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The contraction of flare loops and its impact on the solar lower atmosphere

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Abstract. This short review article will address relevance of three important macroscopic behaviors of solar flares. The behaviors include the contraction of flare loops (implosion), the rapid change of magnetic fields and seismic waves during flares. We show that the phenomena basically reflects a process of rapid restructuring of sheared magnetic field by a release of free magnetic energy. The contraction and rapid magnetic changes might be the direct consequences of the restructuring. Also the flattening of magnetic loops caused by the contraction in the corona will impart momentum down to the photosphere even to the solar interior. Part of the energy transported by the downward momentum can account for seismic waves. All phenomena, putting together, show that the magnetic reconnection process during the early impulsive phase is quite different from during the gradual phase and plays a dominant role in powering solar flares.

Keywords : Sun: flares – Sun: magnetic topology – magnetic reconnection

1. Introduction

Our understanding of solar flares has progressed substantially over the past couple of decades, with extensive observations made at ground and, especially, from space. Indeed, since solar flares will always remain in the area of remote sensing, observations will mainly remain in the area of macroscopic phenomena, from which we explore and infer the basic physics inside them both theoretically and numerically. The macroscopic phenomena includes the spatial and temporal distributions of mass motion, the intensities and polarization states at different energy bands of photons detected all the way from about 30 keV (a typical plasma frequency in the solar wind

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around the Earth) to hundreds of MeV. The macroscopics phenomena can be observed in stereo. Thus, the data set for an observational quantity is at least five-dimensional (x, y, z, t, λ). Even though we have made noticeable progress in observations, our present observations are still in a preliminary stage toward obtaining sufficient wealth of data, which is crucial for a comprehensive understanding of solar flares. Since Carrington first reported the occurrence of a solar flare in 1859, the study and observations of solar flares have roughly undergone three stages: photosphere, chromosphere and corona. Modern observations have taken more emphasis on the observations of solar corona, since it is believed that the releasing of free magnetic energy via magnetic reconnection occurs in the corona.

Recent observations and theories strongly urge us to have a re-examination for the involvement of the lower chromosphere and even the deep photosphere in solar flares (Hudson 2011). Chromosphere still plays a major observational role in many ways (Hudson, 2007). The chromospheric emission from flare kernels inside flare ribbons is well-correlated with hard X-ray (HXR), UV and microwave emissions (e.g., Kurokawa, Takakura & Ohki 1988). Especially, the emissions in the far blue wing of H_α are associated with non-thermal electron precipitation being accelerated during the flaring processes, which are a good tracer of HXR sources (Canfield & Gayley 1984; Ding et al. 2001). Flare emission at the 1.56 microns “opacity minimum” (Xu et al. 2004) further shows the flare’s impact reaching deep into the solar atmosphere. Recent observations suggest that even smallest flares have white-light emissions (Hudson, Wolfson & Metcalf 2006). There are more and more evidences showing that solar flares have a momentum impact to the solar lower atmosphere. Flare induced seismic waves ripple out across the photosphere, as detected by helioseismic techniques (Kosovichev & Zharkova 1998), and strong step-wise changes occur in the photospheric magnetic field (e.g., Wang et al. 2002, Sudol & Harvey 2005). Theoretically, the flare associated restructuring of magnetic fields in the corona will impart momentum down to the photosphere (Hudson, Fisher & Welsch 2008). The restructuring of magnetic fields might be linked with the phenomenon of flare loop contraction, which was fully revealed in recent years (Ji, Huang & Wang 2007).

