Compressive Oscillations in Hot Coronal Loops: Are Sloshing Oscillations and Standing Slow Waves Independent?

S. Krishna Prasad and T. Van Doorsselaere

Centre for mathematical Plasma Astrophysics, Department of Mathematics, KU Leuven, Celestijnenlaan 200B, B-3001 Leuven, Belgium;

krishna.prasad@kuleuven.be

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Abstract

Employing high-resolution EUV imaging observations from SDO/AIA, we analyze a compressive plasma oscillation in a hot coronal loop triggered by a C-class flare near one of its footpoints, as first studied by Kumar et al. We investigate the oscillation properties in both the 131 Å and 94 Å channels and find that what appears as a pure sloshing oscillation in the 131 Å channel actually transforms into a standing wave in the 94 Å channel at a later time. This is the first clear evidence of such transformation and confirms the results of a recent numerical study that suggests that these two oscillations are not independent phenomena. We introduce a new analytical expression to properly fit the sloshing phase of an oscillation and extract the oscillation properties. For the AIA 131 Å channel, the obtained oscillation period and damping time are 608 ± 4 s and 431 ± 20 s, respectively, during the sloshing phase. The corresponding values for the AIA 94 Å channel are 617 ± 3 ± s and 828 ± 50 s. During the standing phase that is observed only in the AIA 94 Å channel, the oscillation period and damping time have increased to 791 ± 5 s and 1598 ± 138 s, respectively. The plasma temperature obtained from the differential emission measure analysis indicates substantial cooling of the plasma during the oscillation. Considering this, we show that the observed oscillation properties and the associated changes are compatible with damping due to thermal conduction. We further demonstrate that the absence of a standing phase in the 131 Å channel is a consequence of cooling plasma besides the faster decay of oscillation in this channel.

Unified Astronomy Thesaurus concepts: Magnetohydrodynamics (1964); Solar coronal waves (1995); Solar coronal loops (1485)

Supporting material: animation

1. Introduction

Flare-associated hot loops, with plasma temperatures exceeding 6 MK, often display compressive oscillations. These oscillations were first discovered in Doppler velocities of hot spectral lines such as Fe XIX and Fe XXI observed by the Solar Ultraviolet Measurement of Emitted Radiation (SUMER) instrument on board the Solar and Heliospheric Observatory (Wang et al. 2002). Their oscillation period was in the range of 7–31 minutes and their phase speed was estimated to be close to the local acoustic speed (Wang et al. 2003a). Additionally, in some cases, a quarter-period phase difference is found between the Doppler velocity and the corresponding intensity oscillations, leading to the interpretation of these oscillations as standing slow magnetoacoustic waves (Wang et al. 2003b). Another characteristic feature of these oscillations is that they exhibit rapid damping with decay times of the same order as the oscillation period. Similar oscillations were observed by the Bragg Crystal Spectrometer (BCS) on board Yohkoh (Mariska 2005, 2006) and the Extreme-ultraviolet Imaging Spectrometer on board Hinode (Mariska et al. 2008). However, the period of oscillations measured from the BCS data is at the lower end with an average value of 5.5 ± 2.7 minutes (Mariska 2006). This discrepancy is explained in terms of the possible observation of shorter loops by BCS because it is sensitive to much hotter plasma (∼12 MK). Since these oscillations are usually preceded by a brightening near one of the footpoints, it is believed that a microflare or similar reconnection event triggers them (Wang et al. 2003a, 2005). Thermal conduction has been shown to be a major cause of their damping (Ofman & Wang 2002), although recent studies indicate that compressive viscosity (Wang et al. 2015, 2018) or thermal misbalance (Nakariakov et al. 2017; Kolotkov et al. 2019) can dominate depending on the physical conditions within the loop. A number of theoretical and numerical investigations have also been made including the application of forward modeling techniques in some cases, especially to study their driving mechanism (Selwa et al. 2005; Selwa & Ofman 2009; Ofman et al. 2012; Wang et al. 2018) and their damping behavior (Bradshaw & Erdélyi 2008; Verwichte et al. 2008; Ruderman 2013; Al-Ghafri et al. 2014; Wang et al. 2018), and to predict/reproduce some of their observational characteristics (Nakariakov et al. 2004; Nakariakov & Melnikov 2006; Fang et al. 2015; Yuan et al. 2015). We refer the interested reader to comprehensive reviews by Wang (2011) and Wang et al. (2021) on this subject.

