White-light QFP wave train and the associated failed breakout eruption

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ABSTRACT

Quasi-periodic fast-propagating (QFP) magnetosonic wave trains are commonly observed in the low corona at extreme ultraviolet wavelength bands. Here, we report the first white-light imaging observation of a QFP wave train propagating outwardly in the outer corona ranging from 2 to 4 \( R_\odot \). The wave train was recorded by the Large Angle Spectroscopic Coronagraph on board the Solar and Heliospheric Observatory (SOHO), and was associated with a GOES M1.5 flare in NOAA active region AR12172 at the southwest limb of the solar disk. Measurements show that the speed and period of the wave train were about 218 km s\(^{-1}\) and 26 min, respectively. The extreme ultraviolet imaging observations taken by the Atmospheric Imaging Assembly on board the Solar Dynamic Observatory reveal that in the low corona the QFP wave train was associated with the failed eruption of a breakout magnetic system consisting of three low-lying closed loop systems enclosed by a high-lying large-scale one. Data analysis results show that the failed eruption of the breakout magnetic system was mainly because of the magnetic reconnection that occurred between the two lateral low-lying closed-loop systems. This reconnection enhances the confinement capacity of the magnetic breakout system because the upward-moving reconnected loops continuously feed new magnetic fluxes to the high-lying large-scale loop system. For the generation of the QFP wave train, we propose that it could be excited by the intermittent energy pulses released by the quasi-periodic generation, rapid stretching, and expansion of the upward-moving, strongly bent reconnected loops.

Key words. shock waves – Sun: activity – Sun: flares – Sun: corona – Sun: magnetic fields

1. Introduction

Coronal quasi-periodic fast-propagating (QFP) wave trains observed at extreme ultraviolet (EUV) wavelengths are composed of multiple coherent and concentric wavefronts emanating successively close to the epicenter of flares, and propagate at supersonic speeds from several hundred to a few thousand km s\(^{-1}\) (e.g., Liu et al. 2011; Shen & Liu 2012a; Shen et al. 2018, 2022; Liu & Ofman 2014; Li et al. 2018). In addition, some possible signals of QFP wave trains are often recorded in radio observations (e.g., Kolotkov et al. 2018; Karlický et al. 2013; Kaneda et al. 2018). A QFP wave train is typically associated with an impulsively generated broadband perturbation such as a flare, and its propagation often experiences three distinct phases including a periodic phase, a quasi-periodic phase, and a decay phase (Roberts et al. 1983; Kolotkov et al. 2021). In addition, a QFP wave train often has a characteristic tadpole or boomerangs signature in the time-dependent wavelet power spectrum (Nakariakov et al. 2004; Kolotkov et al. 2021). Observations showed that QFP wave trains typically first appear at a distance of greater than 100 Mm, and they can propagate up to 200–400 Mm from their origins (Liu & Ofman 2014; Shen et al. 2022). In particular, theoretical studies suggest that a QFP wave train will accumulate at a null point on the path because of the refraction effect around the null point, and the wave energy accumulated around the null point is enough to induce magnetic reconnection (e.g., McLaughlin & Hood 2004, 2005; McLaughlin et al. 2009, 2018; Thurgood & McLaughlin 2012). According to the statistical study performed by Shen et al. (2022), spatially resolved QFP wave trains can be divided into narrow and broad types. Typically, narrow QFP wave trains propagate along magnetic field lines and with a small intensity amplitude of about 1\%–8\% and an angular width of about 10–80 deg (e.g., Yuan et al. 2013; Nisticò et al. 2014; Qu et al. 2017; Ofman & Liu 2018; Miao et al. 2019, 2021; Duan et al. 2022), while broad QFP wave trains propagate across magnetic field lines parallel to the solar surface and with a large intensity amplitude of about 10\%–35\% and a large angular width of 90–360 deg (Li et al. 2012; Kumar et al. 2017; Shen et al. 2019a; Zhou et al. 2021, 2022). In observations, narrow QFP wave trains mainly appear at the 171 Å and occasionally at 193 and 211 Å channels; see Shen et al. 2013; Liu et al. 2016) channel of the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the Solar Dynamic Observatory (SDO), while broad QFP wave trains can be observed in all of the AIA EUV channels. These differences suggest that narrow and broad QFP wave trains might have different origins and physical properties.

