Detection of Flare Multiperiodic Pulsations in Mid-ultraviolet Balmer Continuum, Lyα, Hard X-Ray, and Radio Emissions Simultaneously

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Abstract

Quasi-periodic pulsations (QPPs), which usually appear as temporal pulsations of the total flux, are frequently detected in the light curves of solar/stellar flares. In this study, we present the investigation of nonstationary QPPs with multiple periods during the impulsive phase of a powerful flare on 2017 September 6, which were simultaneously measured by the Hard X-ray Modulation Telescope (Insight-HXMT), as well as the ground-based BLENSW. The multiple periods, detected by applying a wavelet transform and Lomb–Scargle periodogram to the detrended light curves, are found to be ~20–55 s in the Lyα and mid-ultraviolet Balmer continuum emissions during the flare impulsive phase. Similar QPPs with multiple periods are also found in the hard X-ray emission and low-frequency radio emission. Our observations suggest that the flare QPPs could be related to nonthermal electrons accelerated by the repeated energy release process, i.e., triggering of repetitive magnetic reconnection, while the multiple periods might be modulated by the sausage oscillation of hot plasma loops. For the multiperiodic pulsations, other generation mechanisms could not be completely ruled out.

Unified Astronomy Thesaurus concepts: Solar flares (1496); Solar oscillations (1515); Solar ultraviolet emission (1533); Solar x-ray emission (1536); Solar radio emission (1522)

1. Introduction

Solar flares are powerful eruption events on the Sun associated with a rapid and violent release of magnetic free energy through a reconnection process. A typical flare can radiate at almost all wavelengths constituting the solar spectrum, ranging from radio through optical and ultraviolet (UV) to soft/hard X-ray (SXR/HXR) and even γ-rays (e.g., Benz 2017; Tan et al. 2020). Only a small part of the flare radiation is emitted at the shortest wavelengths in the X-ray and extreme-UV (EUV) ranges (Emslie et al. 2012). The quantitative estimation of the radiated flare energy partition suggested about 70% in white light (WL) for solar flares (e.g., Kretzschmar 2011) and 55%–80% in WL for stellar flares (e.g., Kuznetsov & Kolotkov 2021). In other words, most of the flare energy is radiated in the longer wavelengths (Kleint et al. 2016). Between those extremes, the solar UV spectrum from 1000 to 3000 Å, which can be further split into the far-ultraviolet (FUV), the mid-ultraviolet (MUV), and the near-ultraviolet (NUV), is thought to provide an important contribution to the flare radiation (Woods et al. 2006; Milligan et al. 2014; Dominique et al. 2018). For instance, the Lyα spectral line produced by the chromospheric neutral hydrogen, which is centered at 1216 Å (in the FUV spectrum), is among the spectral lines in which flares radiate the most (Allred et al. 2005; Curt et al. 2001; Lu et al. 2021a). The hydrogen Balmer continuum emitted during flares, which is thought to be generated during the recombination of flare-produced free electrons in the chromosphere, is often detected in the MUV and NUV ranges, as well as close to the Balmer recombination edge at 3646 Å (Heinzel & Kleint 2014; Kotrč et al. 2016; Dominique et al. 2018). Both the Lyα and hydrogen Balmer continuum emissions during solar flares are expected to be nonthermal profiles, i.e., similar to the HXR radiation that is produced by the beam of electrons that are accelerated by the magnetic reconnection during the solar flare (e.g., Avrett et al. 1986; Rubio da Costa et al. 2009; Heinzel & Kleint 2014).

