Observations of Two Successive EUV Waves and Their Mode Conversion

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Abstract

In this paper, we present the observations of two successive fast-mode extreme ultraviolet (EUV) wave events observed on 2016 July 23. Both fast-mode waves were observed by the Atmospheric Imaging Assembly instrument on board the Solar Dynamics Observatory satellite, with a traveling speed of $\approx 675$ and 640 km s$^{-1}$, respectively. These two wave events were associated with two filament eruptions and two GOES M-class solar flares from the NOAA active region 12565, which was located near the western limb. The EUV waves mainly move toward the south direction. We observed the interaction of the EUV waves with a helmet streamer further away to the south. When either or one of the EUV waves penetrates into the helmet streamer, a slowly propagating wave with a traveling speed of $\approx 150$ km s$^{-1}$ is observed along the streamer. We suggest that the slowly moving waves are slow-mode waves, and interpret this phenomenon as the magnetohydrodynamic wave-mode conversion from the fast mode to the slow mode. Furthermore, we observed several stationary fronts to the north and south of the source region.

Key words: Sun: corona – Sun: filaments, prominences – Sun: flares

Supporting material: animation

1. Introduction

Eruptive solar flares are associated with full or partial filament/prominence eruptions and now it is established that if the full or partial filament erupts, it will produce coronal mass ejections (CMEs). Therefore, these three physical phenomena (filament eruptions, flares, and CMEs) are often coupled with each other and are syndromes of the same process (Forbes 2000; Aulanier et al. 2010; Chen 2011). Occasionally, these eruptions are accompanied by extreme ultraviolet (EUV) waves, which can be observed over almost the entire solar surface. Historically these were known as “EUV Imaging Telescope (EIT) waves” (Moses et al. 1997; Thompson et al. 1998) because of their discovery by EIT (Delaboudinière et al. 1995) on board the Solar and Heliospheric Observatory satellite (Domingo et al. 1995). Later on, different authors proposed different terminologies, such as “coronal waves” (Wang 2000; Wu et al. 2001), “large-scale coronal propagating fronts” (Nitta et al. 2013), and “coronal propagating front” (Schrijver et al. 2011).

Since the discovery of EUV waves in 1998, extensive studies have been conducted. Besides the EIT telescope, EUV waves were also observed by other space-borne missions such as Hinode, STEREO, and, since 2010, the Solar Dynamics Observatory (SDO; Biesecker et al. 2002; Chen et al. 2002; Harra & Sterling 2003; Okamoto et al. 2004; Chen & Wu 2011; Delannée et al. 2014; Chandra et al. 2016). Diverse observational features have been reported. Some of them remind us of fast-mode waves, e.g., the propagation speeds up to above 1000 km s$^{-1}$ (Nitta et al. 2013) and the wave reflection (Gopalswamy et al. 2009b). However, some of the features tend to oppose the fast-mode wave nature for the EUV waves, e.g., the existence of stationary EUV waves (Delannée 2000), the subsonic wave speed (Tripathi & Raouafi 2007; Thompson & Myers 2009; Zhukov et al. 2009), and the helicity-dependent rotation direction (Podladchikova & Berghmans 2005; Attrill et al. 2007). In order to reconcile these contradicting observational features, Chen et al. (2002, 2005b) proposed that a filament eruption is accompanied by two types of EUV waves with different natures, i.e., the faster one corresponds to the fast-mode wave or shock wave (Thompson et al. 1998; Wang 2000; Wu et al. 2001; Chandra et al. 2018) and is the coronal counterpart of the H$_2$ Moreton wave (Moreton 1960), whereas the slower EUV wave is an apparent motion that is produced by the successive stretching of the closed magnetic field lines overlying the erupting filament. Their magnetic field line stretching model for the slower EUV waves can naturally explain why their velocities are roughly one-third of the fast-mode wave speed in the solar corona. Several other models have been proposed to explain the slower EUV waves (see reviews by Warmuth 2015; Chen 2016; Long et al. 2017; Krause et al. 2018, for details), e.g., slow-mode waves (Wills-Davey et al. 2007; Wang et al. 2009), successive reconnection model (Attrill et al. 2007), and Joule heating at the interface between the erupting magnetic field and the background field (Delannée et al. 2007). The coexistence of two EUV waves has been confirmed by various authors (Chen & Wu 2011; Schrijver et al. 2011; Asai et al. 2012; Cheng et al. 2012; Kumar et al. 2013; Shen et al. 2013; White et al. 2013). In this scenario, it would be confusing to call any wave pattern in EUV images an EUV wave. In order to avoid the ambiguity regarding the two types of EUV waves, Chen (2016) proposed to use different terminologies for them, e.g., coronal Moreton waves for the faster EUV waves and “EIT waves” for the slower EUV waves. Note that in some events only one of the two types of EUV waves is clearly visible.

