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Coronal Quasi-periodic Fast-mode Propagating Wave Trains

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Abstract Quasi-periodic fast-mode propagating (QFP) wave trains in the corona have been studied intensively in the past decade, thanks to the full-disk, high spatiotemporal resolution, and wide-temperature coverage observations taken by the Atmospheric Imaging Assembly (AIA) onboard the *Solar Dynamics Observatory* (*SDO*). In AIA observations, QFP wave trains are seen to consist of multiple coherent and concentric wavefronts emanating successively near the epicenter of the accompanying flares; they propagate outwardly either along or across coronal loops at fast-mode magnetosonic speeds from several hundred to more than 2000 km s^{-1}, and their periods are in the range of tens of seconds to several minutes. Based on the distinct different properties of QFP wave trains, they might be divided into two distinct categories including narrow and broad ones. For most QFP wave trains, some of their periods are similar to those of quasi-periodic pulsations (QPPs) in the accompanying flares, indicating that they are probably different manifestations of the same physical process. Currently, candidate generation mechanisms for QFP wave trains include two main categories: pulsed energy excitation mechanism in association with magnetic reconnection and dispersion evolution mechanism related to the dispersive evolution of impulsively generated broadband perturbations. In addition, the generation of some QFP wave trains might be driven by the leakage of three and five minute oscillations from the lower atmosphere. As one of the new discoveries of *SDO*, QFP wave trains provide a new tool for coronal seismology to probe the corona parameters, and they are also useful for diagnosing the generation of QPPs, flare processes including energy release and particle accelerations. This review aims to summarize the main observational and theoretical results of the spatially-resolved QFP wave trains in extreme ultraviolet observations, and states briefly a number of questions that deserve further investigations.

Keywords: Flares, Magnetic Fields; Coronal Mass Ejections, magnetohydrodynamic (MHD) Waves, Corona

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1. Introduction

The solar atmosphere is divided into the photosphere, chromosphere, transition region and corona based on the distinct different physical properties. The outermost atmosphere layer of the Sun, the corona, is made of high-temperature magnetized plasma, which extends at a height of about 5 Mm above the photosphere into the heliosphere. In the low corona ($\leq 1.3\,R_{\odot}$), the magnetic field strength ranges from 0.1–0.5 gauss in the quiet Sun and in coronal holes to 10–50 gauss in active region resolved elements, with typical temperature (electron densities) of 1–2 MK (10^{9} cm^{-3}) in the quiet Sun and 2–6 MK (10^{11} cm^{-3}) in active regions. These physical parameters determine that the coronal plasma, consisting of electrons and ions, is magnetically confined where charged particles are guided by magnetic field lines in a helical gyromotion along the magnetic field lines (e.g., Aschwanden, 2005).

The tenuous and hot corona stores a large amount of energy mainly in the highly non-potential magnetic field of active regions. Generally, the stored energy can be released impulsively through magnetic reconnection and thus cause large-scale solar eruptions such as flares (Shibata and Magara, 2011), filament/jet eruptions (Mackay et al., 2010; Shen, 2021), coronal mass ejections (CMEs, Chen, 2011). These energetic solar eruptions will inevitably excite various types of magnetohydrodynamic (MHD) waves in the corona (e.g., Nakariakov and Verwichte, 2005; Li et al., 2020a; Van Doorsselaere et al., 2020; Nakariakov and Kolotkov, 2020; Nakariakov et al., 2021; Tian et al., 2021; Wang et al., 2021). In addition, the leakage of photospheric and chromospheric oscillations into the corona can also led to the generation of coronal waves (e.g., Beckers and Tallant, 1969; De Moortel et al., 2002; Sych et al., 2009; Shen and Liu, 2012b), and the mode conversion should occur in the chromosphere where the plasma pressure is approximately equal to the magnetic pressure (e.g., Bogdan et al., 2003). Generally, there are three MHD wave modes, including Alfvén wave, slow and fast magnetosonic waves. Alfvén waves are incompressible in the linear regime and can only cause doppler shifts in observed line measurements, while slow and fast magnetosonic waves are compressional and can cause compression and rarefaction of the plasma density. Hence that compressional magnetosonic waves can be directly imaged through detecting intensity variations, since the optically thin emission measure in extreme ultraviolet (EUV) and soft X-rays is directly proportional to the square of electron density, and thus to the observed flux (Aschwanden, 2005). However, one should be cautions with this, as the column. depth perturbations should also be taken into account (e.g., Cooper, Nakariakov, and Williams, 2003; Gruszecki, Nakariakov, and Van Doorsselaere, 2012). MHD waves not only carry energy away from their excitation sources and dissipate it into the medium where they propagate, but also reflect the physical properties of the waveguides and the background corona. Therefore, the investigation of MHD waves is very important for understanding the heating of the upper solar atmosphere, the acceleration of solar wind, and the physical parameters of the solar atmosphere with the method of coronal seismology (e.g., Nakariakov and Verwichte, 2005; De Moortel and Nakariakov, 2012; Nakariakov et al., 2016; Wang et al., 2021). In addition, since MHD waves are accompanying phenomena of solar eruptions, they are also important for diagnosing the driving mechanism and energy release process of solar eruptions.

Rapidly propagating large-scale disturbances in the solar atmosphere were firstly observed in the chromosphere with group-based Hα telescope; they show as arc-shaped bright fronts and were dubbed as Moreton waves (e.g., Moreton, 1960; Moreton and Ramsey, 1960). Moreton waves propagate rapidly at a speed of 500-2000 km s^{-1} so that they can reach a long distance of the order of 10^{5} km and cause the oscillation of remote filaments (e.g., Eto et al., 2002; Shen et al., 2014a,b). Since it is hard to understand the long distance propagation of Moreton waves in the dense chromosphere (see, Chen, 2016), Uchida (1968) interpreted them as chromospheric response of coronal fast-mode magnetosonic waves or shocks. Uchida's model not only naturally explained the observed features of Moreton waves, but also predicted the existence of large-scale fast-propagating magnetosonic waves or shocks in the low corona. The high temperature of the corona makes the coronal plasma mainly radiates in the EUV and X-ray wavebands. However, due to the strong absorption of these radiations by the Earth's atmosphere, the routine observation of the low corona can only be made in the outer space. Therefore, the large-scale fast-propagating disturbances in the corona were discovered until 1998 by the *Extreme-ultraviolet Imaging Telescope* (EIT: Delaboudinière et al., 1995) onboard the *Solar and Heliospheric Observatory* (*SOHO*), delayed the discovery of chromospheric Moreton waves about 40 years (Moses et al., 1997; Thompson et al., 1998). The observational characteristics of large-scale corona disturbances are similar to those of chromospheric Moreton waves, such as the arc-shaped or circular diffuse wavefronts centered around the epicenter of the associated flares. Therefore, they were quickly thought to be the long-awaited coronal counterparts of chromospheric Moreton waves, i.e., fast-mode MHD waves or shocks excited by flare-ignited pressure pulses (e.g., Thompson et al., 1999; Wang, 2000; Wu et al., 2001). However, this interpretation was challenged by many follow-up studies, due to some abnormal characteristics such as much lower speeds compared to Moreton waves (Klassen et al., 2000) and stationary wavefronts (Delannée and Aulanier, 1999). During the past two decades, observational and theoretical studies were intensively performed to study the driving mechanism and physical nature of these large-scale coronal disturbances. Thanks to the high spatiotemporal resolution observations taken by the *Atmospheric Imaging Assembly* (AIA: Lemen et al., 2012) onboard the *Solar Dynamic Observatory* (*SDO*), now we have recognized that a large-scale propagating coronal disturbance is typically composed of a fast-mode magnetosonic wave or shock followed by a slower wavelike feature, in which the former is often driven by a CME, corresponding to the coronal counterpart of a chromospheric Moreton wave (e.g., Shen and Liu, 2012c; Ma et al., 2011; Cheng et al., 2012), while the origin and physical nature of the latter is still unclear (Liu and Ofman, 2014; Warmuth, 2015; Chen, 2016; Shen et al., 2020). It should be pointed out that a bewildering multitude of names were used in history for large-scale fast-propagating coronal disturbances, such as "EIT waves", "(large-scale) coronal waves", "(large-scale) coronal propagating fronts", and "EUV waves". In this paper, we tend to use the term "EUV waves" based on their main observation waveband.

The launch of the *SDO* started a new booming era in the research of coronal MHD waves, mainly due to its unprecedented observation capability. The AIA onboard the *SDO* observes the Sun uninterruptedly with a full-Sun (1.3 solar diameters) field of view, which has seven EUV channels covering a wide temperature range from 6×10^4 to 2×10^7 K and a high signal-to-noise (sensitivity) for two- to three-seconds exposures. The temporal cadence and spatial resolution of the images taken by the AIA are respectively of 12 seconds and $1''.2$ (Lemen et al., 2012). The combination of these high observation capabilities makes AIA the best ever instrument for detecting coronal MHD waves with small intensity amplitudes. Since the launch of the *SDO* in 2010, besides the great achievements in the study of single pulsed global EUV waves, quasi-periodic fast-mode propagating (QFP) wave trains have also been directly imaged (Liu et al., 2010, 2011). In history, directly imaging observations of QFP wave trains were very scarce, although they had long been theoretically predicted (Roberts, Edwin, and Benz, 1984) and confirmed by numerical studies with similar characteristics (e.e., Murawski and Roberts, 1993c, 1994; Murawski, Aschwanden, and Smith, 1998). This was mainly attributed to the low observation capability of previous solar telescopes, such as their low spatiotemporal resolution, low sensitivity, narrow temperature coverage and small fields of view. As one of the new discoveries of the *SDO*, QFP wave trains have attracted a lot of attentions since the discovery; they were identified as fast-mode magnetosonic waves by using a three-dimensional MHD simulation (Ofman et al., 2011). So far, there are dozens of QFP wave trains that have been analyzed in detail with multi-wavelength observations, and remarkable theoretical attention has been given to their excitation, propagation, and damping mechanisms. The investigation of QFP wave trains is very important at least in the following aspects. Firstly, as a new accompanying phenomenon of solar eruptions, it is worthy to study their basic physical properties and physical connections to solar eruptions. Secondly, since QFP wave trains often show some common periods with those of the quasi-periodic pulsations (QPPs) in the accompanying flares, the study of QFP wave trains can shed light on our understanding of the unresolved generation mechanisms of flare QPPs that show as quasi-periodic intensity variation patterns with characteristic periods typically ranging from a few seconds to several minutes and can be seen in a wide range of wavelength bands from radio to gamma-ray light curves (e.g., Young et al., 1961; Parks and Winckler, 1969; Kane et al., 1983; Nakariakov et al., 2010; Kupriyanova et al., 2010; Van Doorsselaere et al., 2011; Ning, 2014; Zhang, Li, and Ning, 2016; Milligan et al., 2017; Chen et al., 2019; Yuan et al., 2019; Hayes et al., 2020; Kashapova et al., 2020; Li et al., 2020b,c,d,e, 2021b; Clarke et al., 2021; Lu et al., 2021; Li et al., 2021a; Li, 2021). Thirdly, QFP wave trains provide a new seismological tool for diagnosing the physical parameters of the solar corona that are currently difficult, or even impossible to measure. In addition, since the damping of fast-mode magnetosonic waves is fast, they are thought to be important for balancing the typical radiative loss rates of active regions (e.g., Porter, Klimchuk, and Sturrock, 1994; Liu et al., 2011).

The aim of this review is intended to summarize the main theoretical and observational results of the spatially-resolved QFP wave trains in the EUV wavelength band, focusing on recent advances and the seismological applications. Liu and Ofman (2014) had published a preliminary review on QFP wave trains 7 years ago based on only 6 published events at that time. The present review mainly focuses on new observational and theoretical advances in recent years, but also includes previous theoretical and observational studies for without sacrificing completeness. Other types of coronal MHD waves are not covered in this review, interested readers can refer to many excellent review papers published in recent years (e.g., Nakariakov and Verwichte, 2005; Nakariakov and Kolotkov, 2020; Nakariakov et al., 2021; Warmuth, 2015; McLaughlin et al., 2018; Li et al., 2020a; Van Doorsselaere et al., 2020; Shen et al., 2020; Wang et al., 2021; Zimovets et al., 2021).

2. Observational Signature

2.1. Pre-*SDO* Observation

Space-borne solar telescopes before the *SDO* are not good for detecting QFP wave trains, mainly because of their lower observing capabilities such as spatiotemporal resolution and sensitivity. Although the *TRACE* has a superior spatial resolution, but its lower time resolution, poorer sensitivity, and smaller field of view are all not conducive for the detection of QFP wave trains. Therefore, sporadic imaging detections of possibly coronal QFP wave trains were mainly reported during solar total eclipse observations and coronagraph observations, through detecting the intensity, velocity and line width fluctuations (e.g., Pasachoff and Landman, 1984; Cowsik et al., 1999; Pasachoff et al., 2002; Katsiyannis et al., 2003). In addition, indirect signals of QFP wave trains were also studied by using radio observations. During the total solar eclipse on 1995 October 24, Singh et al.

(1997) detected intensity variations with periods of 5–56 seconds. Possible evidence of periodic MHD waves was also reported in other studies using coronagraph observations (e.g., Koutchmy, Zhugzhda, and Locans, 1983; Ofman et al., 1997; Sakurai et al., 2002). Some estimations showed that these observed oscillations and periodic MHD waves carry carry enough energy for heating the active region corona and could contribute significantly to solar wind acceleration in open magnetic field structures, if they are Alfvén or fast-mode magnetosonic waves.

Probably, more reliable imaging detection of QFP wave trains was detected during the total solar eclipse on 1999 August 11, by using the *Solar Eclipse Corona Imaging System* (SECIS: Williams et al., 2001). Detailed analysis results showed that the detected oscillations could be a QFP wave train that travels along active region loops (Williams et al., 2002), whose period, speed, wavelength, and intensity amplitude were about 6 seconds, 2100 km s^{-1}, 12 Mm, and 5.5%, respectively. In a subsequent paper, the authors further detected more periods of the wave train in the range of 4–7 seconds, indicating the wave train's periodicity nature (Katsiyannis et al., 2003). After the launch of the *Transition Region And Coronal Explorer* (*TRACE*: Handy et al., 1999), Verwichte, Nakariakov, and Cooper (2005) probably observed a QFP wave train that propagated along an open magnetic field structure above a post-flare arcade, using the 195 Å wavelength images. Measurements showed that the wave train had a period of 90–220 seconds and propagated at a speed of 200–700 km s^{-1} at a height of 90 Mm above the solar surface. In addition, a quasi-periodic large-scale global EUV wave train was also reported in Patsourakos, Vourlidas, and Kliem (2010), by using the 171 Å imaging observations taken by the Extreme Ultraviolet Imager (EUVI; Wuelser et al., 2004) onboard the *Solar Terrestrial Relations Observatory* (*STEREO Kaiser et al., 2008).* In their observation, multiple large-scale coherent EUV wavefronts propagating over the disk limb were ahead of the CME bubble, and the authors proposed that the quasi-periodic EUV wave train was driven by the fine expanding pulse-like lateral structures in the CME bubble, because the wavefronts appeared as the lateral expansion of the CME bubble slows down and terminates.

2.2. General Properties

Unambiguous signatures of QFP wave trains were directly imaged in EUV images taken by the AIA instrument onboard the *SDO* (Liu et al., 2010, 2011; Shen and Liu, 2012b), and they were identified as fast-mode magnetosonic waves by Ofman et al. (2011) using a three-dimensional MHD model of a bipolar active region structure. Since the initial discovery, QFP wave train has attracted a lot of attentions, and a mass of observational and numerical studies have been performed to investigate their excitation mechanisms and physical properties. The occurrence of QFP wave trains is rather common and is frequently associated with single pulsed global EUV waves, flares and CMEs. According to the first 4.5 years observation of the *SDO*, Liu et al. (2016) performed a simple statistical study of QFP wave trains based on the database of global EUV waves cataloged at LMSAL (Nitta et al., 2013, https://www.lmsal.com/nitta/movies/AIA_Waves), and the authors found that about one third of global EUV waves in association with flares and CMEs are accompanied by QFP wave trains. This occurrence rate is clearly undervalued for all flare activities, because in fact the occurrence of many QFP wave trains do not accompanied by global EUV waves and CMEs. Until now, more than thirty QFP wave trains have been analyzed in detail in the literature. The physical parameters and the main associated solar activities of published QFP wave trains are listed in Table 1. In these events, QFP wave trains exhibit recurrence characteristics in some active regions along specific trajectories (e.g., Yuan et al., 2013; Zhang et al., 2015; Miao et al., 2020; Zhou et al., 2021a) and refraction and reflection effects during their interaction with coronal structures or at the remote footpoints of closed loop systems (e.g., Liu et al., 2011; Shen et al., 2018b,a, 2019). In particularly, turbulent cascade caused by the counter-propagating of two QFP wave trains along the same closed loop system was also observed (Ofman and Liu, 2018).

Based on Table 1, we can make a simple statistical study to QFP wave trains. It can be seen that QFP wave trains propagate at fast speeds of about 305–2394 km s^{-1} and with strong decelerations of 0.1–4.1 km s^{-2}; they can propagate a long distance over 500 Mm ($> 0.7\,R_{\odot}$) before their disappearance. It should be noted that the values of these parameters could be higher, since they are typically measured on the plane of the sky.Their occurrence are typically accompanied by flares and commonly appear firstly at a distance greater than 100 Mm away from the flare epicenter. Such a distance is consistent with the theoretical prediction of the initial periodic phase of an impulsively generated fast magnetosonic wave, during which the intensity amplitude needs time to be amplified for detection (Roberts, Edwin, and Benz, 1983, 1984). In addition, the observability of fast-mode magnetosonic waves is also significantly affected by observation angle (Cooper, Nakariakov, and Williams, 2003). In observation, the amplitude of QFP wave trains does show a first increase and then decrease trend as they propagate outward along funnel-like loops, and this might be due to the combined result of the amplification caused by density stratification and attenuation result from geometric expansion of the waveguide (Yuan et al., 2013). According to Table 1, QFP wave trains are typically associated with large-scale solar activities including flares, CMEs and global EUV waves. One can see that the associated flares can either be energetic GOES soft X-ray M class (e.g., Nisticò, Pascoe, and Nakariakov, 2014; Kumar, Nakariakov, and Cho, 2017), or low-energy events such as small brightening patches (Shen et al., 2018b; Miao et al., 2020) and features of possible reconnection events that can not even cause small GOES flares (Qu, Jiang, and Chen, 2017; Li et al., 2018b). This result might indicate that the occurrence of QFP wave trains does not need too much energy. Alternatively, the presence of special physical condition might be an important factor instead, because in some active regions recurrent flares at the same location are often associated with recurrent QFP wave trains along the same trajectory.

We checked the correlation between QFP wave trains and CMEs based on the CACTUS (https://wwwbis.sidc.be/cactus/) and CDAW (https://cdaw.gsfc.nasa.gov/CME_list/) databases. For the 32 published QFP wave trains, 26 of them are associated with CMEs, which means that the association rate of QFP wave trains with CMEs is about $26/32 \approx 80\%$. The average speeds of those CMEs that are accompanied by QFP wave trains are in the range of 174–1466 km s^{-1}, which suggests that QFP wave trains are associated with both slow and fast CMEs, and no clear correlation preference with the two types of CMEs can be found. For the QFP wave trains propagating along coronal loops, we also checked their correlation with global EUV waves. It is found that 18 of the 27 QFP wave trains were associated with global EUV waves, which translates to an association rate of about $18/27 \approx 70\%$. Moreover, for the global EUV waves that were accompanied by QFP wave trains, 5 of them were not associated with CMEs (Kumar and Manoharan, 2013; Shen et al., 2018b,c; Miao et al., 2020). In other word, these QFP wave trains were associated with failed solar eruptions without association to CMEs, and the ratio of this kind of QFP wave train is about $5/18 \approx 30\%$. For those QFP wave trains that are not associated global EUV waves, almost all of them were associated with CMEs. This is probably the reason why the association rate between QFP wave trains and CMEs (80%) is higher than that between global EUV waves (70%). We noted that in Liu et al. (2016) the authors found that all the QFP wave trains associated with global EUV waves are also associated with flares and CMEs. In addition, based on the simple survey of two flare productive active regions of AR12129 and AR12205, the authors also found an interesting trend of preferential association of QFP wave trains with successful solar eruptions accompanied by CMEs.

Here, based on the survey of the published events, we would like to point out that not all QFP wave trains are simultaneously accompanied by both global EUV waves and CMEs, and the association rate with successful solar eruptions does higher than that with failed ones (say, 80% vs 20%).

