AMPLITUDES OF SOLAR-LIKE OSCILLATIONS: CONSTRAINTS FROM RED GIANTS IN OPEN CLUSTERS OBSERVED BY *KEPLER*

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ABSTRACT

Scaling relations that link asteroseismic quantities to global stellar properties are important for gaining understanding of the intricate physics that underpins stellar pulsation. The common notion that all stars in an open cluster have essentially the same distance, age, and initial composition, implies that the stellar parameters can be measured to much higher precision than what is usually achievable for single stars. This makes clusters ideal for exploring how quantities of solar-like oscillations such as the mode amplitude depend on the global stellar properties. We have analyzed data obtained with NASA's *Kepler* space telescope to study solar-like oscillations in 100 red giant stars located in either of the three open clusters, NGC 6791, NGC 6819, and NGC 6811. By fitting the measured amplitudes to predictions from simple scaling relations that depend on luminosity, mass, and effective temperature, we find that the data cannot be described by any power of the luminosity-to-mass ratio as previously assumed. As a result we provide a new improved empirical relation which treats luminosity and mass separately. This relation turns out to also work remarkably well for main-sequence and subgiant stars. In addition, the measured amplitudes reveal the presence of a number of previously unknown unresolved binaries in the red clump in NGC 6791 and NGC 6819, pointing to an interesting new application for asteroseismology as a probe into the formation history of open clusters.

Subject headings: binaries: general — open clusters and associations: individual (NGC 6791, NGC 6819, NGC 6811) — stars: fundamental parameters — stars: interiors — stars: oscillations — techniques: photometric

1. INTRODUCTION

The highly complex processes involved in the excitation and damping of stochastically excited (solar-like) oscillations makes estimation of their amplitudes from pulsation modelling particularly challenging (e.g. Houdek 2006; Samadi et al. 2007). A scaling relation for the amplitude has therefore been of significant interest since it was first introduced by Kjeldsen & Bedding (1995). Their 'L/M relation', based on theoretical work by Christensen-Dalsgaard & Frandsen (1983) of near main-sequence stellar models, suggested that the amplitude measured in radial velocity would simply scale as the luminosity-to-mass ratio. Using observations of stars made in both radial velocity and intensity Kjeldsen & Bedding (1995) also suggested that the amplitude in intensity, A_λ, would scale as

$$A_\lambda = \frac{(L/M)^s}{\lambda/550\mathrm{nm}(T_{\mathrm{eff}}/5777\,\mathrm{K})^r}\,4.7\,\mathrm{ppm}, \qquad (1)$$

where $s = 1$, λ is the central wavelength of the photometric bandpass, and the observed solar value at 550nm is 4.7 ppm. They found empirically $r = 2.0$, which was a slight modification to $r = 1.5$ derived if they assumed the stellar oscillations to be purely adiabatic. Subsequent modelling by e.g. Houdek et al. (1999); Samadi et al. (2007) has lead to variations of the L/M relation where, in essence, different powers of the L/M ratio have been derived ($s = 0.7$–1.3). Recently, Verner et al. (2011) found $s = 0.4$–1.0 depending on T_{eff} of a large sample (642) of main-sequence and subgiant stars observed by *Kepler* (Koch et al. 2010).

The existence of solar-like oscillations in red giant stars is now well established observationally, most recently from CoRoT (e.g. de Ridder et al. 2009) and *Kepler* (e.g. Gilliland et al. 2010; Bedding et al. 2010b), as well as theoretically (Dupret et al. 2009; Montalbán et al. 2010; Di Mauro et al.

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2011). Despite the significantly different structures of red giants compared to the stars and models on which the L/M relation has been founded, the absence of an alternative have also seen this relation widely used for red giants, including several attempts to determine the exponent, s, that matched the observations best (Stello et al. 2007; Mosser et al. 2010; Baudin et al. 2011). While the majority of results on red giants are on field stars, the recent clear detections in open cluster red giants emerging from *Kepler* (Stello et al. 2010, Paper I) has opened up the seismic exploration of clusters and the advances that clusters bring to the interpretation of asteroseismic data (Basu et al. 2011; Hekker et al. 2011; Miglio et al. in prep.; Stello et al. submitted). In particular, stars in an open cluster are thought to share a common distance and initial chemical composition, which allows one to derive the stellar luminosity to much higher precision than for most field stars. In addition, the common age of red giant stars within each cluster implies that they have practically the same mass, resulting in a relatively low uncertainty on their measured mean mass assuming there is no significant mass loss (Miglio et al. in prep.). Combined with high quality standard photometry we can therefore obtain more robust predictions of the amplitudes from scaling relations and hence investigate these in ways not possible for the field stars observed by the current space mission CoRoT and *Kepler*.

