Oscillations and waves in coronal loops

Recent observations from SOHO and TRACE

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Thanks to: Sami K. Solanki
            Werner Curdt
            Davina E. Innes
Outline

1. Introduction

2. Standing waves
   a) Kink mode oscillations
   b) Slow mode oscillations

3. Propagating waves
   Slow magnetoacoustic waves

4. Summary and questions
Coronal Seismology: Loop Oscillations

- MHD oscillations in magnetic cylinder (Edwin & Roberts 1983; Robert et al. 1984)

- Expected oscillation periods in coronal loops
  - Slow modes: $P = 7 - 70$ min
  - Kink modes: $P = 1.4 - 14$ min
  - Sausage modes: $P = 0.1 - 5$ s
  (Aschwanden 2003)

- Coronal seismology ⇒ (Roberts, 1981; 1986)
  Diagnostic of physical parameters of coronal structure, e.g., magnetic field strength, dissipation coefficients, etc.
Sketches of oscillation modes

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

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

3) Torsional Alfvén modes:
   \[ \rho' = 0 \]
Three types of kink oscillations of a loop

1) Horizontal mode
2) Vertical mode
3) Distortion mode
Observations with SOHO and TRACE in EUV

1) **Standing kink-mode oscillations** — TRACE
   - Aschwanden et al. (1999)
   - Nakariakov et al. (1999)
   - Schrijver & Brown (2000)
   - Aschwanden et al. (2002)
   - Schrijver et al. (2002)
   - Verwichte et al. (2004)

2) **Standing slow-mode oscillations** — SOHO/SUMER
   - Kliem et al. (2002)
   - Wang et al. (2002)
   - Wang et al. (2003a)
   - Wang et al. (2003b)
   - Wang et al. (2005)

3) **Propagating slow mode waves** — SOHO/EIT and TRACE
   - Berghmans & Clette (1999)
   - De Moortel et al. (2000)
   - Robbrecht et al. (2001)
   - De Moortel et al. (2002a,b,c)
   - King et al. (2003)
   - Marsh et al. (2003)
Horizontal loop oscillations observed by TRACE

- Loop oscillations are triggered by a M-class flare (Aschwanden et al. 1999)

Transverse oscillations are excited by a flare blast wave indicated by initial motions away from the flare source

- 12/28 cases associated with metric type II bursts; 24/28 associated with CMEs (Hudson & Warmuth 2004)
• Physical parameters of the transverse oscillations


\[ P = 5.4 \pm 2.3 \text{ min} \quad T_{\text{decay}} = 9.7 \pm 6.4 \text{ min} \]

\[ A = 2.2 \pm 2.8 \text{ Mm} \quad V_{\text{max}} = 42 \pm 53 \text{ km/s} \]
Vertical oscillations of a coronal loop observed by TRACE

(a)-(b): simulated horizontal loop oscillation

(c)-(d): simulated vertical loop oscillation consistent with the observations

Period $P=4$ min,
Decay time $T_d=12$ min

Wave damping mechanisms

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

- **Resonant Absorption**
  (Goossens et al. 2002, A&AL) 1D MHD

- **Effect of loop curvature**
  (Van Doorsselaere et al. 2004, A&A) Theory
  (Brady & Arber 2005, A&A) 2D MHD
  (Selwa et al. 2005, A&A) 2D MHD
  (Murawski et al. 2005, A&A) 2D MHD
  (Miyagoshi et al. 2004, PASJ) 3D MHD
  (Del Zanna et al. 2005, A&A) 2.5D MHD

\[ T_D \sim P^{1.17\pm0.34} \]
\[ T_{PM} \sim P^{4/3} \]
Excitation of loop transverse oscillations

- **1D MHD modeling**
  (Terradas, Oliver & Ballester, 2005 ApJL) in a line-tied loop

- **2D MHD modeling**
  (Selwa et al. 2005, A&A) 2D MHD
  (Murawski et al. 2005, A&A) 2D MHD
  (Del Znna et al. 2005, A&A) 2.5D MHD

- **3D MHD modeling**
  (Miyagoshi et al. 2004, PASJ) 3D MHD

(A hot pulse in density and pressure)

(set an initial velocity at the loop top)
Standing Slow mode oscillations observed by SUMER

1) **Hot loop oscillations**

- **Periods:** $P = 14 – 18$ min
- **Decay time:** $T_d = 12 – 19$ min
- **Phase speed:** $V_p = 2L/P = 240 – 380$ km/s
- **Sound speed:** $C_s = 380$ km/s at $T = 6.3$ MK

