Slow Waves in Coronal Loops

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Outline

- Theoretical Basis
- Manifestation and Properties in Observations
- Theory and Modeling
- Coronal Seismology
- Discussion on Open Questions
- Summary and Perspectives
1. Theoretical Basis for Identification in Observation

- Thin magnetic cylinder model
  (Edwin & Roberts 1983; Robert et al. 1984)

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

- Slow standing (sausage body) mode

  \( B' > 0, \rho' < 0 \)
  \( V_r \ll V_z \)
  Weak dispersion
  \( V_p = \frac{\omega}{k} = C_T = \frac{C_A C_0}{\sqrt{C_A^2 + C_0^2}} \)

  In low-\( \beta \) limit
  i.e. \( C_0 \ll C_A \)

  No dispersion
  \( C_T \approx C_0 \sim \sqrt{T} \)

  \( T = 10 \text{ MK} \)
  \( L = 20 \text{ Mm (short postflare loop)} \)
  \( P = 2L/C_0 = 1.4 \text{ min} \)

  \( L = 200 \text{ Mm (large flaring loop)} \)
  \( P = 14 \text{ min} \)
Mode Identification based on Forward Modeling

Yuan et al. (2015)

Synthetic SUMER Fe XIX (1118 Å)

LOS

Taroyan et al. (2008)

1D HD simulations

Synthetic Hinode/EIS 40” slot (imaging) obs.

Fe XII 195

Fe XI 188

Fe X 190
2. Manifestation and Properties of Slow Waves in different Observations

- Light curves of flux in SXR, HXR, radio
- Spectral observations in UV/EUV
- Imaging observations in EUV, SXR, (visible light)

### Wave properties
- Periods
- Amplitudes
- Decay times
- Trigger or exciter

### Plasma properties:
- Velocity of flow injections
- Plasma density
- Electron temperature

### Loop geometry:
- Length
- Width
- 3D orientation
2.1 Longer-period QPPs in light curves

Early Evidence for standing slow waves

- Long period, QPPs, \( P \approx 20 \ \text{min} \) often associated with (or at the footpoint of) giant flaring arches (Svestka et al. 1982, 1989; Harrison 1987)
- Loop length, \( L = 200 – 300 \ \text{Mm} \)
- Svestka (1994) suggested their source is fundamental standing slow waves
  \( \Rightarrow T = 5-10 \ \text{MK} \) from \( P = 2L/C_s \)
2.1 longer-period QPPs in light curves

- Harrison (1987) interpreted these QPPs by a standing wave or a traveling wave packet in terms of fast or Alfven MHD modes or kink waves considering a rapid damping of slow waves and a long existence of QPPs (up to 4-6 hrs).
- He also argued that the energy to power X-ray QPPs is not directly from the waves because no expected degradation of these bursts is observed.

Recent progresses in observations:

- Review of QPPs (Ivan Zimovets; Today)
- QPPs with IRIS (talk by Dong Li on Tue)
- Solar and Stellar QPPs (talk by Il-Hyun Cho on Wed)
- Solar QPPs (Yingyao Chen on Wed)
- Solar QPPs (Qingmin Zhang on Wed)
- Solar QPPs (Ding Yuan on Wed)

Modeling of solar and stellar QPPs

- talk by James McLaughlin on Tue
- talk by Fabio Reale on Wed
2.2 Properties for Slow Waves in UV/EUV spectra

SOHO/SUMER observations

- Two recurring events in Fe XIX, showing Doppler shift oscillations

Wang et al. (2002)

- Oscillations only seen in hot plasma at T>6 MK
- P=7 – 31 min
- \(T_d/P \sim 1\)

\[
\begin{align*}
\text{Si III} & : 1113 \text{ A} & \text{Ca X} & : 557 \times 2 \text{ A} & \text{Ne VI} & : 1117 \text{ A} & \text{Fe XIX} & : 1118 \text{ A} \\
0.03-0.06 \text{ MK} & & 0.7 \text{ MK} & & 0.3 \text{ MK} & & 6.3 \text{ MK}
\end{align*}
\]
2.2 Properties for Slow Waves in UV/EUV spectra

SOHO/SUMER observations (Wang et al. 2003a)

- Doppler shift in Fe XIX
- Intensity oscillations in Fe XIX associated with M 1.2 flare