Compressive oscillations are observed in other coronal structures too (Nakariakov 2006; De Moortel 2009; Banerjee et al. 2011). Indeed, they are found to be ubiquitous in open/extended loop structures, which are relatively quiescent and cold as compared to the hot flare loops (Krishna Prasad et al. 2012; Morgan & Hutton 2018). However, these oscillations are mainly due to driven waves and are believed to originate in the lower solar atmosphere (Botha et al. 2011; Jess et al. 2012; Reznikova et al. 2012; Krishna Prasad et al. 2015). Their oscillation periods also range from a few minutes to a few tens of minutes and they exhibit rapid damping similar to that of standing waves (McEwan & de Moortel 2006). There have been extensive studies of their characteristic properties, especially their damping behavior in the solar corona, by a number of authors (De Moortel & Hood 2003, 2004; De
Moortel 2009; Krishna Prasad et al. 2012, 2014, 2019; Banerjee & Krishna Prasad 2016, to name but a few). Please refer to Banerjee et al. (2020) for a recent review of these waves.

Analysing the microwave emission from a hot flare loop, Kim et al. (2012) have shown that the associated plasma density exhibits rapidly decaying oscillations with a periodicity of 12.6 minutes and a decay time of about 15 minutes. In addition, co-temporal high-resolution imaging observations of the loop, acquired by the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO), also display similar oscillations. Based on the observed characteristics, the authors interpreted these oscillations as being due to the standing slow magnetoacoustic waves. Subsequently, the high-resolution imaging data from SDO/AIA have revealed spatially resolved longitudinal oscillations in hot coronal loops (Kumar et al. 2013, 2015). These oscillations involve a plasma perturbation bouncing back and forth between the two footpoints of the loop while its amplitude decays rapidly. They are interpreted as reflected propagating slow waves. Later studies refer to them as “sloshing” oscillations (Reale 2016; Nakariakov et al. 2019). The general properties of these oscillations are very similar to those observed by SUMER. Furthermore, these oscillations too appear to be driven by a small flare near one of the footpoints. However, as the spatiotemporal properties of these oscillations do not resemble a standing wave, their association with the standing slow waves discovered by SUMER is not very clear. Wang et al. (2015) report a unique event from the SDO/AIA observations of hot coronal loops, where the authors find clear evidence for standing slow waves. The general properties are again very similar but, in this case, the oscillation does not display significant spatial movements, rather it exhibits antiphase perturbations between the two legs resembling a standing mode. Additionally, employing 1D nonlinear MHD simulations, Wang et al. (2018) have shown that a pressure disturbance generated by a flare-like impulsive event would initially bounce back and forth between the footpoints before transforming into a standing slow wave. They further demonstrated that this transformation can occur immediately after the first reflection if the physical conditions within the loop are favourable to efficiently dissipate higher harmonics. Thus, the authors were able to explain both the sloshing oscillations and the standing slow waves with a common interpretation. However, from observations so far we have only seen either a sloshing oscillation (Kumar et al. 2013, 2015; Mandal et al. 2016b; Nisticò et al. 2017) or a standing wave (Wang et al. 2015), but there has not been ample evidence to support the transformation between them. This raises the important question of whether the sloshing oscillations are an independent class of oscillations (Nakariakov et al. 2019).

In this article, we analyze the same event studied by Kumar et al. (2013), which was interpreted by them as a reflected propagating (or sloshing) wave. We reveal a number of interesting properties including clear evidence for the transformation of sloshing oscillation into a standing wave. We present the details of observations in Section 2, followed by our analysis and results in Section 3, and finally we list our conclusions in Section 4.

2. Observations

The data set employed in this study is the same as that analyzed by Kumar et al. (2013) except that here we extended it to a longer duration. The data mainly consist of imaging observations of a hot coronal loop performed by the SDO/AIA (Lemen et al. 2012; Pesnell et al. 2012). A subfield of about 280° × 280° encompassing the target loop structure within the active region NOAA 11476 is considered (see Figure 1). The image sequences obtained from 17:20 UT until 18:46 UT on 2012 May 7, across six wavelength channels, namely the AIA 94 Å, 131 Å, 171 Å, 193 Å, 211 Å, and 335 Å channels, were analyzed. All the data were processed to level 1.5, incorporating the necessary instrumental corrections by following standard procedures. In particular, the corrections for roll angle and plate scale and the co-alignment across multiple wavelength channels were achieved by using a robust pipeline that is publicly available1. The final pixel scale and the cadence of the data are 0.6 and 12 s, respectively.

