FLARE-GENERATED SHOCK WAVE PROPAGATION THROUGH SOLAR CORONAL ARCADE LOOPS AND AN ASSOCIATED TYPE II RADIO BURST

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ABSTRACT

This paper presents multiwavelength observations of a flare-generated type II radio burst. The kinematics of the shock derived from the type II burst closely match a fast extreme ultraviolet (EUV) wave seen propagating through coronal arcade loops. The EUV wave was closely associated with an impulsive M1.0 flare without a related coronal mass ejection, and was triggered at one of the footpoints of the arcade loops in active region NOAA 12035. It was initially observed in the 335 Å images from the Atmospheric Image Assembly with a speed of \( \sim 800 \text{ km s}^{-1} \) and it accelerated to \( \sim 1490 \text{ km s}^{-1} \) after passing through the arcade loops. A fan–spine magnetic topology was revealed at the flare site. A small, confined filament eruption (\( \sim 340 \text{ km s}^{-1} \)) was also observed moving in the opposite direction to the EUV wave. We suggest that breakout reconnection in the fan–spine topology triggered the flare and associated EUV wave that propagated as a fast shock through the arcade loops.

Key words: Sun: corona – Sun: flares – Sun: oscillations – Sun: UV radiation

Supporting material: animations

1. INTRODUCTION

Type II radio bursts are considered to be an indirect signature of shocks (Nelson & Melrose 1985; Vršnak & Cliver 2008). Most coronal type II radio bursts are excited by coronal mass ejection (CME) pistons (Thompson et al. 2000; Cliver et al. 1999; Gopalswamy et al. 2001). Another source of type II radio bursts is shocks generated by blast waves created by a pressure increase at the flare site (Uchida 1974; Hudson et al. 2003; Hudson & Warmuth 2004). The flare impulsive phase and CME acceleration phase often occur simultaneously (Zhang et al. 2001), therefore it is difficult to confirm the exact driver of coronal shocks in terms of flare blast or CME piston. An argument in favor of the CME driver is that confined flares (even X-class flares) do not produce coronal shocks. On the other hand, shocks are seen only when the associated CME is accompanied by a flare (Cliver et al. 2004; Gopalswamy et al. 2005).

In support of the flare-driven shock, some studies using coronagraph images from the Solar and Heliospheric Observatory (SOHO)/EIT and LASCO suggest the formation of a type II radio burst during the flare impulsive phase when the CME acceleration phase starts 10–20 minutes later or when the CME is too slow to drive a shock wave (\( <500 \text{ km s}^{-1} \)) (Magdalenić et al. 2008, 2010, 2012). The shock waves in such events were associated with impulsive/short-duration flare events with rise times less than 4 minutes. These studies have used low-resolution SOHO/EIT images (12 minutes cadence) and it was therefore not possible to track the low coronal eruptions (plasmoid/jets) related to short-duration impulsive flares and their associated shock waves (\( \sim 1000 \text{ km s}^{-1} \)) in extreme ultraviolet (EUV) images. Now data from the Atmospheric Image Assembly (AIA) images from the Solar Dynamics Observatory (SDO: Pesnell et al. 2012) provide an opportunity to study fast EUV waves and associated plasma ejections in the low corona, and it is therefore possible to investigate the wave driver and kinematics in more detail.

Kumar & Innes (2013) provided evidence of a blast wave (\( >1000 \text{ km s}^{-1} \)) propagating alongside and ahead of an erupting plasmoid that produced a metric type II radio burst. Recently, Kumar & Innes (2015) reported a clear observation of a fast-mode wave propagating along arcade loops and its partial reflection from the other footpoint. They also observed a second fast EUV wavefront propagating perpendicular to the arcade loops, which triggered a metric type II radio burst. The wave was excited by an impulsive C-class flare (without a CME) at one of the footpoints of the arcade loops.

