CORONAL LOOP OSCILLATIONS OBSERVED WITH ATMOSPHERIC IMAGING ASSEMBLY—KINK MODE WITH CROSS-SECTIONAL AND DENSITY OSCILLATIONS

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ABSTRACT

A detailed analysis of a coronal loop oscillation event is presented, using data from the Atmospheric Imaging Assembly on board the Solar Dynamics Observatory (SDO) for the first time. The loop oscillation event occurred on 2010 October 16, 19:05–19:35 UT and was triggered by an M2.9 GOES-class flare, located inside a highly inclined cone of a narrow-angle coronal mass ejection. This oscillation event had a number of unusual features: (1) excitation of kink-mode oscillations in vertical polarization (in the loop plane), (2) coupled cross-sectional and density oscillations with identical periods, (3) no detectable kink amplitude damping over the observed duration of four kink-mode periods (P=6.3 minutes), (4) multi-loop oscillations with slightly (∼10%) different periods, and (5) a relatively cool loop temperature of ≈5 MK. We employ a novel method of deriving the electron density ratio external and internal to the oscillating loop from the ratio of Alfvénic speeds deduced from the flare trigger delay and the kink-mode period, i.e., ne/nl = (vA/vAl)T = 0.08 ± 0.01. The coupling of the kink mode and cross-sectional oscillations can be explained as a consequence of the loop length variation in the vertical polarization mode. We determine the exact footpoint locations and loop length with stereoscopic triangulation using STEREO/EUVI/A data. We model the magnetic field in the oscillating loop using Helioseismic and Magnetic Imager/SDO magnetogram data and a potential-field model and find agreement with the seismological value of the magnetic field, Bkink = 4.0 ± 0.7 G, within a factor of two.

Key words: Sun: corona – Sun: flares – Sun: oscillations – Sun: UV radiation – waves

Online-only material: animations, color figures

1. INTRODUCTION

Propagating waves and standing waves (eigenmodes) in coronal plasma structures became an important tool to probe the physical parameters, the dynamics, and the magnetic field in the corona, in flare sites, and in coronal mass ejections (CMEs). Recent reviews on the theory and observations of coronal seismology can be found in Roberts & Nakariakov (2003), Erdelyi et al. (2003), Roberts (2004), Aschwanden (2004, 2006), Wang (2004), Nakariakov & Verwichte (2005), Banerjee et al. (2007), Andries et al. (2009), Ruderman & Erdelyi (2009), and Taroyan & Erdelyi (2009). Substantial progress was accomplished in applying MHD wave theory to coronal observables with previous instruments, such as the discovery of global waves with the EIT/Solar and Heliospheric Observatory (SOHO; Thompson et al. 1998, 1999), fast kink-mode loop oscillations with the Transition Region and Coronal Explorer (TRACE; Aschwanden et al. 1999; Nakariakov et al. 1999), fast sausage mode oscillations in radio wavelengths (Roberts et al. 1984; Asai et al. 2001; Melnikov et al. 2002; Aschwanden et al. 2004), slow (acoustic) mode oscillations with SUMER/SOHO (Wang et al. 2002; Kliem et al. 2002), slow (acoustic) propagating waves with UVCS/SOHO (Ofman et al. 1997) and Hinode (Erdelyi & Taroyan 2008), EIT/SOHO (DeForest & Gurman 1998), and TRACE (De Moortel et al. 2002a, 2002b), fast Alfvénic waves with SECIS (Williams et al. 2001; Katsiyannis et al. 2003), or fast kink waves with TRACE (Verwichte et al. 2004; Tomczyk et al. 2007). Sausage oscillations observed and identified directly in the cross-sectional area change of a solar magnetic flux tube are reported by Morton et al. (2011). However, temporal cadence of space-borne EUV imagers (such as EIT/SOHO, TRACE, STEREO) was mostly on the order of 1–2 minutes, which is just at the limit to resolve fast MHD mode oscillations (with typical periods of 3–5 minutes) and is definitely too slow to resolve or even detect fast MHD waves that propagate with Alfvénic speed. An Alfvén wave with a typical coronal speed of vA ≈ 1000 km s⁻¹ traverses an active region in about 1 minute. With the advent of the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO), which provides a permanent cadence of 12 s, we have an unprecedented opportunity to study the exact timing of the excitation mechanisms of coronal MHD waves and oscillations, which often involve an initial impulsive pressure perturbation in a flare and CME source site that launches various MHD waves and oscillations in surrounding resonant coronal structures (loops, fans, CME cones, and cavities). Here we conduct a first AIA study on a coronal loop oscillation event, observed on 2010 October 16, which exhibits a favorable geometry, unobstructed view, prominent undamped oscillations, an unusual coupling of kink-mode and cross-sectional (and density) oscillations (not noticed earlier), and a rare case of vertical kink-mode polarization. In Section 2, we present various aspects of the data analysis and modeling, while theoretical and interpretational aspects are discussed in Section 3, with the major findings and conclusions summarized in Section 4.

2. DATA ANALYSIS

2.1. Instrument

The AIA instrument on board the SDO started observations on 2010 March 29 and has produced since then continuous data of the full Sun with four 4096 × 4096 detectors with a pixel...
size of 0′/6, corresponding to an effective spatial resolution of ≈1′/6. AIA contains 10 different wavelength channels, 3 in white light and UV and 7 EUV channels, whereof 6 wavelengths (131, 171, 193, 211, 335, 94 Å) are centered on strong iron lines (Fe viii, ix, xii, xiv, xvii, xix), covering the coronal range from $T \approx 0.6$ MK to $T \gtrsim 16$ MK. AIA records a full set of near-simultaneous images in each temperature filter with a fixed cadence of 12 s. Instrumental descriptions can be found in Lemen et al. (2011) and Boerner et al. (2011).

2.2. Observations and Location

A major flare of GOES-class M2.9 occurred on 2010 October 16, 19:07–19:12 UT at location W26/S20 (+390° west and −410° south of Sun center), which triggered a number of loop oscillations in the westward direction of the active region (NOAA 1112). In this study, we focus on the detailed analysis of a loop at the apex position +698° west and −243° south of the Sun center, which displays prominent oscillations. The location of this loop with respect to the flare center is shown in Figure 1. The oscillating loop is discernible as a faint semicircular structure in the logarithmically scaled intensity image in 171 Å (Figure 1, top panel), or even clearer in the difference image (19:22:36 UT–19:21:00 UT) in Figure 1 (bottom panel), where the times were chosen at the maximum and subsequent minimum of an oscillation period. The 171 Å intensity image (Figure 1) also shows irregular moss-like structure in the background of the oscillating loop of similar brightness, which poses some challenge for the exact measurements of the loop oscillation parameters, because the background is time variable, even on the timescale of the oscillation period.

2.3. Transverse Loop Oscillations

Loop oscillations are traditionally investigated most easily in time-difference movies. (Animations of this oscillation event in 171 Å intensity and running-difference format are available as supplementary data in the online version of this journal.) However, a variety of time-differencing schemes can be applied in order to enhance the best contrast. We explore a variety of time-differencing schemes in Figure 2, for a data stripe oriented perpendicular to the loop axis at its apex with a length of 30 pixels and a width of 10 pixels (indicated with a small rectangle in Figure 1). We construct time-slice plots with $n_z = 150$ time frames on the $x$-axis (covering the time interval from 19:05 UT to 19:35 UT with a cadence of $\Delta t = 12$ s) and a spatial dimension in direction transverse to the loop on the $y$-axis (with $n_y = 30$ pixels), averaged over the $n_w = 10$ pixels of the stripe width (parallel to the loop). We show five different differing schemes of this time slice in Figure 2, using a high-pass filter (Figure 2 top panel), a baseline difference (Figure 2, second panel), and a one-sided (Figure 2, third panel), a symmetric (Figure 2, fourth panel), and a running-minimum difference scheme (Figure 2, bottom panel), which is defined as

$$\Delta F(t_i, y_j) = F(t_i, y_j) - \min[F(t_{i-k}, y_j), \ldots, F(t_{i+k}, y_j)]$$

so it subtracts a running minimum evaluated within a time interval with a length of 2$k$ pixels symmetrically placed around every time slice. Each method has its merits and disadvantages, as can be seen in Figure 2. The biggest challenge is the non-uniformity and time variability of the background. An additional complication is the presence of fainter secondary oscillating loops, which appear like “echoes” in the time-slice plots. For further analysis, we adopt the running-minimum differencing scheme (Figure 2, bottom), which appears to have the best signal-to-noise ratio of the oscillating features.

