Quasi-Periodic Pulsations Detected in Ly$\alpha$ and Nonthermal Emissions During Solar Flares

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Abstract We report quasi-periodic pulsations (QPPs) with double periods during three solar flares (viz. SOL2011-Feb-15T01:44, SOL2011-Sep-25T04:31, SOL2012-May-17T01:25). The flare QPPs were observed from light curves in Ly$\alpha$, hard X-ray (HXR) and microwave emissions, with the Ly$\alpha$ emission recorded by the Geostationary Operational Environmental Satellite, the HXR emission recorded by the Reuven Ramaty High-Energy Solar Spectroscopic Imager and the Fermi Gamma-ray Burst Monitor, and the microwave emission recorded by the Nobeyama Radio Polarimeters and Radioheliograph. By using the Markov chain Monte Carlo (MCMC) method, QPPs with double periods of about two minutes and one minute were first found in the Ly$\alpha$ emission. Then using the same method, a QPP with nearly the same period of about two minutes was also found in HXR and microwave emissions. Considering the possible common origin (nonthermal electrons) between Ly$\alpha$ and HXR/microwave emission, we suggest that the two-minute QPP results from the periodic acceleration of nonthermal electrons during magnetic reconnections. The ratio between the double periods in the Ly$\alpha$ emission was found to be close to two, which is consistent with the theoretical expectation between the fundamental and harmonic modes. However,
we cannot rule out other possible driving mechanisms for the one-minute QPPs in HXR/microwave emissions due to their relatively large deviations.

Keywords: Solar flares — Solar oscillations — Solar ultraviolet emission — Solar X-ray emission — Solar radio emission

1. Introduction

A solar flare is a sudden localized brightening in the solar atmosphere, corresponding to a rapid and violent energy release through the widely accepted magnetic-reconnection process (Masuda et al., 1994; Benz, 2017; Yan et al., 2018; Li et al., 2021). The flare emission often exhibits quasi-periodic temporal variations, which are referred to as quasi-periodic pulsations (QPPs) in solar flares (see Nakariakov and Melnikov, 2009; Van Doorsselaere, Kupriyanova, and Yuan, 2016, for reviews). Based on the time-series analysis, QPPs have been observed from light curves in various wavebands, from radio waves (Kolotkov et al., 2015; Nakariakov et al., 2018; Yu and Chen, 2019; Karlický et al., 2020) through ultraviolet (UV) and extreme ultraviolet (EUV) wavelengths (Brosius, Daw, and Inglis, 2016; Li et al., 2016; Kumar, Nakariakov, and Cho, 2017; Shen et al., 2018; Dominique et al., 2018; Miao et al., 2020) to soft/hard X-rays (SXR/HXR) channels (Li and Gan, 2008; Ning, 2014; Dennis et al., 2017; Inglis et al., 2017; Li and Zhang, 2017; Kolotkov et al., 2018), and even to γ-rays (Nakariakov et al., 2010; Li et al., 2020c). Thanks to spectroscopic observations with high temporal resolution, the flare-related QPPs were also found in spectral-line profiles of emission lines, such as the periodic variations in the line intensity and width, oscillations of the derived Doppler shift (Brosius and Daw, 2015; Li and Zhang, 2015; Li, Ning, and Zhang, 2015; Brosius, Daw, and Inglis, 2016; Zhang, Li, and Ning, 2016; Li et al., 2018), and the Solar Ultraviolet Measurements of Emitted Radiation (SUMER) oscillations with strong damping (Ofman and Wang, 2002; Wang et al., 2002; Wang, 2011). Understanding of the formation mechanism of QPPs is important for us to understand the energy release, particle acceleration, and plasma heating during solar flares, and it may also be useful for the forecast of solar flares (e.g. Van Doorsselaere, Kupriyanova, and Yuan, 2016; McLaughlin et al., 2018).

