005). Zhou & Ji (2009) presented a study of the relationship between magnetic shear and flare shear. In a more recent analysis, Song et al. (2013) used several parameters to quantify the magnetic complexity of AR 11158 and found a correlation with flares in this region.

The above assessment of magnetic non-potentiality is only based on the surface measurement; however, it is likely that the energy that powers flares is stored in the solar corona. As the coronal magnetic field cannot be directly measured with high resolution or precision, extrapolating a magnetic field from the observed photospheric boundary becomes important. Based on LOS magnetograms, a potential (current-free) field can be easily derived as done in Schrijver (2007). It can be further assumed that magnetic field lines run parallel to electric currents and that the ratio between current and field strength is a constant $\alpha$ (i.e. the so-called linear force-free condition). Quick results
from non-potential coronal fields can be obtained in this way (e.g., Gary 1989), and this $\alpha$ can also be used to evaluate the non-potentiality of ARs. Nevertheless, the assumption of a single force-free parameter is far from reality.

One of the most advanced coronal magnetic field modeling tools developed to date is the nonlinear force-free field (NLFFF) extrapolation, in which $\alpha$ can vary among different field lines. Schrijver et al. (2006) and Metcalf et al. (2008) summarized and compared various techniques for implementing the NLFFF assumption. It was shown that the method developed by Wiegelmann (2004) has certain advantages in modeling the 3D coronal field. The efforts at extrapolation have been plagued by the problem that the photospheric magnetic field is not necessarily consistent with the condition of being force-free. To deal with this, Wiegelmann et al. (2006) preprocessed vector magnetograms in order to extract the observed non-force-free photospheric data near a suitable boundary condition in the chromosphere for a force-free extrapolation. The preprocessing routine minimizes a functional that includes two terms respectively corresponding to the force-free and torque-free conditions, with one term controlling how close the preprocessed data are compared to the original magnetogram (noise-level), and one term controlling the smoothing. This preprocessing method removes the net force and torque from the boundary of the photosphere, and hence provides an improved input for the subsequent NLFFF extrapolation (Metcalf et al. 2008).

It is fortunate that the Helioseismic and Magnetic Imager (HMI) onboard the Solar Dynamics Observatory (SDO) that was launched in 2010 provides full-disk vector magnetograms, overcoming the limited field of views (FOVs) that handicapped previous observations. Meanwhile, substantial progress has been made over the past few years in improving the treatment of boundary data and the NLFFF extrapolation method. For example, a new version of Wiegelmann’s extrapolation code has been developed recently that takes the curvature of the Sun’s surface into account, so that extrapolations can be applied to large areas (Tadesse et al. 2013). In addition, the new version also considers measurement errors in photospheric vector magnetograms and keeps a balance between the force-free constraint and the deviation from the photospheric field measurements (Wiegelmann et al. 2012). These improvements allow a more accurate evaluation of magnetic free energy in 3D as well as magnetic helicity density (e.g., Su et al. 2014).

1.2 Dynamic Pre-flare Condition

The above discussions of magnetic non-potentiality are mainly based on individual magnetograms, which only provide snapshots of magnetic conditions. It is well known that magnetic field evolution plays an even more important role in the energy build-up and flare triggering. In this section, we review the dynamic pre-flare conditions, which include new flux emergence, shear and converging flows, sunspot rotation and magnetic helicity injection. We start with a summary of the flow field, a key component that is closely associated with dynamic properties of the magnetic field. The time sequence exhibited by magnetograms is typically analyzed to understand the dynamics associated with pre-flare conditions.

1.2.1 Tracking flows of solar ARs

There are several plasma velocity inversion methods that are summarized and compared by Welsch et al. (2007). The most widely used method in earlier years was based on local correlation tracking developed by November & Simon (1988). Its first application to the time sequence of magnetograms was carried out by Chae (2001). Considering the interaction between flow and magnetic fields in terms of induction equations, Kusano et al. (2002) and Démoûlin & Berger (2003) carefully treated the difference between the horizontal plasma velocity and the apparent velocity due to flux transport. Since then, a number of other methods have been developed, including Fourier Local Correlation Tracking (FLCT; Welsch et al. 2004), Inductive Local Correlation Tracking (ILCT;
Magnetic Fields and Solar Flares

It is notable that the first time derivation of both the vertical and horizontal velocity fields was achieved by DAVE for vector magnetograms (DAVE4VM; Schuck 2008). This method explicitly incorporates the horizontal magnetic field that is necessary for the description of vertical flow, and hence is useful for estimating the vector velocity field on the photosphere. The performance of DAVE4VM was evaluated using the same synthetic data as used by Welsch et al. (2007). It was demonstrated that DAVE4VM substantially outperforms DAVE and is roughly comparable to the MEF method, which was deemed the overall best performing algorithm (Welsch et al. 2007). Furthermore, DAVE4VM is more accurate than MEF in estimating the normal component of perpendicular plasma velocity $v_n$, which is crucial for diagnosing flux emergence and calculating helicity flux that emerges (Schuck 2008). Recently, DAVE4VM has started to be applied to SDO data (e.g., Liu et al. 2013b). Chae & Sakurai (2008) introduced another improved method, the Nonlinear Affine Velocity Estimator (NAVE), and demonstrated that NAVE is more consistent with simulated data. Obviously, these developments will facilitate the photospheric flow tracking using advanced data sets from space missions (e.g., Hinode and SDO) as well as high-resolution observations from ground-based facilities.

1.2.2 Magnetic flux emergence and cancelation

The importance of emerging flux regions that lead to solar eruptions was noted many years ago (e.g., Zirin & Tanaka 1973). Tanaka (1991) derived the complex subsurface magnetic structure in a flare-productive $\delta$ sunspot group. This sunspot group produced many large flares and showed unusually fast changes in magnetic structure. The comprehensive observations provided an excellent opportunity to find the relationship between flare occurrence and evolution of the magnetic configuration. The author inferred magnetic topological structure of the region in the form of a long-winding twisted rope with a number of twisted knots. The unusual evolution of this $\delta$ group as observed on the photosphere was explained by consecutive emergences of a single system through the observable surface.