Besides the low speed, i.e., $\sim 10$–300 km s$^{-1}$, “EIT waves” possess another peculiar characteristic, i.e., they stop at the footprint of magnetic quasi-separatrix layers (QSLs), as illustrated by Figure 7 in Delannée (2000). Such a feature was successfully explained by the magnetic field line stretching model (Chen et al. 2005b) because the magnetic field outside the QSL belongs to another magnetic system and cannot be...
pushed to stretch up by the erupting filament in the source region. Interestingly, when a fast-mode EUV wave passes a magnetic QSL, a bright stationary front is generated behind the continuously propagating but significantly weakened fast-mode wave (Chandra et al. 2016). With two-dimensional magnetohydrodynamic (MHD) simulations, Chen et al. (2016) proposed that, just before the QSL, mode conversion occurs, where the incident fast-mode wave is partly converted to a slow-mode wave. The slow-mode wave propagates along the closed magnetic loop. Seen from the top, the slow-mode wave trapped inside the magnetic loop looks like a stationary front since it cannot cross the quasi-vertical field lines. A stationary wave front is reproduced as a fast-mode wave interacts with the boundary of a coronal hole, which is a special QSL (Piantschitsch et al. 2017). Note that the observations in Chandra et al. (2016) could not show the propagation of the slow-mode wave along closed magnetic loops due to the nonfavoring viewing angle. Therefore, it was conjectured that mode conversion is the mechanism for the formation of the stationary front. The propagation of the slow-mode wave can be best revealed above the solar limb. Only recently, Zong & Dai (2017) clearly showed that after a fast-mode wave interacts with a helmet streamer with an incident speed of 380 km s\(^{-1}\), the wave speed is reduced significantly to 160 km s\(^{-1}\). Whereas their observations strongly support the wave-mode conversion mechanism, the exact speed of the slow-mode wave can be estimated more accurately when the slice is taken along the traveling direction.

In this article, we present the observations of two successive filament eruptions from NOAA active region (AR) 12565 on 2016 July 23. The filament eruptions were associated with two medium-class solar flares and two fast-mode EUV waves. Both EUV waves interacted with a coronal streamer far away in the southern hemisphere, and the newly generated waves after the interactions are detected by SDO. This paper is organized as follows: Section 2 describes the data sets. The observational results are presented in Section 3 and are discussed in Section 4.

2. Observations

The events on 2016 July 23 were well observed by the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the Solar Dynamics Observatory (SDO; Pesnell et al. 2012) satellite. The high cadence (12 s) and high spatial resolution (0.6') of the AIA telescope provide us with an excellent opportunity to analyze the kinematics and dynamics of these events. For our study, we use the AIA data observed in 304, 193, and 171 Å. In order to obtain better quality EUV waves, we first average four images and then make the running difference images in 193 Å. The reason for choosing 193 Å is that EUV waves are best discernible at this wavelength. All the images are co-aligned and corrected for the solar rotation using the routines available in the solar software (SSWIDL; Freeland & Handy 1998).

The flares were also observed by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI; Lin et al. 2002) telescope at different energy channels in X-ray. We construct the X-ray images at different energy bands using the CLEAN algorithm, which provides us with the spatial resolution of 2''.

For the associated CMEs, we use the data from the LASCO coronagraph available at the CDAW website (Gopalswamy et al. 2009a).

3. Results

3.1. Filament Eruptions and Flares

NOAA AR 12565 was located near the western limb (N04W89) on 2016 July 23. The AR with a multipolar (https://www.solarmonitor.org) magnetic distribution produced three GOES M-class and four C-class flares on that day. The evolution of both the flares, observed by GOES in X-rays is given in Figure 1 (top panel). Among them, two flares (hereafter referred to as the first flare and the second flare) were associated with filament eruptions. The first filament eruption occurred at ~05:08 UT. The evolutions of the first filament eruption and the associated GOES M7.6-class flare in AIA 171 and 304 Å are presented in Figure 2. According to the GOES observations, the onset and the peak times of the first flare were at 05:00 UT and 05:16 UT, respectively. Due to the location
of the flare site, which was very close to the limb, the two 
ribbons of the flare were very close to each other, as seen 
in Figure 2. Nevertheless, based on their relative locations, we 
can still judge that the magnetic system has a negative helicity, 
which follows the hemispheric rule (Ouyang et al. 2017).

