Chapter

Variation of Coronal Magnetic Field and Solar Flare Eruption

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Abstract

Solar flares are prominent eruptive phenomenon happening in the solar atmosphere. Major flares usually come from solar active regions (ARs) where strong and concentrated bipolar magnetic field exists and manifests as dark sunspots in photosphere. The photospheric magnetic field acts as the bottom boundary of corona system and confines the magnetic structure of the corona. For complex ARs, the coronal magnetic field generally contains electric current around the magnetic polarity inversion lines, which corresponds to the nonpotential magnetic field and manifests as twisted field lines. The coronal magnetic field structure evolves as the response to the variations of the photospheric magnetic field. This coronal evolution can be quasi-steady and approximated by the force-free condition. In some situations, the variations of photospheric magnetic field may cause sudden changes of topological structure of coronal magnetic field at certain sites in the corona. The plasmas at these sites lost equilibrium and are ejected from their original positions. This process is accompanied with magnetic reconnection and leads to the release of magnetic energy in the corona. Part of the released magnetic energy is converted to the electromagnetic emission which manifests as sudden brightening across a broad range of electromagnetic wave spectrum, and hence the flare phenomenon is initiated.

Keywords: solar flare, magnetic field, plasma, corona

1. Introduction

Solar flares are prominent eruptive phenomenon happening in the solar atmosphere [1–3], where the matters have high temperature and hence in plasma state [4]. The energy of solar flares comes from the magnetic field in the solar atmosphere [1]. Major flares usually originate from solar active regions (ARs). In solar ARs, strong and concentrated bipolar magnetic field exists and manifests as dark sunspots in photosphere [2, 5].

The photospheric magnetic field acts as the bottom boundary of corona system and confines the magnetic structure of the corona [4, 5]. Because in the corona the plasmas are very tenuous, the magnetic force plays the dominant role, and other forces can be neglected. Thus, the plasmas in the corona are distributed along field lines and satisfy force-free condition (i.e., the Lorentz force being zero) for steady corona [6]. For complex ARs, the coronal magnetic field generally contains electric current around the magnetic polarity inversion lines (PILs), which corresponds to the nonpotential magnetic field and manifests as twisted field lines [7, 8]. The coronal magnetic field structure evolves as the response to the variations of the photospheric magnetic field. This coronal evolution can be quasi-steady and approximated by the force-free condition [9, 10].

In some situations, the variations of photospheric magnetic field may cause sudden changes of topological structure of coronal magnetic field at certain sites in the corona. The plasmas at these sites lost equilibrium and are ejected from their original positions. This process is accompanied with magnetic reconnection and leads to the release of magnetic energy in the corona [1, 3, 11]. Part of the released magnetic energy is converted to the electromagnetic emission which manifests as sudden brightening across a broad range of electromagnetic wave spectrum, and hence the flare phenomenon is initiated [2]. The typical electromagnetic emissions include white-light flare in photosphere, optical flare in chromosphere, and soft X-ray flare in the corona [2, 4]. Other released magnetic energy is converted to the mechanical energy of the erupted plasmoid and is also carried off by the high-energy particle radiation [2–4], which might lead to the coronal mass ejections and the solar energetic particles associated with solar flares [12–14].

An overview on the relations between the variation of coronal magnetic field and the solar flare eruption is given in this chapter. In Section 2, the main observational properties of the solar flares are presented. In Section 3, the nonpotentiality of the coronal magnetic field associated with the solar flares is discussed. The process of the flare initiation caused by the variation of coronal magnetic field is described in Section 4. Section 5 provides the summary and conclusion.

2. Solar flare observations

The energy of solar flares comes from the magnetic field in the solar atmosphere. It is natural that almost all major flares were found to be located in solar ARs which possess strong and concentrated bipolar magnetic field and manifests as dark sunspots in photosphere [1–5].