Figure 2 shows a diagram by Tanaka, which demonstrates the topological structure derived from a time sequence of photospheric observations. Similar methodology was used by Leka et al. (1996) in analyzing the current-carrying flux emergence of AR 7265 in 1992 August. With even more advanced observations, Kurokawa et al. (2002) revealed rapid changes in the $\delta$ configuration of AR 9026, that started shortly before intense flares appeared. Based on magnetograph observations, the authors proposed a schematic diagram illustrating an emerging twisted flux rope to explain the evolution of photospheric magnetic structure. Using high resolution observations at BBSO, Zirin & Wang (1993) found the new flux emergence inside the existing penumbrae of sunspots. Such an evolutionary pattern produces the so-called magnetic channels, which are defined as an elongated magnetic structure with alternating polarities. The strong transverse magnetic fields are also found along the channels. Surface plasma flows along the channels are observed as well. Penumbral flux emergence was found to be a common property of super ARs that produced multiple major flares. However, the spatial resolution of magnetograms was not sufficiently high for studying the magnetic channel structure in detail until Hinode was launched. The Solar Optical Telescope (SOT) onboard Hinode has provided unprecedented observations with high spatial and temporal resolutions, allowing advanced study of the nature of magnetic channels as well as their role in powering flares. Wang et al. (2008) and Lim et al. (2010) demonstrated that high spatial resolution and high polarimetry accuracy are required to unambiguously observe the channel structure and other complicated magnetic topology. Figure 3 presents the magnetic channels identified by Wang et al. (2008) using Hinode data.
Fig. 2 Topological structure of a sunspot as derived from a time sequence of photospheric observations. Two magnetic ropes emerged to form a complicated $\delta$ configuration from 1974 July 1 to 5 in AR McMath 13043 (Tanaka 1991), courtesy of Solar Physics.

Fig. 3 An LOS magnetogram (left) that was obtained by Hinode/SOT and the corresponding G-band image (right) at the peak development of magnetic channels around 12:00 UT on 2006 December 13. The vertical line marks the most prominent part of the magnetic channels. The FOV is $48'' \times 48''$ (Wang et al. 2008).

Chintzoglou & Zhang (2013) analyzed observations with a 45 s cadence from SDO/HMI and reconstructed the 3D subsurface magnetic structure of NOAA AR 11158. Advanced visualization methods were used in their study. The authors found that this AR consists of two major bipoles with four anchored footpoints, each of which showed tree-like structure. They concluded that an AR, even appearing to have a highly complicated structure on the surface, may originate from a simple straight flux tube that undergoes both horizontal and vertical bifurcation processes during its rise through the convection zone.

On the other hand, magnetic flux cancelation is another important factor for triggering flares. It is often closely associated with flux emergence. The importance of flux cancelation was introduced in earlier studies such as those by Martin et al. (1985) and Wang & Shi (1993). The connection between magnetic flux cancelation and flares has been solidly established in recent years using more advanced data; e.g. Sterling et al. (2010) used Hinode, TRACE, STEREO and SOHO/MDI data to
Magnetic Fields and Solar Flares

151

carry out a case study, and found strong evidence of magnetic reconnection leading to ejective eruptions. Burtseva & Petrie (2013) surveyed 77 X- and M-class flares, and clearly demonstrated the importance of flux cancelation in triggering the flares. From the perspective of the theory, a well-demonstrated example of the flux cancelation is the tether cutting model (Moore et al. 2001), where the first stage of reconnection happens near the photosphere to form a flux rope. The eruption of the flux rope causes further reconnection in the corona, leading to an ejective eruption.

1.2.3 Flow motions and sunspot rotation in flaring ARs

Evolution of the magnetic field is closely associated with flow motions. For example, photospheric flows may cause flux tubes to twist or bring flux systems together leading to an eventual reconnection. Therefore, flow motions also play an important role in building up energy and triggering eruptions. Obviously, this motivates researchers to combine studies of the flow field and magnetic field evolution, which can provide a key piece of information for understanding the physics of flares and CMEs. In order to observe flows and the magnetic field structure in detail and probe their basic nature, high-resolution and high-cadence observations are typically needed. In some studies, a simple “center-of-mass” (magnetic flux weighted centroids) calculation has been adopted to detect the overall converging and shearing motions in the flaring ARs (Wang et al. 2005; Wang 2006). Both these flow motions show abrupt changes associated with major flares; however, no spatial information about flows is determined with this method.

Harvey & Harvey (1976) found strong horizontal shear motion in the chromosphere along the PILs in flaring regions. They established a strong correlation between the shear motion and flare productivity. Martres et al. (1973, 1982) pointed out how the changes in velocity and magnetic fields could be associated with the onset of flares. Henoux & Somov (1987) further demonstrated that flow motions are closely associated with flare productivity through the resulting rapid evolution of the magnetic field, and that these motions are also related to the generation of electric currents in ARs. Tang & Wang (1993) observed unusual flow patterns inside large δ spots. They inferred that shear motions near PILs can enhance the flare productivity of large δ-spot regions. Keil et al. (1994) and Meunier & Kosovichev (2003) also established the linkage between shear flows and flare productivity. Nevertheless, observations of such shear motions with a subarcsecond spatial resolution have been rare until recent decades when adaptive optics and advanced data processing tools became available.

Yang et al. (2004) presented observations of the proper motions in AR 10486 with subarcsecond resolution that were recorded on 2003 October 29. The data were collected at National Solar Observatory using a high-order adaptive optics system, and were further processed using frame selection and the images were reconstructed with speckle masking. They found that flows on both sides of the flaring PIL are almost exactly anti-parallel, which is clear evidence of strong shear flows. These shear flows are well correlated with flare kernels in the visible and near infrared wavelengths. The maximum speed of the flow is over 1.5 km s⁻¹, and the separation of channels from anti-parallel flows can be less than 1". The authors linked the complicated flow pattern to this extremely flare-productive AR. Figure 4 shows the strong shear flows observed by Yang et al. (2004), which are clearly associated with flare kernels.

In a very recent study, using data from the spectropolarimeter onboard Hinode, Shimizu et al. (2014) found remarkable high-speed flows along the flaring PIL of the X5.4 flare on 2012 March 7. The flows lasted several hours before and after the flare. The authors argued that the observed shear flow increased the magnetic shear and free energy that powered this major flare. On the theory side, Fang et al. (2012) simulated behavior of flux emergence and cancelation when accumulating free magnetic energy in the solar corona, and concluded that these flow motions are critical to producing solar eruptions. In short, both theory and observations point to the importance of shear flows in building up energy for solar flares.
Fig. 4 Photospheric flows and magnetic field configuration of NOAA 10486 on 2003 November 29 (Yang et al. 2004). The authors illustrated the results of flow tracking using data with high spatial resolution, and provided different views of (a) flow vectors, (b) azimuth angle of velocity vectors, (c) magnitude of velocity vectors, and (d) a corresponding LOS magnetic field image superimposed on the PIL.

