Simultaneous Transverse and Longitudinal Oscillations in a Quiescent Prominence Triggered by a Coronal Jet

Q. M. Zhang\textsuperscript{1,2}, D. Li\textsuperscript{1}, and Z. J. Ning\textsuperscript{1}\textsuperscript{©}
\textsuperscript{1} Key Laboratory for Dark Matter and Space Science, Purple Mountain Observatory, CAS, Nanjing 210008, China; zhangqm@pmo.ac.cn
\textsuperscript{2} CAS Key Laboratory of Solar Activity, National Astronomical Observatories, Beijing 100012, China

Received 2017 June 24; revised 2017 November 1; accepted 2017 November 2; published 2017 December 11

Abstract

In this paper, we report our multiwavelength observations of the simultaneous transverse and longitudinal oscillations in a quiescent prominence. The prominence was observed by the Global Oscillation Network Group and by the Atmospheric Imaging Assembly on board the Solar Dynamics Observatory on 2015 June 29. A GOES C2.4 flare took place in NOAA active region 12373, which was associated with a pair of short ribbons and a remote ribbon. During the impulsive phase of the flare, a coronal jet spurted out of the primary flare site and propagated in the northwestern direction at an apparent speed of $\sim 224$ km s$^{-1}$. Part of the jet stopped near the remote ribbon. The remaining part continued moving forward before stopping to the east of the prominence. Once the jet encountered the prominence, it pushed the prominence to oscillate periodically. The transverse oscillation of the eastern part (EP) of prominence can be divided into two phases. In phase I, the initial amplitude, velocity, period, and damping timescale are $\sim 4.5$ Mm, $\sim 20$ km s$^{-1}$, $\sim 25$ minutes, and $\sim 7.5$ hr, respectively. The oscillation lasted for two cycles. In phase II, the initial amplitude increases to $\sim 11.3$ Mm, while the initial velocity halves to $\sim 10$ km s$^{-1}$. The period increases by a factor of $\sim 3.5$. With a damping timescale of $\sim 4.4$ hr, the oscillation lasted for about three cycles. The western part of prominence also experienced transverse oscillation. The initial amplitude is only $\sim 2$ Mm and the velocity is less than 10 km s$^{-1}$. The period ($\sim 27$ minutes) is slightly longer than that of the EP in phase I. The oscillation lasted for about four cycles with the shortest damping timescale ($\sim 1.7$ hr). To the east of prominence, a handful of horizontal threads experienced longitudinal oscillation. The initial amplitude, velocity, period, and damping timescale are $\sim 52$ Mm, $\sim 50$ km s$^{-1}$, $\sim 99$ minutes, and 2.5 hr, respectively. To our knowledge, this is the first report of simultaneous transverse and longitudinal prominence oscillations triggered by a coronal jet.

