Detections of Multi-Periodic Oscillations during a Circular Ribbon Flare

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Abstract We present the analysis of three kinds of oscillating behavior using multi-wavelength observations of the 10 November 2013 (SOL2013-11-10T05:14) circular-ribbon flare. This event is a typical circular-ribbon flare with an outer spine structure and homologous jets. We found three kinds of oscillations (or perturbations): i) flux oscillation (or QPP) with a dominant period of about 20 seconds in X-ray, EUV, and microwave emissions, ii) periodic jets with an intermittent cadence of around 72 seconds, iii) an outer loop perturbing half a cycle with a duration of about 168 seconds. Similar to the periodic jets that could be produced by a nonthermal process, like repeated magnetic reconnection, the flare QPP detected in the thermal emissions could have the same origin as the oscillation seen in the nonthermal emissions. The outer-loop perturbation is possibly triggered by a blast wave driven by the circular-ribbon flare, or it might be modulated by the sausage wave or the slow magnetoacoustic wave. The results obtained provide data for further numerical studies on the physical origin of the flare oscillations.

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

1. Introduction

A solar flare is a powerful and impulsive process of magnetic-free-energy release in the solar atmosphere (see Benz, 2017, for a recent review). Solar-flare topology

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often shows elongated structures seen in the H\textalpha, white light, and ultraviolet (UV) wavelengths, called “flare ribbons”. Typically, two ribbons are located in regions of opposite magnetic polarities, which are parallel to the magnetic polarity inversion line (PIL) and separating the polarities. This is known as a “two-ribbon flare” (a detailed sketch can be seen in Priest and Forbes (2002)) and could be well explained by the classical 2D-reconnection model (Sturrock and Coppi, 1964; Shibata and Magara, 2011; Yan et al., 2018). However, a solar flare actually occurs in a more complicated structure associated with the 3D magnetic null point, i.e. the fan–spine topology (Török et al., 2009). The null point is mainly passed through by the inner and outer spine field lines, and the closed separatrix surface is dominated by the fan structure with a dome-like shape. The magnetic fields at the inner spine footpoint are opposite to those of the dome-shaped fan, producing a circular PIL. This eruptive feature is called a “circular-ribbon flare” (Masson et al., 2009; Wang and Liu, 2012), which is regarded as a result of the null-point reconnection. A schematic picture illustrating the main components and geometrical structures of the circular-ribbon flare was provided by Wang and Liu (2012). During its eruption, the flare radiation at the footpoint of the fan field lines is largely constituting a closed circular ribbon, and at the footpoints of the inner spine field lines is a compact source called a central/inner ribbon. On the other hand, the outer spine field lines could be closed or open, and a remote/outer ribbon is formed at the footpoint of the closed outer spine field lines, while a series of homologous jets could be successively produced along the magnetic-field lines of the open outer spine (e.g. Chifor et al., 2008; Liu et al., 2011; Reid et al., 2013; Hao et al., 2017; Hernandez-Perez et al., 2017; Li et al., 2018a; Song and Tian, 2018; Zhang et al., 2021). This combination of factors results in various kinds of oscillations relating to this type of flare (Mészárosóvá et al., 2013; Kumar, Nakariakov, and Cho, 2015; Kashapova et al., 2020; Zhang, 2020).

Quasi-periodic pulsations (QPPs) are intensity oscillations during solar flares (e.g. Van Doorsselaere, Kupriyanova, and Yuan, 2016; McLaughlin et al., 2018; Zimovets et al., 2021). They often appear as a series of regular and periodic pulses in the flare’s light curve, which could be detected in a broad range of wavelengths, i.e. radio/microwave emissions (Ning et al., 2005; Kupriyanova et al., 2010b; Nakariakov et al., 2017; Karlický and Yasnov, 2021); H\textalpha (Srivastava et al., 2008; Yang and Xiang, 2014; Kashapova et al., 2020a; Li et al., 2020d) and Ly\alpha (Milligan et al., 2017; Li et al., 2020a; Li, 2021; Lu et al., 2021); emissions, UV or extreme-UV (EUV) wavelengths (Pugh et al., 2014; Shen et al., 2018; Kobanov and Chelpanov, 2019; Yuan et al., 2019); soft/hard X-ray (SXR/HXR) channels (Ning, 2014; Inglis et al., 2016a; Li and Zhang, 2017; Kolotkov et al., 2018; Hayes et al., 2020), and even \gamma-ray emission (Nakariakov et al., 2010a; Li et al., 2020b). Such oscillatory features were also observed in the circular-ribbon flare (Mészárosóvá et al., 2013; Kumar, Nakariakov, and Cho, 2015; Kashapova et al., 2020). A typical flare QPP is generally characterized by repetition and periodicity, and the quasi-periods can be observed from sub-seconds through seconds and minutes to dozens of minutes (Fleishman et al., 2002; Tan et al., 2010; Dolla et al., 2012; Kolotkov et al., 2013; Kupriyanova et al., 2016; Ning, 2017; Yu and Chen, 2018; Clarke et al., 2021; Li et al., 2021b). It seems that the
various periods of flare QPPs are always dependent on the detected wavelengths or the temporal resolution of the measuring instruments (see Kupriyanova et al., 2020, for a recent review). These properties indicate the possibility of generating flare QPPs with various periods by different mechanisms (e.g. McLaughlin et al., 2018; Kupriyanova et al., 2020). The short-periodicity QPPs (i.e. sub-seconds) are generally observed in radio or HXR emissions due to their high temporal resolution, which are most likely associated with the kinetic process driven by the dynamical interaction between electromagnetic plasmas and energetic particles trapped in the flaring loop (e.g. Aschwanden, 1987; Fleishman et al., 2002; Ning et al., 2003; Tan et al., 2010; Yu and Chen, 2019). The flare QPPs with long periods on the order of seconds and minutes can be discovered in a broad wavelength range, such as microwave, white light, UV/EUV, SXR/HXR, and even γ-rays (Nakariakov et al., 2010; Dolla et al., 2012; Kolotkov et al., 2013; Li and Zhang, 2017; Kobanov and Chelpanov, 2013; Li et al., 2020; Hayes et al., 2020; Li, 2021). They are probably related to magnetohydrodynamic (MHD) waves in complicated magnetic configurations in the flare region or might be associated with the solar global oscillations (Ofman and Wang, 2002; Tian et al., 2016; Kupriyanova et al., 2018; Shen et al., 2018; Kolotkov et al., 2018; Yuan et al., 2019; Nakariakov and Kolotkov, 2020; Clarke et al., 2021).

Flare QPPs have attracted a lot of attention since they were first found in solar X-ray emissions (Parks and Winckler, 1969). However, the physical mechanism responsible for the generation of flare QPPs is still an open question (Van Doorsselaere, Kupriyanova, and Yuan, 2016; McLaughlin et al., 2018; Kupriyanova et al., 2020). They are generally attributed to MHD waves in slow mode, kink mode, or sausage mode (Yuan and Van Doorsselaere, 2016; Li et al., 2020; Nakariakov and Kolotkov, 2020; Nakariakov et al., 2021; Amiri, Karami, and Ebrahimi, 2021; Wang et al., 2021). They might also be caused by repetitive magnetic reconnections, which could accelerate nonthermal electrons and produce flare emissions with quasi-periodic pulses (e.g. Kliem, Karlíký, and Benz, 2000; Chen and Priest, 2006; Nakariakov and Zimovets, 2011; Kumar, Nakariakov, and Cho, 2015; Li and Zhang, 2015; Guidoni et al., 2016; Yuan et al., 2019; Li et al., 2020). On the other hand, flare QPPs are also interpreted as self-oscillating processes, such as magnetic dripping (Nakariakov et al., 2010; Li et al., 2020) or may be explained by the magnetic tuning-fork model (Takasao and Shibata, 2016) and the LRC-circuit model (Tan et al., 2016; Chen et al., 2019; Li et al., 2020). The supra-arcade downflows were found to collide with post-flare loops at different instances, which could lead to the quasi-periodicity of the flare radiation at wavelengths of UV/EUV and X-ray (Cai et al., 2019; Xue et al., 2020; Samanta et al., 2021). Moreover, the flare QPPs are thought to be related to the fundamental physical processes of solar flares, i.e. magnetic reconnection, energy release, particle acceleration, and also MHD waves (e.g. Nakariakov and Zimovets, 2011). Therefore, they are useful for remotely diagnosing the key physical parameters in flare regions (Brosius and Daw, 2013; Dominique et al., 2013; Yuan et al., 2019).

