Circular ribbon flare triggered from an incomplete fan-spine configuration

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ABSTRACT

Context. Circular ribbon flares are characterised by circular, semi-circular, or elliptical ribbon brightenings. As the physics of such solar events involves a true 3D magnetic topology, they have been extensively studied in contemporary solar research.

Aims. In order to understand the triggering processes and the complex magnetic topology involved in circular ribbon flares, we carried out a thorough investigation of an M-class circular ribbon flare that originated within close proximity of a quasi-separatrix layer (QSL).

Methods. We combined multi-wavelength Atmospheric Imaging Assembly (AIA) and Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) observations with photospheric Helioseismic and Magnetic Imager (HMI) observations and coronal magnetic field modelling analysis using the non-linear force free field (NLFFF) model.

Results. The circular ribbon flare occurred from a complex magnetic configuration characterised by negative magnetic patches surrounded by positive-polarity regions on three sides. As the negative polarity patches were not surrounded by positive-polarity regions on all four sides, the corresponding coronal field was devoid of any null points. This led to the formation of an incomplete fan-spine-like configuration that deviated from classical fan-spine configurations in null-point topology. Further, an observationally identified QSL structure was situated within the active region, very close to the flaring region. The presence of the QSL was verified by the NLFFF modelling. The far end of the spine-like lines terminated very close to one footpoint location of the QSL lines. Our analysis suggests that activities at this location led to the activation of a flux rope situated within the fan-like lines and triggering of the circular ribbon flare via perturbation of the overall fan-spine-like structure. Further, we identified RHESSI X-ray sources from the footpoints of the QSL structure, which suggests that slipping reconnections can also lead to discernible signatures of particle acceleration.

Key words. Sun: corona – Sun: flares – Sun: magnetic fields – Sun: X-rays, gamma rays

1. Introduction

Solar flares are identified as sudden enhancements of local brightness in the solar atmosphere during which energy as high as $\sim 10^{32}$ erg can be released over the entire electromagnetic spectrum (see reviews by Priest & Forbes 2002; Fletcher et al. 2011; Green et al. 2018, etc.). It is globally accepted that the enormous amount of energy that is released during the solar flares is powered by previously stored magnetic energy in the active region, which is then released via a fundamental process called magnetic reconnection (Priest & Forbes 2002). During magnetic reconnection, oppositely directed magnetic fields undergo a topological reformation in magnetised plasma, converting magnetic energy into heat and non-thermal energies (Priest & Forbes 2000). Flares are frequently associated with eruption of plasma and magnetic field in the interplanetary space, a phenomenon known as ‘coronal mass ejection’ (CME; Chen 2011). The magnetic field linked with the Earth-directed CMEs often reconnects with the Earth’s magnetic field, leading to geomagnetic storms (see e.g. Moldwin 2008).

Magnetic reconnection itself is a complex phenomenon and the observational outcomes of magnetic reconnection in the solar corona are directly related to the pre-reconnection magnetic configurations. One of the most convenient ways to understand the pre-flare coronal magnetic configurations is to observe the shape and configuration of the flare ribbons (Hudson et al. 2006). Depending on the coronal magnetic configuration, flare ribbons can appear in a wide variety of shapes; however, morphologically, the majority of the flare ribbons can be classified into two categories: parallel and circular ribbons.

As the name suggests, parallel flare ribbons are characterised by a set of two distinct, parallel (or almost parallel) narrow, elongated bright structures that lie on the opposite sides of the polarity inversion line. Such structures are believed to occur in response to the precipitation of extremely fast electrons in the chromospheric medium along the post-reconnected magnetic loops, which are accelerated either directly or indirectly by magnetic reconnection (see e.g. Priest & Forbes 2000). In order to explain the ‘parallel ribbon flares’, the ‘standard flare model’ (also known as the CSHKP model) was proposed, combining the pioneering works of Carmichael (1964), Sturrock (1966), Hirayama (1974), and Kopp & Pneuman (1976). According to this model, when a pre-existing flux-rope structure is triggered for upwards expansion, magnetic reconnection sets in on a current sheet developed beneath the erupting structure (Shibata et al. 1996). During magnetic reconnection at these current sheets, previously stored magnetic energy is rapidly converted into plasma heating and non-thermal energies that result
in rapid acceleration of particles (see review by Priest & Forbes 2002). The CSHKP model is fairly successful in explaining most of the observable signatures of the parallel ribbon flares, such as looptop and footpoint hard X-ray (HXR) sources during the impulsive phase of the flare, increasing separation between the two parallel ribbons, development of a post-reconnection arcade and hot cusp-shaped structures during the gradual decay phase of the flares, and so on (see e.g. Tsuchiya et al. 1992; Masuda et al. 1994; Sui et al. 2006; Veronig et al. 2006; Miklenic et al. 2007; Joshi et al. 2009, 2017; Mitra & Joshi 2019; Mitra et al. 2020, see also reviews by Fletcher et al. 2011; Benz 2017). Here, it should be noted that, although the standard flare model has been extended in 3D by a series of magnetohydrodynamics (MHD) simulations (e.g. Aulanier et al. 2012, 2013; Janvier et al. 2013, 2014), the model originated as a 2D model and such flares are usually referred to as standard flares. In view of the apparent translation symmetry involved in the geometry of the magnetic configurations associated with such events, a number of studies have successfully simulated the standard flaring processes by implementing 2D or 2.5D symmetries in their computations (e.g. Yokoyama et al. 2001; Nishida et al. 2009; Shen et al. 2018; Kumar et al. 2021).

While parallel ribbon flares can originate from magnetic configurations involving 2.5D symmetries, the circular ribbon flares, characterised by the onset of circular, semi-circular, or elliptical flare ribbons (Masson et al. 2009), involve a true 3D magnetic configuration (Sun et al. 2012). The photospheric configurations associated with such complex processes usually involve the so-called anemone-type active regions, which are identified as a compact magnetic region surrounded by magnetic regions of opposite polarity (Shibata et al. 1994). Such anemone-type active regions usually develop as a compact region of magnetic polarity emerges within an opposite-polarity coronal hole (Asai et al. 2008). The magnetic configuration of such anemone-type active regions usually leads to the formation of a 3D null point (Longcope 2005) and associated fan-spine configurations in the corona (see e.g. Xu et al. 2017; Li et al. 2018; Joshi et al. 2021, etc.). The majority of the circular ribbon flares are triggered when a flux rope within the fan dome undergoes upward eruption, leading to magnetic reconnection at the coronal null point (Sun et al. 2012). In such cases, onset of parallel ribbon is observed within the fan dome which is followed by circular ribbons (Wang et al. 2012; Liu et al. 2015; Joshi et al. 2015; Hernandez-Perez et al. 2017; Li et al. 2017, 2018; Xu et al. 2017; Hou et al. 2019; Shen et al. 2019; Mitra & Joshi 2021).