The measurement of the loop oscillation amplitude variation $a(t)$ as a function of time $t$ can be done (1) by localizing the cross-sectional flux maxima in running-difference time-slice plots, (2) by cross-correlation of subsequent time slices, or (3) by fitting a Gaussian profile to the cross-sectional flux profiles. We find that the first and the latter method are most robust. From the running-minimum time-slice plot (Figure 3, top frame), we perform fits of Gaussian profiles $F_{\text{fit}}(s, t)$ to the observed cross-sectional flux profiles $F(s, t)$ in each time slice $t$ (using the standard GAUSSFIT.PRO routine in the IDL software),

$$F_{\text{fit}}(s, t) = f(t) \exp\left(\frac{-(s-a(t))^2}{2\sigma^2(t)}\right) + b(t),$$

which yields the four coefficients of the peak flux $f(t)$, the oscillation amplitude $a(t)$, Gaussian width $\sigma(t)$, and mean background flux $b(t)$ for each time $t$. The four-parameter fits, the cross-sectional flux profiles $F(s, t)$, and the Gaussian fits $F_{\text{fit}}(s, t)$ are shown in Figure 4 for each time in the interval between $t_1 = 19:05$ UT and $t_350 = 19:35$ UT, while a corresponding time slice with Gaussian fits is rendered in color scale in Figure 3 (second panel). The average Gaussian loop width during the oscillation period is $\sigma_0 = 2.1$ Mm, which corresponds to an FWHM loop width of $w = \sigma_0\sqrt{2\ln 2} = 4.9 \pm 0.6$ Mm.

We are now fitting a sinusoidal function with a linear drift to the location of the oscillation amplitudes $a(t)$ (crosses in Figure 3, fourth panel), using the Powell optimization routine (Press et al. 1986) from the IDL software,

$$a_{\text{fit}}(t) = a_0 + a_1 \sin\left(\frac{2\pi(t-t_0)}{P}\right) + a_2 \frac{(t-t_0)}{P},$$

for which we find a midpoint position $a_0 = 6.3$ Mm, a drift velocity $a_2 / P = 0.8$ km s$^{-1}$, an oscillation period of $P = 395$ s (6.4 minutes), an oscillation amplitude $a_1 = 1.8$ Mm, and a sinusoidal onset time of $t_0 = 393$ s after the start of the time slice at 19:05:00 UT, i.e., at 19:11:33 UT. The onset time of the oscillation will be important to measure the exciter speed of the trigger. The fit of the sinusoidal amplitude function $a_{\text{fit}}(t)$ to the measured amplitude $a(t)$ is shown in Figure 3 (fourth panel). The fitted function with a constant amplitude $a_1$ appears to be appropriate for the duration of $N_{\text{pase}} = (t_350 - t_333)/P = 1407/395 = 3.6$ oscillation periods since we do not observe any significant damping of the amplitude during this time interval.

2.4. 3D Loop Geometry

The projected loop shape is close to a semi-circular geometry (Figure 1, bottom), and thus we can assume that the loop plane is near the plane of sky or nearly perpendicular to the line of sight. The location of the loop curvature center is at a distance of $\approx 740''$ from the Sun center or 0.77 solar radii, which corresponds to a heliographic angle of $\alpha = 50''$ from disk center.

The full three-dimensional (3D) geometry of the loop can be obtained from the combination of the EUVI instrument on board STEREO and AIA observations, a procedure that we carry out for the first time here. The loop was in the field of view of STEREO/A (head) at this time, but was occulted for STEREO/B. The STEREO/A spacecraft was located on 2010 October 16 at a separation angle of $\alpha_A = 83.583$ to the east.
Figure 1. AIA 171 Å image of flare observed on 2010 October 16 19:22:36 UT shown with the flux on a logarithmic flux scale (top panel) and as difference image with respect to 19:21:00 UT (bottom panel). The flare location is marked with a cross (in the center of the diffraction pattern) and a box indicates the location of the oscillating loop. (See also the animations in 171 Å intensity and running-difference formats which are available as supplementary material in the online version of this journal.)

(Animations [A and B] and a color version of this figure are available in the online journal.)

of Earth, at a latitude of $\beta_\text{A} = -0.119$ from the Earth ecliptic plane. In Figure 5, we show nearly contemporaneous AIA and EUVI/A difference images of the loop, which clearly show the oscillatory motion of the loop, after high-pass filtering of the EUVI/A image. Unfortunately, EUVI/A observed only in a different wavelength of 195 Å at this time, while the oscillation is most visible in the 171 Å channel in AIA. EUVI/A also had a lower cadence ($\approx 5$ minutes versus 12 s in AIA) and the spatial resolution of EUVI (1.6 pixels) is about three times coarser than AIA (0.6 pixels). Nevertheless, the image quality is sufficient to approximately determine the 3D loop geometry. We subtracted the earlier image from the later image, and thus a density increase in the difference images (white in Figure 5) indicates an inward loop motion (in the AIA image) and a correlated density compression (in the EUVI/A image). We rotate the two-dimensional coordinates of the loop traced in AIA (Figure 5, left) into the coordinate system of EUVI/A with variable heights and inclination angle of the loop plane. By matching the position and direction of the loop ridge in EUVI/A, we obtain the absolute height range of the traced loop segment, i.e., $21.7 \text{ Mm} < h_{\text{segm}} < 37.4 \text{ Mm}$. In order to locate the positions of the footpoints, we extrapolate the traced loop segment in both directions and define the positions of the loop footpoints where the coplanar extrapolation intersects with a height $h = 0$ above the solar surface. The so-defined extrapolated footpoint positions are found at $F_1 = (685'',-305'')$ (south of traced loop) and $F_2 = (615'',-268'')$ (east of traced loop) with respect to the Sun center (Figure 5). The apex or midpoint of the traced loop segment (at $s = L_{\text{loop}}/2$) is located at position $(x_{\text{apex}}, y_{\text{apex}}) = (698'',-243'')$, for which we show time-slice plots of the oscillation in Figures 2–4 (i.e., segment No. 6 in Figure 6). The apex location will also be used to define the arrival time of the exciting wave and the starting time of the loop oscillation in Section 2.11. The inclination angle
of the loop plane to the local vertical is found to be \( \vartheta \approx 20^\circ \pm 20^\circ \), but cannot be determined more accurately because of the short loop segment detectable in EUVI/A.

From the absolute 3D coordinates \((x_i, y_i, z_i)\), \(i = 1, \ldots, n\), of the stereoscopically triangulated loop we can calculate the full loop length \(L_{\text{loop}}\):

\[
L_{\text{loop}} = \sum_{i=0}^{n-1} \sqrt{[(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2 + (z_{i+1} - z_i)^2]},
\]

for which we find \(L_{\text{loop}} = 163\) Mm. The traced loop segment over which amplitude oscillations are clearly visible covers the fraction from \(s_1/L = 0.23\) to \(s_2/L = 0.78\) of the total loop length and has only a length of \(L_{\text{segm}} = 123\) Mm. If we approximate the 3D loop geometry with a coplanar semicircular shape, the loop curvature radius is estimated to be \(r_{\text{loop}} \approx L_{\text{loop}}/\pi = 52\) Mm.

The plane of transverse loop oscillations with respect to the average loop plane cannot accurately be determined with the
existing STEREO data, but they are roughly coplanar, based on the centroid motion constrained by AIA that is absent in EUVI/A from a near-perpendicular view (Figure 5). Coplanar kink-mode oscillations correspond to a vertical polarization.