Because the occurrence of QFP wave trains is tightly associated with flares, we further checked the temporal relationship between the start time of QFP wave trains and the start and peak times of the associated flares (see Table 1). One can see that the start of QFP wave trains can either be before or after the peak times of the accompanying flares. For those QFP wave trains that appeared before the flare peak times, their start times are usually about 1–57 minutes later

Table 1. Physical parameters of the published QFP wave trains

Event	Associated Phenomena				Physical Parameters									
Date yyyy-mm-dd	Flare Start/Peak Time [UT]	GOES Class	CME $[\mathrm{km\ s^{-1}}]$	EUV Wave [Y/N]	Start Time [UT]	Duration [Min.]	Angular Width [Degree]	Speed $[\mathrm{km\ s^{-1}}]$	Deceleration $[\mathrm{km\ s^{-2}}]$	Period [Sec.]	Wavelength [Mm]	Intensity Amplitude	Energy Flux $[\times 10^{5}\ \mathrm{erg\ cm^{-2}\ s^{-1}}]$	Reference
							Narrow QFP wave trains[1]							
2010-04-08	02:32/03:25	B3.8	174	Y	03:15	65	40	450–1200	0.2–5.8	40–240	—	—	—	Liu et al. (2010)
2010-08-01	07:25/08:57	C3.2	260	N	07:45	60	60	2200	—	40–181	133	1%–5%	0.1-2.6	Liu et al. (2011)
2010-08-01	07:25/08:57	C3.2	260	N	08:06	25	—	1000–2000	—	—	—	—	—	Liu et al. (2011)
2010-09-08	23:00/23:33	C3.3	818	Y	23:11	18	25	1020–1220	3–4	30–240	—	1%–5%	—	Liu et al. (2012)
2011-02-14	05:35/05:50	BP[2]	—	Y	05:53	26	40	322	0.138	390	100	2%–4%	—	Shen et al. (2018b)
2011-02-15	04:29/04:49	C8.3	—	Y	04:38	32	25	388	0.38	200	110	1%–4%	—	Shen et al. (2018c)
2011-03-09	23:47/23:51	BP	—	Y	23:48	22	20	718	—	40	40	—	—	Miao et al. (2020)
2011-03-10	04:05/04:09	BP	—	Y	04:05	12	10	876	—	50	30	—	—	Miao et al. (2020)
2011-03-10	06:39/06:48	C4.0	408	Y	06:40	6	25	682–837	—	45	40	—	—	Miao et al. (2019)
2011-03-25	23:08/23:22	M1.0	—	Y	23:12	6	—	1011–1296	—	180	20–30	—	—	Kumar and Manoharan (2013)
2011-05-30	10:48/10:57	C2.8	248	Y	10:50	12	25	834	—	25–400	23.8	2%–8%	—	Shen and Liu (2012b)
2011-05-30	10:48/10:57	C2.8	248	Y	10:50	12	25	740-850	1.3–2.3	38–58	24–34	2%–8%	—	Yuan et al. (2013)
2011-06-02	06:30/06:36	C1.4	253	Y	06:30	13	20	776	—	120	110	1%–4%	—	Zhang et al. (2015)
2011-06-02	07:22/07:46	C3.7	976	Y	07:35	20	20	978	—	120	110	1%–6%	—	Zhang et al. (2015)
2011-09-23	23:48/23:56	M1.9	617	N	00:06	12	15	320	—	130	40	–	–	Kumar, Nakariakov, and Cho (2016)
2011-11-09	11:40/11:45	RE[3]	627	N	11:45	33	35	305	0.715	74-390	30	1%–5%	—	Qu, Jiang, and Chen (2017)
2011-11-09	11:40/11:45	RE	627	N	11:45	35	20	343	1.17	54-458	30	1%–8%	—	Qu, Jiang, and Chen (2017)
2012-04-23	17:37/17:51	C2.0	355	Y	17:40	23	18	689	1.0	80	33	1%-5%	1.2-4.0	Shen et al. (2013a)
2012-07-14	09:07/09:12	C1.4	561	N	09:14	6	10	538–719	—	180	120	—	—	Duan et al. (2021)
2013-04-23	18:10/18:33	C3.0	403	Y	18:20	60	10	474	—	110	40	1%–4%	0.43	Zhou et al. (2021b)
2013-05-22	12:35/13:32	M5.0	1466	Y	13:32	120	—	1860	—	120–180	320	2%-4%	1.8	Ofman and Liu (2018)
2013-05-22	13:00/13:57	C5.0	—	N	13:05	120	—	1670	—	120–180	—	2%-4%	1.8	Ofman and Liu (2018)
2013-12-07	07:17/07:29	M1.2	909	Y	07:25	15	10	538–2394	—	50–180	46–429	—	—	Nisticò, Pascoe, and Nakariakov (2014)
2013-12-07	07:17/07:29	M1.2	909	Y	07:26	32	55	941–1851	—	50–130	62–181	—	—	Nisticò, Pascoe, and Nakariakov (2014)
2014-03-23	03:05/03:48	C5.0	820	N	03:08	60	80	884–1485	—	25–550	6-20	2%-4%	—	Shen et al. (2018a)
2015-07-12	17:34/17:44	B4.0	416	N	17:37	6	35	1100	2.2	43–79	47–87	—	—	Shen, Song, and Liu (2018)
2019-03-08	03:07/03:18	C1.3	239	Y	03:33	7	35	1083–1366	—	62–66	69–87	—	—	Miao et al. (2021)
2019-03-08	03:07/03:18	C1.3	239	Y	03:35	7	25	536–656	—	65-66	35–43	—	—	Miao et al. (2021)
Range		BP/RE–M	174–1466	19/9		6–120	10–80	305–2394	0.1–5.8	25–550	24–429	1%–8%	0.1–4.0	
							Broad QFP wave trains [4]							
2010-09-08	23:00/23:33	C3.3	818		23:11	12	360[5]	370–650	0.1–0.4	36–212	80–140	10%–20%	—	Liu et al. (2012)
2012-04-24	07:38/07:45	C3.7	443		07:41	9	200	747	—	163	84—100	10%–35%	—	Shen et al. (2019)
2012-05-07	14:03/14:31	M1.9	665		14:06	20	90	664–1416	—	120–240	150	—	—	Kumar, Nakariakov, and Cho (2017)
2011-02-24	07:23/07:35	M3.5	1186		07:30	30	270	668	—	90	58	25%–35%	10-19	Zhou et al. (2021c)
2013-04-23	18:10/18:33	C3.0	403		18:16	7	140	1100	4.1	120	170	15%	12	Zhou et al. (2021b)
Range		C–M	403–1186			7–30	90–360	370–1416	0.1–4.1	36–240	58–170	10%–35%	10–19	

[1] Wave trains propagate along coronal loops.

[2] Brightening Patches

[3] Reconnection Events

[4] Wave trains propagate on the solar surface.

[5] By assuming that the wave train has a dome-shaped structure propagating in all directions.

than the beginning of the accompanying flares, but about 3–51 minutes earlier than the flare peak times. For QFP wave trains that occurred after the peak times of the accompanying flares, their beginning times are about 0–17 minutes later than the flares' peak times. In the 32 published QFP wave trains, there are 24 (8) cases that occurred before (after) the peak times of the accompanying flares. Therefore, we can reach a preliminary conclusion that most of QFP wave trains occur during the impulsive phase of flares (say, 24/32 = 75%). It seems that the energy level of flares are not the key physical condition for determining the start time of a QFP wave train, because for energetic GOES soft X-ray M class flares, the associated QFP wave trains can occur either in the impulsive (e.g., Kumar and Manoharan, 2013; Nisticò, Pascoe, and Nakariakov, 2014; Kumar, Nakariakov, and Cho, 2017; Zhou et al., 2021c) or the decay (e.g., Kumar, Nakariakov, and Cho, 2016; Ofman and Liu, 2018) phases. Whereas, the start times of QFP wave trains are probably associated with the durations of flares. Taken the cases accompanied by M class flares as examples, one can find that the impulsive phase of those flares with short durations tends to launch QFP wave trains during their impulsive phase (e.g., Kumar and Manoharan, 2013; Nisticò, Pascoe, and Nakariakov, 2014; Kumar, Nakariakov, and Cho, 2017; Zhou et al., 2021c), while those with long durations are likely to excite QFP wave trains during their decay phase (e.g., Kumar, Nakariakov, and Cho, 2016; Ofman and Liu, 2018). The lifetimes of the published QFP wave trains are typically in the range of 6–65 minutes, which is comparable to that of the impulsive phases of the accompanying flares (3–68 minutes). The longest duration among all published QFP wave trains was reported by Ofman and Liu (2018), which reached up to about 2 hours. In this case, the flare had a long impulsive phase of about 57 minutes, and the QFP wave train started at the beginning of the decay phase of the accompanying flare.

2.3. Classification

A typical QFP wave train is composed of multiple coherent and concentric arc-shaped wavefronts emanating successively near the epicenter of the accompanying flare and propagate outwardly either along or across coronal loops (e.g., Liu et al., 2011; Shen and Liu, 2012b; Liu et al., 2012; Shen et al., 2019). Imaging observational results based on high spatiotemporal resolution AIA data indicate that QFP wave trains might be broken down into two main categories based on their significant different physical characteristics: namely, narrow and broad QFP wave trains. The main distinct difference between the two types of QFP wave trains mainly include physical parameters of their observation waveband, propagation direction, angular width, intensity amplitude and energy flux (see Table 1). Narrow QFP wave trains are typically observed at the AIA 171 Å channel (occasionally appeared at the AIA 193 Å and 211 Å channels, see Liu et al., 2010; Shen et al., 2013a); they propagate along the apparent direction of the magnetic field within a relatively small angular extent of about 10–80 degree and typically result in intensity fluctuations with a small amplitude of about 1%–8% relative to the background corona (see the top row of Figure 1). The energy flux carried by narrow QFP wave trains is basically in the range of $0.1-4.0\times10^5$ erg cm^{-2} s^{-1} (e.g., Liu et al., 2011; Shen and Liu, 2012b; Shen, Song, and Liu, 2018). Broad QFP wave trains are frequently observed at the AIA's all EUV channels and can cause intensity fluctuations with a large amplitude of about 10%–35% relative to the background corona (see the bottom row of Figure 1). They propagate across magnetic field lines in the quiet-Sun region with a large angular extent of about 90–360 degree and carry an energy flux of about $10-19\times10^5$ erg cm^{-2} s^{-1} (Liu et al., 2012; Shen et al., 2019; Zhou et al., 2021b,c). In comparison, the two types for QFP wave trains have distinct different propagation preferences with respect to the magnetic field orientation, and the temperature coverage range of

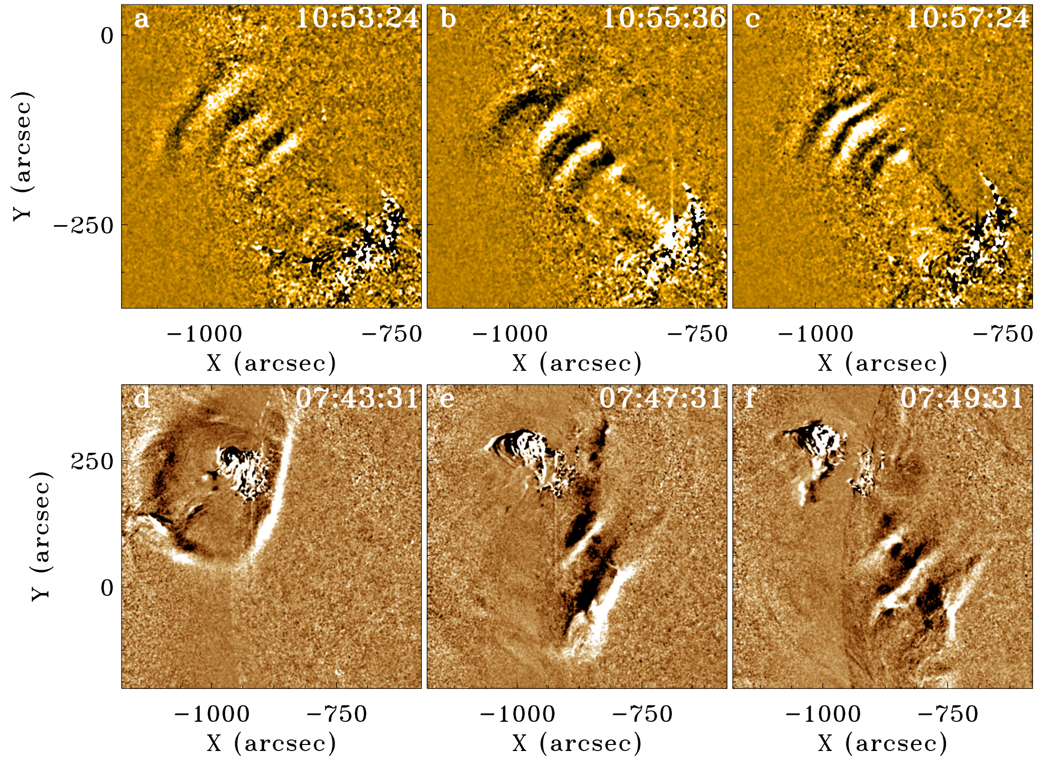

Figure 1. Examples for the two types of QFP wave trains. The top row shows the narrow QFP wave train on 2011 May 30 using the AIA 171 Å running-difference images, which occurred close to the east limb of the solar disk and was analyzed in details in Shen and Liu (2012b) and Yuan et al. (2013). The bottom row shows the broad QFP wave train on 2012 April 24 using the AIA 193 Å running-ratio images, which occurred on the east limb of the solar disk and propagated along the solar surface (see Shen et al., 2019, for details). The wave trains manifest as a chain of arc-shaped bright fronts propagating outwardly from the accompanying flare epicenter.

broad QFP wave trains is significantly wider than narrow QFP wave trains. In addition, all physical parameters including angular width, intensity amplitude and energy flux of broad QFP wave trains are evidently greater than those of narrow QFP wave trains.

Besides the above differences, the two types of QFP wave trains also show some similarities such as their physical parameters of propagation speed, deceleration, period and wavelength (see Table 1). Specifically, for narrow (broad) QFP wave trains, the physical parameters of propagation speed, deceleration, period and wavelength are in the ranges of 305–2394 (370–1416) km s^{-1}, 0.1–5.8 (0.1–4.1) km s^{-2}, 25–500 (36–240) seconds and 24–429 (58–170) Mm, respectively. In some events, broad QFP wave trains can be captured by coronal loops and become narrow QFP wave trains, which might mean the transformation of the former into the latter. For example, Shen et al. (2019) reported a broad QFP wave train propagating across the solar surface, whose east portion was trapped in a closed loop system and propagated at a speed relatively faster than the on-disk component. In other two events reported by Shen et al. (2018c) and Miao et al. (2019), the authors evidenced the transformation of single pulsed global EUV waves into narrow QFP wave trains along coronal loops. The successful capture of global EUV waves by coronal loops was also reported in Zhou et al. (2021b), where the trapped EUV wave showed an interesting firstly slowed down but then speeded up process owning to the variations of the physical parameters along the loop structure. In such a case, the global EUV waves are captured by coronal loops during their interaction, and the formation of the narrow QFP wave trains are probably due to the dispersive evolution of the initial disturbances caused by global EUV waves. In a one-dimensional numerical simulation performed by Yuan et al. (2015), the authors showed that weak, fast wave trains can be formed by dispersion due to a series of partial reflections and transmissions of single pulsed EUV wavefronts during their interaction with loop-like coronal structure (Yuan, Li, and Walsh, 2016). As what had been pointed out by Yuan et al. (2015), the successful capture of an EUV wave may require the width of the coronal loop system approximately equal to half of the initial width of the EUV wavefront. We note that fast-mode global EUV waves were evidenced to convert into slow-mode magnetosonic waves during their interaction with coronal loops (Chandra et al., 2016; Zong and Dai, 2017; Chandra et al., 2018). Chen et al. (2016) numerically studied this phenomenon and found that the conversion occurs near the plasma $\beta \approx 1$ layer in front of the magnetic quasi-separatrix layer; the authors argued that such a mode-conversion process can account for the so-called stationary wavefronts formed when global EUV waves passing through quasi-separatrix layers (Delannée and Aulanier, 1999).

2.4. Kinematics

Kinematics is the most fundamental property of any propagating disturbance, which is generally characterized by physical parameters of speed and acceleration. If the propagating disturbance is an MHD wave, it should exhibit wave phenomena such as reflection, refraction and diffraction effects during its interaction with coronal structures with a steep speed gradient (e.g., Shen and Liu, 2012a; Shen et al., 2013b). Therefore, one can simply base on the speed and propagation behavior to determine the physical nature of a propagating disturbance in the solar atmosphere. For example, if a propagating intensity disturbance in the solar atmosphere that exhibits wave phenomena and propagates at slow (fast) magnetosonic wave speed, one can simply say that the disturbance is probably a slow (fast) magnetosonic wave (e.g., Shen and Liu, 2012c).

For QFP wave trains, there are two frequently-used methods to measure their speeds. The most popular method is the generation of time-distance diagrams along straight paths or sectors across the wavefronts by composing the one-dimensional intensity profiles at different times along a specific path using running- or base-difference time sequence images (see Figure 2(a)). In a time-distance diagram, the wavefronts display as enhanced bright ridges, and the average speed can be obtained by fitting these ridges with a linear function, while the acceleration can be estimated by fitting the ridges with a quadratic function. The other method is the generation of a $k-\omega$ map using the method Fourier analysis of a three-dimensional data tube in (x, y, t) coordinates, where the field-of-view should cover the propagation region of the QFP wave train (see Figure 2(b)). The details of this method can be found in many papers (e.g., DeForest, 2004; Liu et al., 2011; Shen and Liu, 2012b). In the $k-\omega$ map, the wave signature is represented by a steep narrow ridge that describes the dispersion relation of the QFP wave train, and the slope of the ridge gives the average phase ($v_{ph} = \nu/k$) and group ($v_{gr} = d\nu/dk$) velocities (e.g., Liu et al., 2011; Shen and Liu, 2012b). The ridge in the $k-\omega$ map also reveals the frequency distribution in the QFP wave train, which exhibits as some discrete power peaks representing the dominating frequencies of the wave train (e.g., Shen, Song, and Liu, 2018; Shen et al., 2018a). For a specific dominating frequency, one can obtain the Fourier-filtered images with a narrow Gaussian function centered at the dominating frequency (see Figure 2 (c)).

As shown in Table 1 for the published events, the projection speeds of narrow and broad QFP wave trains are in the range of 305–2394 km s^{-1} and 370–1416 km s^{-1}, while their decelerations are in the the range of 0.1–5.8 km s^{-2} and 0.1–4.1 km s^{-2}, respectively. These results indicate that the deceleration of QFP wave trains is significantly strong, and it seems that the faster waves are accompanied by stronger decelerations, consistent with the statistical result of global EUV waves (Long et al., 2017a). The speed of QFP wave trains do not show any preferential correlation with neither successful nor failed solar eruptions. Specifically, the speeds of the six QFP wave trains that were not associated with CMEs (i.e., failed eruptions) are in the range of 322–1670 km s^{-1}, while that of the other events accompanied by CMEs (successful eruptions) are in a similar range of 305–2394 km s^{-1}. Even for events that are associated with fast CMEs whose average speeds are greater than 1000 km s^{-1}, the speeds of the accompanying QFP wave trains can either be slow (668 km s^{-1}; Zhou et al., 2021c) or fast (1860 km s^{-1}; Ofman and Liu, 2018). The speed of QFP wave trains does not show any preferential correlation with the energy class of the accompanying flares. For both low- and high-energy flares, the speeds of the accompanying QFP wave trains are all in the same range from several hundred to over 2000 km s^{-1}. These results might imply that the speed of QFP wave trains is mainly determined by the physical property of the medium in which they propagate, such as plasma density and magnetic strength as defined by the dispersion relation of fast magnetosonic waves. In addition, these results also suggest that QFP wave trains should be freely-propagating linear, or a slightly nonlinear fast magnetosonic waves, as suggested by the small Mach number (1.01) of a narrow QFP wave train (Zhou et al., 2021b).

