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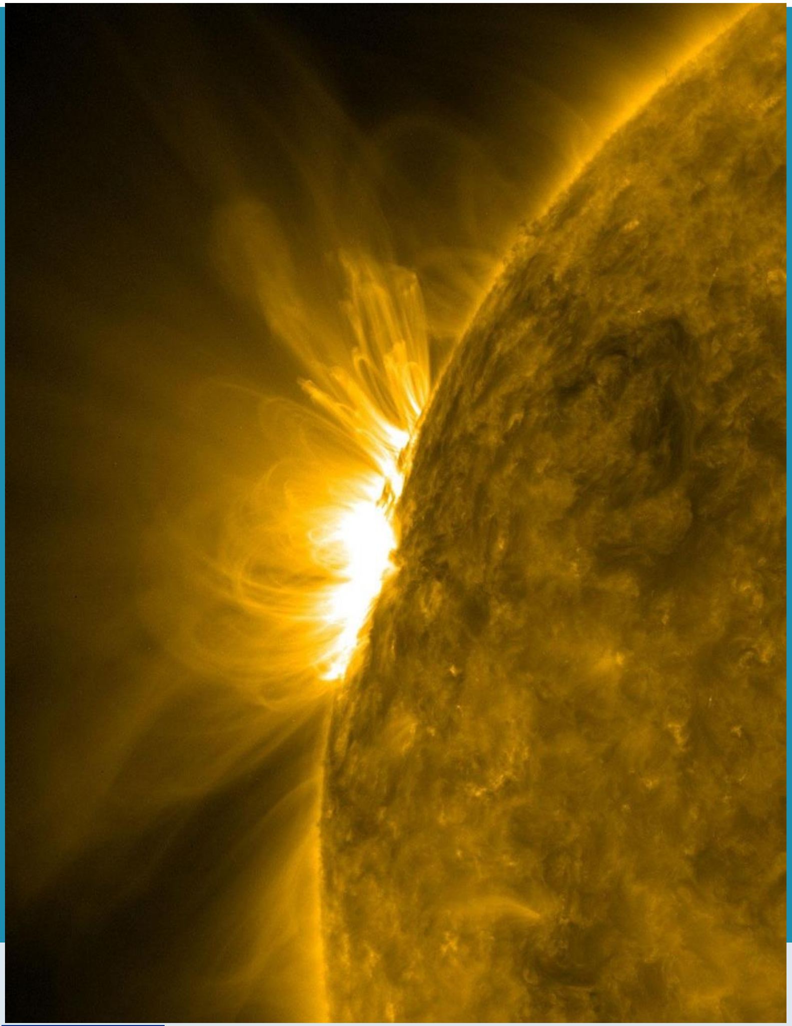
The interplay between slow waves and heating/cooling mechanisms in the solar corona



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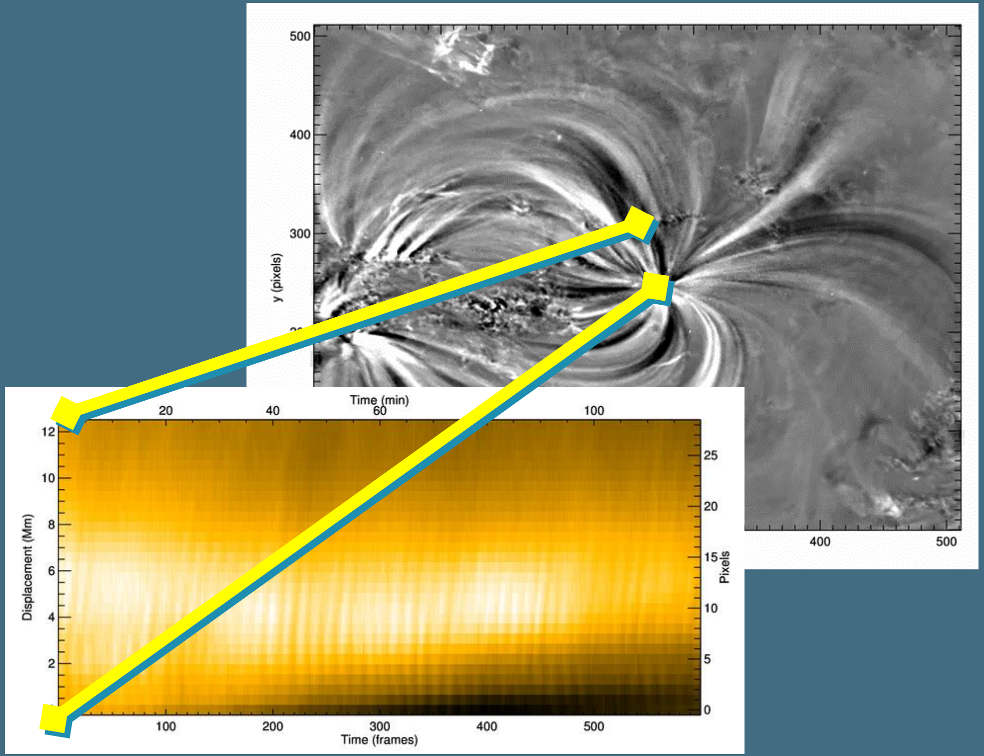
Context: damping of slow waves

Slow magnetoacoustic waves are common in the solar corona, and are strongly affected by the local thermal equilibrium. They may be seen, standing or propagating, in cool coronal loop fans, flaring loops and plumes.

In all cases these waves damp rapidly.