Besides shear flows, sunspot rotation may also play an important role in the energy storage and release that powers solar flares. Ruan et al. (2014) recently found that a sunspot rotated at a high speed of $10^7$ h$^{-1}$. They suggested that such a sunspot rotation rate may cause the gradual rising of the AR filament, and therefore may be the triggering mechanism for flares. These authors also summarized work that studies sunspot rotation, a phenomenon that was first observed by Evershed (1910). Many prior studies have demonstrated that sunspot rotation is an important process in the evolution of solar ARs and the triggering of eruptions (e.g., Stenflo 1969; Barnes & Sturrock 1972; Amari et al. 1996; Tokman & Bellan 2002; Török & Kliem 2003; Brown et al. 2003; Régnier & Canfield 2006; Yan et al. 2008a, 2009; Su et al. 2010). These studies quantitatively confirmed the
important role played by sunspot rotation in transporting helicity (see next section) and energy from the subphotosphere into the corona (e.g., Kazachenko et al. 2009; Vemareddy et al. 2012a). The temporal and spatial correlation between sunspot rotation and solar eruption has been established based on careful data analysis in recent years (e.g., Zhang et al. 2007; Yan & Qu 2007; Yan et al. 2008b,a; Jiang et al. 2012).

1.2.4 Magnetic helicity and injection

One advanced method to analyze the interaction between the magnetic fields, flow fields and coronal response to them is by analyzing magnetic helicity and its evolution. Magnetic helicity quantitatively describes the process in which the magnetic field is sheared and twisted compared to the topology it has when the field shows a minimum in potential energy (Berger & Field 1984; Pevtsov 2008). Therefore, it is an important parameter to characterize the complexity of flaring ARs. Although the magnetic helicity is generated below the surface of the Sun, it is a useful parameter in describing magnetic structure observed above the photosphere, such as the helical patterns in filaments and CMEs, as well as spiral structure in sunspot fibrils (Brown et al. 1999). The investigation of magnetic helicity has concentrated on the process of energy build-up and instability leading to flares and CMEs (e.g., Rust 2001; Kusano et al. 2004; Phillips et al. 2005). Wang et al. (2004c) gave a comprehensive review of the relationship between the accumulation of helicity and onset of CMEs/flares.

Magnetic helicity was originally defined as the volume integral of \( \mathbf{A} \cdot \mathbf{B} \), where \( \mathbf{A} \) is the vector potential of \( \mathbf{B} \), i.e. \( \nabla \times \mathbf{A} = \mathbf{B} \). This form is only valid for flux-enclosed systems, i.e. balanced magnetic flux on the boundary \( S \). In such a system, the helicity is conserved. In order to calculate helicity in open systems such as coronal magnetic fields above an AR, a modified form was introduced by adding a reference field (Berger & Field 1984). The potential field is the most common choice for the reference field. Under this assumption, \( H_r \) is written in the form given by Finn & Antonsen (1985)

\[
H_r = \int_V (\mathbf{A} + \mathbf{A}_p) \cdot (\mathbf{B} - \mathbf{P}) \, dV,
\]

where \( \mathbf{P} \) is the potential field, and \( \mathbf{A} \) and \( \mathbf{A}_p \) are vector potentials of \( \mathbf{B} \) and \( \mathbf{P} \), respectively. The modification maintains its conservative property and makes the quantity gauge invariant (Longcope & Malanushenko 2008). \( \mathbf{A} \) and \( \mathbf{A}_p \) can be derived following the concept of DeVore (2000) and more quantitatively by Fan (2009).

As the ability to perform 3D magnetic field extrapolations has become available in recent years, calculating magnetic helicity \( H_r \) in a coronal volume has also become possible. On the other hand, because of its unique property of being conserved, one can gather information on magnetic helicity by evaluating helicity flux through the photosphere. Extensive studies on the evolution of \( \Delta H|_S \) have been conducted (Nindos et al. 2003; Welsch et al. 2007; Park et al. 2010; Smyrli et al. 2010; Romano et al. 2011; Romano & Zuccarello 2011; Zuccarello et al. 2011; Vemareddy et al. 2012b).

Several studies were carried out to relate the change of magnetic helicity to the problem of impending or triggering solar flares. There are ample reports of the temporal correlation between the impulsive changes in helicity flux and the occurrence of flares/CMEs (Moon et al. 2002a,b; Chae et al. 2004; Romano et al. 2005; Park et al. 2008; Zhang et al. 2008; Smyrli et al. 2010; Romano & Zuccarello 2011). Statistical studies of helicity in ARs show that helicity in eruptive ARs is significantly higher than that in non-eruptive ones (Nindos & Andrews 2004; LaBonte et al. 2007; Tziotziou et al. 2012). In particular, it has been noticed that eruptions occur preferentially in the presence of a particular magnetic topology characterized by two magnetic flux systems with opposite helicities (Yokoyama et al. 2003; Wang et al. 2004c; Jing et al. 2004; Romano et al. 2011; Zuccarello et al. 2011). This agrees with the magnetohydrodynamical (MHD) simulation of Kusano et al. (2004), in which the introduction of reversed helicity is the underlying cause of eruptions. Indeed, in a case study of the notable flare-productive example AR 11158, Vemareddy et al. (2012b)
found there was a sudden enhancement in reversed helicity that coincided with the onset of the X2.2 flare.

Park et al. (2008, 2012) studied the helicity flux variation for a number of events. Their results for two ARs are shown in Figure 5, which demonstrates the characteristic pattern of the helicity variation found in the events analyzed by them. The helicity accumulates at a monotonic rate about one-half to two days before the flare onset, and then becomes almost constant prior to the flares. The authors concluded that typically, magnetic helicity variation has two stages: phase I is the monotonic increase of helicity and phase II keeps relatively constant helicity. It was then suggested that these flares likely took place at the beginning of phase II after a significant amount of helicity accumulation occurred in phase I.

Park et al. (2010) and Jing et al. (2012) compared accumulated helicity injection $\Delta H_S$ (derived by integrating the helicity flux transported across the photosphere over time) with coronal magnetic helicity $H_r$ (derived by estimating helicity in a 3D volume by means of the NLFFF extrapolation). For the two ARs they studied, magnetic helicity derived from the extrapolated field is well correlated with the accumulated helicity measured from LOS magnetograms. Such an example is shown in Figure 6. This gives confidence in applying NLFFF extrapolations to the 3D helicity measurement.

