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The Evolution of the Magnetic Field Triggering Solar Eruptions

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Abstract: Severe solar eruptions pass through the heliosphere and reach the vicinity of the earth, which will have an impact on aviation and technology. Two typical solar active regions were selected to study the relationship between the evolution of active regions and solar eruptions. One of the active regions is AR 13229, which created 1 X-class flare, 2 M-class flares. The other active region is AR 12673, which created 4 X-class flares, 27 M-class flares. We found that new emerging magnetic flux in photosphere induced the changes of higher atmosphere (chromosphere and corona), which triggered the creation of big solar flares. The result can help us predict space weather.

1. Introduction

The solar interior is including nuclear reaction zone, radiation zone and convection zone, followed by photosphere, chromosphere, transition region, and corona. The sun’s energy comes from hydrogen fusion through the proton-proton chain in its core. Ground-based telescopes provide high-resolution imaging and monitoring of the Sun, but are limited by weather conditions and atmosphere interference. Space missions offer continuous 24-hour solar observation, but are expensive to build, launch and repair. Solar flares originate from magnetic energy stored in the solar corona, particularly in sheared or twisted magnetic flux tubes[1]. The CSHKP model [2, 3, 4, 5] proposes that flares occur when a magnetic flux rope moves upward and reconnects with underlying field lines. These energetic bursts are often accompanied by coronal mass ejections (CMEs)[6]. CMEs are immense clouds of magnetized plasma flung into space at high speeds. Sunspots form as part of the emergence of active regions[7]. Individual pores first form when magnetic flux emerges [8]. The pores grow and coalesce to form larger sunspots[9]. Approximately every 11 years, the Sun's magnetic field completely reverses its north and south magnetic poles. This solar cycle affects the formation of sunspots[10]. Solar cycle 25 has started since 2020, solar activities are becoming more and more stronger, simultaneously, solar eruptions will be more frequent and powerful. Strong solar eruption effects the heliosphere, which can destroy the electric network, oil or gas pipelines, satellite equipment etc. It is important to make forecast of solar eruptions before the peak of solar cycle. The study and investigation the origin of solar eruptions is very necessary and crucial. We choose two typical active regions to analyze the evolution of magnetic field and the relationship with correlated solar eruptions.

2. Acquisition and Processing of Astronomical Data from SDO

Launched in 2010 as part of NASA's Living with a Star program, the Solar Dynamics Observatory (SDO) mission contains three instruments -- the Atmospheric Imaging Assembly (AIA), the Extreme Ultraviolet Variability Experiment (EUV), and Helioseismic and Magnetic Imager (HMI). People can utilize helioviewer.org and People can download level 0 FITS files from http://jsoc.stanford.edu. Users can process the corresponding Level 1 files. The FITS data from SDO can be processed by software SAOImageDS9 and python. For astronomical data processing, Python's matplotlib.pyplot, astropy.io and numpy libraries are incredibly useful. The example code shows a method to oricess FITS data through Pythom and the results are shown in Figure 1.

```
with fits.open('filename.fits', ignore_missing_end=True) as hdul:
    data = hdul[0].data
plt.imshow(data, cmap='gray', origin='lower')
plt.colorbar()
plt.show()
```

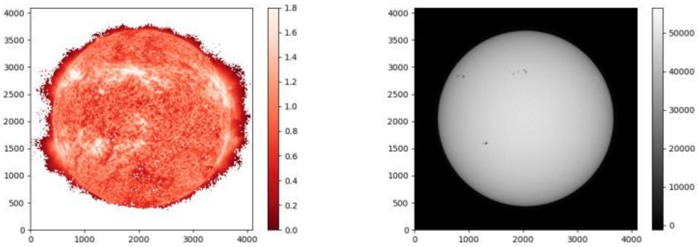

Figure 1: The processed FITS file image of the Active Region on HMI obtained using Python on February 22, 2023, 05:52:10 UTC and the Active Region on AIA304 obtained using Python on February 22, 2023, 05:23:05 UTC

3. Two Active Regions

SDO AIA 304 Å receives light from the chromosphere. SDO AIA 131 Å is designed to study solar flares. SDO AIA 171 Å shows the Sun’s atmosphere, transition region. The SDO HMI Continuum captures photographs of the solar surface and focuses on the photosphere region. The HMI Magnetogram captures images that depict the magnetic fields on the surface of the Sun. Black areas in the images represent locations where the magnetic field lines are pointing towards the Sun, while white areas represent locations where the magnetic field lines are pointing away from the Sun.