3. Analysis and Results

3.1. Time–Distance Maps

Snapshots of the analyzed loop structure, one each from the AIA 131 Å and 94 Å channels, are shown in Figure 1. In these wavelength channels, the corresponding image sequences display the sloshing oscillation of plasma along the loop following a C-class flare near one of its footpoints. In order to study its evolution, we constructed time–distance maps by manually selecting the boundaries of the loop (black dotted lines in Figures 1(a) and 1(b)) and averaging the transverse intensities within that region from the individual images. Subsequently, to enhance the visibility of oscillations, the intensities at each spatial position were detrended and normalized using a 12 minutes (60 points) running average of the corresponding time series. It may be noted that the detrending is done here only to increase the contrast of the oscillation. Besides, the oscillation patterns visible in the original and the detrended time–distance maps are congruent, assuring us that this process did not introduce any unwanted artefacts. The resultant maps are displayed in Figure 1(c) with the top and bottom plots corresponding to the AIA 131 Å and 94 Å channels, respectively.

The vertical dark stripes visible at the beginning of the time series in AIA 131 Å are due to alternating low-exposure frames that are automatically acquired by AIA in specific wavelength channels during flares. These are unavoidable when analyzing the data at full cadence, but in order to minimize their effect the intensities in individual frames were normalized by the respective exposure times at the beginning. Bright slanted ridges forming a “triangular” wave pattern are apparent in the time–distance maps for both the channels. This suggests back and forth motion of the plasma, indicating the presence of sloshing oscillation in the loop. As can be seen, the evolution of the oscillation is not the same across the two channels. In the AIA 131 Å channel, the oscillation decays rapidly and does not seem to possess detectable amplitude beyond three cycles, as noted previously by Kumar et al. (2013). However, in the AIA 94 Å channel, the oscillation appears to have appreciable signal for up to six cycles! This differential behavior, likely suggesting a multithermal nature of the loop, has not been reported by previous authors but it is rather interesting. Another striking feature evident in the 94 Å channel is the eventual transformation of the sloshing oscillation (triangular ridges)

1 http://www.staff.science.uu.nl/~rutte101/riddle/sdolib/
into a standing wave (vertical ridges). Although this evolution is in excellent agreement with the previous nonlinear MHD simulations (Ofman et al. 2012; Wang et al. 2018), this is the first time we have a clear observational detection of such transformation. It may be noted that the earlier hydrodynamic simulations by Reale (2016) do not seem to show any transformation in the evolution of sloshing oscillations in a coronal loop. Furthermore, until now there has only been separate evidence for either a sloshing oscillation or a standing wave, prompting us to consider whether the sloshing oscillations are a different class of oscillation. Therefore, it is remarkable to see what has been earlier reported to be a sloshing oscillation transform itself into a standing wave, albeit in a different temperature channel, suggesting that these two phenomena are not independent but rather part of the same event.

3.2. Properties of Oscillations

As the oscillation appears to slowly transform from a sloshing phase into a standing phase, we derive the properties
for these two phases separately as described in the following sections.

### 3.2.1. Sloshing Phase

The sloshing phase of the oscillation is visible in both the channels. Although it has been standard practice to pick the time series from a particular spatial position and fit a damping sine function (as we show for the standing phase of the oscillation in Section 3.2.2), here we demonstrate that this is not a correct procedure for sloshing oscillations. Because the perturbation exhibits significant spatial movements during this phase, it is not as trivial to extract the oscillation parameters. We also show that the oscillation parameters are dependent on the spatial location from where the time series is extracted. Furthermore, we provide a better model to properly fit and derive the properties of sloshing oscillations.

In order to simulate the sloshing oscillations, we approximate the initial perturbation as a Gaussian whose amplitude is decaying with time, while its location is oscillating between the two end points of a line segment. This model can be described by the equation

\[
I(x, t) = A_0 e^{-t/\tau} e^{i(x-x_0)/\sigma^2}
\]

where \( x_0 = \frac{L}{2} \left( 1 - \cos \left( 2\pi \frac{t}{P} + \phi \right) \right) \). Here, \( x \) is the spatial coordinate, \( t \) is time, \( L \) is the length of the structure, \( P \) is the period of the sloshing motion, \( \tau \) is the damping time, and \( \sigma \) is the width of the perturbation. \( A_0 \) and \( \phi \) are constants.

