KU LEUVEN

The effect of local heating and cooling processes on slow waves in the corona

TIM DUCKENFIELD[1], DMITRII KOLOTKOV[2], VALERY NAKARIAKOV[2]

OBJECTIVES

1. Model how slow waves are affected by their perturbation of local heating + cooling processes
2. Observe slow waves, which are replete in the solar corona
3. Determine change in phase speed + amplification/damping caused by dispersion
4. Infer locally the coronal heating function, assuming radiative losses + transport coefficients

INTRODUCTION

The solar corona is delicately balanced at thermal equilibrium, by radiative losses and some heating mechanism [1]. Both the heating/cooling mechanisms vary with the plasma parameters (ρ, T etc). Slow magnetoacoustic waves perturb these mechanisms enough to be themselves affected [2]. So by understanding this dispersion, we may one day use observations of slow waves as probes, letting us infer the mysterious coronal heating function [3].

RESULTS: SLOW WAVE OVERSTABILITY

In some cases the exchange of energy between the medium and the slow wave can lead to amplification i.e. **overstability**. For a non-zero β plasma, the isentropic instability criterion (see [1]) accounting for *both* thermal misbalance and thermal conduction is:

$$\frac{1}{\tau_2} - \frac{1}{\tau_1} + \frac{\gamma - 1}{\gamma}\frac{4\pi^2}{\tau_{\text{cond}}} < 0$$

If one parameterises the *local* heating function as a power-law $\mathcal{H} \propto \rho^a T^b B^c$ and estimates the radiative losses $\mathcal{L}$ at (ρ, T), then the criterion becomes

$$b > \frac{1}{\gamma - 1}\left\{1 + \left(\frac{\beta\gamma}{2}\right) c - a\right\} + \frac{T_0}{\mathcal{L}_0}\left(\frac{\partial \mathcal{L}}{\partial T}\right)_{T_0, \rho_0} + \frac{C_{\text{V}}}{\tau_{\text{cond}}}\frac{T_0}{\mathcal{L}_0}.$$

The fact that slow waves are only seen to damp in the solar corona, and assuming $\beta = 0$, one may infer constraints on a, b. It was in this way that Kolotkov+ 2020[3] proposed one such heating model, $\mathcal{H} = \rho^{1/2}T^{-7/2}c^0$ used for calculations of $\mathcal{T}_{\text{M}}$ here. Of course, c should also be considered, particularly for large β plasma.

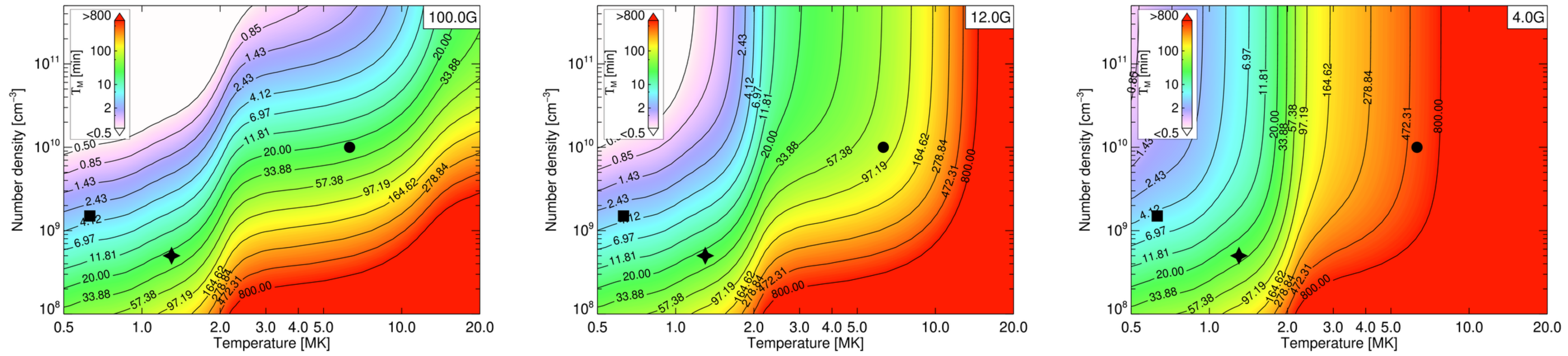
RESULTS: EFFECTS OF FINITE-β

We consider a non-zero β plasma using linearised MHD + the first order thin flux tube approximation [4], accounting for heating/cooling $Q(\rho, T, B)$ and thermal conduction. The resulting dispersion is characterised by timescales

$$\tau_1 = \frac{C_P}{Q_{T[\text{gas } p]}}, \quad \tau_2 = \frac{C_{\text{V}}}{Q_{T[\text{mag } p]}}, \quad \tau_{\text{cond}}(k) = \frac{\rho_0 C_{\text{V}} \lambda^2}{\kappa_{\parallel}},$$

where $Q_{T[i]}$ refers to $\partial Q/\partial T$ keeping *gas* pressure and *magnetic* pressure constant resp [5]. Taking the weakly non-adiabatic limit $\omega \gg 1/\tau_{1,2,\text{cond}}$ the wave phase speed is the tube speed C_T and the effect of thermal misbalance may be combined into a single timescale $\mathcal{T}_{\text{M}}$, over which the wave is amplified or damped:

$$\frac{1}{\mathcal{T}_{\text{M}}} = \left(\frac{2}{2 + \gamma\beta}\right)\left(\frac{1}{\tau_2} - \frac{1}{\tau_1}\right).$$



(a) Plot of $\mathcal{T}_{\text{M}}$ at 100 G. **(b)** Plot of $\mathcal{T}_{\text{M}}$ at 12 G. **(c)** Plot of $\mathcal{T}_{\text{M}}$ at 4 G.