2.5. Spatial Variation of Loop Oscillation

In the next step, we analyze the spatial variation of the transverse kink-mode oscillation $a(t)$ as a function of the spatial loop position, which we specify with a segment number running from segment No. 1 at the loop length coordinate $s_1/L = 0.23$ (near the first footpoint $F_1$) to segment No. 10 at $s_2/L = 0.78$ (near the second loop footpoint). This analysis serves a two-fold purpose: (1) to detect possible asymmetries of the kink mode and (2) to detect possible propagating waves.

In Figure 6, we show the analysis of the loop oscillation of 10 different loop segments, numbered consecutively (Nos. 1–10) from the southern loop footpoint $F_1$ to the northeastern footpoint $F_2$ along the loop axis with loop length coordinate $s$. The location and orientation of the time-slice stripes is in-
Aschwanden & Schrijver

Figure 4. Cross-sectional flux profiles \( F(x, t) \) (blue) obtained from the running-minimum difference technique (Figure 3, top panel) and Gaussian fits (red). (A color version of this figure is available in the online journal.)

The Astrophysical Journal, 736:102 (20pp), 2011 August 1

Aschwanden & Schrijver

Figure 4. Cross-sectional flux profiles \( F(x, t) \) (blue) obtained from the running-minimum difference technique (Figure 3, top panel) and Gaussian fits (red). (A color version of this figure is available in the online journal.)

In Figure 7, we show the spatial variation of the oscillation amplitude \( a_1(s) \) in the context of an intensity image (Figure 7, top left) and a running-minimum difference image (Figure 7, top right). The locations of the 10 azimuthal time-slice stripes are shown in Figure 7 (bottom left), over which the amplitude oscillation was measured in Figure 6. The dependence of the oscillation amplitude \( a_1(s) \) along the loop shows a maximum amplitude of \( a_{1\text{max}} = 2.0 \) Mm near the loop apex. A sinusoidal displacement along the loop axis is ideally expected for a kink eigenmode with fixed nodes (compare with the analogy of a violin string). Our measurements, however, rather show a slightly distorted and asymmetric function, which can be approximated by a squared sine function (to account for the curvature of the loop) and a nonlinear dependence \( a(s^{0.75}) \) on

dicated in the left panels of Figure 6, the running-minimum difference time slices are shown in the middle panels of Figure 6, and the sinusoidal fits \( a_0(t) \) to the loop amplitudes in the right-hand panels of Figure 6, which also contains the best-fit parameters. If we discard the two noisiest segments near footpoint \( F_1 \) (segment Nos. 1 and 2 in Figure 6), we obtain for the others a mean amplitude of \( \langle a_1(s) \rangle = 1.8 \pm 0.4 \) Mm, a mean period of \( \langle P(s) \rangle = 373 \pm 30 \) s (6.2 \pm 0.5 minutes), and a mean starting time of \( \langle t_0(s) \rangle = 399 \pm 35 \) s. Thus the variation of best-fit periods and starting times is only \( \approx 8\% \), and thus we conclude that there is no significant phase shift of the oscillation amplitude along the loop that could be considered as a propagating wave. Thus, we deal with a pure standing wave of the fast MHD kink mode.
Figure 5. SDO and STEREO observations of oscillating loop: An AIA 171 Å difference image (19:19:24–19:21:00 UT) is shown at the bottom left, and a near-simultaneous STEREO/EUVI/A 195 Å difference image (19:15:30–19:20:30 UT) with additional high-pass filtering is shown at the bottom right. The corresponding field of views and loop outlines are shown for both instruments in the top panels. The thick solid curve in the AIA image indicates the tracing of the oscillating loop segment, which is fitted to the corresponding loop segment in EUVI/A by 3D coordinate transformations with variable altitudes and inclination angle of the loop plane, which also constrains the extrapolated footpoint locations ($F_1$, $F_2$) at the solar surface.

(A color version of this figure is available in the online journal.)

the loop length (to account for the asymmetry of the loop, as evident from the stereoscopic triangulation of the footpoints, see Figure 7, bottom right panel),

$$a_1(s) = a_1^{\text{max}} \sin^2 \left[ \pi \left( \frac{s}{L} \right)^{0.75} \right],$$

where $s = 0$ and $s = L$ mark the nodes at the true footpoints $F_1$ and $F_2$. The observed oscillation amplitudes $a(s)$ follow the squared sine function closely in the range of $s/L \lesssim 0.6$, but deviate in the range of $0.6 \lesssim s/L \lesssim 0.75$, probably because of the interference of a secondary oscillating loop.

2.6. Multiple-loop Oscillations

From watching the AIA 171 Å animations (see supplementary online material to this paper) and from the time-slice plots shown in Figures 2, 3, and 6 it appears that multiple loops are involved in kink-mode oscillations. The previous analysis has determined the average dynamic parameters of the collective ensemble of individual loop strands. In Figure 8, we are fitting a two-loop model to the time-slice plots obtained near the loop apex, which yields slightly different periods ($P_1 = 375$ s and $P_2 = 336$ s), oscillation amplitudes ($a_1 = 2.3$ Mm and $a_2 = 2.0$ Mm), and loop centroid positions ($x_1 = 6.8$ Mm and $x_2 = 6.1$ Mm), but a common start time $t_0 = 423$ s (i.e., 19:12:03 UT). Thus the loops are excited in phase, but the secondary loop has an oscillation period that is about 10% shorter. The secondary loop also seems to have a shorter lifetime and is only visible in the 171 Å filter for about two oscillation periods (compared with 3.6 periods of the primary loop.)

2.7. Intensity Modulation During Loop Oscillations

The 171 Å intensity of the background-subtracted loop intensity exhibits strong modulations, being strongest near the beginning, but fading out gradually at the end of the time interval of oscillations. We show in Figure 3 (bottom panel) the background-subtracted intensity flux profile $f(t)$ as measured near the loop apex from the Gaussian cross-sectional profile.
fits (Equation (2)). Amazingly, the intensity flux modulation appears to be synchronized with the oscillation amplitude, which is a very interesting property that we have not noticed in previous observations of loop oscillations (e.g., in the 26 cases observed with TRACE; Aschwanden et al. 1999, 2002). In fact, the loop flux modulation $f(t)$ (Figure 3, bottom panel) occurs in anti-phase to the amplitude modulation $a(t)$ that is measured in the upward direction away from the loop curvature center. In addition to the oscillation-modulated variation, the flux decays as a function of time, which can be described with a linear...
Aschwanden & Schrijver

Figure 7. Location of stereoscopically triangulated loop footpoints (marked with diamonds and labeled with $F_1$ and $F_2$) and 10 loop segments with the rectangular sub-images over which the 10 time slices (shown in Figure 6) were extracted (bottom left panel). The corresponding AIA 171 Å image (top left) and difference image 19:21:00–19:19:24 UT (top right) are also shown. The magnitude of the transverse kink-mode oscillation amplitude is indicated with thick bars (bottom panels), which fit a stretched sine function (Equation (5)).

(A color version of this figure is available in the online journal.)

decay rate $df/dt$, similar to that found for eight loops with kink-mode oscillations during the 2001 April 15, 21:58 UT, flare (Aschwanden & Terradas 2008). Thus, we fit a sinusoidal function with a linear decay rate $f_2/P_f$,

$$f_{in}(t) = f_0 + f_1 \sin \left( \frac{2\pi(t - t_f)}{P_f} \right) + f_2 \frac{(t - t_f)}{P_f}.$$  \hspace{1cm} (6)

We find a peak flux of $f_0 = 61 \text{ DN s}^{-1}$, a flux modulation of $f_1 = 7.5 \text{ DN s}^{-1}$, and a linear decay rate of $f_2/P_f = -0.037$ (DN s$^{-2}$), which defines a loop lifetime of $t_{life} = P_f(f_0/f_2) = 1649$ s (27 minutes) and is compatible to the loop cooling times $\tau_{cool} = 17 \pm 7$ minutes found in Aschwanden & Terradas (2008), modeled also in Morton & Erdelyi (2009, 2010). It is therefore suggested to interpret the observed lifetime of the oscillating loop as the detection time of a loop that cools through the AIA 171 Å passband. For the flux modulation that is anti-correlated with the amplitude oscillation, we suggest an interpretation in terms of density compression by cross-sectional loop width oscillations, similar to a sausage mode, which is modeled in the next section.

