Growing Transverse Oscillations of a Multistranded Loop Observed by SDO/AIA

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Outline

1. Introduction
   a) Basic theory of MHD waves in magnetic flux tube
   b) Brief overview of studies of transverse loop oscillations

2. Analysis of amplitude-growing transverse loop oscillation by SDO/AIA

3. Discussion and Conclusions
Introduction

**Motivation**

- MHD waves ⇒ possible source for coronal heating and solar wind acceleration

- Understand physical processes of excitation and damping mechanisms of various oscillation modes in coronal structures

- Develop coronal seismology ⇒ diagnostic tool for determining physical parameters of coronal structure

  (Roberts, Edwin & Benz 1984; Roberts 2000)
MHD oscillations and waves in coronal loops

- In a straight magnetic cylinder (Edwin & Roberts 1983; Robert et al. 1984)

All disturbances, \( v = v(r) \exp[i(\omega t + n\theta - k z)] \)

Loops length = \( L \), radius = \( a \)

Periods for standing modes
\( P = 2\pi/\omega \)

- Slow modes:
  \[ P_{\text{slow}} = \frac{2L}{jc_T} \approx \frac{2L}{jc_0} \]

- Kink modes:
  \[ P_{\text{kink}} = \frac{2L}{jc_k} \approx \frac{2L}{jV_A} \left( \frac{1 + \rho_e/\rho_0}{2} \right)^{1/2} \]

- Sausage modes:
  \[ P_{\text{sausage}} \leq \frac{2\pi}{k_c V_{Ae}} \approx \frac{2.6 a}{V_A} \left( \frac{1 - \rho_e/\rho_0}{\rho_0} \right)^{1/2} \]

- Expected oscillation periods
  - Slow modes: \( P = 7 \text{ – } 70 \text{ min} \)
  - Kink modes: \( P = 1.4 \text{ – } 14 \text{ min} \)
  - Sausage modes: \( P = 0.1 \text{ – } 5 \text{ s} \) (Aschwanden 2003)

- Longitudinal wavenumber
Sketches of oscillation modes

1) Fast modes:
   (a) sausage (symmetric)
      \[ B' > 0, \rho' > 0 \]

   (b) kink (asymmetric)
      \[ \rho' \approx 0 \]

2) Slow (sausage) modes:
   \[ B' > 0, \rho' < 0 \]

3) Torsional Alfven modes:
   \[ \rho' = 0 \]
Transverse loop oscillations observed by TRACE

- Triggered by flares or CME eruptions (Aschwanden et al. 1999; 2002)

- Excited by a flare disturbance

- Period: 5 - 6 min
  Loop length: 160 - 200 Mm

- Phase speed: \( V_p = \frac{2L}{P} = 1300 \text{ km/s} \)

- Interpretation:
  Standing fast kink mode oscillations in fundamental mode

Movie in 171 Å
Measurement of the physical properties


- Typically with a rapid decay within several periods
- Some oscillations are undamped (Ashwanden & Schrijver 2011)
Excitation of kink modes

- **Observation**
  - Flare-generated disturbance -- a blast wave, or a EIT wave (fast-mode wave) propagate in the corona and produce kink oscillations of nearby loops
  - Triggered by filament eruptions or CMEs

- **Theory and modeling**
  - Slab or cylinder configuration
  - Normal modes or Time-dependent
  - Energy deposit by initial disturbance
  - Single or multi-stranded loop

Luna et al (2008)
Damping mechanism of kink waves

- Phase mixing
  (Nakariakov et al. 1999, sci.)
  (Ofman & Aschwanden 2002)
  viscosity $\nu = 10^{8-9} \nu_{\text{class}}$

\[ T_D \sim P^{1.17 \pm 0.34} \]
\[ T_{PM} \sim P^{4/3} \]

(assuming the inhomogeneity scale, $l \sim w$ or $l \sim L$)

\[ T_d \sim P^{0.98 \pm 0.09} \]

For more than 40 cases (White and Verwichte (2012))
Damping mechanism of kink waves

- **Wave leakage**
  - Footpoint leakage very small
    (Ofman 2002)
  - Lateral leakage by tunneling effect
    (Brady & Arber 2005, A&A) 2D MHD
    (Verwichte et al. 2006)
    (Selwa et al. 2005, A&A) 2D MHD
    (Murawski et al. 2005, A&A) 2D MHD

Brady & Arber 2005

Selwa et al 2007
Damping mechanism of kink waves

- Resonant Absorption
  Conversion of global modes into torsional Alfven mode in thin layer of a loop
  (Goossens et al. 2002, A&AL) 1D MHD

\[
\left( \frac{\tau_D}{P_{\text{thin}}} \right) = q TB \frac{2}{\pi} \left( \frac{r_{\text{loop}}}{l_{\text{skin}}} \right) \left( \frac{1 + q_n}{1 - q_n} \right)
\]

