Stars and their variability observed from space
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INTERNAL STELLAR MAGNETIC FIELDS

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Abstract.
The past five years have seen a remarkable growth in our understanding of internal stellar magnetic fields. The largest advances have occurred for low-mass red-giant stars, for which space-based photometry has yield thousands of detections of mixed modes that penetrate into their radiative cores. Advances in theory have shown how these modes provide tight constraints on the rotation and magnetic field strengths of their degenerate cores. Core rotation rates may be determined by magnetic torques, providing additional insight into evolutionary phases where data are not available.

Keywords: Stars: magnetic fields, interiors

1 Introduction

The ongoing asteroseismic renaissance has led to a paradigm shift in our understanding of internal stellar magnetic fields. Unlike surface fields, which can be probed with Zeeman splitting and polarimetry, little was previously known about internal fields. Prior constraints (e.g., those from helioseismology) were weak because acoustic modes are only sensitive to magnetic fields that contribute significantly to the internal stellar pressure, i.e., magnetic pressure comparable to thermal pressure. Such field strengths ($B > 1$ MG) in main-sequence stars imply implausibly large and theoretically unexpected magnetic fluxes, so those constraints have not been particularly useful.

2 Magnetic fields through an asteroseismic lens

Recent asteroseismic data have been much more useful, because gravity modes are a much more sensitive probe of internal magnetic fields. Unlike pressure modes that are sensitive only to near-equipartition field strengths, gravity modes are sensitive to fields whose magnetic tension restoring force competes with buoyancy forces. High-order g modes, like the mixed modes that propagate in the cores of red giants, are thus sensitive to fields far below equipartition. Fuller et al. (2015) showed that magnetic fields with radial components

$$B > B_{\rm crit} = \sqrt{\frac{\pi\rho}{2}}\frac{\omega^2 r}{N} \tag{2.1}$$

will affect g modes strongly, where ω is the mode's angular frequency and N is the Brunt-Väisälä frequency. In typical red giants, fields in excess of $\sim 10^5$ G near the hydrogen-burning shell will affect the mixed modes strongly and are hence readily observable. These magnetic fluxes are comparable to those in other magnetic stars and to those produced in convective dynamos (e.g., Augustson et al. 2016, so we might expect them to be prevalent in stellar interiors.

To understand the observable signature of magnetic fields, the interaction of gravity waves and magnetic fields have been studied in several recent works. Fuller et al. (2015) showed that gravity waves become evanescent for field strengths in excess of equation 2.1. That work also showed that the wave-field interaction would increase greatly the wavenumber of the mode, transferring power to high angular wavenumbers ℓ, such that the scattered mode would be trapped within the radiative core of a red giant in a so-called "magnetic greenhouse" effect. Hence, any g mode propagating into a strongly magnetized core of the star would not be able to tunnel back towards the surface of the star, so mixed modes would be suppressed and would not be observable in the star's power spectrum.

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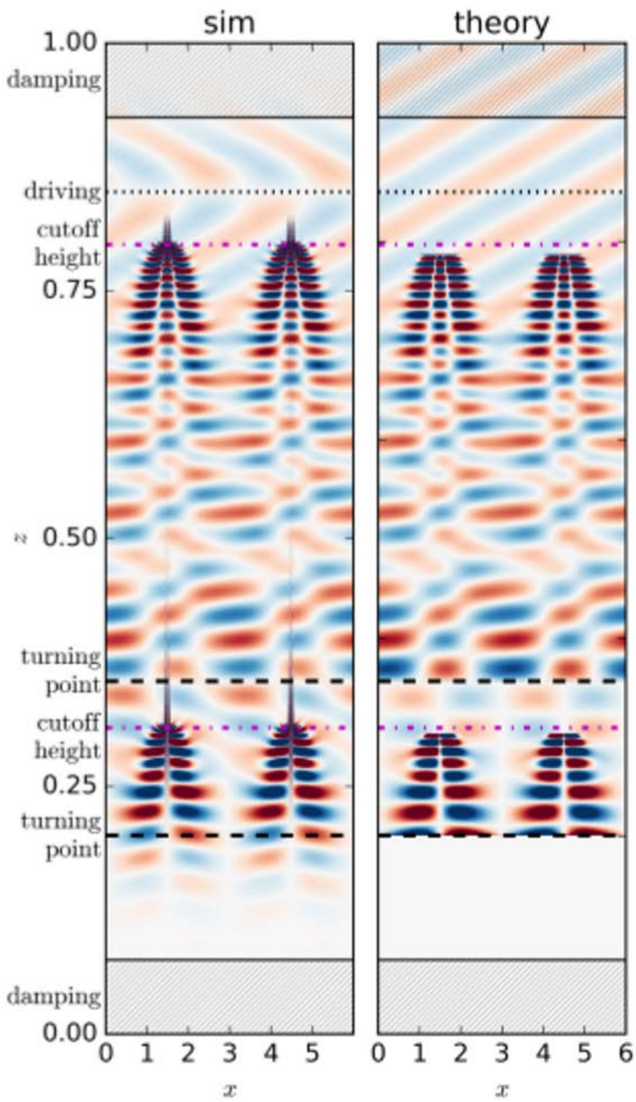

