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Testing Asteroseismic Scaling Relations using Eclipsing Binaries in Star Clusters and the Field

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The accuracy of stellar masses and radii determined from asteroseismology is not known! We examine this issue for giant stars by comparing classical measurements of detached eclipsing binary systems (dEBs) with asteroseismic measurements from the \textit{Kepler} mission. For star clusters, we extrapolate measurements of dEBs in the turn-off region to the red giant branch and the red clump where we investigate the giants as an ensemble. For the field stars, we measure dEBs with an oscillating giant component. These measurements allow a comparison of masses and radii calculated from a classical eclipsing binary analysis to those calculated from asteroseismic scaling relations and/or other asteroseismic methods. Our first results indicate small but significant systematic differences between the classical and asteroseismic measurements. In this contribution we show our latest results and summarize the current status and future plans.

We also stress the importance of realizing that for giant stars mass cannot always be translated to age, since an unknown fraction of these evolved through a blue straggler phase with mass transfer in a binary system. Rough estimates of how many such stars to expect are given based on our findings in the open clusters NGC6819 and NGC6791.

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1 Introduction

The space missions \textit{Kepler} and CoRoT have opened up for large scale applications of asteroseismology - the study of stars through their oscillations. We are entering into a new era of precision asteroseismology where parameters of stars, like masses, radii and ages, can be determined for single stars to a significantly higher precision than before. However, precision is not necessarily accuracy, and therefore it is of importance to test the accuracy level of asteroseismic measurements with independent methods.

While the radii can be tested for nearby single stars with accurate distances or interferometric radii \cite{SilvaAguire:2013}, the only way to compare asteroseismic mass measurements to an accurate model-independent mass is using detached eclipsing binaries (dEBs). We are in the process of building up a set of measurements of dEBs for testing the accuracy of asteroseismic measurements \cite{Brogaard:2015}. One focus area is star clusters where we can extrapolate measurements of dEBs in the turn-off region to the red giant branch and the red clump where we investigate the giants with ensemble asteroseismology. We also study dEBs in the field that have an oscillating red giant component, so that the asteroseismic measurements can be directly compared to the more classical measurements from the eclipsing binary analysis.

So far we are concentrating on testing the asteroseismic scaling relations for mass and radius of giant stars. These relations, introduced elsewhere in these proceedings, use the global asteroseismic parameters known as the large frequency separation $\Delta \nu$ and the frequency of maximum power $\nu_{\text{max}}$ and a non-seismic measurement of the effective temperature $T_{\text{eff}}$. For many stars these are the only data which will be available because the stars are too faint to allow extraction of more information even when observed with \textit{Kepler} or CoRoT. Therefore, we have to be able to trust the asteroseismic scaling relations in order to correctly interpret inferences on distant stars in the Galaxy and to avoid situations where the asteroseismic analysis is questioned when the outcome is not what was expected \cite{Epstein:2014}.

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2 Star clusters

There are four open clusters in the *Kepler* field of view. The two oldest and most crowded ones (NGC6791 and NGC6819) are observed by *Kepler* in terms of so-called super-stamps that are large regions centered on the clusters. For the two younger and less populated clusters, only individually selected targets are observed. From these data we have identified a large number of detached eclipsing binary members of NGC6791 (Brogaard et al. 2016b), and a smaller number in NGC6819 (Jeffries et al. 2013; Sandquist et al. 2013) and NGC6811 (Sandquist et al. 2016). The few candidates we identified in NGC6866 were found to be non-members.

In previous works we compared the masses of red giants in NGC6791 and NGC6819 derived by isochrone extrapolation from eclipsing binaries at the turn-off to those derived from asteroseismic scaling relations using *Kepler* observations of giant stars (Brogaard et al. 2015, 2012; Sandquist et al. 2013). In those cases we found that a small, but significant downward correction to the Δν scaling relation is needed in order to obtain agreement with dEB measurements. In these clusters the giant stars on the red giant branch (RGB) and those in the red clump (RC) were also found to need a different relative correction in order to have identical distances (Brogaard et al. 2015; Handberg et al. 2016; Miglio et al. 2012). These findings are all in agreement with theoretical predictions for corrections to the scaling relations (Miglio et al. 2013).

