SF2A 2023
M. N'Diaye, A. Siebert, N. Lagarde, O. Venot, K. Baillié, M. Béthermin, E. Lagadec, J. Malzac, J. Richard (eds)

IMPACT OF THE MAGNETIC FIELD ON THE STOCHASTIC EXCITATION OF P-MODES

L. Bessila[1] and S. Mathis[1]

Abstract. We model the stochastic excitation of p-modes to take into account magnetic fields. First, we derive the forced wave equation with a magnetic field and compute the source terms which inject energy into the oscillations. We make use of magnetized convection Mixing Length Theory (hereafter noted MLT) to assess how the convective velocity is modified by the magnetic field. Finally, we derive scaling laws for the modes amplitudes depending on the ratio between the local Alfvén and MLT convective velocities.

Keywords: helioseismology, asteroseismology, Sun, Stars, pulsations (including oscillations), convection, magnetic field

1 Introduction

Amplitudes of acoustic modes in solar-like stars are intrinsically linked to the properties of turbulent convection, which acts as their excitation source. Their detection is the best way to determine the key global properties of these stars (i.e. their masses and their radius) and their age (e.g. García & Ballot 2019). Recent observational works using results of the *Kepler* space mission, showed that acoustic modes' signal is not detected in a large fraction of solar-type stars (Chaplin et al. 2011; Mathur et al. 2019), where they are nevertheless expected because of their convective envelope. This non-detection is a function of both stellar magnetism and rotation. One hypothesis is that the excitation source term is too low to trigger the oscillations. In addition, observations of solar-type stars show that the amplitudes of stellar acoustic modes are modulated along their magnetic activity cycles (Garcia et al. 2010). Rotation and magnetic fields strongly influence convection (e.g. Stevenson 1979), but their action is most of the time ignored in the models. For the first time, we extend the theoretical formalism for stochastic excitation of p-modes (Samadi & Goupil 2001) to assess the impact of the magnetic field.

2 Stochastic wave excitation with a magnetic field

Following the method of Samadi & Goupil (2001), we derive the inhomogeneous wave equation :

$$\rho_0 \left(\partial_{\rm tt} - \mathcal{L}\right) (\boldsymbol{u}_{\rm osc}, \boldsymbol{b}_{\rm osc}) + \mathcal{D}(\boldsymbol{u}_{\rm osc}, \boldsymbol{b}_{\rm osc}, \boldsymbol{U}_{\rm t}, \boldsymbol{B}_{\rm t}) = \partial_t \mathcal{S}(\boldsymbol{U}_t, \boldsymbol{B}_t), \tag{2.1}$$

where $\boldsymbol{u}_{\rm osc}$ (resp. $\boldsymbol{U}_t$) is the oscillation velocity (resp. turbulent velocity), $\boldsymbol{b}_{\rm osc}$ (resp. $\boldsymbol{B}_t$) is the wave magnetic field (resp. turbulent magnetic field), $\mathcal{L}$ is the linear wave operator, $\mathcal{D}$ is a damping term, and the oscillations source term is $\mathcal{S} = \mathcal{S}_R + \mathcal{S}_B$. $\mathcal{S}_R = -\nabla : (\rho_0 \boldsymbol{U}_t \boldsymbol{U}_t)$ is the Reynolds-stresses source term, and $\mathcal{S}_B = \nabla : \left(B_i B_j/\mu_0 - \delta_{ij} B^2/2\mu_0\right)$ is the source term due to the Maxwell-stresses, where δ_{ij} is the Kronecker symbol, and we use Einstein convention for the tensorial form of the stresses. Furthermore, as demonstrated in Samadi & Goupil (2001), the temporal average of the squared modes amplitudes is proportional to the squared source term : $\langle |A(t)|^2 \rangle \propto \mathcal{S}^2$.

