Twin Null-Point-Associated Major Eruptive Three-Ribbon Flares with Unusual Microwave Spectra

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Abstract On 23 July 2016 after 05:00 UTC, the first 48-antenna stage of the Siberian Radioheliograph detected two flares, M7.6 and M5.5, which occurred within half an hour in the same active region. Their multi-instrument analysis reveals the following. The microwave spectra were flattened at low frequencies and the spectrum of the stronger burst had a lower turnover frequency. Each flare was eruptive, emitted hard X-rays and $\gamma$-rays exceeding 800 keV, and had a rare three-ribbon configuration. An extended hard X-ray source asso-

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associated with a longest middle ribbon was observed in the second flare. Unusual properties of
the microwave spectra are accounted for by a distributed multi-loop system in an asymmet-
ric magnetic configuration that our modeling supports. Microwave images did not resolve
compact configurations in these flares, which may also be revealed incompletely in hard X-
ray images because of their limited dynamic range. Being apparently simple and compact,
non-thermal sources corresponded to the structures observed in the extreme ultraviolet. In
the scenario proposed for two successive eruptive flares in a configuration with a coronal
magnetic null, the first filament eruption causes a flare and facilitates the second eruption
that also results in a flare. Three persistent flare ribbons reflect magnetic reconnection at the
coronal-null region forced by the filament motions.

Keywords  Flares · Magnetic fields · Magnetic reconnection · Prominences, active · Radio
bursts · X-ray bursts

1. Introduction

Solar eruptions, flares, and similar weaker events draw energy from coronal magnetic fields.
Such events span a vast range of energy and time scales and spatial extent and manifest
in various associated phenomena. The way in which an eruption (flare) develops, its mani-
festations and particularities depend on the magnetic configuration that hosts the event and
magnetic-field transformations that occur in its course. Magnetic reconnection is considered
as the key process that governs solar eruptions and flares.

Several properties of a two-ribbon flare and its development have mainly been explained
by the two-dimensional (2D) standard model (CSHKP: Carmichael, 1964; Sturrock, 1966;
Hirayama, 1974; Kopp and Pneuman, 1976). Reconnection in this model occurs in an X-
point of a vertical current sheet, which is formed due to the rise of a prominence driven
by a current instability (Hirayama, 1974). The flare was implicitly presumed to be caused
by the prominence eruption, whose development was not considered. In modern models of
two-ribbon flares, the prominence (visible as a filament against the solar disk) is replaced by
a magnetic flux-rope. When the standard flare model is generalized to a 3D situation, new
particularities appear in magnetic reconnection and the shapes and location of paired flare
ribbons that are absent in 2D models (see, e.g., Aulanier, Janvier, and Schmieder, 2012;
Janvier et al., 2013 and the references therein).

Two conditions are necessary for the development of a large-scale current instability that
leads to the flux-rope expansion. These are i) formation in the corona of a flux rope, where
the twist $[N]$ of magnetic-field lines certainly exceeds unity ($N > 1$), and ii) its rise to a
height, starting from which the expansion becomes continuous. The second condition is
met, if the component of the external magnetic field transversal to the flux-rope axis falls off
with height fast enough. To fulfill the first condition, sheared magnetic fields of a flux-rope
progenitor should be transformed into a helical flux-rope structure.

The way widely used for the formation of a magnetic-flux rope and initiation of a two-
ribbon flare invokes as boundary conditions different types of photospheric plasma motions
such as shear, converging, or rotational motions (e.g. Inhester, Birn, and Hesse, 1992; Long-
cope and Beveridge, 2007). An intrinsic process in such models is reconnection between
crossed magnetic-field lines anchored in the photosphere that occurs in a current sheet be-
neath the future magnetic flux-rope. Reconnection between isolated bundles of field lines is
often referred to as tether cutting (Moore et al., 2001) and plays an important role in models
of solar eruptions.
It is also possible to form a flux rope in a shorter way relative to photospheric motions. In the dual-filament model (Uralov et al., 2002; Grechnev et al., 2006; see also Hansen, Tripathi, and Bellan, 2004), low-corona reconnection between two or more sections of a filament (flux-rope progenitor) and between their threads (barbs) increases the length and height of the combined filament. This increases its dipole momentum and the total twist up to $N > 1$, launching the standard-model reconnection beneath the erupting filament (flux-rope progenitor). The standard flare model does not require magnetic reconnection above the erupting structure. The presence of such reconnection considerably changes the course of the eruption and CME formation. The breakout model (Antiochos, DeVore, and Klimchuk, 1999; Lynch et al., 2008; Wyper, Antiochos, and DeVore, 2017) employs magnetic reconnection in the corona above the magnetic flux-rope as a crucial process in solar eruptions.

Relatively recently, 3D coronal configurations with a null-point topology (NPT) have been identified above photospheric magnetic islands surrounded by opposite-polarity environment (e.g. Filippov, 1999; Filippov, Golub, and Koutchmy, 2009; Masson et al., 2009; Meshalkina et al., 2009; Pariat, Antiochos, and DeVore, 2009, 2010; Reid et al., 2012; Wang and Liu, 2012). Such configurations are ubiquitous, being responsible for a variety of phenomena from tiny polar X-ray jets up to major flares. A flare that occurs in an NPT-configuration produces a circular ribbon with a brightening in the center. An implicated remote compact site is sometimes detectable.

According to Filippov, Golub, and Koutchmy (2009) and Meshalkina et al. (2009), a reconnection event in an NPT-configuration is generally initiated and governed by the eruption of a small flux-rope-like structure that occurs inside an inverted-funnel-like separatrix surface. Reconnection behind the erupting structure occurs in the same way as in a usual two-ribbon flare. When the eruption passes through the null-point region, its magnetic structure becomes partly or entirely destroyed. A jet is ejected in the latter case (see also Sterling et al., 2016 who came to similar conclusions). This sequence of events is supported by a half-minute delay of the hard X-ray burst relative to the acceleration of the erupting structure measured by Grechnev et al. (2011a) in the event that Meshalkina et al. (2009) considered, where a bright ring-like structure and broad jet were observed in the extreme ultraviolet. Conversely, the numerical magnetohydrodynamic (MHD) simulations of Pariat, Antiochos, and DeVore (2009, 2010) and Masson et al. (2009, 2017) do not require small flux-rope eruptions as significant components of their NPT-associated models of flares and jets (see also a review by Raouafi et al., 2016).