Solar eruptions are generally associated with EUV waves. These waves were discovered by SOHO/EIT (Thompson et al. 1998). There has been a long-lasting debate about their nature (true wave or pseudo wave) and driver (in terms of CME or flare) (Vršnak & Cliver 2008; Veronig et al. 2010; Warmuth 2010, 2015; Warmuth & Mann 2011; Patsourakos & Vourlidas 2012; Liu & Ofman 2014 and references cited therein). At present, high-resolution observations from SDO/AIA suggest the existence of two wavefronts (i.e., fast and slow) (Chen & Wu 2011; Kumar & Manoharan 2013; Kumar et al. 2013). The speed of the fast wavefront (of the order of \( \sim 1000 \text{ km s}^{-1} \)) is about three times larger than that of the slow one, as predicted in the numerical simulation by Chen et al. (2002). The fast wavefront is either a true fast-mode wave or a magnetohydrodynamic (MHD) shock ahead of the slow wavefront. The slow wavefront is basically expanding CME loops interpreted as a pseudo wave (non-wave component). The fast EUV wavefront triggers transverse oscillations in coronal loops (Aschwanden et al. 1999, 2002; Wills-Davey & Thompson 1999; Schrijver et al. 2002; Kumar et al. 2013) or filament channels when passing through these structures (Asai et al. 2012; Shen et al. 2014) and shows reflection, refraction, and transmission when it interacts with neighboring active regions (Kumar & Manoharan 2013) or coronal holes (Gopalswamy et al. 2009; Olmedo et al. 2012). On the other hand, the slow wavefront generally stops at the boundary of an active region or at magnetic separatrices (Delannée &...
Aulanier 1999), therefore supporting the non-wave interpretation.

In this paper, we study a type II radio burst associated with a fast EUV wave observed during an impulsive M-class flare (without a CME) on 2014 April 16. The EUV wave propagates through arcade loops and triggers transverse oscillations in the loop system. We focus on the characteristics of the wave, its propagation, and excitation. In Section 2, we present the observation and results. In the last section, we discuss the results and draw some conclusions.

2. OBSERVATIONS AND RESULTS

2.1. Radio Spectrum

The type II burst was seen in the dynamic radio spectra from e-Callisto (Roswell station, 220–450 MHz) and RSTN (Sagamore hill station, 25–180 MHz) from about 19:57:40 UT to 20:10 UT (Figures 1(a), (b)). The composite spectrum shows both the fundamental and harmonic of the type II burst. The fundamental shows band splitting probably caused by emission from the pre- and post-shock plasma (Vršnak et al. 2001, 2002; Cho et al. 2007). The splitting is typical of that seen in other CME-associated type II bursts and corresponds to a compression ratio of 1.6 around 120 MHz and 1.4 around 40 MHz.

We used the Newkirk onefold and twofold density model (Newkirk 1961) to estimate the height of the type II exciter by selecting a few data points (marked by the + symbol) from the second harmonic of the type II burst. The time–height plot is shown in Figure 2(a). The average speed (from the linear fit) of the type II emission source is ~670 and ~810 km s\(^{-1}\) for the onefold and twofold models, respectively.

An unusual feature of the radio spectrum is a positive drifting feature from ~220 MHz to ~250 MHz, starting simultaneously with the type II burst, which implies that there were sunward-propagating energetic electrons at the same time as the outward-moving shock creating the type II burst. To estimate the exciter speed, we selected the data points marked with a green + sign and converted the frequencies into the emission heights in the corona using the Newkirk density models (considering fundamental emission). The speed of the downward-moving source (by a linear fit to the emission heights) is ~110 and ~130 km s\(^{-1}\) from the Newkirk onefold and twofold density models, respectively.

Figure 1. (a), (b) Dynamic radio spectrum from e-Callisto (Roswell station, 220–450 MHz) and RSTN (Sagamore hill station, 25–180 MHz). F and H denote the fundamental and second harmonic of the type II burst. The black pluses mark the frequencies used for obtaining the type II exciter speed. The green pluses mark the frequencies for calculating the speed of the positive drift feature. (c) RHESSI X-ray flux profiles in 6–12, 12–25, and 25–50 keV channels. Two vertical dotted lines represent the onset time of nonthermal particle acceleration in the radio (type III burst) and hard X-ray (12–50 keV) channels.