* Movies are only available at https://www.aanda.org
There are two main competing physical mechanisms for the generation of QFP wave trains: the dispersion evolution mechanism and the pulsed energy excitation mechanism (see Shen et al. 2022, and references therein). The former refers to the scenario where a QFP wave train can be generated through the dispersive evolution of an impulsive broadband perturbation whose periodicity is determined by the physical properties of the waveguide and the surrounding background (e.g., Roberts et al. 1984; Nakariakov et al. 2004; Pascoe et al. 2013, 2014). The latter refers to the mechanism where a QFP wave train is excited by pulsed energy release in the magnetic reconnection, and the periodicity is determined by the wave source (e.g., Ofman et al. 2011; Yang et al. 2015; Takasao & Shibata 2016; Wang et al. 2021). In addition, the leakage of photospheric and chromospheric oscillations into the corona is also proposed as a possible excitation source for QFP wave trains (Bogdan et al. 2003; Shen & Liu 2012a). For broad QFP wave trains, previous studies suggested that their generation might be tightly associated with a nonlinear physical process in magnetic reconnections (Liu et al. 2012; Zhou et al. 2021b, 2022b), a pulsed energy release caused by unwinding of filament threads (Shen et al. 2019a), and the leakage of guided wave trains into the homogeneous quiet-Sun corona (Pascoe et al. 2017). To date, the generation mechanism of QFP wave trains remains an open question (Shen et al. 2022).

Failed solar eruptions mean that they cannot cause interplanetary coronal mass ejections (CMEs) owing to insufficient kinetic energy to overcome the Sun’s gravity and downward magnetic forces (Ji et al. 2003; Shen et al. 2011b). So far, several physical influencing factors have been proposed to explain the failure of solar eruptions. For example, the strong overlying magnetic field at low altitude (e.g., Liu 2008; Liu et al. 2009; Amari et al. 2018), the small gradient of the overlying magnetic field with respect to the height (e.g., Kliem & Török 2006; Zuccarello et al. 2015; Shen et al. 2012), the insufficient energy released in the low corona through flares or weak kinked magnetic flux ropes (Török & Kliem 2005; Shen et al. 2011b; Liu et al. 2018), as well as the angle between erupting magnetic flux ropes and the overlying magnetic fields (e.g., Baumgartner et al. 2018; Zhou et al. 2019). It should be pointed out that a combination of multiple physical factors must be determined in order to identify a failed solar eruption, rather than relying on just one. To the best of our knowledge, no QFP wave trains related to failed breakout eruptions have yet been reported, and direct white-light imaging of QFP wave trains in the outer corona up to several solar radii is also very scarce. We note that Ofman et al. (1997) reported propagating quasi-periodic variations in the polarized brightness at heliocentric distances from 1.9 to 2.45 solar radii with a period of about 6 min and a lifetime in the range of 20–50 min. The authors proposed that these signatures are possibly the result of density fluctuations caused by compressional, slow magnetosonic waves propagating in polar coronal holes.

In this paper, we report the first white-light observations of a QFP wave train on 2014 October 2 recorded by the Large Angle Spectroscopic Coronagraph (LASCO; Brueckner et al. 1995) on board the Solar and Heliospheric Observatory (SOHO), which was associated with a failed breakout eruption and an M1.5 GOES flare in the low corona. In this study, we mainly use the LASCO/C2 and AIA EUV (at 171, 193, and 131 Å channels) images. The LASCO/C2 images the outer corona from 2 to 6 solar radii using the white-light wavelength band, and it takes images with a 12 min cadence and a pixel size resolution of 11′′9. The AIA on board the SDO takes full-disk images of the corona up to 0.5 solar radii above the solar limb with a 12 s temporal resolution and a pixel size resolution of 0′′6. Taking these observations together, we discuss how the observed broad QFP wave train in the outer corona was related to the failed breakout eruption in the low corona.