The characteristic periods of the flare-related QPPs were found to vary from milliseconds to dozens of minutes (e.g. Kupriyanova et al., 2010; Tan et al., 2010; Dolla et al., 2012; Shen et al., 2013; Cho et al., 2016; Duckenfield et al., 2018; Kobanov and Chelpanov, 2019; Karlický et al., 2020; Hayes et al., 2020; Li et al., 2020a), depending on the different observation wavebands (Tan et al., 2007; Huang et al., 2014; Dennis et al., 2017; Nisticò et al., 2017; Li et al., 2017; Pugh, Broomhall, and Nakariakov, 2019). This implies that the various QPPs are likely to originate from different physical mechanisms (Nakariakov and Melnikov, 2009; Tan et al., 2010), which are still an open issue (see McLaughlin et al., 2018, for reviews). Some studies suggest that the QPPs could be directly interpreted in terms of magnetohydrodynamic (MHD) waves, such as slow waves, kink waves, and sausage waves (Anfinogentov, Nakariakov, and Nisticò, 2015; Wang et al., 2018).
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2015; Mandal et al., 2016; Tian et al., 2016; Yuan and Van Doorsselaere, 2016; Nakariakov et al., 2016, 2019b; Nakariakov and Kolotkov, 2020), while some others tend to associate the QPPs with periodic magnetic reconnections, which could be either spontaneous or triggered by MHD oscillations (Kliem, Karlický, and Benz, 2000; Chen and Priest, 2006; Li, Ning, and Zhang, 2015; Guidoni et al., 2016; Thurgood, Pontin, and McLaughlin, 2017; Yuan et al., 2019).

The Lyman-α (Lyα) line at 1216 Å is a spectral line of hydrogen, which is formed in the chromosphere (Canfield and Puetter, 1981; Allred et al., 2005). Since the solar atmosphere contains a large abundance of hydrogen, the Lyα line is thought to be the strongest emission line in the solar UV spectrum. It was found that Lyα line emission not only shows a significant intensity enhancement during the solar flare (Curdt et al., 2001; Woods et al., 2004; Milligan et al., 2012, 2014; Milligan and Chamberlin, 2016; Hong et al., 2019; Lu et al., 2021), but also shows a clear response to coronal loops (Ishikawa et al., 2017) and filament eruptions (Susino et al., 2018). Moreover, the increased Lyα emission was found to be closely correlated with induced currents in the Earth’s ionosphere, particularly during solar high-activity periods (see Milligan et al., 2020). Thus study of the variation of Lyα emission is helpful for understanding the dynamics of the terrestrial environment.

Flare-related QPPs in Lyα emission have been reported by several authors. Ishikawa et al. (2017) reported short-period variations (<30 second) in the Lyα emission of coronal loops, which is supposed to be driven by nanoflares. ≈3-minute and ≈4.4-minute QPPs were discovered in the full-Sun integrated Lyα emission during the impulsive phase of two X-class flares, both of which were interpreted in terms of flare-induced acoustic waves (see Milligan et al., 2017, 2020; Li, 2021). ≈1-minute QPP is detected in the full-Sun Lyα emission during two solar flares, which is attributed to the repetitive magnetic reconnection (Li et al., 2020b). QPPs with both short (≈8.5 second) and long (≈63 second) periods were discovered in the Lyα channel during a solar flare, which are considered as standing fast and slow sausage modes, respectively (Van Doorsselaere et al., 2011).

The Lyα emission enhancement during solar flares was found to be highly synchronous with emission enhancement in hard X-ray (Nusinov et al., 2006). The source of Lyα emission was further found to be co-spatial with HXR sources located at flare footpoints (Rubio da Costa et al., 2009). Recently, a statistical study made by Jing et al. (2020) shows that the Lyα emission enhancement that appears in the impulsive phase of a solar flare generally follows the Neupert effect (Neupert, 1968). These observations show a close relationship between Lyα and hard X-ray emissions. Considering the common nonthermal origin between HXR and microwave emissions (Dulk, 1985; Holt and Ramaty, 1969; Aschwanden, 1987), a close relation between the Lyα and microwave emission is expected. In the present study, we investigated QPPs that are observed in Lyα, HXR, and microwave emissions during three powerful flares. This article is organized as follows: Section 2 describes the observations and method used in this study, Section 3 presents our primarily results, and Section 4 summarizes the conclusions and discussion.
Table 1. Characteristics of three solar flares studied in this article.

| No. | Flare          | GOES class | NOAA Number | Position  |
|-----|----------------|------------|-------------|-----------|
| 1   | SOL2011-Feb-15T01:44 | X2.2       | 11158       | [205,-222]|
| 2   | SOL2011-Sep-25T04:31  | M7.4       | 11302       | [-688,108]|
| 3   | SOL2012-May-17T01:25  | M5.1       | 11476       | [926,102] |

2. Observations and Method

Three solar flares that occurred on 15 February 2011, 25 September 2011, and 17 May 2012, are selected to investigate the QPPs with double periods, as shown in Table 1. These flares were simultaneously recorded by multiple instruments. The X-Ray Sensor (XRS: Hanser and Sellers, 1996) onboard the Geostationary Operational Environmental Satellite (GOES) observes the full-Sun integrated soft X-ray emissions in both 0.5 – 4 Å and 1 – 8 Å wavebands. The flux measurements in 1 – 8 Å have become a standard for classifying solar flares (A, B, C, M, and X), according to which the three flares under study (one X-class flare and two M-class flares) can be considered as powerful solar eruptions.