Using an arbitrary set of values for all these parameters, a sample sloshing oscillation has been generated whose spatio-temporal evolution is shown in the top panel of Figure 2. An offset at the beginning of the oscillation and a constant background are added on purpose to mimic the observations. As can be seen, the triangular wave pattern broadly describes the sloshing oscillations observed. The temporal evolution of the oscillation at two spatial locations, one near the edge (dotted line) and the other near the center (solid line), is shown in the bottom panel of the figure. These time series are clearly non-sinusoidal. Indeed, such non-sinusoidal signatures with flat bottoms in the light curves were commonly observed in the previous studies (e.g., see Figure 3 of Kumar et al. 2013 and Figure 4 of Mandal et al. 2016b). The time series near the center does not appear as deviant, but one must note that this behavior is heavily dependent on the width of the perturbation. Moreover, it is evident that the oscillation period near the center is twice as long as that near the edge. This is not very surprising since at any location away from the edges, the perturbation crosses twice before completing one full oscillation. Therefore, we emphasize that fitting the time series from any spatial location with a damping sinusoidal function does not provide an accurate description of sloshing oscillation properties.

Ideally, one could use the model described by Equation (1) to perform a two-dimensional fit with the time–distance maps from observations (similar to Pascoe et al. 2020) and extract important oscillation properties. However, because the spatial coordinate in observations is projected and any nonplanar structuring in the loop makes this projection nonuniform along its length, a direct comparison with such models is not possible. To circumvent this problem, we fix the spatial coordinate in our model to one of the end points, i.e., \( x = 0 \), which reduces Equation (1) to

\[
I(0, t) = A_0 e^{-t/\tau} e^{i\phi} = A_0 e^{-t/\tau} e^{i\phi} \left( 1 - \frac{x}{\sigma} \right)^{2} \]  

(2)

where \( x_0 = \frac{1}{2\sigma} \left( 1 - \cos \left( 2\pi \frac{t}{P} + \phi \right) \right) \).

Here \( \sigma_a = \sigma/L \) is the normalized width of the perturbation. Equation (2) is now independent of the spatial coordinate and therefore can be directly applied to a time series obtained near the footpoint of a loop exhibiting sloshing oscillations. To implement this, we first extract a relevant section of the time series (marked by orange solid lines in Figure 1(c)) from both the channels. The original intensities are then detrended and normalized using the background generated from fitting a parabolic curve to the minima of the oscillation.

It may be noted that here we did not use a running average method, as is commonly employed for the construction of background. This is because the perturbation does not appear to be a symmetric modulation during the sloshing phase. The original time series and the constructed background from the AIA 131 Å channel are shown in the top panel of Figure 3 for illustration. As can be seen, the parabolic curve provides a good approximation for the background. The resultant intensities after the background subtraction and normalization are presented in the middle and the bottom panels for the AIA 131 Å and 94 Å channels respectively. The best fits to the data obtained by fitting the model in Equation (2) via chi-square minimization, are shown as solid curves in these panels. The derived oscillation periods from these fits are \( 608 \pm 4 \) s and \( 617 \pm 3 \) s and the respective damping times are \( 431 \pm 20 \) s and \( 828 \pm 50 \) s for the oscillations in AIA 131 Å and 94 Å channels.

For comparison, the oscillation period and damping time obtained by Kumar et al. (2013) from the AIA 131 Å channel are \( 634 \) s and \( 437 \) s, respectively. These values are not very different from those derived here. The reason for this is twofold. First, the authors also preferred a time series closer to the footpoint of a loop exhibiting sloshing oscillations near the apex being more sinusoidal, since the latter exhibits a double peak. Second, the authors average the signal over a larger spatial region, reducing any substantial deviations from a sine curve. Furthermore, in this example, the spatial extent of the perturbation is quite large (as evident from the merging of the oncoming and forward-going parts of the perturbation near the loop apex), which is not always the case. We would expect the discrepancies from a simple sine model to be much larger when the spatial extent of the perturbation is small compared to the length of the loop (see, e.g., Figure 6 of Mandal et al. 2016b). Hence, as such, our model is widely applicable.