Figure 2. (a) Time–height plots (R\(_s\), above the solar surface) estimated from the Newkirk onefold (diamonds) and twofold (triangles) density models using the second harmonic of the type II radio burst. The estimated shock speed from the linear fit is ~670 and ~810 km s\(^{-1}\), respectively, from the Newkirk onefold and twofold density models. The distance of the EUV wave from the center of the flare (Figure 4) using AIA 335 Å (filled diamonds) and 193 Å (filled circles) images is overplotted in red. (b) Profile of the EUV wave speed estimated from the time–distance values (red) taken from panel (a). The GOES soft X-ray flux in the 1–8 Å channel is also included (dark green).
There was also a type III radio burst at high frequencies (220–450 MHz) but not below 200 MHz, suggesting acceleration of subrelativistic electrons that did not escape into interplanetary space.

To find the source of the type II burst and other features of the radio spectrum, we investigated EUV images and magnetic field data from AIA and the Heliospheric and Magnetic Imager (HMI; Schou et al. 2012) on SDO, images and spectra from Hinode’s XRT (X-Ray Telescope; Golub et al. 2007) and EIS (EUV Imaging Spectrometer: Culhane et al. 2007), hard X-ray images from RHESSI (Reuven Ramaty High Energy Solar Spectroscopic Imager: Lin et al. 2002), and coronagraph images from SOHO/LASCO (Brueckner et al. 1995; Yashiro et al. 2004) and STEREO-B COR-1 (Wuelser et al. 2004; Howard et al. 2008).

At the time of the type II burst, there was an M1.0 flare in active region NOAA 12035, when it was located in the southeast (S19E12) with a $\beta\gamma$ magnetic configuration. The M1.0 flare was an impulsive short-duration flare that started at 19:54 UT, peaked at 19:59 UT, and ended at 20:04 UT. Figure 1(c) shows the RHESSI X-ray flux in the 6–12 keV, 12–25 keV, and 25–50 keV channels. The type III radio burst correlates with the hard X-ray flux in the 12–25 and 25–50 keV channels, suggesting that the emission is from nonthermal electrons. The 6–12 keV flux peaked slightly later ($\sim$30 s), which indicates the contribution from thermal emission.

A careful check of the coronagraph images revealed that there was no CME associated with this flare; however, the EUV images showed a fast, outward-propagating wave and the possible source of the positive drifting feature. This study utilizes images from AIA 94 Å (Fe X, Fe XVIII, $T \approx$ 1 MK, $T \approx$ 6.3 MK), 131 Å (Fe VIII, Fe XXI, Fe XXIII, i.e., 0.4, 10, 16 MK), 171 Å (Fe IX, Fe X, Fe XII, Fe XXIV, $T \approx$ 0.7 MK), 193 Å (Fe IX, Fe XII, Fe XXIV, $T \approx$ 1.5, 20 MK), 304 Å (He II, $T \approx$ 0.05 MK), 335 Å (Fe XVI, $T \approx$ 2.5 MK), and 1600 Å (C IV + continuum, $T \approx$ 0.1 MK).

2.2. EUV Wave

Figure 3 displays running-difference images in the AIA 335, 193, and 171 Å channels. The time difference ($\Delta t$) for the difference images is 1 minute. The AIA 335 Å image at 19:56:50 UT shows the EUV disturbance propagating to the left of the flare site. The wavefront is simultaneously observed in the AIA 171 and 193 Å channels as it propagates through the arcade loops connected to the flare site. Note that the initial phase (from 19:56:38 UT to 19:58:38 UT) of the EUV wavefront was best observed in the AIA 335 Å channel. Later it could not be observed in the AIA 335 Å channel, but it was observed clearly in the AIA 193 Å channel from 19:58:42–20:01:35 UT. Figures 3(c) and (d) show the semicircular wavefront (F, yellow arrows) moving outward toward the eastern limb after passing through the arcade loops. We did not see a clear wavefront in the AIA 171 Å channel, but a long coronal loop can be seen expanding at 19:56:37 UT and shortly afterwards contracting in the 171 Å images of the AIA 171, 131, and 94 Å intensity movie (Figure 3) as the loop was crossed by the wave. At 19:59:35 UT, we see brightening in the funnel loops (in the AIA 171 Å channel) possibly caused by compression generated by the propagating wavefront (Figure 3(e)), and later we see a part of the wavefront at 20:00:23 UT (marked by green arrows). The details of the propagating wavefront can be viewed in the AIA 335, 193, and 171 Å running-difference movie (Figure 3). The interesting points to be noted here are: (i) the wavefront is highly directed toward the eastern limb, (ii) the wavefront is not moving in all directions, as generally seen in the case of an expanding CME bubble, (iii) there is only a single wavefront rather than multiple wave trains, (iv) transverse loop oscillations are seen throughout the arcade after the passage of the wave through them, (v) the flare occurred at one of the footpoints of the arcade loops, (vi) we do not see any CME loop or flux rope running behind the propagating wavefront in any of the AIA channels.

