MHD Seismology of Solar Corona Through the Observed MHD Waves: Current and Future Aspects

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Wave and Oscillations in the Solar Corona

• Observational evidence of coronal oscillations is abundant (major contribution by SOHO, TRACE, NoRH, and recently HINODE, STEREO & SDO).

• Possible relevance to coronal heating and solar wind acceleration problems.

• Plasma diagnostics by MHD Seismology.

Coronal thin tubes of low plasma beta where magnetic force can dominate!

Perturbations of magnetic field, density, and finally in velocity field can lead the variety of MHD modes!

MHD seismology can diagnose the crucial plasma conditions based on the detected MHD modes as well as its inversion on theory!
Basic theory: Dispersion relations of MHD modes of a magnetic flux tube:

Magnetohydrodynamic (MHD) equations →
Equilibrium →
Linearization →
Boundary conditions

Theory established more than two decades ago!!!

Zaitsev & Stepanov, 1975; Uchida, 1978; B. Roberts and colleagues, 1981
Main MHD modes of coronal structures:

- **sausage** ($|B|, \rho$)
- **kink** (almost incompressible)
- **torsional** (incompressible)
- **acoustic** ($\rho, V$)
Oscillations of magnetic flux tube

\[ C_T = C_S V_A (C_S^2 + V_A^2)^{-1/2} \]

\[ V_A = B / (4\pi \rho)^{1/2} \]

Compressible

Incompressible

Magnetic and thermal pressure

Longitudinal (Sausage)

Transverse (Kink)

Torsional (Alfvén)

Magnetic curvature force (tension)
Transverse and Longitudinal View of Fundamental Mode Kink Oscillations in A Cylindrical Fluxtube

Credit: Erwin Verwichte, Univ of Warwick, U.K.

Indo-UK Seminar 21-23 January 2013, IIA, India
Fundamental Sausage Mode: A Longitudinal View

Higher Fluting Mode: A Transverse View

Credit: Erwin Verwiche, Univ. of Warwick, U.K.
The theory of the magnetic field estimation is based on certain approximation even in terms of fetched observational quantities: (i) Density inside the loop is uniform; (ii) Density contrast is uniform!!

Recently Von Doersaelere et al. (2008) could measure the B with 10% uncertainty, while they estimated the loop density with uncertainty of 5%!!

Question arises that how to go beyond EIS accuracy of density measurement to constrain more accurate B?

Secondly, how to constrain the exact loop morphology in imaging? Apart from STEREO (Aschwanden’s method), we do not have any method to triangulate the loops?!!!!

Kink wave is assumed to excite in a thin, uniform, and straight cylindrical tube (width is much smaller than length) as well as the $ka<<1$.

Kink speed is derived depending upon the density ratio, and Alfvén speed!!

Do all coronal structures, where kink waves are excited, exactly follow the approximations? If not, then how to apply these seismology aspects?
2. Seismology of the Coronal Loops based on the observations of multiple harmonics of kink waves

<table>
<thead>
<tr>
<th>Source</th>
<th>$P_1$ (s)</th>
<th>$P_2$ (s)</th>
<th>$P_4$ or 5 (s)</th>
<th>$P_1/(2P_2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verwichte et al. (2004)</td>
<td>448 ± 16</td>
<td>247 ± 6</td>
<td></td>
<td>0.91 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>387 ± 8</td>
<td>245 ± 8</td>
<td></td>
<td>0.79 ± 0.03</td>
</tr>
<tr>
<td>De Moortel and Brady (2007)$^b$</td>
<td>(1038–2484)</td>
<td>577–672</td>
<td>250–346</td>
<td></td>
</tr>
<tr>
<td>Van Doorsselaere et al. (2007)</td>
<td>436 ± 5</td>
<td>243 ± 7</td>
<td></td>
<td>0.90 ± 0.03</td>
</tr>
<tr>
<td>O’Shea et al. (2007)$^a$</td>
<td>448</td>
<td>224</td>
<td></td>
<td>(1)$^a,c$</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>164</td>
<td></td>
<td>(1.2)$^a,c$</td>
</tr>
<tr>
<td></td>
<td>476</td>
<td>198</td>
<td></td>
<td>(1.2)$^a,c$</td>
</tr>
<tr>
<td>Verth et al. (2008)</td>
<td>242</td>
<td>157</td>
<td></td>
<td>(0.77)$^c$</td>
</tr>
</tbody>
</table>

$^a$ The identification as a kink mode is uncertain.
$^b$ The mode identification is uncertain.
$^c$ Due to uncorrected magnetic polarity.
Density Stratification can lead the shift of period ration ($P_1/P_2 < 2.0$)

\[ \frac{P_1}{2P_2} = 1 - \frac{1}{\pi^2} \frac{L}{\Lambda_c} + \left( \frac{2}{\pi^4} - \frac{5}{32\pi^2} \right) \left( \frac{L}{\Lambda_c} \right)^2, \quad L \ll \pi \Lambda_c. \]

In spatial seismology, the antinodes of first overtone shifts towards loop’s footpoint in case of longitudinal density structuring.