2. Contraction of flare loops

In Yohkoh HXT data only about 13% of flares exhibit HXR footpoint motions corresponding strictly to separation with respect to the PIL (Bogachev et al. 2005), and are more likely to have a component of motion along the ribbon direction, and also approach one another. Many individual examples confirm HXR footpoint motions that do not agree with the ‘standard model’ predictions of separating footpoints (e.g., Fletcher & Hudson 2002; Krucker, Hurfard & Lin 2003; Ji et al. 2004, 2006). The initial converging motion has also been noted in UV/EUV ribbons (Zhou, Ji & Huang 2008). Furthermore, a number of events observed in hard X-rays, H_α and UV/EUV showed approaching FPs in the early impulsive phase, accompanied by a projected downward motion of the coronal HXR source, and followed by separation of the footpoints and a projected rise in the coronal source (Ji et al. 2004, 2006, 2008; Liu et al. 2009; Joshi et al. 2007). Sometimes, we can only see the descending motion of HXR looptop sources (Sui & Halman 2003; Sui, Halman & Dennis 2004) and the shrinkage of entire radio/EUV flaring loops (Li & Gan 2005, 2006; Reznikova, Melnikov & Shibasaki 2010; Liu et al. 2009). This phenomenon can be summarized as following. That is, during the early impulsive phase of solar flares, HXR) looptop sources or radio/extreme-ultraviolet (EUV) flaring loops have a descending or shrinking motion and, at the same time, H_α ribbons or HXR footpoints (FPs) are converging. Only after the impulsive phase an upward motion for the looptop sources and flaring loops and a corresponding outward motion (the usual separation motion) for the flare ribbons or FPs begin. In most times, the converging motion and the separation motion of FPs are a kind of unshearing motion, travelling at tens of kilometers per second. In the expansion phase of a flare, strong H_α and UV ribbons are visible and they move mainly perpendicular to magnetic polarity inversion line (PIL). In the contraction phase, H_α and UV emissions are complex, sometimes showing multiple FPs that have parallel and approaching motions (Xu et al. 2010; Yang et al. 2009).

Shen et al. (2008) reported the finding of the early abnormal temperature distribution of flares' X-ray looptop sources during the contraction phase of ten solar flares. Fig. 1 shows one of the good samples of the 2002-09-09-T17:40-M2.1 flare. The flare was observed at BBSO at H_α-1.3 Å with a cadence of 40 ms. Figure 1a shows the X-ray light curves for this flare. Figure 1b shows that the distance between the two H_α conjugate kernels decreases during the early impulsive phase of the flare. Only after the early impulsive phase, the distance has a steady increase showing the usual separation motion (Ji et al. 2004). Figure 1c shows that the height of the X-ray looptop sources in the energy ranges of 8-10, 10-13, and 13-16 keV decreases during the early impulsive phase. During the expansion period, the temperature structure shows a temperature structure, which is in agreement with what the standard flare model predicts with an energy releasing site above flare loops. However, during the contraction period, the temperature structure of the LT sources is rather complex or abnormal. The LT sources in the three energy bands are almost mixed with one another. The abnormal temperature distribution in the contraction period obviously suggests a complex magnetic reconnection process. Their results are basically in agreement with the finding of an X-ray sigmoidal structure during the contraction phase of the 2003-10-29-T20:30-X10 flare (Ji et al. 2008). Many papers and talks have been presented for this flare regarding its associated magnetic changes and seismic waves (e.g. Martinez-Oliveros and Donea 2009). During the contracting phase of this flare, Xu et al. (2009) reported 4 X-ray emission footpoints. During the early impulsive phase of solar flares, more than two H_α, UV, or X-ray brightening kernels may be seen. This geometric configuration is very much in the manner predicted by the "tether-cutting" scenario first proposed by Moore et al. (2001). All results show that the magnetic reconnection process during the early impulsive phase is quite different from that during the gradual phase. Magnetic reconnection occurs in a sheared magnetic field during the early impulsive phase and energy releasing during this period dominates all flare energetics. The complicated footpoint motions are likely to be linked to the projection(s)