Quasi-periodic pulsations (QPPs) often refer to the quasi-periodic intensity variations during solar/stellar flares (see Zimovets et al. 2021, for a recent review). In many observations, the flare QPPs were found to show a nonstationary property in the time series integrated over the whole Sun/star or over the oscillation region, for instance, each pulsation has an anharmonic and symmetric triangular profile shape (e.g., Kolotkov et al. 2015; Nakariakov et al. 2019). The signature of flare QPPs can be detected in flare light curves across a broad band of the electromagnetic spectrum, i.e., radio/microwave emissions (Ning et al. 2005; Reznikova & Shibasaki 2011; Nakariakov et al. 2018; Yu & Chen 2019), UV/EUV wavelengths (Shen et al. 2018; Hayes et al. 2019; Reeves et al. 2020; Miao et al. 2021), SXR/HXR and γ-ray channels (Nakariakov et al. 2010; Ning et al. 2017; Hayes et al. 2020; Li et al. 2020c), and the Hα (Srivastava et al. 2008; Kashapova et al. 2020; Li et al. 2020b) or Lyα (Van Doorsselaere et al. 2011; Milligan et al. 2017; Li 2021) emissions. The quasi-periods of these QPPs were reported from subseconds to tens of minutes (e.g., Tan et al. 2010; Shen et al. 2013, 2019; Kolotkov et al. 2018; Karlický & Rybák 2020; Clarke et al. 2021). It should be stated that the observed periods are generally related to the specific channels or flare phases (Tian et al. 2016; Dennis et al. 2017; Pugh et al. 2019), suggesting that the various classes of QPPs could be produced by different generation mechanisms (e.g., Kupriyanova et al. 2020). In the literature, the flare-related QPPs were most often explained by magnetohydrodynamic (MHD) waves, more specifically sausage waves, kink waves,
and slow waves (Li et al. 2020a; Nakariakov & Kolotkov 2020; Wang et al. 2021), or by a repetitive regime of magnetic reconnection that could be spontaneous (i.e., self-oscillatory process) or triggered owing to external MHD oscillations (Thurgood et al. 2017; Yuan et al. 2019; Clarke et al. 2021). They can also be interpreted in terms of the LRC-circuit oscillation in current-carrying loops (Tan et al. 2016; Li et al. 2020b) or caused by the interaction between supra-arcade downflows and flare loops (Xue et al. 2020; Samanta et al. 2021).

The hydrogen Balmer continuum enhancement at MUV wavelengths around 2000 Å was found to be highly synchronous with the enhancement of Lyα emission during a powerful solar flare (Dominique et al. 2018), while the flare radiation in the Lyα and HXR ranges was demonstrated to have a close relationship (Nusinov et al. 2006; Jing et al. 2020; Lu et al. 2021). However, flare-related QPPs were rarely observed simultaneously in these channels. In this study, we report the detection of flare-related QPPs with multiperiodicity in the MUV Balmer continuum, Lyα, HXR, and radio emissions during the impulsive phase of a powerful solar flare.

2. Observations and Instruments

On 2017 September 6, the active region of NOAA 12673 produced the most powerful flare of the solar cycle 24, measured to be of the X9.3 class. It was simultaneously recorded by the space-based instruments of the Large-Yield Radiometer (LYRA) on board the PROject on Board Autonomy 2 (PROBA2) mission (Dominique et al. 2013), the Hard X-ray Modulation Telescope (Insight-HXMT; Zhang et al. 2020), and the Geostationary Operational Environmental Satellite 16 (GOES-16), as well as the ground-based CALLISTO radio spectrograph (Benz et al. 2009) at BLENSW, as shown in Figure 1 and Table 1. Note that all the space- and ground-based instruments observe in a Sun-as-a-star mode. The GOES SXR flux at 1–8 Å (black curve) suggests that the powerful flare begins at about 11:53 UT and reaches its maximum at around 12:02 UT, as indicated by the vertical dashed line in Figure 1(a).