Based on only one month of *Kepler* data of red giants in a single cluster, in Paper I we already demonstrated the potential for investigating the L/M relation by taking advantage of the common cluster properties of the stellar sample. We now have *Kepler* time-series photometry that span 10 times longer for stars in three open clusters (NGC 6791, NGC 6819, and NGC 6811), which exhibit distinctly different stellar masses. In this paper we are therefore extending considerably the analysis of the amplitude scaling relation for solar-like oscillations.

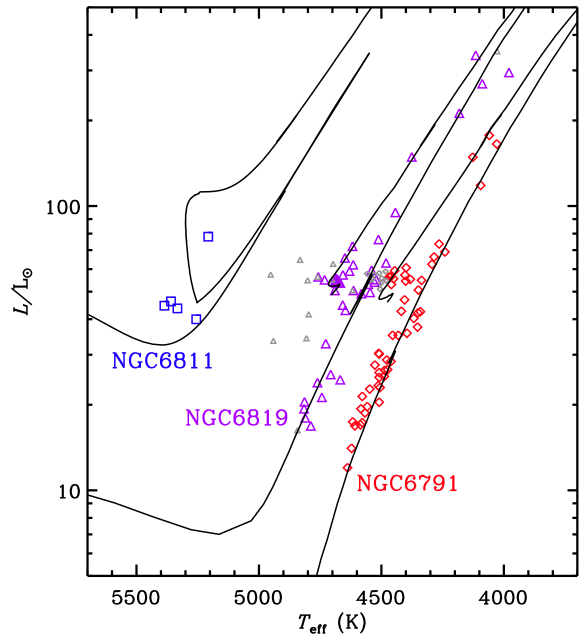

FIG. 1.— H-R diagram of the selected cluster stars. Small gray symbols mark the known and potential binaries. Representative isochrones from Marigo et al. (2008) (NGC 6791 and NGC 6819) and Pietrinferni et al. (2004) (NGC 6811) are shown to guide the eye.

2. OBSERVATIONS, TARGET SELECTION & CLUSTER PARAMETERS

The photometric time-series data were obtained between 2009 May 12 and 2010 March 20 (observing quarters 1–4), providing approximately 14,000 data points per star obtained in the spacecraft's long-cadence mode ($\Delta t 29.4\,$min). A detailed description of the data reduction from raw images to final light curves is given in Jenkins et al. (2010); Garcia et al. (2011) and Stello et al. (submitted).

Our initial star sample was the one selected by Stello et al. (submitted), but excluding the seismic non-members. We further trimmed the sample by removing the brightest (largest) and faintest stars, for which the measurement of the mode amplitude would not be reliable due to: (1) difficulty in determining the noise level at low frequency in the power spectrum of the largest stars (oscillating at very low frequencies) and (2) low signal-to-noise and potential blending of the faintest stars. The increased flux in the photometric aperture from a blending star, such as an unresolved binary companion, will tend to reduce the relative flux variation that we measure as the oscillation amplitude. To minimize this bias futher, we excluded a total of 23 spectroscopic binaries and stars that we expected to be binaries based on their location in the color-magnitude diagram. This still left a large sample of 100 stars for further analysis. We finally investigated effects of blending of single stars based on the results by Stello et al. (submitted). Only few of the blended stars indicated by Stello et al. showed lower than expected amplitudes, but no rigorous criterion for when blending had a significant impact on the amplitude could be obtained from those results. We therefore did not exclude any of our remaining stars that were listed as blends.

