DYNAMO-GENERATED MAGNETIC FIELDS COMMON IN THE CONVECTIVE CORES OF INTERMEDIATE-MASS STARS

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ABSTRACT

Magnetic fields play a role in almost all stages of stellar evolution (Landstreet 1992). Most low-mass stars, including the Sun, show surface fields that are generated by dynamo processes in their convective envelopes (Parker 1955; Donati & Landstreet 2009). Intermediate-mass stars do not have deep convective envelopes (Kippenhahn & Weigert 1990), yet 10% exhibit strong surface fields that are presumed to be residuals from the stellar formation process (Power et al. 2008). These stars do have convective cores that might produce internal magnetic fields (Brun et al. 2005), and these might even survive into later stages of stellar evolution, but information has been limited by our inability to measure the fields below the stellar surface (Aurière et al. 2015). Here we use asteroseismology to study the occurrence of strong magnetic fields in the cores of low- and intermediate-mass stars. We have measured the strength of dipolar oscillation modes, which can be suppressed by a strong magnetic field in the core (Fuller et al. 2015), in over 3600 red giant stars observed by Kepler. About 20% of our sample have mode suppression but this fraction is a strong function of mass. Strong core fields only occur in red giants above 1.1 solar masses (1.1M⊙), and the occurrence rate is at least 60% for intermediate-mass stars (1.6–2.0M⊙), indicating that powerful dynamos are very common in the convective cores of these stars.

Subject headings:

1. Red giants are formed when a low- or intermediate-mass star has finished burning the hydrogen in its core. This leaves an inert helium core surrounded by a thin hydrogen-burning shell and a very thick outer convective envelope. Like the Sun, red giants oscillate in a broad comb-like frequency spectrum of radial and non-radial acoustic modes that are excited by the turbulent surface convection (Ridder et al. 2009). The observed power spectrum has a roughly Gaussian envelope whose central frequency, νmax, decreases as a star expands during the red giant phase (Brown et al. 1991; Stello et al. 2009). The comb structure of the spectrum arises from a series of overtone sequences separated by the so-called large frequency separation, Δν. One of these overtone sequences is seen for each spherical degree, ℓ. For observations of unresolved distant stars, geometric cancellation prevents detection of modes with ℓ > 3. Their spectra are characterised by a pattern of radial (ℓ = 0) and quadrupolar (ℓ = 2) modes that form close pairs, interspersed with dipolar (ℓ = 1) modes located roughly halfway between successive radial-quadrupolar pairs. The octupolar modes (ℓ = 3) are weak or undetectable. The dipole modes have turned out to be particularly useful probes of internal structure (García & Stello 2015). They have been used to distinguish between hydrogen-shell and helium-core burning stars (Bedding et al. 2011; Stello et al. 2013; Mosser et al. 2014) and to measure radial differential rotation (Beck et al. 2011; Mosser et al. 2012). This usefulness arises because each acoustic non-radial mode in the envelope couples to multiple gravity modes in the core, forming several observable mixed modes with frequencies in the vicinity of the acoustic mode (Beck et al. 2011). This coupling is strongest for dipole modes, making them the most useful probes of the core (Dupret et al. 2009).

Figure 1 shows the oscillation power spectra of red giants at three different evolutionary stages observed by NASA’s Kepler mission. For “normal” stars (upper panels), the dipole modes (red peaks) have similar power to the radial modes (black peaks). However, at each stage of evolution we also find stars with greatly suppressed dipole modes (lower panels). Suppressed dipole modes have been reported in a few dozen red giant stars, with an occurrence rate of about 20% (Mosser et al. 2011; García et al. 2014). The cause of this phenomenon has been puzzling until recent theoretical work, which showed that the suppression can be explained if waves entering the stellar core are prevented from returning to the envelope. This occurs for dipole modes if there are strong magnetic fields in the core, giving rise to a “magnetic greenhouse effect” (Fuller et al. 2015).