In NGC6791, the dEB V9 (Kaluzyñ & Rachinski 1993) was found to be a member with an early giant component and companion in the turn-off phase. Measurements of the masses of this system will decrease the range over which the isochrone needs to be extrapolated to compare to the only slightly brighter red giants that have measured oscillations. The measurement of masses of this system is complicated by the fact that the giant is magnetically active due to a short orbital period of 3.187 days. This causes significant out-of-eclipse variations and periodic features in the spectral lines. Despite this, it seems that we will be able to reach a precision and accuracy on the mass measurements below 2% through a careful analysis (Brogaard et al. 2016b). Our preliminary measurement yields MVp = 1.14 ± 0.02 M⊙ in perfect agreement with our previous estimate extrapolated from the turn-off dEBS V18 and V20 (Brogaard et al. 2012) and enforcing the suggestion that the uncorrected asteroseismic scaling relations overestimate masses slightly.

The young open cluster NGC6633 has been observed by the CoRoT mission and three oscillating giant members have been identified (Barban et al. 2013). The investigation by Lagarde et al. (2015) compared radii of the these stars calculated from uncorrected asteroseismic scaling relations to those calculated using distances from the Hipparcos catalog (van Leeuwen 2007, 2009). They found a potential disagreement but concluded that it was likely not significant. However, the corrections to the asteroseismic scaling relations calculated by Miglio et al. (2013;Fig.2) suggest very significant upwards corrections to the Δν scaling for such massive core-helium burning stars. This would enhance the discrepancy found by Lagarde et al. (2013) thus questioning the validity of the corrections to the scaling relations for helium-burning giants with masses around 3M⊙. But of course relies on the accuracy of the Hipparcos distance to NGC6633. We are in the process of obtaining observations of a dEB at the turn-off in this cluster in order to investigate the apparent discrepancy.

2.1 Over-massive stars

As a by-product of the ensemble asteroseismology in the open clusters NGC6791 and NGC6819 we found giant stars that are over-massive compared to the ensemble (Brogaard et al. 2015, 2012; Corsaro et al. 2012; Handberg et al. 2016). We expect those stars to have evolved through a blue straggler phase with mass transfer in a binary system. This means that the present mass cannot be translated into an age as can be done for giant stars that evolved a single stars. While this is not a problem when the star is a cluster member where the age can be determined from the other stars, it would cause severe complications for age estimation if the star was found in the field. As an example, we mention that the young and alpha-rich stars found by Chiappini et al. (2015; Martig et al. 2015) could in principle be old stars that experienced mass-transfer during their evolution.

Our asteroseismic investigation of NGC6819 (Handberg et al. 2016) found a fraction of over-massive giant members of more than 10% in this cluster (5 clear detections and another 6 to be investigated further at the time of writing). For NGC6791 the proper motion study of Platais et al. (2011) found a number of bright giants outside the predicted single star evolution sequence that they suggested belong the the horizontal branch. However, it was found by Brogaard et al. (2012) that the bluer stars in this sample were too faint to belong to the horizontal branch while the redder part would likely belong to a group of stars that evolved through a blue straggler phase due to their positions in the colour-magnitude diagram that were otherwise not easily explainable. These investigators also identified an additional star as belonging to the group of over-massive stars (Brogaard et al. 2013). The radial-velocity study of bright stars in NGC6791 by Tofflemire et al. (2014) revealed that many of the stars suggested by Platais et al. (2011) to be members in non-standard evolutionary phases were in fact non-members. Only three of the redder stars retained their cluster membership. We have conducted a preliminary investigation of these stars and found that two of them are over-massive compared to the ensemble while the third might be blended in the photometry of Platais et al. (2011), as this star sits right in the RC in the photometry of Stetson et al. (2003). All in all we find three giant stars that are over-massive compared to the ensemble of 60 stars (Corsaro et al. 2012). While this is not a complete sample, indications are that about 5% of the
giants are over-massive in this cluster, taking into account
that two of the over-massive stars were not it the sample of
Corsaro et al. (2012). This is not necessarily an indication
that fewer stars evolve through non-standard evolution in
this cluster compared to NGC6819 since NGC6791 also
hosts a group of extreme horizontal branch stars.

