

Exploiting the Open Clusters in the *Kepler* and CoRoT Fields

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Abstract The open clusters in the *Kepler* and CoRoT fields potentially provide tight constraints for tests of stellar models and observational methods because they allow a combination of complementary methods. We are in the process of identifying and measuring parameters for detached eclipsing binaries (dEBs) in the open clusters in the *Kepler* and CoRoT fields. We make use of measurements of dEBs in the clusters to test the accuracy of asteroseismic scaling relations for mass. We are able to provide strong indications that the asteroseismic scaling relations overestimate the stellar mass, but we are not yet able to distinguish between different proposed corrections from the literature. We argue how our ongoing measurements of more dEBs in more clusters, complemented by dEBs in the field, should be able to break the degeneracy. We also briefly describe how we can identify cluster stars that have evolved through non-standard evolution by making use of ensemble asteroseismology.

1 Introduction

Open star clusters are often observed to exploit the advantages of the additional information that comes from observing an ensemble of stars with identical ages and similar metallicities. The open clusters in the *Kepler* and CoRoT fields extend the prospects for such an approach because they make the identification of detached eclipsing binary stars much easier and allow us to combine classical observational methods with asteroseismology of giant stars. We are in the process of identifying and measuring parameters for dEBs in the open clusters in the *Kepler* (NGC6791, NGC6811, NGC6819, and NGC6866) and CoRoT (NGC6633) fields.

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Our long term goal is to test and improve stellar models and gain detailed insights into stellar evolution in the clusters by making use of measurements of multiple dEBs in combination with asteroseismology of single giant stars. In this contribution we use the measurements of dEBs in the clusters to test the accuracy of the asteroseismic scaling relations for mass.

2 Tests of Asteroseismic Scaling Relations

The asteroseismic scaling relations for mass and radius,

$$\begin{aligned} \frac{M}{M_{\odot}} &\simeq \left(\frac{v_{\max}}{v_{\max,\odot}} \right)^3 \left(\frac{\Delta\nu}{\Delta\nu_{\odot}} \right)^{-4} \left(\frac{T_{\text{eff}}}{T_{\text{eff},\odot}} \right)^{3/2}, \\ \frac{R}{R_{\odot}} &\simeq \left(\frac{v_{\max}}{v_{\max,\odot}} \right) \left(\frac{\Delta\nu}{\Delta\nu_{\odot}} \right)^{-2} \left(\frac{T_{\text{eff}}}{T_{\text{eff},\odot}} \right)^{1/2}, \end{aligned} \quad (1)$$

(e.g. see Miglio et al. 2012) provide a relatively easy way of measuring the mass and radius of a star showing solar-like oscillations using a light curve from *Kepler* or CoRoT. However, these relations are only approximate and their accuracy is not known in great detail. Moreover, several corrections have been suggested in the literature. Some are based on observations and/or model predictions (Miglio et al. 2012; White et al. 2011), while others try to deal with systematics arising due to not fulfilling assumptions in the derivation of the scaling relations (Mosser et al. 2013). The accuracy and precision of the scaling relations and their suggested corrections needs verification.

We wish to employ our measurements of eclipsing binaries in the open clusters for such tests. First rough comparisons of masses between the methods were already done for NCG6791 (Brogaard et al. 2012) and NGC6819 (Sandquist et al. 2013). Those results, shown in Table 1, indicate that masses from the asteroseismic scaling relations are slightly overestimated.

Here we do a more detailed comparison for NGC6819 and then elaborate on how including the additional clusters will provide improved insights.

Table 1 Mean mass of giant stars in clusters from different methods

Cluster	Asteroseismic < M_{RGB}/M_{\odot} >	Asteroseismic < M_{RGB}/M_{\odot} >	< M_{RGB}/M_{\odot} > from eclipsing binaries
NGC 6791	$1.22 \pm 0.01^{\text{a}}$	$1.23 \pm 0.02^{\text{b}}$	$1.15 \pm 0.02^{\text{c}}$
NGC 6819	$1.68 \pm 0.03^{\text{a}}$	$1.61 \pm 0.04^{\text{b}}$	$1.55 \pm 0.06^{\text{d}}$

^aBased on asteroseismic grid-modelling measurements by Basu et al. (2011)

^bBased on asteroseismic scaling relation measurements by Miglio et al. (2012)

^cBased on measurements of eclipsing binaries by Brogaard et al. (2012)