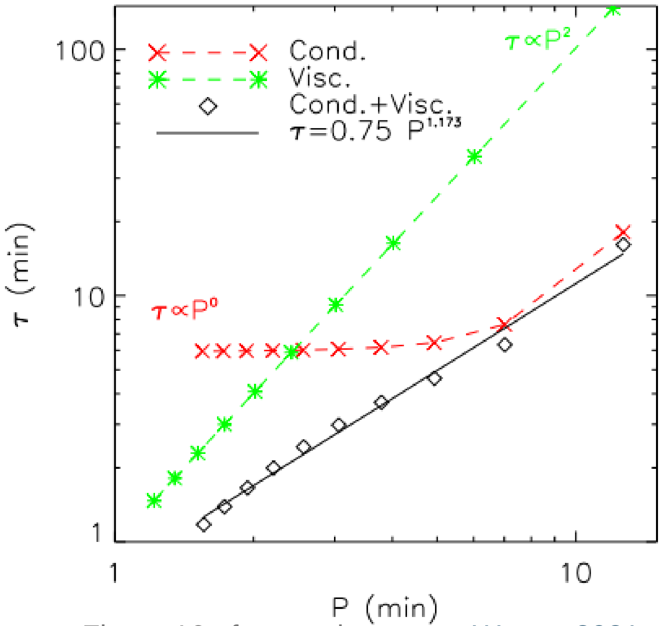


Figure 16a from review paper Wang+ 2021, showing period vs damping time for a model coronal loop's harmonics. No single damping mechanism explains observed quality factors.

Linear theory suggests that non-ideal MHD effects are the cause of damping. In particular, **thermal conduction**, optically thin radiation, and **compressive viscosity**, are proposed mechanisms.

However, these mechanisms predict a specific scaling of damping time upon period. Observations are **inconsistent** with this scaling.

Inconsistency: scaling of damping times

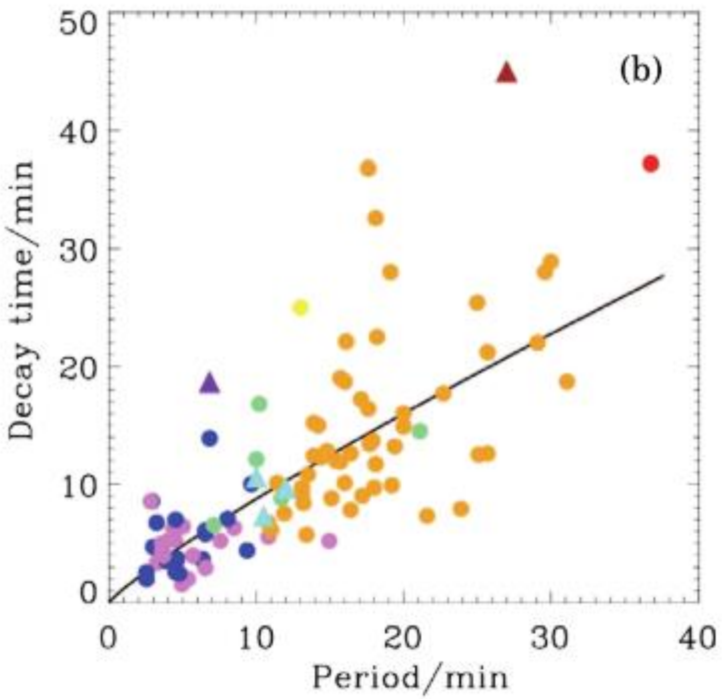


Figure 2a from Nakariakov+ 2019, showing period vs damping time for *sloshing* oscillations (triangles), and standing slow waves aka SUMER oscillations (circles). Note the large ScAttEr.

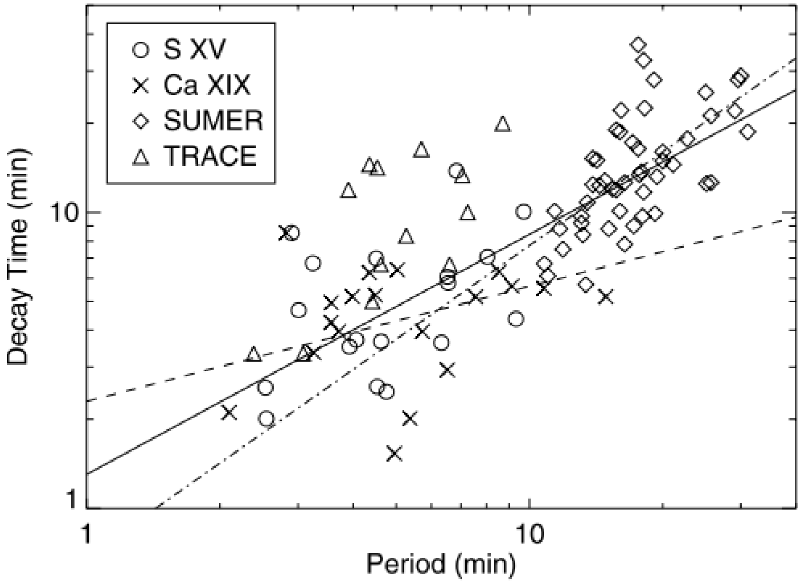


Figure 8 from Mariska 2006, showing period vs damping time for SUMER waves measured with different instruments.