Thanks to high-resolution imaging telescopes in EUV/SXR channels, the spatial motions of displacements have been found in hot coronal loops, and they are regarded as coronal-loop oscillations, which are often related to solar flares (e.g.
Coronal-loop oscillations are also seen as Doppler-shift oscillations using spectroscopic observations (Wang et al., 2002; Tian et al., 2016; Li et al., 2018a). Their displacement amplitudes are found to range from sub-megameters to dozens of megameters (Anfinogentov, Nakariakov, and Nistico, 2015; Su et al., 2018; Goddard and Nistico, 2020; Nakariakov et al., 2021), and their oscillation periods are strongly dependent on loop lengths. While the ratio of the decay time to the oscillation period is systematically related with the displacement amplitudes (Goddard and Nakariakov, 2016). Fast magnetoacoustic waves, detected as wavelet tadpoles, were found in the fan structure of a circular-ribbon flare (Mészáros et al., 2013). Recently, transverse oscillations were discovered in the outer loop of a circular-ribbon flare, which are explained as kink modes of the MHD wave (Zhang et al., 2020; Dai et al., 2021), largely due to their incompressibility or weak compressibility (Yuan and Van Doorsselaere, 2016; Amiri, Karami, and Ebrahimi, 2021). These circular-ribbon flares were also found to be accompanied by repeated and homologous coronal jets. On the other hand, the transverse oscillations detected in the coronal loops can also be interpreted as sausage-mode waves in the plasma loops, and they are often caused by density perturbations in the coronal loops (Tian et al., 2014; Lim, Nakariakov, and Moon, 2013; Li et al., 2020a). However, sausage oscillations excited by circular-ribbon flares are rarely reported in the outer coronal loop.

In this study, we investigated three kinds of oscillating behavior using multi-wavelength observations; they were all related to a circular-ribbon flare on 10 November 2013. The article is organized as follows: Section 2 introduces the observations and instruments, Section 3 presents the data analysis and our main results, and Section 4 gives the conclusion and discussion.

2. Observations and Instruments

We have studied the solar flare of 10 November 2013 (SOL2013-11-10T05:14). It was an X1.1 class flare and occurred in the active region NOAA 11890 (S11W28). The event started at about 05:09 UT, reached its maximum at around 05:14 UT, and ended at roughly 05:22 UT. The flare was simultaneously observed in multiple wavelengths, which was measured by the Geostationary Operational Environmental Satellite (GOES), the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI; Lin et al., 2002), the Nobeyama RadioPolarimeters (NoRP; Nakajima et al., 1985), the Nobeyama RadioHeliograph (NoRH; Hanaoka et al., 1994), Konus-Wind (Aptekar et al., 1995; Pal’shin et al., 2014), the Gamma Ray Burst Monitor (GBM) on Fermi (Meegan et al., 2009), the Atmospheric Imaging Assembly (AIA; Lemen et al., 2012), the Helioseismic and Magnetic Imager (HMI; Schou et al., 2012), and the Extreme Ultraviolet Variability Experiment (EVE; Woods et al., 2012) onboard the Solar Dynamics Observatory (SDO; Pesnell, Thompson, and Chamberlin, 2012); see the details in Table 1.

The X1.1 flare shows a closed circular ribbon and a faint remote ribbon, as well as a faint outer loop that connected the closed circular ribbon and a
Table 1. Instruments used to detect flare oscillations in this study.

| Instrument     | Cadence          | Channels  | Description   | Observation |
|----------------|------------------|-----------|---------------|-------------|
| GOES/XRS       | ≈2 seconds       | 1 – 8 Å  | SXR           | 1D          |
|                |                  | 0.5 – 4 Å | SXR           |             |
| RHESSI         | 4 seconds        | 6 – 12 keV| SXR           | 2D          |
|                |                  | 50 – 100 keV| HXR        |             |
| Fermi/GBM      | ≈0.256 second    | 4.2 – 11.5 keV| SXR       | 1D          |
|                |                  | 11.5 – 26.6 keV| SXR/HXR   |             |
|                |                  | 26.6 – 50.4 keV| HXR       |             |
|                |                  | 50.4 – 102.4 keV | HXR      |             |
| Konus-Wind     | ≈1.024 seconds   | 20–80 keV | SXR/HXR       | 1D          |
|                |                  | 80–300 keV| HXR           |             |
|                |                  | 300–1200 keV | HXR/γ-ray  |             |
| NoRP           | 0.1 second       | 1 GHz     | Microwave     | 1D          |
|                |                  | 2 GHz     | Microwave     |             |
|                |                  | 3.75 GHz  | Microwave     |             |
|                |                  | 9 GHz     | Microwave     |             |
|                |                  | 17 GHz    | Microwave     |             |
|                |                  | 35 GHz    | Microwave     |             |
| NoRH           | 1 second         | 17 GHz    | Microwave     | 2D          |
|                |                  | 34 GHz    | Microwave     |             |
| SDO/EVE        | 0.25 second      | 0.1 – 7.0 nm | SXR     | 1D          |
|                |                  | 17.2 – 20.6 nm | EUV   |             |
|                |                  | 23.1 – 27.6 nm | EUV   |             |
|                |                  | 28.0 – 32.6 nm | EUV   |             |
| SDO/AIA        | 12 seconds       | 171 Å     | EUV           | 2D          |
|                |                  | 1600 Å    | UV            |             |
| SDO/HMI        | 45 seconds       | magnetogram | LOS         | 2D          |

remote brightening, which is seen in 171 Å and 1600 Å images measured by SDO/AIA shown in Figure 1a, b, and d, and in the Electronic Supplementary Material movie. The AIA 1600 Å image was obtained at 05:14:16 UT, which is around the flare maximum, while the AIA 171 Å band image was taken at 05:15:59 UT. At this moment, the outer loop can be more clearly distinguished, especially in the running difference. The lines marked S1 – S3 show the positions of the slits on the outer loop. They are selected to study the jets and the loop perturbation, which will be analyzed in the next section, and the red “∗” symbols mark the zero of the y-axis in Figure 8. Figure 1f gives the line-of-sight(LOS) magnetogram obtained by SDO/HMI (Schou et al., 2012). A closed circular ribbon is associated with the negative magnetic polarity and an inner ribbon is on the compact positive magnetic polarity, while the faint remote ribbon is along
Panels a and b: AIA 171 Å and its running-difference images show the circular-ribbon flare with a FOV of 400′′×400′′. Three groups of solid lines outline the slit positions in Figure 8, and the red symbols of “∗” indicate the zero of the y-axis. Panels c and d: HMI LOS magnetogram and AIA 1600 Å image with a FOV of 400′′×400′′. The blue box outlines a small FOV of about 150′′×150′′ shown in Figure 2a and b.

Figure 1. Panels a and b: AIA 171 Å and its running-difference images show the circular-ribbon flare with a FOV of 400′′×400′′. Three groups of solid lines outline the slit positions in Figure 8 and the red symbols of “∗” indicate the zero of the y-axis. Panels c and d: HMI LOS magnetogram and AIA 1600 Å image with a FOV of 400′′×400′′. The blue box outlines a small FOV of about 150′′×150′′ shown in Figure 2a and b.

the diffuse positive magnetic polarity. The flare event was also observed by the RHESSI and NoRH images in X-rays and microwaves, as indicated by the color contours in Figure 2a and b. The SXR and HXR images at 6–12 keV and 50–100 keV were reconstructed using the CLEAN algorithm from the RHESSI data for the time interval of one minute. This processing allows improving the signal-to-noise ratio. Similar to the AIA 1600 Å band image, the microwave images are obtained at 05:14:16 UT. This event at SXR 6–12 keV (blue contours) and microwave 17 GHz (green contours) and 34 GHz (cyan contours) shows one source, but double HXR footpoint sources at 50–100 keV (red contours). Both the SXR/HXR and microwave emissions appear to overlay the inner flare ribbon seen in the AIA 1600 Å band image. This is consistent with the standard flare model (e.g. Sturrock and Coppi, 1964; Shibata and Magara, 2011), for instance, the double footpoint sources of HXR at 50–100 keV (red contours) are located in the regions with different polarity magnetic fields: one is on the inner ribbon
The X-ray observations have a different temporal resolution than the other instruments (see Table 1). It should be pointed out that the X-ray light curves recorded by *Konus-Wind* and *Fermi/GBM* have been interpolated to the uniform temporal resolution, i.e. 1.024 seconds for the *Konus-Wind* data (e.g. Li et al., 2020d) and 0.256 seconds for the *Fermi/GBM* data (see also, Li, Ning, and Zhang, 2013; Ning, 2017). *NoRP* is a ground-based telescope, which provides solar microwave fluxes at six frequencies with a temporal cadence of ≈0.1 second (Nakajima et al., 1985). The *EUV SpectroPhotometer* for SDO/EVE measures the Sun in one SXR and three EUV wavebands with a temporal resolution of 0.25 seconds (Didkovsky et al., 2012; Woods et al., 2012). Similar to the GOES 1–8 Å light curve, the ESP 0.1–7 nm is a SXR flux. The ESP 17.2–20.6 nm flux includes the line emission mostly from the coronal plasma at about 1–2 MK, while the ESP 23.1–27.6 nm and 28.0–32.6 nm fluxes are mainly dominated by the He \textsc{ii} line in the chromosphere (Didkovsky et al., 2012; Dolla et al., 2012; Li et al., 2021a).