See also the reference of Erdelyi and Verth 2008, McEwan et al., 2006

For details, please see Andries et al., 2009
Magnetic Stratification can lead the shift of period ratio (P1/P2) > 2.0 in spatial seismology, the antinodes of the first overtone shifts towards loop's apex in case of magnetic field expansion and constant density.

Theory is nice, however, how to measure the shift in the antinodes of the first harmonics in the imaging when we observe multiple harmonics of transversal displacement of loop axis.

Is the best current resolution of SDO/AIA allowing this?

Naturally, even during the flare, the fundamental mode is directly observed in maximum cases in the loops.

How to increase the statistics? Should we need the more powerful flares?!

Excitation depends upon extent and properties of the driver as well as on the nature of interaction!

Again, the simplification in the geometry as well as the thin-tube approximation!!
Does the MHD seismology through the thin-tube approximation work everywhere in corona?

Study of Vertical Kink Oscillations in a Plasma Curtain

Vertical Oscillations of the Plasma Curtain
Power spectra of the vertical oscillations in the plasma curtain
Consequences:

[1] There are only few observations of vertical kink oscillations in solar corona (three genuine reports in 2004, 2006, and 2012). We firstly claim the observations of vertical kink oscillations generated in a large-scale diffused plasma curtain.

[3] However, likewise other previous reports, and in matching with the thin flux-tube theory of such waves, the situation is more puzzling as we do not have the information of any distinct fluxtube and rather the collective motion is observed over a wide spatial scale.

[4] Let we concentrate on our observations. Deeper layer oscillates and thereafter vanished out. The decay is not a nice 1/e decay as observed previously.

Moreover, not-decaying transverse motions are appeared at the surface where thin resonance layer can be formed that can transform radial $\rightarrow$ more azimuthal oscillations $\rightarrow$

RARE OBSERVATIONAL CLUES OF RESONANT ABSOPRTION !!!!!!!
Signature of Slow Acoustic Oscillations in a Non-flaring Loop observed by EIS/Hinode (Srivastava and Dwivedi, 2010): Example of MHD Seismology by Multiple Slow Acoustic Oscillations

Observational Parameters:
- 40” Slot, Sit n Stare
- Date: 8th May 2008
- Time: 09:35:20 UT–10:10:49 UT
- Xcen = 254.04”, Ycen = -399.84”
- Xfov = 40”, Yfov = 248”
- Binning = 1” x 1”
- Exposure Time = 20 s

Data Reduction:
- Primary data reduction has been done by Solar-Soft

The Jitter has been removed by the cross-correlation techniques. It has been found that jitter is of subarcsec and thus has none effect upon extracted light curves.
- Observed Loop Length $\sim 60$ Mm, $T = 1.58$ MK,

- In theory, the second spatial harmonics of slow acoustic oscillations will be

$$P_{2\text{nd slow}} = \left( \frac{L}{c_s} \right)^2 = \frac{L}{(1.52 \times 10^5 \sqrt{T})} \approx 313 \text{ s}.$$

- Hence, the observed $\sim 322$ s period near apex may be associated with the second spatial harmonics of slow acoustic oscillations.

- Hence, the observed $\sim 497$ s period near footpoint may be associated with the first spatial harmonics (or fundamental mode) of slow acoustic oscillations.
Slow Acoustic Oscillation Modes in the Coronal Loops

**Fundamental Mode:**
Velocity nodes and pressure antinodes at loop footpoint, while velocity antinodes and pressure nodes at loop apex.

**Second Harmonics:**
Velocity Nodes and Pressure Antinodes at both loop apex and footpoints.

**Harmonics of the Slow Acoustic Oscillations in the Coronal Loops**

**Fundamental Mode:**
Remarkable density modifications and hence intensity oscillations at footpoint.

**Second Harmonics:**
Remarkable density modifications and intensity oscillations at apex as well as at footpoint. However, the observed second harmonic is dominant near apex but not near the footpoint. In the case of symmetrically heated apex, the oscillatory power of this harmonic will be maximum at apex, while it will decrease towards footpoint.
Results and Discussion

- The simultaneous existence of various harmonics of spatial slow acoustic oscillations have been observed in the non-flaring coronal loop system (see also Mariska et al., 2008) after the detection of such oscillations in hot SUMER loops (Wang et al., 2002, 2004, Ofman and Wang, 2004).