Larger-scale phenomena probably caused by reconnection between magnetic structures of erupting filaments and static coronal environment have also been sometimes observed. They are manifested in bifurcation of an erupting structure and dispersal of the erupted material over a large surface far from the eruption region (Slemzin et al., 2004; Grechnev et al., 2005, 2014; Uralov et al., 2014). The dispersed low-temperature material released by reconnection from the filament body can screen large areas on the Sun and cause an extensive darkening in 304 Å and depression of the total microwave flux (Grechnev et al., 2008, 2011b, 2013b). Reconnection in such events is forced by the expansion of an erupting structure that encounters a topological obstacle in its path in the corona. A similar conclusion was drawn by van Driel-Gesztelyi et al. (2014) for the spectacular SOL2011-06-07 event.

While MHD simulations demonstrate the possibility of reconnection in an NPT-configuration without any eruption, observations indicate that such phenomena are caused by interactions of erupting structures with static coronal magnetic fields. In this respect, flares in NPT-configurations do not seem to be considerably different from the usual eruptive two-ribbon flares, where flare processes are caused by eruptions that basically corresponds
to the scenario of Hirayama (1974). This relation is supported by the correspondence between the kinematics of an erupting structure and flare emissions, which were delayed by up to two minutes, as found in studies of several eruptive events of different types and importance (Grechnev et al., 2011a, 2013a, 2015, 2016, 2019). On the other hand, in the absence of eruptions, coronal null points are steady and do not reveal themselves in any way (e.g. Filippov, 1999; Grechnev et al., 2014) that does not favor the scenario, in which an event starts from the null-point reconnection itself.

The morphology was still more outstanding in the events presented by Wang et al. (2014). The authors addressed a pair of successive flares (M1.9 and C9.2) that occurred on 6 July 2012 within half an hour and both exhibited unusual three-ribbon configuration. The flares were accompanied by surges and jets. The authors conjectured that the events were caused by reconnection along the coronal null line in the fan–spine magnetic topology. Bamba et al. (2017) presented a three-ribbon flare that occurred on 25 October 2014.

We consider a pair of three-ribbon flares that also occurred within half an hour in the same active region on 23 July 2016. The flares (M7.6 and M5.5) were stronger than those addressed by Wang et al. (2014), both of them were eruptive and produced conspicuous emissions in microwaves, hard X-rays, and γ-rays. The clear presence of filament eruptions in both events removes the question of their possible involvement. The large size of the flares favors the analysis of various manifestations that were barely detectable in weaker events. Taking advantage of these unprecedented observations, we address the main properties of the two eruptive flares, reveal the magnetic configuration where they occurred, and pursue understanding their common scenario.

Section 2 briefly overviews the twin events and highlights their particularities. Section 3 addresses the coronal configuration, where the events occurred, and infers their scenario. Section 4 addresses manifestations of accelerated electrons in microwave and hard X-ray images and considers the spectra in the two spectral domains. Section 5 summarizes the results. The AIA335.mpg, pot_Br_mod_B.mpg, and nlff_Br_mod_B.mpg movies in the Electronic Supplementary Material illustrate the twin events and particularities of the coronal magnetic configuration.

2. Overview of the Twin Events

2.1. Microwave and Hard X-Ray Non-imaging Data

The Siberian Radioheliograph (SRH: Lesovoi et al., 2014, 2017) commenced test-mode observations early in 2016. In summer 2016, the SRH started to observe the Sun routinely at five frequencies of 4.5, 5.2, 6.0, 6.8, and 7.5 GHz along with the ongoing adjustment of its systems. The temporal interval to scan the five frequencies was 8.4 seconds at that time. The longest SRH baseline of 107.4 m determines its spatial resolution of order 100″ (depending inversely on frequency) that allows locating a microwave source on the Sun but is insufficient to reveal its shape and structure. Real-time beacon SRH data at a set of the operating frequencies with an update every minute are accessible online at the SRH Web site badary.iszf.irk.ru/.

On 23 July 2016, the SRH recorded strong microwave bursts associated with two major flares that occurred within half an hour at N05 W73 in active region, whose parts were numbered 12565 and 12567. The importance was M7.6 for the first flare and M5.5 for the second flare. The Badary Broadband Microwave Spectropolarimeters (BBMS: Zhdanov and
Zandanov, 2011, 2015; Kashapova et al., 2013) that are installed near the SRH measured the total flux up to 400 sfu in the first flare and up to 800 sfu in the second flare.

Figure 1 shows the temporal profiles recorded during the two flares in microwaves and hard X-rays (HXR). Figure 1a presents the so-called correlation plots produced by the SRH that are computed without synthesizing the images as the sum of cross-correlations between all antenna pairs (Lesovoi and Kobets, 2017). The correlation plots represent a proxy of total-flux variations, responding to the changes in both the brightness and the structure of microwave sources. To get indications at total-flux spectra of the sources that were unresolved in these observations, each $i$th correlation plot obtained at a frequency $\nu_i$ was multiplied by $(\nu_i/\bar{\nu})^2$, where $\bar{\nu}$ is the average frequency of the SRH observing range.

Three main peaks numbered 1 – 3 are distinct. Comparison of the peaks at different SRH frequencies indicates that the turnover frequencies (peak frequencies of the spectra) for peaks 1 and 3 were within the SRH range or nearby and higher for peak 2. These indications are confirmed in Figure 1b that presents total-flux variations recorded by the BBMS at 6.6 GHz and by the Nobeyama Radio Polarimeters (NoRP: Torii et al., 1979; Nakajima et al., 1985) at 17 GHz. The peaks had different spectra indeed: while peaks 1 and 3 were stronger at 6.6 GHz, peak 2 was stronger at 17 GHz.
Figure 2  Microwave spectra of the three peaks denoted in Figure 1 c composed from measurements at different total-flux radiometers and NoRH (symbols). The thick color curves represent their simplest fit, from which the peak frequencies indicated near the spectral peaks were estimated. The slopes of the high-frequency branches have considerable uncertainties. The slanted dashed line demonstrates the slope \( \alpha_{LF} = 2.9 \) expected at low frequencies for a single gyrosynchrotron source if it were responsible for peak 2. The shading denotes the SRH observing frequency range. The vertical dotted lines denote the frequencies of 6.6 and 17 GHz, at which the time profiles presented in Figure 1b were measured.