The electromagnetic emissions of solar flares can be observed in the corona, chromosphere, and photosphere of the Sun [2, 4]. In the standard model of solar flare eruption [3, 4], the magnetic reconnection associated with a flare takes place in the corona, just above the AR PIL and beneath the erupting plasmoid. The heat produced in the space of magnetic reconnection is transmitted to the chromosphere along the field lines. At the foot points of the field lines, the matters in chromosphere are heated up to extremely high temperature (about 10^7 K) and manifest as two bright ribbons located at the two sides of the PIL in the filtergrams observed through the chromospheric spectral lines (such as Hα, Ca II H and K, etc.). The flare brightening in chromosphere is traditionally called optical flare since it can be observed via an optical device equipped with a band filter of the selected chromospheric spectral line (see **Figure 1** for an example of flare image in chromosphere). The heated chromospheric materials subsequently fill up the arcade system of field lines over the PIL, which manifests as bright flare loop arcade in the corona in the images observed in extreme ultraviolet (EUV) or soft X-ray band [2, 4] (see **Figure 2**).

The energetic electrons produced by the magnetic reconnections also transmit downward along the field lines and can reach as low as upper photosphere level and cause flare brightening in white-light band [2, 4]. In fact, the first observed major flare event by Carrington in 1859 is white-light flare [15].

Because the photosphere of the Sun is very bright, the white-light flares cannot be observed very easily and frequently [16], whereas the soft X-ray flares originate from the thermal radiation in the corona and have much low background radiation, thus, the solar soft X-ray flux is widely adopted as the basis for standard flare

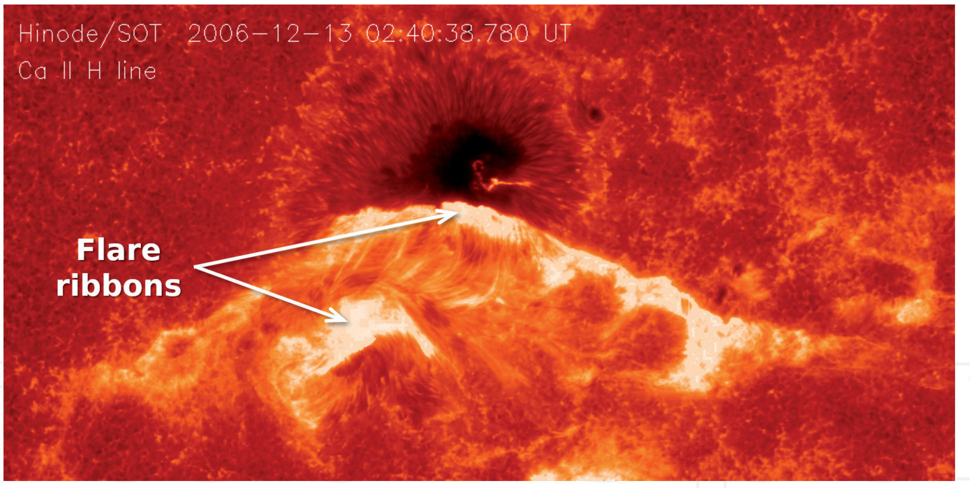

Figure 1.
Chromospheric image of a major flare event on 13 December 2006. The image was observed through the Ca II H spectral line by the Hinode satellite.

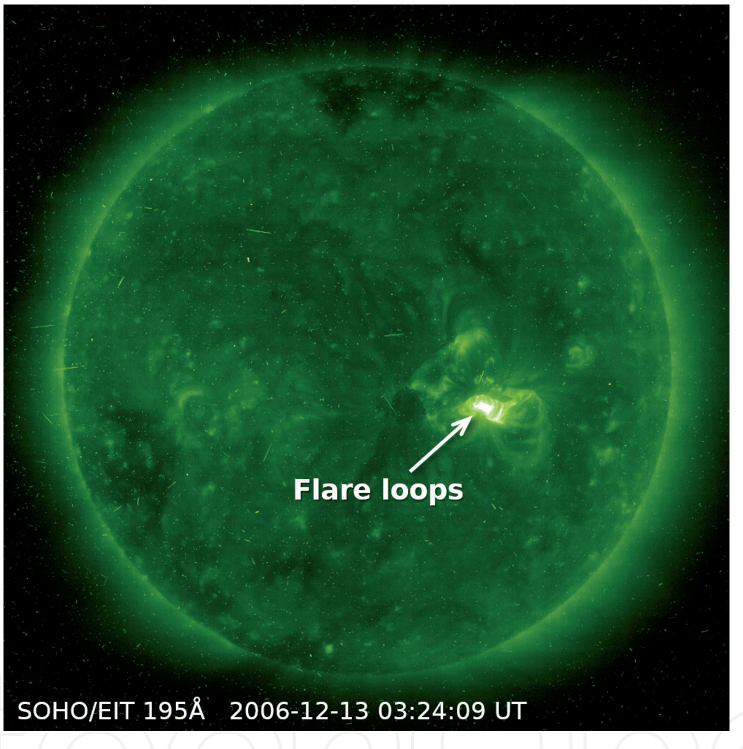

Figure 2.
Coronal image of the flare on 13 December 2006. The image was observed through the 195 Å EUV band by the SOHO spacecraft.