We measured the amount of suppression by comparing the integrated power of the dipole and radial modes (the dipole mode visibility, V2), averaged over the four orders centred on νmax. While the normal stars show dipole mode visibilities of V2 ≈ 1.5, independent of νmax (Ballot et al. 2011; Mosser et al. 2011), the stars with suppressed modes have V2 ≈ 0.5 for νmax ≈ 70 μHz and down to almost zero for the least evolved red giants oscillating above 200 μHz (Fig. 1).

In Fig. 2 we show the dipole mode visibility for about 3600 red giants observed over the first 37 months of the Kepler mission. Our analysis is restricted to a sample of stars with νmax larger than 50 μHz and masses below 2.1M⊙ which, assuming no observational uncertainties, is expected to in-
ally merge as the stars evolve leftwards towards lower $\nu$ (et al. 2015). The decrease of the suppression towards lower house effect caused by strong internal magnetic fields (Fuller leaking into the stellar core is trapped by a magnetic green-
al. 2015). This prediction assumes that all the wave energy lower branch, with suppressed dipole modes, agrees remark-
in agreement with previous results (Mosser et al. 2011). The tion on the lower branch (stars with suppressed dipole modes ) above this threshold suggests that at least some of those sta rs hahn & Weigert 1990). The onset of magnetic suppression tive cores during the core-hydrogen-burning phase (Kippen-
cides with the mass below which they did not have convec-
tive waves in the envelope and gravity waves in the core (Fulle r et al. 2015). With this large sample we have been able to sep-
thetic waves in the envelope and gravity waves in the core (Fulle r 2015). This is a consequence of the weaker coupling between acous-
tic waves in the envelope and gravity waves in the core (Fuller et al. 2015). The decrease of the suppression towards lower $\nu_{\text{max}}$ is a consequence of the weaker coupling between acousti-
ic waves in the envelope and gravity waves in the core (Fuller et al. 2015). With this large sample we have been able to sepa-
rate the stars in Fig. 2 into five different mass intervals, from 0.9 to 2.1$M_\odot$. It is striking how strongly the relative population on the lower branch (stars with suppressed dipole modes) depends on mass.

We quantify the mass dependence in Fig. 3 by showing the relative number of dipole-suppressed stars (those below the dashed line in Fig. 2) in narrow mass intervals. We see no suppression in red giants below 1.1$M_\odot$, which coincides with the mass below which they did not have convective cores during the core-hydrogen-burning phase (Kippenhahn & Weigert 1990). The onset of magnetic suppression above this threshold suggests that at least some of those stars had convectively driven magnetic dynamos in their cores during the core-hydrogen-burning (main-sequence) phase. This is supported by 3D hydrodynamical modeling of these stars (Brun et al. 2005). Red giants no longer contain convective cores, leading us to conclude that the strong magnetic fields in suppressed oscillators are the remnants of the fields produced by core dynamos during the main sequence.

Figure 3 shows that the incidence of magnetic suppression increases with mass, with red giants above 1.6$M_\odot$ showing a remarkable suppression rate of 50-60%. These have evolved from main-sequence A-type stars, among which only up to $\approx$ 10% are observed to have strong fields at their surfaces (Power et al. 2008). We conclude that these magnetic A stars represent only the tip of the iceberg, and that a much larger fraction of A stars have strong magnetic fields hidden in their cores.

In Fig. 4 we show the observed $\nu_{\text{max}}$ and inferred mass of all the stars superimposed on a contour plot of minimum mag-
etic field strengths required for mode suppression (Fuller et al. 2015). For stars with suppressed modes (filled red circles), the underlying color provides a lower bound to the core field strength. For stars without suppressed modes (open black circles), the underlying color represents an upper limit to the field at the hydrogen-burning shell; above or below the shell the field could potentially be larger. Hence, normal and dipole-suppressed stars that fall in the same regions of Fig. 4 may have core field strengths that are only slightly differ-
ent. However, we expect that the dipole-suppressed stars on average exhibit stronger core fields than their normal counter parts.