It is notable that, in both categories of solar flares, flux ropes play a major role. Theoretically, magnetic flux ropes are defined by a set of magnetic field lines, which are twisted around its central axis more than once (Amari et al. 2003; Gibson & Fan 2006). Depending on the temperature and location of flux ropes, they can be observationally identified in many different forms, such as filaments, prominences, hot coronal channels, coronal sigmoids, and so on. Filaments are long, narrow, dark, thread-like features observed in the chromospheric images of the Sun (Zirin 1988; Martin 1998). When these structures are situated over the solar limb, they appear brighter than the background sky and are therefore called prominences (Tandberg-Hanssen 1995; Parenti 2014). Coronal sigmoids are identified as ‘S’ (or ‘inverted S’) shaped structures observed in the hot emission lines, that is, in soft X-ray (SXR) and the extreme ultraviolet (EUV) images (Rust & Kumar 1996; Manoharan et al. 1996; Joshi et al. 2017; Mitra et al. 2018). Hot channels are coherent structures observed in the high-temperature pass-band EUV images of the solar corona; for example AIA 94, 131 Å channel images (Zhang et al. 2012; Cheng et al. 2013, 2014; Mitra & Joshi 2019; Mitra et al. 2020). In the cases of parallel ribbon flares, magnetic reconnection occurring beneath the erupting flux ropes is responsible for the onset of the ribbon structures, while interaction of the erupting flux rope with a fan-spine-configured magnetic field – causing the magnetic reconnection at a coronal null point – is responsible for the onset of circular flare ribbons.

The majority of circular ribbon flares are characterised by a sequence of onset of a set of parallel ribbons followed by the onset of a circular ribbon. However, several recent studies have reported circular ribbon flares where the circular ribbon brightening was observed before the onset of the parallel ribbons (see e.g. Devi et al. 2020; Joshi et al. 2021). Further, Mitra & Joshi (2021) reported a set of homologous flares, which originated from an elongated fan-spine-like configuration that lacked a null point. These recent developments indicate the requirement for further investigation of circular ribbon flares and the associated magnetic configuration in order to obtain a general understanding of the complex solar magnetic configurations and associated transient activities.

In this article, we explore the 3D magnetic topologies and reconnections using the multi-wavelength observations of an intriguing M-class circular ribbon flare that originated from a complex βγδ-type active region NOAA1 12297. Importantly, the circular ribbon was developed from an incomplete anemone-type photospheric configuration where the central polarity was not fully surrounded by opposite-polarity flux regions on all the sides. In Sect. 2, we provide the sources of observational data and numerical techniques used in this article. Multi-wavelength photospheric, chromospheric, and coronal observations of the complex flaring processes are discussed in Sect. 3. Analyses involving photospheric magnetic field, such as computation of photospheric vertical currents, modelling of coronal magnetic field, and so on, are provided in Sects. 4 and 5. We discuss and interpret our results in Sect. 6.

2. Observational data and analysis techniques

For UV and EUV imaging, we used the 4096 × 4096 pixel full-disk observations at a pixel scale of 0.06 from the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the Solar Dynamics Observatory (SDO; Pesnell et al. 2012). AIA provides observations at 12 s cadence in seven EUV channels (94 Å, 131 Å, 171 Å, 193 Å, 211 Å, 304 Å, 335 Å), at 24 s cadence in two UV channels (1600 Å and 1700 Å), and in one white-light channel (4500 Å) every hour.

We used observational data from the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI; Lin et al. 2002) to investigate the X-ray sources from the flaring region. RHESSI observed the full Sun with unprecedented spatial resolution (as fine as ~2″) and energy resolution (1–5 keV) in the energy range 3 keV–17 MeV. For reconstruction of the RHESSI images, we employed the Pixon algorithm (Metcalfe et al. 1996) with the natural weighting scheme for front-detector segments 4–8 (excluding 7).

For photospheric observation, we used the 4096 × 4096 pixel full disk line of sight (LOS) magnetogram and intensity observations at a pixel scale of 0.5″ and time cadence of 45 s by Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) on board SDO. We carried out coronal magnetic field modelling using

\footnote{See https://www.swpc.noaa.gov/}
the vector magnetogram data from the ‘hmi.sharp_cea_720s’ series of HMI at a reduced scale of 1/10 pixel$^{-1}$ as the input boundary condition. For the modelling, we applied the optimisation-based non-linear force free field (NLFFF) extrapolation method developed by Wiegelsmann & Inhester (2010), Wiegelsmann et al. (2012). Extrapolations were done within a volume of $530 \times 332 \times 300$ pixels, which corresponds to the physical dimension of $\approx 384 \times 240 \times 218$ Mm$^3$. The fractional flux ratio ($|f/f_o|$) and the weighted angle between the extrapolated magnetic field ($B$) and current ($J$) were found to be $3.0 \times 10^{-3}$ and $6.8^\circ$. These values can be used to assess the quality of the coronal-field reconstruction (see DeRosa et al. 2015). Based on the NLFFF extrapolation results, we calculated the degree of squashing factor ($Q$) and twist number ($T_n$) in the extrapolation volume using the IDL-based code developed by Liu et al. (2016). For visualising the modelled field lines and the distribution of $Q$ in the active region volume, we used the Visualization and Analysis Platform for Ocean, Atmosphere, and Solar Researchers (VAPOR$^2$; Clyne et al. 2007) software.

3. Multi-wavelength observation and results

3.1. NOAA 12297: Photospheric, chromospheric, and coronal configurations

The active region NOAA 12297 appeared on the eastern limb of the Sun on 7 March 2015 as a simple $\alpha$-type active region. However, it rapidly evolved into a $\beta\gamma$-type active region on 8 March and the most complex $\beta\gamma\delta$-type on 9 March. Flaring activity from the active region started on 8 March in the form of a C-class flare. During its transit through the visible hemisphere of the Sun, NOAA 12297 produced a total of 18 M-class flares and 1 X-class flare along with more than 80 C-class events. In view of the science objective of this article, the most interesting flare from NOAA 12297 occurred on 12 March 2015, which evolved with a circular ribbon brightening with a GOES$^3$ class of M2.7. Figure 1 shows the multi-wavelength overview of the active region prior to the onset of the M2.7 flare, which includes nearly co-temporal images of the photospheric, chromospheric, and coronal layers. Notably, the flare occurred during the most flare-productive phase of the active region (i.e. 11–12 March 2015). The active region disappeared over the western limb of the Sun on 21 March 2015.