LYRA provides the solar irradiance measurement in four wide spectral channels with a high time resolution of 0.05 s (Dominique et al. 2013, 2018). Channels 3 and 4 measure the solar radiation in SXR/EUV ranges at 1–800 Å and 1–200 Å, and they look very similar. Therefore, only the light curve from channel 4 (blue) is shown in Figure 1(a), which exhibits a similar time evolution to the GOES SXR flux. However, the flux peak is a bit later than that of the GOES SXR flux. This could be attributed to the observational fact that the light curve from LYRA channel 4 measures the solar SXR/EUV radiation in a long and broad wavelength range, i.e., 1–200 Å (Dominique et al. 2018), while the GOES SXR flux only covers a short and narrow wavelength range of 1–8 Å. On the other hand, channel 1 observes the solar irradiance in the FUV channel centered at the Lyα 1216 Å line, which is also referred to as the Lyα channel, while channel 2 takes the solar observation in the MUV channel between 1900 and 2220 Å, which is demonstrated to be consistent with the hydrogen Balmer continuum emission around 2000 Å and is formed in the chromosphere (e.g., Dominique et al. 2018). Therefore, LYRA channel 2 is considered to provide the solar radiation in the MUV Balmer continuum. Figure 1(b) draws the normalized light curves between 11:55:07 UT and 12:03:27 UT from LYRA channels in the Lyα (black) and MUV Balmer continuum (cyan) ranges, showing a well-synchronous relationship in the time series. Taking into account that LYRA observes in a Sun-as-a-star mode, it is impossible to conclude that they are radiated from the same source area, due to the lack of the spatially resolved information.

In this study, two X-ray light curves measured by Insight-HXMT (Zhang et al. 2020), which has a time cadence of 1 s, were also used to investigate the flare-related QPPs. The Medium Energy X-ray telescope (ME) observes the X-ray emission normally at 5–30 keV (Cao et al. 2020; Luo et al. 2020). The Anti-Coincidence Detector (ACD) provides the HXR flux at higher energy, i.e., >100 keV, which was adopted from the High Energy X-ray telescope after removing the background that is induced by the particle (Liu et al. 2020). Figure 1(b) presents the X-ray light curves as normalization during 11:55:07–12:03:27 UT derived from the ME (magenta) and ACD (red). They both match well with the LYRA light curves, which serves as the reference for the LYRA channel 4 light curve.

![Figure 1](https://www.thesolarmonitor.org/)

Table 1

| Instruments | Channels | Cadence | Wavelengths | Bandpass |
|-------------|----------|---------|-------------|----------|
| GOES-16     | XRS      | 1 s     | 1–8 Å      | SXR/EUV  |
| HXMT        | ME       | 1 s     | 5–30 keV   | SXR/HXR  |
|             | ACD      | 1 s     | >100 keV   | HXR      |
| BLENSW      |          | 0.25 s  | ~20–76 MHz | Radio    |

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Figure 1. Light curves integrated over the whole Sun during the X9.3 flare on 2017 September 6, recorded by GOES, LYRA, Insight-HXMT, and BLENSW, respectively. Notice that all the light curves except for the GOES flux are shown as normalization. The context image in panel (a) is the ratio dynamic spectra measured by the BLENSW. The short green line marks the radio frequency at 34.75 MHz, which is plotted in panel (b); the dashed line indicates the flare peak time.
curves at channels 1 and 2, but the ACD light curve seems to show a much clearer enhancement after 12:00 UT, as indicated by the red arrow. Moreover, there is almost no time delay between the light curves measured by LYRA and Insight-HXMT, both of which have very burst profiles, confirming their nonthermal profiles.

The major X9.3 flare was also observed by the radio spectrogram from BLENSW (Benz et al. 2009) at low frequencies between about 20 and 76 MHz, which has a time cadence of 0.25 s, as shown by the context image in Figure 1(a) and Table 1. A sequence of transient bursts can be found in the radio dynamic spectrum during the flare impulsive phase, i.e., during ~11:57–12:02 UT. They all drift rapidly from high to low frequencies over a quite short time, which can be regarded as the type III radio bursts and could be helpful to trace the propagating electron beams through the solar atmosphere during solar flares. Figure 1(b) also draws the normalized radio flux (green) at a low frequency of 34.75 MHz, which has been shifted in height to show clearly. It exhibits a burst profile, which is similar to the light curves recorded by LYRA and Insight-HXMT. Obviously, the onset time of the enhancement in radio flux at the low frequency is later than that in light curves at Lyα, MUV Balmer continuum, and HXR emissions.