We adopted the luminosities, masses and effective temperatures from Stello et al. (submitted). We refer to Basu et al. (2011) and Hekker et al. (2011) for further details on the derivation on the mass and effective temperature, respectively. In summary, the average mass (here adopted for each star) is $1.20 \pm 0.01\,\mathrm{M}_\odot$ (NGC 6791), $1.68 \pm 0.03\,\mathrm{M}_\odot$ (NGC 6819), and $2.35 \pm 0.04\,\mathrm{M}_\odot$ (NGC 6811), while the luminosities and temperatures of our final sample are shown in Figure 1 and have typical uncertainties of $\sim 10\%$ and $\sim 2\%$, respectively.

3. MEASUREMENT OF OSCILLATION AMPLITUDES AND $\nu_{\rm max}$

Oscillation amplitudes were extracted by five different teams using pipelines described in Hekker et al. (2010); Huber et al. (2009); Kallinger et al. (2010); Mathur et al. (2010); Mosser & Appourchaux (2009). These methods are all based on the measurement of the integrated oscillation power, which we converted to an amplitude per radial mode. The integrated power was found either by smoothing the power spectrum as described by Kjeldsen et al. (2008) or by fitting a Gaussian function to the oscillation power envelope. Figure 2 shows the former. To obtain the amplitude per radial mode, $P_{\rm obs}$ is multiplied by $\Delta\nu$ to obtain the power per radial order, where $\Delta\nu$ is the frequency separation between consecutive radial orders. Finally we divided by the factor, c, which is the effective number of modes per $\Delta\nu$ (Kjeldsen et al. 2008). We adopted the solar value $c = 3.04$ from Bedding et al. (2010a), which agrees well with the measured mean value for red giants Mosser et al. (in prep.). We note that our final results (Sect. 4.3) were not affected significantly if we adopted the recent factor by Ballot et al. (submitted). Hence, the observed

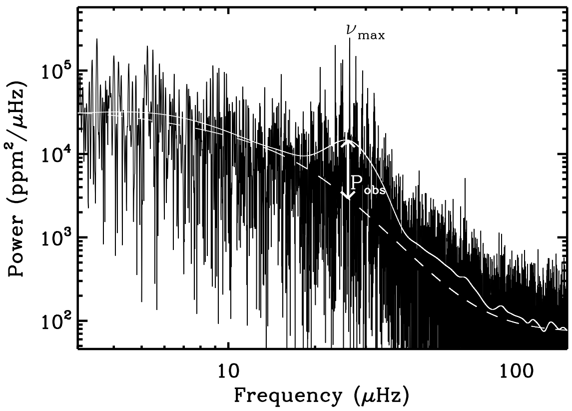

FIG. 2.— Power spectrum of a typical star. The smoothed spectrum (solid white line) and fit to the stellar granulation background (dashed line) are shown. The oscillation power, $P_{\rm obs}$, is evaluated at the frequency of maximum power, $\nu_{\rm max}$.

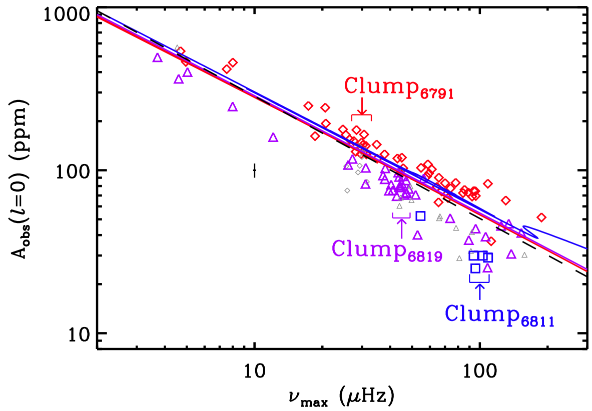

FIG. 3.— Observed amplitude versus $\nu_{\rm max}$ for stars in NGC 6791 (red diamonds), NGC 6819 (purple triangles), and NGC 6811 (blue squares). The binary stars are shown with small gray symbols. The clump stars are marked. The dashed line shows a power law with slope -0.75. Colored lines are the cluster isochrones (Figure 1) where amplitude and $\nu_{\rm max}$ have been derived using Equation 1 with $s = 0.75$ and $\nu_{\rm max} = (M/L)T_{\rm eff}^{3.5}\,3100\,\mu$Hz. The black cross at (10,100) indicates a typical 1-σ error bar.