Evidence for fundamental standing slow-mode waves

- Phase speed close to sound speed
- ¼-period phase shift between V and I

Trigger with initial flows of 100-300 km/s
### 2.2 Properties for Slow Waves in UV/EUV spectra

**SOHO/SUMER observations**

(Wang et al. 2006)

- 55 events occurred within 10 hours; about half associated with oscillations
- Recurrent rate ~ 2-3 events/hr
2.2 Properties for Slow Waves in UV/EUV spectra

Hinode/EIS observations (Mariska et al. 2008, 2010; Tian et al. 2012)

- Low-amplitude Doppler shift and intensity oscillations in Fe XI – Fe XV
  - $T = 1 – 2$ MK
  - $P = 10$ min in 7-14 min
  - Weak or no decay
  - $A_v = 1-2$ km/s, $A_I = 1-2\%$

- Evidence for standing or (upwardly) propagating slow waves

- Wave sources: suggested to be quasi-periodic impulsive heating

- Reason for dependence of amplitudes on $T$ is unclear
2.3 Properties for Slow Waves in Imaging Observations
Longitudinal oscillations with SDO/AIA

Kumar et al. (2013)

- $P=10.6$ min,
- $T_d=7.3$ min,
- $L=158$ Mm,
- $V_p = 2L/P = 460-510$ km/s
- For $T=8 – 10$ MK
- $C_s=152\ T^{1/2} = 430-480$ km/s

Interpretation:
- Reflected propagating slow waves

Event Trigger:
- a C-class flare at one footpoint of a coronal loop
2.3 Properties for Slow Waves in Imaging Observations

Longitudinal oscillations with SDO/AIA

Wang et al. (2015)

- Phase speed agree with sound speed
  
  $L=180$ Mm and $P=12$ min
  
  $V_{ph}=2L/P \sim 470 \text{ km/s}$
  
  $Cs=480 \text{ km/s}$ at $T=10 \text{ MK}$

- Tempo-spatial features: matching standing slow-mode waves

(Yuan et al. 2015)

(Ofman, Wang, Davila 2012)
2.3 Properties for Slow Waves in Imaging Observations
Longitudinal oscillations with SDO/AIA

Flare emission features:
• circular ribbons with a remote brightening,
• suggest magnetic reconnections in a fan-spine topology with a null point near one footpoint.

Wang et al. (2015)

Toy model for a confined flare (Sun et al 2013)
2.3 Properties for Slow Waves in Imaging Observations

Reflecting propagating slow waves with Hinode/XRT

Mandal et al. (2015)

Two events with Hinode/XRT

Features:
- Find 4 cases of a propagating and reflecting intensity disturbance in hot ($T \sim 10$ MK) loops with XRT and AIA
- $V_p < \sim C_s$ supports prop. slow waves
- Triggered by microflare at a footpoint

The event simultaneously observed with Hinode/XRT and SDO/AIA
3. Theory and Modeling

3.1 MHD simulations of the flare-induced slow-mode waves

- Transition from initial propagating wave to standing wave
- Immediate formation of standing modes
- Formation of only reflecting propagating waves

3.2 Analytical and numerical studies of damping mechanisms

- Linear theories
- Nonlinear theories
- Numerical simulations
3.1 Modeling slow magnetoacoustic waves:

- Intermittent loop oscillations by random impulsive heating (Mendoza-Briceno & Erdelyi 2006)

\[ H(s, t) = h_0 + H_0 \sum_{i=1}^{n} u(t - \tau_i) \exp[-\alpha(t - \tau_i)] \]
\[ \times \left\{ \lambda_{l,i} \exp \left[ -\frac{(s-s_{l,i})^2}{\sigma^2} \right] + \lambda_{r,i} \exp \left[ -\frac{(s-s_{r,i})^2}{\sigma^2} \right] \right\} \]

Model setup:
- 1D HD model with gravitational stratification, optical thin radiation loss, heat conduction, heat func
- Heating randomly distributed in time and space near two footpoints
- Each pulse has total Energy \( E_{\text{tot}} \sim 10^{25} \text{ ergs} \);
  \( 20 \text{ s} < \tau_i < 190 \text{ s} \);
  \( L=10 \text{ Mm} \);
  \( \Delta L/L=0.1 \)

Results:
- Standing slow waves with \( P=150-220 \text{ s} \), \( 500-600 \text{ s} \), and \( 800-1000 \text{ s} \) likely by interference
- Provide a possible mechanism for generation of weakly or un-decaying slow waves observed with Hinode/EIS
3.1 Modeling slow magnetoacoustic waves:

- Simulations of standing waves with 2D slab of a straight or curved geometry (Ogrodowczyk & Murawski 2007; Ogrodowczyk et al. 2009)

**Slab models:**
- Ideal MHD
- \( d = \rho_i / \rho_e = 3 \)
- \( \rho = \text{const.} \)
- So \( T_i / T_e = 1/3 \) (cool loop!)

