Magnetic Flux and Magnetic Nonpotentiality of Active Regions in Eruptive and Confined Solar Flares

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Abstract

With the aim of understanding how the magnetic properties of active regions (ARs) control the eruptive character of solar flares, we analyze 719 flares of Geostationary Operational Environmental Satellite (GOES) class \( \geqslant \)C5.0 during 2010–2019. We carry out the first statistical study that investigates the flare–coronal mass ejection (CME) association rate as a function of the flare intensity and the AR characteristics that produce the flare, in terms of its total unsigned magnetic flux (\( \Phi_{\text{AR}} \)). Our results show that the slope of the flare–CME association rate with flare intensity reveals a steep monotonic decrease with \( \Phi_{\text{AR}} \). This means that flares of the same GOES class but originating from an AR of larger \( \Phi_{\text{AR}} \) are much more likely to be confined. Based on an AR flux as high as 1.0 \( \times \) 10\textsuperscript{23} Mx for solar-type stars, we estimate that the CME association rate in X100-class “superflares” is no more than 50\%. For a sample of 132 flares \( \geqslant \)M2.0 class, we measure three nonpotential parameters including the length of steep gradient polarity-inversion line (\( L_{\text{SGPI}} \)), the total photospheric free magnetic energy (\( E_{\text{free}} \)), and the area with large shear angle (\( A_{\phi} \)). We find that confined flares tend to have larger values of \( L_{\text{SGPI}} \), \( E_{\text{free}} \), and \( A_{\phi} \) compared to eruptive flares. Each nonpotential parameter shows a moderate positive correlation with \( \Phi_{\text{AR}} \). Our results imply that \( \Phi_{\text{AR}} \) is a decisive quantity describing the eruptive character of a flare, as it provides a global parameter relating to the strength of the background field confinement.

\textit{Unified Astronomy Thesaurus concepts:} Solar activity (1475); Solar active region magnetic fields (1975); Solar flares (1496); Solar coronal mass ejections (310); Stellar activity (1580)

1. Introduction

Solar flares and coronal mass ejections (CMEs) are the most catastrophic phenomena in the present solar system, driven by a sudden release of magnetic energy stored in the solar corona. Large solar flares are often, but not always, associated with CMEs. We dub flares with a CME as “eruptive” and flares without a CME as “confined” (Moore et al. 2001). There are two main factors that are considered to determine whether or not a flare event is CME-eruptive. One factor is the constraining effect of the background magnetic field overlying the flaring region, i.e., the strength of magnetic field or its decay with height (Wang & Zhang 2007; Yang et al. 2014; Thalmann et al. 2015; Baumgartner et al. 2018). Li et al. (2020) analyzed 322 large flares and found that the flare–CME association rate decreases with the increasing magnetic flux of the active region (AR) that produces the flare, implying that large magnetic flux generally tends to confine eruptions.

Another factor determining the eruptive character of solar flares is thought to be related to magnetic complexity and nonpotentiality of ARs (Sun et al. 2015; Liu et al. 2016; Jing et al. 2018; Duan et al. 2019), such as free magnetic energy, relative helicity, magnetic twists, etc. Numerous statistical studies have revealed that strong flares mostly occur in ARs with a complex configuration and high nonpotentiality of magnetic fields (Mayfield & Lawrence 1985; Falconer et al. 2002; Chen & Wang 2012, 2020; Su et al. 2014). However, there are only a few statistical studies focusing on magnetic nonpotential measures in confined versus eruptive flares (Nindos & Andrews 2004; Cui et al. 2018; Vasantharaju et al. 2018). Nindos & Andrews (2004) and Gupta et al. (2021) found that in a statistical sense the pre-flare coronal magnetic helicity of ARs producing confined large flares is smaller than that of ARs producing eruptive large flares. Bobra & Ilonidis (2016) used machine-learning algorithms to predict CME productivity and found that the “intensive” parameters (those not scaling with the AR size) distinguish between eruptive and confined flares. Until now, the key nonpotential parameters of ARs governing the eruptive character of solar flares are still unknown based on statistical results. Moreover, the access to open flux (open to the interplanetary space) is also thought to influence whether an X-class flare is likely to be eruptive (DeRosa & Barnes 2018).