To estimate the speed of the propagating disturbance, we selected the straight slices S1, S2, and S3 shown in Figures 3(a)–(c) in the AIA 335 and 193 Å channels. The center of the flare is chosen as the origin for all slices. The time–distance intensity (running-difference) plot is displayed in Figure 4. S1 and S2 are selected in almost the same direction and the estimated speeds are the projected speeds of the wavefront. From a linear fit, we estimated the speed of the wavefront in the AIA 335 and 193 Å channels to be $\sim$800 ± 40 km s$^{-1}$ and $\sim$1490 ± 190 km s$^{-1}$ respectively. We assumed an error of 5 pixels in the distance of the wavefront. The speed along slice S3 was $\sim$1360 ± 210 km s$^{-1}$. The initial speed of the front in the 193 Å channel (S2) was $\sim$740 ± 40 km s$^{-1}$. The speed of the semicircular front (outside the arcade loops) is very similar in the 193 Å channel and does not change significantly along S2 and S3.

To show the kinematics of the wavefront, we derived its speed using time–distance measurements from the AIA 335 and 193 Å channels (Figure 2(b)). We utilized a three-point Lagrangian interpolation method to estimate the speed of the wavefront. Initially, the wave traveled slowly ($\sim$700–900 km s$^{-1}$) while passing through the arcade loops. The speed of the wavefront jumped ($\sim$2800 km s$^{-1}$) after leaving the arcade loops and it subsequently showed rapid deceleration ($\sim$2800–1100 km s$^{-1}$).

To see the association of the EUV wave with the M1.0 flare, we overplotted the GOES soft X-ray flux (dashed curve) from the 1–8 Å channel in Figure 4(a). The onset time of the EUV wave ($\sim$19:56 UT) closely matched the flare impulsive phase.

The time–distance measurements of the EUV wave in the AIA 335 and 193 Å channels have been overplotted with the red + symbol and filled circles, respectively in Figure 2. The speed of the type II exciter from the Newkirk twofold model is roughly consistent with the EUV wave speed observed in the AIA 335 Å channel. An exact match cannot be expected because the radio gives the outward speed and the EUV the front speed across the disk. The previous studies have also suggested the consistency of the Newkirk twofold model with the observed shock wave in the AIA (Kumar et al. 2013; Kumar & Innes 2015). Therefore, the EUV disturbance (shock wave) passing through the arcade loops is the exciter of the type II radio burst.

2.3. Transverse Oscillations in the Arcade Loops

The AIA 335, 193, and 131 Å composite movie (running difference; Figure 5) shows transverse oscillations of many loops within the arcade. These oscillations were triggered when the fast EUV wave passed through the arcade loops. The EUV disturbance seems to be reflected back after reaching the opposite footpoint of the arcade loops. Although we observed the loop system from above, it is difficult to say whether it is due to reflection of the disturbance or to transverse oscillations of arcade loops. It is very likely that the fast
wave propagates not only along the arcade loops but also across/perpendicular to the loop system (Kumar & Innes 2015).

It is quite difficult to extract the oscillation of an individual loop due to the orientation and mixing of the complex loop system in the 193 and 171 Å images. However, some of the

Figure 3. AIA 335, 193 and 171 Å running-difference images showing the propagating EUV disturbance (marked by arrows) to the left of the flare site. The green box in panel (c) represents the size of the top panels (a) and (b). (Animations (a and b) of this figure are available.)
loops have been heated and are visible in the 131 Å channel. We can use one of these to illustrate the oscillations. Figure 5(a) shows a stack plot (running-difference intensity) along the slice S4 marked on the 131 Å image (Figure 5(a)). In the 131 Å channel, the oscillation starts at ~20:03 UT, after the passage of the disturbance through it. We can clearly see four peaks.