Figure 2. (a, d) Full-disk light curves (black) observed by LYRA at channels 1 and 2, and their FFT filtered profiles (green). Two green arrows mark the double main peaks in the raw light curves. (b, e) Detrended light curves. (c, f) Morlet wavelet power spectra. The magenta lines outline the significance level of 99.9%.

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3. Results

The flare light curves at wavelengths of MUV Balmer continuum, Lyα, and HXR are characterized by a number of small pulsations, referred to as QPPs. Similar to previous observations (Ning 2014; Li et al. 2017; Milligan et al. 2017; Feng et al. 2020), these small pulsations are superimposed on the strong background. To look more closely at the periodicity of this flare, we apply the wavelet transform method (Torrence & Compo 1998) to the detrended light curves, where detrending is obtained by filtering out the longest periods (i.e., the long-term trend) from the original/raw time series. Here, the wavelet mother function of “Morlet” is used for the wavelet analysis. The results are shown in Figures 2, 4, and 5. Based on the fast Fourier transform (FFT) method, the raw light curves measured by LYRA, Insight-HXMT, and BLENSW are detrended using a cutoff threshold of 60 s, thereby enhancing the periods that are shorter than 60 s. Thus, the periodic features with short periods can be highlighted in the wavelet power spectrum (Feng et al. 2017; Milligan et al. 2017; Ning 2017).

Figures 2 presents the Morlet wavelet analysis results for the LYRA data from two channels. The top two panels draw the raw light curves of Lyα (channel 1) and MUV Balmer continuum (channel 2) emissions; the long-term trend obtained by FFT
filtering is overplotted in green. Two main pulses appear in the raw light curves during about 11:55:40–11:58:20 UT, as indicated by the two green arrows in panels (a) and (d). The oscillatory amplitude of the two main pulses is much larger than that of the short-period QPPs studied in this study, which may result in a weak power of the wavelet analysis. Therefore, to suppress the long-period trend that is caused by the two main pulses, a cutoff period of ∼60 s is used for the raw light curves. The detrended light curves are obtained by subtracting the FFT filtered time series, as plotted in the middle panels. They both show a series of pulsations, and each pulsation has an anharmonic and symmetric triangular profile shape, which can be regarded as the signature of nonstationary QPPs. The bottom panels plot the wavelet power spectra for the detrended light curves in Lyα (panel (c)) and MUV Balmer continuum (panel (f)) emissions, both of which show an enhanced power over a wide range of periods during the impulsive phase of the powerful flare, i.e., between about 11:56 UT and 12:02 UT, implying the multiperiodicity QPPs. The bulk of the detections in the two power spectra are evident at periods of about 20–55 s. Interestingly, the quasi-periods appear to have different lifetimes. For instance, the quasi-periods of ∼20–30 s are seen to happen from about 11:56 UT to 11:57 UT only, while the 30–50 s QPPs are seen to occur between about 11:56 UT and 11:59 UT, and the quasi-periods of 50–55 s are seen to appear during ∼11:57–12:02 UT. However, the 50–55 s QPP signal is very close to the cutoff threshold, which might be an artifact of detrending. Similarly to previous studies (Kupriyanova et al. 2010; Milligan et al. 2017), we then extracted the detrended time series from the raw LYRA data with a long cutoff threshold of 120 s, as shown in Figure A.1 appearing in the Appendix. The wavelet power spectra show a much broader range of periods, such as 20–100 s. The strongest power appears at the period of ∼60–100 s between ∼11:55:40 UT and ∼11:58:20 UT, which is largely due to the two main pulses shown by the green arrows in Figure 2(a) and (d). They are not suppressed when we used a cutoff threshold of 120 s for detrending, as shown in Figure A.1(a) and (b). On the other hand, the short periods of about 20–55 s exhibit a little weak power, but they are still inside the 99.9% significance level, which confirms that the short periods in LYRA channels 1 and 2 are not artifacts of the detrending process.