The continuum image of NOAA 12297 (Fig. 1a) readily reveals the complex nature of this region. The active region was composed of one prominent sunspot (indicated by the blue arrow in Fig. 1a) along with a few relatively small sunspots (within the circle in Fig. 1a). Notably, despite the small size of these dispersed sunspots, we clearly observe umbrae and penumbrae structures associated with them, suggesting high magnetic field strength. The trailing prominent sunspot group is also very interesting, as it contained a few fragmented umbrae structures (indicated by the red arrows in Fig. 1a) along with a very prominent umbral. A comparison of co-temporal magnetogram with the white-light image (cf., Figs. 1a and b) reveals the leading fragmented sunspot group region (within the circle in Fig. 1a) to be associated with many dispersed mixed-polarity magnetic-flux patches. The major umbra of the trailing sunspot group is mostly of positive polarity, while the fragmented umbrae are associated with negative-polarity fluxes. However, the most interesting

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2 https://www.vapor.ucar.edu/
3 Geostationary Operational Environmental Satellite; see https://www.nasa.gov/content/goes-overview/index.html

Fig. 1. Photospheric and coronal overview of the active region NOAA 12297 on 12 March 2015. Panel a: white-light image. The black oval encircles a few small, distinct sunspots. The blue arrow indicates the most prominent sunspot group of the active region. The red arrows indicate a few narrow, elongated umbrae within the major sunspot group. Panel b: co-temporal magnetogram. The sky-coloured arrows indicate two localised magnetic patches within regions of opposite polarity. For correlation, we have plotted two sky-coloured arrows in panel a at exactly the same locations as the sky-coloured arrows in panel b. Panels c–d: EUV images in the AIA 171 and 131 Å channels, respectively. The deep-blue arrows in panel c and pink arrows in panel d indicate an interesting set of coronal loops (also marked ‘QL’ in panel c) which appear similar to quasi-separatrix layers (QSLs). The green arrows in panels c and d indicate another interesting set of coronal lines (also marked ‘FS’ in panel c), which appear similar to a fan-spine configuration. The sky-coloured arrows in panel c indicate two localised bright kernels, which are exactly co-spatial with the magnetic patches indicated by sky-coloured arrows in panels a and b. Co-temporal LOS magnetogram contours are overplotted in panel d. Contour levels are $\pm [500, 2000]$ G. Red and yellow contours refer to positive and negative magnetic flux, respectively.
The flare initiated at \( \approx 23:20 \) UT on 12 March 2015 which covers the GOES M2.7 flare is characterised by two sets of field lines (indicated by the dark blue arrows in Fig. 1b) and a few smaller coronal loops. Overall, these lines constitute an apparent structure similar to the fan-spine configuration associated with coronal null points. From this symmetry, we refer to this loop system as ‘FS’ (in reference to its fan-spine configuration). Comparison of the coronal image with co-temporal LOS magnetogram contours (Fig. 1d) reveals that the longer loops of the structure FS connected the positive-flux regions of the leading part of the active region (marked by the sky-coloured arrows). A few minutes prior to the onset of the flare (indicated by the dashed line marked \( t_2 \) in Fig. 2a), a few of the coronal loops associated with the apparent QSL structure (cf. the blue arrows in Figs. 2b and e) become much brighter. We also note enhanced brightening from the location of the fan-like field lines (indicated by the yellow arrow in Fig. 2e). We further observe rapid restructuring of the spine-like lines (cf. the loops indicated by red and sky-coloured arrows in Fig. 2c with those in Fig. 2f). The peak-phase of the M-class flare (indicated by the dashed line marked \( t_3 \) in Fig. 2a) is characterised by the onset of a clear elliptical flare ribbon (outlined by the white-coloured ellipses in Figs. 2h–j). The southern part of the elliptical flare ribbon appears to be particularly intensely bright in AIA 94 Å images (indicated by the red arrow in Fig. 2h). AIA 304 Å images depict clear signatures of a set of parallel ribbons (indicated by the sky-coloured arrows in Fig. 2j) co-spatial to the intense brightening observed in the AIA 94 Å images. After the flare (indicated by the dashed line marked \( t_4 \) in Fig. 2a), we observe discrete periods of intensity enhancements from the location of the QSL (outlined by the white-coloured ellipses in Figs. 2k–m) which are most likely responsible for the multiple episodes of SXR flux enhancements as recorded by the GOES channels.

In Fig. 3, we compare GOES SXR light curves with the temporal evolution of X-ray counts in different RHESSI energy bands as well as with the (E)UV fluxes computed from different AIA channels. RHESSI observed the entire duration of the M-class flare (Fig. 3a). Comparison of RHESSI and GOES light curves immediately suggests that the counts in the RHESSI channels in low energies (i.e. 6–25 keV) followed a similar temporal evolution to the GOES channels. As expected, the temporal evolutions of the high-energy RHESSI bands (e.g. >25 keV) are characterised by multiple bursts during the impulsive phase of the M-class flare. (E)UV fluxes in the AIA channels – except the 94 Å channel – depict similar temporal evolution in view of the sharp, impulsive flux increase during the impulsive phase of the flare (Fig. 3b). The intensity in the AIA 94 Å channel displays a delayed increase which is expected as the thermal emission leading to 94 Å flux is mostly associated with the post-reconnection arcades. The periods of post-flare SXR flux enhancements are also observed in the (E)UV light curves, which are most prominently observed in the AIA 94 Å channel (Fig. 3b).
Fig. 2. Multi-wavelength evolution of the M2.7 flare on 12 March 2015. Panel a: soft-X-ray evolution GOES 1–8 Å and 0.5–4 Å channels, showing the initiation and evolution of the flare as well as the extended period following the flare that included multiple small peaks. Panels b–m: EUV images of the active region during the period of our observation in AIA 94 Å (left column), 171 Å (middle column), and 304 Å (right column) channels. The panels in each row are co-temporal. The time information for each row is indicated in panel a by the dotted lines (marked ‘t1’–‘t4’). Different arrows in different panels indicate a few important coronal loop systems and brightenings during the interval of observation. The oval shapes in panels h–j outline the circular flare ribbon, while the oval shapes in panels k–m outline brightening from the apparent QSL structure. A movie associated with this figure is available online. The movie has a duration of 40 s and displays the temporal evolution of the active region in AIA 94, 171, and 304 Å wavelengths with 12 s cadence between 21:15 UT and 23:20 UT on 12 March 2015.
3.3. Triggering of flare, flare emission, and large-scale restructuring of coronal loops