3.1 NOAA AR 13229

AR 13229 appeared at the east of the Sun on February 17 and rotated to the west of the Sun on February 25. This active region erupted a series of flares during its passage across the visible solar disk which include 1 X-class and 2 M-class flares. The detailed information about the flares is listed in Table 1.

Table 1: Flare Events from AR 13229 from Feb 17-25, 2023

Event	Date	Start (UT)	Peak	End	Goes Class
1	2023 Feb 17	19:38	20:16	20:50	X2.2
2	2023 Feb 24	20:03	20:30	21:29	M3.7
3	2023 Feb 25	18:40	19:44	20:27	M6.3

In this section, we analyzed the morphological variation, the evolution of magnetic field of AR 13229, and the accompanied solar eruptions.

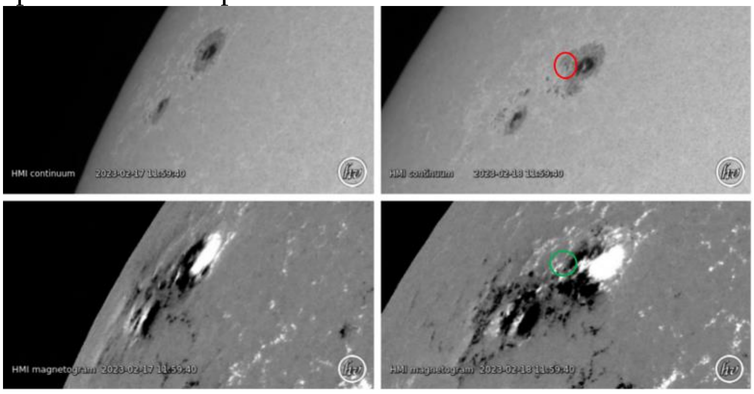

Figure 2: The filtergram (Top) and the magnetogram (Bottom) of AR 13229 on Feb. 17 and Feb. 18 observed by HMI.

3.1.1 The evolution of AR 13229 and X2.2 flare

There are two groups of sunspots in AR 13229 on Feb. 17, 2023, at 11:59, which are shown on top left of Fig. 2. One day later, in the south-east of the north sunspot, a large area of penumbra appeared, which is marked by red circle on top right of Fig. 2. The related magnetograms are shown in the bottom of Fig. 2. The mainly magnetic polarity is positive for the sunspot located in the north-west, and the mainly magnetic polarity is negative for the sunspot located in the south-east (bottom-left in Fig. 2.). Following the increase of the penumbra area, mixed magnetic patches emerged which is marked by green circle in the bottom-right image of Fig. 2.

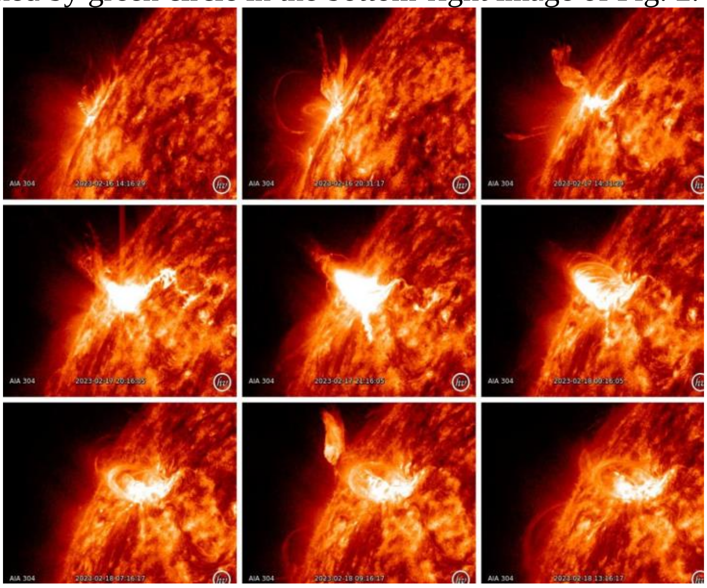

Figure 3: AIA 304 images of NOAA AR 13229 from Helioviewer

Figure 3 demonstrated the evolution of event 1 in the view of AIA 304. From the top images, an obvious filament eruption occurred. In the middle panel， the brightness dramatically increases. At 20:16 UT on Feb. 17, Goes soft x-ray arrived at its peak flux, the flare level is X2.2. In the subsequent image, the brightness continues decreasing, and the bright region shrinks.