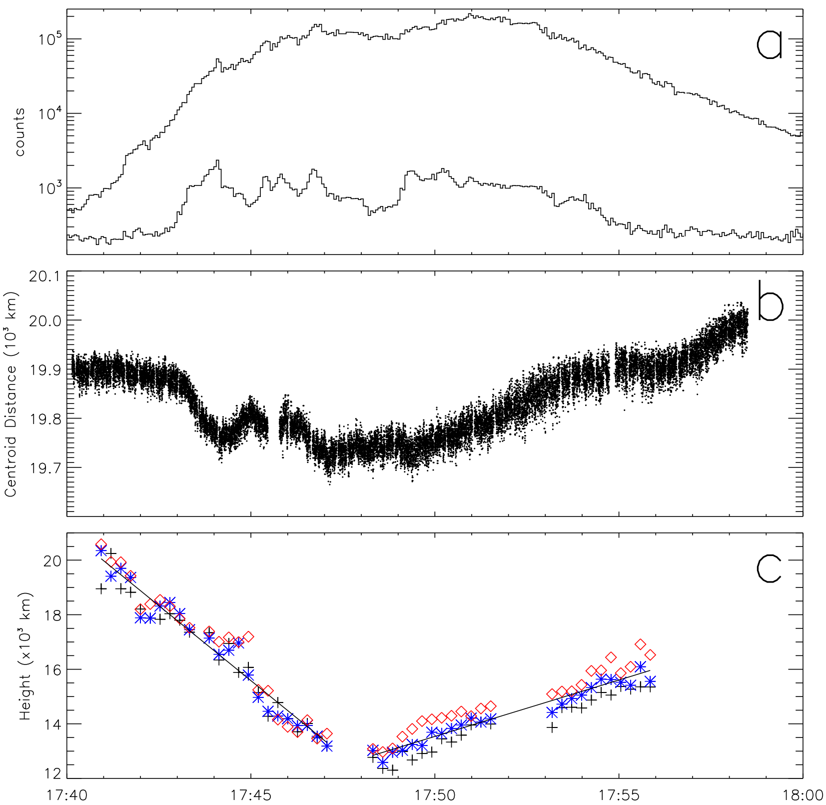

Figure 1. (a) Light curves of HXR emissions in energy bands of 12-25 keV and 25-50 keV of the 2002-09-09 flare. (b) Time profile for the distance between the two conjugate H_α kernels of the flare. (c) Time profiles of the heights of the loop-top source at three different energies (cross: 8-10 keV, diamond: 10-13, asterisk: 13-16 keV). (Shen et al. 2008)

of the locus of reconnection (Moore et al. 2001). Particular examples of this, can also be found in sheared arcade models (Somov et al. 2002), and the "slip-running" reconnection model (Aulanier et al. 2006). It is worth mentioning that recent SDO observation (Zhang & Chen 2011 SPD meeting) shows that CME initiation is associated with magnetic reconnection between flux ropes.

3. The rapid restructuring of magnetic fields and its downward impact

In the solar corona, the plasma β is $\ll 1$ and magnetic field is force-free. It means that magnetic tension and pressure dominates over thermal pressure, controlling the dynamics and topology of solar flares. For this reason, the loop structure forms a basic configuration for the solar corona. It is especially so during the early impulsive

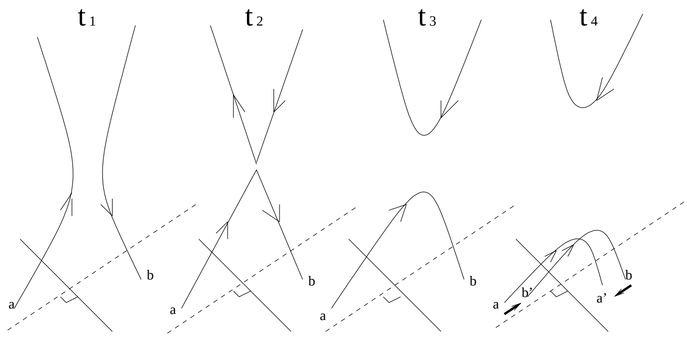

Figure 2. Magnetic reconnection followed by the relaxation of a sheared magnetic field. Dashed lines are the neutral magnetic lines. (Ji et al. 2007)

phases of solar flares. Hudson (2011) proposed that the impulsive phase of the flare dominates the energetics of all flare phenomena, and also pointed out that the energy and momentum in this phase largely reside in the electromagnetic field, not in the observable plasma. Therefore, magnetic topology, like the loop structure, plays a dominant role in shaping solar coronal activities. We can make a conclusion that the early impulsive phase of a solar flare is more associated with the changes in magnetic fields than with tenuous coronal plasmas.

As shown above, the early impulsive phase is usually accompanied by the contraction of flaring loops. The contraction is a 3D phenomenon, which challenges any 2D explanations like the collapsing trap model proposed by Veronig et al. (2006). However, the contraction can be nicely associated with the phenomenon of implosion predicted by Hudson (2000). Therefore, the contraction is believed to be the result of restructuring of highly-sheared magnetic field due to a rapid release of free magnetic energy in the core area of the field. In the framework of sheared linear force-free arcades, Ji et al. (2007) established a quantitative model to show that the release of free magnetic energy will reduce magnetic shear of the arcades and less sheared arcades will have smaller height and span (see the cartoon in Fig. 2). From this point of view, the contracting motion of flaring loops is the result of the relaxation of the sheared magnetic field.