magnitude classification (i.e., A, B, C, M, X-class series of flare classification; see https://www.swpc.noaa.gov/products/goes-x-ray-flux) [14]. Other bands of electromagnetic spectrum, such as radio, ultraviolet (UV), hard X-ray, and γ-ray, are also commonly used for solar flare observations and studies [2, 4].

3. Nonpotentiality of coronal magnetic field

3.1 Force-free magnetic field of steady corona

Since the magnetic reconnection associated with solar flare eruptions takes place in the corona, the coronal magnetic field distribution is crucial for understanding the physical process of flares [1, 3, 4]. In fact, the photospheric magnetic field acts as the bottom boundary condition of corona system and confines the magnetic structure of the corona [4, 5].

In the corona, the temperature is very high (about 10^6 K), and the density of plasmas is very low [4]. Thus, the magnetic force (Lorentz force) dominates the coronal system, and other forces (such as gravity force, pressure, etc.) can be neglected. Then, in steady state of the corona, the plasmas are distributed along the field lines, and the Lorentz force is zero. This condition is called force-free condition, and the corresponding magnetic field is called force-free magnetic field [6]. Note that the essence of the force-free field concept is the dominant role of the magnetic field in a plasma system.

The force-free magnetic field $\boldsymbol{B}$ can be described by the following equation:

$$\nabla \times \boldsymbol{B} = \alpha \boldsymbol{B}. \quad (1)$$

The left part of Eq. (1) represents the electric current density vector:

$$\boldsymbol{j} = \frac{1}{4\pi} \nabla \times \boldsymbol{B} \quad (2)$$

(in electromagnetic CGS units). Then Eq. (1) indicates that the current density vector $\boldsymbol{j}$ and the magnetic field vector $\boldsymbol{B}$ are parallel to each other, and hence the Lorentz force is zero.

The proportional coefficient α in Eq. (1) is called force-free factor. The value of α can be positive, zero, or negative. If $\alpha > 0$, the electric current density $\boldsymbol{j}$ and the magnetic field $\boldsymbol{B}$ have the same directions, and if $\alpha < 0$, they have opposite directions. $\alpha = 0$ means that $\nabla \times \boldsymbol{B} = 0$, i.e., there is no electric current in the magnetic field (see Eq. (2)), and this special case is called potential magnetic field.

By taking the divergence of Eq. (1) and considering the divergence-free property of magnetic field, we have

$$\nabla \alpha \cdot \boldsymbol{B} = 0. \quad (3)$$

Eq. (3) means that along each field line, α is a constant. (Note that for different field lines, the values of α can be different.) This is an important character of the force-free magnetic field in corona.

Eqs. (1) and (3) together give the mathematical expression of the coronal force-free magnetic field model (two variable quantities α and $\boldsymbol{B}$ constrained by two equations) [6]. Given the observed photospheric vector magnetic field as the bottom boundary condition, the 3-D coronal magnetic field in steady corona can be calculated numerically based on Eqs. (1) and (3) [9, 10, 17–20].

3.2 Electric current and nonpotentiality of coronal magnetic field

The dominant force in the corona is magnetic force which acts on the electric current. In potential magnetic field, there is no electric current and hence no magnetic force. Thus, it is not possible for the potential magnetic field to produce eruptive phenomenon since there is no force to accelerate the plasmas.

To yield solar eruptions, the existence of electric current or nonpotential magnetic field in the corona is a necessary condition. In solar ARs with complex photospheric magnetic field, the coronal magnetic field generally contains electric current around the PILs (note that the magnetic field structure in the corona is confined by the photospheric magnetic field). This property (deviation from potential magnetic field) is called nonpotentiality of coronal magnetic field and is commonly employed to reflect the activity level (degree of possibility to produce eruptive events) of solar ARs [7, 8, 10, 11, 21]. The electric current density $\boldsymbol{j}$ (see Eq. (2)) is a physical measure to quantitatively describe the nonpotentiality of coronal magnetic field [10, 11] (see **Figure 3** for an example diagram of the electric current density spatial distribution in a solar AR).