^dBased on measurements of eclipsing binaries by Jeffries et al. (2013) and Sandquist et al. (2013)

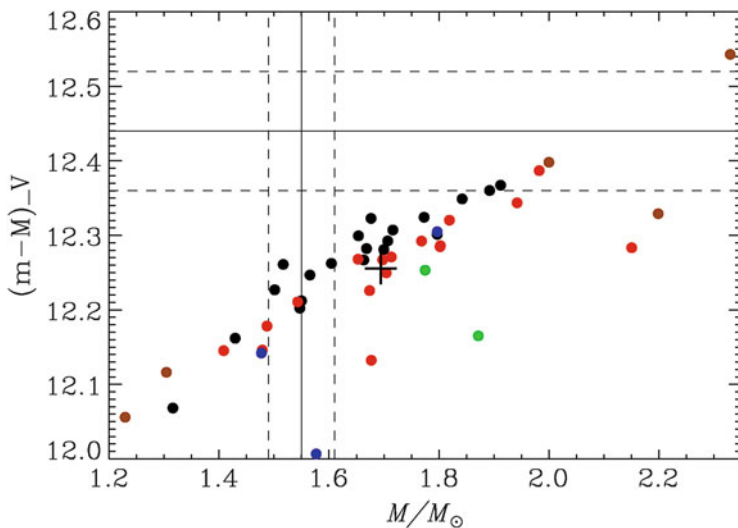


Fig. 1 Measurements of mass and distance modulus for giant stars in NGC6819. The *solid lines* indicate the values inferred from the eclipsing binaries, and the *dashed lines* the corresponding values $\pm 1 - \sigma$ uncertainty. *Solid dots* are values for individual giant stars using the asteroseismic scaling relations in the form of Miglio et al. (2012). *Black dots* are RGB stars. *Brown dots* are cool RGB stars with $(V - K_s)$ colour ≥ 3.1 , which are close to or above the validity level of the colour- T_{eff} relations of Ramírez and Meléndez (2005). *Red dots* are red clump stars determined from asteroseismology, while *blue dots* are RC stars determined from the CMD for cases where asteroseismology could not determine the evolutionary phase. *Green dots* are over-massive RGB stars in binary systems (Corsaro et al. 2012). The plus sign marks the mean asteroseismic values, excluding over-massive stars, see Sect. 3 (Color figure online)

Table 2 NGC6819 parameters determined from eclipsing binary members

Parameter	Value
$(m - M)_V$	12.44 ± 0.08^a
M_{RGB}/M_{\odot}	1.55 ± 0.06^b

^aRecalculated using radii, spectroscopic T_{eff} s and photometric data for the eclipsing binaries from Jeffries et al. (2013) and Sandquist et al. (2013) with bolometric corrections from Casagrande and VandenBerg (2014)

^bFrom range of numbers in Sandquist et al. (2013)

In order to get a more detailed view of the situation we show, in Fig. 1, the measurements in a plot of mass versus apparent distance modulus. The solid lines indicate the measurement of the mass of a star on the red giant branch (RGB) and the cluster distance modulus from the eclipsing binary measurements of Sandquist et al. (2013) and Jeffries et al. (2013), slightly adjusted as in Table 2, due to our use of bolometric corrections from Casagrande and VandenBerg (2014). Each circle marks the asteroseismic measurement of mass and distance modulus for a giant star in the cluster, recalculated *exactly* as in Miglio et al. (2012), e.g. using the scaling relations in the form of Eq. (1), with T_{eff} values calculated using $V - K_s$ colours

and the colour- T_{eff} relations of Ramírez and Meléndez (2005) and bolometric corrections from Flower (1996). The asteroseismic measurements are from Corsaro et al. (2012).

The plus sign marks the ensemble mean, which is too high compared to the binary measurements. Notice how the asteroseismic measurements fall more or less along a tilted line. This is the consequence of the way the random uncertainties in T_{eff} and the seismic parameters affect the position of a star in this diagram; all uncertainties shift the star along approximately the same line. Therefore, there appears to be no way of reaching agreement with the binary result, as the mean asteroseismic values can only shift approximately along the line already defined by the asteroseismic measurements. However, as we shall see, this is an artifact arising due to the use of colour-temperature relations and bolometric corrections from different sources, which underlines the importance of using self-consistent calibrations.

