Transverse Coronal Loop Oscillations Seen in Unprecedented Detail by AIA/SDO

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Abstract

We present the detailed analysis of 11 transverse coronal loop oscillations in three events observed with the Atmospheric Imaging Assembly (AIA) instrument on board the Solar Dynamics Observatory (SDO) spacecraft. Detailed analysis includes analysis of the displacement time series, intensity variations and comparing EUVI and AIA data to estimate the 3D loop geometry.

Time series analysis revealed periods between 1.7 and 10 min and damping times between 2.9 and 13 min. Intensity variations are reliably observed for six of the loops and a comparison between EUVI/STEREO and AIA/SDO data is performed to simulate the polarisation of the kink mode. We conclude that the intensity variations are due to variations in the line of sight column depth of a horizontally polarised transverse loop oscillation. Coronal seismology of the kink mode was applied to determine the range of the internal Alfvén speed and the magnetic field strength for each loop.

Transverse Loop Oscillations (TLO's)

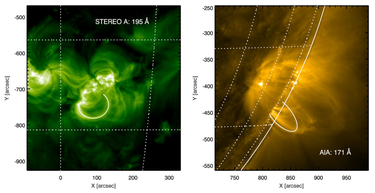
- Coronal loops are magnetic flux tubes filled with heated chromospheric plasma.
- Transverse oscillations are characterised by the displacement of the loop axis and are interpreted as fast MHD kink modes. [Aschwanden et al., 1999; Nakariakov et al., 1999]
- Oscillations are excited by dynamic phenomena such as flares and CME's. [Van Doorsselaere et al., 2007; Verwichte et al., 2009; Aschwanden & Schrijver, 2011]
- TLO's are often observed to damp on very short timescales. Possible damping mechanisms include phase mixing and resonant absorption. [Ruderman & Roberts, 2002; Goossens et al 2002; Aschwanden & Ofman, 2002]
- Parameters such as the period and length of the loop can be used to derive coronal properties such as the magnetic field strength using the technique of coronal seismology. [Nakariakov & Ofman, 2001; Verwichte et al., 2004, 2010]

Inclination Angles Using SDO/AIA and STEREO/EUVI

Where possible inclination angles have been estimated by comparing AIA data with EUVI data from the STEREO spacecraft.

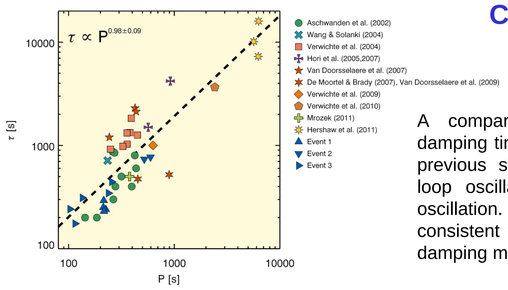
A loop path is chosen on the EUVI image (both 171Å and 195Å were used) and the coordinates are projected onto the AIA image. The reverse process can also be done.

The path is matched to a loop by changing the inclination angle until a good fit is observed. This technique also allows loop length estimates to be made.



Left: EUVI image from STEREO A of Event 1 (active region NOAA 11079) with a chosen loop path plotted. Right: The path coordinates chosen on the EUVI image are projected onto the AIA image. The loop is assumed to be planar.

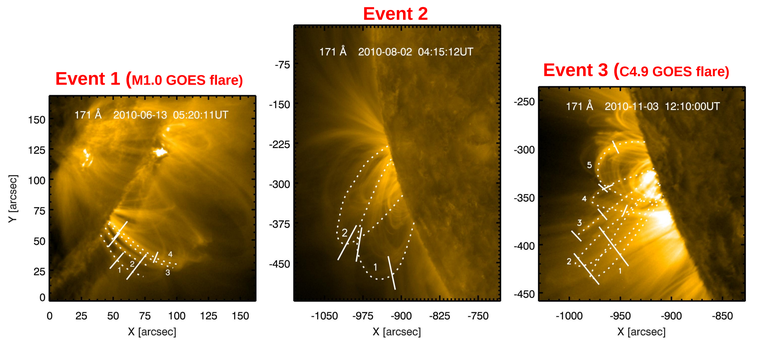
Comparison of TLO Events



A comparison of the periods and damping times of Events 1, 2 and 3 with previous studies of transverse coronal loop oscillations and one prominence oscillation. The fit parameters are consistent with the resonant absorption damping mechanism ($\tau \sim P$).