3. Data Analysis and Results

3.1. NLFFF Extrapolation

To reveal the magnetic topology of the circular-ribbon flare region, we carried out a nonlinear force-free field (NLFFF) extrapolation using the optimization approach proposed by Wheatland, Sturrock, and Roumeliotis (2000) and further developed by Wiegelmann (2004). We used the HMI vector magnetogram retrieved from the HMI.B,720 seconds data series at about 05:00:00 UT as the bottom boundary. The 180-degree ambiguity in the transverse components of the vector magnetic field was removed using the improved minimum energy method (Metcalf et al., 2006; Leka et al., 2009), and the projection effect was also corrected. Then, the vector magnetic field can be used as a boundary condition after a preprocessing to satisfy the force-free and torque-free conditions on the photosphere (Guo, Cheng, and Ding, 2017). The extrapolation cube size is $232 \times 196 \times 196 Mm^3$. As shown in Figure 2c and d, the flare shows a spine–fan magnetic topology, which is similar to the previous result about the circular-ribbon flare (e.g. Mészáros et al., 2013). During the flare event, the dome-like structure is consistent with the closed circular ribbon that is accompanied by the occurrence of a series of coronal jets. This is also followed by the remote ribbon at the western end of the outer spine. In addition, a set of overlying magnetic-field lines indicated by white lines matches well with the faint outer loop observed in AIA 171 Å. Consistent with the previous observation (e.g. Wang and Liu, 2012), this circular-ribbon flare has two HXR footpoint sources on the optical inner and circular ribbons, respectively. The microwave sources at 17 GHz (green contours) and 34 GHz (cyan contours) are located between two HXR footpoint sources. It is reasonable that the microwave emissions at 17/34 GHz are produced by the electrons trapped in the flare loops (part of the fan structure in Figure 2c and
Panels a and b: HMI LOS magnetogram and AIA 1600 Å image with a small FOV. The red and blue contours represent the RHESSI X-ray emissions at 50–100 keV and 6–12 keV, while the cyan and green contours show the microwave emissions in NORH 34 GHz and 17 GHz. The levels are set at 50%, 70%, and 90% of the maximum brightness of each detected channel. Panel c: Magnetic topology for the flare region in the x–y plane observed from the z-direction. The $B_z$ component at the bottom boundary ranges from $-2.1 \times 10^3$ to $2.5 \times 10^3$ Gauss. Panel d: AIA 171 Å image at $\approx 05:11$ UT overlaid with the extrapolated magnetic-field lines. The red and blue lines represent the spine–fan magnetic topology, while the white lines indicate the overlying magnetic loop.

The microwave source at 34 GHz is smaller than that at 17 GHz, because it comes from the higher electrons located near the footpoint of the magnetic loop. The thermal source of SXR at 6–12 keV (blue contours) is not located between two HXR footpoint sources, but at the top of the inner ribbon. Except for the projection effect, another possible location seems to be near the null point of the magnetic field, as shown in Figure 2c and d. The null point is thought to be the reconnection site of the circular-ribbon flare, and is near the fan-structure top (the loop apex in the standard flare model) where the SXR radiate.
3.2. Flux Oscillation During the Circular Ribbon Flare

To investigate the periodicity of this circular-ribbon flare, we first perform the Fast Fourier Transform (FFT) of the raw light curves in SXR 1–8 Å (black) and 0.5–4 Å (magenta) measured by the GOES, as shown in Figure 3. Similar to previous results (e.g. Inglis et al., 2016; Kolotkov et al., 2018; Hayes et al., 2020; Li et al., 2020; Wang et al., 2020), each Fourier power spectrum of the raw light curve shows two dominant features—a power-law spectrum and a flat spectrum, as indicated by the green lines in Figure 3. The first often relates to red noise, while the other spectrum is usually considered white noise in solar physics and astrophysics (e.g. Vaughan, 2005; Liang et al., 2020; Anfinogentov et al., 2021). The FFT power spectra show a clear peak above the 99% significance level (cyan lines) at a value that is close to about 20 seconds, as indicated by the vertical dotted lines. We would like to note that the FFT peaks are a bit broad and do not appear above 30 seconds as shown by the vertical dashed line. On the other hand, the FFT spectrum at GOES 0.5–4 Å demonstrates double peaks close to 40 seconds, which are absent in the GOES 1–8 Å flux. Therefore, only the period of about 20 seconds for the flare flux is considered in the current study.

Figure 4 presents the analysis of periodicity for the circular-ribbon flare recorded by GOES. Similar to a typical solar flare, this event exhibits an impulsive increasing and a slow decaying phase, and no obvious QPP signature is seen in the raw SXR light curves. This is because the flare QPPs in the GOES SXR flux often show a very small amplitude, superimposed on a strong background emission (e.g. Simões, Hudson, and Fletcher, 2015; Feng et al., 2017, 2020; Kolotkov et al., 2013; Hayes et al., 2020). Therefore, the strong background emission should be removed from the original data. In this study, the raw light curve is first decomposed into a slowly varying component and a rapidly varying component using the FFT (Ning, 2014, 2017; Li and Zhang, 2017; Milligan et al., 2017). Figure 3 suggests that the flare QPP in GOES 1–8 Å and 0.5–4 Å shows a clear period near 20 seconds, so a cutoff threshold of 30 seconds is applied as marked by the vertical dashed line in Figure 3. Thus, the long-term trend is suppressed while the short period can be highlighted in the wavelet power spectrum (Kupriyanova et al., 2010; Kolotkov et al., 2012; Kashapova et al., 2020). Here, the slowly varying components are multiplied by 0.9 to avoid overlap with the raw light curves, as shown by the blue curves in Figure 4a. The rapidly varying components during the flare are presented in Panel b, as outlined by two vertical dashed lines in Figure 4b. They are characterized by a series of pulses. Then the wavelet-analysis method (Torrence and Compo, 1998) is applied to the rapidly varying component seen in GOES 1–8 Å as shown in Panel c. The wavelet power spectrum confirms a broad range of enhanced power that is centered at about 20 seconds, suggesting a dominant period of about 20 seconds. However, the enhanced power focuses on the impulsive phase in the GOES SXR channel, largely due to the fact that the amplitudes of flare QPPs change with time. Figure 4c shows some pulses with a small amplitude during the flare-decay phase. In order to rule out the noise, we set a threshold (±3σ) to identify the flare QPP pulses. Here, σ represents the standard deviation of the rapidly varying component. Only those pulse amplitudes that are greater
than the threshold are regarded as valid pulses, as shown by the blue-dashed lines in Panel b. Then, each valid pulse of the rapidly varying component of the GOES 1 – 8 Å is normalized by its pulse amplitude, as shown in Panel d. Finally, Panel e displays the wavelet power spectrum for the normalized rapidly varying component, which exhibits a dominant period of roughly 20 seconds during the flare time, i.e. from the impulsive phase to the decay phase. This is consistent with the 20-second period in the FFT power spectra in Figure 3.