Figure 1c presents HXR and \( \gamma \)-ray bursts recorded by the Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI: Lin et al., 2002) in five energy bands. To reduce the variable background, whose importance increases with increasing energy, its variations in the preceding and following orbits were fitted for each energy band and subtracted. To enhance the signal-to-noise ratio in the two highest-energy bands plotted, the count rates were smoothed with a boxcar average over three neighbors for the 300 – 800 keV band and over five neighbors for the 800 – 7000 keV band. They are magnified in Figure 1c. The three main peaks became detectable at energies exceeding 800 keV.

It is possible to judge qualitatively about the photon HXR spectra by comparing visually the heights of the peaks in a high-energy band (e.g. 300 – 800 keV) and in the 25 – 50 keV band. Peak 1 had the softest photon spectrum, peak 2 had the hardest spectrum, and the spectrum of peak 3 was in between of them. The same relation is expected for high-frequency parts of the microwave spectra of the three peaks (Dulk and Marsh, 1982; White et al., 2011).

Figure 2 presents total-flux microwave spectra of the three peaks integrated over eight seconds around each peak. We used one-second NoRP data, one-second data obtained at the Learmonth station of the US Air Force Radio Solar Telescope Network (RSTN: Guidice, 1979; Guidice et al., 1981), and BBMS data with a temporal sampling of 1.6 seconds. The whole data set had problems. The BBMS consists of two instruments, each of which employs its own spectrum analyzer. The 4 – 8 GHz spectropolarimeter operated in the high-sensitivity mode so that its data were saturated. A few channels of the 2 – 24 GHz spectropolarimeter were out of operation. The triangles in Figure 2 in the 2.34 – 10.1 GHz range represent the data from the BBMS channels that appear to be reliable.

To find the slope of the descending part of the microwave spectrum, high-frequency measurements are important. However, the total-flux variations shown by NoRP at 35 GHz are strongly dissimilar to the temporal profiles recorded at lower frequencies. This indicates improper operation of the 35 GHz instrument. We had to use instead the images produced by the Nobeyama Radioheliograph (NoRH: Nakajima et al., 1994) at 34 GHz. NoRH suffered in this period from hardware problems. We synthesized NoRH images at 34 GHz around
each of the three peaks with intervals and integration times of one second and five seconds. The images in each set were coaligned with each other. To calibrate the images in brightness temperatures, the regions of the solar disk and the sky were analyzed separately, and the most-frequent pixel values were referred to $10^4$ K and zero, respectively (Kochanov et al., 2013). The one-second image set was subjected to the median smoothing along each pixel with widths of three and five. Then the total flux was computed over the flaring region from all image sets. Comparison of the results with each other indicates the calibration stability of the reduced-quality NoRH 34 GHz images of about $\pm 50\%$. The squares in Figure 2 represent probable fluxes at 34 GHz with the $\pm 50\%$ uncertainties shown by the bars.

The ascending and descending branches of the microwave spectra were analyzed separately using the linear fit in the log–log scale. Because of the insufficient measurement accuracy at 34 GHz, the slopes of the high-frequency branches have increased uncertainties, especially for peak 2. The two branches were connected with the antiderivative (indefinite integral) of the error function. The peak frequencies estimated from the fitting curves are indicated at the curves along with low-frequency slopes $[\alpha_{LF}]$ found from the linear fit. The positions of the estimated peak frequencies relative to the SRH frequency range (the shading) are consistent with the assessments that were made from the correlation plots in Figure 1a, while the ongoing adjustment of the SRH hardware systems disfavored accurate calculations of the flux spectrum from the images at that time.

The low-frequency branches of the spectra are flattened with respect to the slope of $\alpha_{LF} = 2.9$ expected for a single homogeneous gyrosynchrotron source (Dulk and Marsh, 1982). This slope is shown by the dashed line for peak 2. A possible cause of the low-frequency spectral flattening may be asymmetry of the flaring magnetic configuration; the magnetic-flux balance requires a larger area of a weaker-field side than of the conjugate region that elevates the low-frequency spectral part and shifts the peak frequency to the left (Grechnev et al., 2017). The change from peak 2 to peak 3 seems to be challenging, because no change in most of the parameters that govern gyrosynchrotron emission displaces the top of its spectrum up and left (Stähli, Gary, and Hurford, 1989). These circumstances indicate that the flare configuration was asymmetric and relatively complex.

2.2. Two Successive Eruptions

The paired events comprised two sequential eruptions that were observed in all extreme-ultraviolet (EUV) channels of the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO: Lemen et al., 2012). The two eruptions are demonstrated by the 2016-07-23_AIA335.mp4 Electronic Supplementary Material. The movie was composed from the images obtained in the low-sensitivity 335 Å AIA channel, which did not suffer from saturation.

Figure 3 presents a few episodes of the two eruptive events. Event 1 started from the eruption of the first filament, Fil1, in Figure 3a that corresponds to the time of peak 1 in Figure 1. The filament brightened up, inflated (Figure 3b), and expanded further. The ragged appearance of the erupting filament in Figure 3c indicates that its structure became partly damaged. Arcade Arc1 in Figure 3d appeared in the first event, whose importance reached a level of M7.6. The yellow contour in Figure 3b presents the unresolved microwave source observed by the SRH at 6.0 GHz at a half-height level that is close to the SRH beam.

The second event associated with the eruption of another filament, Fil2 (Figures 3d–3f), was mainly similar to the first event. Figure 3d corresponds to the time of peak 3 in Figure 1. The structure of the second filament was also damaged; dark filament material dispersed and partly returned back to the solar surface (Figure 3f). The third filament, Fil3, denoted
Figure 3  Two eruptive events observed within half an hour by SDO/AIA in 211 Å. The yellow contours on panels b and e represent the SRH 6.0 GHz images at half-height levels. The arrows indicate eruptive filaments Fil1 and Fil2. Arcade Arc1 formed in the first event is visible. Filament Fil3 did not erupt and partly blocked in EUV the second, southern arcade.

in Figure 3f, exhibited motions and partly hid the southern flare arcade in EUV, being not implicated in the eruptions or flares. The importance of the second event was M5.5. The yellow contour in Figure 3e presents the 6.0 GHz SRH image (similar to Figure 3b).

The two-fold character of the whole event manifested in associated phenomena. Each of the two eruptions produced an EUV wave (Chandra et al., 2018). The online CME catalog (cdaw.gsfc.nasa.gov/CME_list/: Yashiro et al., 2004) presents an associated CME, whose faster northern part was followed by a slower southern part that was launched apparently later.

