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THE IMPACT OF THE MAGNETIC FIELD ON THE STOCHASTIC EXCITATION OF ACOUSTIC MODES BY TURBULENT CONVECTION

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Abstract. In solar-like stars, acoustic (p) modes are excited by turbulence in the convective envelope: this is the stochastic excitation. Observations with the *Kepler* mission have revealed that more than 46% of solar-like stars show no detectable p-modes. This lack of detection appears to be linked to stellar rotation and magnetism. Furthermore, p-mode amplitudes vary along the magnetic cycle: stronger magnetic fields are associated with lower oscillation amplitudes. A possible explanation is that the excitation source, when influenced by rotation and magnetism, becomes too weak to sustain oscillations. We investigate the role of magnetic fields in the stochastic excitation of acoustic modes. We extend the state-of-the-art formalism for the excitation of stellar p-modes by incorporating the effects of a magnetic field. The influence of the magnetic field on convection is treated using the Magnetised Mixing-Length Theory developed by Bessila & Mathis (2025). These results show that the magnetic field can reduce the excitation by up to 50% in a typical solar-like star. It can offer new insights into mode detectability in magnetised stars.

Keywords: Asteroseismology, Magnetic fields, Turbulence, Convection, Waves, Stars: solar-type

1 Introduction

Acoustic waves are key probes of stellar interiors. Following the identification of the solar five-minute oscillations as p-modes (Ulrich 1970; Leibacher & Stein 1971), space-based helio- and asteroseismology have shown that they constrain global stellar parameters such as mass, age, and radius (e.g. Christensen-Dalsgaard 2015; García & Ballot 2019), and provide insights into the solar convective zone properties and rotation (Thompson et al. 2003; García et al. 2007).

In solar-like stars, turbulent convection excites acoustic modes stochastically (Goldreich et al. 1994; Samadi & Goupil 2001). Their amplitudes are strongly affected by magnetic activity, with observations showing an anti-correlation (Garcia et al. 2010; Kiefer et al. 2017; Santos et al. 2018; Salabert et al. 2018). *Kepler* data further indicate that p-modes are not detected in a 40% of solar-like stars (Chaplin et al. 2011; Karoff et al. 2018; Mathur et al. 2019), an effect which depends on rotation and magnetism. Including magnetism in excitation models is therefore essential, particularly for PLATO (Rauer et al. 2024).

Oscillation amplitudes result from the balance between driving and damping. Driving originates from stochastic excitation (Lighthill 1952; Stein 1967; Goldreich & Keeley 1977; Samadi & Goupil 2001; Belkacem 2008), while damping involves non-adiabatic and turbulent processes (Goldreich & Kumar 1991; Balmforth 1992; Belkacem et al. 2012). Both rotation and magnetism modify convection (Chandrasekhar 1961; Hotta 2018; Korre & Featherstone 2021), which in turn affects excitation. Mixing-Length Theory (MLT) (Böhm-Vitense 1958) has been extended to include these effects (Stevenson 1979; Augustson & Mathis 2019; Bessila et al. 2024), showing that magnetic fields tend to reduce convective velocities and convective length scales, and inhibit convection.

The impact of rotation and magnetism on stochastic excitation is being progressively integrated into theory. For acoustic waves, rotation has been shown to reduce amplitudes (Bessila et al. 2024; Biscarrat et al. 2025), while magnetic fields can both inhibit convection and drive oscillations through Maxwell stresses (Bessila & Mathis 2024). Scaling-law predictions of this effect have been proposed, and here we progress by adopting a spectral model of magnetohydrodynamic turbulence combined with Magnetised MLT to provide more realistic estimates of acoustic mode amplitudes in magnetically active solar-like stars.

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2 Formalism for the stochastic excitation in magnetic stars

We compute the power injected into the oscillations of acoustic modes following the formalism of Bessila & Mathis (2024), extending to MHD the theoretical framework introduced by Samadi & Goupil (2001) and Belkacem et al. (2008). The excitation model accounts for the two main sources driving acoustic oscillations in the stellar cavity: the Reynolds stresses and the Maxwell stresses associated with magnetic fields.