**Main results:**
- In a straight slab the fundamental standing mode sets up at \( t_{ex} \sim 4P \) for an initial pulse
- In a curved slab, \( t_{ex} \sim 2.5P \)
- Excitation time and damping time shorter than 1D case due to wave leakage
3.1 Modeling slow magnetoacoustic waves:

- Simulation of standing waves with a resistive, nonlinear, gravitational, isothermal 3D MHD model (Ofman, Wang, & Davila 2012)
  - Triggered by impulsive onset of a steady flow at a footpoint
  - A standing wave forms as indicated by a $\pi/4$ phase shift
  - Strong damping due to wave leakage into the corona
3.1 Modeling slow magnetoacoustic waves:

- Forward modeling of reflective propagating slow-mode waves in a flaring loop (Fang et al. 2015; Mandal et al. 2016)

Model setup:

- 2.5 D MHD model including gravity, anisotropic thermal conduction, radiative cooling, and heating term, initially in LFFF configuration
- Trigger by an impulsive heating with a total duration $t_{\text{dur}} = 180\text{s}$ at $h = 0.3\text{ Mm}$ above TR as footpoint heating.

Results:

- Paths of virtual particle propagating at local sound speed supports the propagating waves
- Synthetic AIA 131 and 94 intensity show QPPs with large amplitudes but not damped sine-func
3.1 Modeling slow magnetoacoustic waves:

- Simulations of standing slow waves using nonlinear 1D model with seismology-determined transport coefficients (Wang et al. 2018, 2019)

Model 1 with $k_0$ and $\eta_0$

Model 2 with $k_0=0$ and $15\eta_0$
3.1 Modeling slow magnetoacoustic waves:

- Simulations of standing slow waves using nonlinear 1D model with seismology-determined transport coefficients (Wang et al. 2018)

Model 1 with $k_0$ and $\eta_0$

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3.1 Modeling slow magnetoacoustic waves:

- Simulations of standing slow waves using nonlinear 1D model with seismology-determined transport coefficients (Wang et al. 2018)

- Dissipation of higher harmonics

- Fourier Decomposition analysis

Simulations with initial condition

\[ V(x, t=0) = V_0 \sin(\pi k x / L) \]

where \( k = 1, 2, 3, \ldots, 6 \)

Model 1: with \( k_0 \) and \( \eta_0 \)

\[ \tau \propto P \]

Model 2: with \( k_0 = 0 \) and \( 15\eta_0 \)

\[ \tau \propto P^2 \]
3.2 Analytical and numerical studies of damping mechanisms

- **Linear theories**
  - Thermal conduction ($k_{//}$) [e.g. De Moortel & Hood 2003]
  - Compressive viscosity ($\eta$) [e.g. Sigalotti et al. 2007]
  - Optical thin radiation loss ($Q(T)$) [e.g. Pandey & Dwivedi 2006]
  - Gravitational stratification ($H$) [e.g. Sigalotti et al. 2007]
  - Cooling background ($T_0(t)$) [e.g. Al-Ghafri & Erdelyi 2013]
  - Wave-caused heating/cooling imbalance ($Q_p+Q_T$) [e.g. Kumar et al. 2016]

- **Nonlinear theories**
  - $k_{//} + \eta$ [e.g. Ruderman 2013]
  - $k_{//} + \eta + (Q_p+Q_T)$ [e.g. Kumar et al. 2016]

- **Numerical simulations**
  - Linear MHD
    - $k_{//} + \eta + H$ [Sigalotti et al. 2007]
  - Nonlinear MHD
    - $k_{//} + \eta$ [e.g. Ofman & Wang 2002]
    - $k_{//} + \text{shock dissipation}$ [Verwichte et al. 2008]
    - $k_{//} + \eta + H$ [e.g. Mendoza-Briceno et al. 2004]
    - $k_{//} + \eta + H + \text{Temperature-stratification}$ [e.g. Erdelyi et al. 2008]
    - $k_{//} + H + \text{Non-equilibrium ionization}$ [Bradshaw & Erdelyi 2008]
    - Ideal MHD + 2D slab [e.g. Orgrodowczyk & Murawski 2007]
3.2 Analytical and numerical studies of damping mechanisms