2.5. Periodicity and Origin

The periodicity in QFP wave trains carries important physical information in the eruption source regions and the medium in which they propagate. Investigating the generation and characteristics of the periodicity in QFP wave trains can help us to probe the eruption mechanism of solar eruptions and the physical property of the supporting medium. Generally, the periods of a QFP wave train can be isolated by using the methods of Fourier analysis and wavelet analysis (Torrence and Compo, 1998, https://atoc.colorado.edu/research/wavelets). Sometimes, one can also directly measure the periods from time-distance diagrams. Based on the published events (see Table 1), the periods of narrow QFP wave trains are in a wide range of 25–550 seconds, while those of broad QFP wave trains are in the range of 36–240 seconds. Because the time cadence of the EUV channels of the AIA is 12 seconds, we are not able to detect periods lower than 24 seconds (Liu and Ofman, 2014). However, this insufficiency can be compensated by high temporal resolution radio observations. For example, some spatially unresolved events observed in radio similar to QFP wave trains demonstrated short periods of seconds (e.g., Karlický, Mészárosová, and Jelínek, 2013; Kolotkov, Nakariakov, and Kontar, 2018) and even subsecond (e.g., Mészárosová, Karlický, and Rybák, 2011; Yu and Chen, 2019). In addition, high temporal resolution data taken during solar eclipses is also important for detecting short periods of QFP wave trains (e.g., Williams et al., 2002; Katsiyannis et al., 2003; Samanta et al., 2016).

Observational studies showed that a QFP wave train often contains multiple periods. It has been confirmed in many events that some prominent periods of QFP wave trains are temporally correlated to QPPs in the accompanying flares, but the others are not (e.g., Liu et al., 2011; Shen and Liu, 2012b). In particular cases, the periods of a QFP wave train are all associated with the QPPs in the accompanying flare (e.g., Shen et al., 2013a, 2018a; Zhou et al., 2021c). However, there are still many cases whose periods are completely not associated with the accompanying flares (e.g.,

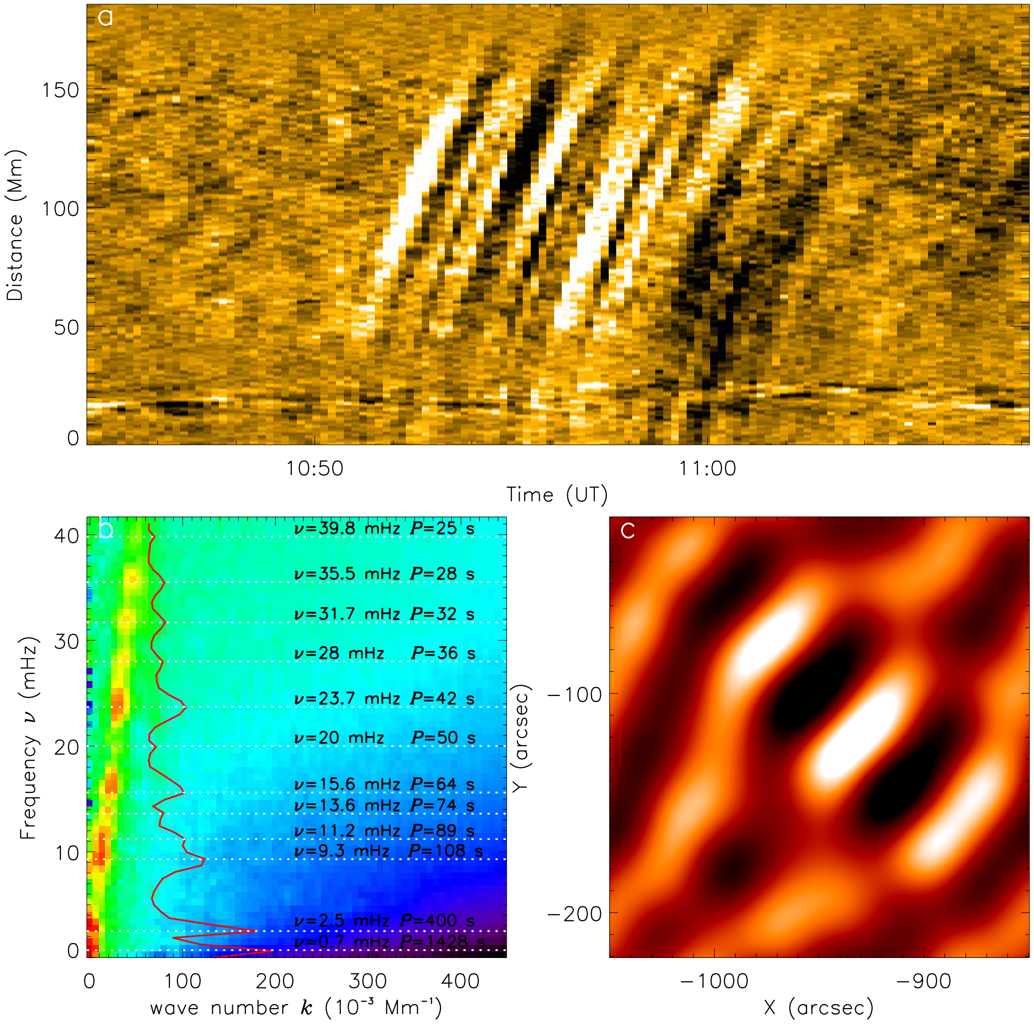

Figure 2. Kinematics analysis of the narrow QFP wave train on 2011 May 30. Panel (a) is the time-distance diagram along the propagation direction of the wave train, in which each bright intensity ridge represents a wavefront. Panel (b) is the $k-\omega$ map, in which the red curve shows the power peaks along the straight ridge. Panel (c) is a Fourier-filtered image around the dominating frequency of 15.6 Hz.

Shen, Song, and Liu, 2018; Shen et al., 2019). These results suggest that the periodicity origin of QFP wave trains should be diversified, and some of them are probably associated with flare QPPs.

Generally, flare QPP is loosely defined as the periodic intensity variations in flare light curves seen in a wide wavelength range from radio to gamma-rays, with characteristic periods ranging from a fraction of a second to several tens of minutes (Nakariakov et al., 2019). In addition, since a light curve is obtained by observing the Sun as a star, i.e., without spatial resolution, it is hard to say what kind of physical process is responsible for the appearance of QPPs in the light curve. Because of these reasons, so far scientists have proposed a handful of possible mechanisms to account for the generation of flare QPPs (see Nakariakov and Melnikov, 2009; Van Doorsselaere, Kupriyanova, and

Yuan, 2016; McLaughlin et al., 2018; Nakariakov et al., 2019; Kupriyanova et al., 2020; Zimovets et al., 2021, and references therein). As pointed out by Nakariakov and Melnikov (2009), the possible mechanisms for QPPs can be divided into two categories including pulsed energy release and MHD oscillations, and both can be relevant to the generation of QFP wave trains (Liu et al., 2011; Shen and Liu, 2012b; Shen et al., 2013a, 2018a). Pulsed energy release can take place in different situations and forms, but it is commonly associated with various nonlinear processes in magnetic reconnections, such as the dynamic evolution of plasmoids (e.g., Kliem, Karlický, and Benz, 2000; Ni et al., 2015; Liu, Chen, and Petrosian, 2013; Li et al., 2018b; Cheng et al., 2018; Miao et al., 2021), oscillatory reconnection (e.g., Craig and McClymont, 1991; McLaughlin et al., 2009; McLaughlin, Thurgood, and MacTaggart, 2012; McLaughlin et al., 2012; Hong et al., 2019; Xue et al., 2019; Thurgood, Pontin, and McLaughlin, 2017, 2019), and modulation resulting from external quasi-periodic disturbances (e.g., Nakariakov et al., 2006; Chen and Priest, 2006; Sych et al., 2009; Shen and Liu, 2012b; Jess et al., 2012; Jelínek and Karlický, 2019). MHD oscillations are relevant to the inherent physical properties of the wave hosts and their surrounding background medium, which can modulate flare energy release (or plasma emission) and therefore result in QPPs and QFP wave trains whose periodicities are prescribed either by certain resonances or by dispersive narrowing of initially broad spectra (Roberts, Edwin, and Benz, 1983; Foullon et al., 2005; Nakariakov and Melnikov, 2009).

Observationally, the periods of QFP wave trains are comparable to the typical period of flare QPPs, both are in the range of a few seconds to several minutes. In addition, while QFP wave trains are mainly observed in flare impulsive and decay phases, QPPs can appear in all flare stages from pre-flare to decay phases. In some cases, the two phenomena can occur simultaneously and with the similar periods, indicating their intimate physical connection. However, the detailed physical relationship between the two phenomena is yet to be resolved. In our view, QFP wave trains and the simultaneous flare QPPs might represent the different aspects of a common physical process such as pulsed energy release or MHD oscillations in flares. In terms of their origins, QFP wave trains could be viewed as a subclass of QPPs in general, since some proposed physical processes for the generation of QPPs might not cause simultaneous QFP wave trains (for example, the oscillation of coronal loops). In addition, in some studies (e.g, Mészárosová et al., 2009b; Kolotkov, Nakariakov, and Kontar, 2018), QPPs observed in radio were thought to be produced by the modulation of the local plasma density by QFP wave trains. In this case, QPPs are actually the result or the indirect signal of QFP wave trains. Because of these correlations, currently the proposed generation mechanisms for QFP wave trains are mainly analogy of those for flare QPPs (see Section 3 for details), since the latter have been investigated for more than half a century after the discovery (see Nakariakov and Melnikov, 2009; Van Doorsselaere, Kupriyanova, and Yuan, 2016; McLaughlin et al., 2018; Nakariakov et al., 2019; Kupriyanova et al., 2020; Zimovets et al., 2021, and references therein).

2.6. Amplitude and Intensity Profile

The physical nature of QFP wave trains is also characterized by the special variation pattern of the wavefront intensity profiles. For example, the intensity profile of global EUV and Moreton waves often show a simultaneous increasing width and decreasing amplitude during the initial propagation stage, consistent with the nature of nonlinear fast-mode or shock waves. For freely-propagating linear or weakly nonlinear fast-mode magnetosonic waves, the integral over the entire wave pulse should be constant, as what has been reported in several studies of global EUV waves (see Warmuth, 2015,

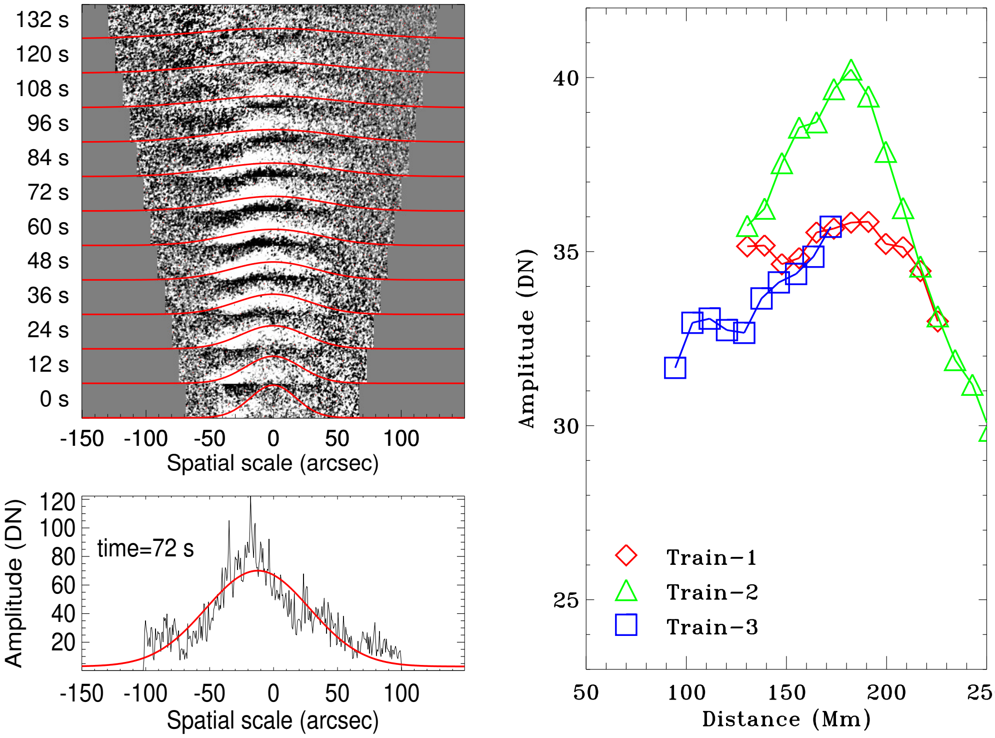

Figure 3. Intensity profile and amplitude of the narrow QFP wave train on 2011 May 30 (Yuan et al., 2013). The upper left panel is the temporal evolution of a specific wavefront at different times from the bottom up, while the left lower panel is the intensity profile of the wavefront at the time of 72 s. The red curves in the left panels are the corresponding Gaussian fitting curves of the intensity profiles. Right panel is the wave amplitudes of the three sub-QFP wave trains plotting as a function of the distance from the flare epicenter. The red diamonds, green triangles, and blue squares denote the parameters of Train-1, -2, and -3, respectively.

and references therein). Commonly, an intensity profile is defined as the intensity distribution along a specific path perpendicular to the wavefronts, which is a function of distance at a particular time. The intensity profile is often expressed as relative intensity change (i.e., I/I_0) or percentage change (i.e., $(I - I_0)/I_0$) over the pre-event background. Here, I and I_0 are the emission intensities at a certain time and the pre-event background emission intensity, respectively.

In practice, one often firstly generates a time-distance diagram and then obtains an intensity profile at a specific distance from the excitation source of a QFP wave train. In this case, the intensity profile is as a function of time as each wavefront traveling to the same distance. Observational results indicate that the peak intensity amplitudes of narrow and broad QFP wave trains are very different. Taking the published events as an example (Table 1), the values of the peak intensity amplitudes for narrow and broad QFP wave trains are in the ranges of 1%–8% and 10%–35%, respectively. It is noted that both narrow and broad QFP wave trains retain their variation ranges of the peak intensity amplitudes on stable levels for different events, and they do not show any notable physical connection with other parameters and the accompanying activities such as flares and CMEs. This may suggest that the intensity amplitudes of QFP wave trains are basically determined by the

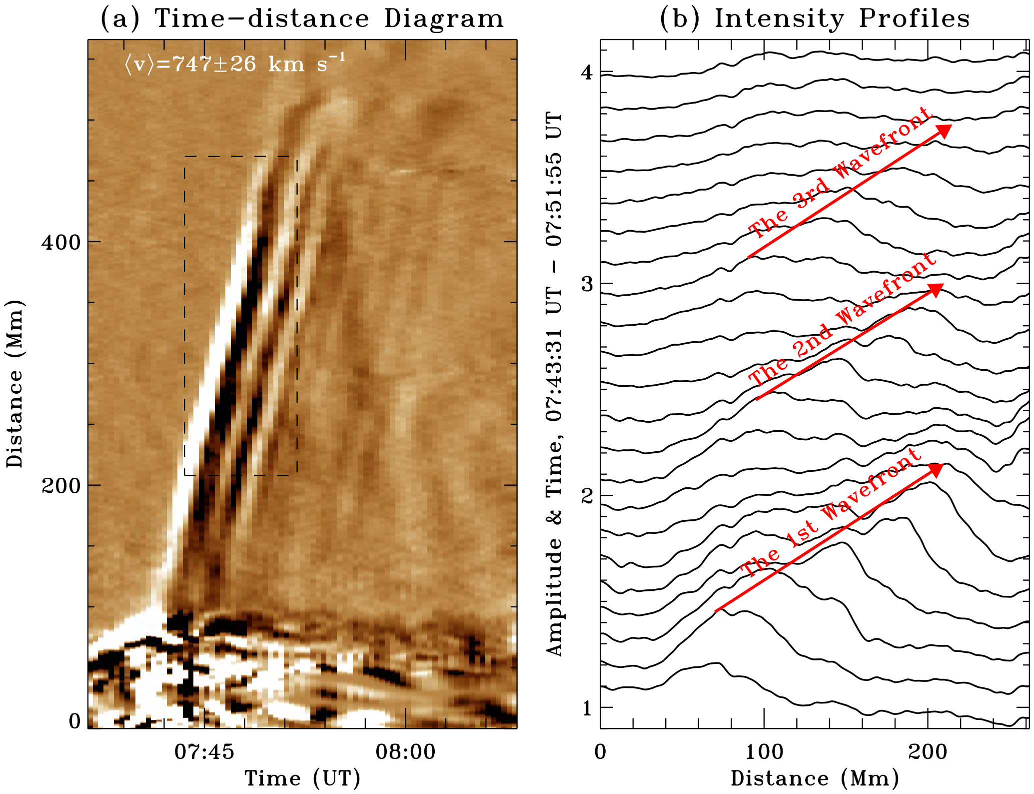

Figure 4. Intensity profile of the broad QFP wave train along the solar surface on 2012 April 24 (Shen et al., 2019). The left panel is a time-distance diagram made from AIA 193 Å running-ratio images, in which the black dashed box show the region where the intensity profiles are checked. The right panel shows the percentage intensity profiles of the wave train at different times based on the AIA 193 Å images, in which the red arrows indicate the first three wavefronts of the wave train.

physical parameters of the supporting medium. Since narrow QFP wave trains propagate along corona loops in which the magnetic field strength and plasma density are typically higher than the quiet-Sun region where broad QFP wave trains propagate, we propose that the peak intensity amplitudes of QFP wave trains are probably affected by physical parameters such as magnetic field strength and plasma density of the medium, and the propagation direction of QFP wave trains with respect to the magnetic field direction. The very different intensity amplitudes of the two types of QFP wave trains are probably mainly caused by their different propagation mediums. As found in Pascoe, Goddard, and Nakariakov (2017), the geometrical waveguide dispersion suppresses the nonlinear steepening of trapped narrow QFP wave trains, while broad QFP wave trains propagate in the quiet-Sun region does not experience dispersion and can steepen significantly into shocks.

For narrow QFP wave trains, Liu et al. (2011) and Shen and Liu (2012b) checked the intensity profiles in the propagation direction at several consecutive times and found that the spatial profiles can be fitted with a sinusoidal function, from which physical information of phase speed, period, wavelength and amplitude can be obtained. Moreover, a variation trend of weak broadening width and decreasing amplitude of the wavefronts can be identified during the propagation. In addition, the authors also checked the temporal variation of intensity profiles, which are then used to periodic analysis with the aid of the wavelet analysis technique. Shen et al. (2018b) reported the successive interactions of a narrow QFP wave train with two strong magnetic regions, they found that although the propagation direction was changed significantly after the interactions, the peak intensity amplitudes of the wave train remain at the same level. Yuan et al. (2013) traced the detailed temporal evolution of the intensity amplitude of the narrow QFP wave train on 2011 May 30, they found that the intensity amplitude underwent a first increasing and then decreasing process (see also Shen et al. (2018a) and the right panel of Figure 3). The authors further check the evolution of a specific wavefront, it was found that the wavefront extended gradually along the waveguide, and the transverse distribution of the intensity profile perpendicular to the wave vector exhibited as a Gaussian profile (see the left panels of Figure 3). For broad QFP wave trains, investigation of the variations of the intensity profiles are scarce. Shen et al. (2019) found the obvious broadening width and decreasing amplitude of the intensity profiles during the propagation of the broad QFP wave train on 2012 April 24 (see Figure 4), and the initial steep intensity profiles weakened quickly with increasing time (Kumar, Nakariakov, and Cho, 2017; Zhou et al., 2021c). In addition, the Alfvén Mach number of the broad QFP wave train was estimated to be 1.39 in Shen et al. (2019), indicating that the wave train was shocked significantly. These characteristics suggest that broad QFP wave trains are more similar to global EUV waves that are strong shocks during the initial stage but then quickly decay into linear or weak non-linear fast-mode magnetosonic waves (e.g., Shen and Liu, 2012c).

2.7. Thermal Characteristics

The AIA takes EUV images in seven channels covering a wide temperature range from 0.05 MK in the transition region to 20 MK in the flaring corona (Lemen et al., 2012). The EUV observing channels of AIA and their peak response temperatures are 304 Å (He II; $T \approx 0.05$ MK), 171 Å (Fe IX; $T \approx 0.6$ MK), 193 Å (Fe XII; $T \approx 1.6$ MK; Fe XXIV; $T \approx 20$ MK), 211 Å (Fe XIV; $T \approx 2$ MK), 335 Å (Fe XVI; $T \approx 2.5$ MK), 94 Å (Fe XVIII; $T \approx 6.3$ MK), 131 Å (Fe VIII; $T \approx 0.4$ MK; Fe XXI; $T \approx 10$ MK). Such a wide temperature coverage provides an unprecedented opportunity for diagnosing the thermal properties of QFP wave trains. Observations showed that narrow QFP wave trains are best seen in the AIA 171 Å channel (occasionally in the AIA 193 Å and 211 Å channels), indicating the narrow temperature dependence. On the contrary, broad QFP wave trains cover a wider temperature range, which can be observed in all AIA's EUV channels (best seen in 193 Å and 211 Å channels) as global EUV waves.