- Using the period ratio and formula of McEwan et al. (2005, A&A, 460, 893), we found that the density scale height \( \sim 10 \) Mm which is very low compared to inner coronal scale height. Hence, the observed EUV loop system seems not to be in the hydrostatic equilibrium, and exhibits the longitudinal density structuring (see also, Luna-Cardozo, Verth, Erdelyi 2012; Macnamara & Roberts, 2010; Kumar and Kumar, 2012).

Macnamara & Roberts (2011), Kumar & Kumar (2012) have reported the effect of viscosity and thermal conductivity as well as effect of radiative loss on the period ratio \( P_1/P_2 \).

Can this be a useful tool to determine such indirect (uncertain too) as well as crucial dissipative agents in corona? We need to be sure, but efforts can be made indeed...
**Multiple Sausage Oscillations in Cool Loops and Its MHD Seismology**

The loop system is also visible in higher temperature lines, e.g., Fe IX/ X 171 EIT/SOHO. This implies that the energy balance is not occurring, and there is temporal change of density, temperature etc. This also implies that the loop is not in hydrostatic equilibrium as we are aware. Hence, the hydrostatic condition of upper or lower solar atmosphere is only a limiting case.

May 2, 2001 AR 9433 (N15, W 88) ,01:00:52 UT – 01:58 :28 UT ---> Post Flare Loop System
The wavelet result for Hα line near the loop apex. The top panel shows the variation of intensity, the wavelet power spectrum is given in the middle panel, and the probability in the bottom panel. The light curve is from the loop apex \((X,Y) = (113\text{th pixel}, 99\text{th pixel})\).

- Observed Loop Length \(\sim 35\text{ Mm},\) Loop Width \(\sim 4\text{ Mm}\)
- The phase speed will be \(\sim 2L/P \sim 109\text{ km/s}\)
- The speed is much higher than the sound speed at this low temperature
- Hence, we suggest the fast tubular sausage modes in this cool loop.
- Period Ratio \(P_1/2P_2 = 0.84\).
Since, the loop is maintained at temperature $10^4$ K. Hence, at low sound-speed we can use the cold plasma approximation. Hence the cut-off wave number $k_c$ will be (Edwin & Roberts 1983, Solar Physics, 88, 179; Roberts et al. 1984, ApJ, 279, 857):

$$k = k_c = \left[ \frac{v_A^2}{v_{Ae}^2 - v_A^2} \right]^{1/2} \frac{j_0}{a} \quad [1]$$

where $v_A$ and $v_{Ae}$ are Alfvén speeds inside and outside the loop respectively, $a$ is the loop radius and $j_0 = 2.4$ is the first zero of the Bessel function $J_0$. The modes with $k > k_c$ is trapped in the loop, while the mode with $k < k_c$ is leaky. We assume $B_0 = B_{e*}$ then the cut-off wave number is (Ashwanden et al., 2004):

$$k_c = \left[ \frac{1}{n_0/n_e - 1} \right]^{1/2} \frac{j_0}{a} \quad [2]$$

$$\frac{n_0}{n_e} \geq \left( \frac{j_0}{\pi} \right)^2 \left( \frac{L}{a} \right)^2 \approx 178 \quad [3]$$
Results and Discussions

- Only very dense loops can support the non-leaky sausage mode in the estimated length and width (Nakariakov et al. 2003, A&A, 412, L7).

- The post flare loops have usually very high density contrast between 100-1000, and thus our selected loop is also an over dense post-flare loop.

- The selected loop is cool postflare loop, and density ratio falls in the expected range. Hence, the trapped sausage mode may occur in the loop, however, wave leakage cannot be ruled out.

- Shift of P1/P2 ratio from 2.0 can be due to the density stratification.

- The estimated density scale height for the observed parameters is ~ 6.0 Mm

The major task is that how to over-rule the long wavelength cut-off issue and high dispersion. Theory must be developed to make the seismology in terms of multiple periods.
OTHER POTENTIAL HOST FOR THE TEST OF MHD SEISMOLOGY!

Dwarfs and Sun-like Stars
# Summary of Detected Stellar MHD Oscillations in Last 12 Years

<table>
<thead>
<tr>
<th>Star</th>
<th>Periodicity</th>
<th>MHD Candidates</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>YZ Cmin</td>
<td>Few seconds to few mins in optical band</td>
<td>???</td>
<td>Contadakis et al., 2012, AN, 333, 583</td>
</tr>
<tr>
<td>EQ-Peg B</td>
<td>10 s optical</td>
<td>Sausage Oscillations</td>
<td>Tsap, Y.T., Stepanov, A.V., et al., AstL., 2011, 37, 49</td>
</tr>
<tr>
<td>RS CVn binary II Peg</td>
<td>220 s in optical</td>
<td>Standing Kink Modes</td>
<td>Mathioudakis et al., 2003, A&amp;A, 403, 1101</td>
</tr>
</tbody>
</table>

**THANK YOU VERY MUCH**