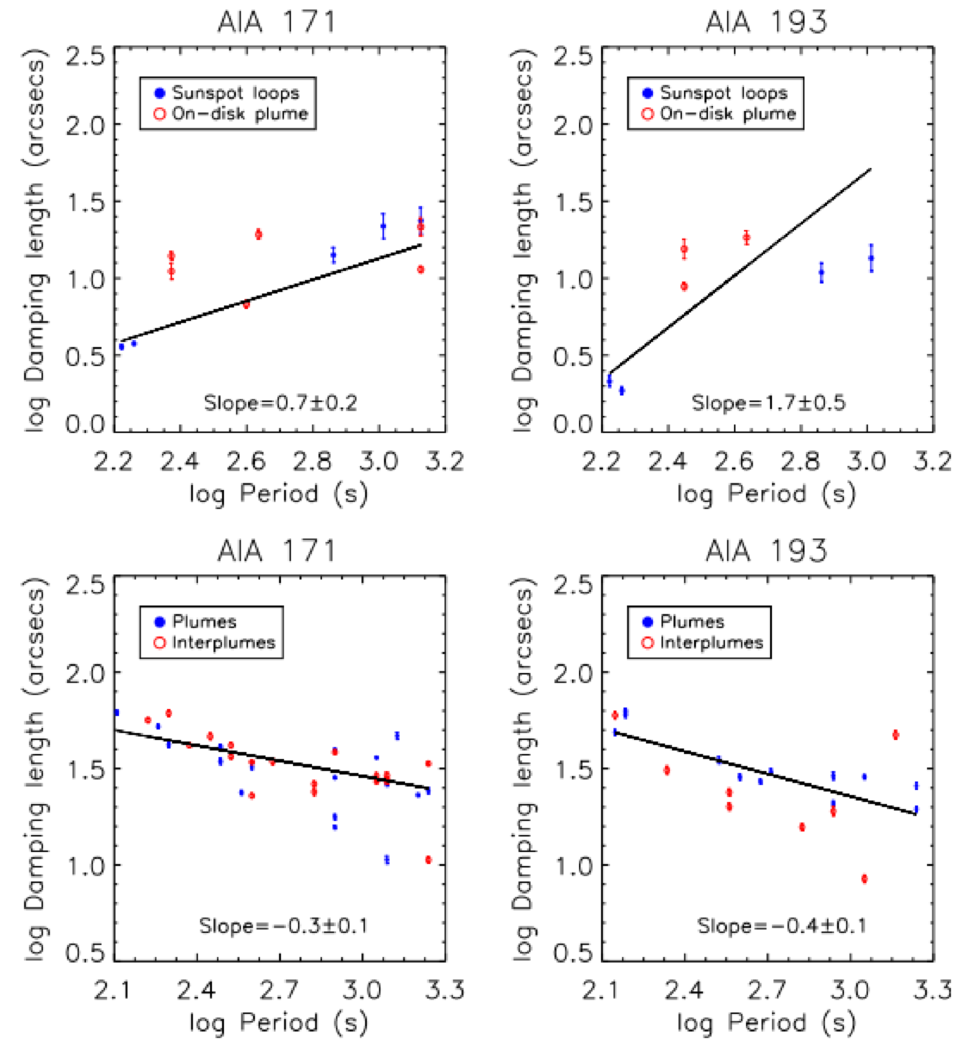
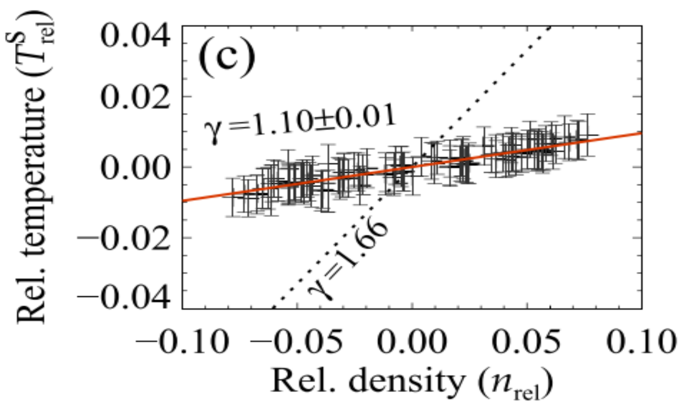
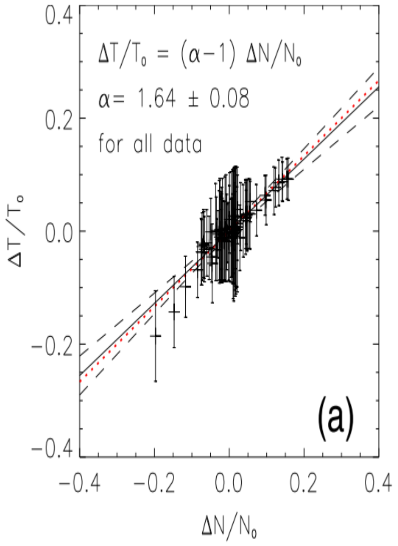