Key words: Sun: filaments, prominences – Sun: flares – Sun: oscillations

Supporting material: animations

1. Introduction

Solar prominences are cool and dense plasma structures suspending in the corona with diverse morphology and rich dynamics (Labrosse et al. 2010; Mackay et al. 2010, and references therein). The densities of prominences are $\sim 100$ times larger than the corona, while the temperatures of prominences are $\sim 100$ times lower than the corona. They can be observed in radio (Gopalswamy et al. 2003), Ca II H (Berger et al. 2008; Ning et al. 2009a), H$\alpha$ (Engvold 1976; Hao et al. 2015), and extreme-ultraviolet (EUV) wavelengths (Heinzel et al. 2008; McCauley et al. 2015). When observed on a disk, the bright prominences appear as dark filaments in the filament channels along the polarity inversion lines (van BalWpoojen & Martens 1989; Martin 1998). They can be found in the quiet region (QR), active regions (ARs), and near the polar region with high latitudes (Leroy et al. 1983; Su & van BalWpoijen 2012). The magnetohydrostatic equilibrium condition of a filament requires that the gravitational force on the filament is balanced by the upward magnetic tension force of the dips, either in sheared arcades (Antiochos et al. 1994; Liu et al. 2012; Zhang et al. 2015) or in twisted magnetic flux ropes (Martens & Zwaan 2001; Keppens & Xia 2014; Terradas et al. 2016). Sometimes, a flux rope and a dipped arcade can coexist along one filament (Guo et al. 2010). Filaments are divided into normal-polarity and inverse-polarity types (Priest et al. 1989; Ouyang et al. 2017). Oscillations are excited in prominence structures when they interact with propagating disturbances such as coronal EIT waves and chromospheric Moreton waves. The periods of oscillations range from a few to tens of minutes (Isobe & Tripathi 2006; Ning et al. 2009b; Schmieder et al. 2013), and the displacements range from a few to tens of Mm (Okamoto et al. 2007; Kim et al. 2014). According to the velocity amplitude, they can be classified into small-amplitude ($\leq 3$ km s$^{-1}$) and large-amplitude ($\geq 20$ km s$^{-1}$) oscillations. In most cases, the amplitudes of oscillations damp with time (e.g., Hershaw et al. 2011; Gosain & Foullon 2012). Recently, a rare case of growing amplitudes of filament oscillations has been reported, which is explained by the thread–thread interaction (Zhang et al. 2017; Zhou et al. 2017). Based on the direction of oscillation with respect to the filament axis, they can be divided into transverse (e.g., Hyder 1966; Ramsey & Smith 1966; Kleczek & Kuperus 1969; Chen et al. 2008) and longitudinal oscillations (e.g., Jing et al. 2003; Vršnak et al. 2007; Li & Zhang 2012; Zhang et al. 2012; Bi et al. 2014; Chen et al. 2014; Luna et al. 2014; Zheng et al. 2017). A prominence can even undergo transverse and longitudinal oscillations simultaneously (Pant et al. 2016; Wang et al. 2016).

The triggering mechanism of filament oscillations is a very important issue. The large-amplitude transverse oscillations are often caused by Moreton waves and EUV waves from a remote site of eruption at speeds of $\sim 1000$ km s$^{-1}$ (e.g., Eto et al. 2002; Gilbert et al. 2008). The strong and impulsive impact of waves can shake the filaments and trigger oscillations. The large-amplitude longitudinal oscillations, however, are usually triggered by flares or subflares near the
footpoints of the filaments (Jing et al. 2003, 2006; Vršnak et al. 2007; Li & Zhang 2012; Zhang et al. 2012). The localized plasma pressure increases impulsively during the flares or subflares, which propels the filament to oscillate around the magnetic dips (Zhang et al. 2013). The component of gravity along the dip serves as the restoring force (Luna & Karpen 2016). Once the initial amplitude exceeds a critical value, chances are that part of the filament material undergoes downward drainage into the chromosphere, while the remaining part continues to oscillate (Zhang et al. 2013, 2017). Considering that the filaments are 3D in nature and are often supported by magnetic flux ropes, the flares or subflares may also result in enhancement of magnetic pressure, which drives longitudinal oscillations (Vršnak et al. 2007). The magnetic pressure gradient is considered as the restoring force, and the poloidal magnetic field of the flux rope can be estimated. In the case of 2010 August 20, the longitudinal oscillation was triggered by episodic jets connecting the energetic event and the filament threads (Luna et al. 2014). On 2016 January 26, an interaction between two filaments took place in a long filament channel. During the interaction, longitudinal filament oscillation was triggered by the moving plasma at a speed of ~165 km s\(^{-1}\) from the flare region (Zheng et al. 2017). Sometimes, when a coronal shock wave impacts a nearby filament during its propagation, it can trigger both transverse and longitudinal filament oscillations (Shen et al. 2014; Pant et al. 2016).

Transverse oscillations in coronal loops triggered by coronal jets have been observed (Sarkar et al. 2016). However, simultaneous transverse and longitudinal oscillations in a prominence triggered by a coronal jet have never been investigated.

In this paper, we report our multiwavelength observations of the large-amplitude oscillations of a quiescent prominence triggered by the jet from a remote C2.4 solar flare on 2015 June 29. The paper is structured as follows. Data analysis is described in Section 2. Results are shown in Section 3. Discussions about the triggering mechanism are arranged in Section 4. Finally, we give a brief summary in Section 5.