Fig. 1. Left panel: Simulation, **right panel:** analytic calculation, of gravity waves interacting with a magnetic field, colour-coded by horizontal velocity, taken from Lecoanet et al. (2017). The turning points correspond to an analytic prediction, similar to that of equation 2.1, for waves of differing parity. The cutoff heights are where the magnetically refracted Alfvén waves reach infinite wavenumber and the waves damp.

Lecoanet et al. (2017) performed a more rigorous calculation of the wave–field interaction that occurs in stellar interiors, finging that for radial field strengths in excess of B_c in equation 2.1 (with weak dependence on magnetic geometry), incident gravity waves would be totally converted into outgoing Alfvén-like waves (Fig. 1). The angular and radial wavenumber of the Alvén waves diverges, causing the waves to be completely damped within the star such that no gravity wave escapes the radiative core and no mixed modes can be formed. The star's dipole mode power would be heavily suppressed relative to radial modes (which do not propagate as gravity waves and do not interact with internal fields) in a very predictable way.

Indeed, Stello et al. (2016) showed that this dipole mode suppression is relatively common and is observed in roughly 20% of red giants in the *Kepler* field (see Fig. 2). These "depressed dipole mode stars" had already been noted by Mosser et al. (2012) and García et al. (2014) but the mechanism had not then been identified. Stello et al. (2016) showed that the level of suppression matches closely the predictions of Fuller et al. (2015) based on core magnetic fields, lending credence to the magnetic hypothesis. Moreover, Stello et al. (2016) showed that dipole mode suppression is very sensitive to stellar mass, occurring in roughly 50% of stars with $M > 1.5\,M_{\odot}$, and almost never occurring for $1\,M_{\odot}$ stars. They interpreted the suppression as arising from core magnetic fields left over from magnetic dynamos in the convective cores of the main-sequence progenitors of red giants.