Assuming stationary and homogeneous turbulence, the mean square amplitude of the modes can be expressed as (Samadi & Goupil 2001; Bessila et al. 2024):

$$\left\langle |A|^2 \right\rangle = \frac{1}{8\eta \left(\omega_0 I\right)^2} \int d^3x_0 \int_{-\infty}^{+\infty} d^3r \, d\tau \, e^{-i\omega_0 \tau} \left\langle (\vec{\xi} \cdot \mathcal{S})_1 (\vec{\xi} \cdot \mathcal{S})_2 \right\rangle , \tag{2.1}$$

where $\langle \cdot \rangle$ denotes a statistical average over an infinite number of independent realisations, η is the mode damping rate, ω_0 the mode frequency, I the mode inertia, and $\boldsymbol{\xi}$ the mode eigendisplacement. Subscripts 1 and 2 refer to the spatio-temporal points $[\vec{x}_0 - \vec{r}/2, -\tau/2]$ and $[\vec{x}_0 + \vec{r}/2, \tau/2]$, respectively. Here, $\boldsymbol{x}_0$ and t_0 denote averaged space-time coordinates, while $\boldsymbol{r}$ and τ characterize local turbulence (see e.g. Belkacem et al. 2008). In convective zones, since eddy lifetimes are much shorter than mode lifetimes, the integration over τ extends to the full range $]-\infty, +\infty[$, while the integration over $\vec{x}_0$ covers the entire stellar convective region. In this framework, $\mathcal{S}$ represents the non-negligible excitation source terms (Bessila & Mathis 2024, e.g.) $\mathcal{S} = \mathcal{S}_R + \mathcal{S}_B$, with the Reynolds stresses contribution: $\mathcal{S}_R = -\nabla : (\rho_0 \boldsymbol{U_t} \boldsymbol{U_t})$ and the Maxwell stresses one $\mathcal{S}_B = \nabla : \left(B_{t,i} B_{t,j}/\mu_0 - \delta_{i,j} B_t^2/2\mu_0 \right)$, where $\nabla :$ denotes the divergence of a tensor, $\boldsymbol{U_t}$ is the turbulent velocity field, B_t the turbulent magnetic field, and $\delta_{i,j}$ the Kronecker symbol. The Einstein summation convention is applied over repeated indices.

3 Magnetised convection

As explained in the introduction, the Maxwell stresses source terms that emerge are not the only effect of magnetism. Convection is also strongly affected by the magnetic field, which in turn influences the excitation. In stellar physics, turbulent convection is usually described by the Mixing-Length Theory (Böhm-Vitense 1958), which models convection through a single dominant eddy but neglects rotation and magnetism. Stevenson (1979) extended MLT to include these effects in the asymptotic limits of weak/strong rotation and magnetic fields, based on the assumption of Malkus (1954) that convection is dominated by the mode transporting the most heat. Later, Augustson & Mathis (2019) generalised this approach to arbitrary rotation rates, including heat and viscous diffusivities, while Bessila & Mathis (2025) further extended it to any value of rotation and magnetic field.

In this framework, the modulation of the convective velocity (resp. wavenumber) by magnetic fields is written $\tilde{U}(A) = u_B/u_0$ (resp. $\tilde{K}(A) = k_B/k_0$), where u_0, k_0 are the standard MLT values and u_B, k_B their magnetised counterparts. The key parameter is the inverse Alfvén number $A = u_A/u_c = B_0/(\sqrt{\rho_0 \mu_0} u_c)$, which measures the ratio of magnetic to kinetic energy densities. Both Stevenson (1979) and Bessila & Mathis (2025) find that magnetic fields inhibit convection, lowering the characteristic convective velocities and lengthscales. Rotating MLT prescriptions have been successfully tested against direct numerical simulations (Barker et al. 2014; Currie et al. 2020; de Vries et al. 2023), while the Magnetised-MLT (M-MLT) has not yet been benchmarked against simulations, but its results qualitatively agree with Hotta (2017) who found reduced convective velocities when increasing magnetic fields. In this work, we adopt the formulation of Bessila & Mathis (2025), as it consistently spans the full range of inverse Alfvén numbers A.