Before the end of the first flare, at ~05:25 UT, we observed 
the second filament eruption from the same AR, which 
produced the second GOES M5.5-class flare. The onset and 
peak times of the second flare were 05:27 UT and 05:31 UT, 
respectively. The second flare was a long duration event and it
continued until 07:00 UT. The evolutions of the second filament eruption and flare in AIA 171 and 304 Å are presented in Figure 3. It shows that the filament eruption was experiencing a whipping motion, one typical asymmetric eruption of solar filaments (Liu et al. 2009). Each of the two filament eruptions was associated with a CME observed by the LASCO coronagraph. The linear speed of the CME was \( \sim 835 \text{ km s}^{-1} \) with an acceleration of \(-15.2 \text{ m s}^{-2}\), according to the CDAW website (https://cdaw.gsfc.nasa.gov).

The strength of the energy release process driven by magnetic reconnections in the wake of filament eruptions can be ascertained from the RHESSI X-ray sources formed underneath the erupting flux ropes (Figures 4(a)–(b)). The RHESSI images show two components of the flare emission: low energy emission imaged at 6–12 keV energy band located closer to the limb and high energy emission as demonstrated by the 12–25 keV and 50–100 keV sources that are almost cospatial. Notably, both flares were associated with very strong HXR emissions up to \( \sim 300 \text{ keV} \). The temporal evolution of both the flares observed by RHESSI in different energy channels is displayed in Figure 1 (bottom panel).

**Figure 4.** Upper row: RHESSI contours of the first (panel a) and second (panel b) flares in different energy bands. Middle row: corresponding AIA 171 Å images of the first (panel c) and second (panel d) flares. Bottom row: SDO/AIA 171 Å image showing the location (by white arrows) of the helmet streamer with which the EUV waves interacted.
3.2. Kinematics of the EUV Waves

The two eruption events on 2016 July 23 were both associated with EUV waves. The first EUV wave appeared at \(\sim 05:10\) UT and it propagated along the southeast direction. Panels (a–b) of Figure 5 display the 193 Å base difference images during the first eruption, where the EUV wave fronts are marked by the yellow arrows. However, it is noted that this wave is very weak and poorly visible in the AIA difference images. Around 20 minutes later, the second filament eruption occurred, producing another EUV wave. This second EUV wave started around 05:30 UT in AIA 193 Å images. Its evolution in AIA 193 Å is presented in panels (c–e) of Figure 5, where the EUV wave fronts are indicated by the red arrows. The time difference between the initiations of the first and second EUV waves is \(\sim 20\) minutes, which is almost the same as the time difference between the first and second filament eruptions. As shown by Figure 5(f), the second EUV wave approached a helmet streamer above the southwestern limb (see also the animation associated with Figure 5). When these EUV waves propagated on the solar disk, several stationary fronts were observed, as marked by the cyan arrows in Figure 6(a) (see also the AIA 193 Å animation). To see the magnetic property of these stationary fronts, we extrapolate the photospheric magnetic field using the PFSS model available in SSWIDL. The result is shown in the right panel of Figure 6. We compare the locations of these stationary fronts with the extrapolated potential magnetic field and find that these locations are all cospatial with QSLs. This confirms the earlier findings (Chen et al. 2002; Delannée et al. 2007; Chandra et al. 2016). Around the solar limb, we can see an EUV wave passing through a helmet streamer, as shown by the green arrows in Figure 5(e–f). Note that the location of the helmet streamer in AIA 171 Å is also indicated in Figure 4(e).

To show the early kinematics of the EUV waves, we select a circular slice parallel to the solar limb as indicated by the white curve in the left panel of Figure 7. The corresponding time–distance diagram is displayed in the right panel. It is seen that two fast-moving EUV waves similar to those in Figure 7, a brighter EUV front propagated away with a speed of 178 km s\(^{-1}\). This slower wave
has a traveling velocity roughly three times smaller than those of the fast-mode waves, as predicted by the magnetic field line stretching model (Chen et al. 2002, 2005b). It is believed that such a nonwave component of the EUV waves corresponds to the CME frontal loop (Chen 2009).