Considering again the low-mass stars ($<1.1M_\odot$), of which none show suppression, we see from Figure 4 that magnetic fields above $\approx 10$ kG are not present at the hydrogen-burning shell when the stars are near the red giant luminosity bump ($\nu_{\text{max}} \approx 50 \mu$Hz). Assuming magnetic flux conservation from the main-sequence phase, this suggests that fields above $\approx 1$ kG do not exist within the cores of Sun-like stars (Fuller et al. 2015). Large scale fields in the solar interiors have been discussed in order to explain the properties of the tachocline (Gough & McIntyre 1998). However, our results do not

![Figure 1](image-url)

**Fig. 1.** — Oscillation spectra of six red giants observed with Kepler. The stars are ordered in three pairs, each representing a different evolution stage ranging from the most evolved (lowest oscillation frequencies) on the left to the least evolved (highest frequencies) to the right. The coloured regions mark the power dominated by modes of different degree $\ell =0\text{–}3$. For clarity the spectra are smoothed by 3% of the frequency separation between overtone modes, which for the most evolved stars tend to create a single peak at each acoustic resonance, even if it comprises multiple closely-spaced mixed modes (red peaks in the left and centre panels). The slightly downward sloping horizontal dashed line indicates the noise level. Observations of each star were made during the first 37 months of the *Kepler* mission (observing quarters Q0–Q14).
rule out strong horizontal fields near the radiative-convective boundary because those fields would be outside the core and could not cause mode suppression when the star evolves into a red giant.

Turning to higher masses we see that, for a given \( \nu_{\text{max}} \), stars above 1.4\( M_\odot \) require increasingly strong magnetic fields to suppress their dipole modes. From Figure 4, there is no clear upper limit to the field strengths present in red giant cores, given that suppressed stars are common even when field strengths \( B > 1 \text{ MG} \) are required for suppression. However, the hint of a decline in the occurrence of dipole-suppressed stars above 2\( M_\odot \) seen in Fig. 3 suggests there may be a mass above which dynamo-generated magnetic fields can no longer cause oscillation mode suppression in intermediate-mass stars.

The high occurrence rate of dipole mode suppression demonstrates that core-dynamo-generated fields can remain through the red giant phase, more than \( 10^8 \) yr after the dynamo has shut off at the end of core-hydrogen-burning. This indicates that, dynamo-generated fields are frequently able to settle into long-lived stable configurations, a result that was not certain from magnetohydrodynamical simulations (Braithwaite & Spruit 2004; Braithwaite & Nordlund 2006; Duez et al. 2010). The occurrence rate of suppressed dipole modes in intermediate-mass red giants is much higher than the occurrence rate of strong fields at the surfaces of the main-sequence A stars from which they evolved. The latter fields are thought to have been generated by a pre-hydrogen-core burning dynamo during star formation (Moss 2004). We conclude that fields generated during core-hydrogen-burning are able to settle into stable equilibrium configurations much more commonly (more than 60% of the time) than fields generated during star formation (less than 10% of the time).

Our results show that main-sequence stars with no observable magnetic field at the surface can still harbour strong fields in the core that survive into the red giant phase. The presence of internal magnetic fields might play an important role for angular momentum transport. Fields too weak to suppress dipole oscillation modes may exist in normal red giants, and these fields may nevertheless transport enough angular momentum to help explain the measured rotation rates of red gi-
ant cores (Mosser et al. 2012; Cantiello et al. 2014). After finishing hydrogen-shell burning, intermediate-mass red giants burn helium in their cores. Suppressed dipole modes in those so-called red clump stars will reveal whether the fields survive until helium-core burning, and whether they can account for magnetic fields observed in stellar remnants such as white dwarfs. Like intermediate-mass stars, more massive stars ($M > 10\,M_\odot$) also undergo convective hydrogen-core burning that generates a magnetic dynamo, and which may produce the magnetic fields observed in many neutron stars.

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