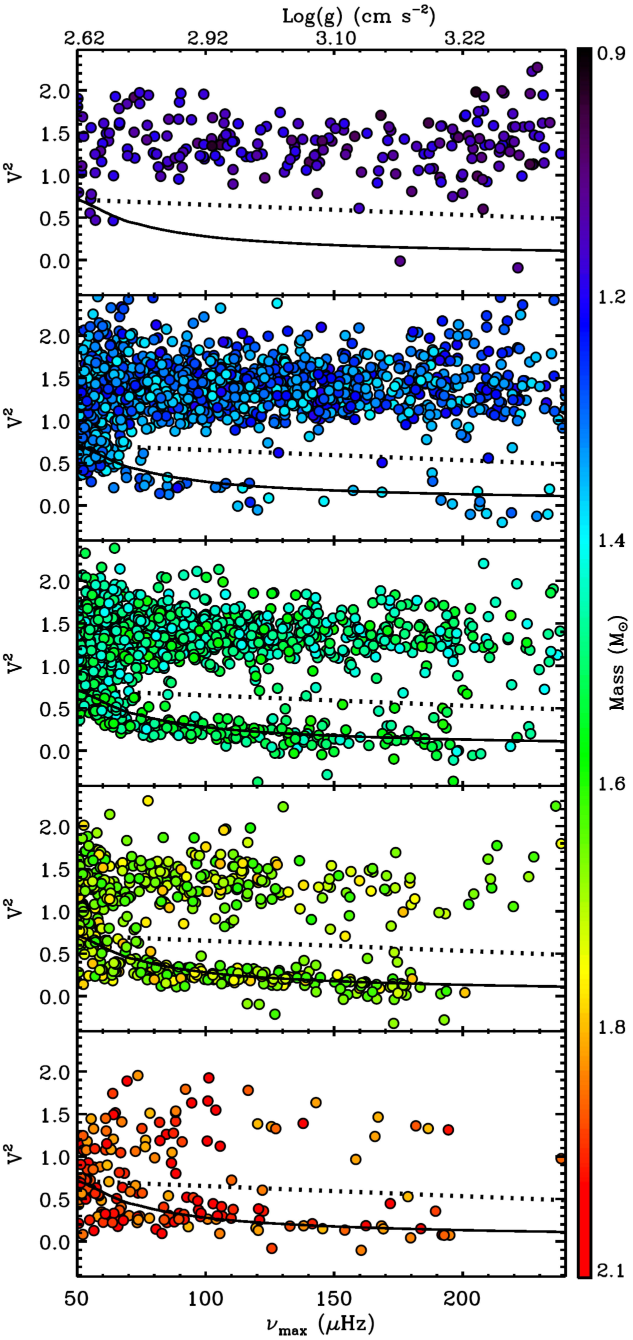

Fig. 2. Dipole mode power compared to radial mode power in a large sample of red giants with *Kepler* data from Stello et al. (2016). Each point corresponds to a different star with frequency of maximum power $\nu_{\rm max}$ and colour-coded mass. The prediction for magnetic suppression from Fuller et al. (2015) is shown by the solid line.

Cantiello et al. (2016) examined the implications of that model and the constraints on magnetic fields possible for a variety of pulsating stars.

That interpretation of Stello et al. (2016) has been challenged by Mosser et al. (2017), who found that the suppressed modes still show signatures of being mixed modes, i.e., there are multiple mixed-mode components surrounding each dipole p mode in the power spectra (see Fig. 3). Mosser et al. (2017) also found evidence of frequency bumping (implying the existence of mixed modes) even when mixed modes are not detectable directly. This contradicts the prediction from Fuller et al. (2015) that strong magnetic fields prevent coherent g modes from existing in the power spectra, and that only a suppressed envelope p mode should be observed.

Currently this issue remains controversial. A counterpoint to Mosser et al. (2017) is that most of the stars

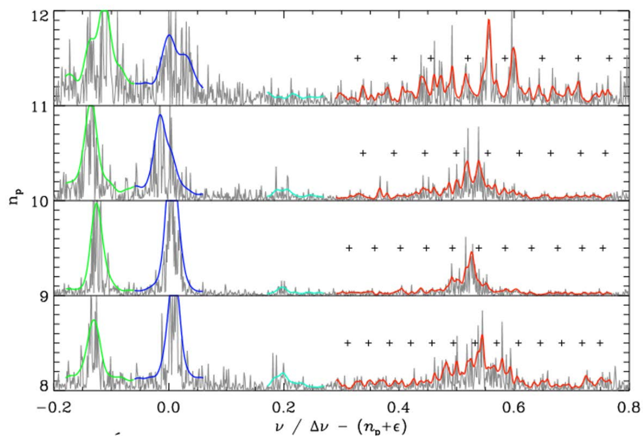

Fig. 3. From Mosser et al. (2017), the power spectrum of a star with low dipole mode amplitude, yet still with possible evidence for dipole mixed modes (red part of the power spectrum). Crosses show the expected period spacing of dipole mixed modes. The magnetic suppression model of Fuller et al. (2015) predicts a single, very broad, Lorentzian profile for dipole modes, similar to (but broader than) that of the radial modes (dark blue line). From Mosser et al. (2017); ©ESO, reproduced with permission.

where depressed mixed modes appear to be observed are either ordinary clump stars (they lie at the left edge of Fig. 2), or they have larger dipole visibilities than most red giants with suppressed dipole modes and could simply be ordinary red giants with weaker dipole modes (they lie near the dotted line in Fig. 2). Both groups agree that the clear presence of mixed modes in a red giant excludes the presence of core magnetic fields with radial components exceeding equation 2.1.