amplitude per radial mode, $A_{\rm obs}(l=0)$ was derived as:

$$A_{\rm obs}(l=0) = (P_{\rm obs}\Delta\nu/3.04)^{1/2}. \qquad (2)$$

For this we normalized the power spectra according to the amplitude-scaled version of Parseval's theorem (Kjeldsen & Frandsen 1992), in which a sine wave of amplitude, A, provides a peak in the power spectrum of A^2. The typical uncertainty in the measured amplitude is $\sim 10\%$.

To explore whether the applied solar conversion factor, c, provided reasonable amplitudes for red giants, we ran simulations that as input took pulsation frequencies derived using the ADIPLS code (Christensen-Dalsgaard 2008a) for a representative set of ASTEC models (Christensen-Dalsgaard 2008b). Details of the simulator can be found in Chaplin et al. (2008). Following Christensen-Dalsgaard (2004), the input mode amplitudes were scaled relative to the radial modes using the mode inertia, I, as $A \propto I^{-2}$. Despite significant differences in the frequency spectra of red giants compared to the Sun, in particular the presence of many mixed modes (Dupret et al. 2009; Beck et al. 2011; Bedding et al. 2011), the pipelines returned amplitudes within 10% of the input values. We regard this as acceptable given the uncertainty from intrinsic scatter of the oscillations and the slightly different approaches for extracting the amplitudes in each pipeline, in particular the fitting and subtraction of the stellar granulation background Mathur et al. (submitted). Based on a representative set of stars, we found good agreement between the different pipelines. In this paper we show the results from the SYD pipeline (Huber et al. 2009), which provided amplitudes for the widest range of stars, and we compare our final result with the CAN pipeline (Kallinger et al. 2010), which exhibited the largest overlap in stellar sample with the SYD pipeline. Both pipelines show robust performances in their estimation of the stellar granulation background (Mathur et al. submitted). We refer to Verner et al. (2011) and Mosser et al. (in prep.) for detailed amplitude comparisons.

In addition to amplitude, the pipelines also measured the frequency of maximum power, $\nu_{\rm max}$ (Figure 2). The uncertainties in $\nu_{\rm max}$ are typically 1–2%.

4. RESULTS

4.1. $A_{\rm obs}$ *versus* $\nu_{\rm max}$

As noted by Stello et al. (2007); Mosser et al. (2010); Huber et al. (2010), it can be convenient to plot the measured amplitude as a function of $\nu_{\rm max}$, since the currently adopted scaling relations predict a simple relation between the two. In particular, by dividing $A_\lambda \propto (L/M)^s T_{\rm eff}^{-r}$ (Equation 1) by $(\nu_{\rm max})^s \propto (M/L)^s T_{\rm eff}^{3.5s}$ (Brown et al. 1991) and rearranging, we obtain $A_\lambda \propto \nu_{\rm max}^{-s} T_{\rm eff}^{3.5s-r}$. Hence, such a purely empirical plot allows one to make some inference on how the amplitude depends on the stellar parameters L, M, and $T_{\rm eff}$ even when those are not very well known (Mosser et al. e.g. 2010; Huber et al. e.g. 2010; Huber et al. in prep.; Mosser et al. in prep.).

In Figure 3 we show the measured amplitude as a function of $\nu_{\rm max}$, where each set of symbols present results of one cluster. We also mark the location of the clump of helium-core burning stars for each cluster, which illustrates the large range in $\nu_{\rm max}$ arising mainly from the difference in the stellar mass between the clusters.

