

A prevalence of dynamo-generated magnetic fields in the cores of intermediate-mass stars

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Magnetic fields play a role in almost all stages of stellar evolution¹. Most low-mass stars, including the Sun, show surface fields that are generated by dynamo processes in their convective envelopes^{2,3}. Intermediate-mass stars do not have deep convective envelopes⁴, although 10% exhibit strong surface fields that are presumed to be residuals from the stellar formation process⁵. These stars do have convective cores that might produce internal magnetic fields⁶, 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 surface⁷. 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 core⁸, in over 3600 red giant stars observed by *Kepler*. About 20% of our sample show mode suppression but this fraction is a strong function of mass. Strong core fields only occur in red giants above 1.1 solar masses ($1.1M_{\odot}$), and the occurrence rate is at least 60% for intermediate-mass stars ($1.6\text{--}2.0M_{\odot}$), indicating that powerful dynamos were very common in the convective cores of these stars.

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 convection⁹. The observed power spectrum has a roughly Gaussian envelope whose central frequency, ν_{\max} , decreases as a star expands during the red giant phase^{10,11}. The comb structure of the spectrum arises from a series of overtone modes separated by the so-called large frequency separation, $\Delta\nu$. 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 $\ell > 3$. Their spectra are characterised by a pattern of radial ($\ell = 0$) and quadrupolar ($\ell = 2$) modes that form close pairs, interspersed with dipolar ($\ell = 1$) modes located roughly

halfway between successive radial-quadrupolar pairs. The octupolar modes ($\ell = 3$) are weak or undetectable. The dipolar modes have turned out to be particularly useful probes of internal structure¹². They have been used to distinguish between hydrogen-shell and helium-core burning stars^{13–15} and to measure radial differential rotation^{16,17}. 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 mode¹⁶. This coupling is strongest for dipole modes, making them the most useful probes of the core¹⁸.

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 dipolar 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 dipolar modes (lower panels). Suppressed dipolar modes have been reported in a few dozen red giant stars, with an occurrence rate of about 20%^{19,20}. 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 dipolar modes if there are strong magnetic fields in the core, giving rise to a “magnetic greenhouse effect”⁸.

We measured the amount of suppression by comparing the integrated power of the dipolar and radial modes (the dipole mode visibility, V^2), averaged over the four orders centred on ν_{\max} . While the normal stars show dipole mode visibilities of $V^2 \approx 1.5$, independent of ν_{\max} ^{19,21}, the stars with suppressed modes have $V^2 \approx 0.5$ for $\nu_{\max} \simeq 70\mu\text{Hz}$ and down to almost zero for the least evolved red giants oscillating above $200\mu\text{Hz}$ (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 ν_{\max} larger than $50\mu\text{Hz}$ and masses below $2.1M_{\odot}$ which, assuming no observational uncertainties, is expected to include only red giants that have not started burning helium in their cores¹⁴. We cross-matched our sample with those of known helium-burning stars^{14,15}, which allowed us to identify and remove a small fraction of evolved stars burning helium that, due to measurement uncertainty, had entered our sample (2% of our sample, almost all with $\nu_{\max} < 70\mu\text{Hz}$).

The stars in Fig. 2 form two distinct branches that gradually merge as the stars evolve leftwards towards lower ν_{\max} . Most stars fall on the “normal” upper branch of $V^2 \approx 1.5$, in agreement with previous results¹⁹. The lower branch, with suppressed dipole modes, agrees remarkably well with theoretical predictions (black curve). This prediction assumes that all the wave energy leaking into the stellar core is trapped by a magnetic greenhouse effect caused by strong internal magnetic fields⁸. The decrease of the suppression towards lower ν_{\max} is a consequence of the weaker coupling between acoustic waves in the

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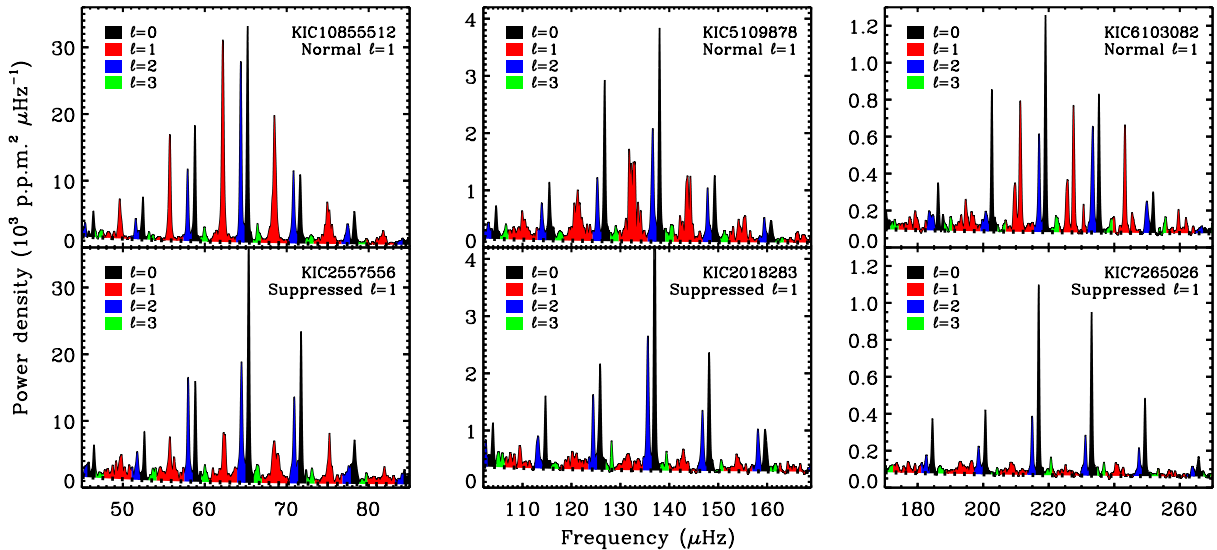