In this Letter, we carry out the first statistical study that investigates the flare–CME association rate \( R \) as a function of the AR characteristics that produce the flare, in terms of its total magnetic flux (\( \Phi_{\text{AR}} \)). Our findings reveal clear differences of \( R \) with the slope of \( R \) as a function of flare intensity being a monotonically decreasing function of \( \Phi_{\text{AR}} \). This result has important implications for the prediction of CMEs occurring in association with large flares as well as for the solar–stellar connection, where the solar flare–CME association rates are used to estimate stellar CME occurrence frequencies. Moreover, we also find the distinct differences of nonpotential parameters characterizing ARs in eruptive and confined large flares.
## 2. Observational Data and Analysis

### 2.1. Data and Event Selection

We check for the soft X-ray (SXRx) flare catalog recorded by the Geostationary Operational Environmental Satellite (GOES) system and select flare events $\geq$C5.0 occurring within 45° from the central meridian, from 2010 to 2019 June. A total of 719 events are selected, including 322 M-class (Li et al. 2020) and 397 C-class flares. To determine whether a flare is associated with a CME, we use the CME catalog\(^6\) of the Solar and Heliospheric Observatory/Large Angle and Spectrometric Coronagraph (Brueckner et al. 1995). The observations from the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the Solar Dynamics Observatory (SDO;Pesnell et al. 2012) and the twin Solar Terrestrial Relations Observatory (Howard et al. 2008; Kaiser et al. 2008) are also used to help determining the CME association (see the detailed description in Li et al. 2020). Out of these 719 flares, 251 events are eruptive and 468 are confined (see Table 1 and the database FlareC5.0\(^1\)). For each event, we calculated $\Phi_{\text{AR}}$ before the flare onset (within 30 min) by using the available vector magnetograms from Space-Weather Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012) AR Patches (SHARP; Bobra et al. 2014). Only pixels that host a radial component of the magnetic field $|B_r| > 100$ G are considered (Kazachenko et al. 2017).

### 2.2. Calculation of Magnetic Nonpotential Parameters of ARs

For a subset of 132 flare events $\geq$M2.0 (86 eruptive and 46 confined), we calculated three nonpotential parameters before the flare onset (within 30 minutes) including the length of polarity-inversion lines (PILs) with steep horizontal magnetic gradient ($L_{\text{SCP}}\text{H}$), the total photospheric free magnetic energy ($E_{\text{free}}$) and the area with strong magnetic shear ($A_{\Psi}$). Magnetic PILs mark the separation between positive and negative magnetic flux in the photosphere of ARs. Properties of PILs in ARs have been found to be strongly correlated to solar flare and CME occurrences (Falconer et al. 2002; Vasanharaju et al. 2018; Kontogiannis et al. 2019; Wang et al. 2020). High-gradient, strong-field PILs are proxies of (near-)photospheric compact electrical currents and the occurrence of major flares was often associated with the emergence of flux with high-gradient, strong-field PILs (Schrijver 2007; Toriumi & Wang 2019). According to the method of Chen & Wang (2012), we measured the length of the PILs with a steep horizontal magnetic gradient ($\geq 300$ G Mm\(^{-1}\)) for each flare event based on the SHARP vector magnetograms.

The energy that is released during a flare is generally believed to originate from the free magnetic energy stored primarily in ARs, which is the amount of magnetic energy in excess of the minimum energy attributed to the potential field (Molodensky 1974). It was found that the higher the free magnetic energy stored in an AR, the larger the size (magnitude) of upcoming flares (Jing et al. 2010; Su et al. 2014). We use a proxy for the total photospheric free magnetic energy (Wang et al. 1996; Chen & Wang 2012), which can be calculated as

$$E_{\text{free}} = \Sigma \rho_{\text{free}} dA,$$

where $\rho_{\text{free}}$ is a proxy for the density of the free magnetic energy in the photosphere, defined as

$$\rho_{\text{free}} = \frac{|B_o - B_p|^2}{8\pi},$$

where $B_o$ and $B_p$ are the observed and the potential magnetic fields, respectively. $B_o$ was derived from the observed $B_p$ component using the Fourier transform method. $\rho_{\text{free}}$ and $E_{\text{free}}$ are in units of (erg cm\(^{-3}\)) and (erg cm\(^{-1}\)), respectively. We measured $E_{\text{free}}$ by only considering the pixels with $\rho_{\text{free}} \geq 4.0 \times 10^{17}$ erg cm\(^{-3}\).

