Precise surface gravities of δ Scuti stars from asteroseismology

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ABSTRACT

The work reported here demonstrates that it is possible to accurately determine surface gravities of δ Sct stars using the frequency content from high precision photometry and a measurement of the parallax. Using a sample of 10 eclipsing binary systems with a δ Sct component and the unique δ Sct star discovered with a transiting planet, WASP-33, we were able to refine the Δν − ρ relation. Using this relation and parallaxes, we obtained independent values for the masses and radii, allowing us to calculate the surface gravities without any constraints from spectroscopic or binary analysis. A remarkably good agreement was found between our results and those published, extracted from the analysis of the radial velocities and light curves of the systems. This reinforces the potential of Δν as a valuable observable for δ Sct stars and settles the degeneracy problem for the log g determination through spectroscopy.

Key words: binaries: eclipsing — stars: oscillations — stars: rotation — stars: variables: delta Scuti

1 INTRODUCTION

δ Scuti (δ Sct) stars are A to F-type pulsating stars located on the main sequence or at the H-shell burning phase. They are placed within the classical instability strip with a mass between ~1.5 and 3 M⊙. The interpretation of the oscillation spectra of δ Sct stars is not an easy task. The intrinsic nature of the modes and the interaction with other important mechanisms, namely rotation, complicates the oscillation spectrum (see e.g. Goupil et al. 2005, for an interesting review on the subject). In the era of space missions like MOST (Walker et al. 2003) CoRoT (Baglin et al. 2006) and Kepler (Koch et al. 2010), despite the significant increase in the number of detected frequencies, the frequency content is still hard to decipher (e.g. Poretti et al. 2009; García Hernández et al. 2009; Pascual-Granado et al. 2015). Even so, relevant progress has been achieved regarding the theoretical modelling of these stars thanks to the inclusion of rotation effects in 2D evolution models, and the use of a non-perturbative approach to compute the oscillation frequencies and mode visibilities (see e.g. Reese et al. 2013; Ouazzani et al. 2012; Rieutord et al. 2016, to name a few). Some advances have been shedding light on the interpretation of the pulsation spectrum thanks to the analysis of frequency patterns (García Hernández et al. 2009, 2013; Paparó et al. 2016; Barceló Forteza et al. 2017; Michel et al. 2017; Reese et al. 2017).

A-type stars are hot and usually fast rotators. Measurements of the surface projected velocities v sin i and statistical inferences on the real rotation rates show that they can
reach values close to the break-up limit (Royer et al. 2007), which severely hampers accurately determining stellar global parameters, such as effective temperature and abundances. In addition, the lack of metallic lines in the spectra is responsible for the well-known degeneracy in surface gravity determinations.

Binary systems with a δ Sct component can help with handling these problems. Accurate physical parameters can be obtained thus avoiding any degeneracy. Observing these systems with recent space satellites allowed us to properly resolve the pulsation spectra of their δ Sct components. In a recent work, García Hernández et al. (2015) (GH15 in what follows) demonstrated that there exists a direct relation between the mean density of δ Sct stars and one of these frequency patterns, a large frequency separation, defined as the difference in frequency between pressure modes (p modes) of the same spherical degree, ℓ, and consecutive radial orders, n.

In this work, we use a well-studied sample of eclipsing binary systems with a δ Sct component to determine the stellar surface gravities only from the pulsation frequencies, which breaks the degeneracy for this physical quantity found by spectroscopic methods. This allows us to accurately measure the physical parameters for A-F type stars.

2 THE SAMPLE

The starting point was the sample of 7 eclipsing binaries in GH15. We added four additional well studied systems: three binary systems and a δ Sct star with a transiting planet. The three binary systems, KIC9851944 (Guo et al. 2016), KIC8262223 (Guo et al. 2017) and KIC10080943 (Schmid et al. 2015), were observed by the Kepler satellite. The combined analysis of their light curves and radial velocity measurements allows us to determine the physical parameters for both components. KIC9851944 and KIC8262223 are eclipsing binary systems, but KIC10080943 is indeed an eccentric, non-eclipsing binary showing periastron brightening events. Nonetheless, a similar analysis to those of the eclipsing systems allows an accurate and precise determination of the masses and radii. Additionally, we included in our study HD 15082, also known as WASP-33, the only δ Sct star discovered with a transiting planet. For this object, the mean density is also measurable in a similar way to the other stars in the sample (Cameron et al. 2010).