According to the explanation given by Liu et al. (2016), the narrow temperature dependence of narrow QFP wave trains are possibly due to two reasons. The first reason is owning to the physical property in the waveguide structures and the small intensity amplitude of narrow QFP wave trains. It is probably that the temperature of the wave-hosting plasma is close to the AIA 171 Å channel's peak response temperature. In addition, due to the small intensity amplitude of narrow QFP wave trains, they are hard to cause large temperature departures, unlike the large intensity amplitude cased by broad QFP wave trains. These possible conditions might account for the absence of narrow QFP wave trains in other AIA's EUV channels. The other reason is possibly due to the detectability of the detectors used for different AIA channels. Since the AIA 171 Å channel has a much higher photon response efficiency than any other channels by at least one order of magnitude, it is particularly sensitive to small intensity variations. The two reasons might work either separately or together. However, so far the exact reasons for the narrow temperature dependence of narrow QFP wave trains are still remain unclear.

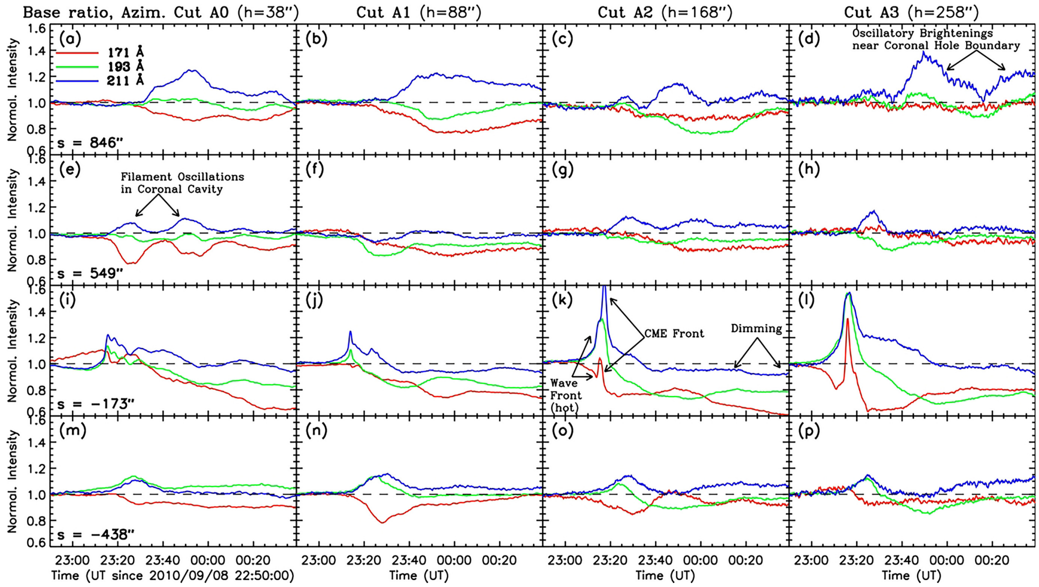

Figure 5. Base-ratio temporal profiles of emission intensity from azimuthal cuts at selected positions shown by the plus signs in Figure 4 in Liu et al. (2012). The general trend of darkening at 171 Å and brightening at 193 and 211 Å indicates heating in the EUV wave pulse ahead of the CME.

In the broad QFP wave train on 2010 September 08, Liu et al. (2012) observed the darkening at 171 Å and brightening at 193 Å and 211 Å of the wavefronts, which followed by a recovery in the opposite direction (see Figure 5). This process indicates the initial heating and then subsequent cooling of coronal plasma, and it can be interpreted by adiabatic heating due to compression followed by cooling with subsequent expansion/rarefaction driven by a restoring pressure gradient force. A similar signature was previously reported in global EUV waves (see Liu and Ofman, 2014, and references therein). Such an adiabatic compression caused by EUV waves can cause a considerable heating to the coronal plasma. For example, Schrijver et al. (2011) estimated that a mild adiabatic compression can result in a maximum density increase of about 10% and a temperature increase of about 7%.

2.8. Energy Flux and Coronal Heating

QFP wave trains carry energy away from their excitation sources, and the energy will be dissipated into the corona in which the waves propagate. Therefore, QFP wave trains can inevitably result in the heating of corona. Earlier observations have suggested that short period oscillations might make a significant contribution to the energy input of the coronal loops (e.g., Williams et al., 2001). The *SDO*/AIA observational results show that the energy flux carried by narrow and broad QFP wave trains are in the range of about $(0.1-4.0)\times10^5$ erg cm^{-2} s^{-1} and $(1-2)\times10^6$ erg cm^{-2} s^{-1}, respectively. Obviously, such an energy flux level is sufficient for sustaining the temperature of active region coronal loops, because the typical energy flux density requirement for heating coronal loops is estimated to be about 10^5 erg cm^{-2} s^{-1} (Withbroe and Noyes, 1977; Aschwanden, 2005). It is noted that the energy flux carried by broad QFP wave trains is at least one order of magnitude higher than that of narrow QFP wave trains. While narrow QFP wave trains are mainly attributed to the plasma heating of active region coronal loops, broad QFP wave trains are more efficient for the plasma heating in the quiet-Sun regions.

The energy flux carried by a QFP wave train can be estimated from the kinetic energy of the perturbed plasma that propagate with phase speed through a volume element. The energy of the perturbed plasma is

$$E = (\frac{1}{2}\rho v_1^2)v_{\rm gr}, \tag{1}$$

where v_1 is the disturbance speed of the locally perturbed plasma (Aschwanden, 2004), and $v_{\rm gr}$ is the group speed of the wave. Generally, for a rough estimation, one can use the measurable phase speed ($v_{\rm ph}$) of a dispersive wave train to replace the group speed ($v_{\rm gr}$) in equation (1). For non-dispersion wave trains, their phase speeds are equal to the values of the group speeds. In addition, in optically thin corona, the emission intensity I is directly proportional to the square of the plasma density ρ, i.e., $I \propto \rho^2$. Therefore, the density modulation of the background density $\frac{{\rm d}\rho}{\rho}$ can be written as $\frac{\rm dI}{2I}$. So, the energy flux of the perturbed plasma could be written as

$$E \geq \frac{1}{8}\rho v_{\rm ph}^3(\frac{\rm dI}{I})^2, \tag{2}$$

if we assume that $\frac{v_1}{v_{\rm ph}}$ is equal to or greater than $\frac{{\rm d}\rho}{\rho}$. Obviously, the energy flux estimated by this equation is determined by the coronal electron density ρ, perturbation amplitude of the emission intensity dI, and the phase speed $v_{\rm ph}$ of QFP wave trains. Since the intensity amplitude of narrow QFP wave trains are all in the range of 1%–8%, their corresponding energy fluxes estimated based on this equation are all on the order of $\approx 10^5$ erg cm^{-2} s^{-1}. On the contrary, the energy fluxes of broad QFP wave trains are about one order of magnitude higher than narrow QFP wave trains, which mainly result from their higher perturbation amplitude of the emission intensity (10%–35%). Here, we would like to point out that the estimated energy fluxes of QFP wave trains are underestimated, since the energy flux decreases quickly by orders of magnitude with height due to the spreading of the waves over a large area as a result of magnetic field divergence (Ofman et al., 2011). However, in practice, many estimations are based on the measurement of the intensity variation far away from their origin.

Observations showed that the occurrence of QFP wave trains are quite common in the corona, although many of them can still not be detected based on our current telescopes (Liu et al., 2016). Besides the association with relatively stronger flares (GOES soft X-ray C- and M classes), they can also be excited by many low-energy small flares (GOES soft X-ray B-class, Liu et al., 2010; Shen, Song, and Liu, 2018), small coronal brightenings (Shen et al., 2018b; Miao et al., 2020), and some signatures of possible magnetic reconnection events that can not even be recognized as flares in the GOES soft X-ray light curves (e.g., Qu, Jiang, and Chen, 2017; Li et al., 2018b). In addition, due to the large-scale propagation nature of QFP wave trains, they are expected to further trigger a plenty of subsequent nano-flares (Parker, 1988) or magnetic reconnection events in the corona with the complicated magnetic field, and these small flaring activities can probably further cause mini QFP wave trains. The energy dissipation of these undetected small-scale energetic events can further contribute more heating to the coronal plasma. Therefore, the contribution of QFP wave trains to the heating of coronal plasma might be more significant than our current perception (Van Doorsselaere et al., 2020).

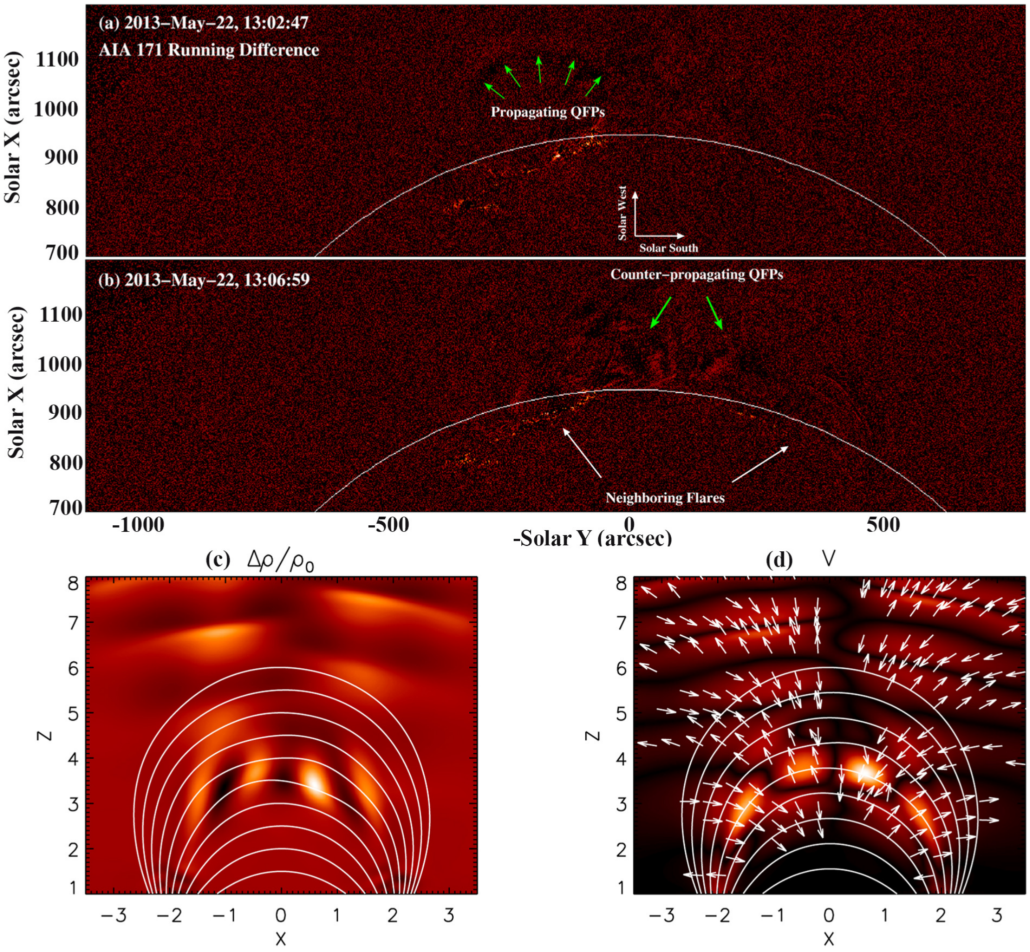

Figure 6. Interaction between counter-propagating narrow QFP wave trains in the same trans-equatorial coronal loop system on 2013 May 22 (Ofman and Liu, 2018). Panel (a) shows the outward-propagating QFP wave train from the primary flare, while panel (b) shows the interaction between the two counter-propagating QFP wave trains from the primary flare on the left and the second flare on the right. The green arrows in panel (a) indicate the outward-propagating wavefronts, the two white arrows in panel (b) indicate the locations of the two flares, and the two green ones indicate the interaction sites. The bottom row show the corresponding numerical simulation results of the event, in which the left and the right panels are the density and velocity perturbations in the $x-z$ plane at $y=0$, respectively. The magnetic field lines and velocity direction (right panel only) are overlaid as white curves and arrows, respectively.

2.9. Interaction with Coronal Structure

The highly structured corona is an inhomogeneous and anisotropic medium full of hot magnetized plasma, which strews with strong magnetic structures such as active regions, coronal holes and filaments. The Alfvén and fast-mode magnetosonic speeds at the boundary of these structures exist a strong speed gradient owning to the sudden changes of the magnetic field strength and plasma density. In addition, due to the gravitational stratification of the solar atmosphere, the plasma density falls off faster than the magnetic field strength in the low corona. Therefore, the

Alfvén and fast-mode magnetosonic speeds in the low corona increase with height on the quiet-Sun regions (Mann et al., 1999). The large-scale propagation of QFP wave trains will inevitably interact with regions of strong gradients of Alfvén and fast-mode magnetosonic speeds, and exhibit wave phenomena such as reflection, refraction and transmission effects. In addition, QFP wave trains can also excite oscillations of filaments and coronal loops during their propagation. The evidence of reflection, refraction and transmission effects of single pulsed global EUV waves have been reported in many studies; interested readers can refer to several recent reviews (Liu and Ofman, 2014; Warmuth, 2015; Long et al., 2017b; Shen et al., 2020).

For narrow QFP wave trains propagating along open funnel-like coronal loops, they do no interact with coronal structures. However, their propagation speed will be alerted by the increase of characteristic fast-mode speed with height. In some cases, QFP wave trains propagate along closed coronal loops, which will be reflected at the remote end of the loop system. Liu et al. (2011) observed the bidirectional propagation of QFP wave trains in a closed loop system that connects the conjugate flare ribbons, but the authors were unclear whether the bidirectional wave trains were generated independently or the same wave train reflected repeatedly between the conjugated loop footpoints. Ofman and Liu (2018) firstly reported the detection of counter-propagating QFP wave trains along the same closed trans-equatorial coronal loop system, which were associated with two flares successively occurred in two neighboring active regions on 2013 May 22. The counter-propagating QFP wave trains propagated at large speeds of the order of >1000 km s^{-1} and interacted at the middle section of the loop system, which further excited trapped kink-mode and slow-mode MHD waves in the coronal loops (see the top and the middle rows of Figure 6). The authors further performed a three-dimensional MHD simulation for this event, and the results are well in agreement with the observations (see the bottom row of Figure 6). The unambiguous reflection of a QFP wave train at the far end of the closed guiding coronal loop was observed by Shen et al. (2019), in their case the incoming and reflected waves propagate at a similar speed of about 900 km s^{-1}, and the guiding closed loop system exhibited obvious kink oscillations. In addition, single pulse global EUV waves trapped in closed loops are also observed in some events, which can also trigger the transverse kink oscillation of the guiding loops (Kumar and Innes, 2015; Zhou et al., 2021b).

When multiple active regions exist simultaneously on the Sun, they are often connected by interconnecting coronal loops. Shen et al. (2018b) reported a special narrow QFP wave train propagates along such closed interconnecting coronal loops, which passed through two different magnetic polarities and its propagation direction also changed significantly after each interaction with the magnetic polarities (see Figure 7). It was noted that the propagation speeds before and after each of interactions showed little difference. This interesting phenomenon was interpreted as the refraction effect of the QFP wave train due to the strong speed gradients around the strong magnetic regions on the path. The refraction of narrow QFP wave trains was also evidenced in Shen et al. (2018a), in which the north part of the wavefronts became broader and more bent during their passing through a strong magnetic field region. This also result in the different propagation speeds of the north (1485 km s^{-1}) and south (884 km s^{-1}) parts of the wave train.

For large-scale broad QFP wave trains propagating across the solar surface, they are more liable to interact with remote coronal structures. In the event studied by Shen et al. (2019), the on-disk propagating wavefronts interacted with a remote active region and showed a significant deformation around the middle section of the wavefronts, similar to what had been observed in global EUV wave (Li et al., 2012; Shen et al., 2013b; Yang et al., 2013). This phenomenon was interpreted as the transmission of a fast-mode magnetosonic wave through an active region in which the central

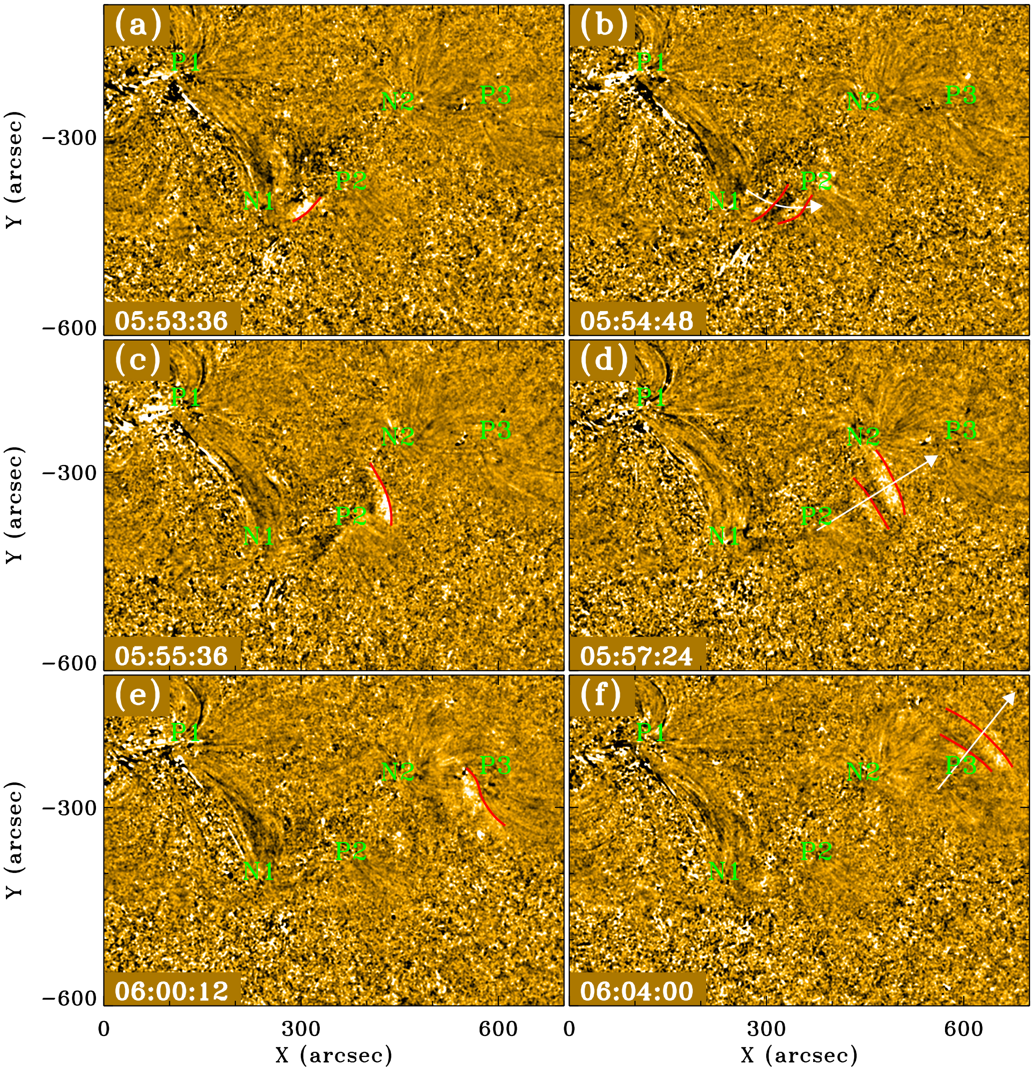

Figure 7. AIA 171 Å running-ratio images show the interaction of the narrow QFP wave train on 2011 February 14 to remote strong magnetic polarities (Shen et al., 2018b). The red curves marks the forefront of the wavefronts, and the white arrows indicate the propagation direction. The green symbols of P1, N1, P2, N2, and P3 mark the regions of strong magnetic fields, where letters P and N represent positive and negative magnetic polarities, respectively.

characteristic fast-mode magnetosonic wave speed is faster than the rim. It was noted that the QFP wave train also result in the transverse oscillation of a remote filament and a closed coronal loop. Liu et al. (2012) studied a limb event in which broad QFP wave trains were observed in both south and north directions over the limb. The propagating wavefronts caused an uninterrupted chain sequence of deflections and/or transverse oscillations of remote coronal structures including a flux-rope coronal cavity and its embedded filament with delayed onsets consistent with the wave travel time at an elevated speed (by ≈50%) within it, which indicates that the wavefronts penetrated through a topological separatrix surface into the cavity. The sequential response of remote coronal structures to the arrival of large-scale broad QFP wave trains reminds us that global EUV waves can also cause the chain of oscillations of separate filaments (Shen et al., 2014a) and even simultaneous transverse and longitudinal oscillations of different filaments (Shen et al., 2014b; Pant et al., 2016). Recently, Zhou et al. (2021c) observed the interaction of an on-disk broad QFP wave train with a remote low latitude coronal hole. During the successive transmission of the wavefronts through the coronal hole, intriguing refraction and reflection effects of the wave were identified around the coronal hole's west boundary. Since the coronal hole had a C-shape, the north and south arms of refracted wavefronts propagated towards each other and finally merged into one on the east side of the coronal hole. This phenomenon was interpreted as the interference effect of broad QFP wave trains, where the coronal hole acts as a concave lens. As mentioned above, observations and wave effects provide compelling evidence for supporting the interpretation of QFP wave trains as fast-mode magnetosonic waves.