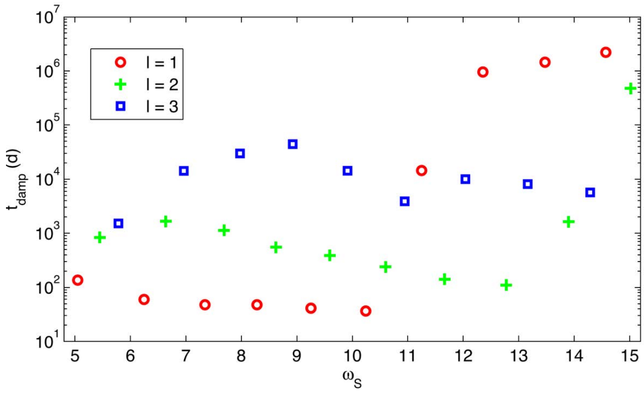

Fig. 4. From Loi & Papaloizou (2017), the damping time of mixed modes of acoustic degree ω_S in a red giant, due to interaction with strong toroidal magnetic fields. Larger field strengths (and lower mode fequencies) produce efficient damping when the toroidal field strength roughly exceeds equation 2.1.

If mixed modes do exist in stars with suppressed dipole modes, another damping mechanism must be at play. The suppressed modes are most evident in stars low on the red-giant branch and for which radiative damping and non-linear damping effects (Weinberg & Arras 2019) are inadequate. The most likely alternative is strong toroidal magnetic fields (i.e., those with a much smaller radial component relative to the horizontal component). Such fields were investigated in a series of papers by (Loi & Papaloizou 2017, 2018, 2019), who showed that gravity-wave energy is sapped by the excitation of Alfvén waves that propagate along the magnetic field lines. Magnetic fields with strengths comparable to equation 2.1 cause the most efficient damping because the phase speed of gravity waves and Alfvén waves are comparable at those field strengths. Fig. 4 shows that, for a given magnetic field strength, the damping is efficient for modes whose frequencies lie below that of equation 2.1, and inefficient for higher-frequency modes. Crucially, because the modes are damped but not totally destroyed, mixed modes would still be apparent in the spectrum, but with suppressed amplitude owing to the extra magnetic damping in the core.

We note that both plausible models of dipole-mode suppression involve strong magnetic fields in the radiative cores of red giants. The question is whether the fields have significant radial components (as examined by Fuller et al. 2015 and Lecoanet et al. 2017), or whether they are nearly toroidal so that the mechanism of Loi & Papaloizou (2017) can operate without complete magnetic suppression of mixed modes. Additional studies of the power spectra of stars with suppressed dipole modes should be performed in order to constrain rigorously and statistically the presence of mixed modes in these stars.

3 Magnetic effects on internal stellar rotation

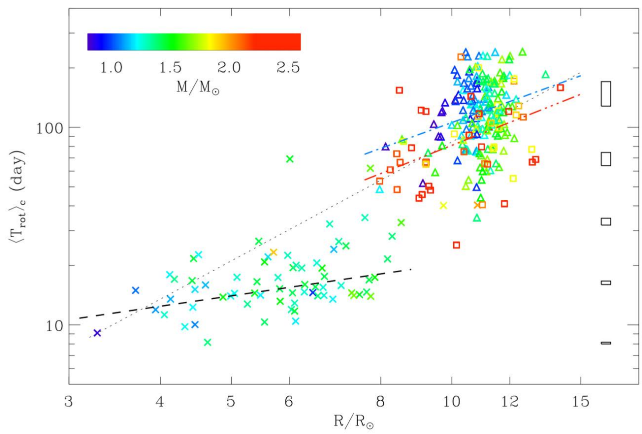

Fig. 5. Asteroseismically measured core rotation periods of a large sample of red giants as a function of stellar radius, colour-coded by mass. From Mosser et al. (2012); ©ESO, reproduced with permission.