2.8. Density Modulation During Loop Oscillations

In the previous sections, we established that the vertical oscillation amplitude amounts to $a_{max}/r_{loop} = 2/52 = 4\%$. If we assume that the loop is embedded in a magnetic field with a constant pressure across the loop cross-section (to first order) in a low plasma $\beta$-parameter environment, the ambient magnetic field lines are expected to oscillate in synchrony with a displacement that is proportional to the loop amplitude. A consequence of this scenario is that the loop cross-sectional radius $r(t) - r_0$ varies proportionally to the loop amplitude $a(t)$,

$$r(t) = r_0 \left( 1 + \frac{a(t)}{a_{max}} \right),$$  \hspace{1cm} (7)
leading to a modulation of the loop cross-sectional area \( A(t) = \pi r^2(t) \) that scales quadratically to the loop radius \( r(t) \),

\[
A(t) = A_0 \left( 1 + \frac{a(t)}{r_{\text{loop}}} \right)^2.
\]  

Since the loop footpoints are anchored at fixed positions in the photosphere, we can characterize the oscillating loop shape with an elliptical geometry to first order, which oscillates around the semi-circular geometry of the loop at rest, as depicted in Figure 7. The loop length of a half-ellipse is mathematically (to first order)

\[
L = \pi \left( r_{\text{minor}} + r_{\text{major}} + \cdots \right),
\]

where \( r_{\text{minor}} \) is the minor semi-axis and \( r_{\text{major}} \) is the major semi-axis of the ellipse. For the semi-circular limit, the radii are equal, \( r_{\text{minor}} = r_{\text{major}} = r_{\text{loop}} \), and the half-loop length is \( L = \pi r_{\text{loop}} \). Assigning the minor axis to the half-footpoint separation, \( r_{\text{minor}} = r_{\text{loop}} \), and the major axis to the vertical radius with a small oscillation amplitude, \( r_{\text{major}} = r_{\text{loop}} + a(t) \), the elliptical loop length varies (to first order) as

\[
L(t) = \pi \left( r_{\text{loop}} + \frac{a(t)}{2r_{\text{loop}}} + \cdots \right) = \pi r_{\text{loop}} \left( 1 + \frac{a(t)}{2r_{\text{loop}}} + \cdots \right).
\]

The volume of the loop, \( V(t) \), then varies consequently with the 5/2 power of the amplitude variation (to first order),

\[
V(t) = A(t)L(t) = V_0 \left( 1 + \frac{a(t)}{r_{\text{loop}}} + \cdots \right)^{5/2}.
\]

The electron density inside the loop, assuming particle conservation in adiabatic compression and expansion processes, varies then reciprocally to the loop volume,

\[
n_e(t) \propto V(t)^{-1} = n_0 \left( 1 + \frac{a(t)}{r_{\text{loop}}} + \cdots \right)^{-5/2}.
\]

For optically thin emission, as is the case in EUV and soft X-rays for coronal conditions, the flux intensity scales with the square
of the electron density times the column depth $dz$ (which is here assumed to be proportional to the loop diameter $dz \propto \sqrt{A(t)}$), yielding an anti-correlation of the flux with the fourth power of $dz$ of the electron density times the column depth 

$$ F(t) \propto n_e(t) dz(t) = F_0 \left( 1 + \frac{a(t)}{r_{loop}} + \cdots \right)^{-4}. \quad (13) $$

Thus, the small-amplitude variation of $a_{\max}^1 / r_{loop} = 2.2 / 52 = 0.042$ is amplified to the fourth power,

$$ F_{\max} = F_0 \left( 1 - 4 \frac{a_{\max}}{r_{loop}} + \cdots \right) \approx 1.18^{-1}. \quad (14) $$

which yields a flux modulation of 18% with respect to the mean value $f_0$. In Figure 3 (bottom panel), we fitted the flux variation and indeed found an average mean modulation factor of $q_f = f_I / (f_0(t)) \approx 7.45(30) \approx 24\%$, for the average of the total flux $\langle f_0(t) \rangle \approx (61 + 10)/2 \approx 30$ DN s$^{-1}$ during the oscillatory episode. Thus our model predicts the correct time phase and approximate amount of oscillatory intensity flux modulation, which is anti-correlated to the sinusoidal loop amplitude oscillation (Figure 9). The MHD wave mode that is associated with cross-sectional variation is called the sausage mode or symmetric $m = 0$ mode of fast MHD waves (e.g., Roberts et al. 1984), which has a distinctly different eigenmode period than the kink mode. The cross-sectional and density variation that were found in synchronization with the kink mode here (which has the same geometric and density properties as the sausage mode, but a different period than predicted by the MHD dispersion relation) are a novel result of this study. This characteristic seems to be a particular property of oscillations in the loop plane (Figure 7), also called “vertical polarization of kink mode” (Wang & Solanki 2004; Verwichte et al. 2006a, 2006b), which would not occur (to first order) for transverse oscillations in the direction perpendicular to the loop plane.

2.9. Density and Temperature Analysis of Oscillating Loop

Having the six coronal AIA filters available that cover a temperature range of $T \approx 0.6$–16 MK for the entire oscillation episode with the same cadence of 12 s we are in an unprecedented position to conduct accurate diagnostics of the electron temperature and density of the oscillating loop. For this purpose, we extract loop-aligned sub-images in all 6 coronal wavelengths in 10 spatial segments ($s_i; i = 1, \ldots, 10$) at the loop locations indicated in Figure 7 (bottom left) and at 10 consecutive times ($t_j; j = 1, \ldots, 10$) during the time interval of 19:05–19:35 UT. We show the 6 × 10 sub-images for the 10 different times for loop segment No. 6 near the loop apex in Figure 10 (left half), as well as the averaged cross-sectional loop profiles resulting from these sub-images in Figure 10 (right half). We also calculate the cross-correlation coefficients of these sub-images with the simultaneous sub-image in the detected wavelength of 171 Å (indicated by the numbers in each subpanel in Figure 10). From this information shown in Figure 10, it is very clear that the oscillating loop exhibits a near-Gaussian cross-sectional profile only in the 171 Å filter, while the 131 and 193 Å filters show only a mild correlation (CCC $\approx 0.4$–0.5) and the remaining filters (211, 335, and 94 Å) are absolutely uncorrelated (CCC $\approx 0.0$–0.1), which already narrows down the loop temperature to the peak response temperature of the 171 Å filter at $T \approx 10^{5.9} \approx 0.8$ MK.