By comparing the images of the magnetic field and AIA 304, people can observe that the magnetic fields emerge in the same locations where flares occur. Consequently, there is a strong correlation between the magnetic field and solar flares.

3.1.2 The evolution of AR 13229 on Feb. 24 and 25

The photospheric filtergrams of AR 13229 are shown in Figure 4. In the images in the top left corner, there are two groups of sunspots on the west side. From the remaining three images, it can be observed that a new sunspot appeared on the northwest side of the two sunspots on the west side of the images. The new emerged area is marked by a blue oval (bottom-left in the left figure in Fig. 4). The corresponding magnetic field evolution for the earlier photospheric evolution images are shown in right figure in Fig. 4. From this map, it can be observed that in the region corresponding to the newly formed sunspot on the northwest side, new magnetic patches have appeared and developed, which are marked by blue ovals in Fig.4.

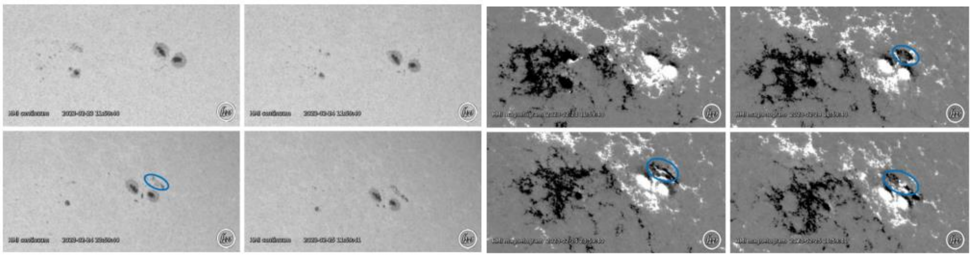

Figure 4: The filtergrams of AR 13229 on Feb. 23, 24 and 25 observed by HMI and The magnetograms of AR 13229 on Feb. 23, 24 and 25 observed by HMI.

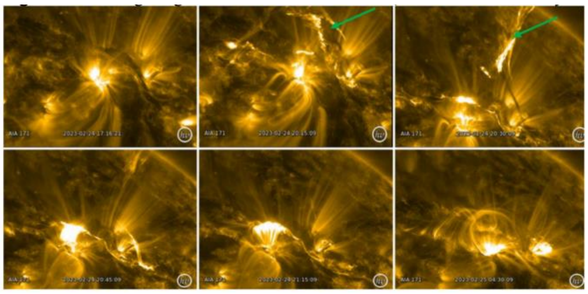

Figure 5: AIA 171 images of NOAA AR 13229 from Helioviewer

The evolution of event 2 observed in 171 Å wavelength is shown in Fig. 5. In the first row, the second and third images show an obvious filament eruption taking place, which are marked by green arrows. In the second row, the first image shows a dramatic increase in brightness. In the subsequent images, the brightness gradually decreases.

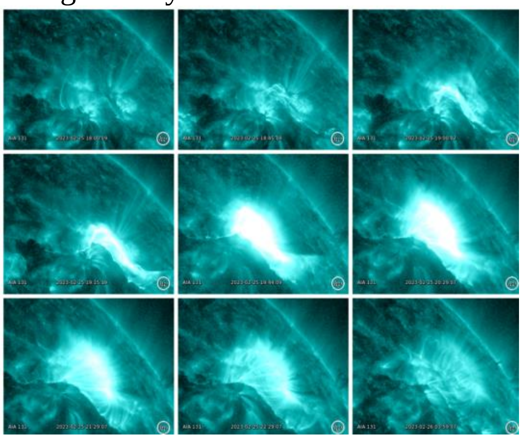

Figure 6: AIA 131 images of NOAA AR 13229 from Helioviewer

The evolution of event3 observed in 131 Å wavelength is shown in Fig. 6. From the images in the first and second rows, it is evident that the bright region noticeably enlarges. However, from the images in the last row, it can be observed that the bright region continues to shrink.