2.3. Three-Ribbon Flare Configuration

A particularity of the two corresponding flares was their three-ribbon configuration. High brightness of the flare ribbons caused strong overexposure distortions in the 1600 Å SDO/AIA channel. The 1700 Å AIA images were also saturated, but their quality was better. Figure 4 presents the flare ribbons observed by AIA in 1700 Å in the two flares near the three main peaks. The contours overlaid on the images represent the polarities of the radial magnetic component that was computed from vector magnetograms produced on 23 July by the Helioseismic and Magnetic Imager (HMI: Scherrer et al., 2012) on board SDO.

Each of the three panels in Figure 4 shows a long N-polarity middle ribbon R2 and two considerably shorter ribbons R1 and R3 in S-polarity regions on both sides of the middle ribbon. The three-ribbon configuration corresponds to the S – N – S structure of the ribbons R1 – R2 – R3. The magnetic fields within the contours were stronger in the S-polarity regions than in the N-polarity region by a factor of about 2.3 on the average. The shorter lengths of
Figure 4 Three-ribbon configurations observed by SDO/AIA in 1700 Å in the two flares near the three main peaks. The blue contours outline the S-polarity radial magnetic component, and the red contour outlines the N-polarity region. The contour levels are $[-240, +120]$ G.

the S-polarity ribbons are determined by the magnetic-flux balance at the conjugate regions. This circumstance confirms the indications suggested by the shapes of microwave spectra that were outlined in Section 2.1.

In summary, observations reveal two successive filament eruptions that occurred within half an hour in the same active region. Each eruption was accompanied by a concurrent M class flare, which possessed three ribbons. In the next section we analyze the coronal configuration that determined the three-ribbon flare morphology and discuss a probable scenario for the twin events.

3. Coronal Magnetic Configuration and Scenario of the Events

3.1. Magnetic Configuration

The 23 July twin events were located not far from the limb, where considerable projection shrinkage complicates the understanding of the magnetic configuration. We firstly consider observations of the active region, which hosted the events that were made a few days before. The active region observed by SDO/HMI on 20 July is shown in Figures 5a (intensitygram) and 5b (line-of-sight magnetogram). Two S-polarity sunspots Ss1 and Ss2 were separated by an extended N-polarity plage region PR. No conspicuous flare manifestations were visible near the eastern N-polarity sunspot Ss3. The magnetic field in the plage region strengthened from 20 to 23 July.

Figure 5c presents a 304 Å AIA image observed 14 hours before the events along with contours of the radial magnetic component computed from a simultaneous HMI vector magnetogram. Two filaments are visible in 304 Å. Filament Fil1 was rooted by the northern end in the S-polarity environment of sunspot Ss1 and mostly located above the neutral line between the Ss1 environment and the plage region PR. Filament Fil2 was rooted by the southern end in the S-polarity environment of sunspot Ss2 and mostly located above the neutral
Figure 5 Pre-flare configuration. Intensitygram (a) and line-of-sight magnetogram (b) of the active region observed by SDO/HMI on 20 July, three days before the events. The yellow labels N and S denote magnetic polarities of sunspots Ss1, Ss2, and Ss3, and plage region PR. (c) SDO/AIA 304 Å image observed on 22 July presents two filaments Fil1 and Fil2 (indicated by the white arrows) that are located between the S-polarity sunspots Ss1 and Ss2 and N-polarity plage region PR. Filament Fil3 has not yet appeared. (d) Scheme of the magnetic configuration inferred from observations. The slanted brown-dashed line denotes the direction of the cross-section that is presented in Figure 7.

The analysis of the observations and magnetic fields reconstructed in the corona allowed us to infer the coronal configuration, where the two events occurred, and their scenario that is considered in the next section. Figure 6 presents the coronal configuration reconstructed in the potential-field approximation from an SDO/HMI magnetogram that was observed on 23 July at 05:00. Two sets of low loops, which are rooted in the extended plage region, where the middle ribbon (R2 in Figure 4) was located, go into opposite directions that indicates the presence of a separatrix surface between them. One set of loops (red in Figure 6) connects the plage region with the vicinity of sunspot Ss1, where ribbon R1 was located. The other set of loops (green) connects the plage region with the vicinity of sunspot Ss2, where ribbon R3 was located. The three ribbons thus map out the bases of the two arcades, which approximately correspond to the flare loops that shared the middle ribbon at the plage region.
Figure 6 Coronal magnetic configuration reconstructed in the potential-field approximation: (a) side view, (b) top view. The gray-scale background shows the magnetogram at the photospheric level. The red and green field lines represent two arcades. The blue lines represent the field lines of the excessive magnetic flux that is rooted in the remote eastern N-polarity sunspot and its environment. The axes show arc seconds from the center of the field of view.

The magnetic flux coming into the S-polarity sunspots is not compensated by the flux outgoing from the N-polarity plage region. An excessive portion of the S-polarity flux is outgoing from the remote N-polarity sunspot Ss3 and its environment. The magnetic configuration suggests the possible presence of a coronal null point or even a portion of a null line where the magnetic-field magnitude $|B|$ is zero.

To verify these conjectures, we investigate the spatial distribution of the coronal magnetic field computed above the active region using the potential approximation (e.g. Uralov, Rudenko, and Rudenko, 2006; Uralov et al., 2008; Grechnev et al., 2014) and non-linear force-free reconstruction that is based on the optimization method by Wheatland, Sturrock, and Roumeliotis (2000) as implemented by Rudenko and Myshyakov (2009). At the first stage, we analyze the behavior of the null line of the radial magnetic component $B_r$ at different heights. The presence of a real null point (which is not an issue of noise or small-scale uncertainties) is visually indicated by the bifurcation of the $B_r = 0$ line that occurs as the height changes. The bifurcation appears as the convergence of the $B_r = 0$ lines followed by their visual “reconnection” and subsequent divergence in the orthogonal direction of the $B_r = 0$ lines that are newly formed. If the bifurcation occurs in both force-free and potential approximations, then the null point (or line) is an element of a sufficiently large-scale magnetic topology. To locate the null point or line accurately, the behavior of the magnetic-field magnitude $|B|$ in the vicinity of the bifurcation region is analyzed.