In addition to GOES, the X1.1 flare was also observed by NoRP, RHESSI, Konus-Wind, SDO/EVE, and Fermi/GBM in radio/microwave, X-ray, and EUV ranges, as shown in Table 1. Similar to the GOES full-disk flux, any of them detect solar radiation from the entire Sun. We should point out that RHESSI provides imaging spectroscopy, but we have focused on the whole disk (Sun-as-a-star) observations in this study. The RHESSI light curve is not used here for periodicity tests, because there have been several changes in the attenuators (see hessi.ssl.berkeley.edu/hessidata/metadata/2013/11/10/hsi_20131110_040600_rate.png).

Then the same wavelet-analysis method (Torrence and Compo, 1998) is used for the periodicity tests in the microwave, SXR/HXR, and EUV wavelengths; the detailed results can be seen in Figures 5 – 7. The raw light curves (black) are decomposed into slowly (blue) and rapidly varying components, as shown in Panels a1, a2, b1, and b2 in Figures 5 and 6. The slowly varying components have been multiplied by 0.9 to avoid overlap with the raw light curves, and some light curves have been shifted in height, so that they can be displayed clearly in the

Figure 3. Fourier power of the flare light curves measured by the GOES at 1 – 8 Å (black) and 0.5 – 4 Å (magenta). The vertical dotted and dashed lines mark the positions with a periodicity of 20 seconds and 30 seconds. The green lines are the best fit, and the cyan lines represent the 99% significance level.
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Figure 4. Panel a: SXR light curves in GOES 1–8 Å (black), and 0.5–4 Å (red) for the 10 November 2013 solar flare, and their slowly varying components (blue, after multiplication by 0.9). Panels b and c: Rapidly varying components of GOES SXR fluxes in the time interval between the two vertical dashed lines in Panel a and its wavelet power spectrum. The blue solid and dashed lines represent the mean and ±3σ at GOES 1–8 Å. Panels d and e: the normalized rapidly varying component at GOES 1–8 Å and its wavelet power spectrum. The red contours represent a significance level of 95%. Anything ‘outside’ the light blue curve in Panels c and e is dubious.
Figure 5. Similar to Figure 4, the light curves (black) detected by NoRP and SDO/EVE, and their slowly varying components (blue, after multiplication by 0.9), as well as the rapidly varying components in the time intervals between the two vertical dashed lines and their wavelet power spectra at NoRP 1 GHz and SDO/EVE 0.1–7 nm. The red contours represent a significance level of 95%.

same window. Panels c1 and c2 present the rapidly varying components observed by NoRP 1 GHz, ESP 0.1–7 nm, KW 20–80 keV, and Fermi 26.6–50.4 keV during the flare, as indicated by two vertical dashed lines in Panels b1 and b2. Here, the NoRP flux at a frequency of 1 GHz is used to perform the wavelet analysis because it exhibits the most obvious oscillation as shown in Figure 4a1 and b1. The wavelet analysis of SDO/EVE ESP 0.1–7 nm is displayed, as it is very similar to the GOES SXR flux. The other light curves measured by NoRP and SDO/EVE also show the QPP feature, but they are very weak, in particular for the EUV flux at ESP 28.0–32.6 nm, as shown in Figure 5b1. Therefore, the wavelet power spectra in the NoRP 1 GHz, ESP 0.1–7 nm, KW 20–80 keV, and Fermi 26.6–50.4 keV are presented here, which show that the pulsation is strongest at a periodicity of 20 seconds, but the oscillation period is not exactly 20 seconds. It is spread over a broad range of periods, but centered at about
20 seconds. This is similar to the previous finding obtained from the GOES SXR flux. Physically, the microwave emission indicates nonthermal processes at frequencies above the frequency related to the flux maximum, the so-called “peak frequency”. In the current case, the microwave emission at NoRP 35 GHz is exactly above the “peak frequency”. Thus, we also present the wavelet analysis method for the microwave flux at the frequency of NoRP 35 GHz, as shown in Figure 7. Similar to previous results, the wavelet power spectrum shows an enhanced power over a broad range of periods, and the strongest power is centered at about 20 seconds. On the other hand, the onset time of the 20-second QPP in NoRP 35 GHz is earlier than in NoRP 1 GHz, i.e. one minute earlier.
Figure 7. Similar to Figure 4, the light curves (black) detected by the NoRP, and their slowly varying components (blue, after multiplication by 0.9), as well as the rapidly varying components in the time intervals between the two vertical dashed lines and their wavelet power spectra at NoRP 35 GHz. The red contours represent a significance level of 95%.

3.3. Periodic Jets Triggered by the Circular Ribbon Flare

Figure 8 shows the time–distance images along three slits derived in the AIA 171 Å image series (a–c) and their running-difference images (d–f). As shown in Figure 1, a faint outer loop appears in the AIA 171 Å during the X1.1 flare, connecting the closed circular ribbon and the remote brightening. Here, the slits are selected to cross the footpoint (S1), the loop apex (S2), and the loop leg (S3).
for the outer loop, as outlined by the white curves in Figure 1b. Panels a and d plot the time–distance images along the Slit 1 (S1) at the footpoint, the bright emission at the bottom is emitted from the closed circular ribbon of the X1.1 flare, which is accompanied by a series of coronal jets. The coronal jets are very weak in the original image, but they are much clearer in the running-difference image, which are characterized by the dark oblique stripes, as indicated by the white arrows in Panel d. The coronal jets exhibit a fast speed that could be as high as 408 km s$^{-1}$. The average jet velocity is estimated by the slope of dark oblique stripes in the running-difference image. The jets occurred periodically. We plotted the intensity variations (white) along the 66" marked by the red line on Panel a. The intensity curves show six peaks corresponding to six jets as J1 – J6 marked on timescale during the time interval of $\approx$432 seconds. Thus, the average cadence of the coronal jets is about 72 seconds. However, we could not find a similar quasi-period in the X-ray or microwave flux. The overplotted blue and red lines are the rapidly varying components in NoRP 1 GHz and GOES 1–8 Å in Figure 5. They both show the short-period oscillation, i.e. a dominant period of 20 seconds, which is much shorter than the average cadence of the coronal jets. Moreover, the 20-second oscillation in GOES and NoRP occurs in the same interval between about 05:12 UT and 05:15 UT as the first two jets J1 and J2, while the other jets from J3 to J6 appear after 05:16 UT, when the 20-second oscillation disappears.

3.4. Transverse Perturbation of the Outer Loop

Figure 8b and c present the time–distance images along slits S2 and S3: the zero of the $y$-axis is marked by the red “*” in Figure 1b. The outer loop shows the transverse perturbation consisting of half a cycle only, for instance, it is displaced from the equilibrium position, reaches maximum displacement, and returns back to equilibrium without overshooting. The transverse perturbation has a duration of about 168 seconds. The onset of the perturbation coincided with the flare eruption, see also the movie in the AIA 171 Å channel. The perturbation amplitude is very large, maybe as high as 20 Mm, suggesting a large-amplitude perturbation. It is interesting that the loop apex (S2) shows an anti-phase perturbation with the loop leg (S3). In other words, the loop apex shrinks, while the loop leg expands. Figure 8e and f give their time–distance images after running-difference. Figure 9 shows the running-difference images in the AIA 171 Å band. The temporal cadence to perform the running-difference image is 24 seconds and not 12 seconds. This is because the AIA images have two different exposure times during this solar flare. Consistent with the anti-phase perturbations in Figure 8 and f, the different parts of the outer loop exhibit the various perturbation directions. For example, at 05:13:59 UT in Figure 9c, the loop leg of P1 shrinks, while the loop apex of P2 and another loop leg of P3 expand. At 05:15:35 UT in Figure 9d, the loop leg of P1 expands, while the loop apex of P2 and another loop leg of P3 shrink. Such anti-phase perturbations are possibly the signature of an MHD wave in the outer loop (see Duckenfield et al., 2010).
Figure 8. Time–distance images along three slits derived from the AIA 171 Å image series (a–c) and their running-difference (d–f). The white line profile in Panel a is the intensity at the site ≈66″, as marked by the red tick on the left hand. The overplotted blue and red lines represent the rapidly varying components in NoRP 1 GHz and GOES 1–8 Å, respectively. The white arrows outline the velocity of the jets. The green curves mark the loop perturbation.