The relevant parameters of these systems are listed in Table 1. The mean density ($\bar{\rho}$), the mean radii ($\bar{R}$), the surface gravity ($\log g_0$) and the large separation ($\Delta \nu$) have been obtained using the values found in the literature (see Sec. 3 for details). We only derived $\Delta \nu$ values for KIC10080943 and HD 15082 for the first time.

In some cases, both components in the system showed pulsations and it was not possible to determine which one is responsible for the large frequency separation found. In our analysis, we did not find any signatures of multiple large separations. Thus, all the parameters in the table refer to the star whose properties best fits the large separation-mean density relation. In the unlikely case that the pattern was a combination of two large separations, it would not fit the $\Delta \nu$-$\bar{\rho}$ relation.

Parallaxes ($\bar{\pi}$), needed to get an independent estimate of the masses were taken from the Gaia mission catalogue (Gaia Collaboration et al. 2016a,b) or from Hipparcos (van Leeuwen & Floor 2010). We describe the complete procedure on how to obtain masses and surface gravities from the parallaxes in Sec. 4. But we need to determine accurately mean densities first.

3 THE $\Delta \nu$-$\bar{\rho}$ RELATION

The analysis of pulsations in δ Sct stars revealed the presence of periodic patterns in their p-mode frequency spectra (see e.g. García Hernández et al. 2009, 2013). These patterns were also predicted theoretically (Reese et al. 2008; Ouazzani et al. 2015) and were found to be compatible with a large separation in the low order regime ($\Delta \nu$, Suárez et al. 2014). In that paper, it was discovered that the large separation extends to the range $n = [2, 8]$ for non-rotating models. A solid confirmation came from the scaling relation found in GH15 between the observed periodic pattern and the mean density computed for a sample of well-known eclipsing binary stars at different rotation rates. As predicted by oscillation models (Reese et al. 2008). $\Delta \nu$ in δ Sct stars scales with the stellar mean density independently of its rotation rate.

We searched for the large separations of KIC10080943 and HD 15082 from the oscillation spectra publicly available. When necessary, we cleaned those spectra in order to remove harmonics and combinations. Likewise, in order to enhance the $\Delta \nu$ pattern in the periodicity analysis, we sought to avoid contamination from g modes, taking only frequencies above ~ 5 d$^{-1}$ (see GH15). We also considered the recent results in which the observed spacing might be a combination of $\Delta \nu$ and the rotational splitting (Paparò et al. 2016; Guo et al. 2017). This is the case of HD 15082, for which the spacing is $\Delta \nu$/2 plus the rotational splitting (work in prep.). The methodology employed to find patterns compares the Fourier transforms of the frequencies (assuming all amplitudes equal 1), the histograms of the frequencies differences and the échelle diagrams to find the best $\Delta \nu$ candidate, as it is described in GH15.

Following GH15, we calculated the mean densities of the new objects of the sample, i.e. considering the Roche model approximation (e.g. Maeder & André 2009), assuming that the measured radii correspond to the equatorial ones. This allowed us to replace the generally adopted spherical radius by a mean radius, $\bar{R}$, defined as the radius of a sphere with the same volume as the real spheroidal star. Such an approximation was validated through comparisons with more realistic Self-Consistent Field (SCF) models (MacGregor et al. 2007). For computing this mean radius, we need the true rotation velocity of the star, calculated from the projected rotation velocity, the equatorial radius, and the assumption that the inclination of the orbital plane is the same as the rotation axis (Claret & Gimenez 1993).

We then refined the relation between the mean stellar density and large frequency separation by implementing a Hierarchical Bayesian linear regression. The calculation is implemented using the JAGS package (Just Another Gibbs Sampler, Plummer 2003). A similar application to fit the mass-radius relation of exo-planets can be found in Wolfgang
Table 1. Characteristics of the systems taken from the literature (see footnote for references) and calculated in this work. Columns 3 to 7 are values inferred from the binary analysis, whereas column 8 is calculated from the parallax. The information corresponds to the component showing the large frequency pattern (which is not necessarily the primary).