Nevertheless, we note some of the important caveats of our model. The Gaussian approximation to the perturbation may not always be reasonable. We did not take into account the spatial/temporal changes in the width of the perturbation. Also, the transition from a sloshing phase to a standing phase of the oscillation is a gradual process, so picking a section of the time series to represent either of the phases is not always obvious. Some of these limitations could be the reason why there is a larger discrepancy between the model and the data during the later part of the oscillation (see Figure 3).
3.2.2. Standing Phase

The standing phase of the oscillation is only apparent in the 94 Å channel. In order to extract its properties, we take the appropriate section of the time series at a selected spatial position along the loop (marked by the pink dashed line in Figure 1(c)) where the oscillations are clearly discernible. The original intensities are first detrended and normalized using a background constructed from a 12 minutes running average of the time series, and the resultant intensities are then fit with a simple damping sine function given by the equation

\[ I(t) = A_0 e^{-t/\tau} \sin \left( \frac{2\pi t}{P} + \phi \right) + B_0 + B_1 t \]  

where \( t \) is time, \( P \) is the oscillation period, and \( \tau \) is the damping time. \( A_0, \phi, B_0, \) and \( B_1 \) are constants. The best fit thus obtained (via chi-square minimization) is shown in the bottom panel of Figure 4 as a solid line over the normalized data. The original intensities and the constructed background are also shown in the top panel of this figure. The oscillation period and the damping time computed from the fitted curve are 791 ± 5 s and 1598 ± 138 s respectively.

3.3. DEM Analysis

By comparing the oscillation properties between the sloshing phase and the standing phase in the AIA 94 Å channel, it is evident that the damping time has increased by nearly a factor of 2 during the latter phase. The oscillation period has also increased, although by a lesser amount. To understand these changes, we seek to find how the plasma thermal properties vary over the duration of the oscillation. Employing a regularised inversion code developed by Hannah & Kontar (2012), we perform differential emission measure (DEM) analysis using the observed intensities in all six AIA coronal channels (94 Å, 131 Å, 171 Å, 193 Å, 211 Å, and 335 Å). DEMs were computed at each spatial location but for every fifth frame, lowering the cadence of these data to 1 minute to reduce computation time. Also, the calculations were not done for the data within the first 20 minutes, i.e., between 17:20 UT and 17:40 UT, because there were many low-exposure frames in some wavelength channels during this period. Subsequently, the temperature \( T \) and emission measure \( EM \) corresponding to the peak emission in the DEM curves are noted and used to build maps of these parameters at each time step. A sample temperature map and the corresponding emission measure map thus obtained are shown in Figure 5. In order to study the temporal changes in these quantities, we choose a region near the loop apex (marked by black/white squares in Figures 5(a) and (c)) and plot the temperature and emission measure values obtained from all the pixels within this region as a function of time in Figures 5(b) and (d) (gray ‘+’ symbols). Many outliers with substantially lower values of temperature/emission measure than the majority have been detected in these plots. These are due to bad DEM fits arising from low signal locations and possibly represent the background. In any case, since we are interested in the hot plasma we exclude these outliers and compute the average values in the individual parameters at each time step. These values are marked by red
diamond symbols in the figure. The corresponding standard deviation values are shown as vertical bars on these symbols. As can be seen from these plots both the temperature and emission measure decrease substantially during the oscillation. A steeper decline in temperature is found until about 17:55 UT, after which the decrease is more gradual. In contrast, the emission measure decreases gradually throughout the duration. Nonetheless, the general decrease in these parameters is natural since the dense hot plasma injected into the loop should eventually cool down and get dispersed.