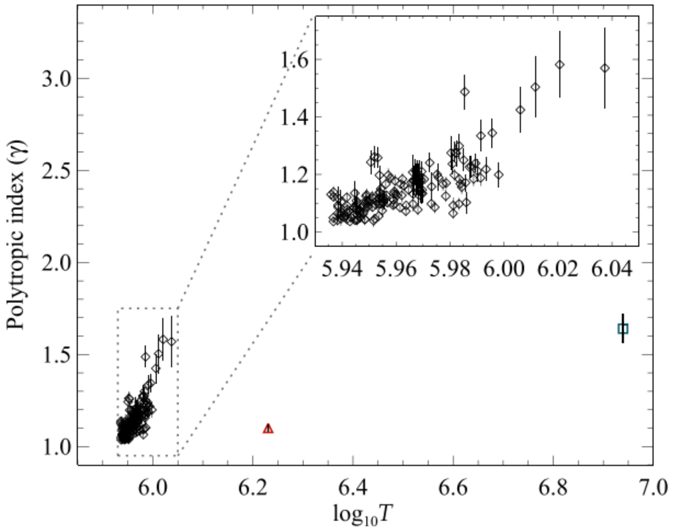
Figure 6 from Prasad+ 2014, showing different dependencies of propagating slow waves with temperature bandpasses and different densities

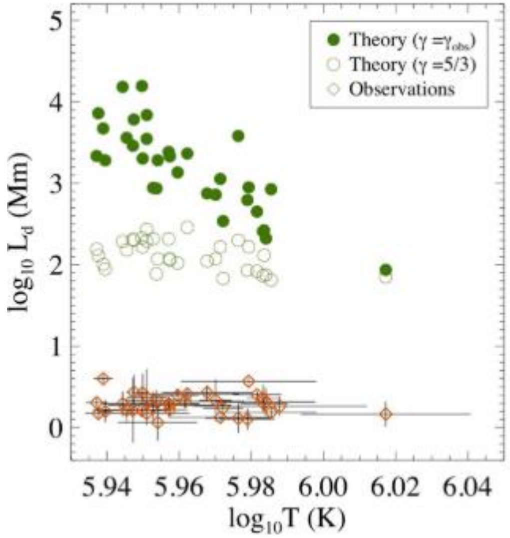
Inconsistency: phase shifts

- Under the polytropic assumption $p \propto \rho^{\gamma_{eff}}$, it follows that $\frac{\tilde{T}}{T_0} = (\gamma_{eff} - 1)\frac{\tilde{\rho}}{\rho_0} \cos\Delta\varphi$. meaning that there is a *phase shift* between temperature and density perturbations.
- By measuring the phase shifts, one may infer the effective polytropic index γ_{eff} (e.g. Wang 2015).
- It has been shown that in general, $\gamma_{eff} \neq {}^5\!/_3$ the classical adiabatic value is not always valid (Van Doorsselaere et al. 2011, Prasad 2018).



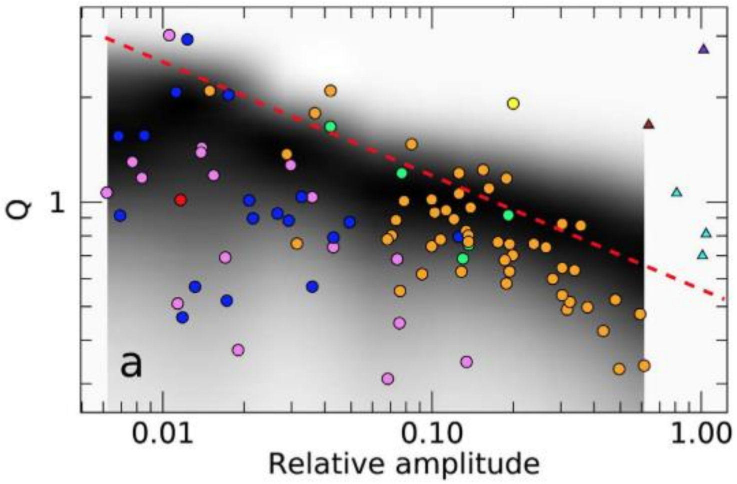




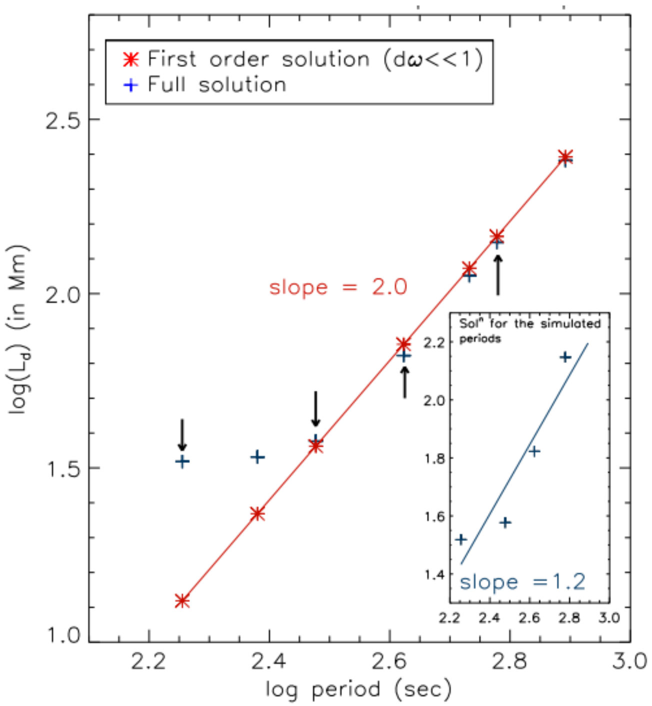


- Any nonadiabatic effect will introduce a phase shift (Owen 2009). E.g. thermal conduction -> $\tan\Delta\varphi = \frac{\pi m_p(\gamma_{eff}-1)\kappa}{k_B C_S^2 P \rho_0}$
- BUT thermal conduction alone has been found insufficient to explain observed phase shifts.
- An observed variation in inferred γ_{eff} with temperature remains unexplained (above Prasad+ 2018, 2019).