The pot_Br_mod_B.mpg, and nlff_Br_mod_B.mpg movies in the Electronic Supplementary Material demonstrate the behaviors of the $B_r = 0$ line (red) and $|B|$ (gray scale and green contour) in the potential and force-free approximations, respectively. We are interested in the region of the null point that is denoted with a circle in the potential approximation and with two slanted crosses in the force-free approximation. In the latter case, only the null point exists (lower cross) instead of a null line. From the null point, a line toward the second cross extends with $B_r$ nearly zero, but with a weak quasi-transversal magnetic component. The length of this quasi-null line is about 15 Mm. The heights of the null points are noticeably different in the potential (between 16 and 17 Mm) and force-free (between 23 and 24 Mm) approximations.

The configuration presented in Figure 6 is similar to the quasi-circular configuration with a null point that was considered previously by Filippov, Golub, and Koutchmy (2009), Mason et al. (2009), and Meshalkina et al. (2009). Wang et al. (2014) analyzed a configuration where paired M1.9 and C9.2 three-ribbon flares occurred that were less powerful than our
events and had not caused any noticeable CME. Unlike our approach, Wang et al. (2014) envisioned the presence of the null line by inference.

3.2. Scenario

Our analysis of observations in different spectral ranges has led to a scenario of the twin events. For simplicity we consider the 2D geometry that is justified to some extent by the presence near the magnetic null point of an extended (about 15 Mm) linear region where magnetic field is weak. The scenario is schematically shown in Figure 7 that presents magnetic domains separated from each other by separatrices (broken lines). Two inner domains in the 2D scheme represent the cross-section of a single dome-like domain, which exists in real three dimensions. Each of the inner domains contains a filament (blue disk). Descending legs of the filaments rooted to the solar surface are located in front of the cross-section’s plane and behind it. In Figure 7a, filament 1 in the inner-left domain starts to lift-off gradually during the initiation phase, while filament 2 in the inner-right domain remains static so far.

Reconnection deep inside the inner-left domain in Figure 7b starts transforming filament 1 into a flux rope. A current instability of this flux-rope progenitor (henceforth flux rope) triggers its eruption with a motion directed to the null point. The lift-off of the flux rope is accompanied by expansion of its body as well as the whole magnetic configuration (not shown). The current sheet (longer pink bar denoted CS) forms from the null point and transfers the magnetic flux into adjacent domains, displacing the separatrices. Three main flare ribbons R1, R2, and R3 appear at the bases of the separatrices and move accordingly.

The instantaneous positions of ribbons R1, R2, and R3 coincide with the photospheric footpoints of a pair of magnetic-field lines that reconnect in the CS. At that time, the field lines are separatrices (dashed lines in Figure 7b). At the next moment, a pair of field lines located on opposite sides of the CS plane reconnects. The photospheric footpoints of this pair determine new positions of R1, R2, and R3. One can see from Figure 7b that R1 moves to the right, R2 to the left, and R3 to the right. It is difficult to compare the expectations from the scenario with observations because of projection shrinkage and saturation distortions in AIA images.

Reconnection in the current sheet beneath the erupting structure (shorter pink bar) causes energy release corresponding to the standard flare model and produces a usual pair of flare ribbons that are located between R1 and R2 and possibly correspond to a saturated strip in Figure 4b. The “usual” ribbons diverge from the photospheric polarity inversion line (PIL) of the radial magnetic field, and ribbons R1 and R2 associated with the coronal null point move toward the PIL. The approaching motion of the two pairs of ribbons completes with their merger into a single pair denoted R1 and R2 in Figure 7c. At that time, the standard-model reconnection in the lower-left domain terminates. Accelerated particles stream down along the field lines, precipitate in dense layers, and produce HXR emission.

Reconnection in the null-point-associated current sheet strengthens with the arrival of the flux-rope sheath, whose azimuthal magnetic component is antiparallel to the magnetic field of the outer-right domain. The inner flux-rope part, which did not reconnect, acquires an additional acceleration due to reconnection of the outer flux-rope part (the “bow effect” in Figures 7c and 7d). In this way, the reconnection rate increases that augments the acceleration of the remaining flux-rope part across the current sheet, and so on. The magnetic flux of the erupting flux rope rapidly diminishes, while its velocity increases. At the same time, the standard-flare current sheet keeps on stretching up. Two options for the subsequent development of the eruption seem to be possible.
In the first option, the flux-rope transversal velocity exceeds the highest possible magnetoplasma inflow velocity (e.g., Alfvén velocity) from the outer-right domain into the current sheet. In this case, the central flux-rope part is able to leave the null-point region. Reconnection and plasma dispersal along magnetic field continues in the outer-right domain. This situation shown in Figure 7c appears to correspond to the EUV observations in our event. Remnants of the erupting filament are detectable in the related CME.

In the second option, the flux-rope transversal velocity is not high enough. Reconnection of the flux rope is fully completed within the null-point region. A similar scenario shown by Wyper, Antiochos, and DeVore (2017) in their Figures 3e–3h (“Breakout jet”) presents the results of numerical simulations of the flux-rope eruption in a null-point configuration.

In the course of reconnection, the flux-rope kinetic energy and magnetic helicity is transferred to reconnected magnetoplasma. Portions of the filament material get released and...
scatter along field lines (blue bars in Figure 7c). New field lines (red) appear in adjacent domains. The current sheet CS changes orientation that facilitates the second eruption.

Then filament 2 erupts and repeats the history of filament 1. After the passage of the null region in Figure 7d, the second flux rope also undergoes reconnection that results in the dispersal of its material. Eventually, the configuration relaxes and returns to the original state.

Three flare ribbons visible throughout the events responded to magnetic reconnection at the coronal-null region that was forced by the filament motions. The ribbons produced by the standard-model flare reconnection beneath the erupting filaments almost merged with the ribbons produced by reconnection at the coronal current sheet CS, being indistinguishable in these events. The passage of the erupting filaments at the coronal-null region was accompanied by the dispersal of their material up and down along magnetic-field lines, but did not cause their total disintegration. The twin events produced a double CME.

The features of this scenario are determined by properties of the coronal configuration. Quasi-circular funnel-like configurations with magnetic null points exist ubiquitously above small magnetic islands within the opposite-polarity environment. Nevertheless, three-ribbon flares are very rare. The particularity of the configuration in our case was the presence of a coronal magnetic quasi-null line with almost zero radial component and small transversal components that made the geometry quasi-two-dimensional. In the scenario described in this section, the first eruption causes the second that was also the case in the events addressed by Wang et al. (2014).

