МАГНИТОГИДРОДИНАМИЧЕСКАЯ СЕЙСМОЛОГИЯ КОРОНЫ СОЛНЦА

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Kink oscillations of coronal loops:

First observation: 14/08/1998 (EUV, TRACE)

Perhaps, longest EM waves resolved in time and space!
Depending on the azimuthal wave number $m$:

- **Kink ($m=1$) mode** (linear polarization)
- RHS or LHS circular polarisation
The kink speed:

the phase and group speed of the kink mode

in the long wavelength limit

\[ C_k = C_A \sqrt{\frac{2}{1 + \rho_{ex}/\rho_{in}}} \]
Damping: linear coupling with Alfvén waves -- effect of resonant absorption of kink waves

If the Alfvén speed is nonuniform in the radial direction, $C_A(r)$, kink motions → local torsional (Alfvénic) perturbations.

$$\tau_{\text{damp}}/P = \text{const}$$
Excitation of kink oscillations:
Possible mechanism: mechanical displacement of the loop by low coronal eruptions from the equilibrium (in 86% cases)

Fig. 2. Schematic illustration of the mechanism for the excitation of kink oscillations of coronal loops, observed in the majority of the studied events. a) Pre-eruption state of the active region. b) Displacement of a coronal loop (solid black curve) from its equilibrium state (dashed black line) by an erupting and expanding plasma structure, e.g. a flux rope (grey loop-shaped structure). c) Oscillatory relaxation of the loop to its equilibrium state after the eruption.
Final demonstration that kink oscillations are natural standing modes of loops

Kink mode: $P_{\text{kink}} \approx \frac{2L}{C_K}$

$C_k = (1300 \pm 50) \text{ km s}^{-1}$

Goddard et al., A&A 585, A137, 2016
$\mu \ P$ - consistent with resonant absorption?
Is the damping a **nonlinear** process?

\[ Q \propto A^{-2/3} \]
Nonlinear damping

Terradas et al. ApJ 687, L115, 2008

and a number of follow up works, e.g., by Antolin et al.

Does it give $Q \propto A^{-2/3}$?
An oscillatory pattern occurs before the onset of the main oscillation.
The parameters of oscillating loops

Li, D. & Long, D.
2023ApJ...944....8L
How can we have a decayless monochromatic oscillation of a damped oscillator?

\[
\frac{d^2a(t)}{dt^2} + \delta \frac{da(t)}{dt} + \Omega_k^2 a(t) = f(t).
\]

\[\Omega_k = \pi \frac{C_k}{L}\]

Linear damping by, e.g., resonant absorption

Can \( f(t) \) be periodic?
(e.g., leakage of p-modes, chromospheric 3-min oscillations)
Demonstration that the decayless kink oscillations are **not** excited by the leakage of p-modes or 3-min oscillations:

Nakariakov et al., A&A 591, L5, 2016

No signatures of resonance
How can we have a decayless monochromatic oscillation of a damped oscillator?

Could the driver $f(t)$ be random, $f(t)=R(t)$? (e.g., granulation motions)
LETTER TO THE EDITOR

Excitation of decay-less transverse oscillations of coronal loops by random motions

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\[
\frac{\partial^2 u}{\partial t^2} + \alpha \frac{\partial u}{\partial t} = C_k^2(x) \frac{\partial^2 u}{\partial x^2},
\]

Random driver can sustain decayless oscillatory patterns
Decayless kink oscillations can be **self-oscillations**: 

In contrast with driven oscillations, a self-oscillator itself sets the **frequency** and **phase** with which it is driven, *keeping the frequency and phase* for a number of periods.
An example of a self-oscillatory system: violine
Rayleigh Eq.:

\[ \frac{d^2 a(t)}{dt^2} + \delta \frac{da(t)}{dt} + \Omega_K^2 a(t) = F \left( v_0 - \frac{da(t)}{dt} \right) \]

\[ \frac{d^2 a(t)}{dt^2} - \left[ \Delta - \alpha \left( \frac{da(t)}{dt} \right)^2 \right] \frac{da(t)}{dt} + \Omega_K^2 a(t) = 0. \]

\[
\alpha_\infty = \sqrt{\frac{4\Delta}{3\alpha \Omega_K^2}} \quad \Delta = \delta_{NF} - \delta
\]
3D simulations of kink self-oscillations:

Wow…, it works!
Seismological estimation of the magnetic field:

\[ B = \sqrt{\mu_0} \frac{\sqrt{2} L_{\text{loop}}}{P} \sqrt{\rho_i \left(1 + \frac{\rho_e}{\rho_i}\right)} \]

Assuming that

- The loop cross-section is constant;
- There is no stratification;
- There is no twist / sigmoidity.