In order to study the distribution of magnetic helicity in the solar corona, Pariat et al. (2005) proposed a new proxy for the helicity flux density that takes the magnetic connectivity into account. Advancing in this direction, Dalmasse et al. (2013, 2014) developed a method to compute such a proxy in practice. Based on analytical case studies and numerical simulations, they showed that this method can reliably and accurately determine the injection of helicity and can reveal the real mixed signals of the helicity flux.

Another useful quantity is current helicity, which is defined as the volume integral of $B \cdot (\nabla \times B)$, where $B$ is the magnetic field vector and $B \cdot (\nabla \times B)$ is referred to as current helicity density $h_c$. The current helicity measures how much the magnetic field is locally twisted. Using the model of the field derived from NLFFF extrapolations, $h_c$ can be computed for every point in a volume; by contrast, previous works were limited to $B_z \cdot (\nabla \times B)_z$ measured on the photosphere (Abramenko et al. 1996; Bao & Zhang 1998; Hagino & Sakurai 2004; Su et al. 2009), or a constant force-free parameter $\alpha (\nabla \times B = \alpha B)$ had to be used for a whole AR (Pevtsov et al. 1995). Furthermore, vector magnetic field data from SDO/HMI allow, for the first time, the study of the evolution of $h_c$ at a cadence of 12 minutes.
Fig. 6 Temporal variation of the coronal magnetic helicity $H_r$ (red dots), the accumulated amount of helicity injection through the photosphere $\Delta H|_S$ (blue dots), and the total unsigned photospheric magnetic flux (black curve), overplotted on GOES 1–8 Å soft X-ray flux (grey curve) (Jing et al. 2012).

As shown in Figure 7, Jing et al. (2012) carried out NLFFF extrapolations for AR 11158 in 2011 February and found that magnetic helicity and current helicity are related to the onset of major flares. The helicity concentration also propagates to the corona as the magnetic flux emerges.
2 RAPID CHANGES OF MAGNETIC FIELDS ASSOCIATED WITH FLARES

2.1 Pre-SDO Research

Although surface magnetic field evolution (such as new flux emergence and shear motions) play important roles in building energy and triggering eruptions as we discussed above, the changes on the photosphere in response to the coronal eruption are expected to be small because of the large inertia of the photosphere. One kind of the reported rapid changes in the photospheric field is the so-called magnetic transients (Patterson 1984; Kosovichev & Zharkova 2001; Qiu & Gary 2003; Zhao et al. 2009), which are an apparent reversal of magnetic polarity associated with flare footpoint emissions. As the short-lived magnetic transients are regarded as an observational effect due to changes in spectral profiles, they are not considered to be a rapid or irreversible change in the photospheric magnetic field associated with flares. In retrospect, Tanaka (1978) detected changes of photospheric magnetic fields associated with a large flare on 1974 September 10 using the videomagnetogram at BBSO. The author explained the change as a transformation of field topology from non-potential to potential fields. However, it is unclear in this earlier study if the changes are permanent or transient. About two decades ago, the BBSO group discovered obvious rapid and permanent changes in vector magnetic fields associated with flares (Wang 1992; Wang et al. 1994). At that time, the authors could not find significant changes in LOS magnetograms although the transverse field showed prominent changes. Part of the results appeared to be counterintuitive: the magnetic shear angle, defined as the angular difference between the measured fields and potential fields, increased following the flares. It is well known that the coronal magnetic fields have to evolve to a relaxed state to release energy in order to power flares. For this reason, there have been some doubts about these earlier measurements, especially because the data were obtained from ground-based observatories and may suffer from some variations induced by seeing.

Kosovichev & Zharkova (2001) studied high-resolution MDI magnetogram data from the 2000 July 14 “Bastille Day Flare” and found regions with a permanent decrease in magnetic flux, which were related to the release of magnetic energy. Using high cadence GONG data, Sudol & Harvey (2005) found solid evidence of stepwise changes in the field associated with a number of flares.

Figure 8 shows the time profiles of some selected points in some selected fields of view. The time scale of the changes is as fast as 10 minutes, and the magnitude of change is on the order of 100 G. Petrie & Sudol (2010), Johnstone et al. (2012), Cliver et al. (2012) and Burtseva & Petrie (2013) also more comprehensively surveyed the rapid and permanent changes in the LOS magnetic fields with GONG data, which were indeed associated with almost all the X-class flares studied by them.

The above studies using LOS field data demonstrated the stepwise property of changes in the photospheric magnetic field that are related to flares; however, the underlying physical picture was not clearly revealed. In the subsequent papers by BBSO for the LOS magnetic field, it was found that, in general, the disk-ward flux in the flaring ARs decreases but the limb-ward flux increases (Wang et al. 2002; Wang 2006; Yurchyshyn et al. 2004; Spirock et al. 2002; Wang & Liu 2010). Such a behavior suggests that after flares, the overall magnetic field structure of ARs may change from a more vertical to a “flatter” configuration, which is consistent with the scenario that a change in the Lorentz force pushes down the field lines (see Sect. 2.2). A typical example of a change that is related to the LOS field is shown in Figure 9 and a diagram is shown in Figure 10 (Wang & Liu 2010). Note that most of the observations listed by Wang & Liu (2010) were made by MDI onboard SOHO, which has a cadence of one minute. It is worth mentioning that Cameron & Sammis (1999) were the first to use observations near the limb made with the magnetograph to characterize how changes in the magnetic fields are related to flares.

From some investigations made after 2003, researchers began to appreciate the consistent pattern of magnetic field changes associated with flares using simple white-light observations (Wang
Fig. 8 A mosaic of time variation plots in four hours of the longitudinal magnetic field strength, for a section of the AR that produced the flare on 2003 November 2. These plots cover a $10 \times 10$ pixel region. The vertical axis spans 500 G. The fit using a step function is overplotted (Sudol & Harvey 2005), courtesy of J. Harvey.

Fig. 9 Top: Time profiles of negative and positive MDI LOS magnetic fields within a boxed region (in panel a) covering the entire $\delta$ spot for the 2001 September 24 X2.6 flare, seen in an EUV Imaging Telescope (EIT) image (panel b). Bottom: In GOES 10 soft X-ray flux (dashed line), the flare started at 09:32 UT, peaked at 10:38 UT and ended at 11:09 UT (Wang & Liu 2010).
et al. 2004a; Liu et al. 2005; Deng et al. 2005; Li et al. 2009; Wang et al. 2013). The most striking changes are the decay of penumbral structure in the peripheral sides of δ spots and the enhancement (darkening) of penumbral structure near the flaring PILs.