- **Linear theories:**

  - **Thermal conduction** ($k_{//}$)

  \[
  \omega^3 - i\omega^2\gamma dk^2 - \omega k^2 + idk^4 = 0. \\
  \text{exp}(\omega t - kz) \\
  (\omega, k, d \text{ are dimensionless})
  \]

  \[
  \frac{1}{d} = \frac{(\gamma - 1)k_{//}T_0\rho_0}{\gamma^2 p_0^2 \tau_s} = \frac{1}{\gamma \tau_{\text{cond}}},
  \]

  - **Lower conduction limit** ($d\omega \ll 1$)
    (for low $\omega$ or long $L$)

  \[
  k = \frac{\omega}{c_s} - i\frac{\omega^2}{2c_s} (\gamma - 1) \quad \rightarrow \quad \tau \propto P^2 \\
  \left(\frac{\tau}{P}\right) \propto P \sim 1/\omega
  \]

  - **Higher conduction limit** ($d\omega \gg 1$)
    (for high $\omega$ or short $L$)

  \[
  k = \gamma^{1/2} \frac{\omega}{c_s} - i\frac{\gamma - 1}{2d \gamma^{3/2} c_s} \quad \rightarrow \quad \tau \propto P^0 \\
  \left(\frac{\tau}{P}\right) \propto P^{-1}
  \]

  Here $\omega d = 2\pi d$ if take $\tau_s = P$

  De Moortel & Hood (2003)

  Krishna Prasad et al. (2014)
3.2 Analytical and numerical studies of damping mechanisms

- Linear theories: Compressive viscosity ($\eta$)

**Sigalotti et al. (2007)**

$$P = \tau_s \left(1 - \frac{16\pi^2\varepsilon^2}{9}\right)^{-1/2}$$

$$\tau_d = \frac{3}{8\pi^2\varepsilon} \tau_s$$

$$\varepsilon = \frac{\eta}{\rho L C_s}$$

$$\tau_d \approx \left(\frac{3\rho_0 C_s^2}{8\pi^2\eta}\right) P^2$$

when $\varepsilon \ll 1$

**Ofman & Wang (2002)**

- For aL=400 Mm, T=8 MK, n=1.5e9 cm$^{-3}$
  - $\tau_s = L/C_s = 14$ min for 2$^{nd}$ harmonic
  - (or for a loop of L=200 Mm for 1$^{st}$ harmonic)
  - $d=0.07 < 0.1$ and $\varepsilon=0.004$

$$\frac{\tau_{\text{cond}}}{P} \approx 1$$

$$\frac{\tau_{\text{visc}}}{P} \approx 10$$

- In weak dissipation approx. (i.e. $d \ll 0.1$) (Ruderman 2013)

$$\tau_{\text{visc}} \approx \eta P$$

$$t_{\text{dl}} = \frac{2\gamma L^2}{\pi^2[\gamma\nu + (\gamma - 1)k]}$$

$$\nu = \frac{4\eta_0}{3\rho}, \quad \kappa = \frac{(\gamma - 1)mk_{\parallel}}{\rho k_B}$$

$$\frac{\tau_{\text{visc}}}{\tau_{\text{cond}}} = \frac{(\gamma - 1)\kappa}{\gamma\nu} \approx 19$$

In the case with classical $k_{\parallel}$ and $\eta_0$, $d \ll 0.1$ is a sufficient condition for $\tau_{\text{cond}} \ll \tau_{\text{visc}}$
3.2 Analytical and numerical studies of damping mechanisms

- Linear theories: conduction ($k_{//}$) + viscosity ($\eta$)

Sigalotti et al. (2007)