Note that a filament eruption inside an NPT-configuration cannot disrupt it, if the coronal-null point is present in both non-potential and potential approximations. A single eruption irreversibly deforms the configuration (see Wyper, Antiochos, and DeVore, 2017). Its corresponding expansion is not shown in Figure 7. The second eruption in our scheme reverts the configuration to the initial state.

Our scenario deduced from observations resembles the numerical simulations of a coronal jet presented by Wyper, Antiochos, and DeVore (2017). With a difference between partial reconnection in our twin events and complete reconnection in the case of a jet, the correspondence between the configurations and processes involved in both observational and numerically-simulated scenarios provides mutual support to the results of the two different approaches.

4. Manifestations of Accelerated Electrons

4.1. Hard X-Ray and Microwave Images

As shown in Section 2.1, the twin events emitted conspicuous microwaves, hard X-rays, and $\gamma$-rays that are produced by accelerated electrons. We compare their manifestations with EUV images using microwave NoRH (Nakajima et al., 1994) and HXR RHESSI (Lin et al., 2002) data. The NoRH enhanced-resolution images at 17 GHz were synthesized by the Fujiki imaging software. Note that the spatial resolution of SDO/AIA is one order of magnitude higher than that of NoRH and two orders of magnitude higher than that of SRH in its present 48-antenna configuration. For the imaging in two HXR energy bands, 25 – 50 keV and 50 – 100 keV, we applied the CLEAN method using RHESSI detectors 3 and 8, which operated at that time.

The AIA 193 Å images (color background) in Figures 8a–8c show the flare arcades that were partly hidden by filament Fil3, which was passive. The yellow contours of the
Figure 8  Non-thermal manifestations in microwaves (top) and hard X-rays (bottom) at three main peaks in comparison with the structures observed in EUV. (a – c) Coronal 193 Å AIA images overlaid with 17 GHz NoRH images (yellow contours) at [0.2, 0.8] of the maximum values. The thin yellow contour on panel a represents the NoRH beam at a half-height level. (d – f) Flare ribbons in 1700 Å AIA images along with RHESSI images at 25 – 50 keV (green contours) and 50 – 100 keV (blue contours) at [0.3, 0.7] of the maximum values.

NoRH 17 GHz images represent non-thermal emissions produced by accelerated electrons gyrating in the arcade loops. Their comparison with AIA 193 Å images is complicated by insufficient pointing and coalignment accuracy of NoRH images that we enhanced to about 10″. Nevertheless, it is clear that each of the microwave sources corresponded to several unresolved arcade loops, while the source in Figure 8c seems to be a superposition of two arcades.

The AIA 1700 Å images (color background) in Figures 8d – 8f show the flare ribbons at the bases of the coronal arcades. These images are least distorted by saturation and do not correspond exactly to the times of the peaks. The HXR sources presented by the blue and green contours occupy sufficiently bright parts of the ribbons. An extended 50 – 100 keV source in Figure 8 is almost as long as the middle ribbon R2. Smaller parts of the 50 – 100 keV sources correspond to ribbons R1 and R2, where magnetic fields were stronger than those beneath ribbon R2. Observations of extended ribbon-like structures in hard X-rays are exceptional (e.g. Masuda, Kosugi, and Hudson, 2001; Liu et al., 2007, 2013).

Masuda, Kosugi, and Hudson (2001) pointed out the limitations on the sensitivity and dynamic range (typically ≈ 10) in the HXR imaging that Fourier-synthesis telescopes provide because of a limited coverage of the (u, v)-plane. Krucker et al. (2014) confirmed this conclusion for RHESSI; sources weaker than about 10% of the brightest in an HXR image are not detectable. For this reason, instrumental limitations of HXR imagers exaggerate the simplicity and compactness of HXR sources, which are usually observed, and disfavor re-
revealing weaker manifestations of non-thermal processes of a larger extent. Conversely, rare observations of ribbon-like HXR sources indicate some atypical conditions such as the uniformity of the magnetic-field strength distribution or the uniformity of electron acceleration along the arcade (Liu et al., 2007).

Microwave and HXR images highlight different parts of the flare configuration, where accelerated electrons were present, but reveal them incompletely. The NoRH images at 17 GHz present unresolved sets of coronal loops, where magnetic field is sufficiently strong. Weaker-field regions are fainter at 17 GHz. With the power-law indices of microwave-emitting electrons [$\delta'$] found in the next section, the emission at optically thin frequencies is expected to be highly dependent on the magnetic-field strength [$B$] as $B^{0.98 - 0.22} \approx B^3$ (Dulk and Marsh, 1982; White et al., 2011). Microwaves and hard X-rays dominate at different sides of an asymmetric magnetic configuration; the magnetic mirroring impedes electron precipitation (and hence the HXR emission) at the stronger-field side, where the optically thin gyrosynchrotron emission is stronger (Kundu et al., 1995).

These circumstances indicate that manifestations of accelerated electrons correspond to the structures observed in the EUV, but they are revealed incompletely because of instrumental limitations of RHESSI and NoRH. This result corresponds to the conclusions drawn previously by Zimovets, Kuznetsov, and Struminsky (2013) and Grechnev et al. (2017).

4.2. Hard X-Ray and Microwave Spectra

The HXR spectra for the three temporal intervals corresponding to the main peaks were computed from RHESSI data using detectors 3 and 8 by means of the OSPEX package (Figure 9). The spectra in the $3-250$ keV range have typical shapes that are consistent with a thermal core and non-thermal tail. The spectra were fitted with a single thermal component at low energies and single power-law component at higher energies. The simplest thermal model, which we do not analyze, determines slightly increased residuals at low energies so that $\chi^2$ is 0.48 for peak 1, 1.50 for peak 2, and 0.85 for peak 3. The results obtained in the analysis of the HXR data are listed in Table 1.
The left part of the table presents the accumulation-time intervals, parameters found for the HXR spectra, and parameters estimated from the HXR emission that govern microwave emission. These are the normalization constant of the HXR spectrum \(A_0\) at a fiducial energy of 50 keV and the power-law index \(\gamma\); the area of the 25–50 keV source at a 50% level \(A_X\); the number index of the electron energy spectrum calculated under the thick-target assumption as \(\delta^{\text{HXR}} = \gamma + 1.5\), the microwave spectral index \(\alpha^{\text{HXR}} = 1.22 - 0.9\delta^{\text{HXR}}\) expected at optically thin frequencies, and the number \(N_t^{\text{HXR}}\) of electrons per unit volume in the distribution above the fiducial electron energy \(E_t = 10\) keV (Dulk and Marsh, 1982; White et al., 2011).

