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Magnetic field configurations leading to solar eruptions

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Abstract. Magnetic fields play an important role in eruptive phenomena in the solar atmosphere. Observations show that magnetic shear, magnetic null point, magnetic connectivity and topology are all important for the occurrence of solar eruptions. In this paper, I discuss magnetic configurations that lead to eruptions on the Sun and the role of magnetic null points in triggering solar eruptions by case study of active regions 10486 and 10808. Studies show that not all flares require high shear, and magnetic complexity and emergence of twisted flux ropes are more important to produce eruptions. Magnetic null points favor flare production, but are not a necessary condition.

Keywords : Sun: magnetic topology – Sun: flares

1. Introduction

The source of energy released in solar flares is generally believed to be the free energy stored in nonpotential magnetic structures. The energy can suddenly be released through magnetic reconnection leading to flares. Magnetic reconnections sometimes require high magnetic shear and/or magnetic complexity. The required high shear can result from shearing motions in the photosphere, flux emergence or cancelling. Such high shear are easily found in active regions (ARs) with complex magnetic configuration, such as the so-called δ AR (Schmieder & van Driel-Gesztelyi 2005), and with flux-rope emergence (Li et al. 2007; Canou et al. 2009; Guo et al. 2010a,b).

It has been proposed that the presence of magnetic null points is related to flares. Observations indicate there may exist magnetic null points in the corona (Filippov 1999). Magnetic null points show solar cycle variations (Cook, Mackay & Nandy 2009). The definition, classification and properties of the null-point have been theoretically described in Lau & Finn (1990). To explore three-dimensional (3D) magnetic

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null points in the corona and study their role in triggering solar eruptions, one needs numerical approaches to compute the magnetic fields in the corona. If any current in a region is confined to heights at or below the photosphere, the field above is a current-free field (CFF); if not, a force-free field configuration ($\vec{J} \times \vec{B} = 0, \vec{\nabla} \times \vec{B} = \alpha\vec{B}$) is commonly assumed because of the low plasma β in the solar atmosphere, corresponding to $\vec{J}$ parallel to $\vec{B}$ (Metcalf et al. 1995). If α is assumed to be constant in all the AR, we get a linear force-free field (LFFF) configuration. So far, extrapolations using CFF and LFFF configurations are commonly used because they are easy to compute with respect to nonlinear force-free field (NLFFF) extrapolations. CFF and LFFF extrapolations only need the longitudinal photospheric field, while NLFFF need the magnetic field vector at each point in the photosphere for the boundary conditions. A NLFFF can relax to an LFFF with the same magnetic helicity (Berger 1984; Taylor 1986; Parker 1989; Aly 1992; Nandy et al. 2003) during an eruptive MHD process. For a complicate flare-productive δ region, NLFFF configuration may nevertheless be a more reasonable, reliable, and promising approximation compared to CFF and LFFF configurations (Song et al. 2006, 2007; Régnier & Priest 2007). It is observed that the magnetic field is nearly force-free in the corona and far from force-free in the lower photosphere (below about 400 km) (Metcalf et al. 1995; Moon et al. 2002).

In this paper, I discuss magnetic field configurations favoring flare production in Section 2 and the relation between magnetic null points and flare occurrence in Section 3. The summary will be given in the last section (Section 4).

2. Magnetic configurations

The conditions favoring the production of big solar flares include (i) a high level of shear, twist, or emerging flux, and (ii) complex magnetic configuration of the AR, such as δ configuration in which two umbrae of opposite polarity share a common penumbra (Schmieder & van Driel-Gesztelyi 2005).

The relation between magnetic shear and flare occurrence and flare-associated shear changes have been extensively studied (e.g., Hagyard 1990; Wang et al. 1994; Li et al. 2000a,b). Wang et al. (1994) studied five flares of GOES X-ray class X, and found that they were related to high magnetic shear and the magnetic shear increased dramatically along a substantial portion of the neutral line during the flares. After studying eight >M1.0 flares, we found that only three of them were associated with high shear and the others were related to flux emergence (Li et al. 2000a,b), indicating that flux emergence is common in flares with low magnetic shear. The small flare-related shear changes, both positive and negative, may be determined by the balance of the energy carried by the emerging flux and that required to power the flare, and its association with the flares was not conclusive. Therefore, the average shear in the flaring areas may be a better parameter to characterize the flare-related shear changes (Li et al. 2000b).

