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MEASURING MAGNETIC FIELDS IN THE CORE OF RED GIANT STARS WITH ASTEROSEISMOLOGY

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Abstract.
Past studies show that stellar models overestimate the internal rotation profile for stars across the Hertzprung-Russel diagram, and especially for red giants. This translates into an underestimated transport of angular momentum. It has been suggested that this transport might be explained by the presence of internal magnetic fields, undetectable until recently, where 47 magnetic stars have been discovered. With the aim of expanding the current catalogue of magnetic red giants, we developed a rigorous method to detect and measure such fields, focussing on stars most likely magnetic. With this process that we present here, we detected significant magnetic fields in 21 additional red giants. These measurements expose detection thresholds possibly explaining a decreasing trend in the intensity of the magnetic field with stellar evolution and show similarities in the distributions for seismic and magnetic red giants. These similarities suggest that core magnetism may be more wide spread than thought, but a number of observations are still inaccessible because of unknown detection thresholds and observational biases.

Keywords: Asteroseismology, PLATO, Red giants, Magnetic fields

1 Introduction

The PLATO mission, scheduled for launch in 2026, will observe large regions of the sky to detect exoplanetary transits and measure the ages of planetary systems. However, stellar evolution models tend to overestimate internal rotation across the Hertzsprung-Russell (HR) diagram (Zahn 1992; Eggenberger et al. 2012; Marques et al. 2013; Ouazzani et al. 2019; Li et al. 2020), particularly in red giants (Ceillier et al. 2013). This underestimation of angular momentum transport can lead to age errors of up to 30% (Maeder & Meynet 2005). Core magnetic fields have long been suggested as a possible explanation, but remained inaccessible, until recently. Asteroseismology allows to probe stellar interiors, though access to the deepest layers is limited to specific configurations. Red giants, which exhibit solar-like pulsations and mixed dipole ($l = 1$) modes, offer such a possibility: these modes behave as pressure (p) modes in the envelope and gravity (g) modes in the core, enabling indirect observation of core magnetic fields. Theoretical understanding of magnetic effects on g and mixed modes exists (Hasan et al. 2005; Gomes & Lopes 2020; Bugnet et al. 2021; Loi 2021; Mathis et al. 2021; Li et al. 2022), but observational evidence only emerged recently. The first detections of stellar core magnetic fields were obtained by Li et al. (2022), with three red giants showing magnetic signatures in their power spectra. This number has since grown to 43 stars (Li et al. 2023; Deheuvels et al. 2023; Hatt et al. 2024), out of over 2000 stars analysed, giving a detection rate of about 2%. The methods used thus far are known to possess strong observational biases (number of detected mode components, field strength, ...). PLATO is expected to greatly expand the number of observable red giants, with over $10,000$ new targets (Rauer et al. 2024). In this proceeding, we present a method to identify core magnetic field signatures in red giants using their power spectra. We first describe the magnetic effects, sample selection, and frequency extraction process. In the second section we follow by fitting asymptotic models to the mixed modes, and finally discuss our results and their relevance for PLATO in the last section.

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2 Models, sample and spectra

2.1 Effects of rotation and magnetic field on mixed mode spectra

For slow rotators, the horizontal part of the modes correspond to spherical harmonics. If rotation is null, non radial modes are degenerate with respect to the azimuthal order m. In our case, the slow rotation of red giants lifts this degeneracy. Using the theory of perturbations (Ledoux 1951; Hansen et al. 1977), one can treat rotation as a perturbation of the oscillation equations. The magnetic field, if weak enough, can also be treated as a perturbation (Gough & Thompson 1990). Its effect has been studied for different cases, such as for pure g-modes (Hasan et al. 2005) or mixed modes in giants for dipolar fields (Gomes & Lopes 2020; Mathis et al. 2021; Bugnet et al. 2021) and for general fields in Li et al. (2022). In the oscillation spectra, rotationally split dipolar modes appear as symmetrical triplets. The effect of the magnetic field appears as a shift in the frequency of mode components, inversely proportional to the cube of the frequency, sometimes accompanied by the creation of an asymmetry in the triplet. Li et al. (2022) showed that the effect of the perturbation from axisymmetric and non-axisymmetric fields on mode frequency is indistinguishable from one another if the rotational frequency splitting is greater than the shift caused by the magnetic field. We can highlight frequency shifts and asymmetries by representing the g mode spectra as échelle diagrams (or stretched échelle diagrams for mixed modes), such as on figure 1. On these figures, one can notice the necessity of a great confidence in the selection of the modes at lower frequencies. Indeed, when identifying modes, selecting a realisation of noise instead of signal can be detrimental to the determination of magnetic shifts, potentially biasing the measure.