2.10. Possible Manifestations of QFP Wave Trains in Radio

In addition to direct imaging observations in EUV wavelength band, quasi-periodic patterns or fine structures in radio dynamic spectrum are generally thought to be the possible indirect signals of spatially-resolved QFP wave trains in EUV. In principle, quasi-periodic fine structures in radio dynamic spectrum can be produced by means of coherent modulating of the local coronal plasma density (Chernov, 2010), and this periodic modulation can be result from the propagation of QFP wave trains in the low corona (Karlický, Mészárosová, and Jelínek, 2013; Karlický, 2013; Sharykin, Kontar, and Kuznetsov, 2018; Kolotkov, Nakariakov, and Kontar, 2018). Roberts, Edwin, and Benz (1983) developed a theory to interpret the observed short period (a second or sub-second) pulsations in type IV radio bursts by means of studying the development and propagation of an impulsively generated QFP wave train within a dense coronal loop, and the authors provided that an impulsive disturbance (such as a flare) can naturally gives rise to quasi-periodic pulsations owning to the dispersive evolution of the disturbance (Roberts, Edwin, and Benz, 1984). From then on, this theory has been applied to explain various quasi-periodic features in radio observations (see Li et al., 2020a, and references therein), such as type IIIb bursts (see the upper left panel in Figure 8, Kolotkov, Nakariakov, and Kontar, 2018), fiber bursts (see the upper right panel in Figure 8, Mészárosová, Karlický, and Rybák, 2011; Karlický, Mészárosová, and Jelínek, 2013), and wiggly zebra patterns (see the bottom panel in Figure 8, Kaneda et al., 2018). Both fiber bursts and zebra patterns are particular quasi-periodic fine structures in solar type IV radio bursts, while type IIIb bursts are fine spectral structuring in type III bursts characterized by multiple narrowband bursts with slow frequency drift (de La Noe and Boischot, 1972; Sharykin, Kontar, and Kuznetsov, 2018). These fine structures in radio spectrum are believed to be important sources of information for probing coronal plasma parameters and diagnosing flare processes (see Chernov, 2006, and references therein).

Solar radio observations typically have high temporal resolution but without spatial resolution. Even for compound interferometer observations, the spatial resolution is still very low. Therefore, the physical connections between various quasi-periodic fine structures in radio and spatially-resolved QFP wave trains in EUV are still unclear. Generally, one often connects quasi-periodic radio structures with QFP wave trains in EUV by comparing their physical parameters such as periods, speeds, and temporal correlation. In the series work published by Mészárosová et al., the periods of the radio pulsations are in the range of 60–80 and 0.5–1.9 seconds. The longer periods are similar to those measured in spatially-resolved EUV observations of QFP wave trains, while

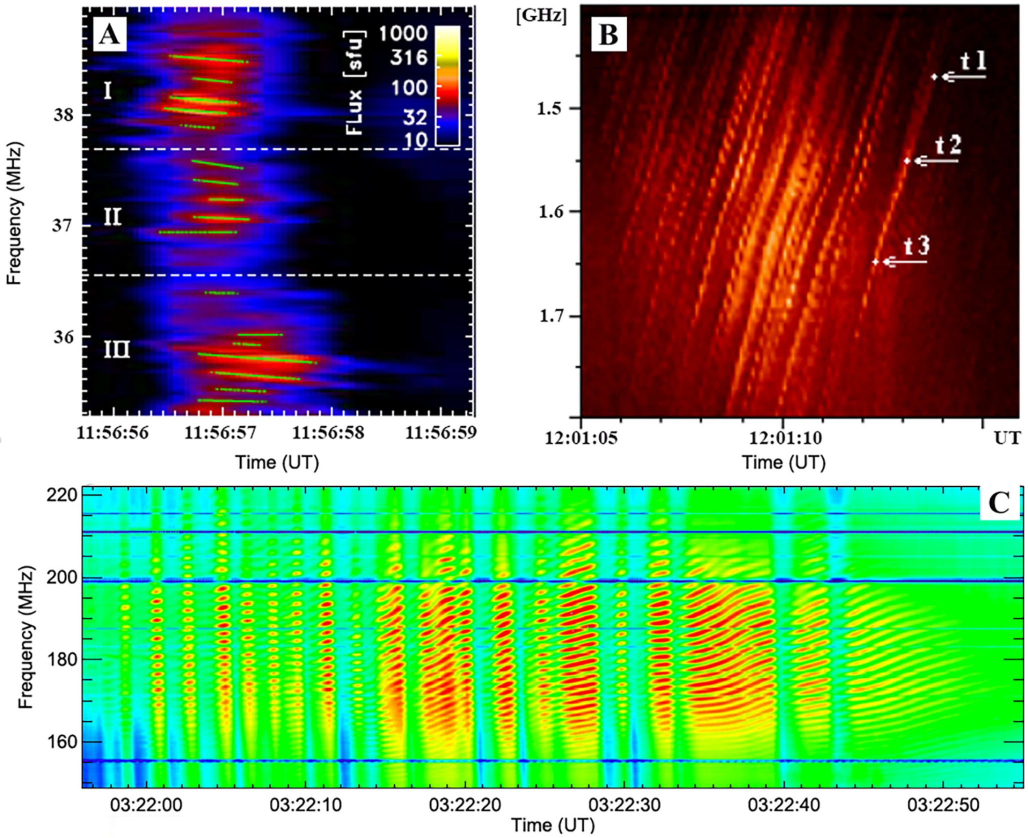

Figure 8. Candidate signatures in radio dynamic spectrums for coronal QFP wave trains. The upper left panel shows the dynamic spectrum of a type III radio burst occurred on 2015 April 16 and observed by the LOFAR in the frequency band of 35–39 MHz, in which the fine horizontal striae that can be fitted by a linear function (green lines) are the so-called type IIIb radio bursts. The regions of apparent clustering of the striae into three distinct groups are indicated by " I," " II," and " III and separated by the horizontal dashed lines (Kolotkov, Nakariakov, and Kontar, 2018). The upper right panel shows an example of radio fiber bursts on 1998 November 23 (Karlický, Mészárosová, and Jelínek, 2013), which was observed by the Ondřejov radio spectrograph (Jiricka et al., 1993). The bottom panel shows an example of radio zebra patter structures in a type IV radio burst on 2011 June 21 (Kaneda et al., 2018), which was observed by the Assembly of Metric-band Aperture Telescope and Real-time Analysis System (Iwai et al., 2012).

the short ones are unclear because current AIA EUV observations can not detect periods lower than 24 seconds (Liu and Ofman, 2014). Similar physical parameters are also derived from the observations of type IIIb radio bursts (Sharykin, Kontar, and Kuznetsov, 2018). For example, Kolotkov, Nakariakov, and Kontar (2018) studied the type IIIb radio bursts observed in a dynamic spectrum of a type III radio burst (see also Karlický, Mészárosová, and Jelínek, 2013; Sharykin, Kontar, and Kuznetsov, 2018). The authors proposed that the formation of the observed type IIIb radio bursts were probably caused by the modulation of the field-aligned propagating electron beam by a QFP wave train along the same bundle of funnel-like coronal loops. Therefore, the observed radio emissions in the type III radio burst also carry the same periodic information of the QFP wave train (see Figure 9). Based on this scenario, the authors further derived the physical parameters

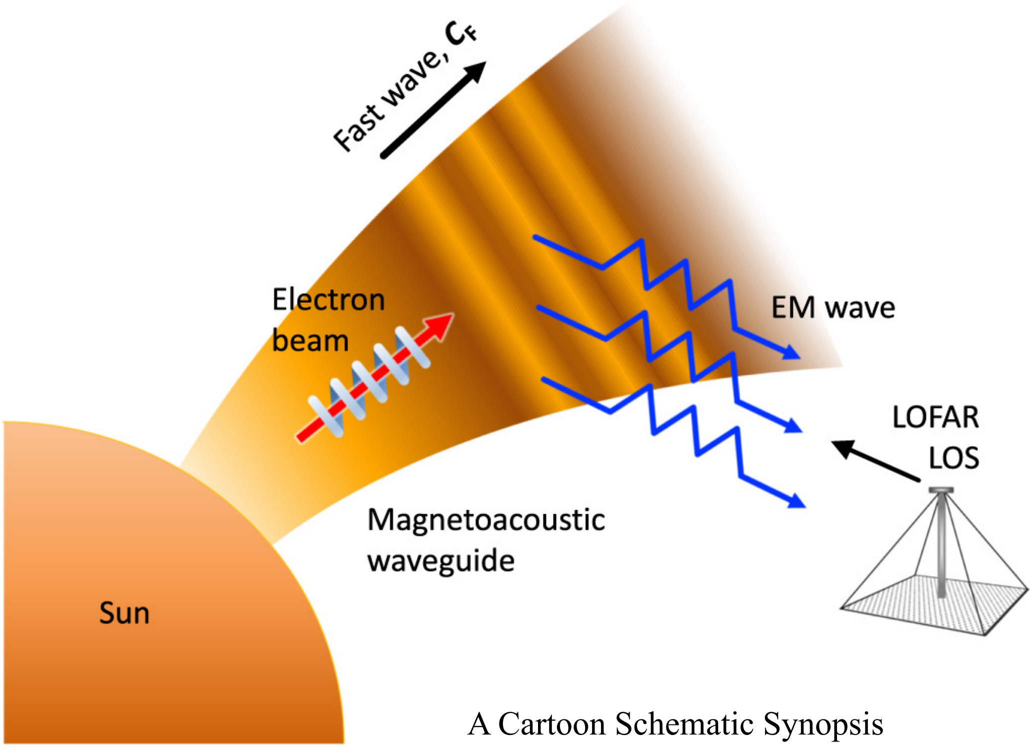

Figure 9. A schematic synopsis illustrates a scenario for the generation of quasi-periodic striations (type IIIb bursts) in the dynamic spectrum of type III bursts by a QFP wave train (Kolotkov, Nakariakov, and Kontar, 2018).

including speed, period, and amplitude of the possible QFP wave train, and their corresponding values are respectively about 657 km s^{-1}, 3 seconds, and a few per cent, in agreement with those detected in spatially-resolved QFP wave trains in EUV observations.

Theoretically, the time signature of an impulsively generated QFP wave train propagating along coronal loops with different density contrast ratios is expected to produce a characteristic tadpole wavelet spectrum, i.e., a narrow-spectrum tail precedes a broad-band head, which indicates that the instantaneous period of the oscillations in the wave train decreases gradually with time (Nakariakov et al., 2004). In observation, the possible QFP wave train detected in the solar eclipse on 1999 August 11 does show such a special signature (Katsiyannis et al., 2003). In some studies, if a tadpole wavelet spectrum can be observed in radio observations, one often speculates the appearance of a possible QFP wave train in the low corona, even though the wave signature does not observed in EUV imaging observations. For example, Mészaárosová et al. detected similar tadpole wavelet spectrum in solar decimetric type IV radio bursts, and they therefore interpreted the detected radio pulsations as the results of possible QFP wave trains traveling along loops through the radio source and modulating the gyrosynchrotron emissions (e.g., Mészárosová et al., 2009a,b; Mészárosová, Karlický, and Rybák, 2011). In combination with imaging observations and radio interferometric maps, Mészárosová et al. (2013) showed that a radio source that exhibits the wavelet tadpole feature was located at the null point of a fan-spine structure in the low corona, and the author suggested that this might imply the passage of a QFP wave train through there.

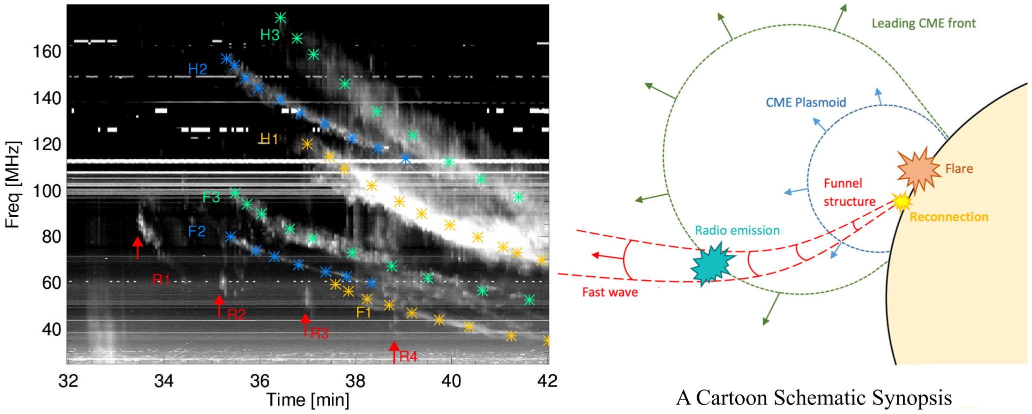

Figure 10. The left panel is the Learmonth radio spectra on 2014 November 03, which shows the discrete regions of enhanced emissions (radio sparks) in association with a type II radio burst. These radio sparks are proposed to be caused by the interaction of a QFP wave train to the leading edge of the accompanying CME (Goddard et al., 2016). The three lanes of fundamental type II radio bursts are indicated by F1, F2 and F3, while the corresponding harmonic emission are indicated by H1, H2 and H3, respectively. The small radio sparks are indicated by the red arrows and symbols R1, R2, R3 and R4. The time axis refers to the time elapsed since 22:00 UT. The right panel is a schematic synopsis for illustrating the generation of the radio sparks in the radio spectrum.

In the above mentioned studies, although in radio observations the authors detected similar physical parameters (e.g., period and speed) as those observed in spatially-resolved QFP wave trains in EUV, and similar characteristic tadpole wavelet spectrum as predicted by the theory, it is also unclear whether various types of quasi-periodic radio features truly result from the modulation of the local coronal plasma by QFP wave trains. Firstly, in all the above studies, the authors did not observe the simultaneous appearance of spatially-resolved QFP wave trains. Vice versa, most QFP wave trains in EUV do not be accompany by quasi-periodic radio fine structures. Secondly, in practical observations, the wavelet spectrums of spatially-resolved QFP wave trains in EUV do not exhibit the tadpole feature.

Recently, Goddard et al. (2016) observed a chain of discrete, quasi-periodic radio sparks preceding a type II radio burst, which were evidenced to be associated with a CME and an ambiguous QFP wave train in the low corona. The authors found that the moving speeds and heights of the radio sparks are comparable to the CME leading edge in time, and the period of the radio sparks is similar to that of the QFP wave train. Therefore, they interpreted the observed radio sparks as the result of the interaction between the QFP wave train and the CME leading edge (see Figure 10). In some spatially-resolved QFP wave trains in EUV, the generation of QFP wave trains are found to be highly correlated in start time with radio bursts (Yuan et al., 2013; Shen et al., 2018a), or their periods are similar to the associated quasi-periodic type III radio bursts (Kumar, Nakariakov, and Cho, 2017). Type III radio bursts are typically associated with electron beams accelerated to small fractions of light speed by magnetic reconnection, and their appearance often suggests the bursty energy releases in the low corona. Therefore, in some studies the generation of QFP wave trains are suggested to be caused by the dispersive evolution of impulsively generated broadband disturbances (e.g., Yuan et al., 2013; Kumar, Nakariakov, and Cho, 2017).

3. Theory and Modeling

As a booming research field in solar physics, corresponding theory and numerical simulation have made significant achievements since the discovery of QFP wave trains. Although there are various aspects that have not yet been fully addressed, the current numerical and analytical results have been in reasonably good agreement with observations, including the morphology, periodicity, velocity, as well as other properties (e.g., Ofman et al., 2011; Ofman and Liu, 2018; Pascoe, Nakariakov, and Kupriyanova, 2013; Pascoe, Goddard, and Nakariakov, 2017). In terms of the generation mechanism, studies are mainly focussed on two interconnected scenarios similar to the generation of flare QPPs (see also Section 2.5). The first scenario is that a QFP wave train can be formed due to the dispersive evolution of an impulsively generated broadband perturbation, and the wave periodicity is determined by the physical properties of the waveguide and its surrounding (e.g., Roberts, Edwin, and Benz, 1983, 1984; Murawski and Roberts, 1994; Nakariakov et al., 2004). The second scenario is that a QFP wave train can be attributed to pulsed energy release involving in the magnetic reconnection process, and the wave periodicity is basically determined by the wave source (e.g., Yang et al., 2015; Takasao and Shibata, 2016).

3.1. Dispersion Evolution Mechanism

The corona hosts many filamentary structures of enhanced plasma density (low Alfvén speed) with respect to the background, such as coronal loops, fibrils, and plumes. These coronal structures act as waveguides for fast propagating magnetosonic waves that are highly dispersive when their wavelengths are comparable or longer than the widths of the waveguides, and the wave dispersion properties are seriously affected by the parameters of the waveguide and the surrounding (e.g., Lopin and Nagorny, 2015, 2017, 2019). Since a fast-mode propagating magnetosonic wave with different frequencies travel at different group speeds in an inhomogeneous structure, an impulsively generated broadband perturbation, i.e., a Fourier integral over all frequencies and wave numbers (wave packets; such as a flare), can naturally give rise to the generation of QFP wave trains in a waveguide at certain distance from the initial site (Roberts, Edwin, and Benz, 1983). In the coronal

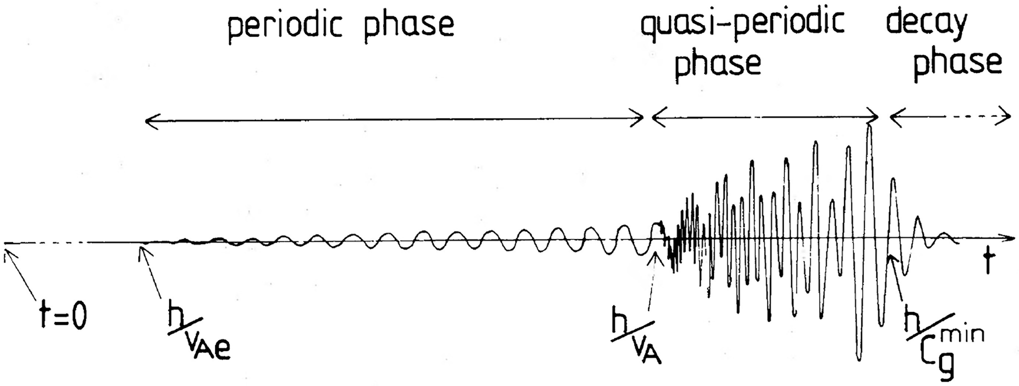

Figure 11. A sketch of the evolution of a fast sausage wave evolved from an impulsively generated perturbation in the low-β extreme, which exhibits three distinct phases including periodic, quasi-periodic, and decay phases (Roberts, Edwin, and Benz, 1984). h is the distance away from the initial perturbation, $v_{\rm A}$ and $v_{\rm Ae}$ are respectively the internal and external Alfvén speeds of the slab, and $c_{\rm g}^{\rm min}$ is the minimum in the group velocity.

context, the speeds of fast propagating magnetosonic waves along coronal loops are on the order of Alfvén speed, which can vary from the minimum Alfvén speed inside of a loop to the maximum Alfvén speed outside of the loop (Aschwanden, 2005). Roberts, Edwin, and Benz (1983, 1984) analytically analyzed the development of QFP wave trains in coronal loops that were modeled as straight slabs with sharp boundaries. The authors found that the group speeds of QFP wave trains with longer wavelength spectral components propagate faster than those with shorter ones, and they qualitatively predicted that a QFP wave train will experience three distinct phases including periodic, quasi-periodic, and decay phases (see Figure 11).