AIA Observations

11 loops in three events on the solar limb are observed to oscillate after a flare/CME event. AIA provides continuous full disk (41′ x 41′) images with a time cadence of 12 s, spatial resolution of 1.5″ and a pixel size of 0.6″.



AIA/SDO 171 Å images of the three events indicating the loops of interest. Left: Event 1 (05:20 - 06:20 UT). White tick marks indicate the regions within which cuts are taken to study the oscillations of the four loops. Centre: Event 2 (04:15 - 05:30 UT), two larger, fainter loops are studied. Right: Event 3 (12:10 - 13:10 UT), five loops are studied.

Displacement Time Series Analysis

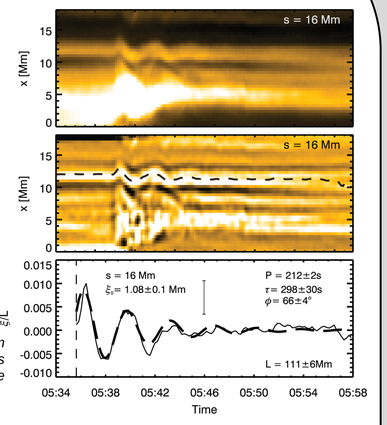
Time distance images extracted from cuts made perpendicular to the oscillations are obtained

Where possible, a Gaussian plus background fitting technique is used to extract the time series, otherwise the time series is estimated interactively by eye.

The background is subtracted by fitting a 3rd order polynomial function to the series and a damped cosine function is fitted to the result:

$$\xi(t) = \xi_0 \exp\left(\frac{-(t-t_0)}{\tau}\right)\cos\left(\frac{2\pi}{P}(t-t_0)-\phi\right)$$

Top: An example of a cut before a 2D Mexican hat wavelet transform was applied to enhance oscillatory features. Middle: The time series has been plotted on the wavelet enhanced cut. Bottom: The extracted loop time series fitted with a damped cosine curve.



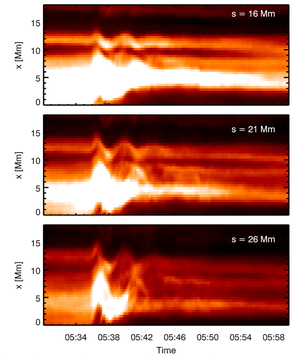
Time series parameters obtained from the analysis of the 11 observed coronal loop oscillations. Loop lengths have either been estimated from the EUVI-AIA comparison or by assuming that the loop is semi-circular and the height of the loop is equal to the radius.

Event	Loop	L (Mm)	θ (°)	t_0 (UT)	P (s)	τ (s)	ϕ (°)	ξ_0 (Mm)	V_{ph} (km s^{-1})
1	1	121 ± 2	38 ± 3	05:35:59	225 ± 40	240 ± 50	150 ± 70	3.26 ± 0.3	1080 ± 220
	2	111 ± 6	26 ± 5		215 ± 5	293 ± 20	69 ± 10	2.76 ± 0.2	1030 ± 110
	3	132	...		213 ± 9	251 ± 40	80 ± 10	1.92 ± 0.1	1240 ± 140
	4	113 ± 4	12 ± 3		216 ± 30	230 ± 20	121 ± 20	4.99 ± 0.3	1050 ± 170
2	1	396	...	04:24:12	520 ± 5	735 ± 50	194 ± 3	1.88 ± 0.1	1520 ± 150
	2	374	...		596 ± 50	771 ± 340	170 ± 30	3.00 ± 0.1	1260 ± 160
3	1	279 ± 3	27 ± 1	12:13:36	212 ± 20	298 ± 30	20 ± 20	5.97 ± 0.3*	2630 ± 360
	2	240 ± 4	29 ± 1		256 ± 20	444 ± 110	107 ± 20	7.76 ± 0.5*	1880 ± 250
	3	241	...		135 ± 9	311 ± 90	155 ± 60	3.40 ± 0.4*	3570 ± 430
	4	159 ± 6	−17 ± 1		115 ± 2	175 ± 30	80 ± 20	2.63 ± 0.3	2770 ± 280
	5	132	...	12:14:36	103 ± 8	242 ± 110	135 ± 30	2.01 ± 0.4	2560 ± 330

