Flux emergence, flux imbalance, magnetic free energy and solar flares

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Abstract

Emergence of complex magnetic flux in the solar active regions lead to several observational effects such as a change in sunspot area and flux imbalance in photospheric magnetograms. The flux emergence also results in twisted magnetic field lines that add to free energy content. The magnetic field configuration of these active regions relax to near potential-field configuration after energy release through solar flares and coronal mass ejections. In this paper, we study the relation of flare productivity of active regions with their evolution of magnetic flux emergence, flux imbalance and free energy content. We use the sunspot area and number for flux emergence study as they contain most of the concentrated magnetic flux in the active region. The magnetic flux imbalance and the free energy are estimated using the HMI/SDO magnetograms and Virial theorem method. We find that the active regions that undergo large changes in sunspot area are most flare productive. The active regions become flary when the free energy content exceeds 50% of the total energy. Although, the flary active regions show magnetic flux imbalance, it is hard to predict flare activity based on this parameter alone.

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1. Introduction

Physical mechanisms responsible for energy storage and release in explosive events on the sun have been the subject of much serious study for many decades (Gold and Hoyle, 1959; Welsch and Longcope, 2003). In the space age, understanding of these events has practical implications (Sterling, 2000). In particular, identification of observable precursors of CMEs on the sun is an important step in space weather forecasting, as well as key to understanding the physics of magnetic explosive events.

The Solar flares and CMEs occur as a result of destabilization of magnetic structure above the photosphere, but their relationship is somewhat more complex as they do not often occur in the presence of each other (Andrews, 2003; Jing et al., 2006). At the same time, observations show that a major fraction, about 88% of earth directed CMEs occur following large flares (Harrison, 1968; Bemporad and Poletto, 2005; Zhou et al., 2003). The energy released from the active region magnetic field is greater prior to the CME launch than after (Green et al., 2001). Even though some CMEs are observed without a chromospheric flare, the ones originating from active regions with strong magnetic field result in higher speed ejected material (Gosling et al., 1976; MacQueen and Fisher,

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1983; Vrnak et al., 2005; Srivastava and Venkatakrishnan, 2002; ?). Clearly, there is a close relationship of flares and CMEs with the size and strength of active region magnetism as the energy released in the explosive phenomena is stored in the three dimensional magnetic structure (Gopalswamy et al., 2010). Therefore studying the precursors of solar flares is useful for CME and space weather research.

Flares happen as the active region magnetic field is destabilized. The energy is continuously added to the three-dimensional (3D) active region structure in twisted magnetic fields resulting in a stressed flux system that eventually becomes unstable (Hahn et al., 2005). As the energy builds through a series of stable non-potential configuration due to foot-point motion or emerged stressed field, the explosion is triggered by tether-cutting or break-out mechanisms due to flux emergence (Hagyard et al., 1986; Moore et al., 1992; Gary and Moore, 2004; Wang et al., 2004; Choudhary et al., 1998; Choudhary et al., 2001). Many studies relate magnetic field evolution with flares. Early work showed that the flare energy is strongly correlated with active region magnetic fields, which is reduced at least after B-class flares (Mayfield et al., 1972; Mayfield and Lawrence, 1985). Modern observations using magnetograms obtained with the GONG network showed that the field change occurs rapidly mostly at the foot-point of the flare ribbons which might result from the penumbral field relaxing upward by reconnecting magnetic fields above the surface (Sudol and Harvey, 2005; Deng et al., 2005; Wang et al., 2011). The field-guided mass motion around the neutral line also shows dramatic changes associated with flares (Deng et al., 2011). In another line of study, Falconer et al. (2009) showed that the magnetic field configuration of active regions explode after achieving their maximum attainable free energy in order to achieve the equilibrium state.

All mechanisms described above require changing the magnetic field of source regions of flares and CMEs. The sunspot area is a good measure of the localized magnetic flux which is a widely observed quantity at the locations of these source regions. Hence, along with the magnetic field measurements, using the variation in sunspot area is a powerful tool to study the temporal evolution of magnetic energy in active regions.

In this study we focus on the relation between the total energy release due to solar flares with the rate of change in sunspot area. We examine if active regions with rapidly changing sunspot area release more flare energy. Since the spot group complexity is also an indicator of flare productivity of the region, we explore the relationship with flux imbalance, which is due to twisted flux emergence among others (Green et al., 2003; Tian and Liu, 2003). Finally, we study the evolutionary stage of active region free energy content with flare occurrence.

2. Data and analysis

The properties of active regions such as Hale classification, sunspot area, sunspot number, flare measure in different type obtained from NOAA/USAF Active Region Summary listed in <http://www.solarmonitor.org/> are given in Table 1. Fig. 1 is the histogram of active region properties during the disk passage. The active region flux emergence is measured as the time derivative of sunspot area. The total flare energy released during the disk passage is computed by adding the energy released by all flares produced by the active region,

$$E_{total} = \sum_i [a * X_i + b * M_i + c * C_i] \quad (1)$$

where the coefficients a , b and c , represent the energy released during X , M and C class flares. The index i is the number of flares in each class.