2. Instruments and Data Analysis

Located north to NOAA AR 12373 (N1SE53), the prominence was continuously observed by the Global Oscillation Network Group (GONG) in the H\(_\alpha\) line center (6562.8 Å) and by the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) onboard the Solar Dynamics Observatory (SDO) in UV (1600 Å) and EUV (94, 171, 304, and 211 Å) wavelengths. The photospheric line of sight (LOS) magnetograms were observed by the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012) onboard the SDO. The level_1 data from AIA and HMI were calibrated using the standard Solar Software (SSW) programs aia_prep.pro and hmi_prep.pro. The full-disk H\(_\alpha\) and AIA 304 Å images were co-aligned with an accuracy of ~1″ using the cross correlation method. The global coronal 3D magnetic configuration was derived from the potential field source surface (PFSS; Schrijver & De Rosa 2003) modeling. The EUV flux in 1–70 Å was recorded by the Extreme Ultraviolet Variability Experiment (EVE; Woods et al. 2012) onboard the SDO. The soft X-ray (SXR) flux in 1–8 Å was recorded by the GOES spacecraft. The observational parameters, including the instrument, wavelength, time, cadence, and pixel size are summarized in Table 1.

3. Results

3.1. Magnetic Field and Configuration

Figure 1 shows the quiescent prominence (N45E90) and AR 12373 in various wavelengths around 17:00 UT. The prominence consisted of two parts, the eastern part (EP) and the western part (WP). The EP of prominence was composed of

| Instrument | \( \lambda \) (Å) | Time (UT) | Cadence (s) | Pixel Size (″) |
|------------|-----------------|-----------|-------------|----------------|
| GONG       | 6562.8          | 17:00−20:55 | 60          | 1.0            |
| SDO/AIA    | 94, 171, 211, 304 | 17:00−03:00+1d | 12          | 0.6            |
| SDO/AIA    | 1600            | 17:00      | 24          | 0.6            |
| SDO/HMI    | 6173            | 17:00      | 45          | 0.5            |
| SDO/EVE    | 1−70            | 17:00−19:00 | 0.25        | ...            |
| GOES       | 1−8             | 17:00−19:00 | 2.05        | ...            |

Figure 1. Prominence and AR 12373 observed before the C2.4 flare in H\(_\alpha\), 304, 171, and 211 Å, respectively. The short slice (S2) in panel (a) is used to investigate the transverse oscillation of the WP.
many bright vertical threads in Hα. However, it appeared as dark fine threads in EUV 171 and 211 Å images due to its low temperature (~0.01 MK) compared to the ambient corona (~1 MK). According to recent statistical results, nearly 96% of the quiescent filaments are associated with a flux rope magnetic configuration, while only 4% are associated with a sheared arcade configuration (Ouyang et al. 2017). Thus, we believe that the vertical threads indicate a flux rope morphology of the prominence magnetic field. The WP of prominence resembles a vertical column and is shorter than the EP.

In Figure 2, the HMI LOS magnetogram at 17:00:40 UT is displayed in the left panel. The inset figure shows the prominence at 17:00:11 UT in 171 Å. It is obvious that the photospheric magnetic field strength beneath the prominence is quite weak. The right panel demonstrates the global magnetic configuration at 18:04 UT using PFSS modeling. It is revealed...
The intensity contours of the three ribbons in panel (d) are superposed on the 94 Å image with thin magenta lines.

3.2. C2.4 Flare and Coronal Jet

During 17:58–19:00 UT, a C2.4 flare took place in AR 12373. To illustrate the flare more clearly, we took the EUV images around 17:00 UT as base images and made base-difference images after 17:00 UT. Figure 3 shows eight snapshots of the base-difference images in 171 Å (see also the online animated figure). At the very beginning of flare, there was no obvious brightening (see panel (a)). As time went on, the flare started to brighten. The jet spurted out of the flare site and propagated northward (see panel (b)). About nine minutes later, part of the jet generated brightening at B3, while the remaining part propagated continuously along closed coronal loops (see panel (c)). The jet stopped to the left of the prominence and caused strong brightening at B4 (see panel (d)). Afterwards, the intensities of the flare and jet decreased gradually.

In Figure 4, the EUV base-difference images around 18:22 UT are displayed in panels (a)–(c). The jet indicated in the 171 Å images are also visible in 304, 211, and 94 Å, implying its multithermal nature (Zhang & Ji 2014). The jet originated from B2 and went through B3 before terminating at B4 where it encountered the prominence. It is noticed that the jet connecting B3 and B4 is not so clear in 94 Å, meaning that the temperature of that segment is not high enough (<6 MK). Interestingly, the flare had three ribbons. Figure 4(d) shows the original UV 1600 Å image when the intensities of the flare ribbons reached the maxima at 18:04:16 UT. The intensity contours of the three ribbons (R1－R3) are superposed on the 94 Å image with thin magenta lines. R1 and R2 at the primary flare site are connected by hot and compact post-flare loops. R3 is close to B3, suggesting that the primary flare site and remote site (R3) are connected by closed magnetic field lines.