The periodic phase starts at some distance h from the perturbation source with low amplitude and constant frequency, whose start and end times are respectively at h/v_{Ae} and h/v_{A}, where v_{Ae} and v_{A} are the external and internal Alfvén speeds of the waveguide, respectively. During the periodic phase, the oscillation amplitude steadily grows, and the start (end) time represents the arriving time of the fastest (slowest) signal component of the perturbation. The quasi-periodic phase after the periodic phase but before the decay phase, which starts at the time h/v_{A} and ends at a time $h/c_{\mathrm{g}}^{\mathrm{min}}$, where $c_{\mathrm{g}}^{\mathrm{min}}$ is the minimum group speed. It can be seen that the end time of the quasi-periodic phase is determined by the minimum group speed of the perturbation. The quasi-periodic phase has a larger amplitude and high frequency than the earlier periodic phase, which makes itself most detectable in observations. After the quasi-periodic phase is the decay phase, during which the amplitude of the perturbation declines quickly (see Figure 11). Initial numerical studies have been performed successfully to study these distinct phases of QFP wave trains (Murawski and Roberts, 1993a,b,c, 1994; Murawski, Aschwanden, and Smith, 1998), and the average periods are found to be of the order of the wave travel time across the waveguides, in agreement with previous analytical results (Roberts, Edwin, and Benz, 1983, 1984).

Nakariakov et al. (2004) numerically modeled the developed stage of a QFP wave train in a smooth slab of a low β plasma. They found that the quasi-periodicity is owning to the geometrical dispersion of the wave train and is determined by the transverse profile of the loop, and the period and the spectral amplitude are determined by the steepness of the transverse density profile and the density contrast ratio in the loop. In addition, the authors further analyzed the time-dependent power spectrum using the wavelet transform technique, which yields that the QFP wave train has a special tadpole shape in the Morlet wavelet spectrum, i.e., a narrow-spectrum tail precedes a broad-band head (see the left column of Figure 12). Comparing with Roberts, Edwin, and Benz (1984), the periodic and quasi-periodic phases correspond respectively to the tadpole tail and head, while the decay phase corresponds to the tadpole head maximum. The typical feature of tadpole wavelet spectrum has been used as a characteristic signature for identifying the presence of possible QFP wave trains in both observational and numerical studies, when direct imaging of QFP wave trains in EUV were unavailable (e.g., Mészárosová et al., 2009b, 2013; Karlický, Jelínek, and Mészárosová, 2011; Karlický, Mészárosová, and Jelínek, 2013; Jelínek, Karlický, and Murawski, 2012; Mészárosová et al., 2014). Recently, Kolotkov et al. (2021) modeled the linear dispersively evolving of QFP wave trains in plasma slabs with varying steepness of the transverse density profile, in which they showed that the development of a QFP wave train evolved from an initial impulsive perturbation undergoes three distinct phases fully consistent with that qualitatively predicted by Roberts, Edwin, and Benz (1983, 1984). In contrast to wave trains in smooth waveguides that produce the tadpole structures (Nakariakov et al., 2004), it is interesting that the wavelet power spectrum develops into a boomerang structure that has two pronounced arms in the longer- and shorter-period parts of the spectrum (see the right column of Figure 12). The authors further pointed out that the duration of different phases and how prominent they are in the whole time profile of the wave train depend on the parameters of the waveguide and the wave perturbation symmetry, and this characteristic signature can be used as a seismological indicator of the transverse structuring of a hosting plasma waveguide. It should be pointed out here that in practice most direct imaging of QFP wave trains in EUV do not show such a tadpole or boomerang structure in the wavelet spectrum. It seems that such a special tadpole wavelet spectrum is more preferable to appear in QFP wave trains with shorter periods of a few seconds (Katsiyannis et al., 2003).

In a series of recent theoretical works, attentions are mainly payed to the geometric effects (e.g., Jelínek, Karlický, and Murawski, 2012; Pascoe, Nakariakov, and Kupriyanova, 2013; Mészárosová et al., 2014; Shestov, Nakariakov, and Kuzin, 2015) and transverse plasma density structuring (e.g., Yu et al., 2015, 2016, 2017; Li et al., 2018a) of the waveguide on the formation and evolution of QFP wave trains. In particular, Oliver, Ruderman, and Terradas (2014, 2015) analytically demonstrated that QFP wave trains experience stronger attenuation for longer axisymmetric (or shorter transverse) perturbations, while the internal to external density ratio has a smaller effect on the attenuation. For typical coronal loops, axisymmetric (transverse) wave trains travel at a speed of 0.75–1 (1.2) times of the Alfvén speed of the waveguide and with periods of the order of seconds. To efficiently excite a QFP wave train, a larger spatial extent (compared to the waveguide width) and a longer temporal duration of the initial impulsive driver are probably necessary conditions (e.g., Nakariakov, Pascoe, and Arber, 2005; Yu et al., 2017; Goddard, Nakariakov, and Pascoe, 2019). Shestov, Nakariakov, and Kuzin (2015) concluded that the characteristics of QFP wave trains are depended on the fast-mode magnetosonic speed in both the internal and external mediums, the smoothness of the transverse profile of the equilibrium quantities, and also the spatial size of the initial impulsive perturbation.

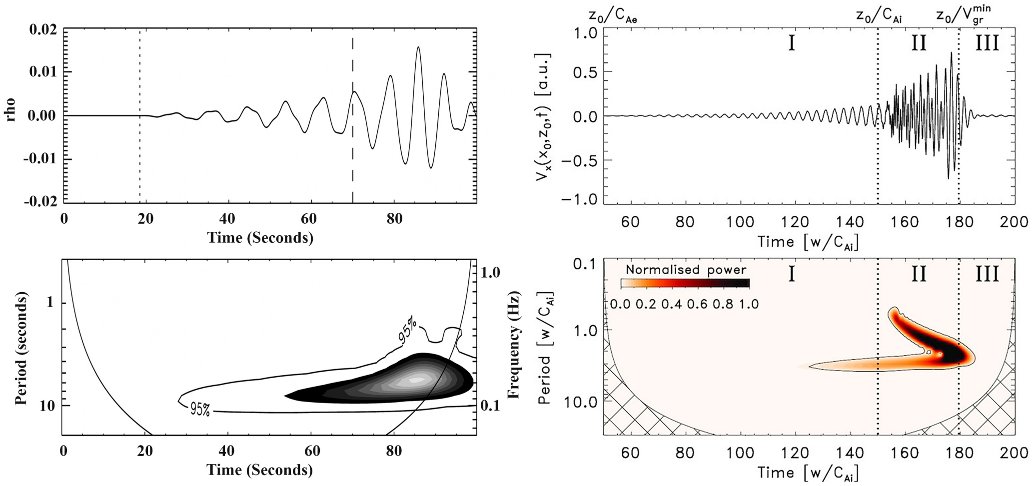

Figure 12. Wavelet power spectrums of dispersively formed QFP wave trains in waveguides. The left column is a numerical simulation of an impulsively generated QFP wave train along a coronal loop with a smooth boundary, in which the top panel shows the density variation profile of the wave train, while the bottom panel is the wavelet transform analysis of the signal, demonstrating the characteristic tadpole wavelet signature. The vertical lines in the top panel show the pulse arrival time if the density was uniform; the dotted line using the external density; and the dashed line the density at the center of the structure (Nakariakov et al., 2004). The right column shows the time profile (top) and wavelet power spectrum (bottom) of a fully developed fast sausage wave train in a steep plasma waveguide. The three distinct developing phases of the wave train are indicated in the figure, and the wavelet spectrum shows a boomerang shape (Kolotkov et al., 2021).

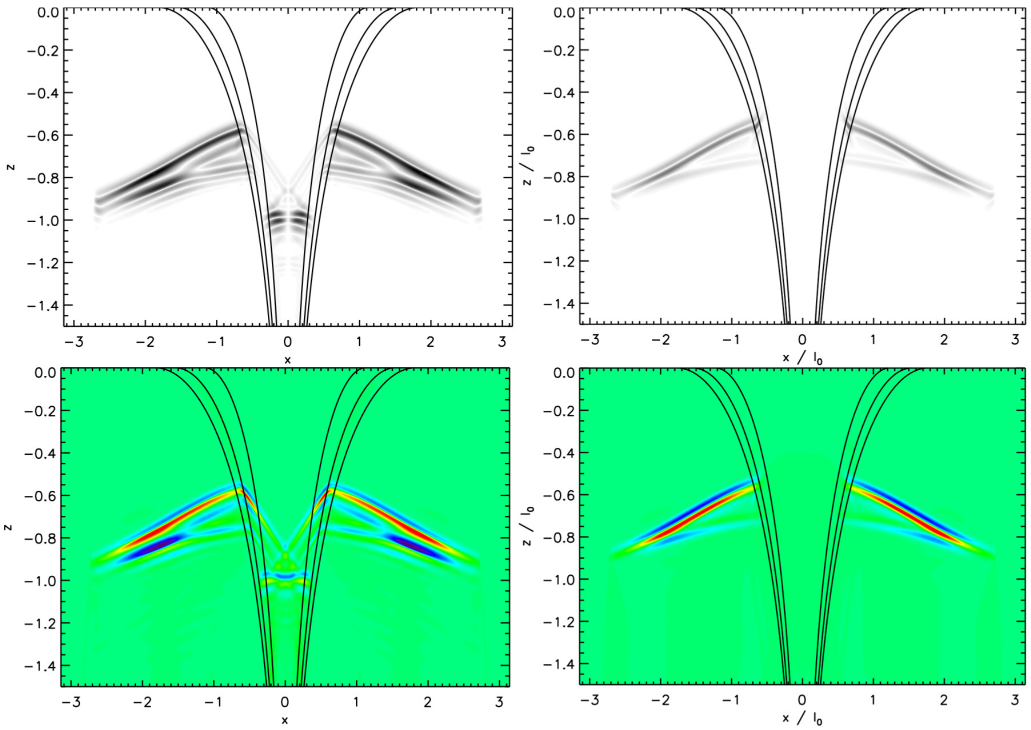

Figure 13. Numerical simulation results of developing QFP wave trains in funnel geometry overdense waveguide (left column, from the paper of Pascoe, Nakariakov, and Kupriyanova, 2013) and underdense anti-waveguide (right column, from the paper of Pascoe, Nakariakov, and Kupriyanova, 2014). For each column, the top (bottom) panels shows the velocity (density) perturbations, while the line contours outline the equilibrium density profile.

The propagation of QFP wave trains can be both trapped and leaky in nature, especially for axisymmetric sausage waves of long wavelengths in smooth slabs (Murawski and Roberts, 1993b). An initial impulsive perturbation can result in the propagation of both trapped and leaky waves inside and outside of a coronal loop, respectively. The trapped and leaky waves occur as a result of a total reflection and refraction around the boundary of a waveguide (Murawski and Roberts, 1994; Pascoe, Nakariakov, and Kupriyanova, 2014). In contrast to previous studies in which coronal loops are considered as straight slabs or cylinders, Pascoe, Nakariakov, and Kupriyanova (2013, 2014) performed two-dimensional numerical simulations to study the evolution of impulsively generated QFP wave trains in a funnel geometry resembling active region coronal loops and coronal holes (e.g., Liu et al., 2011; Shen and Liu, 2012b; Shen, Song, and Liu, 2018), where the funnel expands with height and with a field-aligned enhanced or reduced plasma density in comparison to the surrounding. For both an overdense waveguide and an underdense anti-waveguide, trapped and leaky QFP wave trains appear respectively inside and outside of the waveguides, and the leaky QFP wave trains experience refraction that turns the local wave vector in the vertical direction due to the refraction effect caused by the variation in the magnetic field strength with height (see Figure 13). In comparison, both the trapped and leaky wave trains propagate in perpendicular directions in the case of straight waveguides. In contrast to the case of an overdense waveguide, the leaky wave train in the case of an underdense anti-waveguide is much more pronounced than the

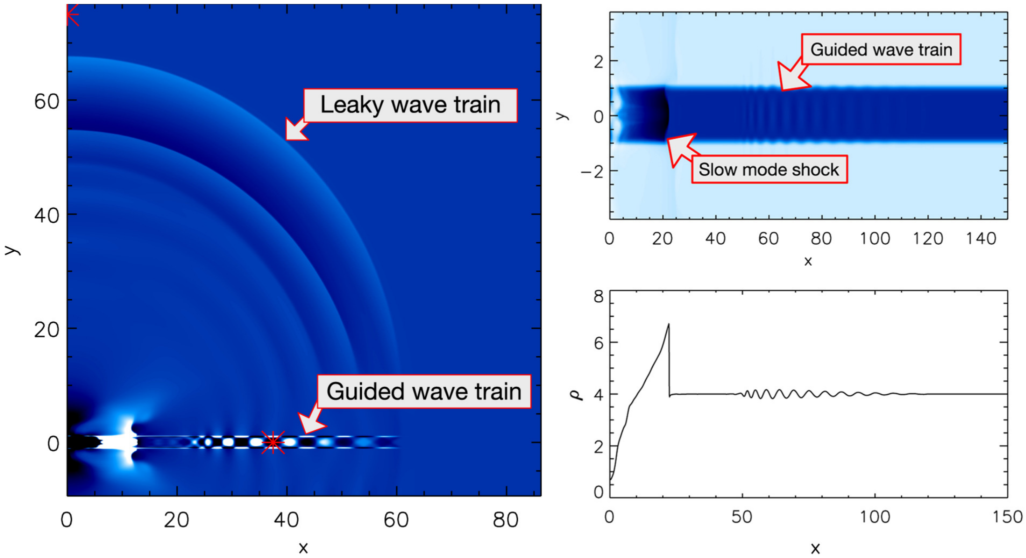

Figure 14. Numerical study on the nonlinear steepening of the trapped and leaky wave trains inside and outside a straight slab (Pascoe, Goddard, and Nakariakov, 2017). The left panel shows the density perturbations, in which the trapped and leaky wave trains are indicated by the two arrows. The upper right panel shows the density of the slab, in which guided a slow-mode shock and a fast-mode wave trains can be identified in opposite directions along the slab. The low right panel shows the intensity profile at the center of the slab (y=0) as shown in the upper right panel.

corresponding trapped component. In addition, the trapped wave train in the case of an underdense anti-waveguide exhibits less dispersive evolution than that in the case of an overdense waveguide.

It has been evidenced in numerical simulation that the propagation properties of the trapped and leaky QFP wave trains are completely different. Pascoe, Goddard, and Nakariakov (2017) showed that the nonlinear steepening of the trapped wave train is suppressed by the geometrical dispersion associated with the waveguide, while the leaky wave train does not undergo dispersion once it leaves the waveguide and therefore it can steepen into shock waves (see Figure 14). The formation of shock waves from the leaky wave train could possibly account for the direct observation of broad QFP waves trains in the low corona (e.g., Liu et al., 2012; Shen et al., 2019; Zhou et al., 2021b,c), or quasi-periodic type II radio bursts in association with one flare. Nisticò, Pascoe, and Nakariakov (2014) reported an interesting event in which both narrow and broad QFP wave trains are possibly simultaneously detected in one event, and their observations are thought to be consistent with the trapped and leaky wave trains as what had been identified in their numerical simulations (Pascoe, Nakariakov, and Kupriyanova, 2013; Pascoe, Goddard, and Nakariakov, 2017).

3.2. Pulsed Energy Excitation Mechanism

Pulsed energy excitation mechanisms of QFP wave trains relate to the magnetic reconnection process that converts magnetic field energy to plasma kinetic, thermal, and non-thermal high energy particle energies (e.g., Fletcher et al., 2011; Shibata and Magara, 2011; Lin et al., 2015). Magnetic reconnection is a complex and highly nonlinear process referring to the breaking and reconnecting of oppositely directed magnetic field lines in a highly conducting plasma due to finite resistivity (Priest

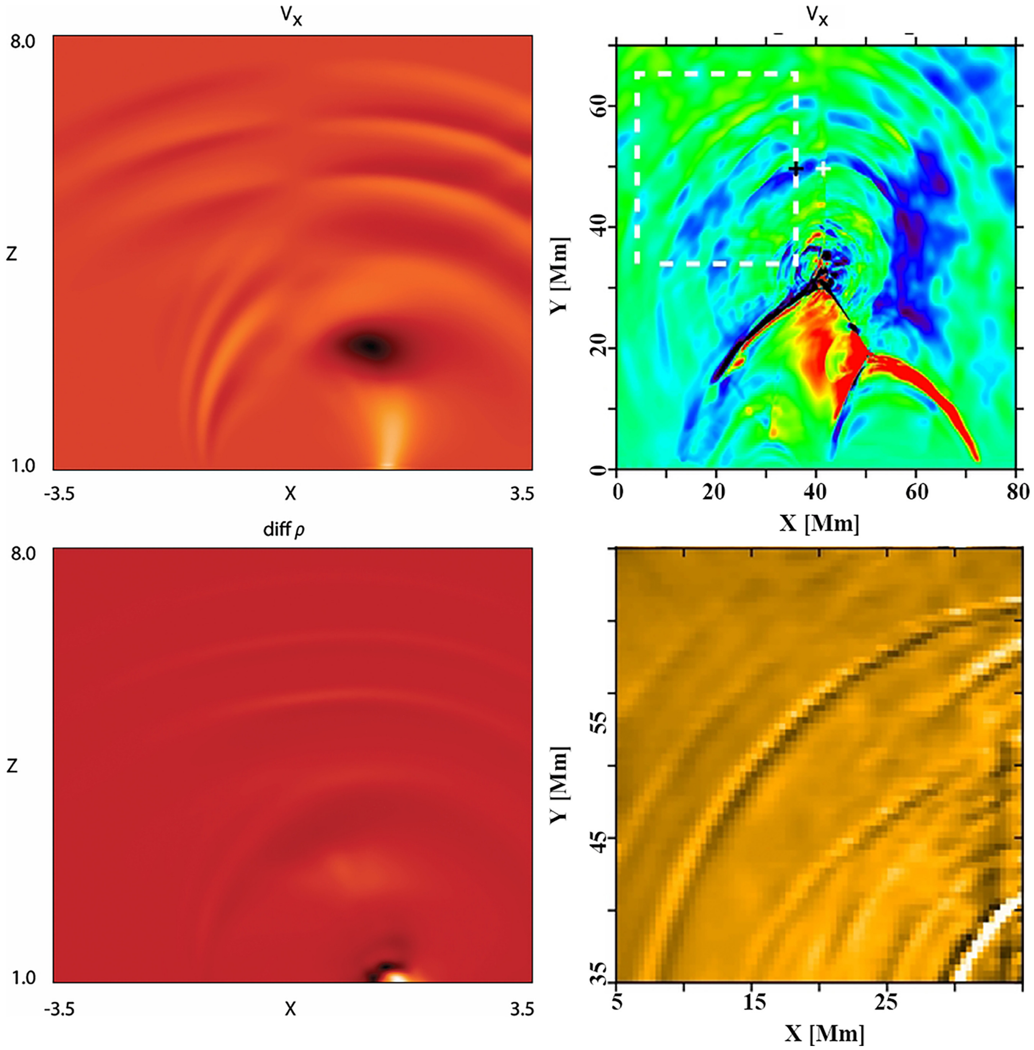

Figure 15. The left column show in simulation results presented by Ofman et al. (2011), in which the top and the bottom panels display the velocity component V_x and the density difference in the xz-plane at the center of the model, respectively. The right column shows the simulation results present by Yang et al. (2015), in which the top and the bottom panels show the horizontal velocity V_x and the running difference of the synthesized real emission at 171 Å wavelength, respectively. The white dashed box in the top panel indicates the field-of-view of the bottom panel.

and Forbes, 2002), which is intrinsic to launch intermittent energy release pulses and therefore cause QPPs in light curves from radio to gamma-ray and QFP wave trains. In observations, some periods of QFP waves are found to be consistent with those of QPPs, which might suggest their common origins. In addition, this also implies the existence of an intimate physical relationship between QFP wave trains and nonlinear physical processes in magnetic reconnection (see Section 2.5).