The wavelet power spectra in Figure A.1 show a broad range of periods with a brightest core and weaker borders. Using the Lomb–Scargle periodogram method (Scargle 1982), the periodogram analysis is performed on the detrended light curves. Figure 3 presents the normalized FFT power spectra at LYRA channels 1 (panel (a)) and 2 (panel (b)), and two different values of cutoff thresholds are used for detrending, e.g., 60 s (black) and 120 s (magenta), respectively. The dashed lines in the FFT spectra represent the significance levels of 99.9%, which are estimated from the red noise in quasi-periodic signals (Vaughan 2005; Liang et al. 2020; Anfinogentov et al. 2021). The short periods of ∼20–55 s can be simultaneously seen in all the FFT power spectra, but the quasi-periods of ∼20–40 s are quite weak in the FFT power spectra from the detrending light curves by applying a big cutoff threshold of 120 s, as shown by the magenta lines. On the other hand, the long period of roughly 80 s is only found in the FFT power spectra from the detrending light curves by applying the 120 s cutoff threshold, and it is well suppressed by the 60 s cutoff threshold, which is similar to Morlet wavelet analysis results. The FFT spectra further confirm that the short periods of ∼20–55 s are not artifacts of the detrending process. However, it is impossible to determine the duration of the short periods, especially the lifetime of periods between 50 and 55 s, since they are also seen at the border edges of the strongest power in the wavelet power spectra in Figure A.1. We also notice that the 80 s period has been studied in the flare emission at wavelengths of Lyα (Li et al. 2020d) and HXR emission (Zhang et al. 2021), respectively. Therefore, we only focused on the short periods of ∼20–55 s in this study.

Figure 4 shows the Morlet wavelet analysis results for the Insight-HXMT data at ME and ACD channels. Using the same FFT method, the long-term trend and detrended time series are separated from the raw light curves, as shown in the top and middle panels. The two main pulses are also found in the raw light curves at HXR channels (a) and (f), which are similar to the double main pulses measured by the LYRA from channels 1 and 2. Then the wavelet analysis technique is applied to the detrended time series, as shown in panels (e) and (f). Thus, the quasi-periods in flare X-ray emissions can be determined in their wavelet power spectra. They both show an enhanced power over a broad range of periods at roughly 20–55 s during the flare impulsive phase, suggesting that they are multiple periods, which is similar to that in Lyα and MUV Balmer continuum emissions. Moreover, the multiple periods appear to show different lifetimes. The quasi-periods of roughly 20–40 s are found to appear between ∼11:56 UT and ∼11:58 UT, and they could be coexistent, while the periods of about 50–55 s are seen to occur from about 11:57 UT to 12:01 UT, that is, they have multiple oscillatory signals with periods of about 20–55 s and have different lifetimes.

Figures 5(a)–(c) present the Morlet wavelet analysis results for the BLENSW radio data at the low frequency of 34.75 MHz. Panels (g) and (h) plot the light curve and its detrended light curve by applying a cutoff threshold of 60 s. They both show a number of repeated and triangular peaks from about 11:57 UT to 12:02 UT, which could be regarded as
the flare QPPs. Moreover, these peaks show a good one-to-one correspondence between the raw and detrended light curves, indicating that they are really QPP signals rather than the artifact of detrending. Panel (c) draws the wavelet power spectrum, which clearly shows an enhanced power over a broad range, suggesting multiple periods in the low-frequency radio flux. On the other hand, the flare QPPs with multiple periods start at about 11:57 UT, which are later than those beginning at HXR channels, such as 1-minute time delay. Panel (d) further shows the normalized FFT power spectra of the low-frequency radio flux by applying the cutoff thresholds of 60 s (black) and 120 s (magenta) for detrending. Similar to previous LYRA results in Figure 3, the short periods of ∼20–55 s can be simultaneously seen in these two FFT power spectra, and they are corresponding well with each other, although their peaks obtained from the 120 s cutoff threshold are a bit low. This confirms that the short periods are not artifacts of the detrending process.