In Figure 5(b), the SXR flux in 1–8 Å and the EVE irradiance in 1–70 Å during 17:00–19:00 UT are plotted with cyan and magenta lines, respectively. The SXR flux increases sharply from ~17:58 and reaches the peak value at ~18:07 UT. Afterwards, the flux decreases rapidly to the initial level at ~19:00 UT. The lifetime of the flare is ~1 hr. The EVE irradiance has a similar evolution to the SXR flux except for a delayed peak time by ~2 minutes. The temporal evolutions of the normalized UV intensities of R1－R3 are plotted in Figure 5(a). There are two major peaks at ~18:01 UT and ~18:04 UT in the light curves. A close inspection reveals that the peak times of the ribbons are sequential rather than coincident. Cross correlation analysis shows that the intensity of R3 lags behind that of R1 by ~48 s. The free magnetic energy of the flare is converted into kinetic energy of jet, thermal/nonthermal energies of the plasmas, and MHD waves. So, the time lag between R1 and R3 implies that the nonthermal energy is transported from the primary flare site to the remote site by the high-energy (10–100 keV) electrons (Nakajima et al. 1985).

It is generally believed that coronal jets are driven by magnetic reconnection (e.g., Yokoyama & Shibata 1996;
Moreno-Insertis et al. 2008; Archontis & Hood 2013; Ni et al. 2017). In order to figure out whether the flare-related jet is associated with magnetic reconnection in this event, we examined the HMI LOS magnetograms with a cadence of 45 s. It is found that there was magnetic cancellation at the jet base. Eight snapshots of the magnetograms during 17:25–18:18 UT are displayed in Figure 6. In panel (e), the region of magnetic cancellation is marked by the black box. The unsigned integrated positive and negative magnetic fluxes within the box are calculated and plotted with red and blue lines in Figure 5(c). It is obvious that the positive magnetic flux increased from $4.5 \times 10^{19}$ Mx at 17:00 UT to $6.2 \times 10^{19}$ Mx at 17:55 UT. During the impulsive and decay phases of the flare, the positive magnetic flux was continuously canceled by the negative field (see the yellow rectangular region). The negative flux increased slightly during the cancellation, probably due to the fact that the rate of flux emergence exceeds the rate of cancellation. Therefore, the flare-related coronal jet may be driven by magnetic reconnection as indicated by flux cancellation near the flaring site.

3.3. Prominence Oscillations

3.3.1. Transverse Oscillation of the EP

From the animation of Figure 3, we found that the jet was stopped by the prominence. However, due to the strong impact of the jet, the prominence started to oscillate periodically. In order to investigate the jet and prominence oscillations, we take a long curved slice (S1) with a length of 468”6 in Figure 3(h). The slice starts from the flare site and goes through the jet and EP of prominence. The time-slice diagrams of S1 in various wavelengths are demonstrated in Figure 7. It is clear that the jet propagated from the primary flare site to the remote site (B3) during 18:04–18:16 UT. The constant apparent velocity ($\sim 224$ km s$^{-1}$) is the same in various EUV wavelengths. The velocity of the jet is comparable to the velocities of jets propagating along a closed magnetic loop and generating sympathetic coronal bright points (Zhang et al. 2016). The remaining part of the jet continues to propagate forward along S1 before terminating to the east of the prominence around 18:30 UT, which is accompanied by strong brightening (B4). The prominence was impulsively pushed aside, moving in the northwest direction. The restoring force makes the prominence decelerate and then move in the opposite direction. Such a cyclic motion, i.e., oscillation, continues for several hours, which is clearly demonstrated in Figure 7. Like most of the cases reported in previous literature, the oscillation is damping. In other words, the amplitude attenuates with time and disappears after several cycles. Owing to the lower resolution and cadence of the Hα observation, the oscillation in Hα is not as obvious as that in the EUV wavelengths. However, the oscillation during 18:20–19:20 UT is identifiable and in phase with the EUV wavelengths.