Aschwanden et al. 2003

Velocity (Terradas et al. 2008) Energy density
2. Observations

- A two-stage flare-CME event on 2011 March 8 using SDO/AIA, STEREO/EUVI-A, and RHESSI by Su et al. (2012)

I: Forming a flux rope

II: Flux rope eruption (CME)

Start time of oscillation from 20:00 – 20:40
3. Analysis of transverse loop oscillations

- Dashed lines outline the oscillating loop seen in 211 A band

- A cut at loop apex used for time stacking plot to measure transverse oscillations

- Oscillation apparently associated with a surge/jet event, but actually not as shown by STEREO-A
3. Analysis of transverse loop oscillations

- Loop consists of temperature-dependent multiple strands showing different dynamic behaviors

- Lower part of loop disappeared associated with dimming in all bands – erupted

- Upper part dimmed in 171 and remain in 193 and 211 - heating

Erupting time of a flux rope
3. Analysis of transverse loop oscillations phase relationship of different strands

- Two strands in 171 show inphase oscillations with growing amplitudes
- Upper strands in 171 and 193 not co-spatial, they are inphase
- Two strands in 193 oscillate in phase for ~2 periods, then a P/4 phase delay set up with periods decreased by ~20%
3. Analysis of transverse loop oscillations
Measurement of displacement oscillations in 171

(a) Time distance map (original)
(b) Time distance map (original)
(c) Time distance map (Double Gauss-fit Model)
(d) Two Gaussian-fit to loop cross-section at 20:19:00
3. Analysis of transverse loop oscillations
Measurement of physical parameters of amplitude-growing oscillations in 171

- Fits of displacement oscillations with amplitude-growing sine-function (with positive damping rate)
- Association with intensity and loop width oscillations
  – intensity oscillation is real confirmed with width-fixed double Gfits
- Positive correlation suggests that loop width variations are artifacts
3. Analysis of transverse loop oscillations

Determination of trigger and loop geometry using STEREO-A

- The oscillating loop identified by fitting with a simple 3D arc-loop model
- Excluding the jet/surge as a trigger
- Association of a footpoint with extending ribbon followed by dimming region suggests that interaction of erupting flux rope (CME) continuously drive the loop oscillating, and lead it heated and partially erupted
4. Discussion

- Coronal seismology

Period $P=230$ s, loop length $L=212$ Mm, obtain $V_p=2L/P=1840$ km/s

$$V_P \approx C_k = V_A \sqrt{\frac{2}{1 + \frac{n_e}{n_i}}}$$

(Roberts et al. 1984)

Obtain Alfven speed $V_A=1360$ km/s if $n_e/n_i=0.1$

magnetic field $B=6 – 20$ G for $n=10^8 – 10^9$ cm$^{-3}$

- Evidence for coupling of kink oscillations of multiple strands
  - similar frequencies
  - in-phase or $\frac{1}{4}$-period phase shift

Questions:
  - no beating behavior as predicted
  - temperature-dependent dynamics of multi-strands not modeled before
4. Discussion

- Amplification of kink oscillation by cooling effect (Rudernan 2011a,b,c)

(Ashwanden & Schrijver 2011)

Expected damping balanced by amplification due to cooling, while $t_{\text{cool}} \sim P$ is required

For the model of stratified loop with constant $T_e$ of external plasma from the measurements $h/H_0 \sim 1.5$ and $n_e/n_i=0.1$,

obtain $t_{\text{amp}} \sim 4 t_{\text{cool}} < t_{\text{grow}}$

Observations $t_{\text{grow}} = 1248$ s and 759 s for upper or lower strands $P=230$ s

obtain $t_{\text{cool}}/P < 1.4$ or 0.8 inconsistent with observations that show the life time of $>4P$ and no change in $P$,

Thus the observed growing oscillations or no damping oscillations are not due to the cooling effect.
4. Discussion

- This suggests that the wave energy in the loop is supplied continuously during the oscillations in our case, i.e. oscillations are forced by continuous, non-periodic driver (e.g. magnetic interaction caused by a CME) with energy input rate faster than damping rate contrast with the initial impulsive excitation suggested by the typical damping scenario of resonant absorption.

5. Conclusions

- For the first time observed clear amplitude-growing kink oscillations suggesting not impulsively generated but by continuous non-periodic driven

- Find the oscillating loop of multithermal strands showing different dynamic behaviors, which have not been studied before in theory and models

- Find the evidence for coupling and collective kink modes of multiple strands in a coronal loop