The relations between the HXR spectra of the three peaks confirm the qualitative conclusions drawn in Section 2.1 from the RHESSI temporal profiles presented in Figure 1. The association of the HXR sources with the flare ribbons in Figure 8 shows that the primary cause of the ribbons was precipitation of electrons, whose spatially-integrated spectra were evaluated from RHESSI data.

Considering the fact that the ribbons represented the bases of the flare arcades, it is possible to verify the correspondence of the microwave spectra to the three-ribbon configuration using the images of the ribbons and the magnetogram actually observed. The most advanced modeling tool, of which we are aware, is the GX Simulator developed by Nita et al. (2015). In particular, this software allows one to model the gyrosynchrotron (GS) spectrum of an inhomogeneous source with various electron distributions based on a real magnetogram (e.g. Kuroda et al., 2018). However, the usage of the GX Simulator with a considerable number of loops seems to be difficult.

For this reason we invoke a different approach based on a multi-loop model. For the background of the approaches, which are based on inhomogeneous or multi-component sources, and a detailed description of the distributed multi-loop model see Grechnev et al. (2017). The model is briefly outlined below for convenience of the reader.

The model contains a considerable number of pairs of homogeneous cubic GS sources in the legs of microwave-emitting loops rooted in the ribbons, each with a different magnetic-field strength and volume. In our flare, one of the legs of each loop is rooted in the middle ribbon. The total flux is the sum of the fluxes emitted by all of the loops, which are considered not to overlap with each other; thus, the number of the loops is about the ribbon length-to-width ratio (13 in our case). The number \([m]\) of paired sources is chosen so that the sum of \([2m]\) sources provides a smooth spectrum with single maximum and the modeled spectrum acceptably matches the observed fluxes measured at different frequencies. The model uses a simplified analytical description of the GS emission presented by Dulk and Marsh (1982). Using the radial magnetic-field distribution on the photosphere and the balance of magnetic fluxes in the conjugate legs of the loops, parameters of each source are estimated. Then the magnetic-field strengths are corrected to the coronal values using a constant scaling factor that is estimated by referring to Lee, Nita, and Gary (2009). The model underestimates the low-frequency part of the spectrum, which we disregard.

In their modeling, Grechnev et al. (2017) did not have HXR data and estimated the number index of the electron energy spectrum \(\delta'\) from microwave observations at optically thin frequencies, and the total number of electrons was a free parameter. We do have HXR spectra, while responsibility of the same electron populations or their fractions for the HXR and microwave bursts is evidenced by the similarity of their temporal profiles in Figure 1. However, the high-frequency slopes of the microwave spectra \(\alpha^{\text{HXR}} = 1.22 - 0.9\delta^{\text{HXR}} \approx 3\) expected from the HXR power-law index \(\gamma\) (Table 1) are considerably steeper than those actually observed (Figure 2).

The difference of 1–2 between the electron energy spectral indices derived from microwave and HXR data is a long-standing issue (e.g. Silva, Wang, and Gary, 2000; White et al., 2011).
Table 1  Parameters of the HXR and microwave spectra.

| Hard X-rays | Microwaves |
|-------------|------------|
| Accumulation time [UTC] | $A_0^a$ at 50 keV | $\gamma$ | $A_X^{10^{18} \text{ cm}^2}$ | $\delta^\text{HXR}$ | $\alpha^\text{HXR}$ | $N^\text{HXR}_{\geq 10 \text{ keV}}$ | $\delta^\prime$ | $\alpha$ | $N_{\geq 10 \text{ keV}}$ | $|B|$ | $v_{\text{peak}}$ | $S_{\text{max}}$ |
| Peak 1 | 05:09:40–05:11:44 | 1.08 | 3.33 | 4.4 | 4.83 | -3.1 | 4.6 | 4.0 | -2.4 | 7.4 | 426 | 6.1 | 380 |
| Peak 2 | 05:14:40–05:15:41 | 0.375 | 3.03 | 1.6 | 4.53 | -2.9 | 1.9 | 3.6 | -2.0 | 3.2 | 765 | 12.4 | 390 |
| Peak 3 | 05:27:12–05:29:00 | 0.748 | 3.16 | 4.3 | 4.66 | -3.0 | 2.3 | 3.9 | -2.3 | 3.4 | 514 | 6.6 | 730 |

\(^a[\text{photons s}^{-1} \text{cm}^{-2} \text{keV}^{-1}]\).

\(^b[10^7 \text{ electrons cm}^{-3}]\).

\(^c[10^7 \text{ electrons cm}^{-3}]\).
et al., 2011). A harder index of microwave-emitting electrons may be due to a broken power-law spectrum that can result from Coulomb collisions of electrons confined in a magnetic trap. The role of trapping was unlikely significant in our events, because the microwave peaks were almost as short as the HXR peaks, while continuous injection into a trap during considerable time is required to flatten the high-energy spectral part (Metcalf and Alexander, 1999). Single power-law pattern persisted in the HXR spectra of each peak at higher energies. The usage of a broken power-law worsened the fit, while the analysis above 600 keV was not reliable because of insufficient statistics.

In view of these circumstances, we adopted in the modeling the values of $\delta'$ indicated by the high-frequency slopes of the microwave spectra. The uncertainties in the slopes are considerable because of poor data at 34 GHz; the modeling does not affect these slopes. By fitting the radio spectrum for each of the three peaks, we estimated the number $N_r$ of microwave-emitting electrons per unit volume in the distribution above $E_r = 10$ keV. The right part of Table 1 lists the power-law indices $[\delta']$ and $[\alpha]$ estimated in the analysis of microwave spectra and the parameters found in the modeling: the value of $N_r$, the average scaled magnetic-field strength in the modeled coronal microwave sources $|\overline{B}|$, the peak frequency $\nu_{\text{peak}}$ of the GS spectrum, and the maximum flux $S_{\text{max}}$ at this frequency found in the modeling for each of the three peaks.