4 Prototype model: numerical estimates

We evaluate the power injected by stochastic excitation into acoustic modes, accounting both for direct source terms due to magnetic fields and for the indirect modulation of convection using the M-MLT model of Bessila & Mathis (2025). We employ a solar-like 1D model computed with the MESA stellar evolution code (e.g. Paxton et al. 2011; Jermyn et al. 2023), and use the GYRE stellar oscillation code (Townsend & Teitler 2013; Townsend et al. 2014) to compute oscillation frequencies and eigenfunctions $\boldsymbol{\xi}$. We adopt a simple dipolar profile anchored at the base of the convection zone $\boldsymbol{B}(r, \theta) = B_{\rm base} \left(r_{\rm CZ}/r\right)^3 \left(\cos\theta \, \hat{\boldsymbol{e}}_r + \sin\theta/2 \, \hat{\boldsymbol{e}}_\theta\right)$, where $r_{\rm CZ} = 0.71 R_\odot$ is the tachocline radius and $B_{\rm base}$ the polar field at its base.

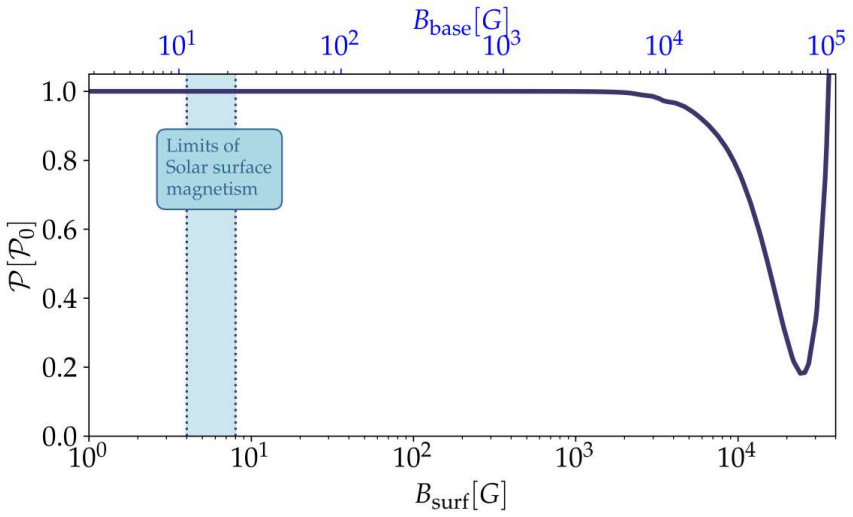

Fig. 1. Power injected into the $\ell = 0, n = 8$ p-mode including the effect of a dipolar magnetic field, normalised to the power in the standard non-magnetised case.

For each acoustic mode, we extract ρ_0, u_0, and k_0 from the MESA model. We then define the magnetic field profile $B(r, \theta)$, and we compute the resulting inverse Alfvén number $A(r, \theta)$. We then derive the modified velocity u_B and wavenumber k_B from Bessila & Mathis (2025). Finally, we evaluate the different contributions from the source terms, and integrate across the whole convective zone.