Figure 11 clearly demonstrates examples of such changes in sunspot structure. The difference image between pre- and post-flare states always shows a dark patch at the flaring PIL that is surrounded by a bright ring, which corresponds to an enhancement in the central sunspot penumbral structure and decay of the peripheral penumbrae, respectively. These examples were discussed in detail by Liu et al. (2005), in which they showed that (1) these rapid changes were associated with flares and were irreversible, and (2) the decay (enhancement) of sunspot penumbrae was related to the penumbral magnetic field turning more vertical (horizontal). Chen et al. (2007) statistically studied over 400 events using TRACE white-light data and found that the change in sunspot structure seems to be positively correlated with the magnitude of flares. Using Hinode/SOT G-band data with high spatiotemporal resolution, Wang et al. (2012a) further characterized the penumbral decay and confirmed its intrinsic linkage to a change in the magnetic field. The authors took advantage of the high spatiotemporal resolution offered by Hinode/SOT data and observed that in sections of peripheral penumbrae swept by flare ribbons, the dark fibrils completely disappear but the bright grains evolve into faculae (a signature of vertical magnetic flux tubes). These results suggest that the component of the horizontal magnetic fields in the penumbra is straightened upward (i.e. turning from horizontal to vertical) due to magnetic field restructuring associated with flares. This change in magnetic topology leads to the transition of penumbrae to faculae.

Figure 12 shows an example of such a rapid transition of uncombed penumbral structure into faculae observed with Hinode/SOT. Also notably, the flare-related enhancement of penumbral structure near central flaring PILs has also been unambiguously observed with the 1.6 m New Solar telescope (NST) at BBSO. Using NST TiO images with unprecedented spatial (0.1′′) and temporal (15 s) resolution, Wang et al. (2013) reported on the rapid formation of sunspot penumbra at the PIL.
Sample Events of Rapid Change of δ Sunspot Structure Associated with Flares

| Date       | Flare Class | AR Number   | Location     |
|------------|-------------|-------------|--------------|
| 2003 Nov 2 | X8.3        | AR10486     | S15E20       |
| 2000 Jun 6 | X2.3        | AR09026     | N33E25       |
| 2001 Apr 9 | M7.9        | AR09415     | S21W04       |
| 2001 Aug 25| X5.3        | AR09591     | S17E34       |
| 2003 Oct 28| X17         | AR10486     | S18E20       |
| 2003 Oct 29| X10         | AR10486     | S15W02       |

Fig. 11 TRACE white-light images of areas associated with six major flares. The rapid changes in δ sunspot structure are observed. The top, middle and bottom rows show the pre-flare, post-flare and the difference images between them after some smoothing. The white pattern in the difference image indicates the region of penumbral decay, while the dark pattern indicates the region outlined by the penumbra. The white dashed line denotes the flaring PIL and the black line represents a spatial scale of 30″ (adapted from Liu et al. 2005).

Fig. 12 Time sequence of G-band images observed by Hinode/SOT on 2006 December 6 including the X6.5 flare. The red box marks the region with a decaying penumbra (in the entire AR 10930, there are several other penumbral decay regions). For reference, the green and yellow boxes mark the stable penumbral and facular regions, respectively. The red dotted lines in the frame of 18:43:38 UT delineate the separating flare ribbons, with the western one sweeping across the penumbral decay region (Wang et al. 2012a).
Fig. 13  BBSO/NST Hα center (a) and blue-wing (b) images at the peak of the 2011 July 2 C7.4 flare, showing the flare ribbons and possible signatures of a flux rope eruption (the arrows in (b)). The NST TiO images about 1 h before (c) and 1 h after (d) the flare clearly show the formation of the penumbra (indicated by the arrow in (d)). The same post-flare TiO image in (e) is superimposed with positive (white) and negative (black) HMI LOS field contours, and NLFFF lines (pink). (f) Perspective views of the pre- and post-flare 3D magnetic structure including the core field (a flux rope) and the arcade field from NLFFF extrapolations. The collapse of arcade fields is obvious (Jing et al. 2014). (g) TiO time slices for a slit (black line in (d)) across the newly formed penumbral area. The dashed and solid lines denote the time of the start, peak and end of the flare in GOES 1–8 Å. The sudden turning off of the convection associated with the flare is obviously shown (Wang et al. 2013).

associated with the 2012 July 2 C7.4 flare, as presented in Figure 13. The most striking observation is that the solar granulation evolves to the typical pattern of penumbra consisting of alternating dark and bright fibrils. Interestingly, a new δ sunspot is created by the appearance of such a penumbral feature, and this penumbral formation also corresponds to an enhancement in the horizontal field.

Wang et al. (2009) carried out a detailed study of the X7.1 flare on 2005 January 20. They found clear evidence of a decrease in the horizontal magnetic fields in some peripheral areas of the δ-spot
group, and an increase in an extended area centered at the flaring PIL. The observed changes are consistent with the darkening of inner penumbrae and weakening of outer penumbrae reported by other authors. The rapid magnetic changes are at the level of 100–300 G, also similar to previous studies.

As we described earlier, for a few events that were studied, some authors also found that magnetic shear near the flaring PILs may increase after flares (e.g., Wang et al. 1994; Liu et al. 2005). This phenomenon was largely left unexplained, until analysis of the evolution of the 3D coronal magnetic field structure associated with flares was made possible by the NLFFF extrapolation technique (see the next section).

2.2 Observations in the SDO Era

The launch of SDO in 2011 February and subsequent operation provide an unprecedented opportunity to study the evolution of the magnetic field associated with flares. The HMI instrument onboard SDO measures vector magnetic fields and flow motions of the solar photosphere (Schou et al. 2012). The full-disk data, which are free from the effects of seeing, have contributed key observations for many studies, as all the ARs on the visible disk are included in the FOV. The baseline HMI observations include LOS magnetograms with a 45 s cadence and vector magnetograms with a 12 minute cadence. The accuracy is on the order of 10 G for the LOS field and 100 G for the transverse field. Wang et al. (2012b) used HMI data to present the first study of changes in the photospheric magnetic field that are related to a flare. They investigated the well-studied X2.2 flare in AR 11158 that was observed on 2011 February 15. The observations clearly demonstrated a rapid and irreversible enhancement in the horizontal magnetic field at the flaring PIL. The mean horizontal fields increased by about 500 G in half an hour. The authors also found that the photospheric field became more sheared and more inclined. The observed changes in the field of this sigmoidal AR are located between the two flare ribbons, which correspond to the initial conjugate hard X-ray footpoints. Hard X-ray images taken by RHESSI and the 3D coronal magnetic field using NLFFF extrapolations are also jointly studied to understand the changes in the magnetic field associated with this event. These unambiguous observational evidences corroborate what were found before using ground-based observations (e.g., Wang 1992; Wang et al. 1994). Later, a number of papers were published using SDO/HMI data to demonstrate similar changes occurred in magnetic fields (Liu et al. 2012; Sun et al. 2012; Wang et al. 2012c; Petrie 2012, 2013; Yang et al. 2014). The observed patterns in these changes are consistent in the sense that the transverse field is enhanced in a region across the central flaring PIL. Figure 14 shows typical time profiles that arise from such field changes.