Figure 1 | Oscillation spectra of six red giants observed with *Kepler*. The stars are ordered in three pairs, each representing a different evolution stage ranging from the most evolved (lowest oscillation frequencies) on the left to the least evolved (highest frequencies) to the right. The coloured regions mark the power dominated by modes of different degree $\ell = 0-3$. 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).

envelope and gravity waves in the core⁸. With this large sample we have been able to separate 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 phase⁴. 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 stars⁶. 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 surfaces⁵. 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 ν_{\max} and inferred mass of all the stars superimposed on a contour plot of minimum magnetic field strengths required for mode suppression⁸. For stars with suppressed modes (filled red circles), the underlying colour provides a lower bound to the field strength at the hydrogen-burning shell. For stars without suppressed modes (open black circles), the underlying colour 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 different. 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 ≈ 10 kG are not present at the hydrogen-burning shell when the stars are just below the red giant luminosity bump ($\nu_{\max} \approx 70 - 100 \mu\text{Hz}$). Assuming magnetic flux conservation from the main-sequence phase, this suggests that fields above ≈ 5 kG do not exist within the cores of Sun-like stars⁸. Large scale fields in the solar interiors have been discussed in order to explain the properties of the tachocline²⁵. However, our results do not 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 ν_{\max} , stars above 1.4 M_{\odot} require increasingly strong magnetic fields to suppress their dipolar modes. From Figure 4, there is no clear upper limit to the field strengths present in red giant cores, given that dipole-suppressed stars are common even when field strengths $B > 1$ 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^{26–28}. 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 formation²⁹. 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).