While the second EUV wave was seen clearly to propagate to the southern hemisphere as revealed by Figure 5, the first EUV wave faded rapidly, becoming very faint outside the source AR. However, when both EUV waves hit the helmet streamer above the southwestern limb, they become slightly brighter. To see the kinematics of the EUV waves across the helmet streamer, we select a slice shown as the white line in the left panel of Figure 9. Such a slice is along one leg of the streamer. The corresponding time–distance diagram along this slice is displayed in the right panel of Figure 9. Again we can see clearly two waves starting from ∼05:25 UT and 05:45 UT. Similar to Figure 7, the two waves in Figure 9 are also separated by ∼20 minutes, which is indicative of the fact that there is one-to-one correspondence between the wave pairs in Figures 7 and 9. However, the traveling speeds of the wave pair in Figure 9 are around 150 km s⁻¹, which is much slower than that of the wave pair in Figure 7.
4. Discussion

Since the discovery of EUV waves in late 1990s, they were initially treated as fast-mode MHD waves. The high speed of the waves in some events tends to favor the fast-mode wave model. However, the fast-mode wave model cannot explain the subsonic EUV waves whose velocity is as low as $\sim 10 \text{ km s}^{-1}$ (Zhukov et al. 2009), and the model was severely challenged by the discovery of stationary wave fronts (Delannée & Aulanier 1999; Delannée 2000). As claimed by Chen et al. (2002, 2005b), a possible solution to these discrepancies is that there are two types of EUV waves, i.e., a fast-mode wave or shock wave that is nearly cospatial with the H$\alpha$ Moreton wave (Vršnak et al. 2002; Chen et al. 2005a; Francile et al. 2016), and an apparent wave whose velocity is typically around one-third of the fast-mode wave. Such coexistence of two EUV waves has been confirmed by various authors (Chen & Wu 2011; Schrijver et al. 2011; Asai et al. 2012; Cheng et al. 2012; Kumar et al. 2013; Shen et al. 2013; White et al. 2013).
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In retrospect, the discovery of the stationary EUV wave front played a very important role in deepening our understanding of coronal EUV waves. However, it was revealed by Chandra et al. (2016) that a stationary front can be generated by the interaction between a fast-mode wave and a magnetic QSL. Inspired by their observations, Chen et al. (2016) proposed that, just prior to the magnetic QSL, there exists a local layer where the Alfvén speed is equal to the sound speed, where MHD waves can be converted from one mode to the other (Cally 2005), in this case, from the fast-mode wave to the slow-mode wave. Since the converted slow-mode wave propagates along the closed magnetic loops, and cannot run across the nearly vertical magnetic field lines, it looks like a stationary front when seen from above. The limb event studied by Zong & Dai (2017) provided the first support for the mode conversion model.

In the compound eruption events of 2016 July 23, two filaments erupted successively within ~20 minutes like sympathetic events. The two events were associated with two GOES medium-sized flares, two fast-mode EUV waves, and two CMEs. In our observations the nonwave component of the EUV waves, or “EIT wave,” was clearly visible in the second event. Around the source region, the two fast-mode waves propagated outward with a speed of 675 and 640 km s\(^{-1}\), respectively. However, when they penetrated into a distant helmet streamer, the waves became slightly brighter and much slower, with a speed of 150 km s\(^{-1}\) along the leg of the streamer. Such a speed is a typical value of sound speed for the coronal plasma with a temperature of 1 MK. The two slow-mode waves were separated by 20 minutes, the same as the time delay between the initial two fast-mode waves, which is strongly indicative of the fact that each fast-mode wave is converted to a slow-mode wave.

It is understandable why the wave-mode conversion happens inside a helmet streamer in both Zong & Dai (2017) and ours: whereas the Alfvén speed is much larger than the sound speed near the base of a streamer in the low corona, the magnetic field at the tip of a streamer is close to zero, where the Alfvén speed is close to zero, there should exist a layer slightly below the streamer tip where the Alfvén speed is equal to the sound speed. It is in such a place where fast-mode waves are converted into slow-mode waves. Since the streamer tip maps to a magnetic QSL, the trapped slow-mode wave cannot cross the field lines, and would be seen to stop near the QSL when observed from the top. It is noted in passing that such a wave-streamer interaction is consistent with the picture that the fast-mode waves driven by filament eruptions have a large-scale dome-shaped structure in the corona (Chen et al. 2002).

To summarize, we analyzed the wave phenomena associated with the possible sympathetic eruption events on 2016 July 23. The results include the following: (1) the two episodes of filament eruptions from the AR NOAA 12565, which were separated by 20 minutes, drove two fast-mode EUV waves or shock waves with a speed of 675 and 640 km s\(^{-1}\); (2) the two fast-mode EUV waves interacted with a helmet streamer in another hemisphere and were observed to propagate along the leg of the streamer, with a speed of 150 km s\(^{-1}\). We claim that slowly propagating waves are slow-mode MHD waves that are converted from the fast-mode waves. These observations strongly support the wave-mode conversion model proposed by Chen et al. (2016) in order to explain some stationary EUV wave fronts at magnetic QSLs.

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