| System       | $\Delta \nu$ | $\rho/\bar{\rho}$ | $\Omega/\Omega_\odot$ | $M_\odot$ | $R_\odot$ | $\log g_\odot$ | $\log g_\star$ | $\bar{\pi}$ | $\Delta M_\text{bol}$ |
|--------------|--------------|--------------------|------------------------|-----------|-----------|---------------|---------------|------------|---------------------|
| KIC35858841  | 29.0 ± 1.0   | 0.0657 ± 0.0021    | 0.075                  | 1.86 ± 0.04 | 3.047 ± 0.010 | 3.740 ± 0.012 | 3.76 ± 0.04  | 1.78 ± 0.22 |
| KIC45445872  | 74.0 ± 1.0   | 0.414 ± 0.039      | 0.17                   | 1.61 ± 0.06 | 1.572 ± 0.030 | 4.252 ± 0.033 | 4.27 ± 0.08  | 1.36 ± 0.41 |
| KIC106617833 | 39.0 ± 1.0   | 0.1255 ± 0.0039    | 0.20                   | 2.100 ± 0.028 | 2.558 ± 0.015 | 3.95 ± 0.011  | 3.95 ± 0.04  | 1.94 ± 0.26 |
| HD172189     | 19.0 ± 1.0   | 0.0283 ± 0.0061    | 0.28                   | 1.78 ± 0.24 | 3.98 ± 0.11  | 3.490 ± 0.082 | 3.53 ± 0.06  | 2.27 ± 0.34 |
| C108066999   | 56.0 ± 1.0   | 0.26 ± 0.11        | –                      | 1.8 ± 0.2  | 1.9 ± 0.2   | 4.14 ± 0.14   | –             | –          |
| HD172189     | 20.0 ± 2.0   | 0.02986 ± 0.00095  | 0.15                   | 2.25 ± 0.04 | 4.224 ± 0.020 | 3.539 ± 0.012 | 3.52 ± 0.10  | 0.96 ± 0.25 |
| HD159561    | 38.0 ± 1.0   | 0.124 ± 0.021      | 0.60                   | 2.4 ± 0.37 | 2.688 ± 0.014 | 3.960 ± 0.072 | 3.93 ± 0.03  | 67.13 ± 1.06 |
| KIC98519448  | 26.0 ± 1.0   | 0.0566 ± 0.0043    | 0.29                   | 1.79 ± 0.07 | 3.162 ± 0.040 | 3.691 ± 0.028 | 3.75 ± 0.25  | 0.41 ± 0.38 |
| KIC8262223   | 77.0 ± 1.0   | 0.423 ± 0.043      | 0.11                   | 1.96 ± 0.06 | 1.667 ± 0.040 | 4.287 ± 0.034 | 4.23 ± 0.10  | 1.93 ± 0.59 |
| KIC10806943  | 52.0 ± 1.0   | 0.205 ± 0.070      | 0.030                  | 1.9 ± 0.1  | 2.10 ± 0.20  | 4.07 ± 0.11   | 4.06 ± 0.08  | 1.06 ± 0.28 |
| HD150821    | 80.0 ± 2.0   | 0.507 ± 0.046      | 0.20                   | 1.495 ± 0.031 | 1.434 ± 0.034 | 4.300 ± 0.030 | 4.31 ± 0.03  | 8.51 ± 0.24 |

The distance modulus relation provided us with the bolometric magnitudes (\(M_\text{bol}\)) that translate into luminosities (with parallaxes measured in mas):

\[
M_\text{bol} - m_\text{bol} = 5 + 5 \log \bar{\pi}.
\]  

We used visual apparent magnitudes provided by the same bibliographic references as for the parallaxes. To get bolometric magnitudes from visual ones, we needed to apply a bolometric correction (BC) that depends on the effective temperature of the star. However, the BC for A-type stars is usually small (see e.g. Hayes 1978) so it can be neglected. Indeed, we checked out that this was the case for our sample and duplicated all our calculations with and without taking into account the BC. To compute the corrections, we followed the empirical formulations given by Torres (2010), obtaining values for BC of the order of 0.01 mag. From \(M_\text{bol}\), we could obtain the luminosities through the relation: \(M_\text{bol,\odot} - M_\text{bol} = 2.5 \log L\), where \(M_\text{bol,\odot} = 4.74\) and where the luminosity is expressed in solar units. We also took into account the relative luminosities of each star to properly calculate the corresponding flux coming from the pulsation component. The relative luminosities are those obtained from the binary analysis. The only exceptions are HD 159561 and HD 15082, for which we used the total fluxes.

The final step is to use a MLR. Using a sample of well studied and detached Algol-type stars, Ibanoglu et al. (2006) refined the MLR for A-F type stars:

\[
L \propto M_\star^{1.92 \pm 0.05}.
\]
With the mean density from the $\Delta v - \bar{\rho}$ relation and the mass from the MLR, we could obtain a radius from the volume of the star assuming spherical symmetry. This radius and the mass allowed us to calculate the surface gravity ($\log g_\star$ in Table 1). The $\log g_\star$ values are remarkably close to those obtained from the binary analysis, which are always within the uncertainties (Table 1 and Fig. 2). Uncertainties on $\log g_\star$ come from a standard error propagation analysis.