Figure 4 shows a series of AIA 94 Å images displaying the evolution of the flaring region during the interval of our observation. As we identify in Sect. 3.1, the coronal configuration associated with the active region NOAA 12297 can be characterised in two parts: FS-configuration and a QL-structure (Fig. 1c). In Fig. 4a, we indicate the FS-configuration with the sky-coloured arrows and mark the apparent QL-loops with the dashed, red oval. Importantly, both the far end of the FS-loops and one end of the QL-loops seem to have a common location of termination (marked by the yellow five-pointed star in Fig. 4a). We refer to this location as the location of common origin (LCO). During the pre-flare phase, the QL-associated coronal loops displayed enhanced brightening (see Sect. 3.2 and Figs. 2b–g). Along with the enhanced EUV brightening, we identify clear RHESSI sources up to energies of $\approx 12$ keV from the footpoint locations as well as from the coronal loops associated with the QL-structure (Fig. 4b). Only a few minutes ($\approx 3$ min) prior to the onset of the flare, we identify clear RHESSI sources up to an energy of $\approx 12$ keV from the fan-like location in addition to the X-ray emission from the QL-structure (Fig. 4c). From $\approx 21.45$ UT, we observe clear signatures of a flux-rope eruption from the fan-like lines (explained in detail in Sect. 3.5), which lead to rapid restructuring and expansion of the spine-like lines. This apparent expansion of the spine-like lines is indicated with the red arrows in Figs. 4e, f, and h. The expansion of the spine-like structure temporally matches the onset of the elliptical ribbon-like brightening around the periphery of the fan-like lines (Fig. 4f). Notably, within the fan-like dome, the eruption of the filament is immediately followed by the onset of two parallel ribbon-like brightenings (indicated by the yellow arrows in the inset of Fig. 4f) followed by the formation of a dense post-reconnection arcade (Figs. 4g–i; a clear view of the post-reconnection arcade is presented in the inset of Fig. 4i). Highly concentrated RHESSI sources with energies up to $\approx 25$ keV are found from the flare ribbons and the post-reconnection arcade (Figs. 4f and h). By $\approx 22.10$ UT, flare emission has decreased significantly and has reached a local minimum, whereafter it
Fig. 4. Series of AIA 94 Å images of the active region NOAA 12297 showing the evolution of the M2.7 flare as well as the extended period following it. Co-temporal LOS magnetogram contours are overplotted in panel l. Contour levels are ±200 G. Red and yellow contours refer to positive and negative magnetic flux, respectively. PIXON re-constructed co-temporal RHESSI 3−6 keV (yellow), 6−12 keV (red), 12−25 keV (blue) contours are overplotted in panels b–d, f, h, j, and k. Contour levels are [50, 70, 90]% of the corresponding peak flux. The sky-coloured arrows in panel a indicate a fan-spine-like configuration while the red dashed oval outlines the coronal loops associated with the QSL structure. The yellow star indicates the common location (LCO) where both the spine-like coronal lines and the QSL-associated coronal loops terminated on the photosphere. The red arrows in panels e, f, and h indicate an expanding loop system. The yellow arrows in the inset of panel f indicate parallel flare ribbons. The sky-coloured arrows in panel l indicate a few large coronal loops connecting the leading part of the active region to the trailing part. The boxes in panels f and i also indicate the FOV of Fig. 7.

increases again (Fig. 3). During the peaks of the post-flare periodic SXR enhancements, X-ray sources are mostly concentrated in the QSL structures (e.g. Fig. 4j). However, we also observe discrete X-ray emissions from the location of post-reconnection arcade, although EUV emission from this region significantly reduces after the flare (Fig. 4k). It is worth mentioning that, during this time, the spine-like lines are completely reconfigured, and instead of one set of spine-like lines, we observe the development of multiple, distinct sets of large coronal loops (indicated by the sky-coloured arrows in Fig. 4l). These loops...
Fig. 5. Series of AIA 171 (panels a–f) and 304 (panels g–l) Å images of the active region NOAA 12297 showing the evolution of the M2.7 flare as well as the extended period following it. The green arrows in panels a–d indicate the rapid restructuring of the spine-like lines during the M-class flare. The sky-coloured arrows in panels a and f indicate a few bright coronal loops associated with the QSL. The red oval in panel d and the green arrows in panel j indicate the circular ribbon brightening during the flare. The sky-blue arrows in panels i and j indicate parallel ribbon brightening. The blue arrows in panels e and k indicate post-reconnection arcade. The blue oval in panel l encloses the brightenings from the location of the QSL. The blue five-pointed stars in panels a and g indicate the LCO.

originate from the positive-polarity regions surrounding the location of the circular ribbon brightening, and terminate in the negative-polarity regions in the trailing part of the active region. Interestingly, the apparent width of these sets of large coronal loops seems to expand significantly towards the trailing part of the active region.

In Fig. 5, we plot a series of AIA 171 (Figs. 5a–f) and 304 (Figs. 5g–l) Å images of the active region during our observation period. As explained in Sect. 3.1, during the pre-flare phase, when the SXR flux was at the background level, the QSL structure at the southeastern part of the active region was the brightest area in the region. In Fig. 5a, the brightest loops associated with the QSL are indicated by the sky-coloured arrow. As identified in the AIA 94 Å images, the QSL structure and the far end of the spine lines have a common LCO (see Fig. 4a). For a better comparison between the multi-channel AIA images, the LCO is
also marked by blue five-pointed stars in Figs. 5a and g. Importantly, AIA 171 Å images clearly reveal signatures of restructuring and rapid evolution of the spine-like lines from a few minutes prior to the onset of the flare (indicated by the green arrows in Figs. 5a and b). Following the initiation of the event, the spine-like lines experience a sudden expansion and within a few minutes, these coronal loops vanish in the AIA 171 Å images (indicated by the arrows in Figs. 5c and d). Here we recall that, the expansion of the spine-like lines following the onset of the flare is also identified in the AIA 94 Å images (Figs. 4e–h). Intense emission from the circular and parallel ribbons caused oversaturation of pixels in the AIA 171 Å images during the peak phase of the flare. The circular ribbon flare is enclosed by the red oval in Fig. 5d and indicated by the green arrows in Fig. 5j, while the small but clearly distinguishable parallel ribbons are indicated by the sky-coloured arrows in Figs. 5i and j. The post-reconnection arcade formed during the gradual phase of the flare is indicated by the blue arrows in Figs. 5e and k. As the flaring emission ceased, the brightening from the active region moved to the QSL region again (indicated by the sky-coloured arrow in Fig. 5f and enclosed by the blue oval in Fig. 5i).