Guided by the fiducial dashed line, we see that stars within each cluster roughly follow a power law with exponent -0.75, but with a clear offset from one cluster to another by up to $\sim 50\%$. The more massive the stars, the lower the oscillation amplitudes at a given $\nu_{\rm max}$. This offset is not expected from the scaling relations for A_λ and $\nu_{\rm max}$, as illustrated by the isochrones in Figure 3. Since the scaling relation for $\nu_{\rm max}$ is probably good to within a few percent (Stello et al. 2009; Belkacem et al. 2011), the observed offsets strongly suggest that $(L/M)^s T_{\rm eff}^{-r}$ does not adequately predict the amplitude for these stars. From a large sample of field red giants Huber et al. (2010) noted that the scatter in the amplitude at a given $\nu_{\rm max}$ was larger than expected from the uncertainties and that this indicated a spread in mass in their sample. However, a qualitative analysis was not attempted due to the relatively large uncertainties in the fundamental stellar parameters. Fortunately, with our cluster sample we can directly fit the measured amplitudes to their predictions derived from well-constrained stellar parameters.

4.2. *Fitting the* L/M *relation*

First, we fitted the observed amplitudes to the predicted amplitudes for NGC 6819. For this purpose we derived the predicted amplitude using the L/M relation (Equation 1) and adopting $\lambda = 650\,\mathrm{nm}$ as the central wavelength of the *Kepler* bandpass, hence $A_{\mathrm{obs},\odot} = 3.98$. The least-squares fit resulted in $s = 0.72 \pm 0.01$ when adopting the empirical value of $r = 2$, which is the value of r we will adopt in the following. Using $r = 1.5$ only has the effect of increasing s by about 0.03. This result is compatible with earlier findings on the same cluster in Paper I, which qualitatively found the best match for s to be slightly higher than 0.7. When repeated for NGC 6791, we found $s = 0.83 \pm 0.01$. The small number of stars in NGC 6811 did not merit a fit on its own, but the two other clusters already indicate inconsistent results.

Hence, we tried next fitting all three clusters simultaneously. Due to the correlation between M and T_{eff} (the hotter and younger clusters have more massive stars; Figure 1), we still kept r fixed. Figure 4(a) shows the result. The best fit resulted in $s = 0.70 \pm 0.01$. It is apparent that the clusters are offset from one another, as expected from Figure 3, but we also see that the fit systematically underestimates the amplitude for the most luminous stars. When r was treated as a free parameter we did obtain a better fit overall, but it still underestimated the amplitudes of the stars in NGC 6791, and in particular the most luminous stars in the sample, by 20–30%. In summary, while the $(L/M)^s$ scaling provided acceptable results when fitted to one cluster at a time (although giving different results for s), our analysis has demonstrated that $(L/M)^s$ cannot explain the observations in all clusters simultaneously.

4.3. *A new scaling relation for amplitudes*

In the following, we therefore fitted the exponents on L and M independently, hence $A_\lambda \propto L^s M^{-t} T_{\mathrm{eff}}^{-2}$. The result, shown in Figure 4(b), is a much improved fit where all three clusters fall on top of each other and follow the one-to-one relation. The best fitting parameters are $s = 0.86 \pm 0.02$ and $t = 1.7 \pm 0.1$ – the same as we obtained from first converting A_{obs} to a bolometric amplitude (Ballot et al., submitted) and then fitting to $A_{\mathrm{bol}} \propto L^s M^{-t} T_{\mathrm{eff}}^{-1}$. For the stars with $A_{\mathrm{obs}} \gtrsim 80\,\mathrm{ppm}$ the scatter of $A_{\mathrm{obs}}/(L^{0.86} M^{-1.7} T_{\mathrm{eff}}^{-2})$ is 14%, in perfect agreement with the quoted uncertainties on A_{obs}, L, M, and T_{eff}. The increased scatter (22%) towards lower luminosity stars is potentially due to remaining issues of blending in the sample and/or an increase in the uncertainties of the measured amplitudes for the faintest stars. The latter was however not reflected in the estimated uncertainties reported by the pipelines showing only slightly increased uncertainties at most. We show the χ^2 in the inset. The location of the minimum for different values of r is shown along the dotted line. The deepest minimum occurs at $r = 2.8$ but all values of r in the range shown result in χ^2 minima within 10%. Hence, if we were to fit r as well, the uncertainty would be very large ($\sigma \sim 0.5$) and we therefore do not recommend using $r = 2.8$ as it is not well constrained by the data.