2. Results

The eruption occurred in active region AR12172 at about 17:00 UT in the low corona, and was located at the west limb of the solar disk. According to the GOES soft-X-ray 1–8 Å flux, the eruption was accompanied by an M1.5 flare that started and peaked at about 17:10 UT and 17:44 UT, respectively. It should be noted that this flare did not cause any CME besides the notable QFP wavefronts. Therefore, this eruption should be classified as a failed solar eruption (e.g., Ji et al. 2003; Shen et al. 2011b). In addition, the M1.5 flare was followed by an M7.3 flare in the nearby active region AR12173 (see Fig. 2f). This M7.3 flare caused a partial halo CME in the outer corona, and its start and peak times were about 18:49 UT and 19:01 UT, respectively.

The pre-eruption corona is shown in Fig. 1a with a composite image made from LASCO/C2 and AIA 193 Å direct images at about 17:10 UT, in which coronal loops above the active region can well be identified in the AIA 193 Å image, while the LASCO/C2 image only showed some weak ray-like structures. The QFP wave train is displayed in Figs. 1b–g; these images show the morphology and evolution of the QFP wave train clearly. It can be seen that the first wavefront appeared at about 18:10 UT in the field-of-view (FOV) of the LASCO/C2 with an angular width of about 90°. The second and third wavefronts then appeared behind the first one at about 18:22 UT and 18:46 UT, respectively. As shown in Fig. 1g, due to the appearance of the following CME associated with the M7.3 in the FOV...
of LASCO/C2, the wave train became too faint to be identified. After that, one can only see the bright CME, and the propagating QFP wave train can no longer be traced (see Figs. 1h and i). As the distribution of coronal magnetic field in the outer corona is mainly radial, the propagation of the observed QFP wave train should be along the magnetic field. Therefore, according to the definition in Shen et al. (2022), the present QFP wave train belongs to the narrow category.

In the low corona, active regions AR12172 and AR12173 were on the disk limb, and some low-laying arcades are enclosed by a high-laying large loop system (see Fig. 2b). To clearly delineate the magnetic structure of the eruption source region, we checked the active regions on 2014 September 28 when they were close to the disk center (see Fig. 2a). It is clear that the eruption source region was a magnetic breakout configuration consisting of three low-laying loop systems enclosed by a large high-laying loop system. In the framework of magnetic breakout configuration, there exists a null point between the middle low-laying loop and the large high-laying one (Antiochos et al. 1999), and magnetic reconnection between the two groups of loops often trigger spectacular CMEs in the heliosphere (e.g., Shen et al. 2012; Chen et al. 2016, 2021; Lynch & Edmondson 2013).

The middle row of Fig. 2 shows the eruption details of the eruption in the AIA 193 Å running-difference images. As indicated by the red arrows, a chain of bright loops were successively generated and expanded outwardly in time, and a hard-X-ray source in the 12–25 KeV energy band was detected below these moving loops (see the red contours in Fig. 2e). Interestingly, the large high-laying loop system did not erupt but only showed some vertical oscillations during the eruption. These observations suggest that the present event should be a failed one, because we do not find a corresponding CME in the outer corona (see the animation available in the online article). The hotter AIA 131 Å showed the hot eruption core field better than in other channels, but the cooler, large high-laying loop system did not appear at this wavelength band (see Fig. 3). The position of the large high-laying loop system determined from the AIA 193 Å at 17:12:18 UT is overlaid as dotted blue curves in each panel of Fig. 3. It can be seen that the hard-X-ray source was above the bright post-flare loop, and hot loops were generated and expanded outward sequentially (see the red contour in Fig. 3d and red arrows in the bottom row of Fig. 3). During the eruption period, the expansion of the newly formed hot loops did not exceed the height of the high-laying loop system except for some vertical oscillations (see the animation available in the online article).