### 3.4. Low-atmospheric localised brightening: Possible signatures of flare triggering

Although AIA EUV images and RHESSI X-ray sources clearly reveal different aspects of the flaring event, including the shift of EUV brightening and X-ray emission from the location of the QSL to the region of the circular ribbon brightening during the flare (Figs. 4 and 5), we are not able identify any clear signature of the triggering of the circular ribbon flare. In order to search for probable signatures of the triggering of the flare, we analysed AIA UV images of the active region in the 1600 Å channel (Figs. 6a–f). In these images, we immediately notice a highly localised bright kernel situated on the eastern boundary of the trailing sunspot region (indicated by the yellow arrows in Figs. 6a–b, d–f). Notably, the location of the bright kernel is adjacent to the LCO (marked by the five-pointed star in Fig. 6a). This bright spot is associated with a photospheric positive polarity patch within negative polarity regions (see Sect. 3.1 and Fig. 1). This bright spot was observed throughout the interval of our analysis, although the brightness and the spatial extension of it varied. A few minutes prior to the onset of the flare, we observe another localized brightening from a region very close to the location of the circular ribbon brightening (indicated by the green arrow in Fig. 6b). Here it should be noted that although very close, the location of this localised bright spot is actually well separated from the location of the circular flare ribbons. To demonstrate this, we plot a green arrow in Fig. 6f with the same coordinates as the green arrow in Fig. 6b. From this comparison, one can easily understand the spatial separation between the bright kernel and the flare ribbons. From ≈21:44 UT, we observe an extremely mild circular and parallel ribbon brightenings (Fig. 6c as well as in the inset), which become very bright following ≈21:46 UT. The circular and parallel ribbon brightenings are enclosed by the blue and red closed curves in Fig. 6e. We further note the onset of brightening from a localised spot close to the trailing sunspot region, which is co-temporal with the circular ribbon brightening (indicated by the red arrows in Figs. 6d–f). This location is co-spatial to one of the fragmented umbrae situated within the northern part of the trailing sunspot group (indicated by the red arrow whose head is to the north of the central umbra in Fig. 1a). Signatures of the circular ribbon brightening mostly disappear by ≈22:00 UT, although we can observe the parallel flare ribbons until ≈22:13 UT (indicated by the sky-coloured arrows in Fig. 6f).

AIA (E)UV images suggest that onsets of both the circular and parallel ribbon brightening take place almost simultaneously. In order to further investigate the temporal correlation between the two types of flare ribbons, we computed light curves (Fig. 6g) by considering the areas within the blue and red closed curves in Fig. 6e. These light curves suggest a mild enhancement of the flare-ribbon brightenings a few minutes prior to the impulsive rise of the ribbon brightenings during the flare. Our analysis suggests that the initial increase in the parallel ribbons takes place at ≈21:39 UT (indicated by the vertical red dashed line in Fig. 6g). Intensity values from the circular ribbon area undergo a mild enhancement at ≈21:42 UT (indicated by the vertical blue dashed line in Fig. 6g), that is, ≈3 min after the onset of the parallel ribbon. As the M-class flare initiates at ≈21:46 UT, we observe an impulsive increase in the intensity values from the flare ribbons. Our analysis suggests the impulsive rise in the parallel and circular ribbon intensities takes place at ≈21:46 UT; although initiation of the circular ribbon brightening lags behind the onset of the parallel ribbons by ≈30 s (indicated by the blue and red dotted vertical lines in Fig. 6g).

### 3.5. Brief eruption of flux rope and signatures of standard flare emission

Within the field-of-view (FOV) of Figs. 4–6, we observe clear signatures of the parallel ribbon flares followed by the development of post-reconnection arcade. According to the standard flare model (Shibata et al. 1995), these features occur following the eruption of flux ropes. However, within the large FOV of the whole active region we do not observe any clear signature of flux-rope eruption. Therefore, in Fig. 7, we focus only on the region of the flare ribbons (indicated by the boxes in Figs. 4i and i) in AIA 131 Å images. Here, we clearly identify a set of coronal loops (indicated by the red arrows in Figs. 7b–e) observed in the emission line, which seem to undergo eruption. These loop-like structures, observed in the emission line of hot AIA EUV filters, can be identified as coronal hot channels, which is one of the observational counterparts of flux rope. Our analysis suggests the initiation of the eruption of a hot channel at ≈21:45 UT (Fig. 7c). As expected, the eruption of the hot channel was immediately followed by the onset of parallel flare ribbons (indicated by the yellow arrows in Figs. 7e and f). The signatures of the erupting feature become indistinguishable within the AIA 131 Å images only after a few minutes (≈21:48 UT). Here we reiterate that, although the eruption signatures of the hot channel become too faint to be detected after ≈21:48 UT, we observe clear signatures of the expansion of the spine-like loops until ≈21:50 UT.

### 4. Photospheric magnetic field and vertical currents

#### 4.1. Evolution of photospheric magnetic field

In order to understand the factors responsible for the localised bright kernels observed in AIA 1600 Å images prior to the onset of the M-class flare (see Fig. 6 and Sect. 3.4), we looked into the evolution of LOS magnetic flux from the active region (Fig. 8). For this purpose, we specified two subregions within the active region NOAA 12297, outlined by the red and blue curves (also marked ‘A’ and ‘B’, respectively, in Fig. 8a) which are co-spatial with the localised UV brightenings (indicated by the yellow and green arrows in Fig. 6b). Figure 8b suggests that magnetic flux
Fig. 6. Low-atmospheric brightenings during the GOES M2.7 flare. Panels a–f: series of AIA 1600 Å images of the active region NOAA 12297 showing the pre- and main flaring phases of the M-class event. The yellow arrows indicate a highly localised bright kernel. The red five-pointed star in panel a indicates the LCO. The green arrow in panel b indicates a secondary bright kernel that appeared only a few minutes prior to the onset of the flare. The green arrow in panel f displays the location of the secondary bright kernel in comparison with the parallel ribbons. The blue and red coloured closed curves in panel e enclose the circular and parallel ribbons, respectively. The sky-blue arrows in panel f indicate the parallel ribbon brightening. The red arrows indicate a localised bright kernel co-temporal with the circular ribbon brightening. Panel g: temporal evolution of AIA 1600 Å intensity from the circular (blue curve) and parallel (red curve) ribbon areas. The horizontal dotted lines indicate the pre-flare values. The dashed vertical lines indicate the onset times of mild intensity enhancement a few minutes prior to the flare. The dotted vertical lines indicate the times of the impulsive intensity enhancements from the circular and parallel ribbons.
of both polarities in the overall active region gradually reduce throughout the period of our investigation. However, within the period of 1 h of the investigation, total positive and negative polarity fluxes from the active region decrease by only $\approx 2\%$ and $\approx 3\%$ of their respective initial values. The positive polarity patch within the region marked ‘A’ in Fig. 8a decays significantly (by $\approx 37\%$ of the initial value) within the observing period (Fig. 8c). Cancellation of negative flux from this region is much less pronounced (only $\approx 5\%$ of the initial value). Further, the evolution of the negative flux from this region can be characterised by a subtle enhancement at $\approx 22:02 – 22:06$ UT (Fig. 8c), which is just after the end of the M-class flare (cf. Fig. 8e). The flux evolution within the region marked ‘B’ in Fig. 8a is rather interesting. While the decay of magnetic fluxes within region ‘A’ and the whole active region is mostly steady, we observe periodic flux cancellation and enhancement of both the polarities within the region marked ‘B’ (Fig. 8d). In this context, we reiterate that AIA 1600 Å images of this region reveal the appearance of a