Starting from 2006, in addition to the XRS, GOES-13 and subsequent GOES-14, GOES-15, etc., began to carry an EUV Sensor (EUVS; Viereck et al., 2007). GOES/EUVS measures the full-Sun EUV radiations in five wavelength channels, viz., A, B, C, D, and E, with the E channel targeting on the Lyα emission, which enables us to make a detailed analysis of flare oscillations in the Lyα waveband. The temporal cadence of GOES/EUVS-E measurements is nominally 10.24 seconds, but it changes to 12.29 seconds every third measurement (see Viereck et al., 2007). Given that the QPP analysis requires an uniform time cadence, the Lyα emission measurements were temporally interpolated to 10.24-second intervals.

The microwave emissions during these flares were measured by the Nobeyama Radio Polarimeters (NoRP: Nakajima et al., 1985) and Radioheliograph (NoRH: Hanaoka et al., 1994). The NoRP provides full-Sun integrated radio fluxes with a temporal cadence of one second at frequencies of 1 GHz, 2 GHz, 3.75 GHz, 9.4 GHz, 17 GHz, and 35 GHz, while the NoRH gives full-Sun images with a nominal temporal cadence of one second at frequencies of 17 GHz and 34 GHz. Generally, ground-based observations are not as stable as observations from space, and they often lose some observation data, in particular for the NoRH images. To acquire temporally uniform data and compare them with Lyα observations, the radio observations were temporally interpolated to ten-second intervals, as done for the Lyα observations.

Hard X-ray radiation during these flares were observed by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI: Lin et al., 2002) as well as the Fermi Gamma-ray Burst Monitor (GBM: Meegan et al., 2009). RHESSI is a photon-counting instrument that records events with a precision ≪ one second. However, to obtain images of the Sun in X-rays and γ-rays, the instrument was designed to rotate with a period of about four seconds. This is why the time series of the RHESSI measurements analyzed here were constructed with a temporal...
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Figure 1. Snapshots at wavelengths of NoRH 34 GHz (left) and Atmospheric Imaging Assembly (AIA) 94 Å (right) during solar flares. The gold and magenta contours represent the RHESSI 25–50 keV and NoRH 17 GHz emissions, their contour levels are set at 80% and 50%, respectively. The black curve in panels e and f marks the solar limb.

Note that there are usually some data gaps due to the RHESSI night times (i.e. the Sun is not visible). Fermi/GBM observes the whole unocculted sky with twelve NaI scintillators (8 keV to 1 MeV) and two bismuth germanate (0.2 to 40 MeV) detectors, and thus it offers capabilities for the analyses of not only γ-ray bursts but also solar flares. The normal temporal resolution...
of Fermi/GBM measurements is 0.256 second, and it increases to 0.064 second automatically once a flare starts (Meegan et al., 2009). In the present study, for a better comparison with observations in Ly $\alpha$, the Fermi/GBM data were also reformatted to a temporal cadence of 10.24 second.

The fast Fourier transformation (FFT) is one of the most powerful analysis tools, which is widely used in astrophysical and solar observations to detect QPP signatures (e.g. Vaughan, 2005; Anfinogentov et al., 2021). The quasi-periods in the present work were determined by analysing the Fourier Power Spectral Density (PSD) of the time series data. Before applying the FFT, the light curve is normalized with $(F - F_0)/F_0$, where $F$ is the flux observed by the above-mentioned instruments, and $F_0$ is the calculated average flux during the observation time. FFT power spectrum is usually a superposition of red noise and white noise. So when determining the significance of possible periodicities in the PSD, the red noise, an intrinsic property of the observed source due to erratic, aperiodic brightness changes, has to be accounted for in order not to severely overestimate the significance of identified periods (Lachowicz et al., 2009). In observations, the red noise has an increasing PSD toward longer periods and usually follows a power-law behavior (Hayes et al., 2019; Pugh, Broomhall, and Nakariakov, 2019; Wang et al., 2020). For the analysis, the function $P(f) = Af^{-\alpha} + C$, where $\alpha$ and $A$ represent the power-law index and normalization parameters, respectively, and $C$ is a constant accounting for the transition between the red and white noises, is applied to fit the FFT data, and the red noise can be estimated from the posterior density of the parameters, which is determined by Markov chain Monte Carlo (MCMC) samples with Multi-parameter Bayesian inferences. A $\chi^2$ test is used to assess the significance level of the PSD (see details in Yuan et al., 2019; Liang et al., 2020). The dominant periods of the detected QPP periods are considered as the peaks above the significance level, and their uncertainties are estimated from the full width at half maximum (FWHM) around the PSD peaks.