As we discussed in Section 1, NLFFF extrapolation is a powerful tool for reconstructing the 3D magnetic topology of the solar corona. Naturally, a question is raised on how the 3D magnetic field structure evolves corresponding to the observed field changes on the surface. Using Hinode/SOT magnetic field data, Jing et al. (2008) showed that magnetic shear (indicating non-potentiality) only increases at lower altitudes but it still largely relaxes in the higher corona. Therefore, the previously observed increase in magnetic shear along with that of the transverse field could be physically reasonable. Using HMI data, Sun et al. (2012) clearly showed that the electric current density indeed increases at the flaring PIL near the surface but it decreases higher up, which may explain the overall decrease in free magnetic energy together with a local enhancement at low altitude (see Fig. 15). They also found that magnetic shear slightly increases in the lower atmosphere but it rapidly relaxes in the higher atmosphere. These results imply that the magnetic field could collapse toward the surface, and such a collapse was even detected in a C7.4 flare on 2012 July 2 as reported by Jing et al. (2014) and shown in Figure 13. Intriguingly, the collapse of magnetic arcades as reflected by NLFFF models across the C7.4 flare is spatially and temporally correlated with the formation of a sunspot penumbra on the surface (Wang et al. 2013).
Fig. 14  Left: An HMI vector magnetogram taken on 2012 March 7 showing the flare-productive NOAA AR 11429 right before an X5.4 flare. Right: Temporal evolution of various magnetic properties of a compact region (green contour in the left panel) at the central PIL, compared with the light curves of GOES 1–8 Å soft X-ray flux (gray) and its derivative (black). The shaded interval denotes the flare period in GOES flux (adapted from Wang et al. 2012c).

Fig. 15  Modeled and observed field changes from before (01:00 UT; (a), (c) and (e)) to after (04:00 UT; (b), (d) and (f)) the 2011 February 15 X2.2 flare. (a–b) Current density distribution on a vertical cross section indicated in (c)–(f). (c–d) HMI horizontal field strength. Contour levels are 1200 G and 1500 G. (e–f) HMI vertical field. Contour levels are ±1000 G and ±2000 G (Sun et al. 2012), courtesy of X. Sun.
### Table 1 Summary of Selected Models and Comparison with Observations

| Model                        | Multipolarity | Filament | CME | B-field Change | Remote Brightening | Reference |
|------------------------------|---------------|----------|-----|----------------|--------------------|-----------|
| Original CSHKP model         | No            | Yes      | Yes | No             | No                 | [1,2,3,4] |
| Erupting flux rope           | Maybe         | Yes      | Yes | Yes            | Yes                | [5,6,7,8,9] |
| Tether cutting               | Yes           | Yes      | Yes | Yes            | Yes                | [10,11,12] |
| Breakout                     | Yes           | Yes      | Yes | Maybe          | Yes                | [13,14,15] |

References: [1] Carmichael (1964); [2] Sturrock (1966); [3] Hirayama (1974); [4] Kopp & Pneuman (1976); [5] Forbes & Isenberg (1991); [6] Chen et al. (1997); [7] Low & Zhang (2002); [8] Gibson & Fan (2006); [9] Fan (2010); [10] Moore & Labonte (1980); [11] Moore et al. (2001); [12] Moore & Sterling (2006); [13] Antiochos (1998); [14] Antiochos et al. (1999); [15] Lynch et al. (2004)

Using vector magnetograms from HMI together with those from *Hinode/SOT* with high polarization accuracy and spatial resolution, Liu et al. (2012) revealed a similarly rapid and persistent increase in the transverse field associated with the M6.6 flare on 2011 February 13, together with a collapse of coronal currents toward the surface in the sigmoid core region. Liu et al. (2013a) further compared the NLFFF extrapolations before and after the event. The results show that about 10% of the flux (∼3 × 10^{19} Mx) from the inner footpoints (e.g., FP2 and FP3 of loops FP2–FP1 and FP3–FP4 respectively) undergo a footpoint exchange to create shorter loops of FP2–FP3.

Figure 16 presents the rapid/irreversible changes of the transverse field and the pre- and post-flare NLFFF models. These provide direct evidence of the tether cutting reconnection model (see the next section). A more comprehensive investigation including the 3D magnetic field restructuring, flare energy release and also the helioseismic response to two homologous flares, the 2011 September 6 X2.1 and September 7 X1.8 flares in NOAA AR 11283, was recently conducted by Liu et al. (2014). Their observational and model results depicted a coherent picture of coronal implosions, in which the central field collapses while the peripheral field turns vertical, as illustrated earlier by Liu et al. (2005). The implosion process was also found to be more abrupt when associated with a fuller eruption.

### 2.3 Theoretical Explanation of the Observations

We realize that the physics of flares and CMEs can only be ultimately understood if observations are coupled to theoretical models. In particular, the afore-described observations of changes in the photospheric magnetic field that are related to flares need to be reconciled with flare/CME models. Table 1 includes some of the models of interest, but it is not intended to be a complete list. Besides a change in the photospheric magnetic field, we also consider a number of other observational features such as remote brightenings, filament association and sigmoid configuration (e.g., Wang 2005, 2006; Liu et al. 2006, 2007b). These observational constraints can help in assessing the applicability of different models. In a recent paper, Longcope & Forbes (2014) gave a review of solar eruption models, which basically belong to three categories: the loss of equilibrium, tether cutting and breakout. The CSHKP model is the original model for loss of equilibrium, while erupting flux rope models are a more advanced version of it. All of the above models can be catastrophic.