Fig. 7. Series of AIA 131 Å images of the area specified by the boxes in Figs. 4f and i showing the eruption of a small flux rope/coronal hot channel (indicated by the red arrows) and onset of flare ribbons (indicated by the yellow arrows).
Fig. 8. Morphology and evolution of photospheric magnetic field of the active region NOAA 12297. Panel a: HMI LOS magnetogram of active region NOAA 12297 prior to the onset of the M2.7 flare. Two regions are specified in the active region, which are enclosed by the curves marked by 'A' and 'B'. The yellow five-pointed star indicates the LCO. Panels b–d: temporal evolution of magnetic flux within the whole active region and within the regions marked by 'A' and 'B', respectively. The dotted curved represent the actual values of magnetic fluxes and the solid curves represent the seven-point running averages of the fluxes. Panel e: GOES 1–8 Å and 0.5–4 Å flux variations.
highly localised bright kernel a few minutes prior to the onset of the flare (indicated by the green arrows in Fig. 6b). Rapid fluctuations of magnetic fluxes from this region can therefore be considered to be responsible for the low-atmospheric, small-scale activity leading to the localised brightenings observed in the AIA 1600 Å channel images.

4.2. Photospheric vertical-current configuration and temporal evolution

As AIA 1600 Å images indicate a probable low-atmospheric triggering of the M-class flare, in order to further investigate the triggering processes of the event, we computed vertical currents \( I_z \) on the photosphere (Figs. 9 and 10). For this purpose, we used the \( x \)- and \( y \)-components of the 'hmi.sharp_cea_720s' series vector magnetograms as inputs and computed the vertical current density using the Ampere’s law (Tan et al. 2006):

\[
j_z = \frac{1}{\mu_0} \left( \frac{dB_y}{dx} - \frac{dB_x}{dy} \right),
\]

To obtain \( I_z \), \( j_z \) was then multiplied by the area of one pixel, that is, \( \approx 13.14 \times 10^{10} \text{ m}^2 \). From the spatial distribution of \( I_z \) (Fig. 9a), it becomes clear that only a few patches of the active region is associated with strong photospheric current: at the northern mixed-polarity sunspot area that was associated with flare ribbons (enclosed by the red box in Fig. 9a), and at the trailing mixed-polarity sunspot area that was associated with the remote brightenings (enclosed by the black box in Fig. 9a).

Notably, the region within the black box is situated adjacent to the LCO (marked by the orange-coloured five-pointed star in Fig. 9a). Figures 9b–g briefly display the evolution of \( I_z \) within the region enclosed by the black box. Here we reiterate that, both the spine-like loops and the apparent QSL-associated coronal loops terminate on the photosphere in this location (LCO; Sect. 3.3, Fig. 4a). This region is characterised by four distinct patches of strong \( I_z \) of both the polarities; among which one positive patch and one negative \( I_z \) patch are situated in extremely close proximity (indicated by the pink arrow in Fig. 9b). The positive \( I_z \) patch between the two negative \( I_z \) patches (enclosed by the pink oval in Figs. 9b–g) is particularly interesting as it undergoes significant decay prior to and during the M-class flare (cf. Figs. 9b and d). Following the M-class event, the positive \( I_z \) patch underwent current accumulation and decay in a periodic manner (cf. Figs. 9e, f, and g). Figures 9h–j show the evolution of the region enclosed by the red box in Fig. 9a. As we find in these panels, one of the negative \( I_z \) patches (enclosed by the pink oval in Figs. 9h–j) undergoes noticeable decay prior to the onset of the flare (cf. Figs. 9h and i). However, after the end of the flare, this region gains significant negative \( I_z \) (cf. Figs. 9h and j).

We note that both the strong \( I_z \)-locations that undergo significant changes (i.e. the positive \( I_z \)-patch enclosed by the pink oval in Figs. 9b–g and the negative polarity patch enclosed by the pink oval in Figs. 9h–j) are associated with localised bright kernels observed in AIA UV 1600 Å images (Fig. 6). In Fig. 10a, these two locations are enclosed by the two pink curves (also marked ‘A’ and ‘B’). In Figs. 10b–d, we plot the evolution of maximum and minimum \( I_z \) in the whole active region and the evolution of total \( I_z \) within the regions ‘A’ and ‘B’, respectively. From Fig. 10b, we find that the maximum value of positive \( I_z \) in the whole active region significantly reduces during the flare and increases again after the event. On the other hand, the minimum value of negative \( I_z \) significantly increases after the flare. The evolution of total \( I_z \) within region ‘A’, that is, the LCO, is most interesting, as both the total positive and negative \( I_z \) from this region rapidly decrease from \( \approx 25 \) min prior to the onset of the flare (Fig. 10c). Even after the end of the flare, current values from this region remain reduced and increase again only after \( \approx 22:35 \text{ UT} \), that is, after a significant period following the flaring event. Both positive and negative \( I_z \)-values within region ‘B’, after briefly undergoing a mild decrease prior to the onset of the flare, steadily increase once the flaring event starts (Fig. 10d).

5. Coronal magnetic-field reconstruction

In order to investigate the coronal magnetic configuration associated with the complex active region and their influence on the flaring activity, we carried out NLFFF coronal magnetic field reconstruction (Fig. 11). The model field lines appear to precisely match with the large-scale coronal loops observed in the AIA 171 Å images (Fig. 1c). In particular, the coronal loops marked by the green arrows in Fig. 1c are accurately represented by the red and orange coloured modelled lines. Further, the model lines shown in dark blue in Fig. 11 closely match the coronal loops indicated by the dark-blue arrows in Fig. 1c. AIA 304 Å images suggest the presence of a small filament (indicated by the green arrows in Fig. 2d) along the PIL between the positive and negative flux region of the northern sunspot group. Accordingly, NLFFF-extrapolation results reveal the presence of a narrow flux rope, which is shown by the pink lines in Fig. 11. The flux rope was immediately enveloped by a set of closed lines represented in sky-blue, which resemble a fan-like structure. Here, the LCO region is indicated by the pink circle in Fig. 11a, which confirms that the spine-like field lines and the QSL field lines terminate in close proximity on the photosphere. Comparison of AIA 304 Å images with the model coronal lines (Fig. 11c) suggests that the circular ribbon brightening occurred along the outer footpoints of these fan-like lines and the footpoints of the spine lines, and the QSL structure is a close match to the chromospheric brightenings. We show only the fan-like lines and the flux rope in Fig. 11e for ease of visualisation (the flux rope is indicated by the black arrow).