Magnetic shear, defined as the angular difference between the measured field and the calculated potential field, is another commonly used parameter in describing the magnetic complexity and nonpotentiality (Wang et al. 1994; Zhang et al. 2007). We measured the area with shear angle $\geq 80^\circ$, $A_\Psi$ (Chen & Wang 2012). The shear angle is given by

$$\Psi = \arccos \frac{B_o \cdot B_p}{|B_o||B_p|},$$

### 3. Statistical Results

#### 3.1. Relations of Flare–CME Association Rate with Flare Intensity and Magnetic Flux of ARs

We investigate the flare–CME association rate $R$ as function of both the flare class and the total flux of the source AR for 719 flares ($\geq$C5.0 class). Figure 1(a) shows the scatter plot of $\Phi_{\text{AR}}$ versus flare peak SXR flux ($F_{\text{SXR}}$). Blue (red) circles are the eruptive (confined) flares. Obviously, when $\Phi_{\text{AR}}$ is large enough ($> 1.0 \times 10^{23}$ Mx; black dashed line), an overwhelming majority (about 97%) of flares do not generate CMEs (57 of 59 flares are confined). Out of the flare events of $\Phi_{\text{AR}} > 1.0 \times 10^{23}$ Mx (a total of 59 events), 52 flares occurred in AR 12192, the huge AR known as flare-rich but CME-poor (Sun et al. 2015), and the fraction is about 54%. If we remove the events in AR 12192, almost all the events are confined (26 of 27 flares are confined).

The value of $\Phi_{\text{AR}}$ for the 719 flares ranges from $8.5 \times 10^{21}$ Mx to $2.3 \times 10^{22}$ Mx, and we divide $\Phi_{\text{AR}}$ into five subintervals. Figure 1(b) shows the relations of the association rate $R$ with $F_{\text{SXR}}$ within the five $\Phi_{\text{AR}}$ subintervals. For each subinterval, $R$ clearly increases with $F_{\text{SXR}}$. Each straight line in Figure 1(b) shows the linear fit

$$R = \alpha \log F_{\text{SXR}} + \beta,$$
where $R$ is in percentage and $F_{\text{SXR}}$ is in units of W m$^{-2}$. For the smallest $\Phi_{\text{AR}}$ subinterval ($\geq 2.0 \times 10^{22}$ Mx), the slope $\alpha$ is $113.8 \pm 13.1$ and $R$ reaches 100% when the flare is $> M1.3$ class (red straight line). For the subinterval of $2.0 < \Phi_{\text{AR}} \leq 3.5 \times 10^{22}$ Mx, the slope $\alpha$ decreases to $82.0 \pm 10.6$ (green straight line). It can be seen that in ARs with a small $\Phi_{\text{AR}}$ about 50% C5.0-class flares have associated CMEs. For the moderate $\Phi_{\text{AR}}$ subintervals (blue and orange lines), the slopes $\alpha$ are $48.2 \pm 5.4$ and $38.4 \pm 6.3$, respectively.

The Spearman rank order correlation coefficients $r_s$ are 0.96 and 0.94, respectively. In ARs with the largest $\Phi_{\text{AR}} (> 9.0 \times 10^{22}$ Mx), $R$ decreases significantly when compared to subintervals characterized by smaller $\Phi_{\text{AR}}$ (black straight line; also see Table 1). The relation between $R$ and $F_{\text{SXR}}$ in the largest $\Phi_{\text{AR}}$ subinterval is

$$R = (22.9 \pm 3.8) \log F_{\text{SXR}} + (125.7 \pm 17.9).$$

Based on Equation (5), only 20% of all M-class flares originating from the largest ARs have associated CMEs and the rate $R$ reaches about 40% for flares $> X2$. Almost all C5.0-class flares are confined due to the strong constraining fields in the largest ARs.

Figure 1(c) shows the relation of the slope $\alpha$ with $\Phi_{\text{AR}}$. $\Phi_{\text{AR}}$ is defined here as the mean of the individual log values in each $\Phi_{\text{AR}}$ subinterval. The plot shows that the slope $\alpha$ decreases monotonically with increasing $\Phi_{\text{AR}}$. We assume ARs in solar-type stars of $\Phi_{\text{AR}} \sim 1.0 \times 10^{24}$ Mx (Maehara et al. 2012; Shibata et al. 2013). Because there are only five known slope values, it is difficult to fit the plot and make an extrapolation. We use the slope in the largest solar ARs, i.e., 22.9, minus the average error estimate of five known slope values ($\sim 7.8$, corresponding to the average error of five diamonds), that is 22.9 minus 7.8 equals 15.1 as the slope $\alpha$ for stellar ARs of $\Phi_{\text{AR}} \sim 1.0 \times 10^{24}$ Mx. We estimate that the slope $\alpha$ might be no more than 15.1 $\pm$ 7.8 (red circle). If C5.0-class flares are all confined on solar-type stars (similar to the subinterval of $\Phi_{\text{AR}} > 9.0 \times 10^{22}$ Mx), we can extrapolate the flare–CME association rate for solar-type stars is given as

$$R = (15.1 \pm 7.8) \log F_{\text{SXR}} + 80.0.$$

Thus, for X100-class superflares in solar-type stars, the estimated association rate $R$ is no more than 50%.