In Figure 11 (left side), we show the AIA temperature response functions, where the low-temperature response of the 94 Å filter is corrected by an empirical factor of $q_{94} = 6.7 \pm 1.7$ (Aschwanden & Boerner 2011). The total fluxes $f^{\text{tot}}(t)$ (histograms with error bars in Figure 11, middle panels) and background fluxes $f^{\text{back}}(t)$ (hatched areas in Figure 11, middle panels) are also shown, where the background is evaluated based on the Gaussian cross-sectional fits (Figure 10). The difference $f^{\text{loop}}(t) = f^{\text{tot}}(t) - f^{\text{back}}(t)$ is attributed to the EUV flux of the oscillating loops and is modeled with a single-Gaussian differential emission measure (DEM) distribution by forward fitting (according to the method described in Aschwanden & Boerner 2011),

$$ \text{EM}(T) = \text{EM}_0 \exp \left( -\frac{(T - T_0)^2}{2\sigma_T^2} \right), \quad (15) $$

with the best-fit DEM solutions shown in Figure 11 (top right panel) for the 10 consecutive time steps. The single-Gaussian DEM fits yield an average peak temperature of
$T_0 = 0.57 \pm 0.14$ MK and a Gaussian temperature width of $\sigma_{\log(T)} = 0.18 \pm 0.10$ (Figure 11, right side), which corresponds to a near-isothermal temperature distribution at the limit of the temperature resolution $\Delta \log(T) \approx 0.3$ of the AIA filters, similar to that found for a statistical set of other loops analyzed from TRACE (Aschwanden & Nightingale 2005) or AIA (Aschwanden & Boerner 2011). The goodness of fit of the best-fit DEM solutions is found to be $\chi^2_{\text{red}} = 1.10 \pm 0.05$. The average agreement of the observed and modeled fluxes is found to be $\lesssim 3\%$ in the three filters with the highest fluxes (Figure 11, middle column). The largest relative deviation occurs in the 94 Å filter, which are known to have an incomplete temperature response function due to missing lines of Fe x transition (Aschwanden & Boerner 2011). Also we have to keep in mind that the largest flux deviations in the fits are on the order of $\approx 0.2$–0.5 DN s$^{-1}$ in the 94, 131, and 335 Å channels, which result mostly from uncertainties in the (time-variable) background evaluation rather than from the statistical photon noise.

Assuming a filling factor of unity, we can estimate the mean electron density in the oscillating loop,

$$n_0 = \sqrt{\frac{EM_0}{w}},$$

for which we obtain a mean value of $n_0 = (1.9 \pm 0.3) \times 10^8$ cm$^{-3}$, based on average loop widths of $w = 4.9 \pm 0.6$ Mm (Figure 11, right side), which is measured near the apex of the loop for segment No. 6 shown as cross-sectional loop profiles in Figure 10.
2.10. Radiative Cooling Timescale

Since the issue has been raised whether the lifetime of oscillating loops (defined by the detection time in a given temperature filter) is commensurable with the duration of an observed oscillation event (Aschwanden & Terradas 2008; Morton & Erdelyi 2009), let us explore whether the theoretically predicted timescales are consistent with the observed flux decay. At the relatively low coronal temperatures of \( T_e \lesssim 1.0 \) MK observed in EUV, radiative cooling is the dominant timescale, while conductive cooling is only relevant at much hotter plasma temperatures in soft X-rays. Assuming an impulsive heating episode with subsequent cooling, we can approximate the temperature evolution with an exponentially decaying function over some temperature range,

\[
T_e(t - t_1) = T_e(t_1) \exp \left( -\frac{t - t_1}{\tau_{\text{cool}}} \right),
\]

where the temperature cooling time \( \tau_{\text{cool}} \) corresponds to the radiative cooling time \( \tau_{\text{rad}} \),

\[
\tau_{\text{rad}}(n_0, T_0) = \frac{9}{5} \frac{k_B T_0^{5/3}}{n_0 \Lambda_0},
\]

with \( \Lambda_0 \approx 10^{-17.73} \text{ erg cm}^3 \text{ s}^{-1} \) being the radiative loss rate at EUV temperatures \( (T \approx 1.0 \text{ MK}) \). For our measured values
of $T_0 = 0.57$ MK and $n_0 = 1.9 \times 10^{10}$ cm$^{-3}$ at the loop apex, we estimate $\tau_{rad} \approx 2750$ s (46 minutes). The loop lifetime $\tau_{171}$ in the 171 Å filter, which has an FWHM temperature range of $T_{171} = 0.53$–1.17 MK, is then $\tau_{171} = 2200$ s (37 minutes) according to Equation (17), which if fully consistent with the observed flux decay time $\tau_{life} = P(f_0/f_0) = 1650$ s (27 minutes) based on the fitted time profile (Equation (6)) to the measurement shown in Figure 3 (bottom panel). Therefore, we can interpret the observed flux decay seen in the 171 Å filter as a consequence of the radiative cooling time. Based on this cooling scenario, we would predict an initial temperature of $T_c(t = t_1) \approx 0.8$ MK at the beginning of the oscillation event and a temperature of $T_c(t = t_2) \approx 0.4$ MK at the end of the oscillation episode. The predicted temperature drop $T_e$ of the oscillation episode. The predicted temperature drop $T_e$ of the oscillation episode.

### 2.11. Excitation of Loop Oscillations

The exciter or trigger of the loop oscillations is very likely the associated flare event to the east of the oscillating loop. If we calculate the projected distance between the flare site ($x_{flare} = +390^\circ$, $y_{flare} = -410^\circ$; Section 2.2) and the apex of the oscillating loop ($x_{apex} = +698^\circ$, $y_{apex} = -243^\circ$, $h_{apex} \approx 50^\circ$; Section 2.4), taking the stereoscopically triangulated 3D loop position into account, we obtain a Euclidian distance of $L_{exc} = 353^\circ$ (256 Mm). Given the time delay between the start of the loop oscillation at the apex (19:12:12 UT) and the flare start (19:10:00 UT; ±6 s), we obtain the following 3D propagation speed of the exciter:

$$v_{exc} = \frac{L_{exc}}{\tau_{exc}} = \frac{256,000 \text{ km}}{132 \pm 6 \text{ s}} = 1940 \pm 125 \text{ km s}^{-1}$$

which is a typical Alfvénic (magneto-acoustic) speed in the solar corona. Thus, we can conclude that the loop oscillation is initially triggered by a fast MHD wave with Alfvénic speed. Moreover, the direction of the initial excitation in the westward direction is in the same direction as the propagation direction of the fast MHD wave that propagates with Alfvénic speed concentrically away from the flare site. Although the angle between the Alfvénic wave direction and the loop oscillation amplitude cannot be determined with high accuracy, it is closer to parallel than perpendicular, as would be expected in a vortex-shielding scenario (Nakariakov et al. 2009), where the kink-mode oscillation occurs in the direction perpendicular to the local plasma flow direction. In the case analyzed here, it appears that the plasma volume in the westward direction is stretched out in the same direction, probably following a narrow-angle cone of open magnetic field where the CME escapes. An associated CME on the southwest side of the Sun is visible in SOHO/LASCO and EIT animations. Generally, excitation of kink-mode oscillations with vertical polarization are rare, because they need special circumstances with an exciter near the curvature center of the loop (Selwa et al. 2011).

### 2.12. External/Internal Density Ratio of Oscillating Loop

Coronal seismology allows us to determine the mean magnetic field in a loop in the kink-mode oscillation mode based on the internal Alfvén speed $v_A$ inside the oscillating loop,

$$v_A = \frac{B_i}{\sqrt{4\pi \rho_i}}$$

which can be related to the (fundamental) k-mode period $P_{kink}$ using the phase speed $c_k$ inside the flux tube (Roberts et al. 1984),

$$P_{kink} = \frac{2L_{osc}}{c_k} = 2L_{osc} \frac{1 + \rho_e/\rho_i}{v_A} \sqrt{\frac{1 + \rho_e/\rho_i}{2}},$$

which depends on the total length $L_{osc}$ of the oscillating loop and the densities external ($n_e$) and internal ($n_i$) to the loop.