2.2 The gravity offset ε_g and the extraction of the modes

In this study, we focused on a small sample of stars with a higher probability of hosting magnetic fields. Since magnetic fields mainly affect the g-modes in red giants (Mathis et al. 2021), our analysis centres on that part for mixed modes. In the asymptotic regime, g-mode periods follow the relation $P_g = \Delta\Pi_1(n_g + \varepsilon_g)$, where $\Delta\Pi_1$ is the period spacing and ε_g the gravity offset. The latter is well constrained both theoretically (Pinçon et al. 2019) and observationally (Mosser et al. 2018), with a typical value of $\varepsilon_g = 0.28 \pm 0.08$ for *Kepler* red giants. Magnetic fields induce a modification of the g-mode pattern, more visible at lower frequencies, as explained earlier. If unaccounted for and fitting with a classical expression, we measure $P'_g = \Delta\Pi'_1(n_g + \varepsilon'_g)$, where ε'_g deviates from the expected value. Using the catalogue of 2006 red giants from Li et al. (2024), which provides precise seismic and rotational parameters but without consideration for magnetic fields, we selected 150 stars showing significant deviations from the expected ε_g value, indicating potential magnetic activity.

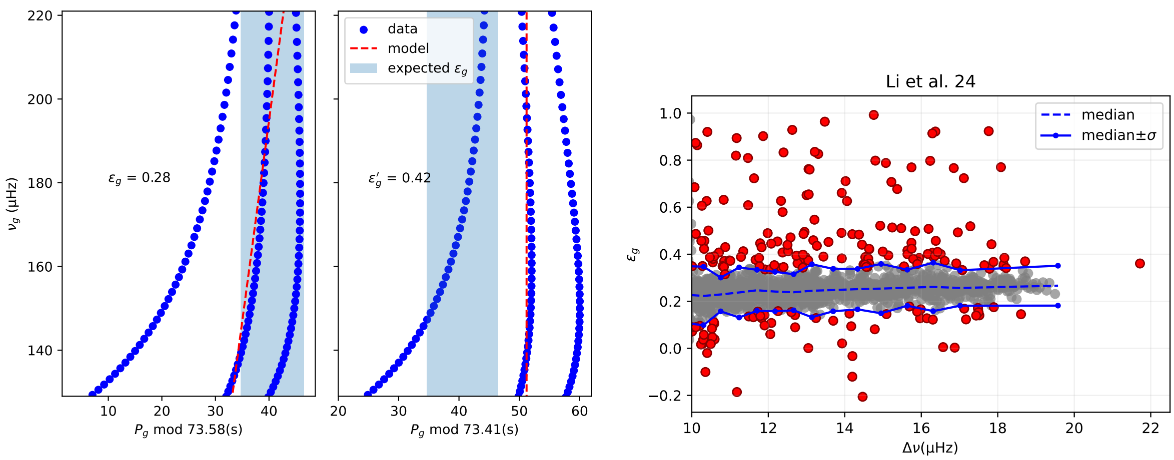

Fig. 1. Left: Échelle diagrams of a simulated g mode spectrum. The left image represents the spectrum folded by the true period spacing $\Delta\Pi_1$ with rotation and magnetic field. The right image represent the same spectrum folded by $\Delta\Pi'_1$, measured without taking magnetic field into account. The shaded area represent the expected period range using the empirical value of ε_g. **Right:** Relationship between ϵ_g and $\Delta\nu$ in the Li et al. (2024) catalogue. Red dots represent stars selected for this study, in contrast to the grayed out dots. Full blue lines represent the delimitation of the bulk distribution at $\pm 1\sigma$ and the dashed blue line is made from the median of every 118 stars slice.

We selected significant peaks in the oscillation spectrum by ensuring a predetermined low false-alarm probability, while maximising the probability of detecting the modes (see details in Villate et al. in prep).

3 Fitting the spectra and Results

3.1 *Detecting magnetic fields*

Once modes were extracted, we applied a Bayesian inference method to fit the detected frequencies to an asymptotic model that includes rotation and magnetic effects (Li et al. 2022; Deheuvels et al. 2023). The fit used a Markov Chain Monte Carlo algorithm (based on Goodman & Weare 2010), allowing us to sample the posterior distributions of seismic and magnetic parameters. Using model comparison on the magnetic shift $\nu_{\rm mag}$, we assessed the probability of magnetic detection for each star. In total, 21 stars show $> 85\%$ odds of being magnetic, increasing the number of detections by 30%. To estimate magnetic field strengths from $\nu_{\rm mag}$, we linked seismic parameters to stellar structures using a grid of 324 MESA models (Paxton et al. 2011), varying in mass, metallicity, and overshoot. We selected models best matching the envelope ($\Delta\nu$, $\nu_{\rm max}$) and core ($\Delta\Pi_1$) structure. The field intensity was then computed using (Li et al. 2022):

$$\langle B_r^2 \rangle = \nu_{\rm mag} \frac{2\pi\mu_0 (2\pi\nu_{\rm max})^3}{\mathcal{I}}\,, \tag{3.1}$$

where $\mathcal{I}$ is an integral from the stellar structure.