In order to precisely calculate the parameters of prominence oscillation, we mark the positions of the EP manually with magenta and cyan plus symbols in Figure 7(d). Then, we fit the curves by using the standard program mpfit.pro in SSW and the function (Zhang et al. 2017)

$$y = y_0 + bt + A_0 \sin \left(\frac{2\pi}{P} t + \phi_0\right) e^{-t/\tau}, \quad (1)$$

where $y_0, A_0,$ and $\phi_0$ represent the initial position, amplitude, and phase, respectively. $b,$ $P,$ and $\tau$ stand for the linear velocity of the threads, period, and damping timescale of the oscillation. Since the periods of oscillation are fairly different before and after $\sim 19:20$ UT, we divide the evolution into two phases, phase I (18:20–19:20 UT) and phase II (19:20–23:59 UT). In
Figure 8, we plot the results of the light curve fitting. The parameters are also listed in the top two rows of Table 2. In phase I, the amplitude and period of oscillation are \( \sim 4.5 \) Mm and \( \sim 25 \) minutes. The maximal velocity of oscillation can reach \( \sim 20 \) km s\(^{-1}\). The oscillation lasts for about two cycles with a damping timescale of \( \sim 7.5 \) hr. Hence, the damping ratio \((\tau/P)\) is calculated to be \( \sim 18.2 \). In phase II, the amplitude of oscillation increases and is \( \sim 2.5 \) times larger than that in phase I. The period also increases and is \( \sim 3.5 \) times larger than that in phase I, implying that the restoring force decreases as time goes by. In addition, the maximal velocity of oscillation halves to \( \sim 10 \) km s\(^{-1}\). The oscillation lasts for at least three cycles with a damping timescale of \( \sim 4.4 \) hr. Hence, the damping ratio is calculated to be \( \sim 3 \), suggesting that the attenuation of oscillation in phase II becomes faster. It should be emphasized that the oscillations of the fine threads of prominence are very complicated and vary from point to point (see Figure 7). We track the positions of the darkest thread, which is representative of the EP.

### 3.3.2. Transverse Oscillation of the WP

Like the EP of prominence, the WP of prominence also experienced transverse oscillation. In Figure 1(a), we extract the intensity along a second slice (S2), which has a length of \( \sim 48 \) Mm and is perpendicular to the WP. The time-slice diagrams of S2 in 171 Å, 211 Å, and H\( \alpha \) are demonstrated in Figure 9. \( s = 0 \) and \( s = 48 \) Mm in the x-axis denote the southeast and northwest endpoints of S2. It is obvious that the...
dark WP underwent transverse oscillation during 18:20–20:20 UT in EUV and Hα wavelengths. The initial direction of the movement of the WP is consistent with that of the EP, meaning that the whole prominence oscillates coherently. Although the resolution and cadence of the Hα observations are lower than AIA, we can still find that the oscillation in Hα and EUV wavelengths are completely in phase.

Like in Figure 7(d), we mark the positions of the WP with white plus symbols in Figure 9 and perform curve fitting. In Figure 10, we plot the results of the curve fitting using Equation (1). The parameters are listed in the third row of Table 2. Compared with the EP, both the amplitude (∼2 Mm) and maximal velocity (<10 km s⁻¹) of the WP are much smaller. The period (∼27 minutes) is slightly longer than that of the EP in phase I. However, the attenuation of the transverse oscillation of the WP is the fastest with a timescale of 1.74 hr and a damping ratio of ∼3.9, which can explain why the transverse oscillation of the WP lasts for only ∼4 cycles until 20:20 UT.

3.3.3. Longitudinal Oscillation of the Horizontal Threads

Apart from the transverse oscillations of the prominence, a handful of horizontal threads oscillated along the arcade to the east of the EP (see also the animated figure). Figure 11 shows 12 snapshots of AIA EUV images in 211 Å. From ∼19:35, the dark threads moved in the southeast direction until ∼20:05 UT. Afterwards, the threads moved reversely, i.e., in the northwest direction until ∼21:00 UT. Then, a second cycle of oscillation of the threads took place during 21:00–22:40 UT (see the bottom panels of Figure 11). After careful inspection of the animation, a total of 2.5 cycles can be identified. Such longitudinal oscillation of the horizontal threads is similar to the case of AR prominence (Zhang et al. 2012). It is also evident in the time-slice diagrams of S1, especially in 304 Å, since S1 goes through the long arcade.