If those conditions are not fulfilled: the field at antinodes.
Seismology of a “quiet” active region by decayless oscillations: 

Alfvén speed map of AR
Does this formula work in the presence of noise?

\[ B = \sqrt{\mu_0} \frac{\sqrt{2} L_{\text{loop}}}{P} \sqrt{\rho_i \left( 1 + \frac{\rho_e}{\rho_i} \right)} \]
Generalised model (self-oscillations + noise):

\[
\ddot{\xi} + \left[ (\delta - \delta_v) + \alpha (\dot{\xi})^2 \right] \dot{\xi} + \Omega_k^2 \xi = N(t),
\]

\[
\delta_v = \delta_{v0} + \delta_{v1} \eta_v(t)
\]

\[
\alpha = \alpha_0 + \alpha_1 \eta_\alpha(t)
\]

\[
N = N_0 \eta_N(t)
\]
What about decay?

If (practically) all loops oscillate decaylessly, is the damping profile the same as when decays to zero? 

\[ \ddot{\xi} + \left[ (\delta - \delta_v) + \alpha (\dot{\xi})^2 \right] \dot{\xi} + \Omega_k^2 \xi = N(t), \]

\[ \xi_0 > \xi_\infty. \]

No. The damping pattern is ”sub-exponential”, 
Asymptotic solution:

\[ D(t) = \frac{2a}{\sqrt{e^{-t/\tau_{as}} + a^2(1 - e^{-t/\tau_{as}})}}. \]

Figure 1. Comparison of the numerical and asymptotic solutions of the self-oscillator equation with the coupling parameter \( \mu = 0.03 \). The left, middle, and right panels show the solutions with the initial amplitudes 5, 15, and 30 times higher than the stationary amplitude, respectively. Solid curves show numerical solutions. Dashed horizontal lines indicate the stationary (decayless) amplitude which is equal to 2 in all cases. Dotted curves show asymptotic solutions. The oscillation period is \( 2\pi \) time units.
Comparison of three damping models:

\[ M_e(t) = \exp\left(-\frac{t}{\tau_e}\right), \]

\[ M_g(t) = \begin{cases} 
\exp\left(-\frac{t^2}{2\tau_g^2}\right), & t \leq t_s, \\
A_s \exp\left(-\frac{t - t_s}{\tau_{ge}}\right), & t > t_s,
\end{cases} \]

\[ M_s(t) = \exp\left[-\left(\frac{t}{\tau_s}\right)^d\right], \]
In 7 out of 10 events the super-exponential damping is found to fit data better

Zhong, Y. et al. (2023MNRAS.525.5033Z)
Oscillation polarisation:
Forward modelling:
Decayless kink oscillations are \textit{linearly polarized}

Can a random driver produce it?

Zhong, S. et al. (2023, Nature Comm. 14, 5298)
The second branch appears because of undersampling, i.e., when observing a harmonic signal with period about the cadence time (as it is in the short loops!)

**Fig. 1.** Scatter plot of periods and loop lengths of decayless transverse oscillations of coronal loops observed by SDO/AIA (blue) and Solar Orbiter/EUI (red).

**Gao et al. 2022, Srivastav et al. 2024**

**Lim et al. 2024 (submitted)**
• Kink oscillations of loops are eigenmodes (standing fast magnetoacoustic waves).
• Appearance of large-amplitude rapidly-damped kink oscillations is associated with low coronal eruptions (LCE) in 86% cases.
• Some cases are clearly inconsistent with this mechanism.
• Evidence of nonlinear damping: the quality-factor depends on the oscillation amplitude, $Q \propto A^{-2/3}$. 
• There is another, decayless and low-amplitude regime of the oscillations.
• The period also depends on the loop length. The recently reported second branch is an artefact.
• Seismology during quiet periods.
• What is the nature of decayless oscillations? Self-oscillations or random driver? (In both scenarios the energy comes from long-period surface motions).
• Possibility to probe free magnetic energy?
Decayless oscillation

Energy supply mechanism

Alfvenic motions, vortices, heating

The decayless oscillation amplitude does not show the converted energy!
Self-oscillation

\[
\frac{\tilde{\xi}}{\tilde{\xi}_\infty} = 1 + \left( \frac{\tilde{\xi}_0}{\tilde{\xi}_\infty} - 1 \right) \exp \left\{ - \frac{t}{t_c} \right\},
\]

\[
\frac{\tilde{\xi}}{\tilde{\xi}_\infty} = 1 + \left( \frac{\tilde{\xi}_0}{\tilde{\xi}_\infty} - 1 \right) \exp \left\{ - \left( \frac{t}{t_c} \right)^d \right\},
\]
Diagnostics of the solar coronal plasmas by magnetohydrodynamic waves: magnetohydrodynamic seismology

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Kink Oscillations of Coronal Loops

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Abstract
Kink oscillations of coronal loops, i.e., standing kink waves, is one of the most studied dynamic phenomena in the solar corona. The oscillations are excited by impulsive energy releases, such as low coronal eruptions. Typical periods of the oscillations are from a few to several minutes, and are found to increase linearly with the increase in the major radius of