### 3.2. Magnetic Nonpotentiality of ARs in Eruptive and Confined Flares

We calculate three nonpotential parameters for 132 flares $\geq M2.0$. Figure 2 shows an example of an eruptive X2.2-class flare occurring on 2011 February 15 in AR NOAA 11158. The SGPIL is located between two flare ribbons, and the distributions of the photospheric free energy density $d_{\text{free}}$ and shear angle $\Psi$ show similar patterns. In Figure 3, we display the scatter plots and histograms of the three nonpotential measures for the whole set of 132 flare events. It can be seen that the distributions of $L_{\text{SGPIL}}$ show evident differences between confined and eruptive cases (Figures 3(a)–(b)). For $L_{\text{SGPIL}} < 22$ Mm (black dashed–dotted line in Figure 3(a)), an overwhelming majority (about 90%) of flares are eruptive. The log-mean value of $L_{\text{SGPIL}}$ for confined flares is $40.2$ Mm (red dotted line in panel (b)), much larger than that for eruptive events (20.8 Mm, blue dotted line in panel (b)). The distributions of $E_{\text{free}}$ are similar to those of $L_{\text{SGPIL}}$. For $E_{\text{free}} < 1.5 \times 10^{23}$ erg cm$^{-1}$ (black dashed–dotted line in Figure 3(c)), 48 in 58 flares are eruptive. For $A_\Psi < 60$ Mm$^2$, about 79% (30 in 38) flares are eruptive (Figure 3(e)). The log-mean values of $E_{\text{free}}$ and $A_\Psi$ for confined flares are much larger than those for eruptive events (Figures 3(d) and (f)).

In Figure 4, we investigate the relationship between the three nonpotential parameters and $\Phi_{\text{AR}}$ in Figure 4. It can be seen that each of the two nonpotential parameters have strong correlations at $r_s \sim 0.69–0.85$ (Figures 4(a)–(c)).
correlation coefficients between $L_{SGPIL}$, $E_{\text{free}}$, and $A_{\Psi}$ imply that ARs with long SGPIL tend to store more free magnetic energy and have strong shearing. The scatter plot of $L_{SGPIL}$ with $\Phi_{\text{AR}}$ illustrates that they have a moderate correlation at $r_s \sim 0.4$ (Figure 4(d)). About 89% of the confined flares occur in ARs with $\Phi_{\text{AR}} > 3.5 \times 10^{22}$ Mx and SGPIL longer than 22 Mm. Moderate correlations were also obtained for $E_{\text{free}}$ versus $\Phi_{\text{AR}}$ and $A_{\Psi}$ versus $\Phi_{\text{AR}}$ (Figures 4(e)–(f)). Their moderate correlations with $\Phi_{\text{AR}}$ indicate that there is some trend that the higher the magnetic flux of an AR, the higher the nonpotentiality of the AR.

4. Summary and Discussion

In this study, we have examined 719 flares $\geq$C5.0 class that were observed on-disk from 2010 to 2019 June. We investigate for the first time the flare–CME association rate $R$ as a function of both the flare class $F_{\text{SXR}}$ and the total flux $\Phi_{\text{AR}}$ of the AR that produces the flare. We find that, for each $\Phi_{\text{AR}}$ subinterval, $R$ clearly increases with $F_{\text{SXR}}$, i.e., larger flares are more likely to be associated with a CME. This result is in agreement with previous findings studying CME-flare association rates (Andrews 2003; Yashiro et al. 2006), who reported overall CME associations of about 60% for M-class flares and 90% for X-class flares. However, what is new and particularly important in our study is that we considered not only the relation to the intensity of the flare but also to the characteristics of the AR in terms of its total magnetic flux. Our results show that the slope of the flare–CME association rate depends on the total flux of the AR that produces the flare, and reveals a steep monotonic decrease with $\Phi_{\text{AR}}$ (Figure 1(c)). This means that flares of the same GOES class but originating from an AR of larger $\Phi_{\text{AR}}$, are much more likely confined. Within the smallest $\Phi_{\text{AR}}$ subinterval ($\leq 2.0 \times 10^{22}$ Mx), all flares $\geq$M1.3 are all eruptive. On the other end of the distribution for the largest $\Phi_{\text{AR}}$ subinterval ($\geq 9.0 \times 10^{22}$ Mx), only about 20% of M-class flares have associated CMEs and the association rate $R$ reaches about 40% for those flares $\geq$X2.