The sky-blue lines constitute a similar structure to the fan structure usually associated with the coronal 3D null-point configuration. However, in our case, the overall configuration combining the sky-blue lines with the red, green, and orange lines significantly differs from the spine-fan configuration of a 3D null-point topology. Coronal fan-spine configurations are developed over the so-called anemone-type active regions, which are characterised by a patch of strong magnetic-flux region completely surrounded by opposite-polarity magnetic regions. However, in the region analysed here, the negative-polarity region associated with the sky-blue lines is surrounded by positive polarity regions on only three sides, with the northeastern side of the negative-polarity patch being devoid of any strong magnetic flux (Fig. 11e). Such photospheric arrangements are not expected to lead to the development of coronal null points. Accordingly, we were not able to establish the presence of any null point in the coronal region associated with the flaring brightenings from our analysis. Further, the spine-like lines (i.e. the red, green, and blue lines) surround the fan-like lines on only three sides, that is, the fan-like-lines are not completely surrounded by the spine-like lines (Figs. 11b–b1), which provides further evidence that the structure constituted by the sky-blue, red, green, and yellow lines cannot be considered a true fan-spine configuration.

The model coronal configuration of the part of the active region marked ‘QL’ in Fig. 1c is shown by the dark-blue
Fig. 9. Morphology and evolution of photospheric vertical current ($I_z$). Panel a: photospheric vertical current ($I_z$) map of the active region NOAA 12297. Contours of the $z$-component of a co-temporal vector magnetogram are plotted in panel a. The contour levels are ±300 G with the black and pink contours referring to positive and negative polarity magnetic fields, respectively. Two regions characterised by strong currents are enclosed by the black and the red boxes. The orange-coloured five-pointed star indicates the LCO. Panels b–g: representative $I_z$-maps of the regions enclosed by the black box showing the evolution of $I_z$ during the interval of our analysis. The pink arrow in panel b indicates a location characterised by extreme close proximity of opposite polarity currents. The oval shapes in panels b–g enclose a positive $I_z$ region which undergoes decay prior to the onset of the flare but grows following the event. Panels h–j: brief evolution of $I_z$-maps of the region encircled by the red box in panel a. The pink oval in these panels encircle a negative current region which undergoes significant changes during the interval of our analysis.

coloured lines. These lines originate from the positive-polarity flux regions in both the northern and the trailing part of the active region and terminate at the negative polarity-flux region of the trailing sunspot region. Such sets of magnetic lines, which change the connectivities drastically, are considered to contain the QSLs (see e.g. Janvier et al. 2013). Mathematically, the presence of QSLs is identified as high values of the degree of squashing factors ($Q$; see Titov et al. 2002). As expected, the dark-blue lines are found to be associated with a relatively high value of $Q$ (see the pink patch over the blue lines in Fig. 11a,
Fig. 10. Temporal evolution of photospheric vertical current ($I_z$). Panel a: same as Fig. 9a, except the $B_z$ contours. Two regions specified as ‘A’ and ‘B’ are enclosed by the pink contours. The orange-coloured five-pointed star indicates the LCO. Panel b: temporal evolution of maximum and minimum vertical currents within the whole active region. Panels c and d: temporal evolution of total positive and negative photospheric vertical currents within the regions marked by ‘A’ and ‘B’, respectively. Panel e: GOES 1–8 Å and 0.5–4 Å channels SXR light curves.

which is also marked with a black arrow, and is characterised by log($Q$) > 3.5. Underneath the deep blue lines, we find a set of low-lying, relatively potential model lines, which are shown in yellow in Fig. 11.

In the background of Fig. 11d, we plot the photospheric QSL map, which readily suggests that the terminating regions of the red coloured lines as well as the dark-blue lines are associated with high $Q$ values. Further, from the $Q$ map at the footpoints of the fan-like lines (Figs. 11d and f), it becomes clear that although the northeastern part of the sky-blue lines are devoid of any magnetic lines, the region is associated with relatively high values of $Q$. 

Fig. 11. NLFFF-reconstructed coronal magnetic field configuration and distribution of the degree of squashing factor ($Q$). The sky-blue lines resemble a 3D fan-like structure. The pink lines within the sky-blue lines represent a flux rope. The red, green, and orange lines show connectivities between the northern positive-polarity flux region with the trailing negative-polarity regions, which resemble a 3D spine-like structure. The blue lines show an interesting structure where two sets of field lines, after originating from different regions, converge towards each other and terminate back on photosphere as parallel lines. The yellow lines show connectivity between the opposite-polarity flux regions within the trailing part of the active region. Panels a, c, and d display all the different sets of model coronal field lines from the top view. The pink circle in panel a indicates the LCO. Panel b shows all the model lines viewed from the northern boundary, i.e. from the top boundary of panel a. Panel b1 shows the fan-like structures viewed from underneath the spine-like lines. Panel e shows only the fan-like lines and the flux rope (indicated by the arrow). The pink patch in panel a (also indicated by the arrow) is characterised by $\log(Q) > 3.5$. The backgrounds in panels a, e are co-temporal HMI LOS magnetogram saturated at ±500 G. The background in panel c is an AIA 304 Å image during the flare-peak showing the flare ribbons and other brightenings in the active region. The background in panel d represents a $Q$-map of the photosphere. Panel f focuses on the fan-spine-like structures along with the flux rope, from a top view. A part of the background in this panel shows a photospheric $Q$-map at the footpoints of the fan-spine-like lines. The colour-coding used for the $Q$-maps in panels d and f is shown in the respective panels.
6. Discussion and conclusions

In this article, we provide a multi-wavelength analysis of a GOES M2.7 flare characterised by the onset of an elliptically shaped flare ribbon, and investigate the probable triggering mechanisms of the flare, as well as the magnetic configuration responsible for the onset of the complex flare ribbons. The flare originated from the βγδ-type active region NOAA 12297, which was configured by two distinct sets of sunspot groups, both of mixed polarities. Our analysis reveals that the complex flare and associated coronal magnetic configuration involved both of the two sunspot groups of the active region (Fig. 1).