3.2 *Some results*

The magnetic field intensity is linked to stellar evolution via the mixed mode density $\mathcal{N} = \frac{\Delta\nu}{\Delta\Pi_1 \nu_{\rm max}^2}$ (Gehan et al. 2018), which increases with age. This relationship is shown in Fig. 2. There, we notice a decreasing

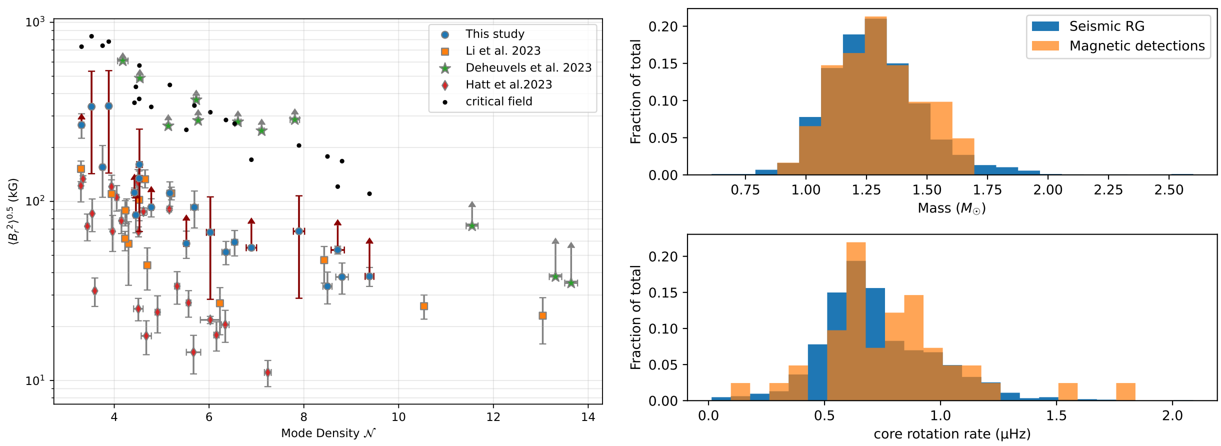

Fig. 2. Left: Magnetic field intensity versus mixed mode density $\mathcal{N}$. **Right:** Mass and core rotation distribution for seismic and magnetic detections.

trend in intensity with evolution. This may appear counter-intuitive: as stellar cores contract, magnetic field intensity should increase if magnetic flux is conserved. One hypothesis to explain this tendency would be that the field intensity does increase, but eventually reaches the critical field strength (black dots on the left of figure 2), over which oscillations are damped, making no detection possible. Another possibility would have to do with the progression of the hydrogen burning shell (HBS) to higher radii with age, if the field originates from a convective core dynamo in the main sequence. As the measure of the magnetic field is especially probed around the HBS (see Li et al. 2022), its increasing radius could exceed the limit of the main sequence convective core, decreasing the measured intensity.

One can also investigate the mass and rotation distributions for the detected stars. Indeed, the now higher number of detections allows us to explore distributions as we approach statistical significance. These distributions are shown in the right panel of Fig. 2. On the top part, we compare the mass distributions for all seismic red giants and for magnetic red giants. There, we notice that the two distributions are very similar, which is validated by a Kolmogorov-Smirnov test. The same trend can be seen with core rotation on the bottom part. This suggests that despite the low rate of detection for core magnetic fields ($\sim 2\%$), magnetic stars are not as peculiar as thought. In turn, this could mean that magnetic fields in the cores of stars are more widespread in the universe, but are as of yet inaccessible because of observational biases and detection thresholds.

4 Conclusions

Overall, we developed a method ensuring high confidence in mode identification from stellar oscillation spectra, which we applied to 150 *Kepler* red giants with suspicions of existing magnetic fields. By fitting asymptotic mixed-mode models including rotation and magnetic effects, using MCMC and Bayesian model comparison, we detected 21 new magnetic stars, increasing known detections by 30%. Our analysis suggests no significant differences in mass or core rotation between magnetic and non-magnetic stars, hinting that core magnetic fields may be more common than previously thought. However, the current sample size remains too small to draw firm conclusions.

Next, we plan to apply this method to more luminous red giants ($\Delta\nu < 10\mu$Hz), then extend it to the full Li et al. (2024) catalogue to strengthen the statistical significance of our findings and further explore the role and origin of magnetic fields.

Looking ahead to the PLATO mission and its expected $10,000$ red giant targets, our method is ready to be applied to its data. This could significantly expand magnetic field detections and contribute to improving stellar models, ultimately refining age estimates for stars and planetary systems.

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