Our results imply that $\Phi_{\text{AR}}$ is a key factor determining the eruptive character of solar flares, consistent with our previous studies (Li et al. 2020). $\Phi_{\text{AR}}$ can be considered to be both a measure of the total flux that is in principle available for flaring as well as being a measure of the background field confinement overlying the flaring region. Our findings imply that the latter is the more important factor here. Large $\Phi_{\text{AR}}$ means a strong confinement and thus the flare–CME association rate is relatively low compared to small $\Phi_{\text{AR}}$. Moreover, based on solar observations, we can speculate the associate rate $R$ on solar-type stars by assuming $\Phi_{\text{AR}}$ of $1.0 \times 10^{24}$ Mx (Maehara et al. 2012; Shibata et al. 2013). For X100-class “superflares” on solar-type stars, no more than 50% of flares can generate stellar CMEs. This may provide an explanation of why the detection of stellar CMEs is rare (e.g., Leitzinger et al. 2014; Argiroffi et al. 2019; Moschou et al. 2019; Vida et al. 2019; Veronig et al. 2021), while extrapolating current flare–CME relations to solar-type stars leads to unphysically high CME rates (Drake et al. 2013; Odert et al. 2017). Our findings provide an important contribution to revise the flare–CME association rates for solar-type stars, by including the distinct differences in these relations in dependence of the AR magnetic flux.

Using HMI vector magnetograms, we also have studied the relation between the degree of magnetic nonpotentiality and the eruptive character of 132 flares $\geq$M2.0, finding distinct
differences between eruptive and confined flares for all three nonpotentiality parameters derived (Figures 3–4). $L_{\text{SGPIL}}$, $E_{\text{free}}$, and $A_\Psi$ all give smaller log-mean values for eruptive flares than noneruptive flares. Each nonpotential parameter shows a moderate correlation with $\Phi_{\text{AR}}$. Our study shows that the three "extensive" parameters (those scaling with the AR size) can only discriminate the flares with small nonpotential parameters. As seen in Figure 3, 42 out of 47 events with $L_{\text{SGPIL}} < 22\, \text{Mm}$...
are eruptive. However, for the remanent 85 flares with $L_{SGPIL} > 22$ Mm, it is difficult to tell whether or not a flare is accompanied by a CME. The appearance of the other two parameters is similar to that of $L_{SGPIL}$. Only a fraction of flare events can be discriminated between confined and eruptive events. Thus we speculate that if we use these “extensive” parameters to predict the CME productivity, the True Skill Score (TSS) value is not high. This is consistent with the study of Bobra & Ilonidis (2016), who shows that TSS for predicting the CME productivity is low based on “extensive” parameters. They show that “intensive” parameters can predict the CME productivity. In our study, we did not calculate “intensive” parameters. In our future work, we will consider “intensive” parameters in confined and eruptive large flares based on our database.

In the statistical results of Cui et al. (2018), confined flares have larger values of $\Phi_{AR}$ and the gradient-weighted area of the polarity-inversion region than eruptive flares, which are in agreement with our results. It was found that large confined flares tend to occur in large ARs (Toriumi et al. 2017; Li et al.

![Figure 4](image-url) Relations between $L_{SGPIL}$, $E_{free}$, $A_{\Psi}$, and $\Phi_{AR}$ for eruptive (blue) and confined (red) flares. The black solid lines show the results of a linear fitting, and slopes $\alpha$ and Spearman rank order correlation coefficients $r_s$ are shown at the bottom right of each panel. Orange dashed-dotted lines in panels (d)-(f) correspond to $\Phi_{AR}$ of $3.5 \times 10^{22}$ Mx. Orange dashed lines denote $L_{SGPIL}$ of 22 Mm, $E_{free}$ of $1.5 \times 10^{23}$ erg cm$^{-1}$, and $A_{\Psi}$ of 60 Mm$^2$. 
2020), and thus $L_{\text{SGPIL}}$, $E_{\text{free}}$, and $A_{\Phi}$ are larger for confined than eruptive flares due to their positive correlations with $\Phi_{\text{AR}}$. Our results imply that $\Phi_{\text{AR}}$ is a key factor in determining whether a flare is eruptive or confined, as it provides a global parameter relating to the strength of the background field confinement.

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