We focus on the power injected into the $\ell = 0, n = 8$ mode as a function of the surface magnetic field $B_{\rm surf}$, which is plotted in Fig. 1. We highlight the solar surface magnetic field values in blue. Solar-like stars typically host fields between 1 and 1000 G (Donati & Landstreet 2009). We identify several regimes depending on $B_{\rm surf}$. For weak fields (1-10^3 G), the magnetic field has little influence and Reynolds stresses dominate the excitation. For intermediate fields (1–10 kG), the cross Maxwell-Reynolds contribution becomes dominant and negative, reducing the injected power by up to 80%. For stronger fields (10 kG-1 MG), Maxwell stresses drive the excitation and the injected power increases by up to four orders of magnitude. Finally, we find that for strong fields ($>$ 1 MG), convection is strongly inhibited, leading to a decrease in the injected power despite Maxwell stresses dominating. As this regime is not realistic for solar-like stars, it is not displayed in the figure.

5 Conclusions

We have developed a theoretical model for the stochastic excitation of acoustic modes, including the impact of the magnetic field. It induces a new source term due to the Maxwell stresses. The magnetic field also influences convection, which we have modelled with the Magnetic Mixing-Length Theory (Stevenson 1979; Bessila & Mathis 2025). In a prototype solar model, we show that within the values of magnetic fields expected for solar-like stars, the power injected into the modes diminishes when the magnetic field increases, by up to 80%. The perspective of this work includes comparing the theory with direct numerical simulations and with existing observations of solar-like stars. Moreover, this model can also be extended to examine the influence of the magnetic field on the excitation of gravity modes.

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References

Augustson, K. C. & Mathis, S. 2019, The Astrophysical Journal, 874, 83

Balmforth, N. J. 1992, Monthly Notices of the Royal Astronomical Society, 255, 639, aDS Bibcode: 1992MNRAS.255..639B

Barker, A. J., Dempsey, A. M., & Lithwick, Y. 2014, The Astrophysical Journal, 791, 13, arXiv:1403.7207 [astro-ph, physics:physics]

Belkacem, K. 2008, Theses, Observatoire de Paris

Belkacem, K., Dupret, M. A., Baudin, F., et al. 2012, Astronomy & Astrophysics, 540, L7

Belkacem, K., Samadi, R., Goupil, M. J., & Dupret, M. A. 2008, Astronomy & Astrophysics, 478, 163, arXiv:0710.1039 [astro-ph]

Bessila, L. & Mathis, S. 2024, Astronomy & Astrophysics, 690, A270, publisher: EDP Sciences

Bessila, L. & Mathis, S. 2025, A model of magnetised and rotating convection for stellar and planetary interiors, arXiv:2505.14650 [astro-ph]

Bessila, L., Ruys, A. D. v., Buriasco, V., et al. 2024, The impact of rotation on the stochastic excitation of stellar acoustic modes in solar-like pulsators, arXiv:2412.14952 [astro-ph]

Biscarrat, G., Bessila, L., & Mathis, S. 2025, The impact of differential rotation on the stochastic excitation of acoustic modes in solar-like pulsators, arXiv:2507.00919 [astro-ph]

Böhm-Vitense, E. 1958, Zeitschrift fur Astrophysik, 46, 108, aDS Bibcode: 1958ZA.....46..108B

Chandrasekhar, S. 1961, Hydrodynamic and hydromagnetic stability (Oxford: Oxford University Press)

Chaplin, W. J., Bedding, T. R., Bonanno, A., et al. 2011, The Astrophysical Journal, 732, L5

Christensen-Dalsgaard, J. 2015, A bright outlook for helio- and asteroseismology, pages: 5-8 Publication Title: Extraterrestrial Seismology ADS Bibcode: 2015exse.book....5C

Currie, L. K., Barker, A. J., Lithwick, Y., & Browning, M. K. 2020, Monthly Notices of the Royal Astronomical Society, 493, 5233, aDS Bibcode: 2020MNRAS.493.5233C

de Vries, N. B., Barker, A. J., & Hollerbach, R. 2023, Monthly Notices of the Royal Astronomical Society, 524, 2661

Donati, J.-F. & Landstreet, J. 2009, Annual Review of Astronomy and Astrophysics, 47, 333