[1] Université Paris-Saclay, Université Paris Cité, CEA, CNRS, AIM, F-91191, Gif-sur-Yvette, France

3 Scaling laws for p-modes amplitudes

We derive scaling laws for the source terms, taking the magnetic field into account. We introduce the ratio between the mode's amplitude with and without magnetic field : $\frac{\langle |A(t)|^2 \rangle_{\rm mag}}{\langle |A(t)|^2 \rangle_0} \propto \frac{\mathcal{S}_{\rm mag}^2}{\mathcal{S}_0^2}$, where $\langle . \rangle$ denotes the statistical average on an infinite number of independent realisations. $\mathcal{S}_{\rm mag}$ (resp. $\mathcal{S}_0$) is the source term with a magnetic field (resp. with no magnetic field). Not only does the magnetic field add up a new source term through the Maxwell-stresses, but it also changes the Reynolds-stresses source term through the modification of convection by the magnetic field. To account for this modification, we use Stevenson (1979) scaling laws in magnetized convection, with MLT. These make use of the inverse Alfvén number : $A = v_A^2/u_0^2$, where $v_A = B^2/\sqrt{\mu_0 \rho_0}$ is the Alfvén velocity and u_0 the convective velocity when the magnetic field is ignored. For values of $A < 1$, which is the case at the top of the convective zone where the acoustic modes are excited in solar-type stars, one has : $\frac{\mathcal{S}_{\rm mag}^2}{\mathcal{S}_0^2} \sim \left(1 - \frac{11A}{75}\right)^2 \left(1 - \frac{A}{(1 - \frac{11}{75A^2})^2}\right)$. For values of $A > 1$, $\frac{\mathcal{S}_{\rm mag}^2}{\mathcal{S}_0^2} \sim \frac{0,92^2}{A} \left(1 - \frac{A^2}{2 \cdot 0,92^2}\right)$. As shown in Fig. 1, there are two different regimes : when increasing the magnetic field, the modes amplitudes tend to be lower and lower, thus it is the tendency found in observations. Above $A = 1$, the Maxwell-stresses become the dominant source and the modes amplitudes increase with the magnetic field.

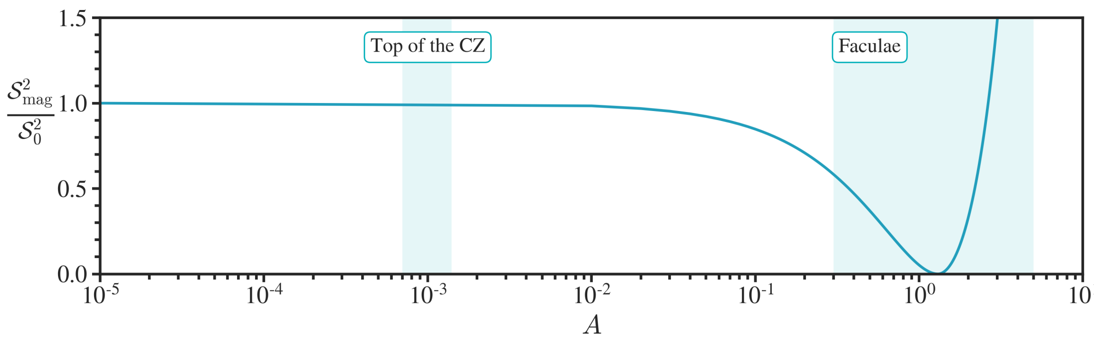

Fig. 1. Scaling of the relative modes amplitude as a function of the inverse Alfvén number A.

4 Conclusions

In this work, we have derived the inhomogeneous wave equation, which allows us to study the stochastic excitation of stellar oscillation modes in the presence of magnetic fields. We identify the supplementary source term due to magnetic Maxwell stresses and account for the modification of convection using the Magnetic MLT. We show that in the weak magnetic field regime the injection of energy diminishes when the field amplitude increases because of the inhibition of Reynolds-stresses by the magnetic field. In the strong field regime, the Maxwell-stresses dominate and the power injection of energy in stellar oscillation is increased.

L. B. and S. M. acknowledge support from the CNES SOHO/GOLF and PLATO grants at DAp/AIM at CEA and from PNPS (CNRS/INSU).

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