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Flare-Triggered Transverse Oscillations in Coronal Loops Observed by SDO/AIA during an X7.1-Class Flare

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Abstract

We present an analysis of flare-induced transverse oscillations in a coronal loop, as observed in ultraviolet intensity images. The event was associated with an X7.1-class flare, which impulsively displaced the loop and excited a kink-mode oscillation. Using space–time analysis along a slit oriented perpendicular to the loop, we identify well-defined periodic displacements of the loop apex. From these maps, we find a decaying oscillatory pattern with a significant number of cycles. In order to minimize the influence of overlapping structures and line-of-sight contamination, we measure the loop displacement along a chosen slit using intensity-based centroiding, which enables us to isolate a unique oscillating feature. We find that the extracted loop displacement time series is well described by a damped sinusoidal function with a period of approximately 11 minutes and a damping time of approximately 80 minutes. The ratio of damping time to period is relatively small compared to strongly damped oscillations. The observed oscillatory pattern might be consistent with flare-induced transverse motions that are typically interpreted as kink-mode oscillations; however, the complex multi-loop environment implies that the observed oscillation may represent a coupled response from neighboring structures rather than a pure isolated mode. These findings demonstrate the ability of large flares to drive global transverse oscillations in the complex loop system and provide new constraints for the processes governing wave damping in the solar corona.

Keywords: Active Regions, Structure; Flares, Dynamics; Waves, Magnetohydrodynamic; Coronal Seismology

1 Introduction

The rapid release of magnetic energy through the process of magnetic reconnection is the driving force behind solar flares and coronal mass ejections (CMEs), two of the most energetic phenomena that occur in the solar atmosphere [1, 2]. In highly stressed areas of the corona, magnetic reconnection reorganises magnetic field lines, transforming magnetic energy stored there into bulk plasma motion, thermal energy, and energetic particles. The solar corona and heliosphere could be significantly impacted by this explosive energy release, which could start a chain reaction of dynamic processes. The production of different magnetohydrodynamic (MHD) waves and oscillations in coronal plasma is one effect of these intense occurrences. Researchers can determine physical parameters like magnetic field strength, plasma density, and temperature structure by using these waves as effective diagnostic tools to probe coronal conditions [3, 4]. The study of MHD waves has thus become central to understanding coronal heating, solar wind acceleration, quasi-periodic pulsations [5–10], and space weather phenomena.

Among the wide spectrum of coronal wave modes, transverse kink oscillations of coronal loops have garnered significant interest due to their clear observational signatures in extreme-ultraviolet (EUV) wavelengths [11, 12]. Usually excited by impulsive disturbances such as solar flares, jets, or eruptive events, kink oscillations involve lateral displacements of coronal loops perpendicular to their axes. These oscillations provide unique seismological access to key coronal parameters including density stratification, magnetic field configuration, and wave damping processes [13, 14]. The oscillation properties, including periods typically ranging from several minutes up to tens of minutes and rapid damping timescales of a few oscillation cycles, reflect the complex interplay between the excitation mechanism and local plasma conditions [15–17].

In this paper, we present an analysis of a flare-induced transverse oscillation observed using high-cadence EUV intensity data at the 171 Å wavelength. We explore the dynamical response of coronal loops to the impulsive energy release associated with an X-class flare. This event triggered distinct transverse oscillations in adjacent coronal loops, allowing us to investigate the excitation conditions and the subsequent temporal evolution of possible kink-mode oscillations with unprecedented detail. Rest of the paper is organized as follows. Section 2 describes the observational data employed in this study. The analysis and results are presented in Section 3. Finally, the summary and conclusions are given in Section 4.

2 Observational Data

We made use of observational data from the Solar Dynamics Observatory's (SDO) Atmospheric Imaging Assembly (AIA; [18]). AIA offers full-disk solar images with a

spatial resolution of 1.5″ (0.6″ per pixel) and a cadence of 12 s. We mainly used the 171 Å passband, which is sensitive to plasma emission at a characteristic temperature of approximately 0.6 MK, to investigate the fine structure and temporal evolution of coronal loops.

3 Analysis and Results

The analysis results are illustrated in Figure 1–3, with detailed descriptions and interpretations provided in the subsequent subsections.

3.1 The Active Region and Flare X7.1

The solar flare event examined in this study occurred in the active region NOAA 13842, which was situated close to the heliographic coordinates S15W05 in the south-west portion of the visible solar disc.