3. Analysis and Results

3.1. The X2.2 Flare on 15 February 2011

On 15 February 2011, a powerful solar flare occurred in the active region (AR) NOAA 11158, close to the solar center, as shown in Figure 1a and b. The left panels in Figure 1 show the microwave images at 34 GHz, with images of 17 GHz overplotted as contours. The right panels show the corresponding EUV images in 94 Å taken by the Atmospheric Imaging Assembly (AIA: Lemen et al., 2012) onboard the Solar Dynamics Observatory (SDO), overplotted with image contours taken at 17 GHz (magenta) and 25–50 keV (yellow).

Figure 2 shows the full-Sun integrated light curves in different wavelengths. In panel a, the red line shows the SXR emission in 1–8 Å, according to which the flare started at 01:44 UT, peaked at 01:56 UT, and then underwent a long decay phase. It is the first X-class (X2.2) flare in Solar Cycle 24 and has been extensively studied. The black line in Figure 2a shows the corresponding Ly $\alpha$
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Figure 2. Light curves of the solar flare on 15 February 2011. Panel a: Full-disk light curves at wavelengths of Ly$_\alpha$ (black) and GOES 1–8 Å (red). Panel b: Full-disk light curves in RHESSI 25–50 keV (black), NoRP 35 GHz (orange), as well as the locally integrated flux at NoRH 34 GHz (magenta) over the flare region shown in Figure 1a. Note that the discontinuities in the RHESSI light curves, caused by the RHESSI attenuator changes, have been empirically corrected.

emission, which exhibits several regular and periodic pulses (signatures of QPPs during the solar flare). The corresponding HXR and microwave emissions that are supposed to have a nonthermal origin (Holt and Ramaty, 1969; Saint-Hilaire and Benz, 2005) are shown in Figure 2b, where the black line shows the HXR flux in 25–50 keV from RHESSI and the orange line shows the microwave emission at 35 GHz from NoRP. As a comparison, the locally integrated microwave flux over the flare region, calculated from NoRH images at 34 GHz, was also overplotted (magenta line). Note that the discontinuities in the RHESSI light curve, caused by the RHESSI attenuator changes, have been empirically corrected, and the microwave light curves were normalized to their maximum values and shifted
Figure 3. PSDs for Lyα and HXR emissions of the X2.2 flare in log–log space. The cyan line is the best (MCMC) fit, and the magenta line represents the 95% confidence level. The double periods studied in this work are marked with “P1” and “P2”, while the blue arrow indicates a quasi-period of roughly three minutes.

vertically to avoid overlap. Similar to the Lyα emission, all these nonthermal fluxes are characterized by a series of small pulses.

Figure 3 presents the QPP analysis of the X2.2 flare at wave channels of Lyα (panel a) and HXR 25–50 keV (panel b) in log–log space. The time interval used to calculate the PSD is the full flare duration, as shown in Figure 2. The cyan line represents the best MCMC fit and the magenta line indicates the 95% confidence (or 5% significance) level, which is often used to detect the solar QPPs (e.g. Pugh et al., 2017; Kolotkov et al., 2018; Yuan et al., 2019; Li et al., 2020a; Liang et al., 2020). In Figure 3a, there are two significant peaks beyond the confidence level, which are considered as double-period QPPs. The double periods are estimated to be ≈1.09 minutes (“P1”) and ≈2.15 minutes (“P2”), the ratio of which is equal to 1.97, which are listed in Table 2. There is also a weak peak that is just reaching the confidence level, as indicated by the blue arrow. It reveals a period value of three minutes, which agrees well with the three-minute oscillations reported by Milligan et al. (2017) for the same flare.