In Figure 7(d), we mark the positions of the horizontal threads with yellow plus symbols. In order to calculate the parameters of oscillation, we perform curve fitting. In Figure 12, we plot the results of the curve fitting using Equation (1). The parameters are listed in the fourth row of Table 2. Compared with the transverse oscillations of prominence, the initial amplitude (∼52.4 Mm), period (∼99 minutes), and peak velocity (∼50 km s⁻¹) of the horizontal threads, oscillation are remarkably larger. The damping timescale is 2.5 hr and the damping ratio is ∼1.5, suggesting a faster attenuation.

### 4. Discussion

4.1. How are the Prominence Oscillations Triggered?

The triggering mechanism of large-amplitude prominence oscillations is an important issue. In most cases of longitudinal oscillations, they are triggered by sunspots or microflares at the footpoints of filaments (e.g., Jing et al. 2003, 2006; Vršnak et al. 2007; Li & Zhang 2012). The local brightenings at the footpoints are sometimes associated with intermittent jets that propagate upward and drive filament oscillations (Luna et al. 2014). The magnetic reconnections during subflares or microflares result in impulsive heating at the chromosphere so that the gas pressure is greatly enhanced, pushing the filament material to oscillate (Zhang et al. 2013; Zhou et al. 2017). Occasionally, when an incoming shock wave from a remote flare encounters a filament, it is likely that it triggers longitudinal or transverse filament oscillations depending on the incident direction (Shen et al. 2014). For transverse prominence oscillations, most of them are triggered by large-scale EUV or Moreton waves from a remote site of eruption (Ramsey & Smith 1966; Eto et al. 2002; Okamoto et al. 2004; Gilbert et al. 2008; Herschaw et al. 2011;
Dai et al. 2012; Gosain & Foullon 2012), though a few of them are associated with emerging fluxes (Chen et al. 2008).

In this study, simultaneous transverse and longitudinal oscillations are triggered by a coronal jet from the remote C2.4 flare in AR 12373, which has never been noticed before. The AR and quiescent prominence, which has a long distance of \(\sim 255 \text{ Mm} \), are connected by closed magnetic field lines, so that the jet from the primary flare site can reach and interact with the prominence. As described in Section 3.3, the oscillations of the prominence and horizontal threads are very complex. For the transverse oscillation of the EP of prominence, the parameters of the two phases, including the amplitudes, velocities, periods, and damping times, are totally different. A question is raised: what is the cause of the big difference? From Figure 7 and the animation of Figure 11, we noticed that the longitudinal oscillation of the horizontal threads was coincident with phase II of the oscillation of the EP. Meanwhile, the material of horizontal threads came from the EP. Therefore, we can draw a conclusion that there was a bifurcation at the end of phase I of the oscillation of the EP (see Figure 7(d)). The material escaping from the EP to the long arcade became the horizontal threads that underwent longitudinal oscillation. The remaining material of the EP continued oscillating in phase II. However, the transfer of mass may change the magnetic configuration of the EP, resulting in fairly different parameters of oscillation in phase II. From Figure 7 and Figure 9, we found that the onsets of transverse oscillations of the WP and EP were coincident. Moreover, the periods of the WP and EP during phase I are very close, indicating that the prominence oscillated coherently. Since the WP is far from the horizontal threads, the transverse oscillation of the WP was not disturbed or disrupted by the mass transfer at the end of phase I.

The timeline of all of the phenomena are illustrated in Figure 13.

It should be emphasized that precise identification of the mode of oscillations suffers from the lack of spectroscopic observation and stereoscopic observation from two perspectives. On the one hand, the 3D morphology of the prominence is unclear from a single perspective. On the other hand, the Doppler velocity of the prominence is unavailable. We are not sure whether the prominence and horizontal threads oscillate in the LOS direction. Additional case studies using spectroscopic and stereoscopic observation are worthwhile to investigate the large-amplitude prominence oscillations.