Flares characterised by circular, semi-circular, or elliptical flare ribbons are categorised as circular ribbon flares. Traditionally, the coronal magnetic configurations associated with such flares are identified by a fan-spine configuration in a 3D null-point topology (Longcope 2005; see also Sun et al. 2013; Hou et al. 2019; Lee et al. 2020; Devi et al. 2020; Joshi et al. 2021). The photospheric magnetic configuration of such fan-spine configurations is identified as the so-called anemone-type active region, where one compact magnetic patch is surrounded by opposite-polarity magnetic-flux regions (Shibata et al. 1994; see also Sharma & Cid 2020). However, the circular ribbon brightening region reported in this article significantly differs from the classical anemone-type active regions, as the central negative-polarity region is surrounded by positive-polarity fields on only three sides (Figs. 8a and 11b, f). It can be naturally assumed that such an asymmetric distribution of photospheric fields will not lead to a 3D coronal null point. Accordingly, the model coronal configuration associated with the flaring event is not exactly a fan-spine type, as the northeastern side of the negative polarity regions is not connected to the LCO region by the spine-like lines (Figs. 11b and e). Further, we were not able to establish the presence of any null point within the flaring configuration from our analysis. Thus, the circular ribbon flare reported in this article seems to differ from the traditional concepts of circular ribbon flares. Here it is worth mentioning that Mitra & Joshi (2021) recently reported a series of circular ribbon flares that originated from a single active region that was also devoid of coronal null points; instead these authors identified the presence of hyperbolic flux tubes (HFTs; Titov et al. 2002) between the inner and outer spine-like lines. In their case, the circular ribbon brightenings were caused by interchange-type reconnection (Fisk 2005) at the HFTs. However, in our case, we observed high $Q$ values at the footpoint regions of the fan-like lines as well as on the photospheric regions in the northern-eastern side of these lines. We believe the high values of the magnetic gradient were responsible for the elliptically shaped ribbon brightening.

Triggering of circular flare ribbons has also emerged as a topic of discussion in contemporary studies of solar flares. The majority of circular ribbon flares are observed to be triggered by a flux rope situated underneath the fan-dome that acquires upward eruption (Yang et al. 2015; Li et al. 2018; Zhang & Zheng 2020; Liu et al. 2020; Zhang et al. 2020; Mitra & Joshi 2021). The initial upward eruptions of the flux ropes in such cases are usually caused via the tether-cutting reconnection as a result of continuous flux emergence and/or photospheric motions (see e.g. Sun et al. 2013; Li et al. 2017; Xu et al. 2017). Observationally, this sequence of activities can be identified as the appearance of a set of parallel ribbon flares within the fan-dome before the onset of the circular ribbon itself. Several circular ribbon flares were recently reported to have been triggered by reconnection activities at the coronal null point governing the fan-spine configuration (e.g. Devi et al. 2020; Joshi et al. 2021). Such events evolve with the onset of the circular ribbon prior to the onset of the parallel ribbons. In the present study, the earliest signatures of the parallel ribbons were identified ≈4 min prior to the earliest appearance of circular ribbon brightening. During this time, both the parallel and circular ribbons were very faint. However, at the onset of the M-class flare, we observe almost simultaneous rapid brightness enhancement from both the circular and parallel ribbons (Fig. 6). The photospheric vertical current ($I_z$) evolution (Figs. 9 and 10) reveals a significant decay of $I_z$ from the LCO (see Sect. 3.3) a few minutes prior to the onset of the M-class flare (Fig. 10). AIA 94 Å images suggest an increase in the brightness in the coronal loops associated with the QSL structure a few minutes prior to the onset of the circular ribbon flare. As the footpoints of the QSL loops and the spine-like loops were very close (the LCO) and the region was associated with high photospheric $Q$-values (Fig. 11), we believe small-scale activities occurring at the LCO potentially served as a perturbation to the fan-spine-like structure through the spine-like loops (shown by the red and orange coloured lines in Fig. 11) as well as to the flux rope through the QSL-associated coronal loops (shown by the dark-blue lines in Fig. 11). This led to an almost simultaneous triggering of both the circular and parallel ribbon brightenings. Therefore, our analysis seems to provide evidence for the remote triggering of circular ribbon flares. Further, as the photospheric activities at the LCO could potentially influence activities at both the fan-spine-like configuration and the flux rope, onset of the circular and parallel ribbon brightenings could take place almost simultaneously.

The evolution of the RHESSI X-ray sources during the event is also interesting. Prior to the onset of the flare, we observe clear RHESSI sources up to energy ≈12 keV from the location of the QSL. While the 3–6 keV emission appears to mostly originate from the coronal loops, the 6–12 keV sources seem to originate from the footpoint locations of the QSL-associated loops (Fig. 4b). As the active region evolves towards the initiation of the flare, we observe a shift of the RHESSI contours from the location of the QSL to the location of the filament or flux rope (Fig. 4c). This dynamical evolution of RHESSI sources further provides support for the scenario of remote triggering of the flaring event.

QSL structures are particularly interesting in the context of solar transient activities. As such structures are characterised by a high magnetic field gradient, they are associated with small-scale current sheets (Aulanier et al. 2005). Local diffusion from these current sheets allows neighbouring magnetic field lines to change connectivity; a phenomenon known as slipping reconnection (Aulanier et al. 2006; Janvier et al. 2013). In the coronal magnetic field modelling analysis, QSLs are identified by high $Q$ values (Priest & Démoulin 1995; Titov et al. 2002). As slipping reconnection activities involve local diffusion from small-scale current sheets in a continuous magnetic field, energy released during such activities and the corresponding particle acceleration are not usually as high as those associated with cut-and-paste-type reconnections (see e.g. Aulanier et al. 2007; Dudík et al. 2014). The continuous exchange of magnetic connectivity from QSL locations has been interpreted as an explanation of the motions of the X-ray sources along the flare ribbons during solar flares (Pontin & Priest 2022). Further, signatures of slipping reconnection during intense flares have been reported multiple times (see e.g. Dudík et al. 2014, 2016). However, in such cases, the QSL lines were directly involved within the main-flaring magnetic configuration and the slipping reconnection was associated with the flaring activities. In the present case, the
detections of X-ray sources from both the coronal loops and footpoint locations of the QSL structure (Fig. 4) suggest that continuous exchange of magnetic connectivity within continuous magnetic field can also lead to the acceleration of particles that can give rise to footpoint X-ray sources.

In summary, in this paper, we provide an observational and numerical analysis of a complex circular ribbon M-class flare. Our work provides novel observations of an ‘incomplete fan-spine-like’ configuration of the flaring region that did not manifest a coronal null point. The photospheric configuration associated with the flare differs from classical anemone-type active regions, as the central negative-polarity region is surrounded by positive-polarity regions on only three sides, that is, it is not completely surrounded. Our analysis reveals further evidence of remote triggering of the flare. We also provide evidence that QSL structures can be associated with HXR sources, suggesting slippage-reconnection activities can also lead to significant particle acceleration. Thus, this study addresses a number of previously unexplored or less-understood aspects of 3D solar magnetic configuration and the flaring events occurring from them.

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