Generally, theoretical and numerical studies have revealed that the launch of a fast magnetic reconnection requires the development of turbulence and the fragmentation of a thin current sheet into many small-scale plasmoids (magnetic islands or flux ropes in three-dimension, Furth, Killeen, and Rosenbluth, 1963; Shibata and Tanuma, 2001; Lazarian and Vishniac, 1999). The formation of plasmoids is owning to the tearing-mode or plasmoid instability of the current sheet when its Lundquist number and aspect ratio are large enough (e.g., Ni et al., 2012, 2015). Plasmoids in a current sheet are typically generated repetitively and exhibit characteristics such as coalescence and bi-directional outward ejections at about the Alfvén speed. These motions reduce the magnetic flux in the current sheet, which in turn enables new magnetic flux to continuously enter the current sheet to achieve a fast reconnection speed (Shibata and Magara, 2011). So far, many numerical simulations have successfully produced such a physical process; and the presence and dynamic characteristics of plasmoids are also observed indirectly in various solar eruptions from radio to gamma-rays (see Shibata and Takasao, 2016; Ni et al., 2020, and reference therein). In some studies, flare QPPs have been related to the repetitive generation, coalescence and ejections of plasmoids in current sheets, in which plasmoids are considered as a trap for accelerated particles that can result in drifting pulsating structures in the radio spectrum (e.g, Kliem, Karlický, and Benz, 2000; Karlický, 2004; Karlický and Bárta, 2007; Bárta, Karlický, and Žemlička, 2008; Takasao and Shibata, 2016; Reeves et al., 2020). Especially, Jelínek et al. (2017) numerically evidenced the merging of two plasmoids, and the resulting larger plasmoid oscillated with a period of about 25 seconds; in the meantime, the downward plasmoids interact with the underlying flare arcade and causes the oscillation of the latter with a period of about 35 seconds. These periods are consistent with those observed in flare QPPs and QFP wave trains. In addition, plasmoid contraction or squashing are suggested as a promising mechanism for particle acceleration (e.g., Drake et al., 2006; Guidoni et al., 2016), and particles are shown to gain more energy in multiple X-points between plasmoids (Li and Lin, 2012; Li, Wu, and Lin, 2017; Xia and Zharkova, 2018).

Recent numerical simulations have studied the physical relationship between the nonlinear processes in magnetic reconnection and the generation of QFP wave trains. Ofman et al. (2011) firstly performed a three-dimensional MHD model in which they identified that the observed QFP wave trains are fast magnetosonic waves driven by quasi-periodical drivers at the base of the flaring region. The simulated QFP wave trains driven by periodic velocity pulsations at lower coronal boundary propagate outward in a magnetic funnel and are evident through density fluctuations due to compressibility. The authors confirmed that the simulated QFP wave trains have similar physical properties as those obtained in real observations, including their amplitude, wavelength, and speeds (see the left column of Figure 15). Using real observations as a guideline, Ofman and Liu (2018) investigated the excitation, propagation, nonlinearity, and interaction of counter-propagating QFP wave trains in a large-scale, trans-equatorial coronal loop system using time-dependent periodic boundary conditions at the two ends of the loop system. Besides QFP wave trains, trapped fast-(kink) and slow-mode waves are also identified in the closed loop system. These results suggest that the counter-propagating QFP wave trains in closed coronal loops can potentially lead to turbulent cascade that carries significant energy for coronal heating in low-corona magnetic structures. Yang et al. (2015) performed a 2.5 dimensional numerical MHD simulation to study the generation of QFP wave trains using the interchange reconnection scenario, they found that QFP wave trains can be launched by the impingement of plasmoids ejected outwardly from the current sheet upon the ambient magnetic field in the outflow region, and an one-to-one correlation between the energy release and the wave generation can be identified. The wave properties are also found to be similar to the observed QFP wave trains (see the right column of Figure 15). However, as pointed out by the authors, the simulated QFP wave train propagates isotropically from the wave source other than along funnel-like loop structures as narrow QFP wave trains. Therefore, QFP wave trains excited by the impingement of plasmoids upon the ambient magnetic field in the outflow region could possibly be used to explain the generation of broad QFP wave trains.

Takasao and Shibata (2016) described an alternative physical picture for the generation of QFP wave trains through a two-dimensional MHD simulation on the flare process, which includes essential physics such as magnetic reconnection, heat conduction, and chromospheric evaporation. It was found that QFP wave trains are spontaneously excited by the oscillating region filled with evaporated plasma above the flaring loop, and the oscillation of this region is controlled by the backflow of the reconnection outflow. Therefore, the authors claimed that the backflow of the reconnection outflow can act as an exciter of QFP wave trains (see Figure 16). The oscillation region has an U-shaped structure due to the continuous impingement of the reconnection outflow, and therefore the generation process of QFP wave trains is similar to the sound wave generated by an externally driven tuning fork. Miao et al. (2021) observed simultaneous bi-directional narrow QFP wave trains originating from the same flaring region, and the authors suggested that their observation might be a good example for supporting such a magnetic tuning fork model. Here, it should be noted that the propagation of the simulated QFP wave train in Takasao and Shibata (2016) is also isotropically as that in Yang et al. (2015). It is hard to understand why the observed bi-directional narrow QFP wave trains in Miao et al. (2021) can be interpreted by the magnetic tuning fork model. We think that this model should be more suitable for broad QFP wave trains, but it could also be used to interpret narrow QFP wave trains when the isotropic propagating wave train is captured by and therefore trapped in some inhomogeneous coronal structures such as coronal loops (e.g., Shen et al., 2019).

Wang, Chen, and Ding (2021) performed a three-dimensional radiative MHD simulation to model the formation of active regions through magnetic flux emergence from the convection zone to the corona, in which the eruption of a magnetic flux rope produced a C-class flare and a QFP wave train with a period of about 30 seconds in-between the erupting flux rope and a preceding global EUV wave that was driven by the erupting flux rope (see Figure 17). Obviously, the propagation of the generated QFP wave train is a broad QFP wave train perpendicular to magnetic field lines (Liu et al., 2012; Shen et al., 2019; Zhou et al., 2021b,c) rather than along magnetic field lines as narrow QFP wave trains (Liu et al., 2011; Shen and Liu, 2012b; Shen et al., 2013a, 2018a). Therefore, this simulation provided an additional numerical model for the generation of broad QFP wave trains, as well as the simultaneous preceding global EUV wave. The generation of the QFP wave train in Wang, Chen, and Ding (2021) occurs spontaneously without any artifactual exciters as used in previous simulations (e.g., Ofman et al., 2011; Pascoe, Nakariakov, and Kupriyanova, 2013). The authors proposed that excitation of the QFP wave train was possibly due to pulsed energy release in the accompanying flare, as what had been proposed in Liu et al. (2012). However, the authors also pointed out that the essential physical cause of the excitation mechanism still needs further investigation using higher spatiotemporal resolution three-dimensional simulations. This is true because there may be other excitation mechanisms for broad QFP wave trains. For example, Shen et al. (2019) proposed that the generation of broad QFP wave trains behind the CME-driven global EUV wave can possibly be driven by the pulsed energy release caused by the periodic unwinding and expanding twisted thin threads in the erupting filament, because the period of the observed QFP wave train is similar to the unwinding filament threads instead of the QPPs in the accompanying flare. In addition, the generation of broad QFP wave trains is possibly in association with the fine structure of CMEs. We note the appearance of large-scale quasi-periodic EUV wavefronts ahead of the CME in numerical simulations with a period of about 84–168 seconds (see Figure 1 of Chen et al. (2002) and Figure 2 of Chen, Fang, and Shibata (2005) for details).

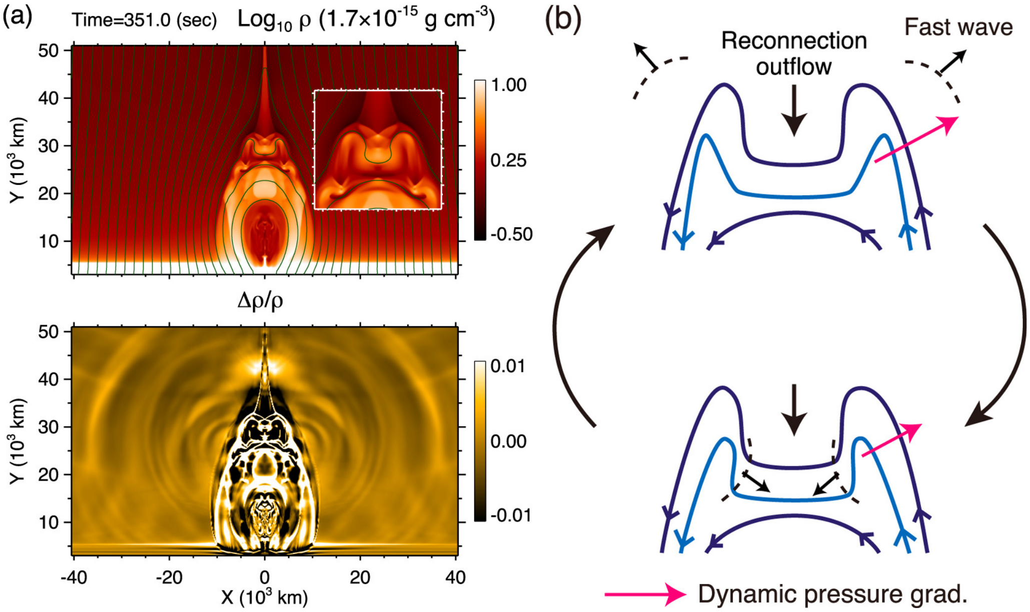

Figure 16. The numerical simulation results presented by Takasao and Shibata (2016). The upper left is the density map overlaid with magnetic field lines, and the above-the-loop-top region is plotted as an inset. The bottom left panel shows the running difference image of the density perturbation, in which multiple wavefronts can be clearly identified. The right panel is a schematic for illustrating the generation of QFP wave trains due to the above-the-loop-top oscillation, in which the pink arrows indicate the dynamic pressure gradient, the black vertical arrow indicates the downward reconnection outflow, and the short black arrows indicate the generated QFP wave trains.

Although the authors did not analyze these interesting wavefronts, their period is well consistent with those of broad QFP wave trains (Shen et al., 2019). Besides, Patsourakos, Vourlidas, and Kliem (2010) also observed the appearance of broad QFP wave trains ahead of a CME, where the authors proposed that the wave train was excited by the fine expanding pulse-like lateral structures in the CME. Recently, Shen et al. (2022) found the generation of a broad QFP wave train can be driven by the sequential stretching of expansion of the newly formed reconnected magnetic field lines, it is also a good observation supporting the scenario of pulsed energy release in magnetic reconnection.

Other nonlinear physical processes in association to pulsed energy release in magnetic reconnection include the mechanism of oscillatory reconnection which couples resistive diffusion at X-type null points to global advection of the outer fields (e.g., Craig and McClymont, 1991; McLaughlin et al., 2009; McLaughlin, Thurgood, and MacTaggart, 2012; McLaughlin et al., 2012; Hong et al., 2019; Xue et al., 2019; Thurgood, Pontin, and McLaughlin, 2017, 2019), 3) patchy magnetic reconnection shows as supra-arcade downflows (e.g., Linton and Longcope, 2006; McKenzie and Savage, 2009; Savage, McKenzie, and Reeves, 2012; Xue et al., 2020; Cai et al., 2019; Reeves et al., 2020), and 4) the fluctuation of current sheets result from super-Alfvénic beams and Kelvin-Helmholtz instability nonlinear oscillations (e.g., Ofman and Sui, 2006; Li et al., 2016). In addition, periodicities in magnetic reconnection can also be launched by external quasi-periodic disturbances from lateral or lower layers of the solar atmosphere through interaction and therefore modulating the reconnection process (e.g., Nakariakov et al., 2006; Chen and Priest, 2006; Sych et al., 2009; Shen and Liu, 2012b; Jess et al., 2012; Jelínek and Karlický, 2019). Basically, all these possible physical processes are potentially to produce both flare QPPs and QFP wave trains. However,

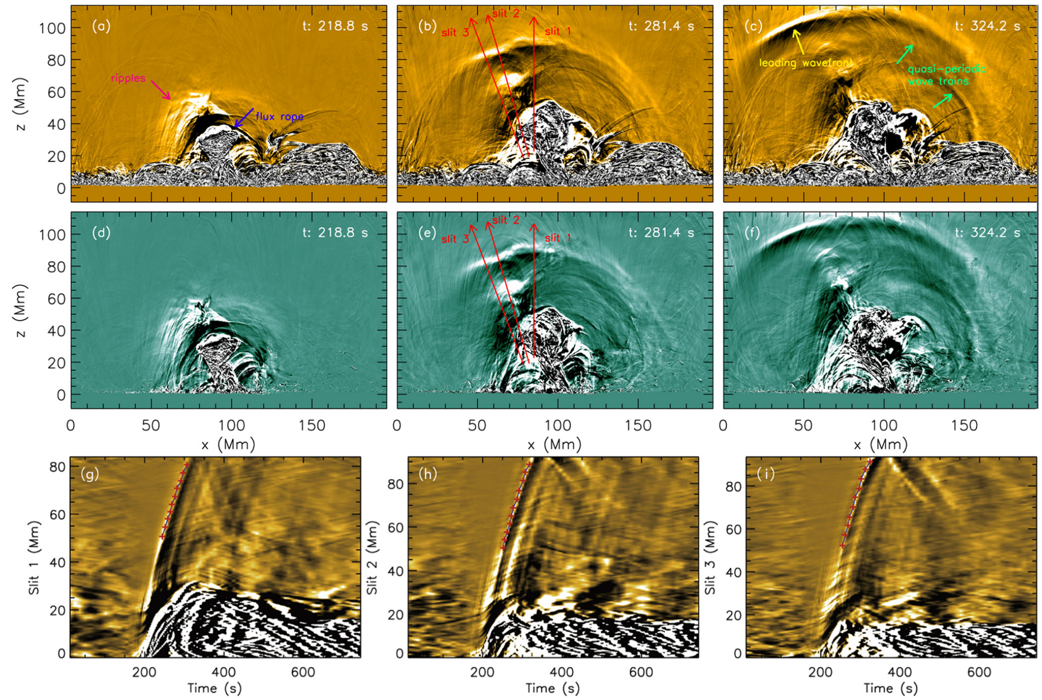

Figure 17. The simulation results presented by Wang, Chen, and Ding (2021). The top and middle rows display the synthetic 171 Å and 94 Å running difference images, respectively. The leading EUV wavefront and the following QFP wave train are indicated respectively by the yellow and green arrows in panel (c). The three red arrows in the panels (b) and (e) are used to generate the time-distance diagrams plotted in the bottom row (based on the synthetic 171 Å running difference images).

although a number of numerical and theoretical studies have been performed to investigate the excitation mechanism of flare QPPs based on these scenarios (Nakariakov and Melnikov, 2009; Van Doorsselaere, Kupriyanova, and Yuan, 2016; McLaughlin et al., 2018; Kupriyanova et al., 2020; Zimovets et al., 2021), the physical relationship between these processes and the generation of QFP wave trains have not yet been established. Therefore, in the future more attentions should be paid to these candidate mechanisms for the generation of QFP waves.

3.3. Discussion of the Current Models

The current models showed that the two kinds of possible generation mechanisms of QFP wave trains are both supported by some observational evidence (e.g., Liu et al., 2011; Shen and Liu, 2012b; Shen, Song, and Liu, 2018; Shen et al., 2019; Yuan et al., 2013; Nisticò, Pascoe, and Nakariakov, 2014). However, for a particular event, the generation of the QFP wave train is owning to a specific mechanism or the combination of both is still unclear. Here, we would like to make some preliminary discussions about this problem based on previous observational and theoretical studies.

The dispersion evolution mechanism was firstly developed to interpret short period pulsations of a few seconds observed in radio emission, and these pulsations were thought to be the manifestation of plasma emission modulated by QFP wave trains propagating in inhomogeneous coronal structures such as coronal loops that act as overdense plasma tubes (Roberts, Edwin, and Benz, 1983, 1984).

Obviously, QFP wave trains formed by the dispersion evolution mechanism require the presence of overdense waveguides. In actual observations, many spatially-resolved narrow QFP wave trains in the EUV can satisfy such a requirement, since they propagate along coronal loops. In addition, it has been widely accepted that such a dispersively formed QFP wave train should lead to a characteristic tadpole structure in the time-dependent wavelet spectrum (Nakariakov et al., 2004), if the driver is a broadband perturbation (Nakariakov, Pascoe, and Arber, 2005). Up to now, the characteristic tadpole structure has not been detected in all published narrow QFP wave trains observed by the AIA. This might be attributed to the relatively longer period (25–550 seconds, see Table 1) of the narrow QFP wave trains observed by the AIA, since we note that a tadpole wavelet spectrum did detect in the QFP wave train observed by SECIS during the total solar eclipse on 1999 August 11, where the period was about 6 seconds Katsiyannis et al. (2003). Besides, as what had been pointed out in Nakariakov, Pascoe, and Arber (2005), the absence of the tadpole wavelet spectrum of narrow QFP wave trains could also be due to the more monochromatic and narrowband driver.

For broad QFP wave trains propagating in the homogeneous quiet-Sun region where the magnetic field has a strong vertical component, they are non-dispersive in nature and their propagation can be viewed as perpendicular to the magnetic field. As evidenced in simulations (e.g., Murawski and Roberts, 1993b; Pascoe, Nakariakov, and Kupriyanova, 2013), an impulsively perturbation can dispersively evolved into both trapped and leaky wave trains inside and outside of the waveguide. Pascoe, Goddard, and Nakariakov (2017) showed that broad QFP wave trains can be formed through steepening the leaky component of a dispersively formed wave train in an overdense waveguide, while the trapped component does not experience nonlinear steepening; the trapped and leaky wave trains have the same periods of about 6 seconds, and their velocity amplitudes are estimated to be respectively about 30% and 10% with respect to the local Alfvén speeds. This simulation might imply that broad QFP wave trains formed by the leaky component of dispersively formed QFP wave trains should also have relatively short periods as what we have discussed in the above paragraph. The pulsed energy excitation mechanism include various forms as what has been stated in Section 3.2, in which the dynamic evolution of plasmoids and their interaction with magnetic structures in the reconnection outflow region often excite broad QFP wave trains with periods of dozens of seconds (e.g., Yang et al., 2015; Takasao and Shibata, 2016; Jelínek et al., 2017; Wang, Chen, and Ding, 2021), in quantitative agreement with the lower limit of the period of the published broad QFP wave trains observed by the AIA (36–240 seconds, see Table 1). In addition, broad QFP wave trains with longer periods of about several minutes are probably associated with the other kinds of pulsed energy release processes in association to magnetic reconnection. For example, the periodic untwisting motion of twisted erupting filament threads (Shen et al., 2019), the intermittent generation and stretching (or expansion) of reconnected magnetic field lines (Shen et al., 2022), and the sequentially eruption of coronal loops (Patsourakos, Vourlidas, and Kliem, 2010).

Based on the above discussions, it is noted that both narrow and broad QFP wave trains can be produced by the two different generation mechanisms. In general, it appears that the dispersion evolution mechanism seems more preferable for the generation of QFP wave trains with short periods of about a few seconds, while the pulsed energy release excitation mechanism seems more preferable for the generation of QFP wave trains with relatively long periods typically of about dozens of seconds to a few minutes. In principle, the two different generation mechanisms do not contradict to each other. For the dispersion evolution mechanism, it requires that the initial perturbation should be broadband. For pulsed energy release excitation mechanism, the initial perturbation is more monochromatic. Here, we would like to point out that these preliminary thoughts are premature, and they need to be verified with high spatiotemporal resolution observations and theoretical works in the future.

4. Seismological Application

Seismology is the study of earthquakes and seismic waves that move through and around the Earth. This technique has been extended to other areas of science such as helioseismology, stellar seismology, as well as MHD spectroscopy of laboratory plasma. Coronal seismology uses MHD waves and oscillations to probe unknown physical parameters of the solar corona (Nakariakov and Verwichte, 2005), which was originally proposed by Uchida (1970) for global and Roberts, Edwin, and Benz (1984) for local seismology. In principle, coronal seismology requires the combined application of theoretical modeling knowledge and observational parameters of MHD waves and oscillations, which yields the mean parameters of the corona that are currently not accessible in the absence of in situ instruments, such as the magnetic field strength and Alfvén velocity and coronal dissipative coefficients (De Moortel, 2005; De Moortel and Nakariakov, 2012). So far, different types of MHD waves have been detected in the corona, and the technique of coronal seismology has also been successfully applied to estimate various coronal parameters (Nakariakov and Kolotkov, 2020). In previous studies, particular attentions have been paid to derive the elusive coronal magnetic field, and the results are often comparable with those obtained by using other direct or indirect methods including polarimetric measurements using Zeeman and Hanle effects (Lin, Penn, and Tomczyk, 2000; Lin, Kuhn, and Coulter, 2004), extrapolations using photospheric magnetograms (Zhao and Hoeksema, 1994; Liu and Lin, 2008), and radio observations of gyrosynchrotron emission with a coronal density model (Gary and Hurford, 1994; White and Kundu, 1997; Ramesh, Kathiravan, and Sastry, 2010; Subramanian, Ebenezer, and Raveesha, 2010). Here, we only briefly review the applications of coronal seismology by using QFP wave trains, those for other types of waves can refer to several recent reviews (e.g., De Moortel, 2005; De Moortel and Nakariakov, 2012; Jess et al., 2015; Liu and Ofman, 2014; Li et al., 2020a; Nakariakov and Verwichte, 2005; Nakariakov and Kolotkov, 2020).