For more massive stars in younger star clusters our
statistics is not as good. In NGC6811 only 6 giant members
have been identified with asteroseismology (Corsaro et al.
2012, Hekker et al. 2011, Molenda-Zakowicz et al. 2014,
Stello et al. 2011) and non of them are found to be over-
massive compared to the ensemble. This only puts a very
week limit of ≲ 14% over-massive stars in this mass range.
Adding asteroseismic ensemble studies from more open
clusters in the K2 fields will give us better statistics in the
future.

With the current information indications are that about
5-10% of stars in open clusters are over-massive stars that
underwent non-standard evolution that prevents estimates of
age from their masses. Whether or not a similar number is to
be expected for field stars depends on whether binary frac-
tions are significantly different in the field compared to open
clusters. An additional complication is that most of the over-
massive stars identified in NGC6819 were found to belong
to very long period binary systems while those in NGC6791
seem to be single stars. Therefore it is not clear how the
percentages will change for samples of stars where binarity can
be ruled out. But the potential appearance of over-massive
stars arising from non-standard evolution is certainly some-
thing that should be considered when interpreting astro-
seismic ages for large populations of giant stars.

3 Field stars
We are in the process of observing and analysing several de-
tached eclipsing binaries with a red giant component show-
ing solar-like oscillations. These were identified in the Ke-
pler eclipsing binary catalog (Prsa et al. 2011). From those
that were found to show solar like oscillations and a total
eclipse several days long in the Kepler light curve we se-
lected the ones that were most likely to be SB2 binaries
for spectroscopic follow-up with the FIES spectrograph at
the Nordic Optical Telescope and/or the HERMES spectro-
graph at the Mercator telescope, both located at the Observa-
torio del Roque de los Muchachos on La Palma.

We finished the eclipsing binary analysis of the first of
these systems, KIC8410637, which is published in
Frandsen et al. (2013a). The second system, KIC9540026,
is still under our analysis and the details will be published
elsewhere (Brogaard et al. 2016a). Two studies provided
partial analysis of this system; Gaulme et al. (2014) did a
light curve analysis of the binary orbit and measured global
seismic parameters while Beck et al. (2014) published their
estimates of the global seismic parameters along with a
spectroscopic orbit determined from radial velocities of the
primary component only. From the same data we have now
measured also the radial velocities of the secondary which
allowed us to derive precise masses and radii. Additional
HERMES spectra were obtained during the total eclipse for
the purpose of $T_{\text{eff}}$ and abundance analysis (Frandsen et al.
2013a) but the S/N was not high enough for optimal results
so we ended up basing that part of the analysis on disen-
tangled spectra using all HERMES spectra. We include
our preliminary results here to add to the discussion of the
asteroseismic scaling relations. The parameters derived for
the giant in each of the two systems can be found in Table 1
and mass-radius diagrams are shown in Figs. 1 and 2. The fact
that the two systems are found to have very similar ages is
either a coincidence or due to a selection effect that we have
not worked out yet.

Table 1 Parameters of the giant components of the dEBs

| Property       | KIC8410637   | KIC9540026  |
|----------------|-------------|-------------|
| Mass ($M_\odot$) | 1.547 ± 0.028 | 1.473 ± 0.029 |
| Radius ($R_\odot$) | 10.74 ± 0.11  | 13.93 ± 0.28  |
| $T_{\text{eff}}$ (K) | 4800 ± 80 | 4780 ± 55 |
| log g | 2.57 ± 0.01 | 2.32 ± 0.01 |
| [Fe/H] | +0.08 ± 0.13 | −0.21 ± 0.10 |
| age (Gyr) | 2.6 ± 0.2 | 2.6 ± 0.2 |

As can be seen in Fig. 1 the mass and radius of the red
giant differ significantly when the asteroseismic scaling
relations are used without corrections, while they are in
agreement well within the asteroseismic error-bar when
using a correction based on Miglio et al. (2013). However,
this correction assumes that the giant star in on the RGB
burning hydrogen in a shell. If the star is instead in the red
clump (RC) phase of evolution, burning helium in its core,
the predicted correction is of similar size but in the opposite direction, which would cause a discrepancy close to the 3–σ level. This could either be taken as evidence that the giant is in the RGB phase or that we are not able to predict corrections to the asteroseismic scaling relations properly. The evolutionary state of the star needs to be firmly established before we will know. Hopefully this can be established through a detailed asteroseismic modeling of individual frequencies.