In order to verify the oscillation periods, we did the same QPP analysis for the contemporaneous observations in other wavelengths. Figure 3b and Figure 4
Figure 4. PSDs for microwave emissions of the X2.2 flare in log–log space. The cyan line is the best (MCMC) fit, and the magenta line represents the 95% confidence level. The double periods studied here are marked with “P1” and “P2”.

show the PSDs calculated from the light curves in HXR 25–50 keV and microwaves, respectively. Note that, the PSD in Figure 4a is calculated from the full-Sun microwave emission at 35 GHz from NoRP, while the PSD in Figure 4b is calculated from the local microwave emission (integrated over the flare region) at 34 GHz from NoRH. They both exhibit nearly the same double periods (“P1” and “P2”) as those in HXR 25–50 keV (as listed in Table 2), implying their nonthermal origin from the flare region. Comparing with double periods in the Lyα emission, “P2” is quite similar, while “P1” is a little different, for instance, a deviation of about 0.28 minutes is detected between the Lyα and microwave emissions, as seen in Table 2. On the other hand, the PSD peaks are very broad in the nonthermal emission at HXR and microwave channels, suggesting quite large uncertainties of HXR/microwave QPPs.

3.2. The M7.4 Flare on 25 September 2011

On 25 September 2011, the GOES/XRS recorded a soft X-ray event that started at 04:31 UT, had its maximum at 04:50 UT, and ended at 05:05 UT. The event was classified as an M7.4 flare according to the peak soft X-ray emission. The
Figure 5. Light curves of the solar flare on 25 September 2011. Panel a: Full-disk light curves at wavelengths of Ly\(\alpha\) (black), and GOES 1–8 Å (red). Panel b: Full-disk light curves in RHESSI 25–50 keV (black) and Fermi 27–50 keV (cyan) and NoRP 35 GHz (orange), as well as the locally integrated microwave flux at NoRH 34 GHz (magenta) over the flare region shown in Figure 1b. Here the Fermi data are from the GBM detector NaI 4 and the discontinuities in the RHESSI count rate, caused by the RHESSI attenuator changes, have been empirically corrected.

imaging observations reveal that it took place in AR 11302, as shown in Figure 1c and d.

Figure 5 shows light curves of the flare in different wavelengths between 04:32 UT and 04:59 UT. Panel a gives light curves of full-Sun integrated solar radiation in Ly\(\alpha\) line (black) and SXR 1–8 Å (red). As can be seen, there are multiple regular and periodic pulses in the Ly\(\alpha\) light curve, which are supposed to be signatures of QPPs during the flare. Panel b gives the full-Sun integrated solar radiations at channels of RHESSI 25–50 keV (black), Fermi 27–50 keV (cyan), and NoRP 35 GHz (orange), as well as the locally integrated microwave flux over the flare region at NoRH 34 GHz (magenta). For the analysis, the
Figure 6. PSDs for Lyα and HXR emissions of the M7.4 flare in log-log space. The cyan line is the best (MCMC) fit, and the magenta line represents the 95% confidence level. The double periods studied here are marked with “P1” and “P2”.
Figure 7. PSDs for microwave emissions of the M7.4 flare in log–log space. The cyan line is the best (MCMC) fit, while the magenta line represents the 95% confidence level. The double periods studied here are marked with “P1” and “P2”.

CTIME data from the Fermi/GBM detector NaI 4 (Sun-facing) is used, and the discontinuities in the RHESSI light curve, caused by the RHESSI attenuator changes, have been empirically corrected. All of these solar emissions are supposed to have a nonthermal origin, which exhibit similar QPP signatures as those in Lyα light curve. The similarity between the RHESSI and Fermi measurements rules out the possibility of an instrumental effect.

To find the periodicity of QPPs, we calculate the PSDs of the light curves shown in Figure 5. Our calculation results are shown in Figures 6 and 7. From the PSD of the Lyα light curve (Figure 6a), two broad peaks (labeled “P1” and “P2”) with periodicities of ≈1.33 minutes and ≈2.42 minutes stand out above the 95% confidence level. The ratio between the double periods was estimated to be 1.82. The double-period oscillations were also detected in the full-Sun HXR fluxes measured by the RHESSI 25–50 keV (Figure 6b) and Fermi 27–50 keV (Figure 6c), as well as the full-Sun and locally integrated microwave fluxes at the frequencies of NoRP 35 GHz and NoRH 34 GHz (see Figure 7). The quasi-periods are listed in Table 2. As can be seen, the flare emission in the Lyα, HXR and microwave show a very similar long period (“P2”) except for the RHESSI 25–
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Figure 8. Light curves of the solar flare on 17 May 2012. Panel a: Full-disk light curves at wavelengths of Ly$\alpha$ (black) and GOES 1–8 Å (red). Panel b: Full-disk light curves in NoRP 17 GHz (black), and the local NoRH flux at the frequency of microwave 17 GHz (magenta) that is integrated over the flare region, as shown in Figure 1c and d.