3.3 Various manifestations of nonpotentiality

For a solar AR with single polarity magnetic field in photosphere, the coronal magnetic field is usually simple and tends to be potential field. The nonpotentiality

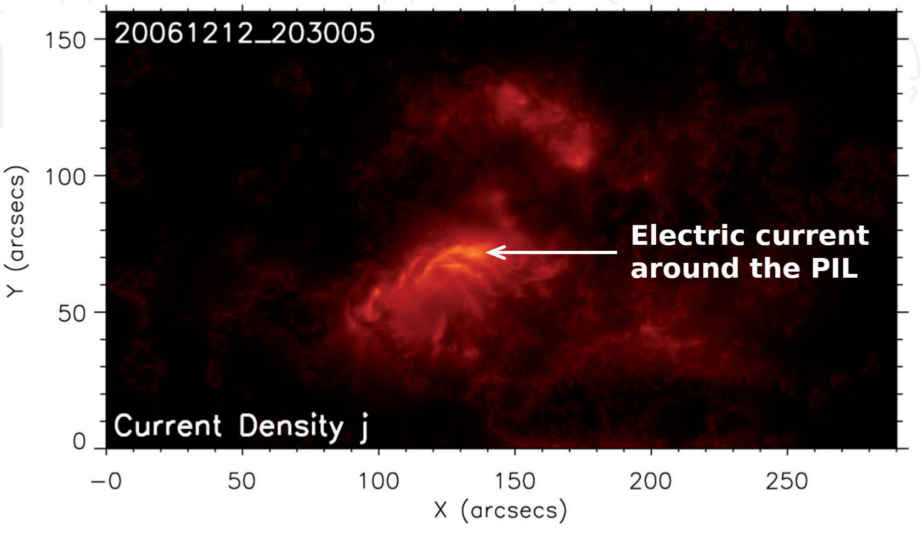

Figure 3.
Spatial distribution of electric current density in the source AR of the flare event on 13 December 2006 [11]. The electric current density values were derived from the 3-D coronal magnetic field data by using Eq. (2), and the coronal magnetic field data were calculated based on the force-free field model (see Eqs. (1) and (3)).

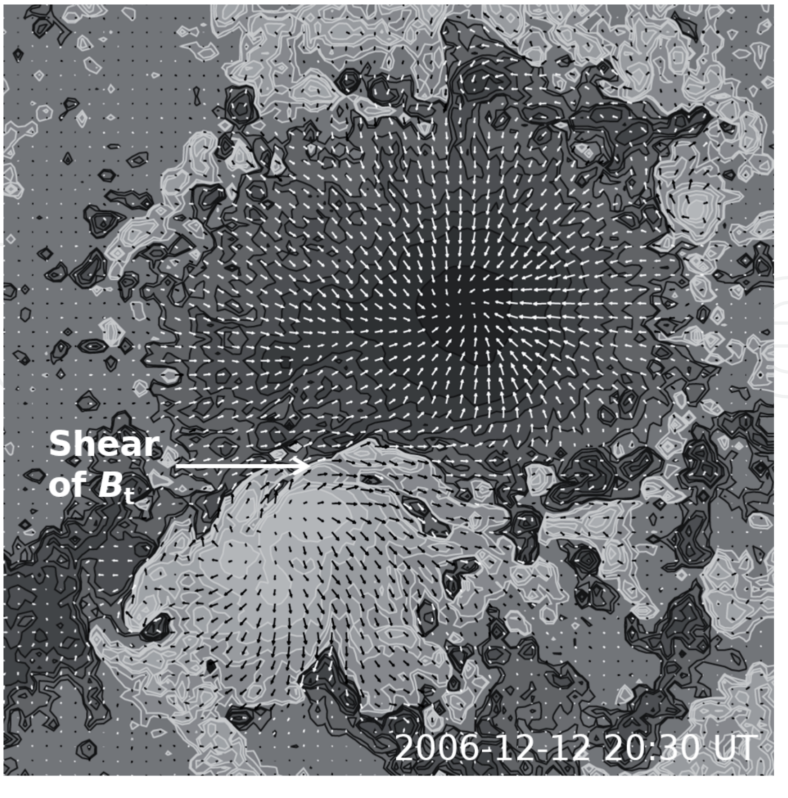

Figure 4.
Shear of the transverse component $\mathbf{B}_t$ of the photospheric magnetic field around the PIL in the source AR of the flare event on 13 December 2006 [11]. The small arrows indicate the directions of $\mathbf{B}_t$. The contours show the vertical component (and the two polarities) of the photospheric magnetic field. White contours represent the positive polarity, and black contours represent the negative polarity.