To assess the impact of these changes in plasma properties on the oscillation, we select two specific instants in time, 17:40 UT and 18:20 UT, as representative of the sloshing and standing phases of the oscillation, respectively. During the period between these two instants, the temperature dropped from about 11.6 MK to 6.6 MK while the corresponding emission measure decreased from about $2.7 \times 10^{28} \text{ cm}^{-5}$ to $1.4 \times 10^{28} \text{ cm}^{-5}$. Assuming the emission depth to be equivalent to the width of the loop ($w$) (i.e., a symmetric cross section), the respective densities ($\rho$) were estimated as $5.6 \times 10^9 \text{ cm}^{-3}$ and $4.1 \times 10^9 \text{ cm}^{-3}$ by following $\rho = \sqrt{\text{EM}/w}$. The width of the loop was calculated from the FWHM of a Gaussian fitted to the cross-sectional intensity profile from the AIA 94 Å channel near the loop apex. This value did not change much between the two instants and was found to be about $8.5 \pm 0.3 \text{ Mm}$ at 17:40 UT and $8.4 \pm 0.3 \text{ Mm}$ at 18:20 UT. Using the temperature and density values, along with the oscillation periods derived from the AIA 94 Å channel for the two phases, we solve the dispersion relation for slow waves in the presence of thermal conduction damping (e.g., see Equation (5) of Krishna Prasad et al. 2014). Since the oscillations in the present case are standing, we seek solutions for the angular frequency, $\omega$, and then deduce the damping time from the imaginary part of the appropriate root. We use a standard value for $\gamma (= 5/3)$ in these calculations. Theoretical damping times ($\tau'$) and other relevant parameters of the
oscillation obtained thus are listed in Table 1. The derived $\tau''$ values are 945 s and 2396 s, respectively, for the two phases of the oscillation. An important aspect to consider here is that the oscillation during the sloshing phase is not a simple sinusoidal wave but rather a traveling impulsive perturbation. Following Fourier’s theorem, such a perturbation can be expressed as a sum of multiple harmonic oscillations. Since the amplitudes of higher harmonics tend to get lower (see, e.g., Nakariakov et al. 2019), we consider the first 10 harmonics to effectively represent the sloshing perturbation. The resultant damping time in such a scenario is estimated to be 882 s, which is slightly lower than that obtained from the fundamental period alone. Nevertheless, the theoretical values are of the same order as those obtained from the observations, and importantly they demonstrate that an increase in damping time by a factor of 2 can be readily explained by the decrease in the efficiency of thermal conduction as the plasma cools down. Moreover, additional damping mechanisms such as compressive viscosity (Wang et al. 2018) or thermal misbalance (Nakariakov et al. 2017; Kolotkov et al. 2019) can further reduce these damping times, possibly closing the gap to the observations. It may be noted that a direct comparison of these theoretical damping time values with those from observations is not trivial because the dominant emission in a particular wavelength channel could be coming from a plasma at a different temperature, depending on the corresponding filter response function. Additionally, the square root dependence of the sound speed on temperature implies a reduction in the sound speed by a factor of 1.33 from the sloshing to the standing phase, which should effectively increase the oscillation period by the same factor. During this time, the observations reveal an increase in the oscillation period by 1.28 times, showing a good agreement with the theory.

As mentioned earlier, a sloshing perturbation can be understood as the simultaneous existence of multiple harmonic oscillations. Under this view, any damping mechanism that effectively dissipates higher harmonics (shorter periods) faster would assist in quickly establishing the fundamental standing mode in a coronal loop. The compressive viscosity is one such mechanism. Using 1D nonlinear MHD simulations, Wang et al. (2018) have shown that greatly enhanced compressive viscosity could explain their earlier observations (Wang et al. 2015), where a standing oscillation was found to appear immediately after the initial perturbation due to a flare. In the present scenario, however, we see a gradual transformation of the sloshing oscillation into a standing wave. This is perhaps largely in agreement with model 1 of Wang et al. (2018), where classical values for transport coefficients (thermal conduction and compressive viscosity) are used. Additionally, we speculate here that the steep decrease in plasma temperature during the initial few cycles plays a role in the transformation. It can be shown that in the limit of strong thermal conduction, the damping of slow waves due to thermal conduction is independent of the oscillation period, whereas the same in the limit of weak thermal conduction is very effective at shorter periods (see Table 1 of Krishna Prasad et al. 2014; Mandal et al. 2016a). Although the observed decrease in temperature does not support such extreme changes in thermal conduction, the effect of the cooling plasma on the dissipation of higher harmonics has to be explored in detail through a numerical study. We plan to do this in a follow-up work.
3.4. Phase Difference

We also investigate whether there is any phase difference between the oscillations in the 131 Å and 94 Å channels. For this purpose, the time series at each spatial position from the 131 Å channel is cross-correlated against that from the 94 Å channel, and any respective time lag corresponding to a peak in the cross-correlation is noted. Because the oscillation is observed for a shorter duration in the 131 Å channel, we only consider the section of the time series marked by the orange solid lines in Figure 1(c). The obtained time lag and the associated cross-correlation coefficient are plotted in Figure 6(a) as a function of distance along the loop. As can be seen, the time lag (solid line) is positive and appears to increase from the footpoints toward the apex, around which it displays sudden random changes. The cross-correlation coefficient (dotted line) is positive and close to 1.0 (implying a high correlation) near the footpoints but gradually drops to a lower value toward the apex, where it also displays sudden random changes. The lower oscillation amplitudes and the possible (de)merging of the oncoming and forward-going perturbations near the loop apex are likely the reasons behind the poor correlation near the loop apex. Ignoring this region where the cross-correlation coefficient drops below 0.5 (i.e., within the cross-hatched region), the positive time lag values indicate that the oscillation in the 94 Å channel is lagging behind that in the 131 Å channel.