During the contraction phase, rapid enhancement of transverse magnetic field is expected, since the rapid restructuring caused by the rapid removal of magnetic stresses (shear) is likely to make the field more horizontal after flares (Fig. 2). In recent years, strong step-wise changes of magnetic field have been observed in the photosphere (Wang 1992; Wang et al. 2002; 2004; Sudol & Harvey 2005; Wang, Zhao & Zhou 2009), and this kind of changes are often associated with obvious changes in the sunspot, particularly with rapid motion and the disappearance of a part of the penumbra (e.g., Anwar et al. 1993, Wang et al. 2004, Liu et al. 2005). Non-thermal gyrosynchrotron radiation can be used for diagnostics for the magnetic field during flares. With this method, Huang, Ji & Wu (2008) found that the magnitude of the transverse magnetic field summed around the magnetic neutral line of the SOHO MDI magnetogram has a short-term impulsive increase during the rising phase of the 2004-11-01-T03:18-M1.1 solar flare. Step-wise magnetic changes is the phenomenon of magnetic restructuring during solar flares or CMEs.

Theoretically, the flare associated restructuring of magnetic fields in the corona will impart momentum down to the photosphere (Hudson, Fisher & Welsch 2008). This kind of impact may be the driving force of seismic waves. Intuitively, this must be so due to momentum conservation. Since a flare, especially a large one, is often accompanied by upward mass motions like CMEs. Given changes of magnetic field $\delta\mathbf{B}$ in the photosphere and assuming the magnetic field decays sufficiently fast as $z \to 0$, Hudson, Fisher & Welsch (2008) estimated resulting vertical Lorentz forces per unit area as:

$$\delta f_z = (B_z \delta B_z - \delta B_x B_x - B_y \delta B_y)/4\pi.$$

This kind of force must usually be negative after the flattening of magnetic fields on the Sun. Some observations have proven this to be true. Wang & Liu (2010) reported that δf_z is generally negative for nearly all cases they have investigated. Wang et al. (2011) analyzed in detail the 2005-01-15-T22:40-X2.6 flare and found rapid transverse field enhancement near the magnetic PIL. They also computed the Lorentz force near the flaring PIL using above equation and reported sudden downward force during the flare (Fig. 3). In Fig. 3, we can see that the Lorentz force has an irreversible and sudden change associated with the flare, with a drop of magnitude of 6000 dyne cm^2. Integrating over the area of interest yields a change of Lorentz force of 1.0×10^{22} dyne consistent with what was approximated by Hudson, Fisher & Welsch (2008). It is possible that this kind of sudden loss of balance may be responsible for the excitation of seismic waves. Unfortunately, there has been no report of seismic wave for this particular event due to lack of Doppler observations. Martinez-Oliveros & Donea (2009) studied an X1.2 flare accompanied by well-observed seismic waves, which occurred 20 hours earlier in the same active region. It is demonstrated that the flare is located in the same site as the X2.6 flare in this study.

4. Summary

Solar dynamo creates stressed magnetic fields that ascends from the convection zone through the photosphere and emerges into the corona. During the energy storage phase of an active region, the stress is under accumulation for a certain trigger and then relax suddenly, producing a flare and/or a CME. We still do not know what causes this kind of sudden relaxation of magnetic field. Nevertheless, we know that, the relaxation/restructuring will cause flaring magnetic loops to contract and even cause rapid magnetic changes that can be observed on vector magnetograms of photosphere. It should be worth noting that rapid magnetic changes during flares can also be diagnosed with non-thermal gyrosynchrotron radiation mechanism. A mutual comparison would be very interesting. From simple quantitative evaluation, it is believed that

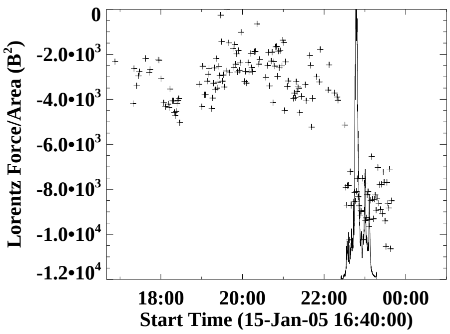

Figure 3. The change of Lorentz force per unit area in the region pointed by arrow in Figure 5 of Wang et al. (2011), which has the strongest transverse field enhancement after the flare.

restructuring of magnetic fields in the corona will impart momentum down to the photosphere even to the solar interior. Part of the energy can account for seismic waves, as have been observed for several flares. On the other hand, upward momentum will push upper atmosphere outward during the course of flares, producing CMEs.

These will motivate future studies to link all the aspects of flares mentioned in this article, such as contraction of flaring loops, rapid change of magnetic fields, loss of force balance, and excitation of seismic waves, towards a full understanding of the flaring phenomenon. Future high-resolution flare observations for these aspects will be very much desirable with telescopes like RHESSI, Hinode, SDO, NST (at BBSO) and NVST (at Fushine Lake) etc.

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