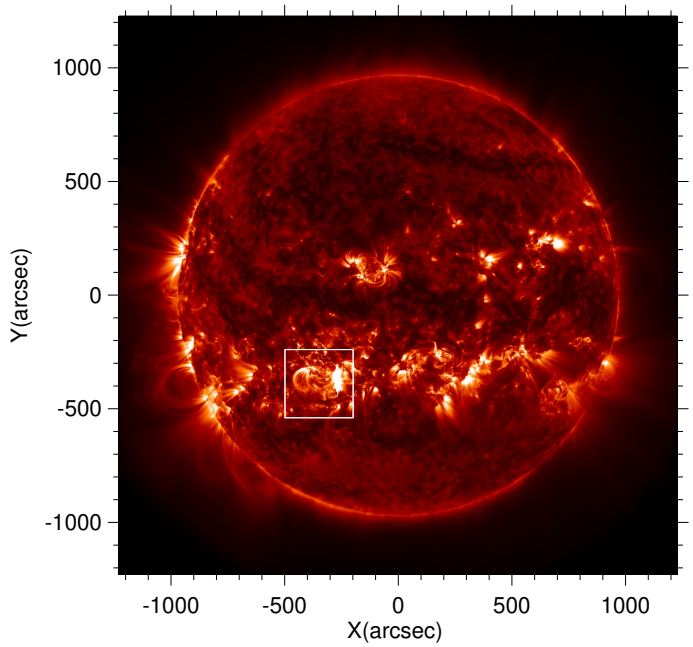


Fig. 1 The box indicates the flare's location in this full-disk intensity image of the Sun in SDO/AIA 171 Å.

During the observation period, this area was magnetically active and complex, generating a number of notable flares in late September and early October 2024. We examined the October 1, 2024 flare event to study the coronal response to the impulsive energy release from this region.

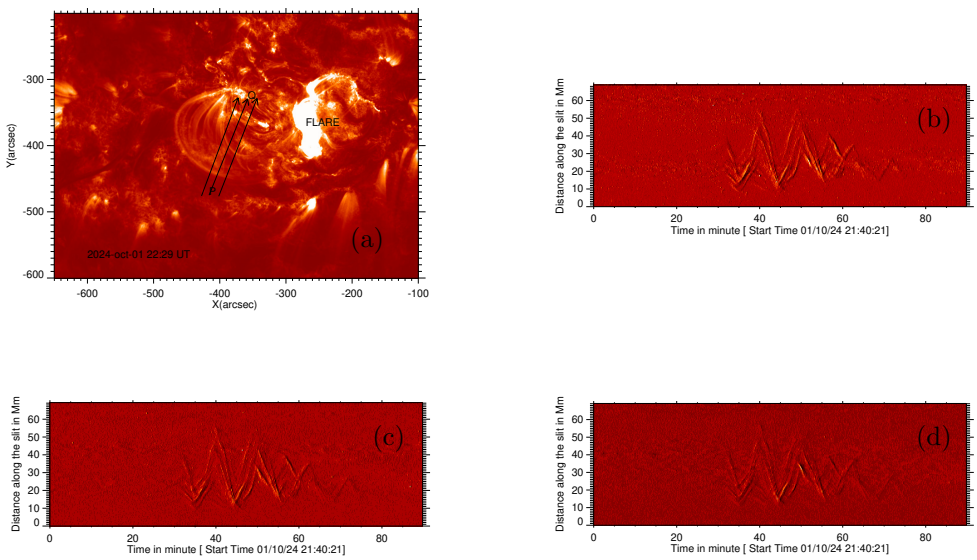


Fig. 2 Panel (a) shows magnified view of the flaring region displaying coronal loops with three perpendicular slits to the loops, where the space–time map of the oscillating coronal loops is constructed using the line segment PQ, as shown in panel(b) and Figure 3, additionally panel (c) and (d) shows other two space–time maps along two lines other than PQ in panel (a).

The flare was classified as an X7.1-class event, which started at approximately 21:58 UT, reached its peak intensity at 22:20 UT, and decayed by 22:29 UT. Figure 1 shows the full extent of the active region, with a white box highlighting the region of interest encompassing the flare site and adjacent coronal loop system. The cropped view (Figure 2(a)) reveals a coronal loop exhibiting a clear transverse displacement immediately following the flare eruption. To quantitatively characterize this oscillatory motion, a slit PQ along with two other slits was positioned perpendicular to the loop axis (see, Figure 2 (a)) to construct a space–time diagram along the slit PQ (Figure 3), providing insight into the temporal evolution of the loop oscillations triggered by the flare. We have constructed the multiple space–time map (Figure 2 (b),(c) and (d)) along the slits in Figure 2 (a) to be ensure that transverse oscillations are not confined to a single location. Additionally, due to the complexity of the loop system and the presence of strong flare emission, running-difference images were employed to enhance the visibility of dynamic features while suppressing slowly varying background intensity. The resulting space–time maps reveal clear oscillatory signatures at multiple slit locations, suggesting that the disturbance propagates coherently across the loop system.