To investigate the robustness of our fit we did the following. If we ignored the NGC 6811 stars in the fitting, the result and hence the excellent alignment of all three clusters was very similar (s and t within 1σ). This is perhaps not surprising given the few stars in our NGC 6811 sample. Nevertheless, this result is reassuring since the amplitudes of NGC 6811 are then correctly predicted from a fit based only on NGC 6791 and NGC 6819. We further investigated the effect on the fit

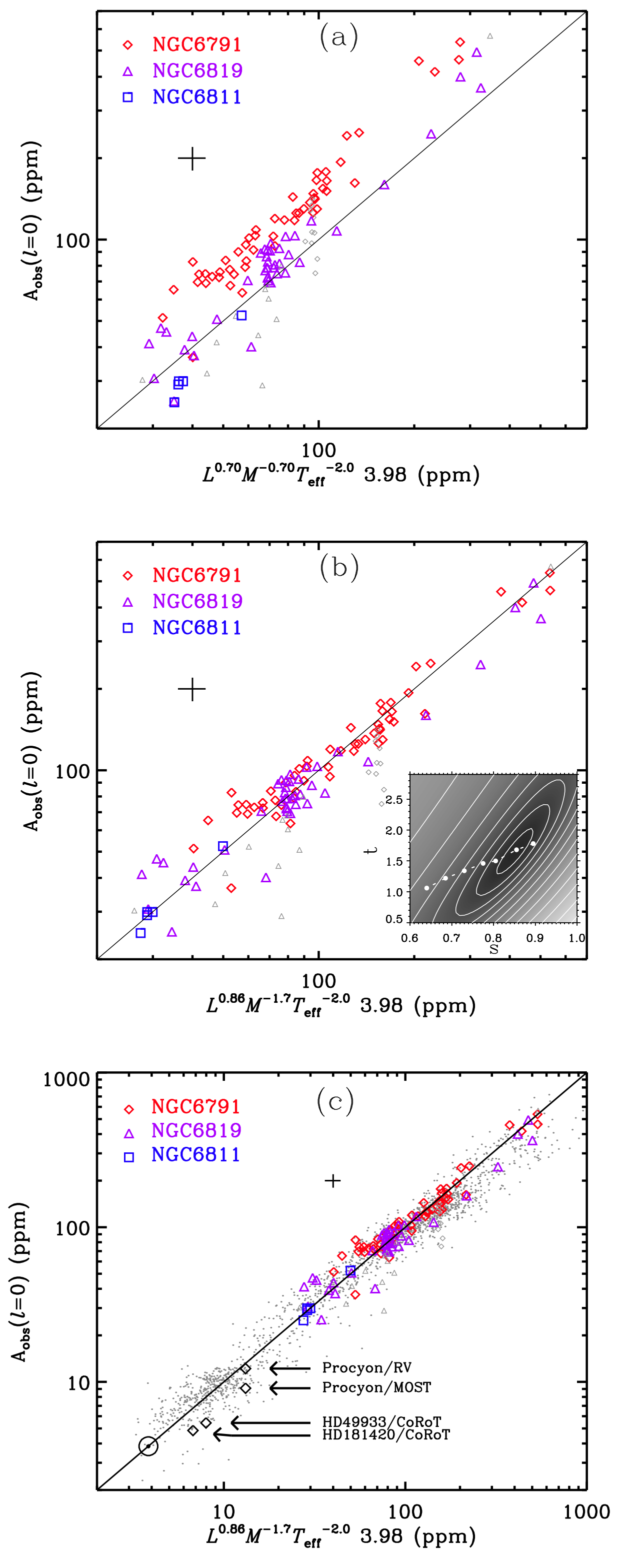

FIG. 4.— (a) Observed versus predicted amplitude for the best fitting relation of the form $A_\lambda \propto (L/M)^s T_{\mathrm{eff}}^{-2}$. Symbols are the same as in Figure 3. Binaries, which are shown with small gray symbols, were not included in the fit. (b) As panel (a) but fitting to $A_\lambda \propto L^s M^{-t} T_{\mathrm{eff}}^{-2}$. The inset shows the χ^2 near its minimum for $r = 2$. The dotted line shows the location of the minimum for varying r from 4.5 (left) to 1.5 (right) in steps of 0.5. (c) Illustration of how well the fit in panel (b) predicts amplitudes for other main-sequence, subgiant, and red giant stars (see text).

if we ignored all clump stars to obtain an even more homogeneous sample, which showed practically no change to the best fitting parameters. A small systematic change of a few percent on s and t was, however, observed by removing some of the most deviant stars at low amplitudes. Finally, we repeated the fit on the sample of stars that were in common between the SYD and CAN pipelines. The differences in s and t based on these different pipelines were 2% and 15% in s and t, respectively, the latter only just within 3σ of the formal uncertainty.