Figure 9. Running-difference images to show the outer loop in AIA 171 Å at 05:13:59 UT (a), 05:15:35 UT (b), 05:17:01 UT (c). P1–P3 mark the loop apex and two loop legs.
4. Conclusion and Discussion

Based on observations obtained by various instruments in the X-ray, microwave, and UV range, we investigate flare-related oscillations during the SOL2013-11-10T05:14 event. SDO/AIA–1600 Å and 171 Å bands show that the X1.1 flare is a typical circular-ribbon flare. The spine-fan magnetic structure derived from the NLFFF extrapolation model (Wheatland, Sturrock, and Roumeliotis, 2000; Wiegelmann, 2004) confirmed the magnetic topology specific to the circular-ribbon flare. For instance, the dome-like structure is consistent with the closed circular ribbon: A set of overlying magnetic-field lines is consistent with the faint outer loop seen in the AIA 171 Å band image (see Figure 2). Our NLFFF extrapolation agrees with previous results using the potential magnetic-field extrapolation (e.g. Mészárosóvá et al., 2013). We found three types of oscillations: i) flare QPP with a quasi-period of roughly 20 seconds in the SXR/HXR, radio, and EUV channels, ii) periodic jets following the circular-ribbon flare with a cadence of about 72 seconds, iii) a transverse perturbation with a duration of about 168 seconds in the faint outer loop.

The FFT and wavelet-analysis methods are applied to determine the periodicity of the flare fluxes at multiple wavelengths, and both show an oscillatory period of roughly 20 seconds. The wavelet spectra show an enhanced power over a broad range, but the wavelet power is always centered at the periodicity of around 20 seconds in SXR/HXR, radio, and EUV passbands. The GOES SXR flux shows a sharp, increasing trend during the flare, so the small-amplitude QPPs only appear clearly during a short time interval, as shown in Figure 4c. They could be clearly seen during the whole flare time after normalization, as shown in Figure 4d. The flare QPP with a similar period can also be observed in the X-ray, radio/microwave, and EUV wavelength ranges recorded by other instruments. This is similar to previous observations (Nakariakov et al., 2010; Milligan et al., 2013; Kupriyanova et al., 2020). The flare QPP with a period range of 10–83 seconds has been found in a circular-ribbon flare (Mészárosóvá et al., 2013), containing our 20-second periodicity. They further identified the wavelet tadpoles from the radio source and explained them as fast magnetoacoustic waves propagating in the coronal loop. However, we could not get the wavelet tadpoles from the wavelet power spectra. The flare QPP with a dominant period of ≈20 seconds is most likely triggered by the nonthermal process. Our multi-wavelength observations suggest the co-existence of thermal and nonthermal processes during the circular-ribbon flare. The flare QPP is detected at SXR and EUV wavelengths, which is a thermal process. It is also seen in the microwave emissions, which obviously decay after reaching the maximum, indicating nonthermal gyrosynchrotron emission during the flare (Dulk, 1985; Warmuth et al., 2016; Li et al., 2020). Moreover, the flare QPP can also be observed in the HXR and high-frequency (i.e. NoRP 35 GHz) microwave emissions, implying an energy-release process by nonthermal electrons. The Neupert effect (Neupert, 1968; Ning, 2003, 2004; Ning and Cao, 2010) is plasma heating as a result of energy released by nonthermal electrons. So, the oscillations of the accelerated electron emission are one reason for the oscillations detected in the thermal emissions in this study.
Similar to previous findings (e.g. Reid et al., 2012; Shen et al., 2012; Zhang et al., 2016; Lu et al., 2019), we have found a series of coronal jets triggered by the circular-ribbon flare at the footpoint of the outer loop, and they appear to have a regular and repeated occurrence with an average periodicity of roughly 72 seconds. These periodic jets could be regarded as repeated outflows produced by magnetic reconnection during circular-ribbon flare (Chitta et al., 2017; Shen et al., 2019; Zhang, 2020). Therefore, the periodic jets at the footpoint might be produced by a nonthermal process during the circular-ribbon flare, i.e. by repetitive magnetic reconnection. This is consistent with previous findings (Kumar, Nakariakov, and Cho, 2015), that found that repeated magnetic reconnection at the footpoint could drive the periodic acceleration of nonthermal electrons. However, we could not detect a similar periodicity such as 72 seconds in flare light curves in HXR and microwave emissions, both of which are often related to the nonthermal electron. The dominant period of the flare QPP is about 20 seconds, which is far from the periodicity of coronal jets. So it is difficult to conclude whether the flare QPP has affected the periodicity jets or whether it is the result of it.

The outer-loop appears to show a transverse perturbation with a duration of about 168 seconds during this event. The perturbation is similar to previous observations of transverse oscillations in the outer loop of the circular-ribbon flare (e.g. Zhang et al., 2024; Dai et al., 2021). However, the perturbation feature studied here only persists for about half a cycle and then disappears, so it cannot be regarded as an oscillation or periodicity. Here, the 168 seconds are regarded as the perturbation duration of the loop apex and leg. It is interesting that loop apex perturbed in anti-phase to one of the loop legs, which would suggest that the loop perturbation is probably driven and modulated by a sausage wave (Tian et al., 2016; Li et al., 2020a) or a slow magnetoacoustic wave (Mészárosóvá et al., 2013; Kumar, Nakariakov, and Cho, 2015). It should be pointed out that the outer-loop perturbation only remains half a cycle, which might be due to the large perturbation amplitude, since the decay time depends on the perturbation/oscillation amplitude (e.g. Goddard and Nakariakov, 2016).

Acknowledgments The authors thank the reviewer for their valuable comments. We thank T. Wiegelmann, Y. Guo, and K. Yang for sharing the NLFFF and vector magnetic-field analysis codes. We would also acknowledge Prof. Brian Dennis for helping the RHESSI image data.

We thank the teams of SDO/AIA, SDO/HMI, GOES, SDO/EVE, RHESSI, Konus-Wind, Fermi, NoRP, and NoRH for their open-data-use policy. Data courtesy of NASA/SDO and the AIA science team. The Ramaty High Energy Solar Spectroscopic Imager is a NASA Small Explorer mission. The Nobeyama Radioheliograph and Nobeyama Radio Polarimeters are operated by the Nobeyama Solar Radio Observatory, NAOJ/NINS.

This work is supported by NSFC under grants 12073081, 12003072, 11973092, 11790302, 11729301, U1731241, as well as CAS Strategic Pioneer Program on Space Science, Grant No. XDA15052200, XDA15320301. Y. Wang also acknowledges the Youth Fund of JiangSu No. BK20191108. D. Li is also supported by the Surface Project of Jiangsu No. BK20211402. The Laboratory No. is 2010DP173032.

Declarations

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

Amiri, S., Karami, K., Ebrahimi, Z.: 2021, Resonant absorption of kink MHD waves in inclined and asymmetric coronal loops. *Mon. Not. Roy. Astron. Soc.* 502, 2172. [DOI][ADS]

Anfinogentov, S.A., Nakariakov, V.M., Pascoe, D.J., Goddard, C.R.: 2021, Solar Bayesian Analysis Toolkit—A New Markov Chain Monte Carlo IDL Code for Bayesian Parameter Inference. * Astrophys. J. Suppl.* 252, 11. [DOI][ADS]

Aptekar, R.L., Frederiks, D.D., Golenetskii, S.V., Ilyinskii, V.N., Mazets, E.P., Panov, V.N., Sokolova, Z.J., Terekhov, M.M., Sheshin, L.O., Cline, T.L., Stilwell, D.E.: 1995, Konus-W Gamma-Ray Burst Experiment for the GGS Wind Spacecraft. *Space Sci. Rev.* 71, 265. [DOI][ADS]

Aschwanden, M.J.: 1987, Theory of Radio Pulsations in Coronal Loops. *Solar Phys.* 111, 113. [DOI][ADS]

Aschwanden, M.J., de Pontieu, B., Schrijver, C.J., Title, A.M.: 2002, Transverse Oscillations in Coronal Loops Observed with TRACE II. Measurements of Geometric and Physical Parameters. *Solar Phys.* 206, 99. [DOI][ADS]

Benz, A.O.: 2017, Flare Observations. *Liv. Rev. Solar Phys.* 14, 2. [DOI][ADS]

Brosius, J.W., Daw, A.N.: 2015, Quasi-periodic Fluctuations and Chromospheric Evaporation in a Solar Flare Ribbon Observed by IRIS. *Astrophys. J.* 810, 45. [DOI][ADS]

Cai, Q., Shen, C., Raymond, J.C., Mei, Z., Warmuth, A., Roussev, I.I., Lin, J.: 2019, Investigations of a supra-arcade fan and termination shock above the top of the flare-loop system of the 2017 September 10 event. *Mon. Not. Roy. Astron. Soc.* 489, 3183. [DOI][ADS]