First of all, we determined the positions of the oscillating loop from the stack plot. We subtracted a second-order polynomial profile in order to detrend the oscillation profile. We fitted a decaying sine function \( y = A \cos[2\pi (P + \phi)] e^{-\tau/T} \) to the oscillation profile (red curve), where \( A, \phi, P, \) and \( \tau \) are the initial amplitude, phase angle, period, and decay time of the oscillation. The estimated period and decay time of the oscillation are 210 s and 506 s, respectively.

To determine the phase speed of the wave, we need to measure the loop length. This active region was lying nearly behind the western limb of STEREO-B. Therefore, we need to determine the 3D structure of the loop with observation from a single point. We used the curvature radius maximization method (Aschwanden 2009) to determine the loop length \( \ell \). The estimated loop length was \( \sim 0.17 \, R_\odot \) (Figure 5(b)). The calculated phase speed of the wave (for the fundamental mode) is \( 2 \ell/P \approx 1140 \, \text{km s}^{-1} \) and the Alfvén speed is \( 840 \, \text{km s}^{-1} \).

2.4. Magnetic Configuration

In the previous subsections, we described the wave propagation through the arcade loops toward the eastern limb. Figure 6(a) displays the potential field extrapolation of the active region based on the HMI magnetogram at 19:45 UT (before the flare onset). The black and white curves represent the closed and open field lines, respectively. A small negative-polarity region is surrounded by opposite-polarity (positive) regions at the flare site, creating a quasi-circular polarity inversion line (PIL). An enlarged view of the flare site (marked by the red box) is shown in Figure 6(b). We can see the fan loops connecting to the negative polarities from the surrounding opposite-polarity field region. This morphology is quite similar to the fan–spine topology (Pariat et al. 2010).

Figure 6(c) shows the Hinode/XRT image (Al-poly filter) of the active region before the flare (19:54:12 UT). Two sets of loops are observed here: lower small loops and higher loops, which is consistent with the extrapolated field lines. Note that the higher loops are most affected by the flare and associated EUV wave. Also the fan loops at the flare site are clearly observed in the XRT image (Figure 6(d)). These images are overlaid by the HMI magnetogram contours of positive (green) and negative (yellow) polarities to view the connectivity of the coronal loops.

In Figures 6(e) and (f), we display the AIA 1600 Å images during the flare (19:58:16 UT). Interestingly, we see the formation of a quasi-circular ribbon at the flare site. In addition, there is a remote ribbon toward the eastern side of the flare. These ribbons are the precipitation sites of nonthermal electrons accelerated during the flare. The formation of a quasi-circular ribbon confirms the fan–spine topology at the flare site (Masson et al. 2009). Therefore, reconnection most likely occurred at the null point of the fan–spine topology, producing a quasi-circular ribbon. One of the footpoints of the higher loops was connected to the flare site, therefore accelerated particles propagated along these loops and precipitated to the opposite footpoint to form the remote ribbon.

2.5. Eruption

There was a small eruption at the time of the flare. To investigate the eruption, we analyzed AIA 94 and 304 Å images. The evolution of the plasma at the site of the eruption is illustrated in Figure 7, which shows stack plots of the AIA 94 Å intensity along the slices S5 and S6 (marked in Figure 7(c)). S5 is selected to show the timing along the quasi-circular ribbon (Figure 7(b)). The first brightening (ribbon) was at ~19:55:30 UT, followed by plasma ejections. The AIA 94 Å movie shows a sequential brightening that propagates along the quasi-circular ribbon in the counterclockwise direction with a speed of \( \sim 80 \pm 10 \, \text{km s}^{-1} \). The slice S5 was selected along the direction of the cool plasma ejection. Initially there was a small filament along the quasi-circular polarity inversion line (see the AIA 304 and 94 Å composite movie). At flare onset (19:55:30 UT), the southern end of the filament, overlaid by hard X-ray contours in Figure 7(c), brightened at all wavelengths and the quasi-circular ribbon appeared, followed by eruption of the filament. The speed of the plasma ejection (i.e., the small filament) was \( \sim 340 \pm 40 \, \text{km s}^{-1} \). After the first ejection, we see a series of minor ejections below the filament, which look like multiple plasma blobs or small plasmoids. The AIA 171, 131, 94 Å