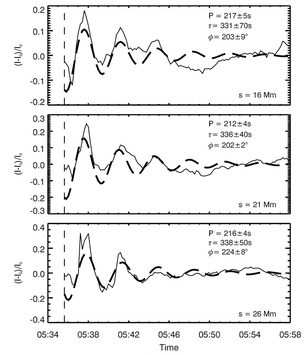
Notes. * Indicates recorded amplitudes that are at the approximate loop apex positions.

Intensity Variations

Intensity variations are extracted along the time series points. They are reliably observed by eye for loops 2 and 3 in Event 1 and loops 1-3 and 5 in Event 3. The extracted relative intensity time series are analysed using the same procedure as for the displacement time series analysis.



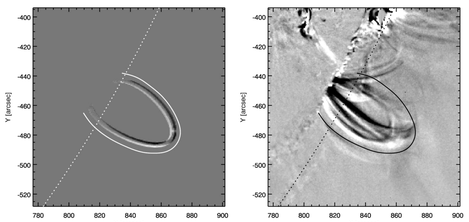
Time distance images taken from three cuts used to analyse loop 2 in Event 1. The images have been saturated to highlight the intensity variations along the loop. Loop 2 is the isolated loop above the bundle of loops.



Intensity time series analysis for loop 2 in Event 1. The solid line shows the intensity time series which has been fitted with a damped cosine function (thick dashed line). The background subtracted intensity amplitude has been normalised by the background. The vertical dashed line indicates the reference time of 05:35:59 UT.

Event	Loop	I_A	P (s)	τ (s)	ϕ (°)
1	2	0.22 ± 0.02	215 ± 2	350 ± 30	213 ± 10
	3	0.22 ± 0.02	247 ± 40	313 ± 20	184 ± 70
2	1	(0.06)	(550)	(552)	(126)
	2	(0.05)	(612)	(422)	(300)
3	1	0.06 ± 0.01	306 ± 3	623 ± 70	75 ± 50
	2	0.16 ± 0.02	235 ± 20	407 ± 160	90 ± 40
	3	0.27 ± 0.02	148 ± 40	224 ± 60	114 ± 10
	4	(0.22)	(130)	(180)	(50)
	5	0.10 ± 0.02	99 ± 2	314 ± 140	94 ± 30

Intensity oscillation parameters determined for each event. The intensity amplitude I_A is the background subtracted intensity that has been normalised by the background. Results in brackets were not reliably observed in the time distance images.



Left: simulated difference image for the modelled horizontally polarised loop 2 from Event 1. Right: difference image of Event 1. The dotted line indicates the solar limb.

EUVI/STEREO data is compared to AIA/SDO data to obtain three-dimensional models of the loop geometry. We model the loop with a radius of 1 Mm and a density contrast of 10 with the background plasma and perturb the model loop to investigate both the polarisation of the oscillation and the intensity variations. We conclude that the loops are horizontally polarised and intensity variations are most likely due to line of sight effects. [Verwichte et al., 2009, 2010]

Conclusions

- Performed the analysis of 11 coronal loop oscillations, determining periods, damping times and phases. 3D geometry was obtained for 6 loops using EUVI/STEREO.
- Oscillations with periods of less than 2 minutes are observed.
- Intensity oscillations reliably observed in 6 of the loops.
- From visual inspection of the data sets and from modelling the oscillation of loop 2, Event 1, we conclude that the intensity variations are most likely due to line of sight effects of the horizontally polarised kink mode.
- Coronal seismology of the kink mode is applied to the results. Field strengths between 3 and 19 G are found, consistent with Nakariakov & Ofman (2001).