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STRONG MAGNETIC FIELDS DISCOVERED IN RED GIANT CORES USING SEISMOLOGY

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Abstract. We here provide a short summary of the first direct detection and measurement of magnetic fields in the cores of 24 red giants stars observed with the *Kepler* satellite (Borucki et al. 2010). For more detailed information, please see Li et al. (2022), Deheuvels et al. (2023), and Li et al. (2023).

Keywords: asteroseismology, stars: magnetic fields, stars: interiors, stars: evolution

1 Introduction

Magnetic fields affect stars throughout their lives. They are thought to play a crucial role in the redistribution of angular momentum within stars (e.g. Maeder & Meynet 2005). This impacts the rotational transport of chemical elements, and in turn the evolution of stars. Understanding the interaction between magnetic fields and rotation is thus a crucial step toward improving the precision to which stellar models can predict stellar ages. Until very recently, magnetic fields had been observed only at the surface of stars using spectropolarimetric observations (e. g. Donati & Landstreet 2009). The opacity of stellar matter had so far precluded direct detection of internal magnetic fields inside stars. Asteroseismology, which consists in the study of waves that propagate inside stars, is currently the only tool at our disposal to probe stellar interiors.

The seismology of red giant stars has become a crucial tool to test stellar physics. Red giant stars show extended convective envelopes, in which oscillation modes are stochastically excited, like in the Sun. For red giants, the frequency range of pressure (p) modes is comparable to that of gravity (g) modes. These two types of modes can thus couple, giving rise to so-called mixed modes, which probe both the envelope (where they behave as p modes) and the core (where they act as g modes). Since their detection in subgiants (Deheuvels & Michel 2010) and red giants (Beck et al. 2011), mixed modes have provided a wealth of information, for instance about their evolutionary status (Bedding et al. 2011), or their internal rotation (e.g. Beck et al. 2012, Deheuvels et al. 2012, Mosser et al. 2012). We here provide a short summary of how mixed modes were used to provide the first direct detection and measurement of magnetic fields in the cores of 24 red giants stars observed with the *Kepler* satellite (Borucki et al. 2010). For more detailed information, please see Li et al. (2022), Deheuvels et al. (2023), and Li et al. (2023).

2 Effects of magnetic fields on oscillation mode frequencies

To introduce the effects of magnetic fields on oscillation frequencies, it is convenient to first explain how they are impacted by rotation. By breaking the spherical symmetry of the star, rotation lifts the degeneracy between the frequencies of oscillation modes with same radial order n, same angular degree l, but different azimuthal orders m. This produces co-called *rotational multiplets* with $2l+1$ components. For slow rotators, such as red giants, the rotational multiplets are nearly symmetrical with respect to the central $m=0$ component. Until very recently, deviations from the symmetry of multiplets had been observed only in p-dominated modes for certain red giants, owing to so-called near-degeneracy effects (Deheuvels et al. 2017).

The effects of magnetic fields on oscillation mode frequencies have been explored early on (Goossens 1972), and later extended to place constraints on the solar magnetic field (Gough 1990). They add to the effects of

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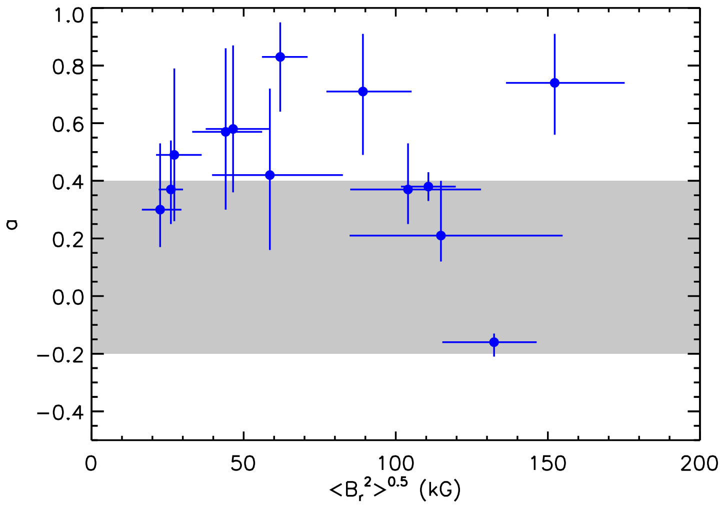