The spectra of the three peaks obtained in the modeling of 13 pairs of microwave sources are shown in Figure 10 along with the observed values (similar to Figure 2). The modeling acceptably reproduces the turnover parts of the actual spectra and their adjacent branches between 2 and 17 GHz. The modeled spectra are underestimated at 2 GHz and lower frequencies (not shown). It is only possible to state that the modeled spectra do not contradict the fluxes estimated at 34 GHz, because their uncertainties are large. A formal increase in the number of sources does not bring the modeled spectra closer to the observations.
The modeling is illustrated for peak 1 in Figure 10, where the thin violet curves represent the spectra of 26 individual sources magnified by a factor of four. The spatial link between the conjugate sources is lost in the model, while the result of the summation of individual spectra does not depend on their combination. The magnetic-field strength in a source and its size are specified at each individual spectrum. The thin dashed-violet line, which represents the model spectrum obtained for peak 1 with $\delta^{\text{HXR}} = \gamma + 1.5 = 4.83$, demonstrates that the corresponding high-frequency slope is too steep even with respect to the measurements at 15.4 and 17 GHz that are more or less certain.

It is possible to compare the numbers of electrons $N_r$ listed in Table 1 that were found in the modeling of microwave spectra with the numbers $N^{\text{HXR}}_r$ estimated from the HXR spectra using Equation 2.6 from White et al. (2011) for the thick-target model. The $N^{\text{HXR}}_r$ numbers calculated for the values of $[\gamma]$ listed in Table 1 are lower than the corresponding $N_r$, on the average, by a factor of about 1.6. Thus, a harder spectral index of microwave-emitting electrons is accompanied by their excess over the number derived from HXR data.

According to Hannah and Kontar (2011), the relation between $\gamma$ and $\delta$ for the thick-target HXR emission is considerably modified, if an electron beam is not stationary but injected impulsively, which was the case in our events (note that the relation between the power-law index $\delta$ of the electron flux spectrum used in HXR studies and the index $\delta'$ of the electron density spectrum responsible for microwaves is $\delta' = \delta + 0.5$ in the non-relativistic regime). Wave–particle interactions exacerbate the deviation. These circumstances may shed light on the discrepancy between the two diagnostic methods.

The magnetic-field asymmetry characterized by a ratio of the average field strengths in the sources located in opposite-polarity regions is 2.5 – 2.8 that determines the low-frequency flattening of the microwave spectra. This pattern is governed by the magnetic-flux balance at conjugate footpoints of the flare loops (Section 2.1; Grechnev et al., 2017). Probably, this circumstance might also be implicated in the result of Lee (2018) expressed in terms of a broader microwave spectrum for a higher degree of magnetic inhomogeneity.

Our analysis and modeling of the microwave spectra leads to the following conclusions:

i) A distributed microwave-emitting system of multiple loops, which are rooted in the observed extended flare ribbons but unresolved in the microwave images considered, explains the low-frequency flattening of the microwave spectra.

ii) In particular, considering the actual S–N–S magnetic polarities and field strengths within the three ribbons, the modeling reproduces the overall microwave spectra. This result supports a double-arcade structure inside the NPT-configuration, as the magnetic-field reconstruction in the corona showed.

iii) On the other hand, it is unlikely possible to infer the presence of two arcades from the analysis of microwave spectra alone.

iv) By taking account of instrumental and observational limitations, it is possible to state that manifestations of accelerated electrons in HXR and microwaves correspond to the structures observed in the EUV.

v) While microwaves were most likely emitted in coronal loops by the same populations of accelerated electrons, whose precipitation produced hard X-rays in both flares, the electron energy spectral indices derived from microwave spectra are harder by 0.8 – 0.9 than those obtained from HXR data. This circumstance was noticed in several previous studies. In addition, the number of electrons found from microwaves is larger than their number estimated from hard X-rays by a factor of about 1.6.
5. Summary and Concluding Remarks

Having got a pointing from SRH at two major flares, which occurred within half an hour in the same active region and exhibited different emission spectra, we analyzed the twin events using EUV, hard X-ray, and microwave data along with magnetograms. Observational difficulties such as overexposure distortions in SDO/AIA images and the near-the-limb location of the flare site that hampered the analysis of the ribbons, and the presence of a passive filament, which partly hid the flare loops in EUV, disfavored a comprehensive analysis of the flares. It was possible to establish the following.

Both events were eruptive flares, each of which had an unusual three-ribbon configuration. The magnetic configuration, where they occurred, was characterized by a considerable excess of the S-polarity magnetic flux over the N-polarity flux in an extended plage region. The excessive S-polarity flux high above the plage region was concentrated within a tube-like outer spine that was rooted in a remote N-polarity sunspot. The coronal configuration just above the plage region had a shape of an inverted funnel that contained a null point in the waist. Because of the extended geometry, the funnel and the null-point region were stretched along the solar surface parallel to the plage region.

Each of the two magnetic domains inside the funnel contained a filament before the events. The filaments erupted one after another within half an hour. The events led to a CME, whose structure indicated its origin due to the twin eruptions. A scenario was inferred from multi-spectral observations that combines the twin events in terms of null-point-associated successive eruptions. Each rising filament moved to the null-field region that inevitably resulted in partial reconnection between the erupting structure and static coronal environment. Two successive flares developed in this way that basically resembled circular-ribbon flares with the following modifications: The central brightening extended into the middle ribbon located in the N-polarity plage region and the circular ribbon transformed into two ribbons located in S-polarity magnetic fields on both sides of the middle ribbon. Thus, a three-ribbon flare configuration appeared. In this scenario, the first filament eruption facilitates the second.

The two flares produced considerable microwave, hard X-ray, and \( \gamma \)-ray bursts that are detectable at energies exceeding 800 keV. Microwave and hard X-ray images highlighted different parts of the flare configuration, where accelerated electrons were present. Hard X-ray sources occupied parts of the ribbons that were sufficiently bright in the EUV. An extended hard X-ray source in the second flare was almost as long as the middle ribbon. Two microwave sources, which resembled two footpoints of a single loop, represented in fact two different arcades that is supported by the modeling of microwave spectra. Manifestations of accelerated electrons in hard X-rays and microwaves corresponded to the structures observed in the EUV, but they were revealed incompletely because of instrumental limitations of RHESSI and NoRH.

The results indicate that the spatial resolution achievable in microwave observations, which are currently available, may be insufficient to discern the structures in compact flares. On the other hand, the dynamic range of hard X-ray imagers may be insufficient to reveal the structures of hard X-ray sources perfectly. Hence, higher-resolution images with a sufficient dynamic range obtained in different spectral domains should be invoked for a correct interpretation of non-thermal flare sources. This approach was also used by Gary et al. (2018) and Chen et al. (2020) in recent studies based on advanced observations with Expanded Owens Valley Solar Array (EOVSA).
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