All the above models can explain the observations in some ways. We use the tether cutting model as an example of the comparison with observations. Figure 17 illustrates the general idea of this model as originally proposed by Moore & Labonte (1980) and further developed by Moore et al. (2001) and Moore & Sterling (2006). It applies a two-step reconnection that leads to eruptions in the form of flares and CMEs, in particular, for sigmoidal ARs. The first stage of reconnection occurs at the onset of the eruption, near the solar surface. It produces a low-lying shorter loop across the PIL and a longer twisted flux rope connecting the two far ends of a sigmoid. The second stage starts when the formed twisted rope becomes unstable and erupts outward. It causes an expansion of the larger scale envelope field that overarches the sigmoid. The opened legs of the envelope fields
Fig. 16 Top: Temporal evolution of the horizontal magnetic field measured by HMI and Hinode/SOT in a compact region around the PIL, in comparison with X-ray light curves from the M6.6 flare on 2011 February 13. The red curve is the fitting to HMI data with a step function (Liu et al. 2012). Bottom: Extrapolated NLFFF lines before and after the event, demonstrating the process of magnetic reconnection is consistent with the tether cutting reconnection model (Liu et al. 2013a).

Fig. 17 The tether cutting reconnection model depicting the onset of flares and subsequent eruptions (Moore et al. 2001), courtesy of R. Moore. There is a two-step reconnection process: the first stage is the reconnection near the solar surface, forming an erupting flux rope. The second stage involves the interaction between the erupting rope and the larger-scale arcade fields. Please note that after the eruption, a short, flat loop is formed near the photosphere, which is evident from our observations of an enhanced transverse field near the flaring PILs and is consistent with the result of Hudson et al. (2008).
Magnetic Fields and Solar Flares

165

reconnect back to form an arcade structure while the ejecting plasmoid escapes in the form of the CME. The concept of two-stage reconnection was proposed earlier by Wang & Shi (1993). Please note that tether cutting is still phenomenological in nature. The full MHD modeling, especially data driven modeling, is required in order to understand the physics related to the observations.

It is possible that in an earlier phase of the flare, contraction of the shorter flare loop occurs. This has received increasing attention recently (e.g., Ji et al. 2006), possibly corresponding to the first stage. The ribbon separation as described in the standard flare models such as the CSHKP model is manifested in the second stage. This model can also likely explain other observational findings such as: (1) transverse magnetic field as indicated by flaring PILs increases rapidly/inversely immediately following flares (Wang et al. 2002, 2004b; Wang & Liu 2010). (2) Penumbral decay occurs in the peripheral penumbral areas of δ-spots, indicating that the magnetic field lines turn more vertical after a flare occurs in these areas (Wang et al. 2004a; Liu et al. 2005). (3) RHESSI hard X-ray images show four footpoints, two inner ones and two outer ones. Sometimes the hard X-ray emitting sources change from a confined footpoint structure to an elongated ribbon-like structure after the flare reaches its maximum intensity (Liu et al. 2007a,b).

An experimental comparison between simulations and observations has been made by Li et al. (2011). Figure 18 shows some of their results. The authors selected a lower level in the simulation to examine the magnetic structure near the surface. It is clear that the observed patterns in the magnetic field change after flares/CMEs are indeed generated by the simulation:

(1) The most striking match is at the flaring PIL (blue box), where field lines in the simulation are found to be more inclined (blue line in the top right panel) with a corresponding enhanced transverse field strength (blue line in the middle right panel) after the eruption. Such a change in inclination angle of magnetic fields by about 10° and enhancement in the transverse field were observed in several events (e.g., Li et al. 2009; Wang & Liu 2010) and also predicted by Hudson et al. (2008).

(2) In the outside region of the simulated sunspot penumbral area (red box), field lines turn more vertical with a decreased transverse field (red lines in the top and middle right panels). This strongly corroborates our previous speculation on the physical nature of the observed penumbral decay (Liu et al. 2005).

(3) The simulation also exhibits the expected downward net Lorentz force pressing on the lower boundary (bottom right panel), which was elaborated on by Hudson et al. (2008) and Fisher et al. (2012) and was also suggested by observations (Wang & Liu 2010).

The work by Hudson et al. (2008) and Fisher et al. (2012) has made fundamental advances in the theory to explain the observed changes in magnetic fields associated with a flare. The authors quantitatively assessed the so-called back reaction on the solar surface and interior as a result of the coronal field evolution required to release energy. They made the prediction that after flares, at the flaring PIL, the photospheric magnetic fields become more horizontal. The analysis is based on the simple principle of energy and momentum conservation: the upward erupting momentum must be compensated by downward momentum as the back reaction. This is one of the very few models that specifically predict rapid and irreversible changes in the photospheric magnetic fields associated with flares. As we discussed earlier, the tether cutting reconnection model is closely related to this scenario. If we examine the magnetic topology close to the surface, one would find an irreversible change in magnetic fields that agrees with the scenario as described above: the magnetic fields turn more horizontal near the flaring PIL. This is due to the newly formed short loops as predicted by the tether cutting model in the first stage of the reconnection.

The quantitative treatment by Hudson et al. (2008) was carried out by Fisher et al. (2012), in which changes in the integrated vertical and horizontal Lorentz force exerted on the photosphere
Fig. 18 Left panels: The transverse magnetic field before (top) and after (bottom) the flare ∼9.5 Mm above the solar surface, obtained based on the MHD simulation. The red and blue boxes denote the region with peripheral penumbral decay and darkening near the flaring PIL, respectively. Right panels: From top to bottom, temporal variation of the mean magnetic inclination angle, transverse field strength and change of Lorentz force in the two regions illustrated in the left panels. The dashed line indicates the time of eruption. The unit of time is $R_\odot/v_{A0} = 356.8$ s (Li et al. 2011).

From the corona are formulated as

$$\delta F_{z,\text{downward}} = \frac{1}{8\pi} \int dA(\delta B_z^2 - \delta B_h^2),$$  \hspace{1cm} (2)

and

$$\delta F_h = \frac{1}{4\pi} \int dA\delta(B_zB_h),$$  \hspace{1cm} (3)

where $dA$ is the surface element of the vector magnetogram, and $B_z$ and $B_h$ are the radial and horizontal components of $B$. Concentrating on the downward vertical component $\delta F_z$, the authors suggested that it has to balance the upward perturbation from the Lorentz force that accelerates CMEs, and they further predicted that such a change in the Lorentz force might be correlated with (1) the acceleration of CMEs and (2) the power of seismic waves excited by the downward “jerk” (McClymont & Fisher 1989). A schematic diagram illustrating the collapse of field lines after flares occur is shown in Figure 19.