50 keV flux, which exhibits a slightly shorter period. For the short period “P1”, it is also slightly different; for instance, the flare emission in the Ly$\alpha$ and HXR show a quite similar period (“P1”), while the period in the microwave emission is slightly shorter.

3.3. The M5.1 Flare on 17 May 2012

On 25 May 2012, a (west) limb flare occurred in AR 11476, as shown in Figure 1e and f. According to the GOES observations in 1–8 Å, the flare was classified as an M5.1 flare, which started at 01:25 UT, peaked at 01:47 UT, and ended at 02:14 UT. Figure 8 draws the light curves for this flare between about 01:26 UT and 01:57 UT. Similar to the above-described two flares, Figure 8a presents light curves of the full-Sun radiations in Ly$\alpha$ (black) and SXR 1–8 Å (red),
Figure 9. PSDs for Lyα and microwave emissions of the M5.1 flare in log–log space. The cyan line is the best (MCMC) fit, and the magenta line represents the 95% confidence level. The double periods studied here are marked with “P1” and “P2”.
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and Figure 8b displays the full-Sun (black) and locally integrated (magenta) microwave emissions at the frequency of 17 GHz, recorded by NoRP and NoRH, respectively. As can be seen, the light curves in both Lyα and microwave emissions show clear signatures of QPP features. Note that RHESSI was in the orbit night until 01:39 UT and images of the NoRH 34 GHz exhibit a very poor quality; thus observations from these two instruments were not used here.

Figure 9 presents the PSDs of light curves at wavelengths of Lyα (panel a) and 17 GHz (panels b and c) in log–log space. Note that, Figure 9b shows the PSDs of the full-Sun integrated light curve at 17 GHz while Figure 9c shows the PSDs of the locally integrated light curve. Above the 95% confidence level, we found three significant peaks with dominant periods of ≈5 minutes, ≈2.19 minutes, and ≈1.12 minutes in the Lyα emission. The latter two periods and the ratio (i.e., 1.96) between them are quite similar to the double periods found in previous two flares, which may imply a similar physical process. On the other hand, similar double periods can also be found in the microwave emission. Regarding the five-minute period, it was supposed to result from the three main pulses during the impulsive phase between ≈01:29 UT and ≈01:44 UT (see Figure 8), which may corresponding to three repeated magnetic reconnections, but it is beyond the scope of this study.

4. Conclusions and Discussion

The Lyα line is the brightest emission line in the solar UV spectrum, but it has rarely been studied due to limited observations, in particular the imaging observations. In the present study, we investigated QPPs observed in Lyα, HXR, and microwave emissions during three powerful solar flares that occurred on 15 February 2011, 25 September 2011, and 17 May 2012, respectively. By applying the MCMC sampling technique, QPPs with double periods of about two minutes (P2) and one minute (P1) were first detected in the Lyα emission recorded by the GOES/EUVS. Note that the short period (P1) actually ranges between about 1.09 and 1.33 minutes, and the long period (P2) varies from roughly 2.15 to 2.42 minutes; here we simply regard them as one- and two-minute QPPs, as was done in previous studies (Milligan et al., 2017; Ning, 2017; Li et al., 2020b). Then using the same technique, the flare QPPs with double periods were also found from light curves of full-Sun HXR (25 – 50 keV, 27 – 50 keV) and microwave (35/17 GHz) emissions, with the HXR emission recorded by RHESSI and Fermi/GBM, and microwave emission recorded by NoRP. As a comparison, the QPP analysis technique was also applied to local light curves integrated over the flaring region in NoRH images (34/17 GHz), and again the double periods were obtained. This implies that the QPPs originate from the flaring region rather than the solar background radiation. Table 2 shows the double periods as well as the ratio between them for the three flares under study.