Figure 2 shows the situation when all measurements are made using the bolometric corrections and colour-temperature calibrations of Casagrande and Vandenberg (2014) based on MARCS models. We assumed $E(B - V) = 0.15$ and $E(V - K_s)/E(B - V) = 2.72$ since this results in T_{eff} for the red clump stars in agreement with spectroscopic measurements (Bragaglia et al. 2001). This shifts the asteroseismic measurements such that there is an overlap region with the binary results. However, to shift the mean asteroseismic mass close to the binary result, a correction to the scaling relations was still needed. We have therefore also applied

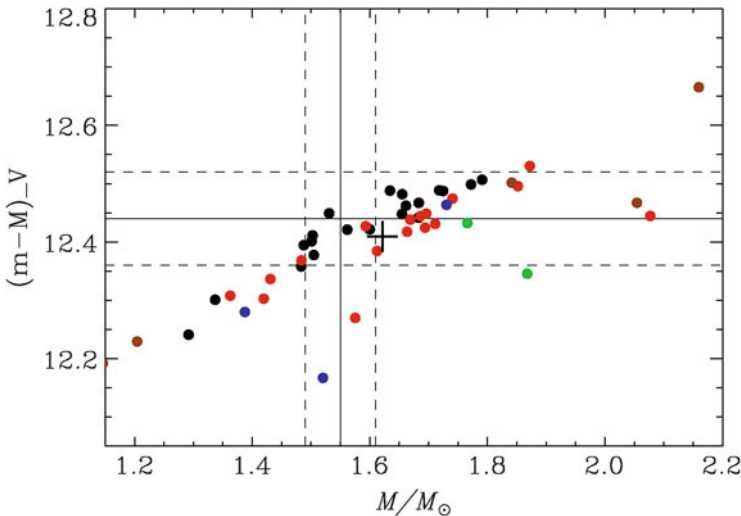


Fig. 2 As Fig. 1 but using bolometric corrections and colour-temperature relations from Casagrande and Vandenberg (2014) and the correction to the scaling relations from White et al. (2011). We use a modified version of their suggested correction, since it is clear from their Fig. 5 that the form of their correction breaks down below $\sim 4,700$ K. Below that value we keep the correction constant. The relative correction between RGB and RC stars determined by Miglio et al. (2012) is still applied to the RC stars

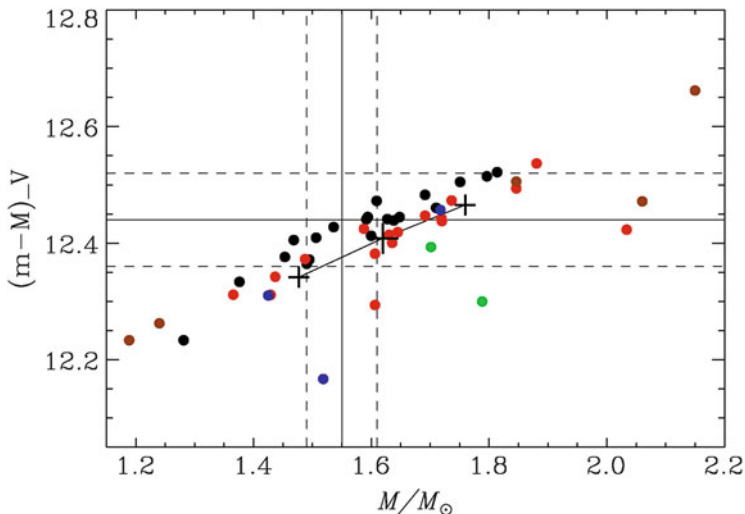


Fig. 3 As Fig. 1 but using bolometric corrections and colour-temperature relations from Casagrande and Vandenberg (2014) and the correction to the scaling relations from Mosser et al. (2013). The relative correction between RGB and RC stars determined by Miglio et al. (2012) is still applied to the RC stars

the correction to the scaling relations suggested by White et al. (2011) in Fig. 2. That way, we can obtain a reasonable agreement! However, as shown in Fig. 3, a similar agreement can be obtained by using instead the correction suggested by Mosser et al. (2013). In principle, the correct correction might be expected to decrease the scatter among the measured masses and distance moduli, but unfortunately the different corrections are too similar and random uncertainties too large to allow such a test (the small plus signs attached to the mean value in Fig. 3 shows the effect on the cluster mean when ν_{\max} is changed by $\pm 1 - \sigma$ for all stars). Thus, we are left in a situation where indications are that the asteroseismic scaling relations overestimate masses of giant stars, but we cannot distinguish between different suggested corrections, because they both work equally well, at least in this situation.