Table 1

Comparison of Oscillation Properties between the Sloshing (17:40 UT) and Standing (18:20 UT) Phases

| Time    | T (MK) | $\rho$ (cm$^{-3}$) | $P$ (s)  | $\tau$ (s) | $\tau'$ (s) |
|---------|--------|-------------------|----------|------------|-------------|
|         |        |                   | AIA 131 Å | AIA 94 Å   | AIA 131 Å   | AIA 94 Å   |          |
| 17:40 UT| 11.6   | $5.6 \times 10^9$ | 608 ± 4  | 617 ± 3    | 431 ± 20    | 828 ± 50   | 945       |
| 18:20 UT| 6.6    | $4.1 \times 10^9$ | …        | 791 ± 5    | …           | 1598 ± 138 | 2396      |

Note. $\tau'$ is damping time due to thermal conduction estimated from linear wave theory.
Since the 94 Å channel predominantly captures emission from relatively colder plasma, the perturbation in this channel could be propagating at a slower speed, and consequently positive phase lags with respect to the oscillation in the 131 Å channel are expected. However, the reason for the increase in time lag from the footpoints to the apex is not immediately obvious. Also, there is an asymmetry in the time lag between the two footpoints, with higher values obtained near the left footpoint (as in Figure 1). In order to understand this behavior, we construct two time–distance maps from our sloshing oscillation model (see Equation (1)) using two different speeds and perform a cross-correlation between them. The obtained time lag as a function of distance is shown in Figure 6(b). Although the distance and the time lag are in arbitrary units, it is evident that the time lag peaks near the center, and the asymmetry in the values between the left and right edges is also clearly reproduced. We note that this is an average behavior resulting from the gradually increasing time lag as the perturbation propagates between the two end points. Additionally, we find that this spatial dependence is sensitive to the section of the time series considered, particularly the starting phase and the ending phase of the oscillation. While the time lag values are positive in all cases (indicating the slower perturbation is lagging behind), a minimum time lag near the center is found in some cases, and the asymmetry between the footpoints is flipped with a larger lag on the right edge in other cases. Unfortunately, because of the strong damping and low cycle count in observations, we have little freedom to verify this changing shape, but nevertheless we can conclude that the observed time lag and its spatial dependence both indicate lower phase speed in the 94 Å channel. One may perhaps use the actual time lag values to extract more information (e.g., difference in phase speed between the two channels) but, as the plasma properties are varying with time, an advanced model would be necessary.

3.5. Multithermal Behaviour

As mentioned before, there are significant differences in the appearance of the oscillation in the AIA 131 Å and 94 Å channels. The perturbation is barely visible beyond the sloshing phase in the 131 Å channel. During this phase, the oscillation period is approximately the same in both the channels but the damping time is much shorter in the 131 Å channel. The phase difference analysis reveals that the propagation speed is lower in the 94 Å channel. Since the general appearance of the loop is congruent between the channels, this differential behavior in oscillation properties is indicative of multithermal structure within the loop. Indeed, the plasma temperature near the loop apex exhibits a three-part structure during the initial phase of the oscillation (see Figure 5(b)), supporting the multithermal nature. Yet the complete absence of the standing phase of the oscillation, as if we are observing a distinct loop structure in the 131 Å channel, is difficult to comprehend.

The faster decrease of oscillation amplitude observed in the 131 Å channel definitely supports a quicker disappearance of the oscillation but, as we demonstrate in the following, that is only part of the reason.

In Figure 7(a) we plot the average light curves for both 131 Å and 94 Å channels obtained from the same box region near the loop apex (see Figure 5) where the evolution of temperature and emission measure were studied. Evidently, the intensity in the AIA 131 Å channel peaks at about 17:40 UT and quickly drops to the pref flare level by about 18:10 UT. These two instants are marked by vertical dotted lines in the figure. On the other hand, the intensity in the AIA 94 Å channel gradually increases, peaks much later than that in the 131 Å channel, and slowly decreases, maintaining values above the pref flare level until the end of our data set. In Figure 7(b), we plot the temperature response functions (version 10) of both the AIA channels. These are double-peaked, with the second peak in the 131 Å channel corresponding to slightly higher temperatures than that in the 94 Å channel. The two instants marked in Figure 7(a) are also shown in this plot by vertical dotted lines considering the respective dominant plasma