Fig. 1. Measured asymmetry parameter a as a function of the measured field strength for the 13 targets studied by Li et al. (2023). The gray shaded area shows the range of values of a covered by dipolar fields with various inclinations.

rotation by modifying the structure of rotational multiplets. Non-axisymmetric magnetic fields are known to produce up to $(2l+1)^2$ components per multiplet (Unno et al. 1989, Gough 1990), which can severely complicate the picture. For simplicity, most studies addressing this issue assumed specific configurations of the magnetic field. In particular, they commonly considered axisymmetric fields (aligned with the rotation axis), which do not modify the number of components in rotational multiplets, but can produce characteristic multiplet asymmetries. In this context, Hasan et al. (2005) showed that a dipolar axisymmetric field induces a highly-frequency-dependent perturbation to high-order g modes ($\delta\omega \sim \omega^{-3}$). The case of mixed modes in red giants was later addressed by Gomes & Lopes (2020), Mathis et al. (2021), and Bugnet et al. (2021), also assuming axisymmetric dipolar fields. Mathis et al. (2021) showed that the magnetic perturbations to mixed modes are dominated by contribution from the core field (i.e., by the effects on g-dominated modes), and Bugnet et al. (2021) explored the multiplet asymmetries caused by such magnetic fields. The effects on mixed modes of a dipolar field inclined with respect to the rotation axis were addressed by Loi (2021).

3 Detection of core magnetic fields in Kepler red giants using multiplet asymmetries

In Li et al. (2022) and Li et al. (2023), we detected clear asymmetries in the dipole multiplets of 13 red giants observed with *Kepler*. These asymmetries show features that closely correspond to what is expected in the presence of a core magnetic field: (i) they are stronger for g-dominated modes, (ii) they strongly decrease (in absolute value) as a function of frequency (the decrease is compatible with a dependency $\propto \omega^{-3}$), and (iii) they have the same sign for all multiplets in a given star (they are positive for 12 targets, and negative for only one star). We were able to safely rule out all known sources of multiplet asymmetries aside from magnetic fields. Indeed, we measured the internal rotation of these stars and found that they are all slow rotators, like other red giants. Also, the detected asymmetries cannot arise from near-degeneracy effects because they would then be stronger for p-dominated mixed modes, and also the asymmetries of consecutive modes would have alternate signs (Deheuvels et al. 2017).

To compare the detected asymmetries with theoretical magnetic perturbations, in Li et al. (2022) we generalized previous works to the case of magnetic fields with an arbitrary topology. We found that the average magnetic frequency shift of the components in a multiplet $\omega_{\rm B}$ can be expressed as $\omega_{\rm B} \propto \omega^{-3} \int_{\rm g} K(r) \overline{B_r^2}\,{\rm d}r$, where the weight function $K(r)$ depends on the core structure and $\overline{B_r^2}$ is a horizontal average of the square of the radial field. We showed that provided the ratio b between the magnetic shift $\omega_{\rm B}$ and the rotational shift $\omega_{\rm R}$ remains below unity, the effects of non-axisymmetry of the field on the oscillation modes remain negligible. In this case, the multiplet asymmetries can be expressed as $\delta_{\rm asym} = 3a\omega_{\rm B}$, where a corresponds to a horizontal average of B_r^2 weighted by the second order Legendre polynomial $P_2(\cos\theta)$, and thus depends on the geometry of the field. We showed that a is maximal ($a = 1$) for a field entirely concentrated on the poles, and a is minimal ($a = -1/2$) for a field concentrated on the equator. This demonstrated that multiplet asymmetries can take on negative values, while previous theoretical studies, which considered particular field geometries, all predicted positive asymmetries. A purely dipolar field yields values of a ranging from $-1/5$ (when it is aligned with the equator) and $2/5$ (when it is aligned with the rotation axis). Mathis & Bugnet (2023) later specified the relation between the inclination angle of the dipolar field and the value of a.