Figure 4. Time–distance intensity (running-difference) plots along the slices S1 (AIA 335 Å), S2, and S3 (AIA 193 Å). The red dashed curve in panel (a) shows the GOES soft X-ray flux profile in the 1–8 Å channel.
intensity movie reveals the formation of postflare loops below the erupting filament. The eruption did not produce a CME. It looks as though the filament material was stopped by the overlying arcades. Therefore, the filament eruption failed (e.g., Kumar et al. 2011).

In the case of a piston-driven shock, the speed of the shock could be 2–3 times the speed of the driver. The wavefront should be initially located ahead of the driver and can decouple (from the driver) later to propagate freely. An important thing to note is that in this flare the eruption and EUV wave move simultaneously in opposite directions. Also, the speed of the EUV wave is about 3–4 times larger than the speed of the erupting plasma, so it is unlikely that the wave was triggered by the filament eruption. If the wave was driven by the small filament; we should have seen the EUV wavefront ahead of the filament, at least for some duration, as reported by Kumar & Manoharan (2013). An alternative mechanism for non-CME type II bursts has recently been proposed by Su et al. (2015). They suggest that the rapid expansion of loops following reconnection may provide a suitable piston to generate shocks in the lower corona. In this event, we saw no evidence for rapidly expanding loops that could have driven the shock.

Figures 7(d)–(f) show the AIA 304 Å images (chromosphere and transition region) overlaid with the RHESSI X-ray contours in 6–12 keV (green) and 12–25 keV (blue) energy channels (refer to Figure 1(c) for the flux profiles). To construct the

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**Figure 5.** (a), (b) AIA 131 and 94 Å images showing the flare and arcade loops. (c) AIA 131 Å intensity (running-difference) plot along the slice S4 (marked in panel (a)) showing the kink oscillation of the arcade loops. (d) Fit of a decaying sine function (red color) to the kink oscillating loop. The period of oscillation is ~210 s. The start time is ~20:04 UT. (An animation of this figure is available.)
X-ray images, we used the PIXON algorithm (Metcalf et al. 1996) with an integration time of 30 s for each image. The evolution can be followed in the AIA 304 and 94 Å composite movie in Figure 7. The RHESSI 12–25 keV contours (Figure 7(d)) show two footpoint sources. If we compare them with the RHESSI flux profile in 12–25 keV, they are associated with the flare impulsive phase (mostly nonthermal emission). The erupting filament and two ribbons (R1 and R2) underneath are marked in Figure 7(e). Note that R1 is a part of the quasi-circular ribbon. We observed RHESSI footpoint sources (below the filament) in the 6–12 and 12–25 keV channels from 19:57:30–19:59:00 UT. These sources are almost co-spatial with the ribbons R1 and R2.

The position of the footpoint sources seems to have changed from the impulsive phase to the decay phase, probably due to the change in the particle precipitation site. We speculate that this may be somehow connected with the sequential brightening observed in the counterclockwise direction, which may...
change the particle precipitation site associated with the rise of the small filament.

As mentioned before, we observed the formation of a remote ribbon (AIA 1600 Å) and a circular ribbon. Most of the particles accelerated during the flare were confined along the field lines (higher arcade loops) in the low corona. The electron beam from the reconnection site (null point of the fan–spine topology) precipitates downward into the chromosphere (along the fan loops), forming a circular ribbon. In addition, high-energy electrons probably follow the higher arcade loops and cause a remote ribbon seen in the 1600 Å images in the eastward direction.