Figures 6. (a) Time lag between the oscillations in the 131 Å and 94 Å channels as a function of distance along the loop. The dotted line shows the corresponding peak cross-correlation coefficient values with their scale on the right. The cross-hatched region highlights a section around the apex where the cross-correlation coefficient drops below 0.5. The time lag within this region is less emphasized. (b) Time lag obtained from the model (see Equation (1)) by cross-correlating a sloshing oscillation with that propagating at a lower speed.
temperatures. As can be seen, the expected emissivities vary significantly between the two instants in both channels. In particular, the decrease in temperature by 18:10 UT has resulted in a significant reduction in the emissivity (by more than an order of magnitude) in the 131 Å channel whereas the same has led to enhanced emissivity in the 94 Å channel. As a result, if one considers the corresponding decrease in density (emission measure; see Figure 5), the reduction in the emission seen by the 131 Å channel is much more pronounced whereas the same in the 94 Å channel is somewhat compensated, thus explaining the sharper decline in intensity observed in the former channel. Because the 131 Å channel observes hotter plasma, faster damping (a shorter damping time) is expected due to thermal conduction. The low intensity further compounded by the lower oscillation amplitude made it difficult to detect the oscillation in the 131 Å channel after 18:10 UT. We believe that, had the intensity remained sufficiently large, the standing phase of the oscillation would have been visible in the 131 Å channel as well. So the stark contrast in the appearance of the oscillation in the two AIA channels is due to an interplay between the oscillation amplitude, the plasma temperature, and the filter response curves. Therefore, one should be careful while interpreting the observations of sloshing oscillations that do not appear to transform into a standing wave.

4. Conclusions

We study the compressive plasma oscillation in a hot coronal loop triggered by a C-class flare near one of its footpoints. Recent studies using high-resolution imaging observations by SDO/AIA have resulted in interpretations of such oscillations in terms of either a reflected propagating (sloshing) wave (Kumar et al. 2013) or a standing wave (Wang et al. 2015). The sloshing oscillations are expected to eventually transform into a standing wave (Wang et al. 2018) but the observational evidence for this has not been very clear until now. It has also been argued that the sloshing oscillations could be an entirely different class of oscillation (Nakariakov et al. 2019). Here, we revisit the event studied by Kumar et al. (2013), extend their data set to a longer duration, and analyze the oscillation properties in both the AIA 131 Å and 94 Å channels in detail. Our results indicate a number of interesting new properties of the oscillation, which was earlier interpreted as a reflected propagating wave by Kumar et al. (2013). The main conclusions of our study are listed below.

1. We find that the oscillation is visible up to six cycles in the AIA 94 Å channel in contrast to only three cycles observed in the AIA 131 Å channel as reported earlier. The longer-duration data set used here has allowed us to reveal this observation. Furthermore, the oscillation evidently transforms into a standing wave during the later part of the time series in the AIA 94 Å channel. This suggests that the sloshing oscillations are perhaps not an independent class of oscillation.

2. As we observe the oscillation for a longer duration, we are able to extract the oscillation properties separately for the sloshing phase and the standing phase. We find that the oscillation period and the damping time are longer during the latter phase.

3. For the sloshing phase, we demonstrate that a damping sinusoid function fitted to the time series at any particular spatial location does not always provide an accurate description of the oscillation properties. Instead, we provide an analytical expression (Equation (2)) that may be generally used to fit the time series near the loop footpoint in order to derive the oscillation properties.

4. Using DEM analysis, we find that the plasma is cooling down during the oscillation. Considering this, the observed oscillation properties and the associated changes between the sloshing phase and the standing phase are shown to be compatible with damping due to thermal conduction.

5. The phase difference between the oscillations in the 131 Å and the 94 Å channels indicates a lower propagation speed in the latter channel. The distinct oscillation characteristics observed across the two AIA channels imply a multithermal nature of the loop. The standing
phase of the oscillation is not detectable in the 131 Å channel due to a steep decline in the loop intensity (caused by the cooling plasma) in addition to the faster decay in the oscillation amplitude.

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**ORCID iDs**

S. Krishna Prasad @ https://orcid.org/0000-0002-0735-4501
T. Van Doorsselaere @ https://orcid.org/0000-0001-9628-4113

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