Three big flares are analyzed in this section. There are new regions with new emerged magnetic field. The emerged mixed magnetic patches triggered the higher atmosphere, which make the filament lifting and flare eruption.

3.2 Active Region 12673

AR 12673 is a very active region that produced numerous solar flares during the time it passed across the solar disk, including four X-class flares, 27 M-class flares, and many smaller flares [11]. The X9.3 flare that occurred on 2017 September 6 at 11:53 UT is the strongest flare of solar cycle 24. Observations suggest this flare may have been caused by the kink instability of a filament[12]. Pre-flare photospheric motions and magnetic properties also contributed to the large eruption, including the high magnetic gradient across the polarity inversion line, fast helicity injection, and high ratio of nonpotential to total helicity [13, 14, 15]. Coronal magnetic field extrapolations indicate the eruption was likely due to the interaction of a multi-flux rope system[16, 17]. Data-constrained MHD simulations reproduced the reconnection process between the twisted flux systems that eventually formed a large coherent flux rope during the eruption, suggesting the torus instability played a key role in triggering and driving the eruption [18, 19].

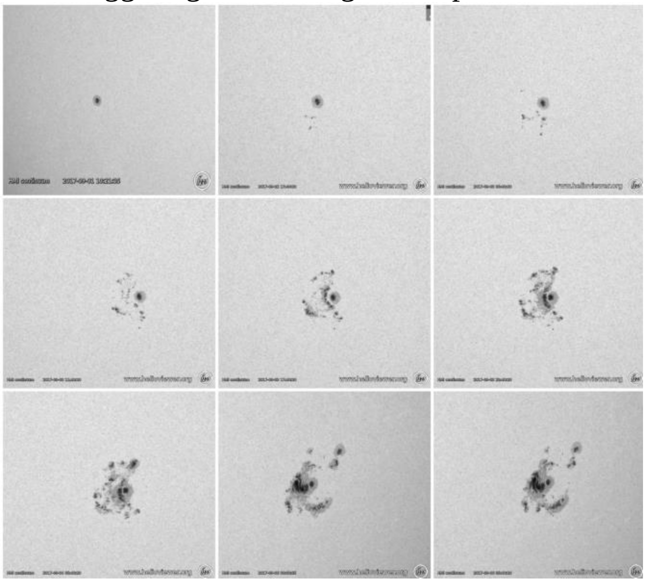

Figure 7: The filtergrams of AR 12673 observed by HMI.

AR 12673 evolved rapidly (Fig.7). It began as a simple mature sunspot. In the images in the second and third columns of the first row, a small group of sunspots appeared in the southeast direction of the original sunspot and gradually increased in number. In the images in the second row, sunspots emerged in the southeast, east, northeast, and north directions of the original sunspot. In the first image of the third row, a sunspot appeared in the northwest direction of the original sunspot. In the image in the second column of the third row, the sunspot in the northwest direction split into two sunspots.

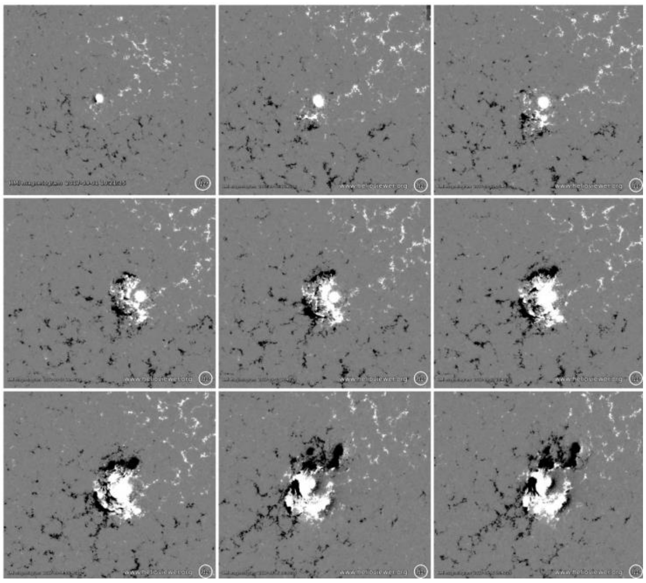

Figure 8: The magnetograms of AR 12673 observed by HMI.