2) Evidence for standing slow mode


Doppler shift time series in Fe XIX line

a) Doppler shift oscillations
   \( P = 17.6 \) min

Line intensity oscillations
   \( P = 17.1 \) min

b) 1/4-period phase difference between velocity and intensity
3) Overview of measured physical parameters

Comparison with TRACE result (Wang et al. 2003b, A&A)

- Period
  - $P = 17.6 \pm 5.4$ min

- Decay time
  - $T_d = 14.6 \pm 7.0$ min
  - ($T_d/P \sim 1$)

- Maximum Doppler velocity
  - $V_{\text{max}} = 75 \pm 53$ km/s

- Displacement amplitude
  - $A_{\text{max}} = 13 \pm 10$ Mm
4) Observation of oscillations at different parts of the loop

Oscillations are clearly seen at the apex of the loop, but not at the legs. This result supports the fundamental mode.
5) Measurements of coronal magnetic field strength

a) For a global standing kink mode,

\[ C_k = \frac{2L}{P}, \quad \text{and} \quad C_k = V_A \left( \frac{2}{1 + n_e/n_i} \right)^{\frac{1}{2}} \]


\[
B = 18 \left( \frac{L}{100 \text{ Mm}} \right) \left( \frac{P}{300 \text{ s}} \right)^{-1} \sqrt{\frac{n_{\text{loop}}}{10^9 \text{ cm}^{-3}}} [G].
\]

For loop length: 2L=200 Mm, osci. period: P = 5 min, in 26 coronal loops
loop density \( n_{\text{loop}} = 10^9 \text{ cm} \),

Obtain: mean: B = 18 G
range: B = 3 – 30 G

Aschwanden et al. (2002): B = 3 – 30 G for 26 cases

Nakariakov & Ofman (2001): B = 4 – 30 G for 2 cases
5) Measurements of coronal magnetic field strength

b) For a global standing slow mode,

\[ P = \frac{2L}{c_t}, \quad \text{and} \quad c_t = \left( \frac{1}{c_s^2} + \frac{1}{v_A^2} \right)^{-1/2} \]

\[ c_s = \left( \frac{\gamma k_B T}{\mu m_p} \right)^{1/2} = 1.52 \times 10^4 T^{1/2} \]

\[ V_A = \frac{B}{\sqrt{\mu \rho}} = 2.18 \times 10^{11} B n_e^{-1/2}. \]

For \( P = 17 \) min and \( L = 200 \) Mm, obtain \( C_t = 390 \) km/s.

Al12/Be119 filter ratio shows \( T \approx 8 \) MK, and \( n_e \approx 4 \times 10^9 \) cm\(^{-3}\), giving

\[ c_s = 430 \text{ km/s}, \quad V_A = 926 \text{ km/s} \]

\[ \Rightarrow B = 27 \text{ Gauss} \]
6) Initiation of oscillations: Spectral feature

26 out of 54 cases show the presence of two spectral components. The shifted components on the order of 100–300 km/s, suggesting that the oscillations are likely triggered by a pulse of hot plasma injection (Wang et al. 2005, A&A)
7) Trigger of hot loop oscillations by small or micro-flares

- Case on 2000 September 29 (Wang et al. 2003b, A&A)

Initiations of two recurring events are associated with a footpoint brightening
8) Cooling of hot oscillating loops

Intensity

Fe XIX (6.3 MK)
Fe XVII (2.8 MK)
Ca XIII (2.0 MK)
Ca X (0.7 MK)

Doppler shift

Fe XIX
Fe XVII

**Fe XIX**

**Fe XVII**

**Fe XIX**

**Fe XVII**

**Fe XIX**

**Fe XVII**
9) Propagating feature

Case on 11 Apr 2002  (Wang et al. 2003b, A&A)

Propagating speeds:  $V = 10 - 100$ km/s

Along the slit

Time  (observing cadence = 50 s)

In Fe XIX
10) Main properties of SUMER oscillations

1. Standing waves are set up quickly about a half period after the onset of events.

2. These oscillations are the fundamental mode; No evidence for the 2\textsuperscript{nd} harmonics are found yet.

3. Initial loop temperature is above 2–3 MK, then impulsively heated to a temperature of 6–8 MK.

4. The duration of flarelike brightenings is several times the oscillation period.

5. Except for strong initial injected flows lasting for about half a wave period, no background flow is present.
11) Wave damping mechanism

- Slow-mode standing oscillations
  - Thermal conduction 
    (De Moortel & Hood 2003, A&A)