Time–distance plots are made along the black dashed line as shown in Fig. 3c in order to investigate the kinematics of the expanding loops (Fig. 4a), the large high-laying loop (Fig. 4d), and the wavefronts (Fig. 4e). The newly formed expanding loops experienced an acceleration phase of about 20 min from 17:10 UT to 17:30 UT, before they started a linear expansion phase. We measured the acceleration and the expanding speed of the expanding loops, finding values of about 11 m s$^{-2}$ and 195 km s$^{-2}$, respectively. The details of the acceleration phase are displayed in Fig. 4b using the time–distance plot made from running-difference images, in which one can see several strips that represent the expanding loops. The corresponding intensity profile along the black line in Fig. 4b is plotted in Fig. 4c, which shows the loops more clearly (each peak represents a loop). Figure 4d shows the time–distance plot made from AIA 171 Å images, which shows the oscillation of the large high-laying loop system, but the hot expanding loops cannot be identified. Fig. 4e is the time–distance plot made from LASCO/C2 running-difference images, from which it is measured that the speeds of the wave train and the following CME were about 218 and 322 km s$^{-1}$, respectively. The corresponding intensity profiles within the dashed blue box in Fig. 4e at different times are plotted in Fig. 4f. One can see that the amplitude of the wavefronts showed a trend of first increasing and then decreasing.
Fig. 4. Kinematics and periodic analysis of the expanding loops, the wave train, and the flare. Panel a shows the time–distance plot made from AIA 131 Å images along the black dashed line as shown in Fig. 3c. Panel b shows the time–distance plot within the red box region in panel a, which is made from the AIA 131 Å running-difference images. The running-difference intensity profile along the dashed black line in panel b is plotted in panel c. Panel d is the same as a, but is made from AIA 171 Å images. Panel e is the time–distance made from LASCO/C2 running-difference images along the same path as panel a, and panel f shows the intensity profiles at difference times within the blue dotted box in panel e. Panel g is the wavelet spectrum generated using the intensity profile as shown in panel c, while panel h is generated using the time derivative of the GOES 1–8 Å flux.

This characteristic might be evidence of the true wave nature of the observed wave train, as it resembles the evolution pattern of large-scale EUV waves (e.g., Shen & Liu 2012b; Warmuth 2015). Based on the intensity profile at 18:46:52 UT, the wavelength of the wave train can be estimated to be about 345 Mm. By dividing the wavelength by the speed, we estimate the period of the observed wave train to be about 26 min. It should be pointed out here that the measured period of the wave train might be highly inaccurate because of the significantly low spatiotemporal resolution of the LASCO/C2 observations (12 min). With the aid of the wavelet software (Torrence & Compo 1998), the wavelet spectrums of the expanding loop and the flare pulsations are respectively generated using the percentage intensity profile as shown in Fig. 4c and the time derivative of the GOES 1–8 Å flux, and they reveal that the period of the expanding loops was about 320 ± 50 s (see Fig. 4g), while the periods of the accompanying flare were about 360 ± 30 and 500 ± 60 s (see Fig. 4h). It is clear that the periods of the flare and the expanding loops in the low corona are significantly shorter than that of the wave train derived from the low-resolution LASCO/C2 observations.

3. Interpretation and discussion

Our observational results suggest that the eruption of the source region should be a classified as a failed breakout eruption, in which the magnetic reconnection took place between the two lateral low-lying loop systems. In this case, the reconnection around the null point results in negative feedback to the instability of the breakout magnetic system. Although the failed eruption did not cause a CME in the outer corona, it excited a QFP wave train because of the rapid stretching and expansion of the newly formed large-scale high-lying loops.

