Non-linear damping of kink waves
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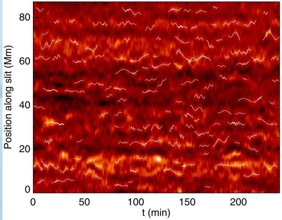
Standing and propagating kink waves in solar corona.
Observations of non-linear damping.

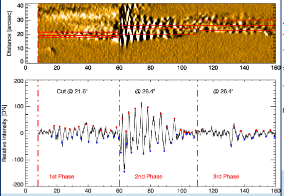
Propagating transverse waves in the coronal loops and plumes

Thurgood et al. (2014)

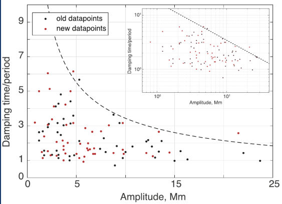


Standing transverse waves (after flares & decayless)

Nistico et al. (2013)



Damping of standing transverse waves is amplitude dependent



Nechaeva et al. (2019):
$\tau/P \sim A^{-0.7}$

Non-linear damping through KHI and uniturbulence

Previous simulations of standing kink waves show KHI
Propagating kink waves have uniturbulence
Cascade to small scales, loss of energy from mode → damping.

Elsässer variables:

$$\vec{z}^{\pm} = \vec{v} \pm \frac{\vec{b}}{\sqrt{\mu\rho}}$$

Governing equations:

$$\frac{\partial \vec{z}^{\pm}}{\partial t} \mp \vec{v}_A \cdot \nabla \vec{z}^{\pm} = -\vec{z}^{\mp} \cdot \nabla \vec{z}^{\pm}$$

Uniturbulence:

$$(\omega + \omega_A)\vec{z}^{+}_{\perp} = (\omega - \omega_A)\vec{z}^{-}_{\perp}$$

Edwin & Roberts (1983):
Standing kink waves

$$P'(r, \varphi, z, t) = \mathcal{R}(r) \cos\varphi \cos(k_z z) \cos(\omega t)$$

Propagating kink waves

$$P'(r, \varphi, z, t) = \mathcal{R}(r) \cos\varphi \cos(k_z z - \omega t)$$

with

$$\mathcal{R}(r) = \begin{cases} A\frac{J_1(\kappa_i r)}{J_1(\kappa_i R)} & \text{for } r \leq R, \\ A\frac{K_1(\kappa_e r)}{K_1(\kappa_e R)} & \text{for } r > R, \end{cases}$$

	MHD turbulence		Uniturbulence	
	Upward	Downward	Upward	Downward
z^-	✓		✓	
z^+		✓	✓	
	counterpropagating $\omega = \pm\omega_A$		co-propagating $\omega \neq \pm\omega_A$	

Damping of propagating waves

RMS average z^2 and $\epsilon = \vec{z} \cdot \nabla w$ over period, wavelength, cross-section

Energy density

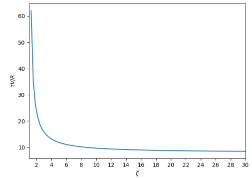
$$\langle w \rangle = \pi R^2 \frac{\rho_\mathrm{i}+\rho_\mathrm{e}}{2} V^2$$

$$\langle \epsilon \rangle = V^3 \frac{\sqrt{5\pi}R}{10} \frac{\rho_\mathrm{e}}{\omega^3} |\omega(\omega^2 - \omega_\mathrm{Ae}^2)|$$

Damping time:

$$\tau = \sqrt{5\pi} \frac{R}{V} \frac{2(\zeta+1)}{|\zeta-1|} = \sqrt{5\pi} \frac{P}{2\pi a} \frac{2(\zeta+1)}{|\zeta-1|}$$

with density contrast $\zeta = \rho_\mathrm{i}/\rho_\mathrm{e}$, velocity amplitude V and maximal displacement $\eta = aR$



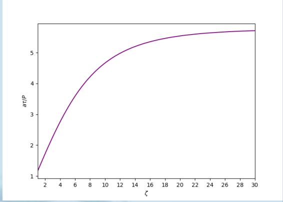
Examples:

- Pant et al. (2019): $V = 22\mathrm{km/s}$, $R = 250\mathrm{km}$, $\zeta = 3$ $\rightarrow \tau \sim 180\mathrm{s}$
- plumes with $R = 1\mathrm{Mm}$, $V = 4\mathrm{km/s}$, $\zeta = 3$: $\rightarrow \tau \sim 3960\mathrm{s}$

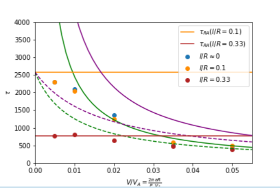
Damping of standing waves

Damping time:

$$\tau = 20\sqrt{\pi}\frac{R}{V}\frac{1+\zeta}{\sqrt{\zeta^2-2\zeta+97}} = 20\sqrt{\pi}\frac{P}{2\pi a}\frac{1+\zeta}{\sqrt{\zeta^2-2\zeta+97}}$$

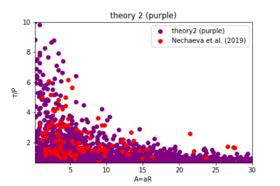


Blue, yellow and red dots: simulations of Magyar & VD (2016)



Full line: non-linear damping
Horizontal: resonant absorption
Dashed: harmonic average

Red dots: Nechaeva et al. (2019)



Purple: 5000 draws from
$\zeta \in U[1, 9.5]$,
$l/R \in U[0, 2]$,
$A \in U[0.2, 30]\mathrm{Mm}$,
$R \in U[0.5, 5]\mathrm{Mm}$

Theoretically:
A^{-1} power law.