- Gravitational stratification 
  cause 10–20% reduction of $T_d$

Pressure scale height $H=300–400$ Mm 
at $T=6–8$ MK

>> the height of typical coronal loops (with length $L=200$ Mm)
12) Excitation of slow-mode standidng waves

1) The second standing harmonics
of flaring loops (T=30-40 MK) are excited by impulsive energy deposit in the loop apex. (Nakariakov et al. 2004, A&AL)

2) The fundamental mode or the 2\textsuperscript{nd} harmonics
are excited depending on the location of the trigger (simulated as a hot pulse in density and pressure). Wave excitation time: > 3 periods (parametric study) (Selwa, Murawski, & Solanki 2005, A&A)

3) The fundamental mode oscillations
are set up immediately after an impulsive heat deposition at the footpoint of a loop if the duration of the pulse matches the fundamental mode period (Taroyan et al. 2005, A&A)
Quasi-periodic compressive waves

1) In solar polar plumes seen by EIT


period: $P = 10 - 15$ min,
propagating speed: $V = 75 - 150$ km/s
Quasi-periodic compressive waves

2) In coronal loops seen by EIT

(13 May 1998)

Berghmans & Clette (1999, Sol Phys.):

- Propagating speed $V = 75 - 125$ km/s
- Period $P = 10 - 15$ min

Time evolution of intensity along Loop E
Quasi-periodic compressive waves in coronal loops seen in EUV

- For 38 examples, (De Moortel et al. 2002, A&AL):
  1. 10 loops above Sunspots: $P=2.9 \pm 0.5$ min (3-min umbral osci)
  2. 25 loops above plage regions: $P=5.4 \pm 1.2$ min (5-min p-modes)

- Physical parameters: (De Moortel et al. 2002a,b)
  $$V_p=122 \pm 43 \text{ km/s}, \quad P=282 \pm 93 \text{ s}, \quad \text{amplitude} \, I/I_0=4.1 \pm 1.5\%$$
  Detected length of propagating disturbances $d=8.9 \pm 4.4 \text{ Mm}$
Damping of propagating slow magnetoacoustic waves

- Thermal conduction, enhanced compressive viscosity, and stratification (Nakariakov et al. 2000, De Moortel & Hood 2003)

- Effects of gravitational stratification and field line divergence on the damping scale along the loop (De Moortel et al. 2004, A&A)

- Coupling of slow and fast modes and "Phase mixing" of the slow waves due to the (horizontal) density inhomogeneity in 2D Model (De Moortel & Hood 2004, A&A; Voitenko et al. 2005, A&AL)

  1) Dissipation, pressure and temperature stratification are the most important effects in the low corona.
  2) To explain the observed damping, thermal conduction described by classic transport theory is sufficient, anomalous processes are not necessary.
Excitation of propagating slow magnetoacoustic waves

- Stable, long-term remaining, Not likely driven by flares (De Moortel et al. 2002a,b)

- Leakage of $p$-mode photospheric oscillations into the chromosphere and corona, due to the increase of the acoustic cut-off period in an inclined flux tube (De Pontieu et al. 2004, Nature) (De Pontieu, Erdelyi, & De Moortel, 2005 ApJL)

  The photospheric oscillations develop into shocks which drive chromospheric spicules and reach the corona, forming propagating magneto-acoustic waves observed by TRACE.

  However, because the model does not include the thermal conduction, whether the damping scale of the propagating coronal shocks in consistent with the observations are not verified.
Summary

1. TRACE has discovered transverse (horizontal and vertical) loop oscillations, and interpreted as a global kink mode. The exciter could be the flare shock.

2. SUMER has discovered slow-mode standing waves in hot (T>6MK) coronal loops. The trigger could be small flare-like events at a single footpoint.

3. EIT and TRACE have found propagating intensity oscillations in fan-like coronal loops, and interpreted as the propagating slow magneto-acoustic waves. The trigger may be the leakage of p-mode photospheric oscillations.

4. The observed kink and slow mode standing oscillations can be used as a new diagnostic tool for determining the mean magnetic field strength in coronal loops.

5. These oscillations are all strongly damped. The kink modes are most likely damped by phase mixing and resonant absorption, and the slow mode oscillations and waves are mainly damped by thermal conduction.
Outlook

**Solar-B and Solar Orbit:**

Detections of high-frequency fast mode (kink and sausage) and torsional Alfven waves and oscillations in coronal loops, which are believed to be important for coronal heating.