Similar nonstationary QPPs with multiple periods can be simultaneously detected at wavelengths ofLyα, MUV Balmer continuum, HXR, and low-frequency radio during the impulsive phase of a powerful solar flare. To further study their relationship, we then draw the correlation between the HXR flux and Lyα emission (black), as well as the MUV Balmer continuum emission (cyan), as shown in Figure 6(a). Here, the LYRA data have been interpolated into a time cadence of 1 s, which is the same as that of the Insight-HXMT data, so that the correlation between two different instruments can be well underlined. Notice that the raw light curve rather than the detrended one is used here. The high correlation coefficients (cc.) are obtained between them, which are 0.88 and 0.85, respectively. On the other hand, low correlation coefficients are found between the SXR flux at GOES 1–8 Å and the MUV Balmer continuum or Lyα emissions, i.e., coefficients of 0.12 or 0.19. These correlation coefficients further confirm that both the Lyα and MUV Balmer continuum emissions recorded by LYRA at channels 1 and 2 show nonthermal temporal behaviors rather than thermal profiles, which agrees well with previous findings (e.g., Dominique et al. 2018; Milligan et al. 2020).

The time delay is found between the HXR and low-frequency radio data, as shown in Figure 1(b). To further investigate their links, we then perform their cross-correlation analysis, as well as the cross-correlation analysis between the HXR and LYRA data, as shown in Figure 6(b). A maximum correlation coefficient of ∼0.57 between the HXR and low-frequency radio data is seen at the time lag of around 60 s, as indicated by the magenta vertical line, which indicates a time delay of about 60 s between them. On the other hand, the maximum correlation coefficients of 0.88 and 0.85 are found between the HXR and LYRA data at the time lag of 0 s (black vertical line), suggesting no time delay between them, which is
We would like to state that the raw light curves rather than the detrended time series are used for the cross-correlation analysis. The maximum correlation coefficient between the HXR and radio data is only \( \sim 0.57 \), which is slightly lower than those between HXR and LYRA data. This is because the pulses in radio flux show large amplitudes, for instance, increasing and decaying rapidly with respect to their background emission, while the HXR/LYRA light curves only exhibit small-amplitude pulsations, as shown in Figure 1(b). The positive correlation between the HXR and radio signals suggests that they are produced by the same process of energy releases, i.e., magnetic reconnection during the solar flare.

### 4. Summary and Discussion

Using the observations measured by PROBA2/LYRA, Insight-HXMT, and BLENSEW, we investigate the nonstationary QPPs with multiple periods during the impulsive phase of the X9.3 flare on 2017 September 6, which was the most powerful flare of solar cycle 24. Based on the wavelet analysis technique (Torrence & Compo 1998) and the Lomb–Scargle periodogram method (Scargle 1982), the multiple periods from roughly 20 s to about 55 s are simultaneously identified during the flare impulsive phase in the Ly\( \alpha \) emission, the MUV wavelengths around 2000 Å, and HXR and radio channels. Multimode QPPs with nonstationary properties were studied in similar to previous findings in Figure 1.
the microwave/HXR emission during solar flares (Inglis & Nakariakov 2009; Kolotkov et al. 2015). Using the wavelet analysis method, Inglis & Nakariakov (2009) demonstrated that the multiple periods of multimode QPPs could coexist nearly simultaneously, and there was almost no significant period (or frequency) shift over time. In this study, the flare QPPs are detected simultaneously in multiple wavelengths, i.e., MUV, Lyα, HXR, and low-frequency radio. On the other hand, the multiple periods observed in this flare are not coexisting. The quasi-periods of 50–55 s are affected by the two main pulses, which makes it difficult to determine their onset time and lifetimes. However, the quasi-periods of ~20–40 s can only be found during ~11:56–11:59 UT, which are obviously shorter than the 50–55 s periods. This suggests that the multiple periods have different lifetimes. Thus, the flare QPPs observed here are regarded as multiple periods with different lifetimes. Previous studies suggested that the MUV wavelengths around 2000 Å agreed well with the hydrogen Balmer continuum emission produced in the optically thin chromosphere (Dominique et al. 2018). Therefore, this is the first report of flare-related QPPs with multiple periods in the MUV Balmer continuum emission.