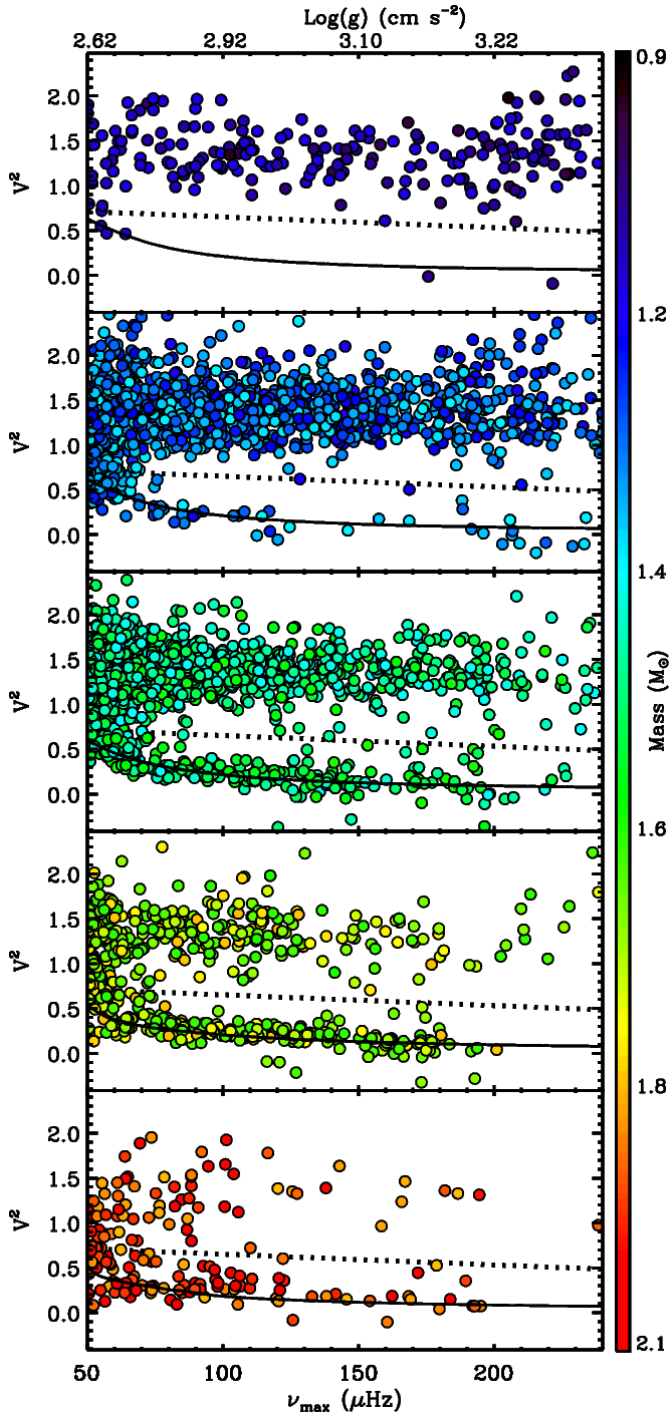


Figure 2 | Visibility of dipolar modes for red giants observed with *Kepler*. The abscissa is the central frequency of the oscillations, which correlate closely with surface gravity shown at the top axis. Stars evolve from right to left in the diagram, corresponding roughly to the beginning of the red giant phase to the red giant luminosity bump²². The upper limit on ν_{\max} is set by the sampling of the *Kepler* data. Each panel shows stars in a different mass bracket increasing from top to bottom (indicated by the colour bar annotation on the right). Mass is calculated from asteroseismic scaling relations¹⁴, and has a formal uncertainty of 10%²³. The solid black line shows the theoretical predicted visibility of suppressed dipole modes⁸ assuming a stellar mass of $1.6M_{\odot}$ and a mode lifetime for radial modes of 20 days²⁴. The fiducial dashed line separates the two branches of normal and dipole-suppressed stars.

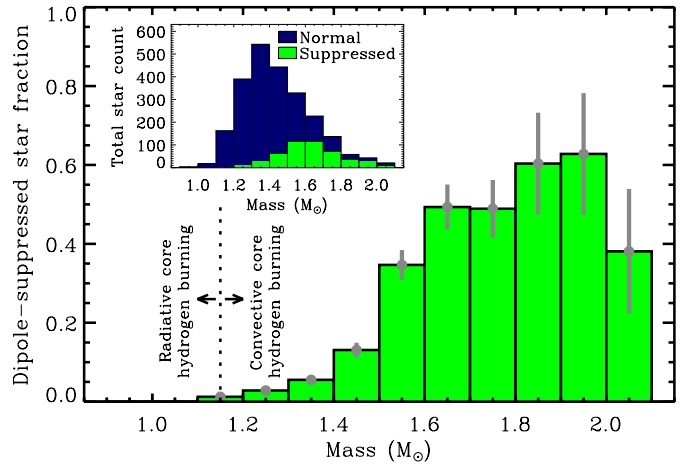


Figure 3 | Observed fraction of stars with suppressed dipolar modes. The abscissa is the stellar mass (in solar units). For each mass bin we calculated the dipole-suppressed star fraction as the number of stars that fall below the dashed line in Fig. 2, relative to all stars in that same mass bin. To make the distinction unambiguously between normal stars and stars with suppressed dipoles, we only counted stars with $\nu_{\max} > 70\mu\text{Hz}$. The uncertainty in the fractions (grey vertical errorbars) are based on Poisson statistics of the total star counts (inset: blue plus green) and of the number of dipole-suppressed stars (inset: green). The vertical dotted line separates stars for which hydrogen-core burning took place in either a radiative or convective environment for solar metallicity⁴.

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 dipolar 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 giant cores^{17,30}. After some time, intermediate-mass red giants also start burning helium in their cores. Suppressed dipolar 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 ($M > 10M_{\odot}$) 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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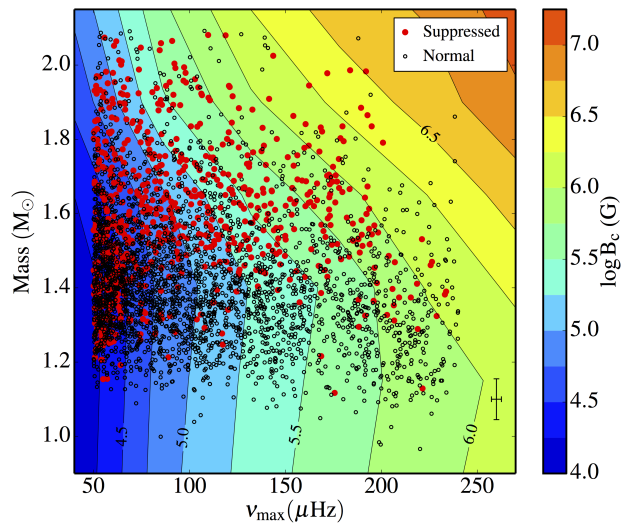


Figure 4 | Critical magnetic field strength required to suppress dipole mode oscillations. The abscissa is the observed central frequency of the oscillations. The ordinate is the inferred asteroseismic mass. The coloured contours indicate the minimum magnetic field at the hydrogen shell required for mode suppression (the critical field, B_c). Filled red circles mark stars with observed suppressed modes, and open circles mark normal (not suppressed) stars. The cross shows a typical errorbar for the data points. The uncertainty in B_c due to uncertainty in mass is negligible for stars below $1.4M_{\odot}$ and is no more than 25% for the more massive stars.

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Author contributions

D.S. measured and interpreted mode visibilities; M.C. and J.F. calculated and interpreted theoretical models; D.H. and D.S. calculated power spectra and measured large frequency separations; R.A.C., T.R.B., L.B., and V.S.A. contributed to the discussion of the results. All authors commented on the manuscript.

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