We finally tested the new scaling relation suggested by Kjeldsen & Bedding (2011), but found it to overestimate the amplitude for the cluster stars similar to the result found by Huber et al. (in prep.) and Mosser et al. (in prep.).

4.4. *Main-sequence and subgiant stars*

Now, with an improved scaling relation for red giant stars, it will be interesting to see how well it applies to main-sequence and subgiant stars. To investigate this we took amplitude measurements of the *Kepler* field stars presented by Huber et al. (in prep.), the CoRoT F-type stars HD49933 and HD181420 from Michel et al. (2008) (converted to $A_{\rm obs}(l{=}0)$), and Procyon from Arentoft et al. (2008) and Huber et al. (2011). The amplitude measurement in velocity of Procyon was converted to intensity using models by Houdek (2010). We used our new scaling relation to predict the amplitudes based on L, M, and $T_{\rm eff}$ from Huber et al. (in prep.) (*Kepler* sample), Bruntt (2009) (HD49933/181420), and Bonanno et al. (2007) (Procyon). Given that the new relation is only based on the cluster red giants, it is remarkable how well it agrees for this broad range of stars. We note that the uncertainty in the mass of the *Kepler* (~ 10–20%) and CoRoT (~ 5–10%) field stars is significantly larger than for Procyon (~ 2%) and the cluster stars (~ 1–2%). While the values of s and t found in this Letter are slightly different, though still in agreement within the uncertainties, than those found by Huber et al. (in prep.) for the *Kepler* field stars, the qualitative agreement across all stars is quite similar to that found by Huber et al. (their Fig. 5).

4.5. *Unresolved binaries*

It is evident, particularly from Figure 4(b), that many of the known and potential binaries (small gray diamonds and triangles) show relatively low amplitudes. For NGC 6791 we had no spectroscopic determination of binaries, but a significant fraction of its red clump stars show lower than expected amplitudes and hence strong evidence for 'diluted' light curves due to the presence of unresolved binary companions. This shows a new exciting way of applying asteroseismology to identify binary stars and hence to probe the formation of these stars in clusters, which will be investigated in detail in a forthcoming paper.

5. CONCLUSIONS

Our analysis of solar-like oscillations in 100 red giant stars in three open clusters revealed that previously adopted scaling relations based on the luminosity-to-mass ratio for predicting amplitudes are not adequate for red giants. We found an empirical scaling relation by fitting the observed amplitudes to a more general form than the previous L/M relation. The result,

$$A_\lambda \propto L^{0.86}/(M^{1.7}T_{\rm eff}^2) \tag{3}$$

and

$$A_{\rm bol} \propto L^{0.86}/(M^{1.7}T_{\rm eff}), \tag{4}$$

which showed considerable improvement for red giants, turned out to also work remarkably well for main-sequence and subgiant stars.

Interestingly, the lower than expected amplitudes of some red clump stars in NGC 6791 and NGC 6819 revealed that they were likely unresolved binaries, many of which were not known previously. This method for identifying binaries could add interesting new insight to the formation history of these clusters.

In this investigation we ignored any possible effect on amplitude from metallicity differences of the three clusters (Samadi et al. 2007). To improve on that will require better determination of the cluster metallicities. In addition, we would need more clusters (with significantly different stellar parameters) to allow the fitting of a rigorous empirical relation including one more free parameter such as metallicity.

With more *Kepler* data in the future, we expect to have cluster stars covering a large range of $T_{\rm eff}$, which will include turn-off stars at the end of the main sequence, allowing us to also fit the exponent, r, of the $T_{\rm eff}$ dependence in the amplitude scaling relation.