Magnetic fields almost certainly have a huge impact on angular momentum transport and the internal rotation profiles of stars. Asteroseismic measurements of core rotation rates of red giants from Mosser et al. (2012); Gehan et al. (2018) reveal core rotation periods of ∼15 days on the red-giant branch, and ∼ 100 days on the clump, with considerable scatter (Fig. 5). Although the cores rotate much faster than the stellar surfaces (see, e.g., Beck et al. 2012; Deheuvels et al. 2014), they rotate much slower than predicted by the most popular pre-existing angular momentum transport models (see Fig. 6 and Cantiello et al. 2014) based on the magnetic Tayler-Spruit dynamo (Spruit 2002).

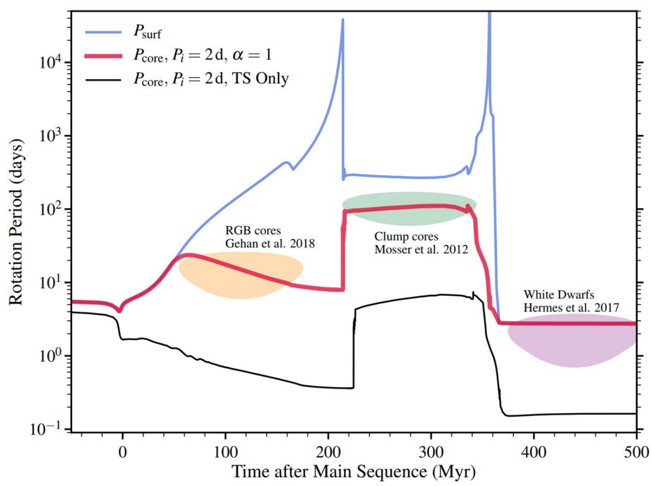

Fig. 6. From Fuller et al. (2019), a model of the core rotation rate of a 1.6 $M_\odot$ star evolving from the main sequence to the white-dwarf stage. The blue line shows the model's surface rotation period, while the red line shows the core rotation period with an updated angular momentum transport prescription based on the Tayler instability. The black line is the core rotation period using the Tayler-Spruit dynamo (Spruit 2002). Shaded ovals indicate typical core rotation rates measured by Mosser et al. (2012), Gehan et al. (2018), and Hermes et al. (2017).

Fuller et al. (2019) re-examined the Tayler instability in stellar interiors, arguing that energy is dissipated more slowly than the model of Spruit (2002). That would allow the magnetic fields to become larger in amplitude and exert stronger magnetic torques and transport more angular momentum. Applying their model to the MESA stellar evolution code (Paxton et al. 2011), they found core rotation rates much more compatible with asteroseismic data for red giants, clump stars and white dwarfs (Fig. 6). The most plausible alternative to this model is that nearly rigid core rotation is enforced by magnetic fields too strong to be wound up by differential rotation. In that case, strong differential rotation must exist within the convective envelopes of those stars (with inner rotation rates a factor of 10–100 larger than surface rotation rates), as advocated by Kissin & Thompson (2015). Detailed modelling of sub-giant stars (as in Eggenberger et al. 2019), where both core and surface rotation rates can be measured, will help to distinguish between the models, and will be enabled by upcoming *TESS* data.

4 Conclusions

Asteroseismology has delivered a wealth of surprising new insights on the magnetic fields that lurk deep within stellar cores. These fields manifest themselves by suppressing gravity modes, or by altering internal rotation rates. Internal magnetic fields could also suppress g-mode oscillations in many types of stars that would otherwise pulsate, such as stars in the γ-Doradus, SPB, and ZZ-Ceti instability strips. More detailed modelling of magnetic impacts on stellar pulsations (e.g., Prat et al. 2019) and new data from *TESS* on a variety of stellar pulsators (especially sub-giant stars) will shed new light on magnetic fields hidden deep within stars of all types.

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