Figure 5 shows a cartoon illustrating the proposed physical picture. Figure 5a shows the initial magnetic configuration, which is a typical magnetic breakout topology consisting of three low-lying closed-loop systems enclosed by a large high-lying one. Naturally, a magnetic null point forms between the middle and the high-lying loops (or between the two lateral low-lying loops). In response to an unknown factor, the two lateral low-lying loops move close to each other and magnetic reconnection is therefore triggered between them (see the red cross symbol in Fig. 5b). The consequence of the reconnection is the formation of two new loop systems as shown by the red curves in Fig. 5c. The hard X-ray source should be located around the reconnection site in comparison with the observation. While the downward-moving hot reconnected loops form the observed post-flare-loop, the upward moving reconnects loops correspond to the observed expanding loops in the hot AIA 131 Å images. As the middle section of the upward-moving reconnect ed loop is curved upward, magnetic tension force in the same direction will stretch it and lead to the outward acceleration and expansion. When the loop becomes curved downward, the magnetic tension force also becomes downward, as in the initial high-lying large loop. As a result, the loop will decelerate and move downward to reach a stable state, during which the loop might undergo an oscillation phase. We propose that each upward-moving reconnect ed field line can excite a wavefront during its fast acceleration phase. Due to the sequential generation of upward-moving reconnect ed magnetic field lines in the reconnection, it is reasonable to expect the generation of an outward-propagating QFP wave train as shown in Fig. 5d. Our observation not only reveals the reconnection around the null point, but also the acceleration, expansion, and contraction of the newly formed high-lying loops.

The magnetic breakout mode was initially developed to interpret the generation of large-scale CMEs, in which the magnetic
reconnection occurs between the middle low-lying loop and the high-lying one (Antiochos et al. 1999). In this case, the reconnection rapidly removes the high-lying restraining field and therefore allows the low-lying core field to escape. To date, this model has been confirmed by many multi-wavelength observations, and it can nicely explain multi-ribbon flares in tripolar and quadrupolar magnetic regions (e.g., Sterling & Moore 2001; Lynch et al. 2004; Shen et al. 2012, 2019b; Chen et al. 2016, 2021; van der Holst et al. 2009; Zhou et al. 2021a) and small-scale coronal jets (Wyper et al. 2017, 2018; Kumar et al. 2018, 2019; Hong et al. 2019; Shen et al. 2019b, 2011a; Shen 2021). The magnetic breakout mode can also produce failed solar eruptions without association to CMEs if the reconnection occurs between the two lateral low-lying loop systems as shown in our cartoon (see Fig. 5). In this case, the upper reconnected loops spring upward and continuously feed magnetic flux to the previous existing high-lying loop system during the reconnection. Therefore, the confinement ability of the high-lying loop system will be enhanced significantly, and such negative feedback to the instability of the magnetic breakout system can naturally produce failed solar eruptions. In previous studies, a hard-X-ray source above failed filament eruptions (e.g., Ji et al. 2003; Alexander et al. 2006) and the presence of four weak flare ribbons preceding a strong two-ribbon flare (Williams et al. 2005) might contribute to the magnetic reconnection between the two lateral low-lying loop systems. In addition, numerical simulation results also indicate that such a reconnection can cause failed eruptions (DeVore & Antiochos 2008).

Based on our findings, we propose that the wave train was possibly excited by the rapid expansion of the newly formed high-lying loops as illustrated by the cartoon, although the period of the wave train (26 min) was significantly different from those of the expanding loops (320 ± 50 s), and the wave train was not detected in the low corona. Here, we propose two possible ways to reconcile such a discrepancy. Firstly, some relatively weak wavefronts in the QFP wave train may not be detected by the LASCO/C2 because of the low spatialtemporal resolution, or some of the initially generated wavefronts may have dissipated when they reached the FOV of the LASCO/C2. Secondly, the LASCO/C2 may not detect periods of shorter than 24 min because of the limitation of the Nyquist frequency of 0.7 mHz given by its 12 min cadence. The fact that the QFP wave train did not appear in the FOV of the AIA might be due to the small FOV of the AIA. Previous observations indicate that a QFP wave train often firstly appears at a distance of greater than 100 Mm from the associated flare epicenter (Shen et al. 2022). However, for our case, such a distance is out of the AIA FOV. In a numerical simulation, Pascoe et al. (2017) found that the geometrical dispersion associated with the waveguide suppresses the nonlinear steepening for trapped compressive perturbations. This might be why QFP wave trains always appear at a certain distance far from the generation source region.