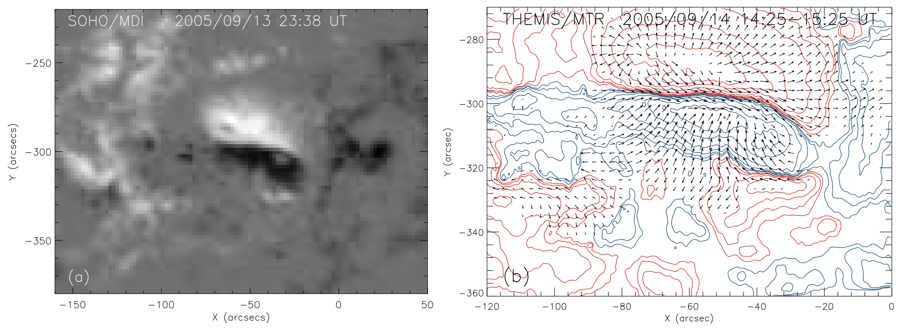

Figure 1. (a) MDI LOS magnetogram for AR 10808. White stands for positive polarity and black for negative one; (b) vector magnetogram of the AR from THEMIS observation in MTR mode.

Magnetic flux emergence can occur on both a large scale and a small scale. Various methods have been developed to predict solar flares, including statistics or systematic detection of parameter changes such as shear, tilt, strength of the magnetic field (e.g., Li et al. 2000a,b; Falconer 2001; Leka & Barnes 2003). Indirect methods based on determining the magnetic configuration of an AR have been under development for more than 40 years. Numerical simulations have shown that interactions of the new emerging flux with pre-existing corona magnetic fields lead to the onset of coronal mass ejections (CMEs), solar flares, and coronal X-ray jets (e.g., Chen & Shibata 2000; Yokoyama & Shibata 2001).

Li et al. (2006) studied the magnetic field evolution of AR 10486 and showed that this AR was characterized by continuous flux emergence, sunspot motion and rotation, leading to the formation of its δ configuration. The magnetic shear increases along the neutral line (Fig.1(a) in Li et al. (2006)) to a value for getting flares. The 1N/M1.9 flare occurred in the δ region AR 10484 on 20 October 2003 was associated with fast sunspot rotation and flux emergence (Li, Berlicki & Schmieder 2005). During the flaring process, magnetic reconnection took place near magnetic separatrices or quasi-separatrices, which are locations where magnetic reconnections are possible.

The flare-productive AR 10808 produced many large flares during its passage, of which two X-class flares occurred on 13 September 2005. This AR was characterized by continuous emergence of sheared and twisted magnetic field (Li et al. 2007). Fig.1 gives examples of magnetograms from MDI and THEMIS observations. Study of magnetic configuration associated with these two flares showed that there were short sheared magnetic field lines before the eruption and less sheared ones after the reconnection, and the connectivity of the field lines involved in the flaring activity was modified after the reconnection process (see Fig.2(d) in Li et al. (2007)). The evolution of the photospheric magnetic field over a few days shows the continuous emergence of a large-scale magnetic flux tube, the tongue-shape of the two main polarities of the active region being the signature of such an emergence. After the previous X1.5 flare, the emergence of the tube continues and favors new magnetic energy storage and the onset of the X1.7 flare. This postulation was later confirmed by Canou et al. (2009). Through NLFFF extrapolation, they found clear evidence for the twist flux rope emergence (refer to Figure 3 in their paper). Of course, this is not the only possible type of configuration that may lead to an eruption.

Emergence of flux ropes, which are frequently associated with large solar flares, has been found for other AR (Guo et al. 2010a,b). NLFFF extrapolation of the observed photospheric magnetic fields showed that a pre-eruptive magnetic flux rope along the polarity inversion line (PIL) in AR 10767 led to a confined M1.1 flare on 27 May 2005. The observed strong writhing motion of the erupting structure also suggested the presence of a flux rope (Guo et al. 2010a). The magnetic flux rope along the PIL co-existed with a magnetic dip (sheared arcade), which supports the Hα filament (Guo et al. 2010b).