In addition, we analyzed the available Hinode/EIS spectra of the flare. The EIS field of view is shown in Figure 7(b) by a rectangular box (red color). It only covered part of the arcade loops located east of the flare site and not the flare ribbons. These are the arcade loops through which the fast EUV wave propagated. Figures 8(a)–(c) display profiles of Fe XXIV (192.03 Å, log \( T = 7.1 \)) line intensity, velocity, and width starting at 19:57:13 UT (from right to left). Note that, by that time, the fast EUV wave had already passed through these loops (see Figures 3(a) and (b)), and therefore we see the afterwave signatures in the spectra. Interestingly, we see strong blue shifts (~50–100 km s\(^{-1}\)) along the higher loops in the Fe XXIV line. The same loops are also seen in the Fe XXIII line (263.76 Å, log \( T = 7 \)) (Figure 8(d)), confirming that these are 10 MK loops. The Fe XXIV line is considered the most prominent EIS line during large flares (Zanna & Mason 2005). The observed blueshifted upflows may be generated by chromospheric evaporation along the higher loops. They coincide with hot arcade loops emanating from the flare site seen in AIA 131/94 Å images. The image of Fe XVI (251.063 Å, log \( T = 6.4 \)) intensity shows the higher coronal parts of the lower arcade loops that are also visible in the Hinode/XRT image. The image of Fe XII (193.5 Å, log

Figure 7. (a)–(c) Stack plots of the AIA 94 Å intensity along the slices S5 and S6. The red rectangular box indicates the EIS field of view (refer to the next figure). (d)–(f) AIA 304 Å images overlaid by RHESSI X-ray contours in 6–12 keV (green) and 12–25 keV (blue) channels. The contour levels are 30%, 50%, 70%, and 90% of the peak intensity. HMI magnetogram contours of positive (white) and negative (black) polarities are overlaid in panel (e). R1 and R2 indicate the flare ribbons. (An animation of this figure is available.)
$T = 6.1$) intensity is more patchy because it is emitted from the cooler, lower parts of the loops, closer to their photospheric footpoints.

3. DISCUSSION AND CONCLUSION

We reported on the direct observation of a fast EUV wave propagating through coronal arcade loops and its associated type II radio burst (without a CME). Initially, the wave was best observed in the AIA 335 Å channel with a speed of $\sim 800 \text{ km s}^{-1}$ and later in the AIA 193 and 171 Å channels (1490 km s$^{-1}$). The fast wave was most likely triggered during breakout reconnection in a fan–spine topology. At the site of flare onset, a quasi-circular ribbon was seen just before a small, failed-filament eruption ($\sim 340 \text{ km s}^{-1}$) and, in the opposite direction, the launch of a fast EUV wave across the arcade loops. We rule out the small filament as a driver of the EUV wave because (i) the speed was $\sim 3–4$ times smaller than the speed of the fast EUV wave, (ii) it moves in the opposite direction, and (iii) we do not see the EUV wavefront ahead of the filament apex as expected in the case of a piston-driven shock.

The propagation of fast EUV waves is generally affected by active regions and coronal holes. The EUV waves may suffer reflection, trapping, and transmission when they encounter nearby active regions or coronal holes (Gopalswamy et al. 2009; Olmedo et al. 2012; Kumar & Manoharan 2013; Kumar & Innes 2015).

The speed of the EUV wave was initially lower as it passed through the arcade loops. Later, after it had escaped, it speeded up. A similar jump in shock speed was inferred from the dynamic radio spectrum (type II radio burst). The jump probably occurred because the arcade loops have higher density.
than the corona, so the wave could travel faster in the corona. A shock wave propagating through the high-density loops (at greater heights, \(\sim 0.1 \, R_\odot\)) could strengthen due to its lower Alfvénic speed (Cho et al. 2013). The denser overlying loops around the active region may have a relatively weaker field, and therefore lower Alfvénic speed (Pohjolainen et al. 2008). This scenario is probably similar to the excitation of a type II radio burst by a shock wave passing through a denser coronal streamer (i.e., regions of lower Alfvénic speed) (Cho et al. 2011; Kong et al. 2012). The shock wave is stronger while passing through the denser loops and can excite the fragmented type II radio burst as suggested by Pohjolainen et al. (2008). In our case, the structure of the type II radio burst is fragmented during the passage of the fast EUV wave through the denser overlying loops. The wave showed acceleration while passing through the arcade loops, as reported in numerical simulations (Pohjolainen et al. 2008).