Complicating factors…



Nonlinearity may be crucial, e.g. shock formation.
This figure (Nakariakov+ 2019) shows that quality factor depends on AMPLITUDE.

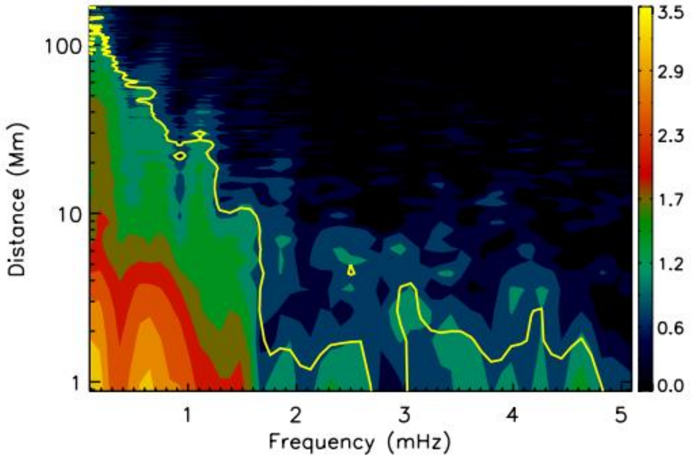


The wave may be undergoing nonadiabatic processes which are neither

- WEAK (dω<<1) → expect a slope of 2 in log-log plot
- nor STRONG (dω>>1) → expect the damping length independent of wave period

This figure (Mandal+ 2016) forward modelled the general case, finding the shorter periods are not well described by dω<<1.

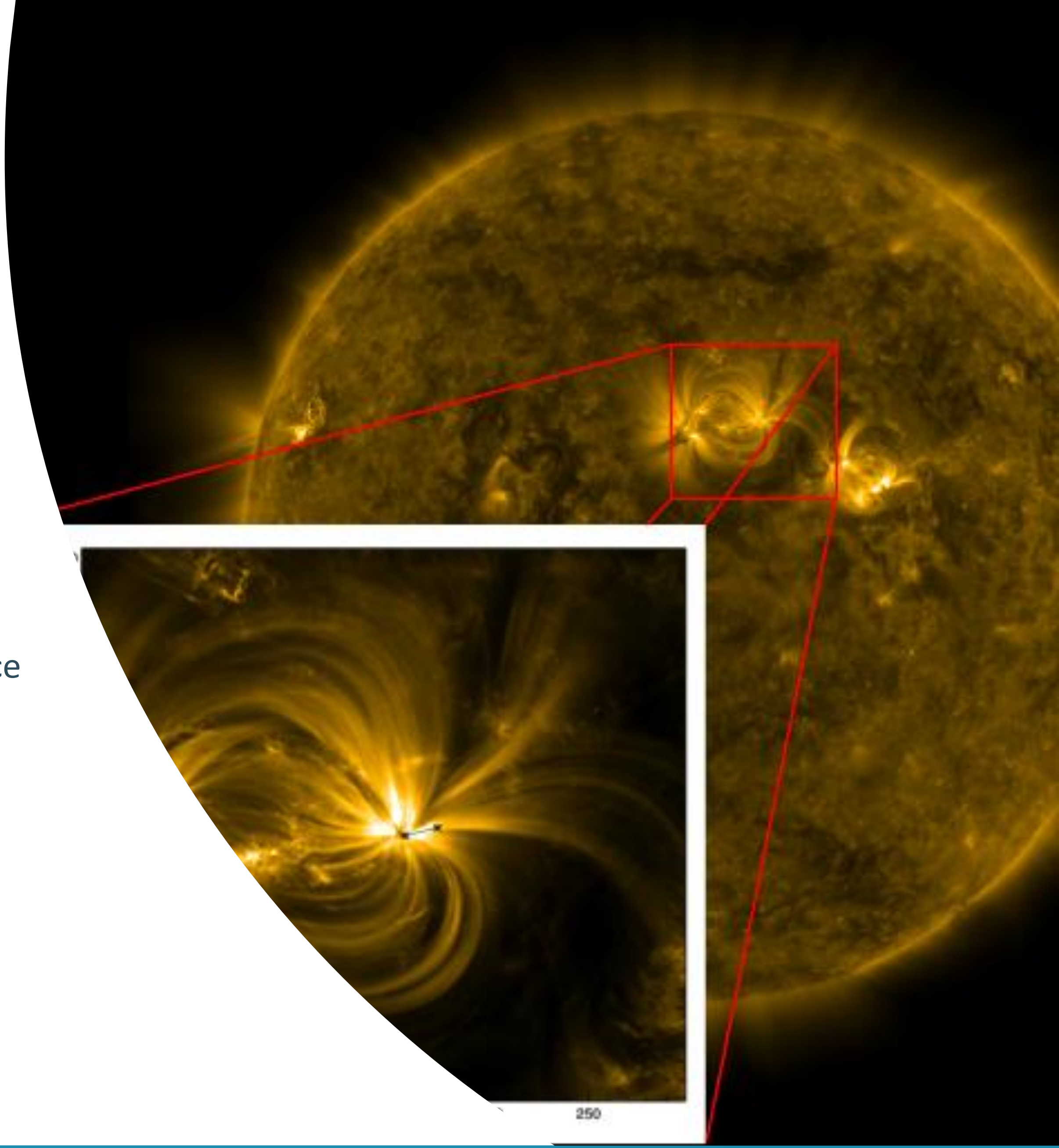
Gupta+ 2014 found damping in a plume has a **frequency** dependence. Heavy damping in first 10 Mm, only weak damping above!
Similar results found in Mandal+ 2018.