In Fig.8, in the second and third columns of the first row, a small patch of negative field appeared in the southeast direction of the original sunspot and gradually increased in number. In the images in the second row, negative patches emerged in the southeast, east, northeast, and north directions of the original sunspot. In the images in the third column, the negative patch on the north side continued to grow. Overall, the emergence of negative patches coincided with the emergence of sunspots.

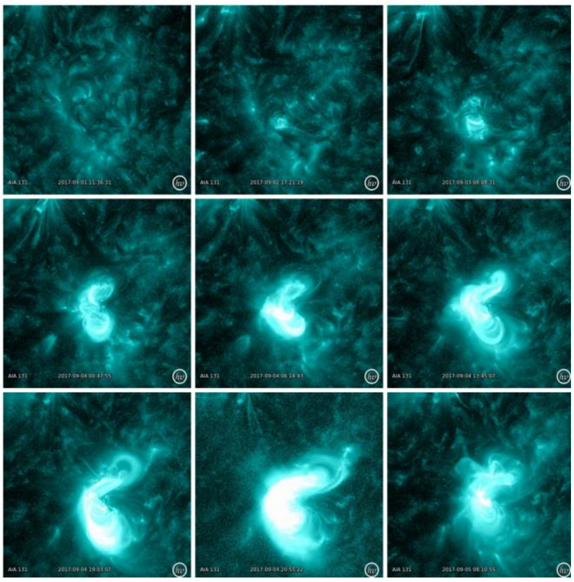

Figure 9: AIA 131 images of NOAA AR 12673 from Helioviewer

During the solar flare, a bright region appeared in the center of the image in the second column of the first row (Fig.9). Then, in the subsequent images, the bright region continued to expand, reaching its maximum size. Finally, starting from the image in the bottom right corner, the bright region began to shrink. The emergence and cancellation of magnetic bipoles resulted in the formation and decay of sunspots in AR 12673. Newly emerging flux and its interaction with preexisting magnetic fields determined the manner of penumbral evolution in the various sunspots, including how the penumbra developed, changed shape, and disappeared. The evolving surroundings likely affected the penumbral formation and decay through emerging flux and convective effects[20].

4. Results

Based on the observation of SDO, we used the images downloaded from Helioviewer, analyzed two typical active regions. One active region is AR 13229, which erupted 3 big flares (1 X-class, 2 M-class), the other active region is AR 12673, which erupted more than 30 big flares (4 X-class, 27 M-class). AR 13229 appeared on the Sun in February, 2023. We analyzed the evolution of sunspot, the variation of related magnetic field, and the eruption process of the three events. For the first event, the new penumbra in the mature sunspot with the new emerging mixed magnetic field induced the eruption of the filament, triggered the flare. For the second and third events, the new sunspots close to the mature sunspot brought new rapid emerging magnetic fields. The continually emerging magnetic patches triggered two different flares. AR 12673 is a productive active region, which was observed in September, 2017. Several scientists have studied this active region. We analyzed the formation and evolution processes of the active region, studied the variation of photospheric magnetic field, also demonstrated the morphological change in corona.

5. Conclusion and Discussion

In order to investigate the triggering mechanism of solar eruptions, we choose two typical active regions and analyzed the relationship between solar flares and magnetic variation in photosphere. AR 13229 was observed in 2023, which belongs to the increasing phase of solar cycle 25. AR 12673 was observed in 2017, which belongs to the decreasing phase of solar cycle 24. Both of two active regions produced several big solar flares.

Following results are found in this work:

(1) AR 13229 created 1 X-class and 2 M-class flares and AR 12673 created 4 X-class and 27 M-class flares.

(2) New emerging sunspot and new emerging penumbra are accompanied by emerging magnetic flux. The new emerging magnetic flux in photosphere induced the changes of higher atmosphere (chromosphere and corona), triggered the eruption of filament and the occurrence of flares.

(3) The rapid evolved active region is accompanied by the emergence and cancellation of sophisticated magnetic flux, which contributed to the creation of flares.

The emergence of sunspots is accompanied by the emergence of magnetic fields, generating free magnetic energy. Some of the free magnetic energy is converted into thermal energy. As the thermal energy gathers, flares occur. Some of the free magnetic energy is transformed into kinetic energy, causing coronal mass ejections (CMEs). With the gradual enhancement of solar cycle 25, there will be more and more solar eruptions that will affect near-earth space. Our results will lead to better predictions of space weather.

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