With regard to the X2.2 flare on 15 February 2011, it has been studied by many authors (see Milligan and Ireland, 2018, for a simple statistic). Using the Chinese Solar Broadband Radio Spectrometer at Huairou, Tan et al. (2012) found QPPs with a period of ≈375 ms in the microwave emission at 6.8 GHz
Table 2. Double periods observed in the Ly $\alpha$, HXR, and microwave emissions during solar flares.

| Date/Time         | GOES Ly $\alpha$ | RHESSI 25–50 keV | NoRP 35 GHz | NoRH 34 GHz | GOES Ly $\alpha$ | RHESSI 25–50 keV | Fermi 27–50 keV | NoRP 35 GHz | NoRH 17 GHz | GOES Ly $\alpha$ | NoRH 17 GHz |
|-------------------|------------------|------------------|-------------|-------------|------------------|------------------|------------------|-------------|--------------|------------------|--------------|
| SOL2011-02-15T01:44 | 1.09±0.05 | 1.26±0.19 | 1.37±0.12 | 1.37±0.19 | 1.33±0.19 | 1.37±0.16 | 1.27±0.12 | 1.12±0.11 | 1.19±0.10 | 1.12±0.05 | 1.12±0.06 |
|                   | 2.15±0.15 | 2.13±0.32 | 2.17±0.36 | 2.13±0.33 | 2.42±0.24 | 2.24±0.31 | 2.46±0.33 | 2.41±0.29 | 2.39±0.28 | 2.19±0.16 | 2.33±0.35 |
|                   | 1.97±0.23 | 1.69±0.52 | 1.58±0.41 | 1.56±0.47 | 1.82±0.45 | 1.64±0.43 | 1.94±0.45 | 2.15±0.48 | 2.00±0.41 | 1.96±0.23 | 2.08±0.43 |

Double periods observed in the Ly $\alpha$, HXR, and microwave emissions during solar flares were previously found in X-ray emission (Zimovets and Struminsky, 2010), H $\alpha$ images (Srivastava et al., 2008), microwave emission (Tan et al., 2010), and even UV spectral lines (Tian et al., 2016). However, these periods are usually detected in different phases of solar flares, for example one period in the impulsive phase and the other period in the decay phase (Huang et al., 2014; Kolotkov et al., 2018; Hayes et al., 2019). Moreover, the ratio between these periods is usually found to be significantly different from two (e.g. Srivastava et al., 2008; Inglis and Nakariakov, 2009; Tian et al., 2016; Hayes et al., 2019). In the present work, double periods of QPPs were observed during three flares in both Ly $\alpha$ and nonthermal (HXR/microwave) emissions. The period ratio detected in the Ly $\alpha$ emission was very close to two, which is consistent with the theoretical expectation between the fundamental and harmonic modes for the weakly dispersive MHD modes (e.g., Nakariakov and Melnikov, 2009; Nakariakov and Kolotkov, 2020). However, considering that

and attributed it to a very short period pulsation (VSP). Then, Milligan et al. (2017) reported a three-minute QPP in the full-Sun Ly $\alpha$ and Lyman continuum emissions (similar QPP can also be seen in our analysis result, as indicated by the blue arrow in Figure 3a), and explained it as the acoustic wave in the chromosphere. Milligan et al. (2017) also found a period of about two minutes in both HXR and chromospheric emission, which is consistent with the two-minute QPP reported here. It should be stated that, instead of simply applying the wavelet-analysis technique to a detrended light curve (having removed the filtered time profile) as was done by Milligan et al. (2017), we performed the FFT analysis for light curves without detrending applied, thus more oscillation periods are detected, such as the one-minute QPP, which has been extensively studied at wavelengths of X-ray and EUV during different solar flares (see Van Doorsselaere et al., 2011; Cho et al., 2016; Ning, 2017; Hayes et al., 2019; Li et al., 2020b). Our findings here agree with previous results, suggesting that the QPP analysis technique (Liang et al., 2020) that we used is reliable.

The double or even more periods of flare QPPs were previously found in X-ray emission (Zimovets and Struminsky, 2010), H $\alpha$ images (Srivastava et al., 2008), microwave emission (Tan et al., 2010), and even UV spectral lines (Tian et al., 2016). However, these periods are usually detected in different phases of solar flares, for example one period in the impulsive phase and the other period in the decay phase (Huang et al., 2014; Kolotkov et al., 2018; Hayes et al., 2019). Moreover, the ratio between these periods is usually found to be significantly different from two (e.g. Srivastava et al., 2008; Inglis and Nakariakov, 2009; Tian et al., 2016; Hayes et al., 2019). In the present work, double periods of QPPs were observed during three flares in both Ly $\alpha$ and nonthermal (HXR/microwave) emissions. The period ratio detected in the Ly $\alpha$ emission was very close to two, which is consistent with the theoretical expectation between the fundamental and harmonic modes for the weakly dispersive MHD modes (e.g., Nakariakov and Melnikov, 2009; Nakariakov and Kolotkov, 2020). However, considering that
the PSDs were calculated from the full flare duration, we can not rule out the possibility that the double periods occurred at different phases of the flares. The period ratios in the HXR and microwave emissions were found to vary from about 1.56 to 2.15, some of which significantly deviated from the theoretical expectation, i.e., for the highly dispersive modes. On the other hand, considering the large uncertainties in the HXR and microwave emissions, the period ratios here are roughly equal to that found in the Ly$\alpha$ emission for the same flare event.