Thermal conduction is always acting, but with different strengths on different l e n g t h s c a l e s .

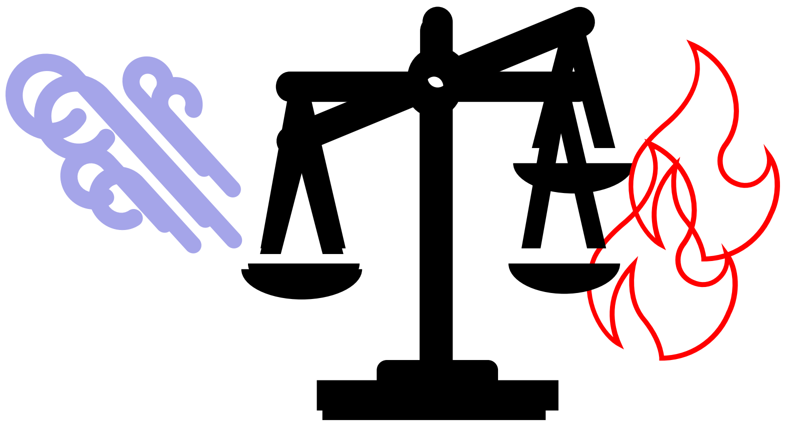
We need another nonadiabatic damping mechanism…

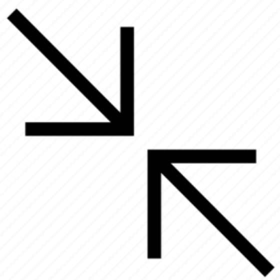
- The wide spread of dependencies of wave period against damping length may be explained by the presence of other damping mechanisms.
- This mechanism need not be effective everywhere all the time but must have some temperature dependence and density dependence to explain the findings above.
- Compressive viscosity would need to be enhanced well beyond Braginskii's classical values (Wang+ 2015, 2018, 2019).
- Radiative losses alone do not explain the variation of results (e.g. Sigalotti+ 2007).
- We propose that this is linked to the coronal heating problem.
- Even without knowing the exact form of heating function, we can study the effect of **wave-induced thermal misbalance**.



Wave-induced thermal misbalance

- Coronal plasma maintained at (approximate) thermal equilibrium by a delicate balance between heating and cooling mechanisms.
- As a slow wave propagates through the plasma it perturbs mechanical AND thermal equilibrium; changes T, ρ.
- Wave induces a **misbalance** between the competing heating + cooling processes.
- Resultant dispersion can lead to *damping*





Note the wave is **not** the heating source. We investigate the effect of misbalance upon the wave.

Mathematical formulation: linearised MHD

$$\frac{dp}{dt} - \frac{\gamma p}{\rho}\frac{d\rho}{dt} = (\gamma - 1)\left(\kappa_{\parallel}\frac{\partial^2 T}{\partial z^2} - \rho Q(\rho, T, B)\right),$$

$$\rho\frac{du}{dt} + \frac{\partial p}{\partial z} = 0,$$

$$p + \frac{B^2}{8\pi} = p_{\text{total}}^{\text{ext}},$$

$$\frac{\partial B}{\partial t} + u\frac{\partial B}{\partial z} + 2Bv_r = 0$$

$$\frac{\partial \rho}{\partial t} + 2\rho v_r + \frac{\partial}{\partial z}(\rho u) = 0,$$

$$p = \frac{k_{\text{B}}}{m}\rho T$$

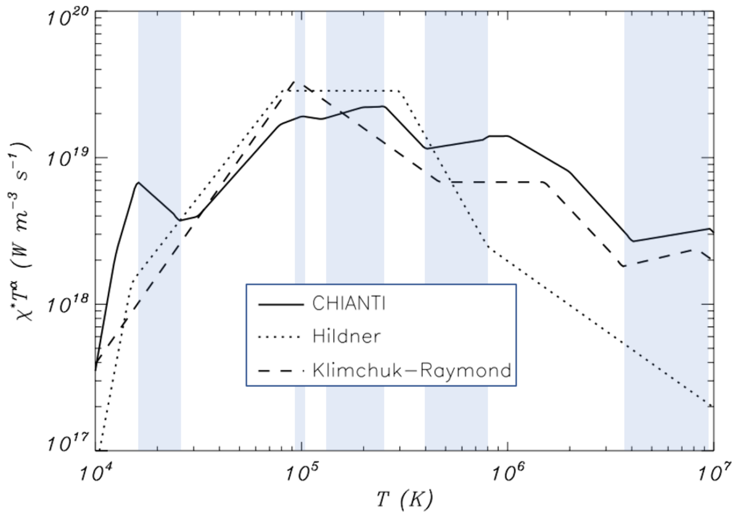
Thermal conduction

Combined cooling + heating

$Q = \mathcal{L} - \mathcal{H}$

ρ^{a}?T^{b} B^{c}

Radiative losses



- Parameterise the unknown coronal heating function as a power law (if you know a better local parameterisation, please email me!)
- Extract radiative losses from from CHIANTI database, though non-unique.