### 4.2. Curvature Radius and Magnetic Field Strength of the Dip

Magnetic tension force is widely accepted to be the restoring force of transverse prominence oscillations (Kleczek & Kuperus 1969). However, the restoring force of longitudinal prominence oscillations remain unclear hitherto. In the context of a 1D model, gravity of the prominence along the magnetic dip is considered to be the dominant restoring force (Luna & Karpen 2012; Zhang et al. 2012, 2013; Luna et al. 2014, 2016a, 2016b), although the gas pressure gradient is not neglectable for very shallow dips. In this study, the longitudinal oscillation of the horizontal threads along the arcade can easily been understood using the pendulum model. The period is expressed as

\[
P \approx 2\pi\sqrt{\frac{\Delta R}{g_s}}.
\]

Taking the observed value of \(P\) (1.65 hr), one can derive the lower limit of the transverse magnetic field strength of the arcade using a simple analytical expression \((B_t[G] \geq 17\text{ P/hr})\); Luna et al. 2014).
5. Summary

In this paper, we report our multiwavelength observations of a quiescent prominence observed by GONG and SDO/AIA on 2015 June 29. The main results are summarized as follows.

1. A C2.4 flare occurred with a lifetime of ~1 hr in AR 12373, which was associated with a pair of short ribbons and a remote ribbon in the chromosphere. During the impulsive phase of the flare, a coronal jet spurted out of the primary flare site and propagated in the northwest direction at an apparent speed of ~224 km s⁻¹. Part of the jet stopped near the remote ribbon and generated brightenings in various EUV wavelengths. The remaining part, however, continued moving and terminated to the east of the prominence.

2. Once the jet encountered the prominence, it produced localized brightening and pushed the prominence to oscillate periodically. The EP of prominence, consisting of many vertical threads, experienced transverse oscillation, which can be divided into two phases. In phase I, the initial amplitude, velocity, and period are ~4.5 Mm, ~20 km s⁻¹, and ~25 minutes, respectively. The oscillation lasted for about two cycles with a damping timescale of ~7.5 hr. In phase II, the initial amplitude increases to ~11.3 Mm, which is ~2.5 times larger than that of the first phase. The initial velocity, however, halves to ~10 km s⁻¹. The period increases by a factor of ~3.5, indicating that the restoring force reduced in phase II. The oscillation lasted for about three cycles, with the damping timescale decreasing significantly, which means that the attenuation of the oscillation became faster.

3. The WP of prominence also underwent transverse oscillation. The initial amplitude is only ~2 Mm and the velocity is < 10 km s⁻¹. The period (~27 minutes) is slightly longer than that of the EP in phase I. The oscillation lasted for about four cycles with the shortest damping timescale (~1.7 hr).

4. To the east of the prominence, a handful of horizontal threads experienced longitudinal oscillation along an arcade. The initial amplitude, velocity, and period are ~52.4 Mm, ~50 km s⁻¹, and ~99 minutes, respectively. The oscillation lasted for ~2.5 cycles with a damping timescale of ~2.5 hr. The oscillation of the horizontal threads can be explained by the 1D pendulum model where projected gravity of the threads serves as the restoring force. The curvature radius (~244 Mm) and the lower limit of the magnetic field strength (~28 G) of the arcade are estimated. Additional case studies and numerical simulations are required to investigate large-amplitude prominence oscillations.

We would like to thank H.S. Ji, Y.N. Su, V. Nakariakov, P.F. Chen, Y. Guo, Y.H. Zhou, J.T. Su, S.H. Yang, X.L. Yan, and Y. D. Shen for fruitful and valuable discussions. Q.M.Z. acknowledges support from the International Space Science Institute (ISSI) to Team 314 on “Large-Amplitude Oscillation in prominences” led by M. Luna. SDO is a mission of NASA’s Living With a Star Program. AIA and HMI data are courtesy of the NASA/SDO science teams. This work utilizes GONG data from NSO, which is operated by AURA under a cooperative agreement with NSF and with additional financial support from NOAA, NASA, and USAF. This work is supported by the Youth Innovation Promotion Association CAS, NSFC (Nos. 11333009, 11773079, 11603077, 11573072), the Fund of
Figure 13. Timeline of all of the phenomena, including the C-class flare, coronal jet, transverse oscillations of the EP and WP of prominence, and longitudinal oscillation of the horizontal threads.

Jiangsu Province (Nos. BK20161618 and BK20161095), and the CAS Key Laboratory of Solar Activity, National Astronomical Observatories (KLSA201716).

ORCID iDs
Q. M. Zhang https://orcid.org/0000-0003-4078-2265
D. Li https://orcid.org/0000-0002-4538-9350
Z. J. Ning https://orcid.org/0000-0002-9893-4711

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