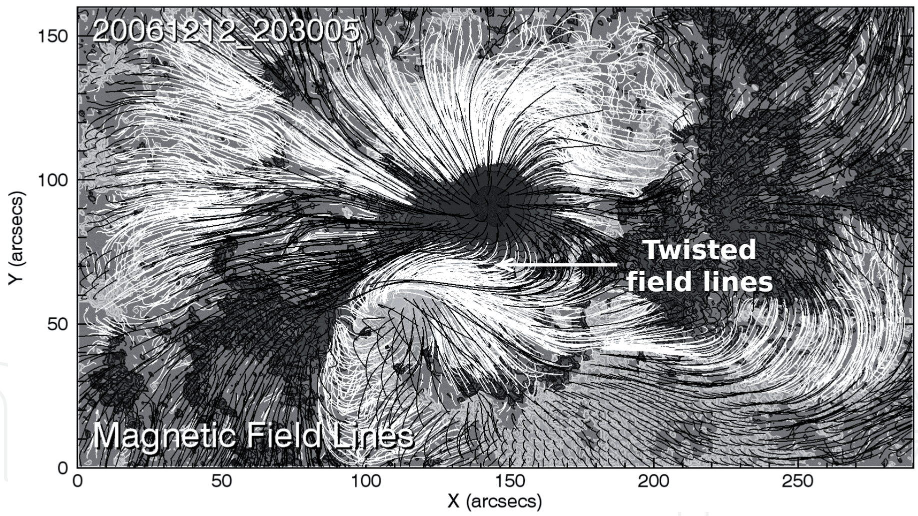

Figure 5.
Twisted field lines of the coronal magnetic field in the source AR of the flare event on 13 December 2006 [11]. Closed field lines are in white and open field lines are in black. The white and black background contours show the two polarities of the photospheric magnetic field. The coronal magnetic field was calculated based on the force-free field model.

is more prominent around the PILs of ARs with complex bipolar photospheric magnetic field. The typical characteristic of the photospheric vector magnetic field associated with the nonpotential magnetic field in the corona is the shear of the transverse component (denoted by $\boldsymbol{B}_t$) of the photospheric magnetic field. For potential magnetic field, the direction of $\boldsymbol{B}_t$ is generally vertical to the PILs, whereas for nonpotential magnetic field, the direction of $\boldsymbol{B}_t$ tends to be parallel to the PILs. The shear property reflects the direction deviation of the real $\boldsymbol{B}_t$ from the potential $\boldsymbol{B}_t$ [7] (see **Figure 4** for a diagram illustration).

Owning to the shear of $\boldsymbol{B}_t$ in photosphere, the field lines in the corona also show shear behavior around the PILs, i.e., the field lines tend to be parallel to the PILs. For a closed field line which starts at positive polarity, shears around the PIL, and ends at negative polarity, the three segments (start, shear, and end segments) of the field line compose a twist (S-shaped or inverse S-shaped) morphology (see **Figure 5** for an example diagram of the twisted field lines in corona). The twisted field lines indicate the existence of electric current in the corona and are another manifestation of the nonpotential magnetic field [8].

4. Variation of coronal magnetic field and solar flare eruption

4.1 Quasi-steady evolution of the corona

Because the photospheric magnetic field confines the magnetic structure in corona, along with the evolution of the photospheric magnetic field, the coronal magnetic field also evolves accordingly as the response to the variations in photosphere. The evolution in the photosphere is relatively slow owing to its relatively dense plasma, and the evolution in the corona is fast for its very tenuous condition. Thus, the corona can catch up the variations in photosphere promptly. If there are no eruptions on the Sun (quiet state), the coronal evolution (along with the evolution of the photosphere) can be quasi-steady and approximated by the force-free condition [4].