We found that the above expressions were able to account very well for the detected asymmetries in the 13 *Kepler* red giants. By measuring $\omega_{\rm B}$ and a for these stars, we obtained measurements of the core field strengths ranging from 20 to 150 kG. We could also place constraints on the field topology. As shown in Fig. 1, the values of a we measured cover a large part of the possible range, which shows that there exists a wide diversity of field topologies in red giants cores. Also, for several stars, our measurements of a significantly exceed the maximal possible value for dipolar fields. This means that for these stars, the core field is more concentrated near the poles than a pure dipolar field aligned with the rotation axis.

4 Detection of strong core fields in Kepler red giants using g-mode periods

In the non-magnetic case, the periods of high-radial order g modes of degree l are nearly regularly spaced by the period spacing $\Delta\Pi_l$. A strong core magnetic field can produce significant deviations from this regularity (Loi 2020, Bugnet et al. 2021, Li et al. 2022). In Li et al. (2022), we showed that in this case, the period spacing $\Delta\Pi_l$ measured when ignoring magnetic effects is expected to be abnormally low (compared to other red giants) and non-constant with frequency. Several stars showing precisely these features had been identified in another context by Deheuvels et al. (2022). In Deheuvels et al. (2023), we found several other such stars and we showed that strong core fields account very well for the observations. The alternate explanation for these anomalies (so-called *buoyancy glitches*) was found to be very unlikely. We found minimal core fields in these stars ranging from 40 to 610 kG. These intensities are comparable to the critical field strength $B_{\rm c}$ above which the propagation of magneto-gravity waves are expected to be inhibited in the core (Fuller et al. 2015). The presence of core magnetic fields stronger than $B_{\rm c}$ was invoked by Fuller et al. (2015) to account for the unexpectedly low amplitudes of dipole mixed modes in about 20% of red giants (Stello et al. 2016), although this interpretation remains debated (Mosser et al. 2017). In Deheuvels et al. (2023), we found that the only star for which the measured field exceeds $B_{\rm c}$ shows mixed mode suppression at low frequency, which further suggests that this phenomenon might be related to strong core magnetic fields.

5 Origin and evolution of core magnetic fields

These first detections of internal magnetic fields bring direct observational constraints to investigate the origin of stellar magnetism. For stars in the mass range of our targets, the most commonly quoted origin is through dynamo action in the main-sequence convective core. The Ohmic dissipation time being longer than the lifetimes of the stars, such fields could persist long after the end of the main sequence. By assuming conservation of the magnetic flux, we found that the detected fields could be the remnants of main-sequence fields of a few kG. These estimates are lower but comparable to the field strengths predicted by numerical simulations of core convection (Brun et al. 2005) or by dynamo scaling laws (Bugnet et al. 2021). Another possibility is that these fields originate from fossil fields inherited from the stellar formation history.

Fig. 2 shows the measured field intensities as a function of the density of mixed modes, which is a good proxy for the evolution along the red giant branch (Gehan et al. 2018). We observe an overall decrease of the field strength with evolution. At first sight, one could have expected the contrary. Indeed, the core of red giants keeps contracting, which should produce an increase in the core field intensity, assuming conservation of the magnetic flux. In Deheuvels et al. (2023) and Li et al. (2023), we proposed that the observed decrease is related to the critical field strength $B_{\rm c}$, which itself decreases with evolution with a similar trend as the observed field strengths (see Fig. 2). The argument of Fuller et al. (2015) is that whenever the core field exceeds $B_{\rm c}$, mixed modes can no longer form. If it is indeed the case, we would then be unable to seismically detect the core field. The impact of a field stronger that $B_{\rm c}$ on global oscillation modes in red giants is currently a matter of debate (e.g., Rui & Fuller 2023).