- Assumption of $p_0 = 0.55$ dyn/cm$^2$ = const
  For $T=6.3, 8.0, 10$ MK, giving $N=[3.0, 2.5, 2.0] \times 10^8$ cm$^{-3}$
  \[
  d = \frac{(\gamma - 1)k_{//}T_0\rho_0}{\gamma^2p_0^2P} \approx 4.1\left(\frac{T_0^{3/2}}{n_0P}\right)
  \]
  \[
  \varepsilon = \frac{\eta}{\rho Lc_s},
  \]
- $\varepsilon$ decrease with $T$
- $\tau$ increase with $T$

\[
\begin{align*}
T=6.3 \text{ MK, } L=50-400 \text{ Mm} &\Rightarrow d = 2.4 - 0.3, \quad \varepsilon = 0.08 - 0.01 \\
T=8.0 \text{ MK, } L=50-400 \text{ Mm} &\Rightarrow d = 4.9 - 0.6, \quad \varepsilon = 0.16 - 0.02 \\
T=10 \text{ MK, } L=50-400 \text{ Mm} &\Rightarrow d = 9.6 - 1.2, \quad \varepsilon = 0.32 - 0.04
\end{align*}
\]

$\varepsilon \sim 10 \varepsilon_0$

$d > 0.1$ for all cases

Solid, long-dashed, short-dashed for $T=6.3, 8, 10$ MK

Graphs showing $\tau$ decrease with $T$ and $\tau$ increase with $T$.
3.2 Analytical and numerical studies of damping mechanisms

- Interpretation of $\tau \propto P$ by linear theory with conduction ($k_{//}$) + viscosity ($\eta$)

- For best fitting scaling $\tau \propto P^{\alpha}$
  - $\alpha = 0.09$ for conduction
  - $\alpha = 2.0$ for viscosity
  - $\alpha = 1.09$ for conduction + viscosity
  - $\alpha = 1.10$ for nonlinear HD simulations

- For $L = 180$ Mm, $T = 9$ MK, $n = 2.6e9$ cm$^{-3}$
  - $d = 0.06 < 0.1$ and $\varepsilon = 0.003$
  - $\tau_{\text{cond}} / P \approx 1$ and $\tau_{\text{visc}} / P \approx 13$

(wang et al. 2015)

Sigalotti et al. (2007)
3.2 Analytical and numerical studies of damping mechanisms

- **Linear theories:** Optically thin radiation loss

\[
Q(T) = \frac{\chi}{m^2 p} T^\alpha,
\]

\[
H(s, 0) = \rho^2 Q(T),
\]

\[
r = \frac{\tau_s}{\tau_{rad}} = \frac{(\gamma - 1)\rho^2 \tau_s Q}{\gamma p}
\]

\[
\omega \approx 2\pi + i \frac{r}{2} [2 + \alpha(\gamma - 1)]
\]

- **Radiation damping is negligible in hot loops**

  - \(r=1.1e-4 \rightarrow 9.4e-4\) for \(L=50 \rightarrow 400\) Mm, \(T=6.3\) MK, \(N=3e8\) cm\(^{-3}\)
  - \(r=5.1e-5 \rightarrow 4.1e-4\) for \(L=50 \rightarrow 400\) Mm, \(T=8\) MK, \(N=2.5e8\) cm\(^{-3}\)
  - \(r=2.4e-5 \rightarrow 1.9e-4\) for \(L=50 \rightarrow 400\) Mm, \(T=10\) MK, \(N=2e8\) cm\(^{-3}\)

- **Strong damping** \((\tau/P \sim 1)\) occurs at \(N=10^8 \rightarrow 10^9\) cm\(^{-3}\)

- **Weak damping** \((\tau/P > 2)\) occurs at \(N=10^9 \rightarrow 10^{10}\) cm\(^{-3}\)

- Radiation reduces \(\tau\) by up to 20% in weak damping case

Sigalotti et al. (2007)
3.2 Analytical and numerical studies of damping mechanisms

- **Viscosity + Gravitational stratification**

\[ \tau_d = \frac{3\tau_s}{\varepsilon \left(8\pi^2 - \frac{1}{\mathcal{H}_0^2}\right)} \]

\[ \mathcal{H} = -\left(\frac{1}{\rho} \frac{d\rho}{ds}\right)^{-1} = -\frac{p}{\rho g(s)} \]

- In linear case
  Stratification increases damping time due to viscosity by 1-2% for large loop (L=400 Mm) compared to nonstratified case.
  The effect is negligible for short loops.