Chen, X., Yan, Y., Tan, B., Huang, J., Wang, W., Chen, L., Zhang, Y., Tan, C., Liu, D., Masa, S.: 2019, Quasi-periodic Pulsations before and during a Solar Flare in AR 12242. *Astrophys. J.* 878, 78. [DOI][ADS]

Chifor, C., Isobe, H., Mason, H.E., Hannah, I.G., Young, P.R., Del Zanna, G., Krucker, S., Ichimoto, K., Katsukawa, Y., Yokoya, T.: 2008, Magnetic flux cancellation associated with a recurring solar jet observed with Hinode, RHESSI, and STEREO/EUVI. *Astron. Astrophys.* 491, 279. [DOI][ADS]

Chitta, L.P., Peter, H., Young, P.R., Huang, Y.-M.: 2017, Compact solar UV burst triggered in a magnetic field with a fan-spike topology. *Astron. Astrophys.* 605, A49. [DOI][ADS]

Clarke, B.P., Hayes, L.A., Gallagher, P.T., Maloney, S.A., Carley, E.P.: 2021, Quasi-periodic Particle Acceleration in a Solar Flare. *Astrophys. J.* 910, 123. [DOI][ADS]

Dai, J., Zhang, Q.M., Su, Y.N., Ji, H.S.: 2021, Transverse oscillation of a coronal loop induced by a flare-related jet. *Astron. Astrophys.* 646, A12. [DOI][ADS]

Didkovsky, L., Judge, D., Wieman, S., Woods, T., Jones, A.: 2012, EUV SpectroPhotometer (ESP) in Extreme Ultraviolet Variability Experiment (EVE): Algorithms and Calibrations. *Solar Phys.* 275, 179. [DOI][ADS]

Dolla, L., Marquê, C., Seaton, D.B., Van Doorsselaere, T., Dominique, M., Berghmans, D., Cabanas, C., De Groof, A., Schmutz, W., Verdini, A., West, M.J., Zender, J., Zhukov, A.N.: 2012, Time Delays in Quasi-periodic Pulsations Observed during the X2.2 Solar Flare on 2011 February 15. *Astrophys. J. Lett.* 749, L16. [DOI][ADS]

Dominique, M., Zhukov, A.N., Dolla, L., Inglis, A., Lapenta, G.: 2018, Detection of Quasi-Periodic Pulsations in Solar EUV Time Series. *Solar Phys.* 293, 61. [DOI][ADS]

Duckenfield, T.J., Goddard, C.R., Pascoe, D.J., Nakariakov, V.M.: 2019, Observational signatures of the third harmonic in a decaying kink oscillation of a coronal loop. *Astron. Astrophys.* 632, A64. [DOI][ADS]

Dulk, G.A.: 1985, Radio emission from the sun and stars. *Rev. Astron. Astrophys.* 23, 169. [DOI][ADS]

Feng, S., Yu, L., Wang, F., Deng, H., Yang, Y.: 2017, Midterm Periodicity Analysis of the Mount Wilson Magnetic Indices Using the Synchrosqueezing Transform. *Astrophys. J.* 845, 11. [DOI][ADS]

Feng, S., Deng, Z., Yuan, D., Xu, Z., Yang, X.: 2020, Propagating slow sausage waves in a sunspot observed by the New Vacuum Solar Telescope. *Res. Astron. Astrophys.* 20, 117. [DOI][ADS]
Li, D., Zhang, Q.M.: 2017, Quasi-periodic pulsations with multiple periods in hard X-ray emission. *Astrophys. J.* 807, 72. [DOI ADS]

Li, D., Ning, Z.J., Zhang, Q.M.: 2015, Imaging and Spectral Observations of Quasi-periodic Pulsations in a Solar Flare. *Astrophys. J.* 700, 103. [DOI ADS]

Li, D., Yuan, D., Su, Y.N., Zhang, Q.M., Su, W., Ning, Z.J.: 2018, Non-damping oscillations at flaring loops. *Astron. Astrophys.* 617, A86. [DOI ADS]

Li, D., Feng, S., Su, W., Huang, Y.: 2020a, Preflare very long-periodic pulsations observed in Lyman-α emission before the onset of a solar flare. *Astron. Astrophys.* 639, L5. [DOI ADS]

Li, D., Lu, L., Ning, Z., Feng, L., Gan, W., Li, H.: 2020c, Quasi-periodic Pulsation Detected in Lyman-α Emission during a Solar Flare. *Astrophys. J.* 893, 7. [DOI ADS]

Li, D., Kolotkov, D.Y., Nakariakov, V.M., Lu, L., Ning, Z.J.: 2020d, Quasi-periodic Pulsations of Gamma-Ray Emissions from a Solar Flare on 2017 September 6. *Astrophys. J.* 888, 53. [DOI ADS]

Li, D., Warmuth, A., Lu, L., Ning, Z.: 2021a, An investigation of flare emissions at multiple wavelengths. *Research in Astronomy and Astrophysics* 21, 066. [DOI ADS]

Li, D., Ge, M., Dominique, M., Zhao, H., Li, G., Li, X., Zhang, S., Lu, F., Gan, W., Ning, Z.: 2021b, Detection of Flare Multiperiodic Pulsations in Mid-ultraviolet Balmer Continuum, Lyman-α, Hard X-Ray, and Radio Emissions Simultaneously. *Astrophys. J.* 921, 179. [DOI ADS]

Li, T., Zhang, J.: 2015, Quasi-periodic Slipping Magnetic Reconnection During an X-class Solar Flare Observed by the Solar Dynamics Observatory and Interface Region Imaging Spectrograph. *Astrophys. J. Lett.* 804, L8. [DOI ADS]

Li, T., Yang, S., Zhang, Q., Hou, Y., Zhang, J.: 2018b, Two Episodes of Magnetic Reconnections during a Confined Circular-ribbon Flare. *Astrophys. J.* 859, 122. [DOI ADS]

Liang, B., Meng, Y., Feng, S., Yang, Y.: 2020, Estimating red noise in quasi-periodic signals with MCMC-based Bayesian. *Astrophys. Space Sci.* 365, 40. [DOI ADS]

Lim, D., Nakariakov, V.M., Moon, Y.-J.: 2018, Sausage oscillations in a plasma cylinder with a surface current. *J. Atmos. Solar-Terr. Phys.* 175, 49. [DOI ADS]

Lin, R.P., Dennis, B.R., Hurford, G.J., Smith, D.M., Zehnder, A., Harvey, P.R., Curtis, D.W., Pankow, D., Turin, P., Bester, M., Caillauguy, A., Lewis, M., Madden, N., van Beek, H.F., Appleby, M., Raudorf, T., McTiernan, J., Ramaty, R., Schmah, E., Schwartz, R., Krucker, S., Akiyama, R., Quinn, T., Berg, M., Hashii, M., Sterling, R., Jackson, R., Pratt, R., Campbell, R., Maloni, D., Landis, D., Barrington-Leigh, C.P., Slassi-Sennou, S., Cork, C., Clark, D., Amato, D., Orwig, L., Boyle, R., Banks, I.S., Shirley, K., Tolbert, A.K., Zarro, D., Snow, F., Thomsen, K., Hennec, R., McHedlishvili, A., Ming, P., Vivian, M., Jordan, J., Wanner, R., Crubb, J., Preble, J., Matranga, M., Benz, A., Hudson, H., Canfield, R.C., Holman, G.D., Curren, C., Kosugi, T., Emslie, A.G., Vilmer, N., Brown, J.C., Metcalf, T., Conway, A.: 2002, The Reuven Ramaty High-Energy Solar Spectroscopic Imager (Rhessi). *Solar Phys.* 210, 3. [DOI ADS]

Liu, W., Berger, T.E., Title, A.M., Tarbell, T.D., Low, B.C.: 2011, Chromospheric Jet and Growing “Loop” Observed by Hinode: New Evidence of Fan-spin e Magnetic Topology Resulting from Flux Emergence. *Astrophys. J.* 728, 103. [DOI ADS]

Liu, L., Feng, L., Li, Y., Li, D., Ning, Z., Gan, W.: 2019, Spectroscopic and Stereoscopic Observations of the Solar Jets. *Astrophys. J.* 887, 154. [DOI ADS]