3.2 Coronal Loop Oscillations

The space–time map (Figure 3) reveals a well-defined oscillatory displacement of the loop apex, probably consistent with transverse kink oscillations triggered by the flare-associated disturbance.

The transverse displacement of the loop was obtained by tracking the position of the oscillating ridge in the selected space–time map (Figure 3). At each time step, the loop position was determined by identifying the peak intensity along the slit, effectively tracing the motion of the loop axis. The tracked positions are overplotted on the space–time map, showing a smooth and coherent trajectory associated with a complex multi–loop environment. Since the definitive identification of a single isolated loop is challenging due to the limited spatial resolution so the motion may represents the collective response of neighbouring loops.

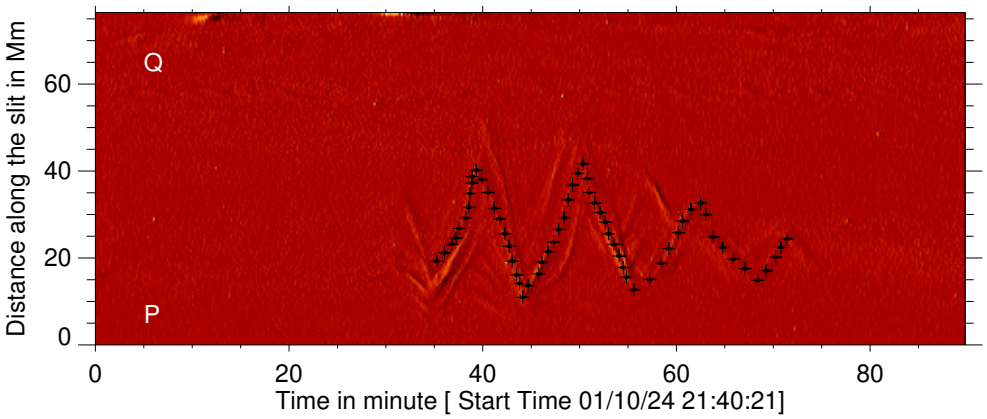


Fig. 3 Time-distance intensity map constructed along the line PQ as marked in Figure 2(a).

We clearly see three complete oscillations of the loop. The oscillation amplitude is largest during the initial cycles and decreases progressively with time, indicating damping. Such attenuation of kink mode like oscillations has been widely reported in earlier studies and is generally attributed to mechanisms such as resonant absorption or phase mixing in an inhomogeneous coronal plasma.

The observed displacement pattern therefore provides likely an evidence of flare-triggered kink-mode oscillations of coronal loops. These results highlight the close connection between flare energy release and the dynamical response of coronal structures, offering valuable constraints for models of wave–plasma interactions and energy dissipation in the solar corona.

The time-series plot in Figure 4 (a) clearly demonstrates the presence of damped transverse oscillations in the coronal loop. With the amplitude steadily declining over the 2500 s interval, the periodic displacement clearly shows the oscillatory motion. A number of processes, including resonant absorption, phase mixing, and less-than-ideal plasma effects like viscosity and thermal conduction, can cause the dissipation of

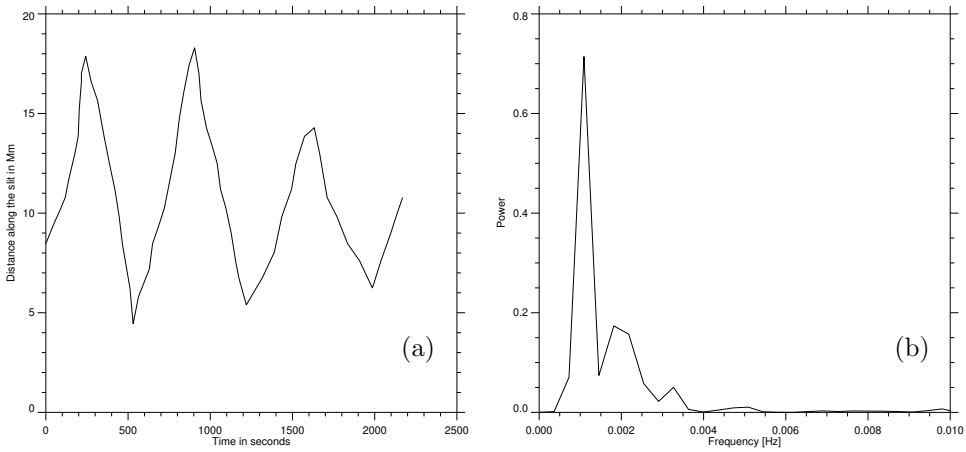


Fig. 4 (a) Extracted time series of the damped oscillations of the coronal loop obtained from the space–time map (see Figure 3). (b) Fourier power spectrum of the time series shown in panel (a).