Provided a time series of observed photospheric vector magnetograms of a solar AR, by numerical modeling of the coronal magnetic fields based on the force-free field model for each magnetogram, we can obtain a time series of 3-D coronal magnetic field data associated with the photospheric magnetograms. These time series coronal magnetic field data quantitatively describe the quasi-steady evolution of the corona [9, 10]. By deriving the electric current density distributions from these coronal data, the time evolution of the nonpotentiality in the corona can also be revealed [10, 11].

4.2 Sudden change of coronal magnetic field structure and flare initiation

During the period of quasi-steady evolution of the corona, the plasmas in the corona are in quasi-equilibrium state, and the topological structure of coronal magnetic field evolves continuously. In some situations, the variations of photospheric magnetic field may cause sudden changes of topological structure of coronal magnetic field at certain sites in the corona [1, 3, 11]. The plasmas at these sites lost equilibrium and are ejected from their original positions. The magnetic reconnections occur beneath the erupted plasmoid, and then the flares are initiated. After the flare eruptions, the corona returns to equilibrium state and continues its quasi-equilibrium evolution [3, 11].

During the period of flare eruptions, the plasmas are in dynamic state, and the force-free condition is not satisfied. Out of the flare eruption period, the force-free field model is a well approximation to the coronal magnetic field [11].

Because the plasmoid ejection associated with the flare initiation needs magnetic force and the magnetic force (Lorentz force) only acts on the electric current, the sites of flare initiation are always located in the areas with strong electric current which in turn concentrates around the PILs of ARs. That is why the flare phenomenon is connected with the nonpotentiality (indicated by the electric current) of solar ARs, and flares always occur above the PILs.

4.3 Release of magnetic energy by flare eruption

Not all magnetic energy in the solar atmosphere can be depleted by flare eruptions. For example, the magnetic energy of a potential magnetic field cannot be consumed since no flare eruptions can occur in the potential magnetic field. Only the magnetic energy associated with the electric current in a nonpotential magnetic field can be accessed by flare eruptions. This part of available magnetic energy (energy bundled with the electric current) is called the free magnetic energy [4, 22].

During a flare eruption, a fraction of the total electric current around the PIL is ejected out together with the plasmoid eruption, and the corresponding part of the free magnetic energy is released. After the flare eruption, the total free magnetic energy decreases, and the twisted field lines around the PIL relax to a certain extent owing to the loss of electric current and the depletion of free magnetic energy [11].

A proportion of the released magnetic energy is converted to the electromagnetic emission which manifests as sudden brightening across a broad range of electromagnetic wave spectrum, and that is why the flare phenomenon is named [2]. Other parts of the released magnetic energy are converted to the mechanical energy of the erupted plasmoid and are also carried off by the high-energy particle radiation [2, 4]. The erupted plasmoid might lead to the coronal mass ejections (CMEs) accompanied with solar flares, and the high-energy particles might lead to the solar energetic particle (SEP) events associated with solar flares [12–14].

5. Conclusion

As a prominent eruptive phenomenon happening in solar atmosphere, solar flares usually come from solar ARs which possess strong and concentrated bipolar magnetic field in the photosphere. Between the two opposite polarities is the PIL of the magnetic field. Around the PIL is the sheared vector magnetic field in photosphere and twisted field lines in the corona, which are the manifestations of electric current distribution around the PIL and the existence of free magnetic energy bundled with the electric current. When a flare happens, the variation of the photospheric magnetic field causes sudden change of topological structure of coronal magnetic field at a site in the strong electric current area. The electric current and associated plasmas at this site lost equilibrium and are ejected from their original position. The magnetic reconnection occurs beneath the erupted plasmoid, and the flare is initiated. Part of the released free magnetic energy is converted to the electromagnetic emission of flares, which manifests as sudden brightening across a broad range of electromagnetic wave spectrum, such as white-light flare in photosphere, optical flare in chromosphere, and soft X-ray flare in the corona. Other released magnetic energy is transferred to CMEs and SEPs associated with flares. Big solar flares and the associated CMEs and SEPs can cause severe disturbances to the space weather condition in the solar-terrestrial space as well as in the whole heliosphere [14, 23–25].

Besides the Sun, flare phenomenon was also observed on the solar-type stars that possess magnetic activity [26–29]. In recent years, owing to the continuous light-curve observations for a large volume of stellar objects by the space missions, such as the Kepler space telescope [30], much more stellar flare samples were obtained and available for analysis [27, 29]. The understandings about the solar flares can provide a good physical framework basis for investigating the eruption mechanism of stellar flares [31, 32].

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