On the other hand, we can estimate the external Alfvén speed $v_{Ae}$, which depends on the external magnetic field $B_e$ and density $n_e$,

$$v_{Ae} = \frac{B_e}{\sqrt{4\pi \rho_e}}$$

If we interpret the exciter speed $v_{exc}$ between the flare site and the (apex) location of the oscillating loop (Equation (19)) as an Alfvénic wave, we obtain a direct measurement of the external Alfvén speed (supposing the wave is not super-Alfvénic),

$$v_{Ae} = \frac{v_{exc}}{v_{exc}} = \frac{L_{exc}}{\tau_{exc}}.$$  

Moreover, since the magnetic pressure is generally dominant over thermal pressure in the solar corona, the magnetic field $B_i$ internal and $B_e$ external to the loop boundary have to match for a self-consistent magnetic field model of a loop embedded into an external plasma. Based on the definitions of the Alfvén speeds (Equations (20) and (22)), the ratio of the Alfvén speeds then depends only on the density ratio,

$$B_e = B_i \implies v_{Ae} = \frac{v_{exc}}{v_A} = \sqrt{\frac{n_i}{n_e}},$$

which can be directly determined from the kink-mode period, loop length, and exciter speed with Equations (21) and (23),

$$\frac{n_i}{n_e} = \frac{1}{2} \left( \frac{L_{exc} P_{kink}}{L_{osc} T_{exc}} \right)^2 - 1.$$
of the Alfvén speeds is then expected to be \( \frac{v_{\text{Ae}}}{v_{\text{A}}} = \sqrt{n_i/n_e} \approx \sqrt{12} \approx 3.4 \). In our case, the external Alfvén speed is \( v_{\text{Ae}} \approx 1940 \pm 100 \text{ km s}^{-1} \), and the internal Alfvén speed is \( v_{\text{A}} \approx 560 \pm 100 \text{ km s}^{-1} \).

### 2.13. Magnetic Field Modeling

With this novel method of measuring the density ratio \( n_e/n_i \) from Alfvénic propagation speeds external and internal to the flux tube, the magnetic field in the oscillating flux tube and immediate surroundings is then fully constrained with Equations (20) and (21) (Nakariakov et al. 1999),

\[
B = \frac{L_{\text{osc}}}{P_{\text{kink}}} \sqrt{8\pi \mu_m n_i (1 + n_e/n_i)},
\]

for which we obtain \( B = 4.0 \pm 0.7 \text{ G} \), based on the measurements of \( L_{\text{osc}} = (143 \pm 20) \times 10^8 \text{ cm} \), \( P_{\text{kink}} = 375.6 \text{ s} \), \( n_i = (1.9 \pm 0.3) \times 10^8 \text{ cm}^{-3} \), and the density ratio \( (n_e/n_i) \approx 0.08 \pm 0.01 \). This magnetic field scenario can be tested with observed magnetic field data from the Helioseismic and Magnetic Imager (HMI) on SDO. In Figure 12 (bottom), we show an HMI magnetogram recorded at 19:04:16 UT, at the beginning of the analyzed time interval. The flare location is situated in the core of the AR, right at the neutral line with the largest magnetic flux gradient, while the oscillating loop is located beyond the western boundary of the active region in a low magnetic field region that is governed by a “salt-and-pepper pattern” of positive and negative magnetic pores (see enlargement in Figure 13, top left). A potential-field source surface (PFSS) model calculation is shown in Figure 12 (top panel), which is dominated by a bipolar arcade above the neutral line in the east–west direction.

The magnetic field in the environment of the oscillating loop can be modeled with potential-field or non-potential-field models, but both are known to show misalignments with the 3D geometry of stereoscopically triangulated loops of the order of \( \alpha_{\text{mis}} \approx 20^\circ - 40^\circ \) (DeRosa et al. 2009; Sandman et al. 2009).
while simple potential-field models calculated from a small set of unipolar magnetic charges (Aschwanden & Sandman 2010) or magnetic dipoles (Sandman & Aschwanden 2011) achieved a reduced misalignment of $\alpha_{\text{mis}} = 13^\circ-20^\circ$. For a simple plausibility test of the magnetic field strength inferred from coronal seismology, we model the 3D field at the location of the oscillating loop with an analytical model of two unipolar charges with opposite magnetic polarities that are buried in depths $z_1$ and $z_2$ and have maximum longitudinal magnetic field strengths of $B_{\parallel 1} = +187$ G and $B_{\parallel 2} = -63$ G at the observed positions $(x_1, y_1)$ and $(x_2, y_2)$ of the nearest magnetic pores in the HMI magnetogram (marked with circles in Figure 13, top left panel), where $(x, y, z)$ is a Cartesian coordinate system with the xy-plane parallel to the solar surface. The corresponding absolute field strengths vertically above the buried charges are $B_1 = B_{\parallel 1}/\cos(\vartheta_1) = 296$ G and $B_2 = B_{\parallel 2}/\cos(\vartheta_2) = -89$ G, where $\vartheta_j$ are the line-of-sight angles. Thus, in this model we have only the two free variables of the depths $z_1$ and $z_2$ to fit the model of resulting magnetic field lines to the observed loop. The magnetic field resulting from the superposition of two unipolar magnetic charges is then given by (Aschwanden & Sandman 2010)

$$B(x) = \sum_{j=1}^{N} B_j(x) = \sum_{j=1}^{N} B_j \left( \frac{z_j}{r_j} \right)^2 \frac{r_j}{r_j},$$  \hspace{1cm} (27)

in terms of the vector $r_j = [(x-x_j), (y-y_j), (z-z_j)]$, with $(x_j, y_j, z_j)$ being the locations of the buried unipolar magnetic charges and $B_j$ the magnetic field strength at the solar surface above the magnetic charges. The ratio of the two free variables $z_1$ and $z_2$ determines the asymmetry of the field lines. For the observed oscillating loop, we find values of $z_1 = 0.5$ and $z_2 = 1.5$ to reproduce approximately the observed shape (Figure 13, bottom left). The field line that fits the projected location of the oscillating loops closest has magnetic field strengths of $B_1 = 296$ G and $B_2 = 29$ G at the photospheric field line footpoints and $B = 6$ G at the apex, which compares favorably with the magnetic field strength of $B_{kink} = 4.0 \pm 0.7$ G deduced from coronal seismology.

However, since the magnetic field $B(s)$ varies along the loop, the Alfvén speed varies proportionally and the Alfvénic transit time during one oscillation period is given by

$$P = \int_0^P dt = \int_0^{2L} \frac{1}{v_A(s)} ds,$$  \hspace{1cm} (28)

which defines an average magnetic field $\langle B \rangle$ that is equivalent to a flux tube with the same kink-mode period $P$ and a constant magnetic field value $\langle B \rangle$ by

$$\langle B \rangle = \left[ \int B(s)^{-1} ds \right]^{-1},$$  \hspace{1cm} (29)
Observables and Physical Parameters of Analyzed Loop Oscillation Event

| Parameter                                      | Value                      |
|------------------------------------------------|----------------------------|
| Date of observations                           | 2010 Oct 16                |
| Time interval of analyzed observations         | 19:05–19:35 UT             |
| Time range of GOES flare                       | 19:07–19:12 UT             |
| Flare onset of impulsive phase                 | 19:10:00 (±6 s) UT         |
| Start of loop oscillations                     | 19:12:12 (±6 s) UT         |
| GOES flare class                               | M2.9                       |
| Active region number                           | NOAA 1112                  |
| Flare location                                 | [390°, –410°], W26/S20     |
| Location of oscillating loop footpoints        | [685°, –305°], [615°, –268°]|
| Location of loop apex                          | [698°, –243°]              |
| Distance of flare to loop apex L_{esc}         | 275 Mm                     |
| Delay of flare start to loop oscillation T_{esc}| 132 ± 10 s                |
| Exciter speed v_{exc} = v_{Ac}                 | 1940 ± 100 km s⁻¹          |
| Height of loop apex n_{apex}                   | 37 Mm                      |
| Distance from Sun center                       | 740° (0.77 R_S)            |
| Full loop length L_{loop}                      | 163 Mm                     |
| Length of oscillating loop segment L_{seg}     | 123 Mm                     |
| Loop curvature radius r_{loop}                 | 52 Mm                      |
| Loop FWHM diameter w                          | 4.9 ± 0.6 Mm               |
| Loop inclination angle to vertical ð            | 20° ± 20°                  |
| Polarization angle of kink oscillation         | 0° ± 10°                   |
| Drift velocity of loop centroid ds/dt          | 0.8 km s⁻¹ (toward west)   |
| Oscillation period of loop P                   | 375.6 s (6.3 minutes)      |
| Oscillation amplitude of loop a_1             | 1.7 ± 0.4 Mm               |
| Number of oscillation periods N_{p}            | 3.6                        |
| Loop lifetime t_{life} = f_0/(df/dt)           | 1650 s (27 minutes)        |
| Ratio of loop amplitude to radius a_1^{max}/r_{loop}| 0.042                   |
| Observed flux modulation f_1/f_0               | 0.24 (0.18 predicted)      |
| Electron temperature T_e                      | 0.57 ± 0.14 MK             |
| Temperature width r_{log}(T_e)                 | 0.18 ± 0.10                |
| Electron density n_e                          | (1.9 ± 0.3) × 10^{6} cm⁻³ |
| External Alfvén speed v_{exc} = v_{Ac}         | 1940 ± 100 km s⁻¹          |
| Internal Alfvén speed v_A                     | 560 ± 100 km s⁻¹           |
| External/internal density ratio n_e/n_i       | 0.08 ± 0.01                |
| Magnetic field at loop apex B_{apex}           | 4.0 ± 0.7 G                |
| Magnetic field at loop footpoints B_{foot}     | +296, –89 G               |
| Damping time ratio τ_{damp}/P                  | 204                        |