The full disk magnetograms were obtained by the Helioseismic and Magnetic Imager (HMI) on board the Solar Dynamics Observatory (SDO). We have extracted the field of view containing the active region for successive days to compute the flux imbalance parameter and magnetic energy content. The flux imbalance is computed by,

$$Flux\ Imbalance = \frac{B_+ - B_-}{B_+ + B_-} \quad (2)$$

where B_+ and B_- are total positive and negative magnetic field.

The total energy and free energy contained in the active region are computed using the magnetic Virial theorem (Klimchuk et al., 1992). The energy contained in a force

Table 1
Active regions.

NOAA	First day of disk appearance	Complexity change	Spot area max/min	Spot number max/min	Flare measure
11283	2011 September 1	$\beta \rightarrow \beta\gamma\delta$	230/100	29/10	815.8
11302	2011 September 23	$\beta\gamma \rightarrow \beta\gamma\delta$	1070/700	26/10	1569.6
11429	2012 March 4	$\beta\gamma \rightarrow \beta\gamma\delta$	1270/700	28/8	2603.6
11165	2011 March 6	$\beta \rightarrow \beta\gamma\delta$	420/160	21/5	427.3
11164	2011 March 6	$\beta \rightarrow \beta\gamma\delta$	760/350	28/9	129.1
11158	2011 February 12	$\beta \rightarrow \beta\gamma\delta$	620/40	39/5	157.4
11216	2011 May 17	$\alpha \rightarrow \alpha$	110/60	1/1	0
11410	2011 January 15	$\alpha \rightarrow \beta\gamma$	540/200	22/13	129.4
11402	2012 January 24	$\beta \rightarrow \beta\gamma$	370/60	11/3	230.9

Fig. 1. Daily Evolution of the sunspot area and number of 9 active regions. The letters “N” and “A” in the top panel corresponds to the sunspot number and area of the active regions. The arrow marks show the maximum number of flares occurred for a large active region.

free coronal magnetic field is given by a surface integral across the photospheric plane ($z > 0$)

$$E(z > 0) = \frac{1}{4\pi} \int_{z=0} (xB_x - yB_y)B_z dx dy \quad (3)$$

$$\text{Fractional free energy} = \frac{(\text{Total Energy} - \text{Potential Energy})}{\text{Total Energy}} \quad (4)$$

3. Sunspot area evolution

Fig. 2 shows the relationship between the total flare energy released by an active region, (Flare index) as described in Section 2, with sunspot area and number. While the flare index does not show systematic dependence with either sunspot area or number in the active region, there is a clear trend with the time derivative of sunspot area. Fig. 2(a) shows the flare index as a function of the time derivative of sunspot area. During the decay phase, which is represented by the negative time derivative, the flare index is lower than the growing phase of the active region, which is consistent with an earlier finding that sudden changes in sunspot group area are associated in major flares with the pre-maximum growth (Newton and Howe, 1952). It was also found that complex spot groups produce the most flares per unit area compared to unipolar spots (Bell and Glazer, 1959). Greatrix (1963) examined nearly 4000 solar flares and found that intensity of a flare is dependent on the complexity of the geometry of the source region magnetic field and the flare intensity does not depend on the rate of change in the area of spot group. On the other hand, he found that the flare frequency is a linear function of rate of change of spot area. However, the changes in flare related sunspot area is not clear (Howard, 1963; Sivaraman, 1969). The probability of solar flare occurrence rate based on complexity and rate of change of

sunspot area shows that magnetic flux emergence enhances the occurrence of major solar flares (Lee et al., 2012; Contrino et al., 2012). Recent high spatial resolution observations of sunspot configuration and magnetic field measurements show that the spot area changes due to permanent changes in magnetic field configuration (Wang et al., 2001; Liu et al., 2005). The relation of stellar flares to the spotted area on the stellar surface adds to the notion that the spot area can be used to study the flare occurrence rate and estimate the total flare energy release at the active region (Dal and Evren, 2012).

The relationship between sunspot area changes and flare occurrences has been carried out for a long time since the spot group is an approximate measure of magnetic flux passing through the active region. Thus, the relationship between solar flares and spot area can be regarded as the relation between solar flare and magnetic flux. Early observations have shown that solar flares often occur at the same locations of the active regions flux emergence (Dodson and Hedeman, 1949). We do not find the relationship of absolute value of sunspot area with flare index is consistent with the previous results.

The sunspot number dependence of the flare index shows a bimodal distribution. Regions that contain several small spots or few larger spots are flare productive as may be noticed in Fig. 2(d). However, the flare index of active regions do not show any trend. Finally, we also observed that active regions with a single sunspot that did not exhibit temporal evolution of area were without any flares.