- Nonlinearity effect  \textit{Sigalotti et al. (2007)}

  For T=6.3 MK, L=50 – 400 Mm => \( \tau_{g=0} = 1.0 – 34.8 \) min
  \( \tau_{g\neq0} = 1.0 – 32.0 \) min

  For T=8 MK, L=50 – 400 Mm => \( \tau_{g=0} = 0.4 – 23.3 \) min
  \( \tau_{g\neq0} = 0.4 – 20.5 \) min

  For T=10 MK, L=50 – 400 Mm => \( \tau_{g=0} = 0.8 – 12.1 \) min
  \( \tau_{g\neq0} = 0.8 – 10.5 \) min

- In stratified loops
  nonlinearity causes a reduction by 3-13% of damping time compared to nonstratified loops

\[ H \approx 50 \ (T/MK) \ Mm \]

So \( H \approx 500 \ Mm \) for \( T=10 \ Mm \)
3.2 Analytical and numerical studies of damping mechanisms

- Nonlinear theories: conduction \((k_{//})\) + viscosity \((\eta)\)

Verwichte et al. (2008)

- Solution of standing slow mode in first-order approx.
  \[
  \xi = \omega \left(t - \frac{x}{c_s}\right), \quad \eta = \omega \left(t + \frac{x}{c_s}\right),
  \]
  \[
  \omega = \pi c_s / L.
  \]
  \[
  u_1 = c_s [f(\xi) - f(\eta)]
  \]

  \(u_1 = 0\) at \(x = 0, L\)

Ruderman (2013)

- Evolution of weakly-dissipative, nonlinear slow wave - Burgers equation
  \[
  \frac{\partial f}{\partial \tau} - 2\lambda f \frac{\partial f}{\partial y} - \frac{\partial^2 f}{\partial y^2} = 0,
  \]
  where \(\tau = t / t_{dl}\),

\[
  t_{dl} = \frac{2\gamma L^2}{\pi^2 [\gamma \nu + (\gamma - 1) \kappa]}, \quad \lambda = \frac{\varepsilon \gamma (\gamma + 1) c_s L}{2\pi [\gamma \nu + (\gamma - 1) \kappa]}
  \]
3.2 Analytical and numerical studies of damping mechanisms

- Nonlinear theories: conduction ($k_{//}$) + viscosity ($\eta$)

Ruderman (2013)

$$u = 2\epsilon c_s \sin \frac{\pi x}{L}, \quad \rho = \rho_0, \quad p = p_0, \quad T = T_0 \text{ at } t = 0.$$  

Initial velocity amplitude $V_0 = 0.2 C_s$

$$\tau_d = \frac{t_d}{t_{dl}}$$  (ratio of damping times between nonlinear and linear cases)

From $\tau_d < \approx 0.9$ when $\lambda > \approx 1$

obtain that nonlinearity effect becomes important for $V_0/Cs > 0.2$
3.2 Analytical and numerical studies of damping mechanisms

- Nonlinear theories: conduction ($k_{//}$) + viscosity ($\eta$)

Case 1: $k_{//} + \eta_0$

Case 2: $\frac{1}{3} k_{//} + \eta_0$

Nonlinear simulations for cases $V_0 = 0.23$ Cs

(Wang & Ofman 2019)
4. Application of Coronal Seismology

• Determination of magnetic field strength
  (Wang et al. 2017; Jess et al. 2015)
• Longitudinal structuring
  (Srivastava & Dwivedi 2010; Srivastava et al. 2013)
• Polytropic index
  (Van Doorsselaere et al. 2011; Wang et al. 2015;
  Krishna Prasad et al. 2018)
• Transport coefficients
  (Wang et al. 2015, 2018, 2019)
• Heating function
  (Taroyan et al. 2007; Reale 2016; Reale et al. 2018;
  Kolotkov et al. 2019)
4. Application of Coronal Seismology

- Forward modeling of standing slow waves in a flaring hot loop observed with SOHO/SUMER (Taroyan et al. 2005, 2007)

- Observations

  ![Fe XIX Doppler shift](image1)

  ![Line-integrated intensity](image2)

- 1D HD model with gravity, thermal conduction, heating terms and Chr and TR

- Determination of heating rate in time and space

- Rapid formation of the fundamental standing waves by a footpoint microflare

- Explain the absence of intensity oscillations

- Impulsive heating at a footpoint with $t_{dur} \sim P = \frac{2L}{C_s}$
4. Application of Coronal Seismology

- Evidence for thermal conduction suppression (Wang et al. 2015)