The mass–radius diagram of KIC9540226 in Fig. 2 shows that in this case there is agreement between the mass and radius of the giant as found from the eclipsing binary analysis and the asteroseismic scaling relations even without a correction. Applying the correction suggested by Miglio et al. (2013) under assumption that the giant is on the RGB makes the agreement even better. However, when comparing to the isochrone it is found that also in this case the spectroscopic $T_{\text{eff}}$ is only consistent if the star is in a helium burning phase – this time on the early asymptotic giant branch burning Helium in a shell. If so, that would again mean that the correction to the scalings should be in the opposite direction, creating significant disagreement with the classical measurements. However, it would have been even more difficult for this system to have survived the evolution through the upper RGB, since the orbital period, and therefore also the distance between the stars is much smaller in this case than for KIC8410637, and therefore the components would have been in deep contact. This suggests that the giant in KIC9540226 is on the RGB and that our measured $T_{\text{eff}}$ is too high or the $T_{\text{eff}}$ predicted by the PARSEC models is too low. If we assume that this systematic is the same for the case of KIC8410637 then that system is also likely to be in the RGB phase and the corrections to the asteroseismic scaling relations seem to be working well. We hope to obtain photometric $T_{\text{eff}}$ estimates of the systems and measure their reddening from the interstellar Na lines (Munari & Zwitter 1997) to investigate this further.

Despite the complications it seems that the asteroseismic scaling relations including a correction according to Miglio et al. (2013) are doing quite well. We note especially the extreme agreement for $\log g$ between the classical and asteroseismic measurements, at the level of 0.01 dex, which is the uncertainty of the asteroseismic measurement. This suggests that at least for the observed masses and metallicities the scaling of $\nu_{\text{max}}$, which is the only asteroseismic parameter that enters the equation for $\log g$, is quite accurate. Therefore, $\log g$ values derived from the asteroseismic scaling relations can be trusted to within their uncertainty and the asteroseismic $\log g$ values should be exploited in spectroscopic analysis of stars where uncertainties in $\log g$ are often about an order of magnitudes larger and $\log g$ correlates with other parameters.

4 Conclusions and outlook

Our on-going investigations of the asteroseismic scaling relations suggest that they are accurate to within their uncertainties for giant stars as long as corrections to $\Delta \nu$ are calcu-
Fig. 2  As Fig. 1 but for the eclipsing binary KIC9540226. The PARSEC isochrone is for our measured metallicity and an age of 2.6 Gyr.

lated and applied along the lines of [Miglio et al. (2013)]. The fact that asteroseismic log\(_{g}\) values are extremely consistent with our independent measurements implies that the scaling for \(\nu_{\text{max}}\) is reliable. Consistency among the different formulations of the scaling relations for stars in clusters with independent distance estimates, once an expected correction to \(\Delta\nu\) has been applied, also suggests that no correction is needed for \(\nu_{\text{max}}\).

In some cases there are suggestions that discrepancies could be present, but at the moment these cannot be claimed to be due to the scaling relations, since they could also be caused by systematic uncertainties in our spectroscopic \(T_{\text{eff}}\) scale, the temperature scale of the PARSEC stellar models, and the Hipparcos distance to NGC6633.

From our investigations we find that a fraction of 5-10\% of stars in open clusters are over-massive and emphasize the need to consider the potential presence of such stars when interpreting asteroseismic analysis of large populations of stars. Unfortunately we do not know whether the fraction of over-massive giants is the same for field stars and open clusters.

The surface gravity determined from asteroseismic scaling relations is found to be identical to that derived from the eclipsing binary analysis to well within the asteroseismic uncertainty estimate, even when that uncertainty reaches as low as 0.01 dex. Since this is about an order of magnitude better than is usually derived from a spectroscopic analysis we advocate the use of asteroseismically determined log\(_{g}\) values in spectroscopic analysis to minimize errors caused by correlations between log\(_{g}\) and \(T_{\text{eff}}\).

We will continue to investigate these issues in more detail and extend our analysis to more dEBs and star clusters observed by the K2 mission. This will expand the mass and metallicity range where we can have faith in the accuracy of the asteroseismic scaling relations.

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