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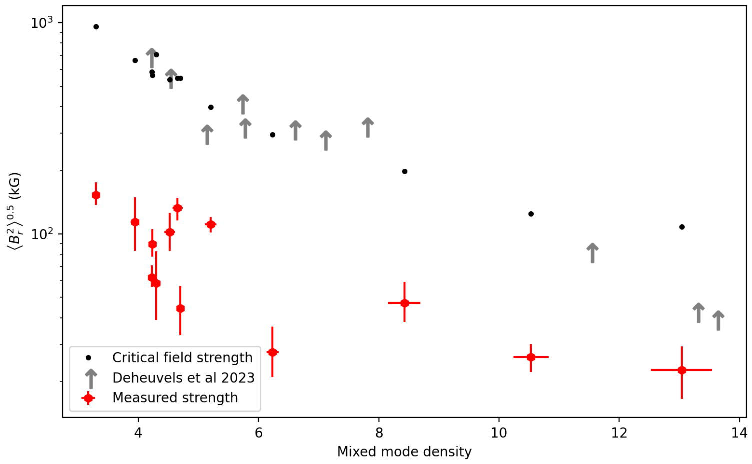

Fig. 2. Field strength as a function of mixed mode density, which is a proxy for evolution (stars evolve from left to right). The red hexagons are the field strengths of the 13 stars from Li et al. (2023), and the black dots are their critical field strengths. The grey vertical arrows show the lower limits of the field strengths reported by Deheuvels et al. (2023). Figure from Li et al. (2023)

References

Beck, P. G., Bedding, T. R., Mosser, B., et al. 2011, Science, 332, 205
Beck, P. G., Montalban, J., Kallinger, T., et al. 2012, Nature, 481, 55
Bedding, T. R., Mosser, B., Huber, D., et al. 2011, Nature, 471, 608
Borucki, W. J., Koch, D., Basri, G., et al. 2010, Science, 327, 977
Brun, A. S., Browning, M. K., & Toomre, J. 2005, ApJ, 629, 461
Bugnet, L., Prat, V., Mathis, S., et al. 2021, A&A, 650, A53
Deheuvels, S., Ballot, J., Gehan, C., & Mosser, B. 2022, A&A, 659, A106
Deheuvels, S., García, R. A., Chaplin, W. J., et al. 2012, ApJ, 756, 19
Deheuvels, S., Li, G., Ballot, J., & Lignières, F. 2023, A&A, 670, L16
Deheuvels, S. & Michel, E. 2010, Ap&SS, 328, 259
Deheuvels, S., Ouazzani, R. M., & Basu, S. 2017, A&A, 605, A75
Donati, J. F. & Landstreet, J. D. 2009, ARA&A, 47, 333
Fuller, J., Cantiello, M., Stello, D., Garcia, R. A., & Bildsten, L. 2015, Science, 350, 423
Gehan, C., Mosser, B., Michel, E., Samadi, R., & Kallinger, T. 2018, A&A, 616, A24
Gomes, P. & Lopes, I. 2020, MNRAS, 496, 620
Goossens, M. 1972, Ap&SS, 16, 386
Gough, D. O. 1990, in Lecture Notes in Physics, Berlin Springer Verlag, Vol. 367, Progress of Seismology of the Sun and Stars, ed. Y. Osaki & H. Shibahashi, 283
Hasan, S. S., Zahn, J. P., & Christensen-Dalsgaard, J. 2005, A&A, 444, L29
Li, G., Deheuvels, S., Ballot, J., & Lignières, F. 2022, Nature, 610, 43
Li, G., Deheuvels, S., Li, T., Ballot, J., & Lignières, F. 2023, arXiv e-prints, arXiv:2309.13756
Loi, S. T. 2020, MNRAS, 493, 5726
Loi, S. T. 2021, MNRAS, 504, 3711
Maeder, A. & Meynet, G. 2005, A&A, 440, 1041
Mathis, S. & Bugnet, L. 2023, A&A, 676, L9
Mathis, S., Bugnet, L., Prat, V., et al. 2021, A&A, 647, A122
Mosser, B., Goupil, M. J., Belkacem, K., et al. 2012, A&A, 548, A10
Mosser, B., Pinçon, C., Belkacem, K., Takata, M., & Vrard, M. 2017, A&A, 600, A1
Rui, N. Z. & Fuller, J. 2023, MNRAS, 523, 582
Stello, D., Cantiello, M., Fuller, J., et al. 2016, Nature, 529, 364
Unno, W., Osaki, Y., Ando, H., Saio, H., & Shibahashi, H. 1989, Nonradial oscillations of stars (Tokyo: University of Tokyo Press) (University of Tokyo Press)