Lu, L., Li, D., Ning, Z., Feng, L., Gan, W.: 2021, Quasi-Periodic Pulsations Detected in Lyman-α and Nonthermal Emissions During Solar Flares. *Solar Phys.* 296, 130. [DOI ADS]

Maissone, S., Pariat, E., Aulanier, G., Schrijver, C.J.: 2009, The Nature of Flare Ribbons in Coronal Null-Point Topology. *Astrophys. J.* 700, 559. [DOI ADS]

McLaughlin, J.A., Nakariakov, V.M., Dominique, M., Jelinek, P., Takasao, S.: 2018, Modelling Quasi-Periodic Pulsations in Solar and Stellar Flares. *Space Sci. Rev.* 214, 45. [DOI ADS]
Meegan, C., Lichti, G., Bhat, P.N., Bissaldi, E., Briggs, M.S., Connaughton, V., Diehl, R., Fishman, G., Greiner, J., Hoover, A.S., van der Horst, A.J., von Kienlin, A., Kippen, R.M., Kouveliotou, C., McBreen, S., Paciesas, W.S., Preece, R., Steinle, H., Wallace, M.S., Wilson, R.B., Wilson-Hodge, C.: 2009, The Fermi Gamma-ray Burst Monitor. Astrophys. J. 702, 791. DOI. ADS.

Mészáros, H., Dudák, J., Karlický, M., Madsen, F.R.H., Sawant, H.S.: 2013, Fast Magnetooacoustic Waves in a Fan Structure Above a Coronal Magnetic Null Point. Solar Phys. 283, 473. DOI. ADS.

Metcalf, T.R., Leka, K.D., Barnes, G., Lites, B.W., Georgoulis, M.K., Pevtsov, A.A., Balasubramaniam, K.S., Gary, G.A., Jing, J., Li, J., Liu, Y., Wang, H.N., Abramenko, V., Yurchyshyn, V., Moon, Y.-J.: 2006, An Overview of Existing Algorithms for Resolving the 180° Ambiguity in Vector Magnetic Fields: Quantitative Tests with Synthetic Data. Solar Phys. 237, 267. DOI. ADS.

Milligan, R.O., Fleck, B., Ireland, J., Fletcher, L., Dennis, B.R.: 2017, Detection of Three-minute Oscillations in Full-disk Lyα Emission during a Solar Flare. Astrophys. J. Lett. 848, L8. DOI. ADS.

Nakajima, H., Sekiguchi, H., Sawa, M., Kai, K., Kawashima, S.: 1985, The radiometer and polarimeters at 80, 35, and 17 GHz for solar observations at Nobeyama. Pub. Astron. Soc. Japan 37, 163. ADS.

Nakariakov, V.M., Kolotkov, D.Y.: 2020, Magnetohydrodynamic Waves in the Solar Corona. Rev. Astron. Astrophys. 58, 441. DOI. ADS.

Nakariakov, V.M., Zimovets, I.V.: 2011, Slow Magnetooacoustic Waves in Two-ribbon Flares. Astrophys. J. Lett. 730, L27. DOI. ADS.

Nakariakov, V.M., Ofman, L., Deluca, E.E., Roberts, R., Davila, J.M.: 1999, TRACE observation of damped coronal loop oscillations: Implications for coronal heating. Science 285, 862. DOI. ADS.

Nakariakov, V.M., Inglis, A.R., Zimovets, I.V., Foullon, C., Verwichte, E., Syrch, R., Myagkova, I.N.: 2010a, Oscillatory processes in solar flares. Plasma Phys. Control. Fusion 52, 124009. DOI. ADS.

Nakariakov, V.M., Foullon, C., Myagkova, I.N., Inglis, A.R.: 2010b, Quasi-Periodic Pulses in the Gamma-Ray Emission of a Solar Flare. Astrophys. J. Lett. 708, L47. DOI. ADS.

Nakariakov, V.M., Anfinogentov, S., Storozhenko, A.A., Kurockhin, E.A., Bogod, V.M., Sharykin, I.N., Kaltman, T.I.: 2018, Quasi-periodic Pulses in a Solar Microflare. Astrophys. J. 859, 154. DOI. ADS.

Nakariakov, V.M., Anfinogentov, S.A., Antolin, P., Jain, R., Kolotkov, D.Y., Kupriyanova, E.G., Li, D., Magyar, N., Nisticò, G., Pascoe, D.J., Srivastava, A.K., Terradas, J., Vasheghani Farahani, S., Verth, G., Yuan, D., Zimovets, I.V.: 2021, Kink Oscillations of Coronal Loops. Space Sci. Rev. 217, 73. DOI. ADS.

Neupert, W.M.: 1968, Comparison of Solar X-Ray Line Emission with Microwave Emission during Flares. Astrophys. J. Lett. 153, L59. DOI. ADS.

Ning, Z.: 2008, RHESSI Observations of the Neupert Effect in Three Solar Flares. Solar Phys. 248, 99. DOI. ADS.

Ning, Z.: 2009, The investigation of the Neupert effect in two solar flares. Science in China: Physics, Mechanics and Astronomy 52, 1686. DOI. ADS.

Ning, Z.: 2014, Imaging Observations of X-Ray Quasi-periodic Oscillations at 3 - 6 keV in the 26 December 2002 Solar Flare. Solar Phys. 289, 1239. DOI. ADS.

Ning, Z.: 2017, One-Minute Quasi-Periodic Pulses Seen in a Solar Flare. Solar Phys. 292, 11. DOI. ADS.

Ning, Z., Cao, W.: 2010, Investigation of the Neupert Effect in the Various Intervals of Solar Flares. Solar Phys. 264, 329. DOI. ADS.

Ning, Z., Ding, M.D., Wu, H.A., Xu, F.Y., Meng, X.: 2005, Microwave type III bursts and pulsation groups. Astron. Astrophys. 437, 691. DOI. ADS.

Ofman, L., Wang, T.: 2002, Hot Coronal Loop Oscillations Observed by SUMER: Slow Magnetosonic Wave Damping by Thermal Conduction. Astrophys. J. Lett. 580, L85. DOI. ADS.

Pal'shin, V.D., Charikov, Y.E., Aptekar, R.L., Golenetskii, S.V., Kokomov, A.A., Svinkin, D.S., Sokolova, Z.Y., Ulanoz, M.V., Frederiks, D.D., Tsvetkova, A.E.: 2014, Konus- Wind and Helicon- Coronas-F observations of solar flares. Geomag. Aeronom. 54, 943. DOI. ADS.

Parks, G.K., Winckler, J.R.: 1969, Sixteen-Second Periodic Pulses Observed in the Correlated Microwave and Energetic X-Ray Emission from a Solar Flare. Astrophys. J. Lett. 155, L117. DOI. ADS.
Detections of Multi-periodic Oscillations During a Circular Ribbon Flare

Pesnell, W.D., Thompson, B.J., Chamberlin, P.C.: 2012, The Solar Dynamics Observatory (SDO). *Solar Phys.* **275**, 3. DOI, ADS

Pugh, C.E., Nakariakov, V.M., Broomhall, A.-M., Bogomolov, A.V., Myagkova, I.N.: 2017, Properties of quasi-periodic pulsations in solar flares from a single active region. *Astron. Astrophys.* **608**, A101. DOI, ADS

Reid, H.A.S., Vilmer, N., Aulanier, G., Pariat, E.: 2012, X-ray and ultraviolet investigation into the magnetic connectivity of a solar flare. *Astron. Astrophys.* **547**, A52. DOI, ADS

Samanta, T., Tian, H., Chen, B., Reeves, K.K., Cheung, M.C.M., Vourlidas, A., Banerjee, D.: 2021, Plasma heating induced by tadpole-like downflows in the flaring solar corona. *The Innovation* **2**, 100083. DOI, ADS

Shen, Y., Liu, Y., Su, J., Deng, Y.: 2012, On a Coronal Blowout Jet: The First Observation of a Simultaneously Produced Bubble-like CME and a Jet-like CME in a Solar Event. *Astrophys. J.* **745**, 164. DOI, ADS

Shen, Y., Liu, Y., Song, T., Tian, Z.: 2018, A Quasi-periodic Fast-propagating Magnetosonic Wave Associated with the Eruption of a Magnetic Flux Rope. *Astrophys. J.* **853**, 1. DOI, ADS