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REFERENCES

Arentoft, T., et al. 2008, ApJ, 687, 1180
Basu, S., et al. 2011, ApJ, 729, L10
Baudin, F., et al. 2011, A&A, 529, 84
Beck, P. G., et al. 2011, Science, 332, 205
Bedding, T. R., et al. 2010a, ApJ, 713, 935
—. 2010b, ApJ, 713, L176
—. 2011, Nature, 471, 608
Belkacem, K., Goupil, M. J., Dupret, M. A., Samadi, R., Baudin, F., Noels, A., & Mosser, B. 2011, A&A in press (arXiv:1104.0630)
Bonanno, A., Küker, M., & Paternò, L. 2007, A&A, 462, 1031
Brown, T. M., Gilliland, R. L., Noyes, R. W., & Ramsey, L. W. 1991, ApJ, 368, 599
Bruntt, H. 2009, A&A, 506, 235
Chaplin, W. J., et al. 2008, Astronomische Nachrichten, 329, 549
Christensen-Dalsgaard, J. 2004, Sol. Phys., 220, 137
—. 2008a, Ap&SS, 316, 113
—. 2008b, Ap&SS, 316, 13
Christensen-Dalsgaard, J., & Frandsen, S. 1983, Sol. Phys., 82, 469
de Ridder, J., et al. 2009, Nature, 459, 398
Di Mauro, M. P., et al. 2011, MNRAS in press (arXiv:1105.1076)
Dupret, M., et al. 2009, A&A, 506, 57
Garcia, R. A., et al. 2011, MNRAS in press (arXiv:1103.0382)
Gilliland, R. L., et al. 2010, PASP, 122, 131
Hekker, S., et al. 2010, MNRAS, 402, 2049
—. 2011, A&A in press (arXiv:1104.4393)
Houdek, G. 2006, in ESA Special Publication, Vol. 624, Proceedings of SOHO 18/GONG 2006/HELAS I, Beyond the spherical Sun
Houdek, G. 2010, Ap&SS, 328, 237
Houdek, G., Balmforth, N. J., Christensen-Dalsgaard, J., & Gough, D. O. 1999, A&A, 351, 582
Huber, D., Stello, D., Bedding, T. R., Chaplin, W. J., Arentoft, T., Quirion, P., & Kjeldsen, H. 2009, Communications in Asteroseismology, 160, 74

Huber, D., et al. 2010, ApJ, 723, 1607
—. 2011, ApJ, 731, 94
Jenkins, J. M., et al. 2010, ApJ, 713, L120
Kallinger, T., et al. 2010, A&A, 522, 1
Kjeldsen, H., & Bedding, T. R. 1995, A&A, 293, 87
—. 2011, A&A, 529, L8
Kjeldsen, H., & Frandsen, S. 1992, PASP, 104, 413
Kjeldsen, H., et al. 2008, ApJ, 682, 1370
Koch, D. G., et al. 2010, ApJ, 713, L79
Marigo, P., Girardi, L., Bressan, A., Groenewegen, M. A. T., Silva, L., & Granato, G. L. 2008, A&A, 482, 883
Mathur, S., et al. 2010, A&A, 511, 46
Michel, E., et al. 2008, Science, 322, 558
Montalbán, J., Miglio, A., Noels, A., Scuflaire, R., & Ventura, P. 2010, ApJ, 721, L182
Mosser, B., & Appourchaux, T. 2009, A&A, 508, 877
Mosser, B., et al. 2010, A&A, 517, 22
Pietrinferni, A., Cassisi, S., Salaris, M., & Castelli, F. 2004, ApJ, 612, 168
Samadi, R., Georgobiani, D., Trampedach, R., Goupil, M. J., Stein, R. F., & Nordlund, Å. 2007, A&A, 463, 297
Stello, D., Chaplin, W. J., Basu, S., Elsworth, Y., & Bedding, T. R. 2009, MNRAS, 400, L80
Stello, D., et al. 2007, MNRAS, 377, 584
—. 2010, ApJ, 713, L182
Verner, G. A., et al. 2011, MNRAS in press (arXiv:1105.0571)