For a linear fast-mode magnetosonic wave in a homogeneous medium, its propagation is weakly depends on the direction of the wave vector with respect to the magnetic field, which means that it propagates in any direction. The restoring force is the resultant force of the magnetic and the gas pressure gradient forces, and the speeds is combinedly determined by the Alfvén speed and the sound speed of the local plasma medium. Theoretically, the speed of a fast-mode magnetosonic wave v_{f} in a uniform medium is written as

$$v_{\mathrm{f}} = [\frac{1}{2}(v_{\mathrm{A}}^2 + c_{\mathrm{s}}^2 + \sqrt{(v_{\mathrm{A}}^2 + c_{\mathrm{s}}^2)^2 - 4v_{\mathrm{A}}^2 c_{\mathrm{s}}^2 \cos^2\theta_{\mathrm{B}}})]^{1/2}, \tag{3}$$

where c_{s}, v_{A}, and θ_{B} are the sound speed, Alfvén speed, and the angle between the wave vector and the magnetic field, respectively. Specifically, the mathematical expressions of c_{s} and v_{A} are

$$c_{\mathrm{s}} = \sqrt{\frac{\gamma \kappa T}{\bar{\mu} m_{\mathrm{p}}}} \tag{4}$$

$$\text{and } v_{\mathrm{A}} = \frac{B}{\sqrt{4\pi\rho}} = \frac{B}{\sqrt{4\pi\bar{\mu} m_{\mathrm{p}} n}}, \tag{5}$$

respectively, where $\gamma = 5/3$ is the adiabatic exponent for fully ionized plasmas, κ the Boltzmann constant, T the temperature, $\bar{\mu}$ the mean molecular weight, m_{p} the proton mass, B the magnetic field strength, ρ the mass density, and n the total particle number density. According to Priest (1982), $\bar{\mu}$ and n are often respectively taken as 0.6 and $1.92n_e$, with n_e as the electron density.

Obviously, for a fast-mode magnetosonic wave traveling in a particular direction, its speed depends on coronal parameters including the temperature, plasma density, and magnetic field strength. Particularly, if a wave propagates perpendicular to the magnetic field (i.e., $\theta_{\rm B} = 90°$), Equation (3) reduces to a simple form of

$$v_{\rm f} = \sqrt{v_{\rm A}^2 + c_{\rm s}^2}, \tag{6}$$

and the magnetic field strength of the medium in which the wave propagates can be estimate through measuring the wave speed and coronal parameters including plasma density and temperature. In the case of $\theta_{\rm B} = 0°$, i.e., the wave propagates along the magnetic field, Equation (3) becomes as

$$v_{\rm f} = v_{\rm A} = \frac{B}{\sqrt{4\pi\rho}}, \tag{7}$$

namely, the fast-mode magnetosonic wave speed is equal to the Aflvén speed. Therefore, one can simply measure the wave speed and the plasma density to estimate the magnetic field strength of the waveguide.

In the corona, magnetic field lines are believed to be highlighted by coronal loops due to the coupling of hot plasma and magnetic field. Therefore, coronal loops commonly manifest the orientation and distribution of the coronal magnetic field. In practice, since narrow QFP wave trains travel along coronal loops, their propagations are along magnetic fields. Therefore, one often uses Equation (7) to estimate the magnetic field strength of the guiding magnetic field. Williams et al. (2002) estimated that the magnetic field strength of an active region loop is about 25 Gauss. Liu et al. (2011) obtained that the magnetic field strength of an active region funnel-like loop is greater than 8 Gauss. Shen et al. (2019) derived that the magnetic field strength of a closed transequatorial loop is about 6 Gauss. Zhou et al. (2021b) estimated that the magnetic field strength of an interconnecting loop is about 5.6 Gauss, in agreement with the result (about 5.2 Gauss) derived from the simultaneous global EUV wave. Miao et al. (2021) reported a bi-directional QFP wave event, in which simultaneous QFP wave trains are observed in two opposite funnel-like loops rooted in the same active region. The magnetic field strengths of the two funnel-like loops are estimated to be respectively about 12.8 and 11.3 Gauss, consistent with the results alternatively obtained by using magnetic field extrapolation. Radio observations of possible QFP wave trains were also used to estimate the magnetic field strengths of coronal loops, which are found to be in the range of 1.1–47.8 Gauss (Mészárosová, Karlický, and Rybák, 2011; Kolotkov, Nakariakov, and Kontar, 2018). It should be pointed out that these results are all obtained by using average parameters (plasma density and wave speed) along the entire loop structure. In practice, since narrow QFP wave trains decelerate fast as they propagate outward, it should be better to estimate the magnetic field strengths of the different sections of the waveguiding loop. According to this line of thought, Shen et al. (2013a) obtained that the magnetic field strengths of the footpoint, middle, and outer sections of an active region loop are about 5.4, 4.5, and 2.2 Gauss, respectively. This indicates the fast decreasing of the magnetic field strength with the increasing of height of active region coronal loops. Here, it should be pointed out that the above magnetic field strength estimations based on Equation (7) are only approximations but with a certain accuracy. As what has been introduced in Section 3.1 (for more details, one can refer to many books or reviews (e.g., Aschwanden, 2005; Roberts and Nakariakov, 2003; Nakariakov and Verwichte, 2005)), the speeds of QFP wave trains along coronal loops are on the order of Alfvén speed, which is greater than the Alfvén speed inside of a loop but less than the Alfvén speed outside of the loop. Therefore, the derived values based on Equation (7) should be approximately consistent with the lower limit of those estimated based on the theory of QFP wave trains along inhomogeneous waveguides.

In the simulation work performed by Nakariakov et al. (2004), the authors found that the mean wavelength of the QFP wave train is comparable to the width of the guiding loop. Since the fast-mode wave speed is equal to the Alfvén speed of the waveguide, the relationship among wavelength (λ), period (P) and wave speed (v_f) can be written as

$$P = \frac{\lambda}{v_\mathrm{f}} \simeq \frac{w}{v_\mathrm{A}}, \tag{8}$$

where w and v_A are the width and Alfvén speed of the guiding loop. Therefore, with the measurable physical parameters of period and wave speed, one can estimate the width of the guiding loop. For example, in the absence of imaging observations, Mészárosová, Karlický, and Rybák (2011) and Mészárosová et al. (2013) estimated the loop widths with the results derived from radio observations, which are in the range of about 1–30 Mm.

If simultaneous slow- and fast-mode waves are observed in the same waveguide, one can further estimate the plasma β of the medium which is defined as the ratio of gas pressure to magnetic pressure (Van Doorsselaere et al., 2011). Zhang et al. (2015) reported the first imaging observation of simultaneous slow- and fast-mode wave trains propagating along the same coronal loop at speeds were about 80 and 900 km s^{-1}, respectively. By assuming that the speeds of the observed slow- and fast-mode wave trains are respectively equal to the sound speed and Alfvén speed of the waveguide, the plasma β can be expressed with the slow- (v_s) and fast-mode (v_f) characteristic speeds, i.e.,

$$\beta = \frac{2\mu p}{B^2} \approx \frac{2}{\gamma}(\frac{v_\mathrm{s}}{v_\mathrm{f}})^2, \tag{9}$$

where p, μ, γ and B are the gas pressure, the permeability, the adiabatic index and the magnetic field magnitude, respectively. In the corona, the value of γ often ranges from 1 to 5/3 for isothermal and adiabatic sases, respectively. For the case analyzed by Zhang et al. (2015), the authors derived that the value of the plasma β ranges from 0.009 to 0.015, confirming the low β nature of the low corona.

Broad QFP wave trains commonly travel parallel to the solar surface which has a strong vertical magnetic field component. Therefore, the propagation of broad QFP wave trains are assumed to be perpendicular to the magnetic field, and one often uses Equation (6) to derive the magnetic field strength of the supporting medium. This method is the same with the magneto-seismology by using global EUV waves (see Liu and Ofman, 2014; Warmuth, 2015, and references therein), and one need to firstly determine the sound speed and plasma density of the supporting medium. For example, (Zhou et al., 2021c) used the observation of a broad QFP wave train to estimate the magnetic field strength in the quest-Sun, which yields a result of about 4.7 Gauss.

The large extent propagation of broad QFP wave trains is potential to trigger oscillations of remote coronal structures such as coronal loops and filaments. The transverse oscillation of these coronal structures can be interpreted as kink global standing mode of the loops, and one can use the measured oscillation parameters for coronal seismology (Aschwanden et al., 1999; Nakariakov et al., 1999; Nakariakov and Verwichte, 2005). According to Nakariakov and Ofman (2001), the observed wavelength of a global standing kink mode is double the length of the loop, one can estimate the phase speed C_k based on the observable period P and loop length L with the formula

$$P = \frac{2L}{C_\mathrm{k}}. \tag{10}$$

Assuming that in the low β coronal plasma the magnetic field is almost equal inside and outside the waveguide, the equation of the kink speed can be rewritten as

$$C_\mathrm{k} = \sqrt{\frac{\rho_i v_\mathrm{Ai}^2 + \rho_\mathrm{e} v_\mathrm{Ae}^2}{\rho_i + \rho_e}} \approx v_\mathrm{Ai}\sqrt{\frac{2}{1+\rho_\mathrm{e}/\rho_\mathrm{i}}}, \tag{11}$$

where ρ_i (ρ_e) is the internal (external) density, v_Ai (v_Ae) is the internal (external) Alfvén speed. As the density contrast $\rho_\mathrm{e}/\rho_\mathrm{i}$, the density inside the waveguide ρ_i and the kink speed C_k can be measured from observations, one can estimate the magnetic field strength B of the waveguide using equation (10) that can be rewritten as

$$B = v_\mathrm{Ai}\sqrt{4\pi\rho_\mathrm{i}} = \frac{L}{P}\sqrt{8\pi\rho_\mathrm{i}(1+\rho_\mathrm{e}/\rho_\mathrm{i})}. \tag{12}$$

This formula can be written as a more convenient practical formula with measurable parameters of the distance between the footpoints of the loop d, the number density inside the loop n_i, the number density contrast $n_\mathrm{e}/n_\mathrm{i}$, and the period of the loop oscillation P, i.e.,

$$B \approx 7.9 \times 10^{-13}\frac{d}{P}\sqrt{n_\mathrm{i}+n_\mathrm{e}}, \tag{13}$$

where the magnetic field B is in Gauss, the distance d is in meter, the number densities n_i and n_e are in m^{-3}, and the period P is in seconds (Roberts and Nakariakov, 2003).

Ofman and Liu (2018) studied the transverse oscillation of a coronal loop caused by the counter-propagating of two quasi-simultaneous narrow QFP wave trains in it. The authors firstly measured the width and length of the loop, and then they derived the background and loop density with the technique of differential emission measure (DEM; see Cheung et al., 2015, for instance). With the knowledge of loop length, oscillation period, and the background and loop densities, the magnetic field strength of the loop is estimated to be about 5.3 Gauss with equation (12). Such a value is consistent with their numerical model that can produce similar observational characteristics to those obtained from the real observations. Shen et al. (2019) reported an interesting broad QFP wave train that propagated simultaneously along a transequatorial loop and on the solar surface, and the trapped part of the wave train result in the transverse oscillation of the loop system. Using the same methods as in Ofman and Liu (2018), the authors estimated that the magnetic field strength of the transequatorial loop is about 6 Gauss. In addition, the authors also estimated the magnetic field strength of the loop with equation (7) by using the physical property of the wave train, which yields a value of about 8.3 Gauss. This result is obviously inconsistent with that obtained by using the oscillation property of the loop. The different magnetic field strengths for the same loop derived from different methods are mainly because of that the broad QFP wave train was actually a shock rather than linear fast-mode magnetosonic wave. Therefore, the authors further derived the Alfvén Mach number, and then estimated the magnetic field strength of the loop by using the characteristic fast-mode speed obtained through dividing the measured wave speed by the Alfvén Mach number. Finally, the authors obtained the same result as that derived from the loop oscillation, which also confirmed the reliability of the two seismology methods.

Filaments (or prominence) oscillations include transverse and longitudinal oscillations, and their oscillation parameters have also been applied into prominence seismology with various inversion techniques (see Arregui, Oliver, and Ballester, 2018, and reference therein). In previous studies, filament oscillations are commonly observed to be caused by the interaction of global EUV waves (e.g., Shen and Liu, 2012a; Shen et al., 2014a,b, 2017; Zhang and Ji, 2018). Liu et al. (2012) observed the transverse oscillation of the limb cavity, as well as the hosting prominence caused the passing of a broad QFP wave train. Taking the oscillation as a global standing transverse oscillation as those observed in coronal loops, the authors derived the cavity's magnetic field strength is about 6 Gauss with a pitch angle of about 70°, suggesting that the observed cavity is a highly twisted flux rope. Shen et al. (2019) studied the transverse oscillation of a remote filament caused by the interaction of an on-disk propagating broad QFP wave train. The authors estimated the radial component of the magnetic field of the filament by using the method proposed by Hyder (1966) with the measured parameters of oscillation period and damping time, and the derived value is about 12.4 Gauss. These results are in agreement with those obtained by the inversion of full-Stokes observations (e.g., Casini et al., 2003).

5. Conclusion and Prospect

As one of the new discoveries of *SDO*/AIA, spatially-resolved QFP wave trains in EUV wavelength band have attracted a lot of attentions in the past decade. In this paper, we have reviewed the observational properties, the possible formation mechanisms, and the associated coronal seismology applications of coronal QFP wave trains. Generally, a QFP wave train consists of multiple coherent and concentric wavefronts emanating successively near the epicenter of the accompanying flare and propagating outwardly either along or across coronal loops at fast-mode magnetosonic speed from several hundred to more than 2000 km s^{-1}. Based on the statistical study of the published QFP wave trains observed by the AIA, we propose that QFP wave trains could possibly be divided into two distinct categories including narrow and broad QFP wave trains. Although both narrow and broad QFP wave trains are fast-mode magnetosonic waves in the physical nature and with similar speeds, periods and wavelengths, they also show distinct differences including physical properties of observation wavelength, propagation direction, angular width, intensity amplitude and energy flux. The energy flux carried by QFP wave trains is found to be enough for heating the local low corona plasma, and the measured parameters such as period, amplitude and speed can be used to seismological diagnosing of the currently undetectable coronal parameters such as magnetic field strength.

Observations suggest that the generation of QFP wave trains are intimately associated with flare QPPs owning to their similar period and close temporal relation, and the two different phenomena might manifest the different aspects of the same physical process. Detailed theoretical and numerical studies revealed that the periodicity origins of QFP wave trains should be diversified, but they can be summarized as two interconnected groups dubbed as dispersion evolution mechanism and pulsed energy excitation mechanism. The dispersion evolution mechanism refers to a QFP wave train that develops from the dispersive evolution of an impulsive generated broadband perturbation in an inhomogeneous overdense waveguide, because for a wave packet which represents a Fourier integral over all frequencies and wave number, different frequencies propagates at different group speeds. In this regime, the periodicity of the wave train is not necessarily connected with the wave source, but can be created by the dispersive evolution of the initial perturbation based on the physical conditions inside and outside of the waveguide. For the pulsed energy excitation mechanism, it means that the generation of a QFP wave train is periodically driven by pulsed energy releases owning to some nonlinear physical processes in association to magnetic reconnection, such as the repetitive generation, coalescence and ejection of plasmoids, oscillatory reconnection, and the modulation of the magnetic reconnection by external disturbances. Quasi-periodic motions in solar eruptions such as the unwinding motion of erupting twisted filament threads and expansion of coronal loops can also launch broad QFP wave trains in the corona. In addition, it is also noted that some periods in QFP wave trains are possibly connected to leakage of photospheric and chromospheric three and five minute oscillations into the corona. The generation mechanism of QFP wave trains should be diversified and more complicated than we thought; therefore, it should be pointed out that for a specific QFP wave train, it might be generated by a single physical process or by the combination of different ones.

Despite significant progress achieved in both theoretical and observational aspects on the study of coronal QFP wave trains in the past decade, thanks to the high spatiotemporal resolution and full-disk, wide-temperature coverage observations taken by the *SDO* and the tremendous improvement in computing and calculation techniques, there are still many important open questions that deserve further in-depth investigations. The following is a list of some outstanding issues.

1. Statistical surveys by considering large samples should be performed to explore the common properties of QFP wave trains. So far, only Liu et al. (2016) performed a preliminary survey based on the database of global EUV waves, where the authors found the high occurrence rate of QFP wave trains. In addition, the present review, as well as Liu and Ofman (2014), also provides a simple statistical study of QFP wave trains observed by the AIA using the published events. Since the intensity variations caused by narrow QFP wave trains are too small to be observed in the direct EUV images, one should alternatively use the running-difference or running-ratio images to search narrow QFP wave trains. Coupled with the difficulties caused by the AIA's massive data base, one need to develop sophisticated automatic detection software to perform a complete survey and to obtain more reliable physical parameters and other properties of QFP wave trains.
2. The excitation mechanisms of QFP wave trains are still unclear, although various possible mechanisms have been proposed in previous studies. The high spatiotemporal resolution, multi-angle observations, three-dimensional radiate MHD simulations using more realistic initial conditions, and data-driven simulations that use multi-wavelength observations in tandem with MHD simulation are all required to clarify the real excitation mechanism of QFP wave trains, as well as the waveguide properties. In addition, more attentions should be paid to the possible excitation of QFP wave trains by the leakage of photospheric and chromospheric three and five minute oscillations into the corona. As what has been discussed in Section 3.3, one needs to consider which mechanism is more suitable for which kind of QFP wave trains, or are there any new generation mechanisms?
3. QFP wave trains are typically associated with flares, but not all flares cause QFP wave trains. In addition, QFP wave trains do not show any obvious dependence tendency on the flare energy class. It is worthy to investigate that what type of flares are more in favor of the occurrence of QFP wave trains. Our survey based on the published events suggests that broad QFP wave trains are associated with more energetic flares than the narrow ones. Liu et al. (2016) found an interesting trend of preferential association of QFP wave trains with successful solar eruptions accompanied by CMEs based on the survey of two flare productive active regions. Wang and Zhang (2007) found that failed and successful solar eruptions tend to occur closer to the magnetic center

and to the edge of active regions, respectively. Does QFP wave trains also have such a location preference to occur more frequently in association with flares close to the edge of active regions? These special trends of preferential association with flares need further statistical investigations by using large statistical samples of QFP wave trains.

4. The relationship between QFP wave trains and QPPs in solar and stellar flares deserves further in-depth investigations. These investigations can help us to diagnose the flaring process and physical properties of the waveguides, coronal and stellar crown conditions, as well as the generation mechanism of QFP wave trains.
5. Studies based on high temporal resolution radio observations combined with EUV imaging observations are important to investigate the fine physical process in the generation of QFP wave trains. The relationship between narrow and broad QFP wave trains is worthy to study to answer why they appear together in some events but separately in other individual ones. Does this mean different generation mechanisms or different propagation conditions? For broad QFP wave trains propagating in large-scale areas, they will inevitably interact with remote coronal structures such as coronal holes, active regions, filaments and coronal loops. The phenomena occurred during these interactions can be applied to coronal seismology to diagnose the physical properties of the structures and the local coronal conditions.
6. Since QFP wave trains carry energy away from the eruption source regions and propagate along or across magnetic field lines, it is important to investigate their possible roles in energy transport, coronal heating, and the acceleration of solar wind.

Future studies of QFP wave trains will continuously benefit from the joint observations taken by ground-based and space-borne solar telescopes. Especially, the massive database of the *SDO* remains to be fully exploited with sophisticated automatic detection techniques. The *Solar Orbiter* launched in 2020 operates both in and out of the ecliptic plane and images the polar regions of the Sun (Müller et al., 2020); the EUV imager and spectrometer onboard it can make further contributions to the investigation of QFP wave trains. In addition, the combination of the *SDO* and the *Solar Orbiter* can make a stereoscopic diagnosing to QFP wave trains. Other solar telescopes including the 4-meter Daniel K. Inouye Solar Telescope (DKIST; Rast et al., 2021), the *Advanced Space-based Solar Observatory* (ASO-S; Gan et al., 2019), the Goode Solar Telescope (GST; Cao et al., 2010; Goode et al., 2010), the New Vacuum Solar Telescope (NVST; Liu et al., 2014), the *Interface Region Imaging Spectrograph* (IRIS; De Pontieu et al., 2014), and the *Parker Solar Probe* (PSP; Fox et al., 2016) are all important for the diagnosis the eruption source region and the associated magnetic reconnection process. A combination of the measurements of magnetic field, spectroscopy, imaging and *in situ* observations provided by these solar telescopes and high temporal resolution radio telescopes will undoubtedly lead to a significant breakthrough in the comprehensive understanding of coronal QFP wave trains in the future.

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