Figure 1: Damping timescales due to thermal misbalance $\mathcal{T}_{\text{M}}$ for the heating model $\mathcal{H} \propto \rho^{1/2}T^{-7/2}B^0$, as functions of ρ, T and for different magnetic field strengths. Green depicts observed slow wave periods + damping times, 10-100 min. Symbols correspond to typical coronal conditions; square=cool loop, star=plume, circle=flaring loop.

The dispersive effect of thermal misbalance on slow waves is found to be comparable to that by thermal conduction. For typical coronal conditions, slow waves are damped and $\mathcal{T}_{\text{M}}$ matches observed slow wave periods + damping times. This implies the importance of the effect of misbalance, and its historic exclusion as a damping mechanism may explain observed damping times for which viscosity + thermal conduction is insufficient.

REFERENCES

[1] G. B. Field. Thermal Instability. *ApJ.*, 142:531, aug 1965.

[2] D. Zavershinskii, D. Kolotkov, V. Nakariakov, N. Molevich, and D. Ryashchikov. Formation of quasi-periodic slow magnetoacoustic wave trains by heating/cooling misbalance. *Phys. Plasmas*, 26(8):082113, aug 2019.

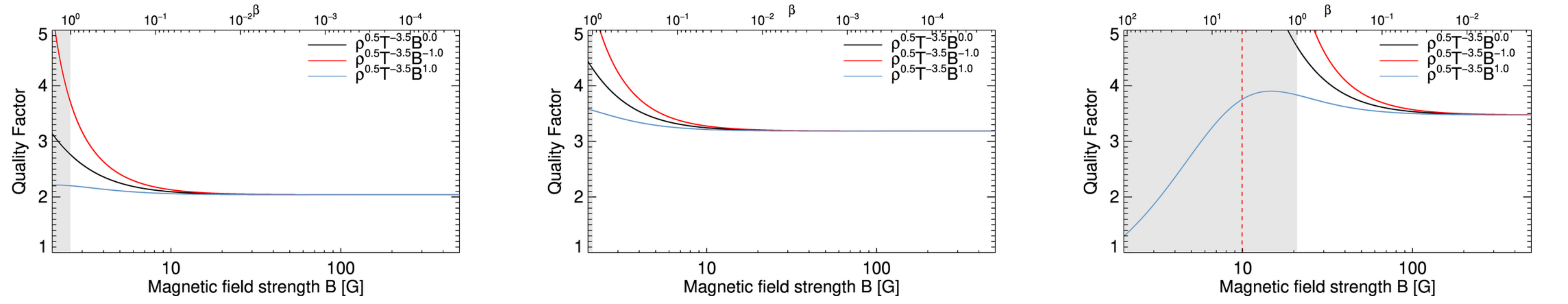
[3] D. Y. Kolotkov, T. J. Duckenfield, and V. M. Nakariakov. Seismological constraints on the solar coronal heating function. *Astron. Astrophys.*, 644, oct 2020.

[4] B. Roberts and A. R. Webb. Vertical motions in an intense magnetic flux tube. *Sol. Phys.*, 56(1):5–35, jan 1978.

[5] T J Duckenfield, D Y Kolotkov, and V M Nakariakov. The effect of the magnetic field on the damping of slow waves in the solar corona. *Astron. Astrophys.*, 646:A155, feb 2021.

RESULTS: INSENSITIVITY TO $\mathcal{H}(B)$

One may expect coronal heating to vary with magnetic field strength, i.e. $\mathcal{H} = \mathcal{H}(B)$. Yet we find for sufficiently strong B, the damping of slow waves is *independent* of the heating/cooling functional dependence upon magnetic field. As a rule of thumb, the infinite magnetic field approximation is suitable in the corona for magnetic field strengths greater than ≈ 10 G.



(a) Typical cool loop exhibiting propagating 3 min oscillations [square]. **(b)** Typical cool plume with upwardly propagating slow waves [star]. **(c)** Typical post-flare loop with standing modes, aka SUMER oscillations [circle].

Figure 2: Oscillation damping time/period as a function of magnetic field strength for different heating models. Each plot corresponds to different, common coronal slow mode parameters matching Fig. 1. Grey denotes $\beta > 1$.

CONCLUSIONS

- Slow magnetoacoustic waves can perturb the coronal heating + cooling mechanisms enough to be able to infer the coronal heating's local power-law indices, if one can see a slow wave's damping, phase speed, radiative losses and plasma parameters.
- Slow wave damping by thermal misbalance is typically comparable to that by thermal conduction.
- For sufficiently strong magnetic strength, the slow wave dynamics is insensitive to *any* dependence of the heating function on B.
- Interested readers please see Duckenfield+ 2021 [5] + email tim.duckenfield@kuleuven.be for more information.

erc European Research Council
BOSS WAVES