for which we obtain ⟨B⟩ = 11 G, which is a factor of 1.8 higher than the minimum value at the apex, B_{apex} = 6 G, or a factor of 2.8 higher than inferred from seismology, B_{kink} = 4.0 ± 0.7 G. This difference between the seismological and magnetogram-constrained magnetic field value, derived for the first time for an oscillating loop here to our knowledge, is perhaps not too surprising, given the ambiguity of potential-field models, non-potential-field models, and uncertainties of the footpoint locations (which require stereoscopic information).

3. DISCUSSION

In this well-observed loop oscillation event, which we analyzed with AIA/SDO, HMI/SDO, and EUVI/STEREO, we derived a comprehensive number of physical parameters (listed in Table 1) that could not be determined to such a degree in previous observations. In the following discussion, we compare the observational results with theoretical models, predictions, and discuss interpretational issues.

3.1. Coupled Kink-mode and Cross-sectional Oscillations

The basic theory for fast magneto-acoustic waves, which predicts kink and sausage eigenmodes for slow (acoustic) and fast (Alfvénic) MHD waves, has been derived for a straight (slender) cylindrical flux tube (e.g., Edwin & Roberts 1983). For such an idealized geometry, the periods of the fast kink and sausage mode have quite different regimes, and the sausage mode has a wavenumber cutoff with no solution of the dispersion relation for ka ≲ 1 (with k the wave number and a the flux tube radius), which corresponds to a cutoff at a phase speed of v_{sh} = v_{Ac}. From this theory, no sausage eigenmode is predicted for periods that correspond to kink-mode oscillations, P_{kink} = 2L/v_A. In contrast, our analysis clearly demonstrates the presence of a kink mode with coupled sausage-like behavior, as measured by the cross-sectional loop width variations and anti-correlated density variations. The question arises why this dynamical behaviour is not predicted by existing theory. One possible explanation is that the loop length is not constant but changes as a function of time in synchrony with the transverse oscillation amplitude. This is most plausibly seen in Figure 1, where the excitation direction originating from the flare location propagates in approximately the same direction as the loop plane, and thus excites a significant component of the “vertical” polarization mode (i.e., the loop plane and the oscillation plane are near-parallel), as inferred for one case in Wang & Solanki (2004) and analytically studied in Verwichte et al. (2006a, 2006b). Most kink-mode oscillations have horizontal polarization, as determined with STEREO (e.g., Verwichte et al. 2009), but density oscillations have also been noted in previous kink-mode oscillations (e.g., Verwichte et al. 2009, 2010). If the loop oscillates in vertical polarization, the length of the loop can vary during the kink-mode oscillations, with a linear dependence on the oscillation amplitude to first order (in the elliptical approximation, see Equations (9) and (10)). Thus, the periodic shrinking and stretching of the flux tube is likely to cause a bulging and thinning of the central loop cross-section, which is exactly what a sausage mode does. A consequence of the length variation L(t) is also a magnetic field variation B(t), which scales reciprocally to the cross-sectional area of the sausage mode, i.e., B(t) ∝ A⁻¹(t), due to the conservation of the magnetic flux, i.e., B(t)A(t) = constant.

The coupling of kink-mode and (sausage-like) cross-section and density oscillations thus might be a special case that occurs only when the loop length is varied, which most likely occurs for vertical polarization and requires an initial excitation in the direction of the loop plane. It would be interesting to investigate this prediction of coupled cross-section and density oscillations as a function of the exciter direction or kink-mode polarization, which depends on the location and orientation of the loop plane with respect to the propagation direction of a flare or CME-related disturbance. Since CME bubbles and erupting flux ropes get stretched out during the initial expansion, it is natural that ambient magnetic field lines become stretched too, which also applies to oscillating loops. Statistics on different polarizations types of kink-mode oscillations is still small and their identification based on difference images is often ambiguous (Wang et al. 2008).

An alternative interpretation of the amplitude-correlated flux variation is an aspect-angle change of the oscillating loop, which causes a variable line-of-sight column depth of the loop diameter w(t) = w_0 cos(θ(t)) (Cooper et al. 2003), and hence would introduce a variation of the optically thin EUV flux f(t) ∝ n_0^2(t)w(t). However, the observed flux variation with a mean of ≈24% would require an aspect-angle change of Δθ ∼ 40°, which is inconsistent with the observed stationarity of the loop shape during the entire oscillation episode.
3.2. Multi-loop Oscillations

Evidence that multiple loops or strands are involved in this oscillation event is shown in Figure 8, where we found slightly different periods (by ≈10%), amplitudes, centroid positions, and possibly different lengths (although not directly measured). The eigenmodes in a two-slab system were studied in Arregui et al. (2008) and it was found that the kink-mode periods may differ from a single loop when the distance between the loops is less than a few loop diameters. In our case, the projected centroid position is displaced by Δx = 0.7 Mm, while the loop diameters are w ≈ 4.9 ± 0.6 Mm, so they could be close to each other. Luna et al. (2008) numerically simulated the MHD behavior of two parallel loops and found four collective modes, kink (asymmetric) and sausage (symmetric) modes in both the parallel and perpendicular directions to the plane that contains the axis of both loops, with four different frequencies, which is a generalization of the two modes of a single-loop oscillation. However, analytical solutions of a two-loop system yield only two different frequencies (Van Doorsselaere et al. 2008), which might differ from the numerical results of four different frequencies (Luna et al. 2008) due to the neglect of higher-order terms (Ruderman & Erdelyi 2009).

A multi-threaded model with four loop threads was modeled with a 3D MHD code (Ofman 2009). For parallel threads, the evolution of the ensemble exhibits the same period and damping rate as a single loop, but for twisted threads, the periods become irregular and the damping much stronger, which seems not to apply to our case here. Either the multiple loops are near-parallel or sufficiently distant to each other.

Resonant absorption in complicated multi-strand loops was investigated by Terradas et al. (2008) and it was found that the damping behavior is not compromised by the complicated geometry of composite loops. One theoretical prediction regarding multi-loop oscillations is that the collective width w(t) increases with time due to a shear instability (Terradas 2009), but we do not observe such an effect (Figure 11, bottom right panel), either because the two oscillating loops are not in sufficiently close spatial proximity or because the lifetime of the oscillating loops in the detected wavelength is too short.

3.3. Damping by Resonant Absorption

An unusual property of this oscillation event is that we do not observe any significant damping of the kink-mode amplitude over the duration of the oscillatory episode, so the ratio of the damping time to the period must be much longer than the observed number of periods, i.e., τD/P ≫ 4. This is in contrast to a statistical sample of 11 well-observed events with TRACE, where strong damping was found to be the rule, i.e., with τD/P ≈ 1.8 ± 0.8 (Aschwanden et al. 2002).