- Linear MHD theory with Spitzer thermal conduction (Van Doorsselaere et al. 2011):

\[
\tan \Delta \phi = \frac{\mu m_p \pi (\gamma - 1) \kappa_0}{\gamma k_B} \left( \frac{T^{3/2}}{nP} \right)
\]

\[
(\gamma - 1) \cos \Delta \phi = \alpha - 1
\]

- Measurement of the polytropic index

\[
\frac{T'}{T_0} = (\alpha - 1) \frac{n'}{n_0},
\]

\[
\alpha = 1.64 \pm 0.08
\]

The slow waves propagate in the approximate adiabatic process or suppression of conduction.
4. Application of Coronal Seismology

- Implication of largely enhance compressive viscosity (Wang et al. 2015)

\[
\frac{\partial^2 v'}{\partial t^2} - \frac{\partial^2 v'}{\partial s^2} = \frac{4}{3} \varepsilon \frac{\partial}{\partial t} \left( \frac{\partial^2 v'}{\partial s^2} \right)
\]

\[
\omega^2 - i \frac{4}{3} \varepsilon k^2 \omega - k^2 = 0
\]

\[
P = \tau_s \left( 1 - \frac{16\pi^2 \varepsilon^2}{9} \right)^{-1/2}
\]

\[
\tau_d = \frac{3 \tau_s}{(8\pi^2 \varepsilon)}
\]

\[
\varepsilon = \frac{\eta}{\rho c_s^2 \tau_s} \text{ and } \tau_s = 2L/C_s
\]

\[
\eta = \frac{0.72(m_p k_B^5)^{1/2}}{\pi^{1/2} \varepsilon^4 \ln \lambda} T^{5/2} = \bar{\eta} T^{5/2}
\]

\[
\eta = \frac{3 \rho c_s^2 \tau_d}{8\pi^2 (\tau_d / P)^2 + 2}
\]

For the measured parameters:

- \(P_{\text{obs}} = 12 \text{ min}, \ \tau_{d,\text{obs}} = 9.2 \text{ min}\)
- \(T = 8.7 \text{ MK}, \ \text{and} \ n = 2.6 \times 10^9 \text{ cm}^{-3}\)

\(\eta_{\text{eff}} = 360 \text{ g cm s}^{-1}\)

\(\eta_0 = 23 \text{ g cm s}^{-1}\)

\(\chi = \frac{\eta_{\text{eff}}}{\eta_0} \approx 15\)

classical Braginskii viscosity for protons
4. Application of Coronal Seismology

- Determination of transport coefficients by parametric simulations based on nonlinear 1D HD model (Wang et al. 2019)

Two-step scheme:
- Determine the thermal conduction coefficient from observed phase shift between N1 and T1
- Determine the viscosity coefficient from observed damping times based on the model with the thermal conduction determined in Step-1
5. Discussion on Open Questions

- Can QPPs be directly generated by slow magnetoacoustic waves considering their physical properties from imaging observation? (e.g. strong damping)

- Are these slow-mode oscillations of flaring loops observed with SOHO/SUMER, SDO/AIA, and Hinode/XRT the same phenomena considering their trigger sources and wave properties? (microflares and flares, standing or reflecting propagating waves)

- What is the main factor that determines whether a standing mode or a reflecting propagating mode generated in a flaring coronal loop? (e.g. transport coefficients, nonlinearity effect, wave leakage)

- Can slow-mode QPPs, standing waves, and reflecting propagating waves be interpreted in a unified model or picture?

- What are the effects of transverse N- and T-structuring on wave excitation and damping? (e.g. hot loops pre-existing in SUMER but absent in AIA; these flaring loops typically wider of width $\approx 10 \text{ Mm}$)
6. Summary and Perspectives

• Slow-mode QPPs need to identify and be understood by coordinated imaging observations (to find location of sources and associated coronal structure)

• Statistic study of SDO/AIA and Hinode/XRT longitudinal oscillations including large samples need to be done (to quantify wave and plasma properties)

• More reliable inverse method (to derive N and T) and more realistic forward modeling (considering real 3D geometry) need to be developed

• Comprehensive 3D MHD simulations based on real magnetic configuration and in an inhomogeneous atmosphere including the chromosphere and TR, with full energy equation including various non-ideal processes

• New observations from new instruments (e.g. DKIST, Solar Orbit, new-generation EUV and X-ray spectroscopic imaging telescopes)