Interpreting the dispersion relation

$$\omega^3 + i\frac{2}{2+\gamma\beta}\left\{\frac{4\pi^2}{\tau_{\rm cond}(k)}\left(1+\frac{\beta}{2}\right) + \frac{1}{\tau_2} + \frac{\gamma\beta}{2}\frac{1}{\tau_1}\right\}\omega^2$$
$$- C_{\rm T}^2 k^2 \omega - iC_{\rm T}^2\left\{\frac{1}{\gamma}\frac{4\pi^2}{\tau_{\rm cond}(k)} + \frac{1}{\tau_1}\right\}k^2 = 0.$$

$$\begin{aligned}
\frac{1}{\tau_M} &= \frac{C_{\rm T}^2}{C_{\rm S}^2}\left(\frac{1}{\tau_2} - \frac{1}{\tau_1}\right), \\
&= \left(\frac{2}{2+\beta\gamma}\right)\left(\frac{1}{\tau_2} - \frac{1}{\tau_1}\right), \\
&= \frac{2}{2+\beta\gamma}\left\{\frac{\gamma-1}{\gamma}\frac{Q_T}{C_V} + \frac{1}{\gamma}\frac{\rho_0}{T_0}\frac{Q_\rho}{C_V} - \frac{\beta}{2}\frac{B_0}{T_0}\frac{Q_B}{C_V}\right\}.
\end{aligned}$$

$$\Longrightarrow \quad \omega_{\rm I} \approx -\frac{1}{2}\left(\frac{2}{2+\beta\gamma}\frac{\gamma-1}{\gamma}\frac{4\pi^2}{\tau_{\rm cond}} + \frac{1}{\tau_M}\right).$$

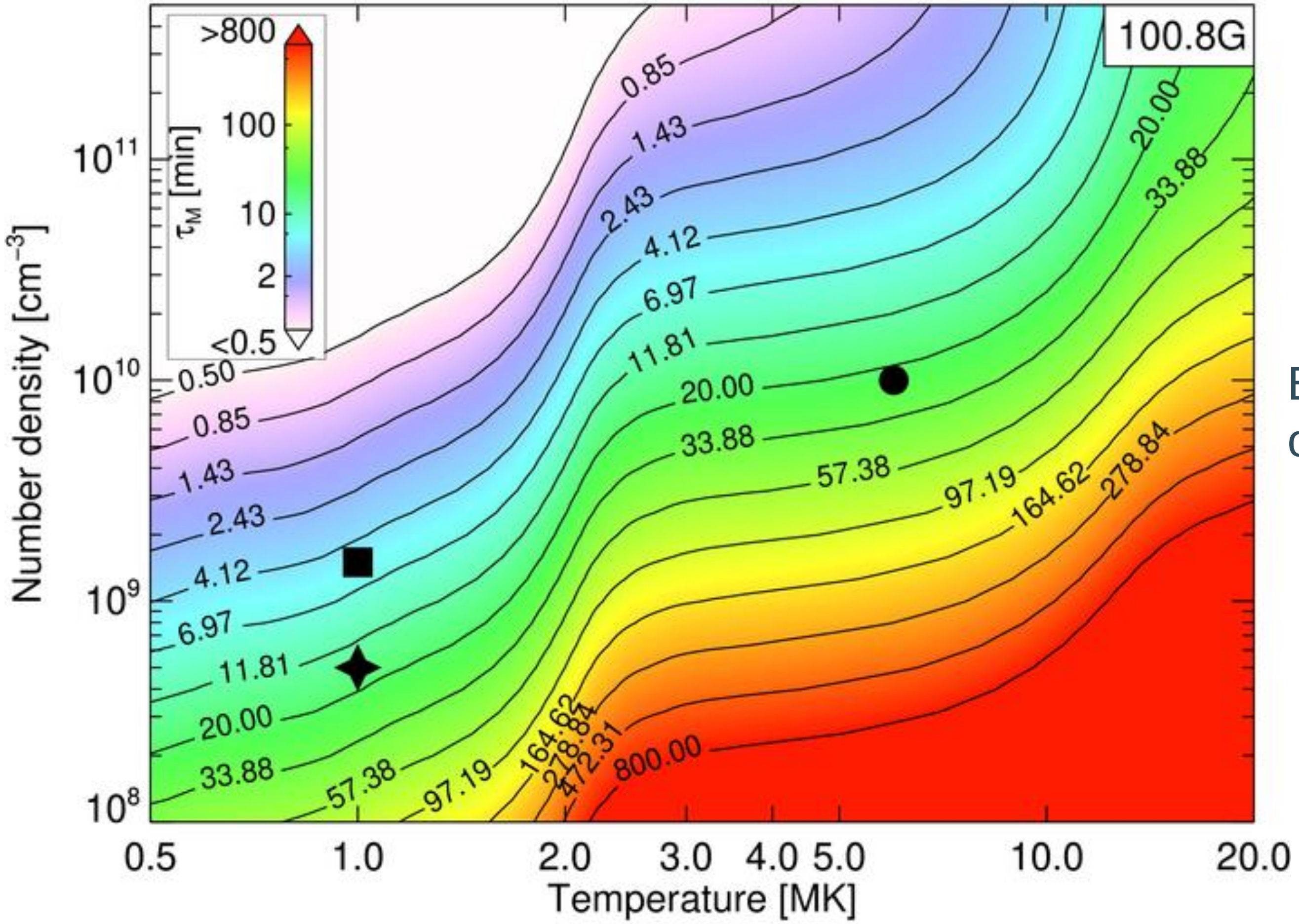
- Find the dispersion relation, describing how slow modes behave in presence of heating/cooling + finite-β plasma.
- Can fully characterise effects of heating/cooling misbalance with x2 timescales, even with three variables!
- Express these timescales in terms of derivatives of heating function Q with respect to constant *gas* pressure and constant *magnetic* pressure.
- In the limit of weak non-adiabaticity (wave only mildly affected by transfer with the active medium) : $\omega \gg 1/\tau_{1,2,cond}$, the equation simplifies. Can define a single characteristic timescale (DAMPING timescale) τ_M

Damping of slow modes by thermal misbalance

In limit of weak non-adiabaticity $\omega \gg 1/\tau_{1,2,cond}$, and for most coronal conditions, slow modes are damped over damping time τ_M (plotted).