Resonant absorption as a damping mechanism for kink-mode oscillations was considered in Goossens et al. (2004) and by Van Doorsselaere et al. (2004) for thick boundaries, where qTB ≈ 0.75 is the correction factor for the thick-boundary layer, lskin is the skin depth or thickness of the loop boundary that contains a density gradient, and qe = ne/ni is the ratio of the external to the internal electron density in the loop. This density ratio was previously measured to qe = 0.30 ± 0.16, based on loop flux intensities and hydrostatic models of the background corona (Aschwanden et al. 2003), and a skin depth ratio of r0/lkin = 1.5 ± 0.2 was inferred, and hence the typical ratio of the damping time to the oscillation period was found to be τD/P ≈ 1.3.

In our case, a similar density ratio of qe ≈ 0.08 was measured. We can reconcile the observed long damping time ratio of τD/P ≫ 4 only with a very small skin depth of lskin/r0 ≪ 1/4. While previously analyzed kink-mode oscillations with TRACE exhibited typical temperatures of Tc ≈ 1.0–1.5 MK, we deal here with a significantly cooler loop with a temperature of Tc ≈ 0.5 MK. It appears that such cooler loops have either a smaller skin depth or larger loop diameters than the warmer coronal loops, but no hydrodynamic model is known that predicts such an effect.

3.4. Magnetic Field Comparisons

Coronal seismology determines the magnetic field strength by setting the kink-mode period Pkink equal to the Alfvénic crossing time 2L/vA forth and back along the loop length L, which yields a relationship for the magnetic field Bkink as a function of the loop length L, period Pkink, internal ne, and external density ne (Equations (21) and (26)). This method is one of the foundations of coronal seismology, initially applied by Roberts et al. (1984), Aschwanden et al. (1999), and Nakariakov & Ofman (2001). In principle, this analytical relationship can be put to the test by 3D MHD simulations of kink-mode oscillations of a plasma flux tube by comparing the theoretical with the experimental values of the kink-mode oscillation periods Pkink or magnetic fields B. Such a test was conducted by DeMooertel & Pascoe (2009), but surprisingly the coronal seismology formula predicted a field strength (Bkink = 15–30 G) that was about a factor of 1.5 higher than the input values of B = 10–20 G of the MHD simulation.

Here we attempted to validate the seismological magnetic field value (Bkink = 4.0 ± 0.7 G) by a potential-field model that consists of two unipolar magnetic charges with opposite polarities that are buried near the footpoints of the oscillating loop and are constrained by the longitudinal magnetic field strengths observed in HMI magnetograms. The best-fit field line yielded a magnetic field value of Bpex = 6 G, which is a factor of 1.4 higher than the seismological value. If we correct for the variable Alfvén speed along the loop, we predict a seismological value of Bavg = 11 G, which is a factor of 2.8 higher than the theoretical value. We note that the discrepancy of our best-fit potential-field model is in the opposite direction to the discrepancy found from the 3D MHD simulations by DeMooertel & Pascoe (2009). We believe that the discrepancy from magnetic field modeling methods mostly stems from the uncertainty of the footpoint locations, the spatial resolution of magnetograms, and the ambiguity of potential and non-potential-field models. Stereoscopically triangulated loop oscillations hold the promise of obtaining more accurate measurements of the loop length and footpoint location. The most powerful self-consistency test needs to employ a combination of stereoscopy, numerical 3D MHD simulations, coronal seismology theory, and analytical magnetic field models.

4. CONCLUSIONS

Here we present the first analysis of a loop oscillation event observed with AIA/SDO, which occurred on 2010 October 16, 19:05–19:30 UT. The capabilities of AIA enable us for the
first time to study such an event with sufficiently high cadence, spatial resolution, and comprehensive temperature coverage, allowing us to derive all important physical parameters. In addition, magnetic modeling with HMI data can validate the magnetic field measurements based on coronal seismology. The major observational findings, interpretations, and conclusions are as follows.

1. A flare with an associated CME that escapes the Sun along a narrow cone (in westward direction) excites kink-mode oscillations with a period of $P = 6.3$ minutes in a loop at a distance of $L_{\text{exc}} = 256$ Mm away from the flare site, after a time delay of $T_{\text{exc}} = 132$ s, which yields an exciter speed of $v_{\text{exc}} = L_{\text{exc}}/T_{\text{exc}} \approx 1900$ km s$^{-1}$, which we interpret as a magneto-acoustic wave with Alfvénic speed and can be used as a direct measurement of the average external Alfvén speed $v_{Ae} = v_{\text{exc}}$ outside the oscillating loop.

2. The direction of the excitation and kink-mode oscillation amplitude is roughly in the same direction as the loop plane, which corresponds to a vertical polarization of the kink mode, causing a periodic stretching of the loop length and coupled cross-section and density oscillations, evident from the compression and rarefaction of the density, which produces an intensity variation that is amplified by the fourth power of the amplitude displacement. This behavior of kink modes with coupled cross-sectional and density variations are unusual and perhaps occur only in vertical polarization. They are not predicted by theory, which needs to be generalized for temporal variations of the loop length $L(t)$.

3. There is evidence for a multi-loop system. The oscillations are not synchronized to the same period indicates a spatial separation of more than a few loop diameters.

4. A full DEM analysis with all six coronal AIA temperature filters yields a temperature of $T \approx 0.5$ MK and a density of $n_e \approx 2 \times 10^8$ cm$^{-3}$. Consequently, the loop oscillations are primarily observable in the 171 Å filter, very faint in the 131 and 193 Å filters, and essentially undetectable in the other filters. From these temperature and density measurements, we estimate a radiative cooling time of $t_{\text{rad}} = 46$ minutes, which explains the loop lifetime of $t_{\text{life}} = 27$ minutes in the 171 Å filter.

5. The measurement of the external Alfvén speed $v_{Ae} \approx 1900$ km s$^{-1}$ from the exciter speed and the internal Alfvén speed $v_A = 560$ km s$^{-1}$ from the kink-mode period provides a direct measurement of the density ratio external and internal to the loop, $n_e/n_i = 0.08 \pm 0.01$, which is commensurate to earlier hydrostatic models of the background corona ($n_e/n_i = 0.30 \pm 0.16$; Aschwanden et al. 2003). This value provides a fully constrained magnetic field measurement of the oscillating loop by coronal seismology, $B_{\text{link}} = 4.0 \pm 0.7$ G.

6. For an independent estimate of the magnetic field in the oscillating loop, we used a potential-field model with two unipolar magnetic charges, constrained by the photospheric magnetic field strengths ($B_1 = +296$ G, $B_2 = -89$ G) obtained from HMI/SDO magnetograms near the footpoints of the oscillating loop, which were localized by stereoscopic triangulation from STEREO/EUVI/A images. A best-fit model yields a magnetic field strength of $B_{\text{apex}} = 6$ G at the loop apex, or $B_{\text{avg}} = 11$ G when averaged along the loop.

7. The oscillating loop exhibits no detectable damping over the observed four periods, which is unusual, compared with the statistical values of $T_{\text{damp}}/P = 1.8 \pm 0.8$ found from previous measurements. Damping by resonant absorption can only be reconciled with this observation if the skin layer (of the density gradient at the loop boundary) is much smaller than the loop radius. It is not clear if this property is a consequence of the unusual low loop temperature of $T \approx 0.5$ MK.

The excellent quality of the AIA data has provided more physical parameters of a coronal loop oscillation event than was possible to determine in previous TRACE observations, especially due to the much better cadence of 12 s, which also allows us to resolve multi-loop oscillations spatially and temporally. The measurements of more physical parameters provide stronger constraints on the theory and raise new problems that need to be addressed by analytical theory or MHD simulations:

1. What is the 3D geometry and timing of the exciter mechanism and how does it affect the polarization of kink-mode oscillations?
2. Can we explain the coupling of kink mode and (sausage-like) cross-sectional and density oscillations?
3. Can we explain kink-mode oscillations with no damping?
4. How do multi-loop oscillations interact with each other and how do the MHD wave modes couple?
5. How accurate are magnetic field measurements based on coronal seismology and how can they be validated with magnetic field models?

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