Garcia, R. A., Mathur, S., Salabert, D., et al. 2010, Science, 329, 1032, arXiv:1008.4399 [astro-ph]

García, R. A. & Ballot, J. 2019, Living Reviews in Solar Physics, 16, 4, aDS Bibcode: 2019LRSP...16....4G

García, R. A., Turck-Chièze, S., Jiménez-Reyes, S. J., et al. 2007, Science, 316, 1591, aDS Bibcode: 2007Sci...316.1591G

Goldreich, P. & Keeley, D. A. 1977, The Astrophysical Journal, 212, 243, aDS Bibcode: 1977ApJ...212..243G

Goldreich, P. & Kumar, P. 1991, The Astrophysical Journal, 374, 366, aDS Bibcode: 1991ApJ...374..366G

Goldreich, P., Murray, N., & Kumar, P. 1994, The Astrophysical Journal, 424, 466, aDS Bibcode: 1994ApJ...424..466G

Hotta, H. 2017, The Astrophysical Journal, 843, 52, publisher: IOP Publishing

Hotta, H. 2018, The Astrophysical Journal, 860, L24, aDS Bibcode: 2018ApJ...860L..24H

Jermyn, A. S., Bauer, E. B., Schwab, J., et al. 2023, The Astrophysical Journal Supplement Series, 265, 15, aDS Bibcode: 2023ApJS..265...15J

Karoff, C., Metcalfe, T. S., Santos, A. R. G., et al. 2018, The Astrophysical Journal, 852

Kiefer, R., Schad, A., Davies, G., & Roth, M. 2017, Astronomy & Astrophysics, 598, A77

Korre, L. & Featherstone, N. A. 2021, The Astrophysical Journal, 923, 52, aDS Bibcode: 2021ApJ...923...52K

Leibacher, J. W. & Stein, R. F. 1971, Astrophysical Letters, 7, 191, aDS Bibcode: 1971ApL.....7..191L

Lighthill, M. J. 1952, Proceedings of the Royal Society of London Series A, 211, 564, aDS Bibcode: 1952RSPSA.211..564L

Malkus, W. V. R. 1954, Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, 225, 196, publisher: The Royal Society

Mathur, S., Garcia, R. A., Bugnet, L., et al. 2019, Frontiers in Astronomy and Space Sciences, 6, 46, arXiv:1907.01415 [astro-ph]

Paxton, B., Bildsten, L., Dotter, A., et al. 2011, The Astrophysical Journal Supplement Series, 192, 3, aDS Bibcode: 2011ApJS..192....3P

Rauer, H., Aerts, C., Cabrera, J., et al. 2024, The PLATO Mission, arXiv:2406.05447 [astro-ph]

Salabert, D., Régulo, C., Pérez Hernández, F., & García, R. A. 2018, Astronomy & Astrophysics, 611, A84

Samadi, R. & Goupil, M.-J. 2001, Astronomy & Astrophysics, 370, 136

Santos, A. R. G., Campante, T. L., Chaplin, W. J., et al. 2018, The Astrophysical Journal Supplement Series, 237, 17

Stein, R. F. 1967, Solar Physics, 2, 385

Stevenson, D. J. 1979, Geophysical & Astrophysical Fluid Dynamics, 12, 139, publisher: Taylor & Francis

Thompson, M. J., Christensen-Dalsgaard, J., Miesch, M. S., & Toomre, J. 2003, Annual Review of Astronomy and Astrophysics, 41, 599

Townsend, R., Teitler, S., & Paxton, B. 2014, 301, 505, conference Name: Precision Asteroseismology Place: eprint: arXiv:1309.4455 ADS Bibcode: 2014IAUS..301..505T

Townsend, R. H. D. & Teitler, S. A. 2013, Monthly Notices of the Royal Astronomical Society, 435, 3406, aDS Bibcode: 2013MNRAS.435.3406T

Ulrich, R. K. 1970, The Astrophysical Journal, 162, 993, aDS Bibcode: 1970ApJ...162..993U