wave energy, which is reflected in this amplitude decay. A crucial diagnostic of energy transport and dissipation in the solar corona, the observed damping behaviour offers valuable information about the potential role of oscillatory energy in local heating processes within coronal loops.

Figure 4 (b), which presents the Fourier power spectrum of the same time series, shows a dominant narrow peak at a frequency of approximately 0.001 Hz. This distinct, powerful spectral peak indicates that the oscillation is primarily monochromatic, meaning it has only one oscillation period. Given the sharpness of the spectral peak, it can be concluded that the oscillation is coherent and that other frequency components contribute very little. The two panels work together to show that the transverse oscillations are highly periodic and measurable damping, which makes them a great choice for seismological diagnostics of the solar corona. We are able to constrain basic physical parameters of the coronal plasma, such as density contrast, magnetic field strength, and energy dissipation rates, by combining temporal and spectral analysis. The period which has been obtained after damped fitting on the displacement time series might be different from the period obtained by fourier spectra due to the non-stationary and damped nature of the signal, which increases the spectral peak [19, 20].

3.3 Analysis of Transverse Loop Oscillations

We have fitted the corresponding displacement time series obtained with the damped sinusoidal [21] given as:

$$x(t) = A\, e^{-t/\tau} \sin\left(\frac{2\pi t}{P} + \phi\right) + C, \tag{1}$$

with parameters such as initial amplitude A, period of oscillation P, damping time τ, phase ϕ, and equilibrium position C.

For comparison, an undamped sinusoidal model was also fitted to the data (Figure 5). The fitting procedure was performed using a least-squares minimisation

technique, and the goodness of fit was evaluated using the reduced chi-square statistic and the Bayesian Information Criterion (BIC).

The damped model provides a significantly better representation of the observed oscillatory behaviour, yielding lower values of both the reduced chi-square and BIC compared to the undamped model. This indicates that the oscillation undergoes substantial damping over time.

From the best-fit damped model (1), the following parameters were obtained:

- Period: $P \approx 678$ s ($\sim$11.3 min)
- Damping time: $\tau \approx 4848$ s ($\sim$80.8 min)

The ratio of damping time to period is found to be:

$$\frac{\tau}{P} = 7.15 \pm 2.46 \tag{2}$$

indicating that the oscillation is weakly damped.