It is noted that one period of the flare (360 ± 30) was similar to that of the expanding loops (320 ± 50 s), which might suggest that the intermittent energy release caused by stepwise reconnection between different loops can directly modulate the flare pulsation. The present observation of the sequential generation of expanding loops provides clear evidence of the existence of some common periods in QFP wave trains and the accompanying flares. In addition, the generation mechanism of quasi-periodic pulsations in flares is still hotly debated, although various candidate models have been documented in the literature (e.g., Nakariakov & Melnikov 2009; Van Doorsselaere et al. 2016; Kupriyanova et al. 2020; Zimovets et al. 2021; Li et al. 2020a,b). Our observation also provides an explanation as to the generation of quasi-periodic pulsation in flares.

The energy flux carried by the QFP wave train can be estimated from the kinetic energy of the perturbed plasma that propagates at the group speed, namely, $E = (\frac{1}{2}\rho v_t^2)\nu_g$, where $\rho$ is the plasma density, $v_t$ is the disturbance amplitude of the locally perturbed plasma, and $\nu_g$ is the group speed of the wave train. For a rough estimation, one can assume that the group speed is equal to the value of the measured phase speed. In addition, in the optically thin corona, the emission intensity $I$ is directly proportional to the square of the plasma density, namely $I \propto \rho^2$. Here, it should be pointed out that the emission intensity is also proportional to the column-depth perturbations, and is especially pronounced if the spatial resolution is limited (Cooper et al. 2003; Gruszczek et al. 2012). For a rough estimation, the density modulation of the background density $\Delta\rho$ can be written as $\frac{\rho}{\rho_0}$, and the energy flux of the perturbed plasma can be rewritten as $E \geq \frac{1}{2}\rho v_t^2(\frac{\rho}{\rho_0})^2$ if one assumes that $\frac{\rho}{\rho_0}$ is equal to or greater than $\frac{\Delta\rho}{\rho_0}$ (see Shen et al. 2022, and references therein). For the present case, the phase speed and the relative amplitude of the wave train are about 218 km s$^{-1}$ and 50%, respectively. In addition, based on the coronal plasma density model presented in Sittler & Guhathakurta (1999), the electron number densities at the heights of 2–4 $R_\odot$ are 0.5–0.1 $\times 10^6$ cm$^{-3}$. Therefore, we derived that the energy flux of the wave train at the height of 2–4 $R_\odot$ is in the range of 324–65 erg cm$^{-2}$ s$^{-1}$.

For a fast-mode wave guided by a field-aligned plasma nonuniformity, its speed has a value somewhere between the Alfvén speeds inside and outside the nonuniformity. Therefore, assuming the observed wave train was a linear fast-mode magnetoionic wave along coronal magnetic field lines, we can estimate the magnetic field strength in the height range of 2–4 $R_\odot$ using the measured wave speed of $v_p = \frac{E}{\frac{I}{2\mu I}} = \frac{\sqrt{\mu I}}{r}$, where $\mu = 1.27 \times 10^{-24}$ g is the proton mass. The derived results show that the magnetic field strength in the height range of 2–4 $R_\odot$ was in the range of 0.11 – 0.05 Gauss.

4. Conclusions

We report the first white-light imaging observation of a QFP wave train recorded by LASCO/C2 high above the limb (at heliocentric distances from 2 to 4 solar radii), the speed, period, and wavelength of which were about 218 km s$^{-1}$, 26 min, and 345 Mm, respectively. We propose that the QFP wave train might be excited by the rapid outward expansion of low coronal loops generated by the magnetic reconnection between the two lateral low-lying loop systems of the magnetic breakout configuration in active region AR12172. In addition to the generation of the QFP wave train, the reconnection also led to the enhancement of the high-lying confining magnetic field strength of the system, which can be regarded as a main physical factor leading to failed solar eruption. We find that the intermittent generation of the outward-moving reconnected loops is intimately associated with the stepwise nonlinear reconnection process, which can easily account for the existence of common periods in flares and QFP wave trains. Using the wave properties of the wave train and the coronal plasma density model, it is estimated that the energy flux carried by the wave train was in the range of 324–65 erg cm$^{-2}$ s$^{-1}$, while the magnetic field strength at the height of 2–4 $R_\odot$ was in the range of 0.11–0.05 Gauss.
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