4. Energy estimation with magnetic Virial theorem and magneto-frictional method

The total energy contained in the active region and its temporal evolution were used to study the flare productivity of the active regions listed in Table 1. One part of the

Fig. 2. Dependence of total flare index with sunspot area and number. (a) The total flare index and rate of change of sunspot area (dA/dt). The solid line is the lower limit below which most active regions do not exhibit flare activity. (b) The dependent of flare index on the total spot area. (c) Dependence of flare Index on sunspot number. (d) Dependence of flare index on the sunspot to number ratio.

general Virial theorem states that, for a force free magnetic field, the energy contained within a volume is given by the surface integral over the bounding surface (Chandrasekhar, 1961, chap 13). Klimchuk et al., 1992 derived magnetic Virial theorem with reasonable assumptions and devised a useful scheme to compute the energy with observed photospheric vector magnetograms that would have noise contained in the polarization signal. We have used this method to determine the energy of active regions that will provide a basis for comparison. The Virial theorem gives the total magnetic energy, but it is only the free energy (the excess over the potential field energy) that is available to power a flare or CME. It is important to examine the free energy as a fraction of the total energy, rather than simply the total energy or the free energy. A large active region can have a lot of total energy and be potential, but it might never produce a CME or flare. Similarly, a large active region that is minimally stressed (modest deviation from potential) may have more free energy than a small active region that is highly stressed (large deviation from potential). The small active region is more likely to erupt even though it has less free energy. It is possible to compute the potential field energy using only the boundary data with the Virial theorem (Klimchuk and Sturrock, 1992). They used a magneto-frictional method to produce the desired photospheric flux distribution and field line connectivity. We implement this method to estimate the fractional free energy defined in Eq. (4), which is an indicator of an impending flare or CME. This fraction should be a rough indicator of the level of stress in the field and therefore the propensity of the field to break. Fig. 3 shows an example of the temporal evolution of estimated energy contained in magnetic field structure using magnetic Virial

theorem. Two major flares occurred at the time marked with vertical dashed lines, when the magnetic free energy was high. There is also indication of decreasing free energy after the flares. Rapid time variation of energy content (may be due to flux emergence) to flares. Most of the large flares are observed at the time when the active region has free energy $>50\%$ of total energy. Steady free energy content does not produce flares.

5. Active region flux imbalance

Imbalance of magnetic flux contained in the active region is another indicator of the local complex field configuration. Fig. 4 is an example of the evolution of magnetic field in terms of flux imbalance in NOAA 11283. The flux imbalance steadily increased as negative polarity continuously emerged. We find that the majority of CMEs and flares occur during or after new flux emergence that shows significant flux imbalance. The steady imbalance flux (could be due to visibility issue) does not produce flares. The flux imbalance has been observed in

Fig. 3. Magnetic Free energy of the active region NOAA11283 as a function of time.

Fig. 4. Temporal evolution of the flux imbalance of active region NOAA 11283. The dashed vertical lines mark the occurrence of large solar flares.

solar active regions for a long time (see Grossmann-Doerth et al., 1987). Flux imbalance can be up to 30% in ephemeral active regions and reach about 62% (Livi et al., 1985; Sheeley, 1966; Stenflo, 1967; Choudhary et al., 2002). The local imbalance of magnetic flux in the active region can be primarily due to the emergence of tilted magnetic structure as found by analyzing more than 200 active regions (Green et al., 2003). The photospheric electric current in the field structure can produce magnetic field in several directions leading to observed imbalance of magnetic flux (Gary and Rabin, 1995). The flux imbalance can also be due to long distance connection through field lines that leads to unstable magnetic field structures (Choudhary et al., 2002). Also, the diffused nature of one of the polarity, generally the following polarity in Hale sense, can lead some flux below the detection limit that will result in a measurable flux imbalance (Grossmann-Doerth et al., 1987). Tian and Liu (2003) found that the net fluxes of seven active regions associated with strong solar storms significantly decreased within 2 or 3 days prior to the major flares associated with the storms. They also found that the flux imbalance reduced before the onsets of the flares. This suggest a possible relationship between significant decrease of the flux imbalance of active regions and instability of large-scale magnetic fields. Such phenomena can occur due to the sudden emergence of flux in preexisting magnetic field structure leading to large flares and CMEs.

6. Conclusions

The evolution of observed magnetic properties of solar active regions and their flare productivity is useful to develop space weather prediction tools. Several past studies exhibited partial success in relating the flare occurrence to the temporal change of magnetic field of their source region. In this paper we combine an old technique namely evolution of sunspot number and area with energy estimation with photospheric magnetic fields along with their flux imbalance. The main results of this study are:

- Evolving active regions, in which large spots (concentrated flux) emerges are flare and CME productive.
- Sudden flux emergence that results in an imbalance of photospheric flux and large flares.

- The flare activity is observed when the free energy exceeds 50% of total energy.

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