Shen, Y., Qu, Z., Zhou, C., Duan, Y., Tang, Z., Yuan, D.: 2019, Round-trip Slipping Motion of the Circular Flare Ribbon Evidenced in a Fan-spine Jet. *Astrophys. J. Lett.* **885**, L11. DOI, ADS

Shibata, K., Magara, T.: 2011, Solar Flares: Magnetohydrodynamic Processes. *Liv. Rev. Solar Phys.* **8**, 6. DOI, ADS

Simões, P.J.A., Hudson, H.S., Fletcher, L.: 2015, Soft X-Ray Pulsations in Solar Flares. *Solar Phys.* **290**, 3625. DOI, ADS

Song, Y., Tian, H.: 2018, Investigation of White-light Emission in Circular-ribbon Flares. *Astrophys. J.* **867**, 159. DOI, ADS

Srivastava, A.K., Zaqarashvili, T.V., Uddin, W., Dwivedi, B.N., Kumar, P.: 2008, Observation of multiple sausage oscillations in cool post-flare loop. *Mon. Not. Roy. Astron. Soc.* **388**, 1899. DOI, ADS

Sturrock, P.A., Coppi, B.: 1964, A New Model of Solar Flares. *Nature* **204**, 61. DOI, ADS

Su, W., Guo, Y., Erdélyi, R., Ning, Z.J., Ding, M.D., Cheng, X., Tan, B.L.: 2018, Period Increase and Amplitude Distribution of Kink Oscillation of Coronal Loop. *Sci. Rep.* **8**, 4471. DOI, ADS

Takasao, S., Shibata, K.: 2016, Above-the-loop-top Oscillation and Quasi-periodic Coronal Wave Generation in Solar Flares. *Astrophys. J.* **823**, 150. DOI, ADS

Tan, B., Zhang, Y., Tan, C., Liu, Y.: 2010, Microwave Quasi-Periodic Pulsations in Multimicrosecond Associated with a Solar Flare/CME Event. *Astrophys. J.* **723**, 25. DOI, ADS

Tan, B., Yu, Z., Huang, J., Tan, C., Zhang, Y.: 2016, Very Long-period Pulsations before the Onset of Solar Flares. *Astrophys. J.* **833**, 206. DOI, ADS

Tian, H., Young, P.R., Reeves, K.K., Wang, T., Antolin, P., Chen, B., He, J.: 2016, Global Sausage Oscillation of Solar Flare Loops Detected by the Interface Region Imaging Spectrograph. *Astrophys. J. Lett.* **823**, L16. DOI, ADS

Török, T., Aulanier, G., Schmieder, B., Reeves, K.K., Golub, L.: 2009, Fan-Spine Topology Formation Through Two-Step Reconnection Driven by Twisted Flux Emergence. *Astrophys. J.* **704**, 485. DOI, ADS

Torrence, C., Compo, G.P.: 1998, A Practical Guide to Wavelet Analysis. *Bull. Am. Meteor. Soc.* **79**, 61. DOI, ADS

Van Doorsselaere, T., Kupriyanova, E.G., Yuan, D.: 2016, Quasi-periodic Pulsations in Solar and Stellar Flares: An Overview of Recent Results (Invited Review). *Solar Phys.* **291**, 3143. DOI, ADS

Vaughan, S.: 2005, A simple test for periodic signals in red noise. *Astron. Astrophys.* **431**, 391. DOI, ADS

Wang, H., Liu, C.: 2012, Circular Ribbon Flares and Homologous Jets. *Astrophys. J.* **760**, 101. DOI, ADS
Z. Ning et al.

Wang, T., Solanki, S.K., Curdt, W., Innes, D.E., Dammash, I.E.: 2002, Doppler Shift Oscillations of Hot Solar Coronal Plasma Seen by SUMER: A Signature of Loop Oscillations? Astrophys. J. Lett. 574, L101. DOI [ADS]

Wang, T., Ofman, L., Yuan, D., Reale, F., Kolotkov, D.Y., Srivastava, A.K.: 2021, Slow-Mode Magnetoacoustic Waves in Coronal Loops. Space Sci. Rev. 217, 34. DOI [ADS]

Wang, Z.-K., Feng, S., Deng, L.-H., Meng, Y.: 2020, Spatial distributions of sunspot oscillation modes at different temperatures. Research in Astronomy and Astrophysics 20, 006. DOI [ADS]

Warmuth, A., Shibasaki, K., Iwai, K., Mann, G.: 2016, Microwave observations of a large-scale coronal wave with the Nobeyama radioheliograph. Astron. Astrophys. 593, A102. DOI [ADS]

Wheatland, M.S., Sturrock, P.A., Roumeliotis, G.: 2000, An Optimization Approach to Reconstructing Force-free Fields. Astrophys. J. 540, 1150. DOI [ADS]

Wiegmann, T.: 2004, Optimization code with weighting function for the reconstruction of coronal magnetic fields. Solar Phys. 219, 87. DOI [ADS]

Woods, T.N., Eparvier, F.G., Hock, R., Jones, A.R., Woodraska, D., Judge, D., Didkovsky, L., Lean, J., Mariska, J., Warren, H., McMullin, D., Chamberlin, P., Berthiaume, G., Bailey, S., Fuller-Rowell, T., Sojka, J., Tobiska, W.K., Vieheck, R.: 2012, Extreme Ultraviolet Variability Experiment (EVE) on the Solar Dynamics Observatory (SDO): Overview of Science Objectives, Instrument Design, Data Products, and Model Developments. Solar Phys. 275, 115. DOI [ADS]

Xue, J., Su, Y., Li, H., Zhao, X.: 2020, Thermodynamical Evolution of Supra-arcade Downflows. Astron. Astrophys. J. 898, 88. DOI [ADS]

Yan, X.L., Yang, L.H., Xue, Z.K., Mei, Z.X., Kong, D.F., Wang, J.C., Li, Q.L.: 2018, Simultaneous Observation of a Flux Rope Eruption and Magnetic Reconnection during an X-class Solar Flare. Astrophys. J. Lett. 853, L18. DOI [ADS]

Yang, S., Xiang, Y.: 2016, Oscillation of Newly Formed Loops after Magnetic Reconnection in the Solar Chromosphere. Astrophys. J. Lett. 819, L24. DOI [ADS]

Yu, S., Chen, B.: 2019, Possible Detection of Subsecond-period Propagating Magnetohydrodynamics Waves in Post-reconnection Magnetic Loops during a Two-ribbon Solar Flare. Astrophys. J. 872, 71. DOI [ADS]

Yuan, D., Van Doorselaere, T.: 2016, Forward Modeling of Standing Kink Modes in Coronal Loops. I. Synthetic Views. Astrophys. J. Suppl. 223, 23. DOI [ADS]

Yuan, D., Feng, S., Li, D., Ning, Z., Tan, B.: 2019, A Compact Source for Quasi-periodic Pulsation in an M-class Solar Flare. Astrophys. J. Lett. 886, L25. DOI [ADS]

Zhang, Q.M.: 2020, Simultaneous transverse oscillations of a coronal loop and a filament excited by a circular-ribbon flare. Astron. Astrophys. 642, A159. DOI [ADS]

Zhang, Q.M., Li, D., Ning, Z.J., Su, Y.N., Ji, H.S., Guo, Y.: 2016, Explosive Chromospheric Evaporation in a Circular-ribbon Flare. Astrophys. J. 827, 27. DOI [ADS]

Zhang, Q.M., Dai, J., Xu, Z., Li, D., Lu, L., Tan, K.V., Xu, A.A.: 2020, Transverse coronal loop oscillations excited by homologous circular-ribbon flares. Astron. Astrophys. 638, A32. DOI [ADS]

Zhang, Q.M., Huang, Z.H., Hou, Y.J., Li, D., Ning, Z.J., Wu, Z.: 2021, Spectroscopic observations of a flare-related coronal jet. Astron. Astrophys. 647, A113. DOI [ADS]

Zuzurova, I.V., McLaughlin, J.A., Srivastava, A.K., Kolotkov, D.Y., Kuznetsov, A.A., Kupriyanova, E.G., Cho, I.H., Inglis, A.R., Reale, F., Pascoe, D.J., Tian, H., Yuan, D., Li, D., Zhang, Q.M.: 2021, Quasi-Periodic Pulsations in Solar and Stellar Flares: A Review of Underpinning Physical Mechanisms and Their Predicted Observational Signatures. Space Sci. Rev. 217, 66. DOI [ADS]