The QPP behaviors of the X9.3 flare have been studied at wavelengths of radio, SXR, HXR, and even γ-ray (Kolotkov et al. 2018; Karlický & Rybák 2020; Li et al. 2020c; Zhang et al. 2021). Kolotkov et al. (2018) first investigated the QPP signals during the X9.3 flare. They found that the QPP periods varied from around 12 to 25 s in the thermal emission during the flare impulsive and decay phases and attributed them to the sausage oscillations of flaring loops. Next, Li et al. (2020c) studied the flare-related QPPs with periods of about 20–30 s at channels of radio, HXR, and γ-ray during the impulsive phase, and the similar periods were also reported by Zhang et al. (2021). Then, Karlický & Rybák (2020) detected multiple periods (i.e., 1–2 s, 5.3–8.5 s, and 11–30 s) mainly in the radio emission during the pre-impulsive and impulsive phases of the X9.3 flare. In this study, we report the multiperiodic QPPs during the flare impulsive phase in Lyα, MUV Balmer continuum, low-frequency radio, and HXR channels simultaneously. The short periods of 20–40 s are detected during ~11:56–11:59 UT, which are similar to previous findings in the radio, HXR, and γ-ray channels (Li et al. 2020c; Zhang et al. 2021). However, they could not study the QPP behaviors after 11:59 UT, largely due to their observational limitations. Here, the long periods of ~50–55 s are also found from roughly 11:57 UT to 12:02 UT. We would like to point out that a much longer period of roughly 80 s could also be seen in the LYRA data, and it is mostly caused by the two main pulses during ~11:55:40–11:58:20 UT in the raw light curves, which are similar to the intermittent feature in the HXR emission (Zhang et al. 2021). However, it is not suitable for a typical QPP, since it only remains for two cycles (e.g., two pulses). Moreover, the flare QPPs with periods of about 60–80 s have been reported in the Lyα emission during solar flares (Li et al. 2020d). So, only the short periods between ~20 and ~55 s are studied at wavelengths of Lyα, MUV Balmer continuum, HXR, and low-frequency radio in this study.