Flare QPPs observed in HXR and microwaves are supposed to be associated with periodic acceleration of charged particles that radiate HXR and microwave emissions via bremsstrahlung and gyrosynchrotron mechanisms, respectively (Dulk, 1985; Aschwanden, 1987; Masuda et al., 1994; Druett and Zharkova, 2019), and they are often well correlated. For example, the kink oscillation excited in a coronal loop near the reconnection site could periodically trigger magnetic reconnections, during which charged particles are periodically accelerated, inducing QPPs in HXR and microwave (Foullon et al., 2005; Nakariakov et al., 2006; Inglis and Nakariakov, 2009). The Ly$\alpha$ emission enhancements during solar flares were found to be highly synchronous with emission enhancements in HXR (Nusinov et al., 2006; Rubio da Costa et al., 2009), which suggests that the same population of energetic electrons is responsible for radiation in Ly$\alpha$. Thus we suppose that QPPs in Ly$\alpha$ are also associated with nonthermal electrons that are accelerated by repetitive magnetic reconnections during solar flares. The repeated magnetic reconnections that generate the long period (P2) might be spontaneous via magnetic dripping (Li et al., 2020b), or modulated by a MHD mode, such as the standing sausage mode (Van Doorsselaere et al., 2011). The observation of double-periodic QPPs on the Sun can be utilized to deduce the density scale height of solar loops (McEwan et al., 2006; Duckenfield et al., 2019). Similarly, the multi-periodic QPPs observed on other Sun-like stars could be used to diagnose the longitudinally-structured stellar loops (Srivastava, Lalitha, and Pandey, 2013; Zimovets et al., 2021). It should be noted that the double periods studied here have broad peaks, which are usually attributed to the non-stationary property of the QPP signals and could be interpreted by gradual change of the physical or geometrical parameters of the flare region or by a superposition of multiple oscillatory processes (see Nakariakov et al., 2019a; Kupriyanova et al., 2020, for recent reviews of this issue). In our study, considering a self-oscillation model, the broad PSD peaks in the power spectra are supposed to be caused by the variation of inflow rates, or the anomalous resistivity in local electric currents.

It should be stated that, from the FFT spectra shown in Figures 3, 4, 6, 7, and 9, the flare QPPs in different wavelengths are not exactly the same, but show some deviations from each other, in particular for the short period (P1), which could have a deviation of roughly 0.28 minutes. This is probably because Ly$\alpha$, HXR, and microwave emissions do not originate from a completely coincident source region. For example, the HXR source of the M7.4 flare on 25 September 2011 deviates obviously from the microwave sources, as shown in Figure 1d, the corresponding QPPs in these two wavelengths also shows a significant deviation. However, it is still impossible to determine the source region of Ly$\alpha$ emission due
to the lack of the corresponding imaging observations. Some instruments that have been launched recently, such as the Extreme Ultraviolet Imager (Rochus et al., 2020) and the Spectrometer/Telescope for Imaging X-rays (Krucker et al., 2020) onboard the Solar Orbiter, and instruments to be launched in the near future, such as the Lyα Solar Telescope (Li et al., 2019; Feng et al., 2019) and the Hard X-ray Imager (Su et al., 2019) onboard the Advanced Space-based Solar Observatory (Gan et al., 2019; Huang et al., 2019), will provide joint imaging observations in Lyα and HXR channels, which will help to address these issues. Finally, we should point out that the short period (P1) detected in the Lyα, HXR, and microwave emissions might be driven by the different mechanisms, due to their large periodic deviation. To answer this question, a new technique is needed to reduce the error/uncertainty of the detected period, such as the Solar Bayesian Analysis Toolkit (Anfinogentov et al., 2021).

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Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

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