3. Magnetic null points

Magnetic null points in 3D coronal structure favor the formation of current sheet (Pontin et al. 2007), which is a signature of magnetic reconnection. Magnetic reconnection leads to changes in the topology of the magnetic field, and energy being released as heat, kinetic energy and acceleration of particles. Reconnections at/near null points have been widely studied in the literature (e.g., Priest & Forbes 1992; Priest & Démoulin 1995; Antiochos, Karpen & DeVore 2002; Al-Hachami & Pontin 2010; Galsgaard & Pontin 2011). Zhao et al. (2005) proposed a method to identify magnetic null points in 3D coronal magnetic field data cube. Applying this method to magnetic field data derived from extrapolations, we identified magnetic null points in the corona above AR NOAA 10486 in different phases of its evolution (26 and 28 October 2003) with both CFF (Li et al. 2006) and LFFF (Schmieder et al. 2007) assumptions and studied their role in triggering solar eruptions.

We found two null points above the AR using the data cube extrapolated from MDI and THEMIS observations of line-of-sight field (Li et al. 2006). TRACE observations show brightenings about 10 min before the onset of the main flare in both 1600 Å and 195 Å in several regions located around the intersections of the fan surface and the spine structure of the low-altitude null point with the planes of the photosphere and the chromosphere, suggesting energy deposition in these regions and providing evidence for the magnetic reconnection near the low-altitude null point. However, this reconnection and brightness enhancement have no direct relation to the main flare. Brightenings corresponding to the high-altitude null point were observed just after the main flare, suggesting magnetic reconnection associated with this null. Therefore, the existence of the two null points has no crucial role in triggering the main flare. Other authors also showed that large flares were produced independent of the presence of the null points (Mandrini et al. 2006).

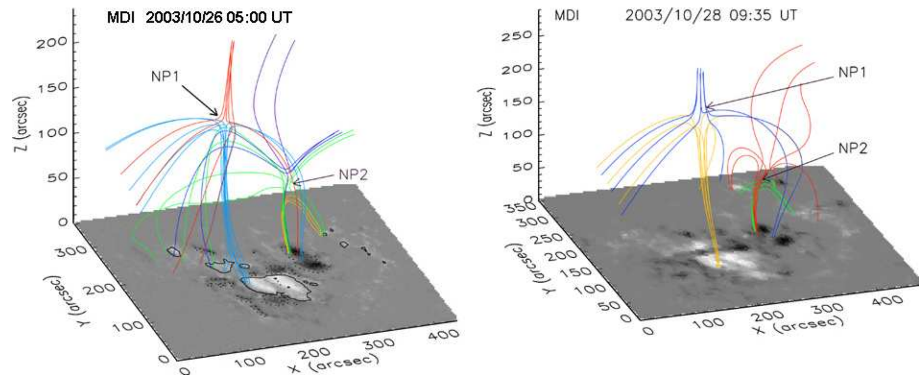

Figure 2. Magnetic null points found above AR 10486 on 26 (left) and 28 (right) October 2003. The data cube is extrapolating results from MDI observation with an LFFF assumption (Figure 3 in Schmieder et al. (2007)).

Using extrapolated data with LFFF assumption, Schmieder et al. (2007) also identified two null points above this AR on 26 and 28 October 2003, respectively (Fig.2). They found that the presence of magnetic null points does not always lead to the occurrence of flares, consistent with the results of Aulanier et al. (2006) from 3D MHD simulations.

4. Summary

Magnetic complexity and emergence of twisted flux are more important to produce flares (eruptions). Magnetic configurations with high shear are in favor of large flares, but not all flares require high shear. The presence of magnetic null points favors magnetic reconnection and flare production, but it is not a necessary condition to get a big flare. However, the spatial properties of the magnetic null points in coronal field determine the location where reconnection takes place (Démoulin, Hénoux & Mandrini 1994). Our works indicate that all the above properties (magnetic complexity, twisted flux emergence, high shear, null points, etc.) can be used as a predictor of solar eruptions with a certain confidence.

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