We improved the surface gravities from the literature using the provided masses and the mean radius, as defined in Sec. 3, to take into account the stellar deformation due to rotation. In general, our calculations give similar results to those in the literature, since the majority of the stars do not move away from sphericity. However, it is important to notice that a unique $\log g$ value for rapid rotating stars cannot be defined. This is the case for HD 159561, for which we followed the same procedure as the others just to show the consistency of the results.

We emphasize that masses calculated by this method might not be accurate enough, i.e., within the uncertainties, just $\log g$. This is because the validity of the MLR relation is for main-sequence stars and some of the stars in our sample are in the H-shell burning phase. Radii are less affected because of the dependency on the cube-root.

5 DISCUSSION

A few conclusions can be derived immediately from our work. Even when the spherical approximation is used to obtain both the radius and the $\log g$, the calculated values agreed within the uncertainties with the quantities from the binary analysis. However, the uncertainties coming from the joint analysis of the radial velocity curve and the light curve of an eclipsing binary system are still much lower than those derived using our methodology. This is expected, since masses and radii from the binary analysis are much more precise than those obtained from the MLR and the $\Delta v - \bar{\rho}$ relation. Indeed, the uncertainty in the exponent of the $\Delta v - \bar{\rho}$ relation has the largest impact on the accurate determination of $\log g$. Additionally, precisely determining parallaxes is crucial: the larger the uncertainty on the parallax, the larger the uncertainty on the surface gravity. This explains the large uncertainty for KIC 9851944.

Nonetheless, we carried out a simple test to check the robustness of the calculated $\log g$. Instead of deriving masses using parallaxes, we used random values in the range $[1, 3] M_\odot$. The maximum dispersion in these new calculated $\log g$ was 0.2 dex ($\pm0.1$ dex). This must be considered as an upper limit for the errorbars related to the masses, unless precise masses measurements reduce this uncertainty.

The only value of $\log g$ not derived from the binary analysis is that of HD 159561. The high oblateness of this fast rotator prevented us from getting a unique solution for the surface gravity but rather an average value, which still follows the identity relation. In absence of the actual rotation profile of stars, this new averaged surface gravity might be useful for characterizing rapidly rotating stars. For example, this surface gravity could be compared even to non-rotating models to get an accurate determination of the mass.

All the typical error-bars on the surface gravity are of the order of those obtained with high resolution spectroscopy, some of them are even shorter.

6 CONCLUSIONS

In this work, we demonstrated that the analysis of pulsations in $\delta$ Sct stars allows us to accurately obtain some physical parameters of the stars, in particular the mean density and the surface gravity.

To achieve these results, we analysed a sample of 10 well studied eclipsing binary systems with a $\delta$ Sct component, thus enlarging the sample of GH15. Additionally, we also used the only $\delta$ Sct star with a known transiting planet, HD 15082. For all these systems, precise and model-independent masses and radii were available in the literature. We obtained the large separations for each oscillation spectrum of the pulsating component, following the method by GH15. We correlated the mean densities calculated with the masses and radii with $\Delta v$. Applying a Hierarchical Bayesian linear regression, we could confirm and reduce the uncertainties on the $\Delta v - \bar{\rho}$ relation from GH15. Again, we showed that this relation is independent of the rotation velocity of the star.

We went then a step further. Using the precise parallaxes given by the Gaia mission, when available, and Hipparcos measurements, we determined the luminosities of the stars. These quantities and the MLR by Ibanoglu et al. (2006) allowed us to estimate masses in an independent way. With this value and the mean density from the $\Delta v - \bar{\rho}$ relation, we obtained a mean radius from which we calculated surface gravities for the stars of the sample. We checked that the BC has little influence on the calculation of $\log g$, as expected because it is usually small for A-type stars.

We compared surface gravities obtained in this way with those from the literature, obtained from the radial velocity and light curves of the binary systems. We demonstrated that there exists an equivalence between both methods. This fact strengthens the main conclusion of the work: the sur-
face gravity degeneracy can be overcome just analysing the pulsations of δ Sct stars and using parallaxes measurements.

All these results shed light on the understanding of the pulsation spectrum and precise characterisation of δ Sct stars, and show that finding $\nu$ is a major breakthrough to achieve such ambitious goal.

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