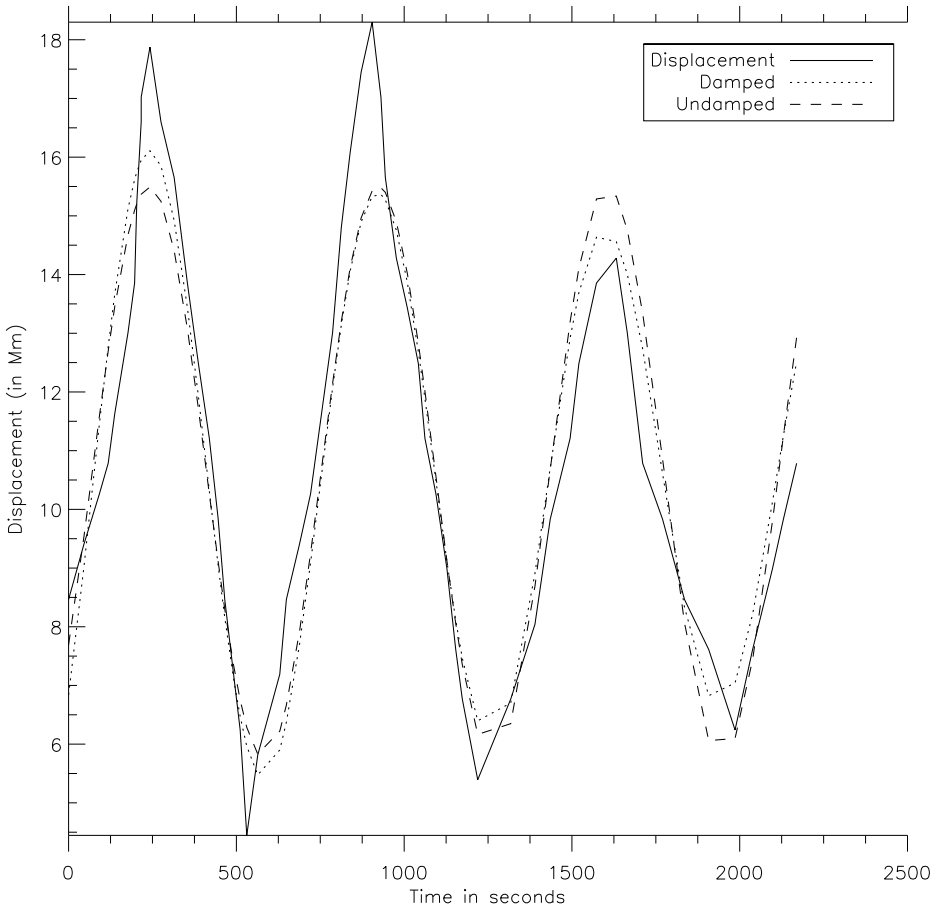


Fig. 5 Displacement (solid line) of the coronal loop as a function of time, where the oscillatory motion is extracted from the time-distance map. The observed points are shown along with the best-fit damped sinusoidal model (Dotted line), as well as the undamped sinusoidal model (dashed line). The damped sinusoidal model is a better fit for the decay in amplitude over time.

4 Summary and Conclusions

In our investigation, we have studied the transverse motion of a coronal loop system in response to the strong X7.1 class flare event, and we have employed high-cadence observations in the EUV band to analyze the phenomenon. The flare causes significant lateral motion in loops that are not in the core region, indicating the impulsive transfer of energy to the surrounding structures. For the analysis, we have created time–distance diagrams employing several slit positions perpendicular to the loop arcade. The use of several slit positions helps to determine the spatial coherence of the oscillatory signal and minimize the possibility that the observed motion is due to the line-of-sight superposition of unrelated structures.

The space-time maps show an oscillatory pattern that is consistent for different positions of the slits, indicating that the disturbance is not localized to a single strand but rather a collective effect in the loop system. However, due to the presence of closely spaced loops and emission, a clear and continuous intensity ridge was present only for a single slit that was chosen for quantitative analysis. The loop displacement was measured by following the intensity ridge in the time-distance map to ensure that the signal was from a single coherent structure.

The resulting displacement time series shows a well-defined decaying oscillation, and a damped sinusoidal model is found to be a good representation of the observed motion, giving a period of approximately 11 minutes and a damping time of approximately 80 minutes. The ratio of damping time to period, $\tau/P = 7.15 \pm 2.5$, shows that the damping is weak, as opposed to the strongly damped transverse oscillations. A statistical comparison, as given by the reduced chi-square and the Bayesian Information Criterion (BIC), shows that the inclusion of damping is justified, even though the decay is gradual.

The observed oscillatory behavior is consistent with flare-induced transverse motions that are typically interpreted as kink mode oscillations of coronal loops [11, 12]. The large value of τ/P also suggests that the damping is weaker than expected in efficient resonant damping, which generally gives a value of τ/P in the range of $\sim$1-3 [15, 17].

Another reason for the minor difference in the value of the time period obtained using the Fourier analysis and the time domain analysis could be the non-stationarity and damping effect of the signal, resulting in a broadening peak in the Fourier analysis. These aspects have also been discussed in the context of time-dependent oscillations in the solar corona, which emphasize the use of a combination of spectral and time domain analysis [22].

The results from this analysis suggest that large flares are capable of exciting a coherent transverse motion in large structures in the solar corona. While the observed oscillation appears to bear many hallmarks of kink-mode oscillations, the multi-loop complexity may indicate that it is more representative of a collective transverse motion rather than an eigenmode of the loop itself. This work serves to illustrate the potential for flare-induced oscillations to be used as a means to diagnose coronal plasma, as well as emphasizing the importance of interpreting observations in structurally complex regions. Future studies will be able to further constrain the physical processes at work in the solar corona through multi-wavelength observations and forward modeling.

Declarations

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- The authors acknowledge the use of AIA/SDO data from NASA's Living With a Star program and thank the SDO/AIA science team.
- Sachin R.K., Swetha G. performed the data reduction, analysis, and interpretation of the observations, developed the analysis methodology. Sachin R.K. drafted the manuscript. R.A. Maurya has guided the research work and edited the manuscript.

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