In most of the recent studies, such a downward change in the Lorentz force has been detected (e.g., Wang et al. 2012b,c; Liu et al. 2012; Sun et al. 2012; Petrie 2013). Routine calculations of a change in the Lorentz force are now made possible using SDO/HMI data (Petrie 2014). Importantly,
Fig. 19  Schematic drawing that shows how the initial photospheric field vector turns to a more horizontal state as a result of coronal restructuring during a flare (based upon fig. 3 in Hudson et al. (2008), courtesy of B. Welsch). This agrees with many observational results (see text for details).

Fig. 20  Top: Flow maps of the preceding spot in AR 11158 before and during the 2011 February 15 X2.2 flare and the associated change in horizontal Lorentz force. Bottom: Same as the top panels, but for the following spot in AR 11158. The direction of angular acceleration of both spots agrees with the torque due to the change in horizontal Lorentz force (Wang et al. 2014b).

the Lorentz force perturbation as formulated above has a transverse component and may be related to sudden sunspot motion associated with flares (Anwar et al. 1993). Very recently, Wang et al. (2014b) examined variations in the photospheric sunspot structure after the X2.2 flare erupted on 2011 February 15. They found that both of the two main sunspots in this AR show a sudden increase in rotation speed, and that the direction of angular acceleration is consistent with the torque produced by the change in transverse Lorentz force (see Fig. 20). Under some assumptions about physical quantities, it was further shown that the amplitude of angular acceleration may agree with that derived from the torque and moment of inertia.
3 CONCLUSIONS AND PROSPECTIVES

Numerous studies in the past decades have identified a number of physical parameters that can reflect the non-potentiality and dynamics of flare productive solar ARs. These include, but are not limited to, the magnetic free energy, magnetic shear, helicity injection, new flux emergence and magnetic cancellation, shear motions and sunspot rotation. Rapid changes in magnetic fields associated with solar flares, i.e. the central field becomes more inclined at flaring PILs while the peripheral field turns to a more vertical configuration, have also been consistently detected, not only on the photosphere but also in 3D with the aid of the NLFFF extrapolation technique. These observational and model results can be understood as being due to the change in Lorentz force in the framework of the back reaction theory of eruptions. In particular, the tether cutting reconnection model has been shown to be able to accommodate various observational features, especially the enhancement of the transverse field that is related to the flare.

It has been realized that modeling the evolution of the coronal magnetic field is an important approach for gaining a comprehensive understanding of the physical nature of how the flare is related to the magnetic field evolution. Extrapolations of the coronal field based on the NLFFF assumption are a useful tool, which, however, have some limitations (e.g. AR magnetic fields are not in the force-free state during the flare process). Some non-force-free modeling has been attempted. For example, Hu et al. (2010) developed a non-force-free extrapolation code and applied it to the real magnetic field measurement of AR 10953. The authors showed that the result was satisfactory based on quantitative evaluations. The data-driven MHD simulation may also provide a step forward in understanding the evolution of magnetic fields associated with flares (e.g., Fan et al. 2012). Jiang et al. (2013) used the extrapolated NLFFF data as the initial condition for MHD simulations, which are based on the model of Wu et al. (2006). They were able to simulate a realistic initiation and subsequent evolution of the eruptive flux rope in a sigmoidal AR. The buildup process and instability condition of the flux rope were further investigated by Jiang et al. (2014). A comprehensive review of different models to drive solar eruptions was given by Schrijver (2009). Obviously, a quantitative comparison between modeling results and observations is highly desirable.

Most of the above discussions are associated with a common magnetic structure called a sigmoidal AR. Flares with a closed circular-like ribbon have been studied with recent advanced observations (Masson et al. 2009; Reid et al. 2012; Wang & Liu 2012; Deng et al. 2013; Sun et al. 2013; Wang et al. 2014a). The events can be explained by the fan-spine magnetic topology: the dome-shaped fan characterizes the closed separatrix surface and the inner and outer spine field lines. These different connectivity domains pass through a coronal null point (Lau & Finn 1990; Török et al. 2009). Interestingly, the outer spine can return to the surface, but can also be open. In the former case, the slipping/slip-running reconnection occurs within the quasi-separatrix layers and leads to the sequential brightening of the circular fan ribbon. The null-point reconnection further causes the brightening in the remote area where the closed spine returns to the surface (Masson et al. 2009; Reid et al. 2012). In the latter case, the null-point reconnection generates surges/jets that erupt outward (Pariat et al. 2009, 2010). These different scenarios were summarized by Wang & Liu (2012). These researches provide a new direction for understanding solar eruptions. The identification of a skeletal structure for this kind of topology is challenging, but has been developed in recent years (e.g., Zhao et al. 2008; Sun et al. 2013).

High-resolution observations will provide another breakthrough in monitoring the evolution of magnetic fields associated with flares and tracking flows in ARs. The recent completion of major telescopes such as the 1.6 m NST at BBSO, the 1.5 m GREGOR at Tenerife, and the 1.0 m New Vacuum Solar telescope in Yunnan, China, all demonstrate an ability to monitor the Sun with 0.1″ resolution. An example of recent flare studies using BBSO/NST images has been shown in Figure 13, in which the formation of sunspot penumbra is clearly observed to be associated with the occurrence of a C-class flare. Another example is the recent study by Wang et al. (2014a) that disclosed the
fine structure of three-ribbon flares, corresponding to a complicated circular ribbon flare structure as described above. The next generation solar telescope, the 4 m Daniel K. Inouye Solar Telescope (formerly called ATST) will provide views of even finer structure in flaring ARs. More accurate polarization measurements can also be made with these large telescopes.

Finally, using helioseismology to study magnetic field evolution and the problem of flare onset will advance the physical understanding of the sub-surface magnetic and flow structures in flare productive ARs. By making an early diagnosis of ARs before they emerge on the surface, helioseismology can reveal the process of energy build-up and triggering in eruptions. Studies in this direction began to produce important results in recent years. Leka et al. (2013) reviewed various tools for detecting pre-emerging ARs. Limitations of these tools and future studies were also discussed. Follow-up studies of this work were presented by Birch et al. (2013) and Barnes et al. (2014). Efforts have also been devoted to analyzing the velocity signature of the emergence process (e.g., Ilonidis et al. 2013) and the correlation between surface current helicity and subsurface kinetic helicity (Gao et al. 2013). It is anticipated that research applying helioseismic analysis to help probe pre-flare conditions will be fruitful.

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