The correction suggested by White et al. (2011) depends on T_{eff} and similar corrections have been calculated by Miglio et al. (2013), where they also extend to the helium-burning red clump phase of evolution, showing a different correction to red clump stars compared to stars in the red giant branch phase (see the details in Fig. 5 of White et al. 2011 and Fig. 2 of Miglio et al. 2013). Note especially that for the case of the open cluster NGC6811, where the giants are younger and hotter, the correction predicted by Miglio et al. (2013) becomes small while for the red clump stars of the even younger clusters NGC6866 and NGC6633 this correction becomes large, but in the opposite direction! On the other hand, the correction suggested by Mosser et al. (2013) does not depend on T_{eff} . Therefore, by extending our investigation to other clusters of different ages, and therefore different masses and T_{eff} 's for the giant stars, it should be possible to find a suitable form of

a correction. We are already in the process of identifying, observing and analysing detached eclipsing systems and oscillating giant stars in the open clusters NGC6791, NGC6811, NGC6866, and NGC6633.

There are, however, some additional difficulties in this procedure. One issue we have noticed is that the T_{eff} of the red clump stars measured spectroscopically for NGC6819 (Bragaglia et al. 2001) and NGC6811 (Molenda-Żakowicz and et al. 2014) are higher than the corresponding T_{eff} calculated by Miglio et al. (2013) for the corresponding asteroseismic masses. As shown in the contribution by A. Miglio in this volume, different models predict different T_{eff} for the giant stars. This introduces an additional challenge when wanting to apply a correction to the asteroseismic scaling relations based on model T_{eff} 's.

It is also not currently known whether a correction that depends directly on the metallicity should be made (to either $\Delta\nu$ or ν_{max} , or perhaps both?). Unfortunately, there are no metal-poor clusters in the sample of open cluster in the *Kepler* and CoRoT fields, so no such tests can presently be done. In order to check for possible metallicity effects, we are instead working on potentially metal-poor detached eclipsing binaries in the *Kepler* field which contain a giant star showing solar-like oscillations. We will analyse these along the lines of Frandsen et al. (2013) and compare directly to the asteroseismic signal of the giant component of the binary. Our sample contains three systems that have $[\text{Fe}/\text{H}] \approx -0.4$ according to the *Kepler* input catalogue.

3 Identification of Stars That Evolved Through Non-standard Evolution

The red giant phase of evolution is so short-lived that the difference in mass among the giants in a cluster is much smaller than our asteroseismic measurement uncertainty. Therefore, it makes sense to use the ensemble mean mass as the most precise measure of the mass of an RGB stars in a cluster. However, if there are giants in the sample that did not evolve as a single star, they are likely to have a different mass and should be excluded when calculating a mean mass from the ensemble.

An asteroseismic study by Corsaro et al. (2012) has already identified such stars in NGC6819 by investigating the period spacing of dipole modes caused by gravity modes in the oscillation spectra, ΔP_{obs} . By comparing their Fig. 8 diagram of $\Delta\nu$ versus ΔP_{obs} to the corresponding diagram in Fig. 4 of Stello et al. (2013) calculated using models, one sees that for red clump stars, the differences in $\Delta\nu$ are caused by a combination of differences in mass *and* evolution. Returning to Fig. 3 we find a red clump star with a mass of $2.05 M_{\odot}$. It turns out that this star, KIC5023953, sits in the expected location for normal red clump stars of NGC6819 in Fig. 8 of Corsaro et al. (2012), despite our evidence of a larger mass. But since the red clump sequence in that diagram is also affected by evolution during the helium-burning phase, the star is consistent with being an over-massive star well into the helium-

burning phase. The fact that the star is a binary (Stello et al. 2011; Hole et al. 2009) supports this interpretation, since the higher mass could have originated from mass-transfer. This example shows that it is wise to combine information from several diagrams before drawing definitive conclusions about specific stars. Any star not lying along the scatter line of the majority of stars in a diagram like Fig. 3 should be investigated for signs of non-standard evolution.

Conclusions

We have shown indications that the asteroseismic scaling relations for solar-like oscillators [Eq. (1)] will overestimate the mass of a star unless some kind of correction is applied. At present we are unable to distinguish between different corrections suggested in the literature, since they work equally well. An ongoing expanded investigation employing eclipsing binaries in more open clusters and in the field will allow more firm conclusions to be made.

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