These timescales match observed wave periods and damping times → **effect of thermal misbalance important**. Comparable to the effect by thermal conduction.

■ Warm loop (171Å)
✦ Coronal plume
● Hot loop (SUMER)

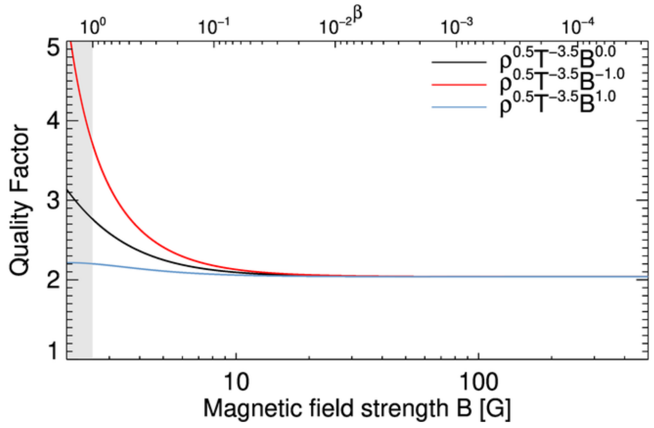


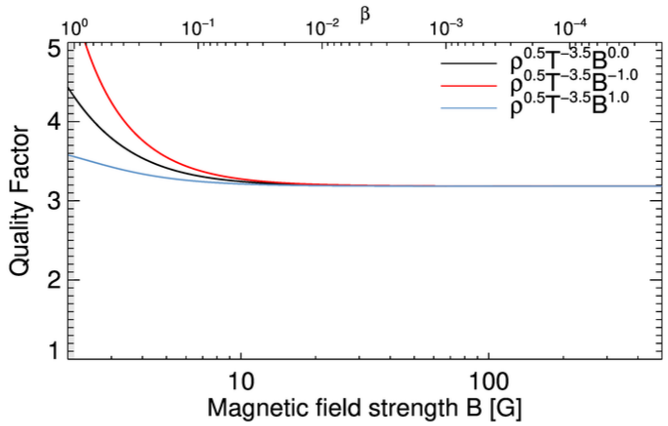
But what is the effect of the non-zero β?

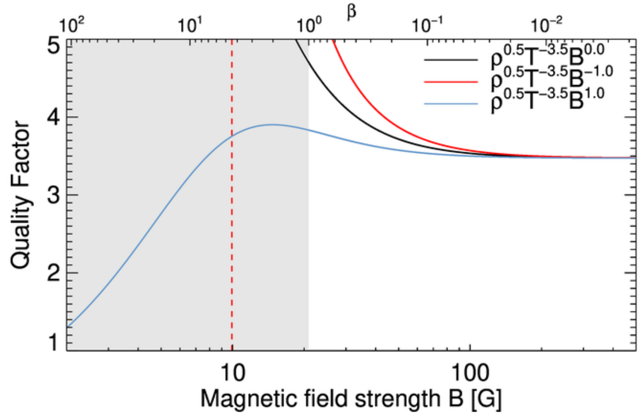
Effect of non-zero β

Can calculate the damping time/period for waves in plasma with given temperature, density and magnetic field strength. Have to choose a heating function $\mathcal{H} \propto \rho^a T^b B^c$, interested in variation with c.

Plot for three typical plasma conditions where slow waves are observed. Show three different heating functions, and how the quality factor varies with stronger magnetic field (β→0).







■ Warm loop (171Å)
✦ Coronal plume
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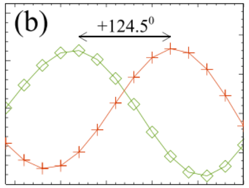
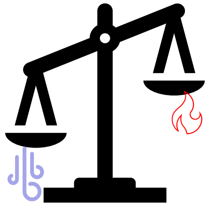
Take home message: **for sufficiently strong magnetic field, the damping of slow waves is independent of the heating and cooling functional dependence upon magnetic field.**
See Duckenfield+ 2021.

Summary

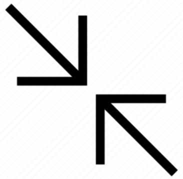
- There are discrepancies between the theory of slow wave damping and observations: temperature dependencies; scaling between damping and period; phase shifts. Need another wide-ranging nonadiabatic damping mechanism.



- A slow wave will perturb the local heating/cooling, which has a dispersive effect (damping) on the wave: wave-induced thermal misbalance.



- Thermal misbalance appears to damp slow waves on the order of that observed, for most coronal conditions.



- The damping by thermal misbalance is insensitive to the heating function's dependence on magnetic field, for sufficiently strong magnetic field (> 10G).

Thank you for listening,

Questions are welcome!

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Recent review on slow waves:
Wang+ 2021

Paper this work is based on:
Duckenfield, Kolotkov & Nakariakov 2021

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