It is necessary to discuss the generation mechanism that can be responsible for the multiperiodic QPPs detected simultaneously at wavelengths of Lyα, MUV Balmer continuum, HXR, and low-frequency radio. The Lyα irradiance during a solar flare is found to be closely related to the MUV Balmer continuum emission, and it also appears highly synchronous with the HXR emission (Rubio da Costa et al. 2009; Dominique et al. 2018). On the other hand, the flare radiation in HXR and low-frequency radio channels during the impulsive phase is generally produced by the bidirectional nonthermal electrons accelerated by the magnetic reconnection (e.g., Benz 2017). Therefore, the flare QPPs simultaneously observed in the Lyα, MUV Balmer continuum, HXR, and low-frequency radio channels are most likely to be triggered by the same repeated energy release process, i.e., the periodic regime of magnetic reconnection (Li et al. 2017, 2020c; Clarke et al. 2021). The pulsed, bidirectional electron beams are accelerated by the intermittent magnetic reconnection during the flare impulsive phase. The downward accelerated electrons precipitated toward the chromosphere along the flare loop, resulting in quasi-periodic enhancements in Lyα, MUV Balmer continuum, and HXR emissions, while the upward electron beams escaped along an open magnetic field line and generated radio pulsations at the low frequency of 34.75 MHz. The time delay of about 60 s between the HXR QPP and the low-frequency radio QPP is attributed to the traveling time of the upward electron beams propagating outward from the Sun (Li et al. 2015; Clarke et al. 2021). It is generally accepted that the type III radio burst is produced by the electron beam traveling along the magnetic field and outward from the Sun (Reid & Ratcliffe 2014). In particular, the radio emissions at frequencies of about 200–0.03 MHz are often dominated by the plasma emission mechanism (e.g., Gary & Hurford 1989). That is, the radio frequency (f) is roughly proportional to the local electron density (νe), such as f ≈ 8980/νe (e.g., Lu et al. 2017). Based on the electron density model developed by Vršnak et al. (2004), the radio flux at the frequency of 34.75 MHz is produced at the heliocentric height of roughly 2.5 Rc (Rc represents the solar radius) above the Sun, and it agrees with previous models (e.g., Gary & Hurford 1989; Krupar et al. 2014). Then, the average speed of the electron beam is estimated to be ~0.1c (c is the light speed), which is consistent with previous findings in the range of 0.1c–0.5c (Dulk et al. 1987; Reid & Ratcliffe 2014; Clarke et al. 2021). Considering that the multiple periods have different lifetimes, the repetitive magnetic reconnection is probably induced rather than spontaneous. The similar short periods have been found in the major X9.3 flare (Kolotkov et al. 2018) or in the flare Lyα emission (Van Doorsselaere et al. 2011), which were interpreted in terms of sausage oscillations. Therefore, the multiple periods of ~20–55 s might be modulated by the sausage oscillations of hot plasma loops in the flare region (Chen et al. 2015; Guo et al. 2016). The flare-related QPPs with multiple periods could also be related to the length of flare loops and each other (e.g., Reznikova & Shibasaki 2011; Pugh et al. 2019). However, the other generation mechanisms, for instance, driven directly by MHD waves, or by LRC-circuit oscillations, could not be completely ruled out, largely due to the absence of the spatially resolved information, i.e., high-resolution images at wavelengths of MUV, Lyα, radio, and HXR.

It should be stated that Insight-HXMT is primarily used to scan the Galactic plane and study X-ray binaries and gamma-ray bursts (Zhang et al. 2020). However, the present study reveals that it can also capture the HXR emission of solar flares, like, in this case, the X9.3 flare on 2017 September 6. The X9.3 flare was measured by Konus-Wind in HXR and γ-ray wavelengths, but these
observations only covered a total duration of about 250 s (Li et al. 2020c), which makes it impossible to study the flare-related QPPs during the whole impulsive phase. Here, using the observations recorded by Insight-HXMT, PROBA2/LYRA, and BLENSW, we detect the similar flare-related QPP behaviors at channels of HXR, Lyα, MUV Balmer continuum emission, and the low-frequency radio, for instance, the multiple periods with different lifetimes. Our findings confirm the nonthermal temporal behaviors of flare radiation in Lyα and MUV Balmer continuum, which is consistent with previous observational results. In the study of Dominique et al. (2018), the derivative of the GOES SXR flux was used as a proxy for the HXR light curve, largely due to the absence of HXR measurements from solar telescopes. Thus, this study also provides an idea that some astronomical satellites such as Insight-HXMT or Fermi could also be used to study solar powerful eruptions, in particular the larger solar flare.

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### Appendix

Figure A.1 presents the Morlet wavelet analysis results for the LYRA data. Here, a long cutoff threshold of 120 s is used to the raw light curves (upper panels), and then the detrended time series can be obtained, as shown in the middle panels. The bottom panels show the wavelet power spectra, which display a much broader range of periods, i.e., 20–100 s. This result is consistent with that shown in the FFT power spectra (Figure 3).

*Figure A.1.* Following Figure 2, the Morlet wavelet analysis results for the LYRA data. Here, the detrending signals and their wavelet power spectra are obtained from the cutoff period of 120 s. The magenta lines outline the significance level of 99.9%.
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