The lower loops (in the AIA 171 Å channel) in the active region did not show transverse oscillation and were almost unaffected by the EUV wave. The higher loops were mainly affected by the EUV wave and exhibit strong transverse oscillation. These higher loops are the most likely candidate for exciting the type II radio burst (second harmonic \(>300 \, \text{MHz}\)).

Fast EUV waves generally follow the path of lower Alfvénic speed (Vršnak & Cliver 2008), and type II radio bursts could be excited by the flare-generated fast shock wave passing through the high-density loops at the periphery of the active region. This could be a reason why the EUV wave does not propagate in all directions from the center of the flare and follows only the denser loops.

In addition, we did not observe any slow wavefront behind the observed fast EUV wave. Slow wavefronts generally have speeds three times smaller than the fast wave and are usually interpreted as CME-stretched loops (i.e., a pseudo wave) running behind the fast wave (Chen et al. 2002; Chen & Wu 2011; Kumar et al. 2013). Alternatively, a pseudo wave may be explained by the current shell model (Delannée et al. 2008) and the reconnection front model (Attrill et al. 2007). In our case, the wave excitation closely matches the flare impulsive phase. This observation reveals that a low coronal type II radio burst can be generated by a shock wave ignited by an impulsive flare (i.e., a blast wave). We agree that most of the low coronal type II radio bursts are generated by a CME. However, our finding suggests that not all of them may be generated by a CME (piston-driven).

As the fast EUV wave propagated through the coronal arcade loops, it triggered kink oscillations of the loops. This suggests the wave was highly directional. According to Hudson & Warmuth (2004), a high directionality is a common characteristic of flare blast waves that trigger kink oscillations of a certain loop system while other nearby loops remain stationary (Smith & Harvey 1971; Warmuth et al. 2004). For one of the loops the kink oscillation had a period of 210 s and a phase speed of \(\sim 1140 \, \text{km s}^{-1}\).

For the first time, we see a positive, slowly drifting burst (\(\sim 220 \, \text{MHz}\)) simultaneously with the onset of a type II radio burst and closely associated with magnetic reconnection. The emission source drifts downward at a speed of \(\sim 100–130 \, \text{km s}^{-1}\). In the AIA 94 Å channel, we observed a co-temporal brightening propagating counterclockwise along the circular ribbon with a projected speed of \(\sim 80 \, \text{km s}^{-1}\). It is likely that the propagating brightening could be evidence of the rotation/slippage of fan loops around the spine. The speed of the radio source is roughly consistent with the rotating brightening. Therefore, we suggest that the downward-moving radio source could be generated by the slippage of the field lines that may cause the shift in the reconnection point (inclined motion), resulting in particle acceleration at increasing densities along the slipping field lines. However, more observational studies are needed to validate this interpretation. According to 3D numerical simulation, torsional spine reconnection or slipping reconnection is expected in a fan–spine magnetic configuration (Pontin & Galsgaard 2007; Masson et al. 2009; Priest & Pontin 2009). Alternatively, the narrow-band positive drifting structure may also be interpreted as a particle acceleration (downward) at a termination shock generated by a reconnection outflow (Aurass et al. 2002; Mann et al. 2009; Chen et al. 2015) because it was observed simultaneously during the type II radio burst. Mann et al. (2009) explained radio emission features (200–400 MHz) as evidence of particle acceleration at the termination shock generated by reconnection outflow.

We also observed a two-ribbon flare within the circular flare ribbon. This result is consistent with our previous finding of a two-ribbon flare (within a global circular ribbon) generated by untwisting small jets produced during the coalescence of two sheared J-shaped Hα loops (Kumar et al. 2015). The magnetic field configuration was quite similar in both cases, i.e., a fan–spine topology with a quasi-circular ribbon (Pontin & Galsgaard 2007; Masson et al. 2009; Priest & Pontin 2009; Pariat et al. 2010; Wang & Liu 2012). Here we observed breakout reconnection followed by the failed eruption of a small filament with a speed of \(\sim 340 \, \text{km s}^{-1}\).

In summary, breakout reconnection in a fan–spine topology launched a fast-mode MHD shock that propagated perpendicular to the arcade loops and generated a type II radio burst. We speculate that a specific magnetic configuration may be an important candidate for the flare-ignited shock wave. However, future studies with high-resolution observations will shed more light on this issue.

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