KIC 10080943: a binary star with two $\gamma$ Doradus/$\delta$ Scuti hybrid pulsators. Analysis of the g modes

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ABSTRACT

We use four years of Kepler photometry to study the non-eclipsing spectroscopic binary KIC 10080943. We find both components to be $\gamma$ Doradus/$\delta$ Scuti hybrids, which pulsate in both p and g modes. We present an analysis of the g modes, which is complicated by the fact that the two sets of $\ell = 1$ modes partially overlap in the frequency spectrum. Nevertheless, it is possible to disentangle them by identifying rotationally split doublets from one component and triplets from the other. The identification is helped by the presence of additive combination frequencies in the spectrum that involve the doublets but not the triplets. The rotational splittings of the multiplets imply core rotation periods of about 11 d and 7 d in the two stars. One of the stars also shows evidence of $\ell = 2$ modes.

Key words: asteroseismology – binaries: spectroscopic – stars: individual: KIC 10080943 – stars: oscillations – stars: variables: $\delta$ Scuti – stars: variables: general
that orbital variations in the light arrival times of some of the p-mode pulsations occur in anti-phase with others. This demonstrates that both stars pulsate in p modes as discussed by Schmid et al. (2015). The same methodology cannot be applied to the g modes because the higher frequency density demands an unachievable frequency resolution, given the sampling required for the short orbit. Nonetheless, the focus of this paper is to show that both components also pulsate in g modes.

2 DATA ANALYSIS & RESULTS

When analysing high-order g modes, we are guided by the expectation that they are equally spaced in period (Tassoul 1980). However, the steep composition gradient (µ gradient) between the core and outer layers can cause deviations from this uniform period spacing (Miglio et al. 2008). Furthermore, as shown by Bouabid et al. (2013), stellar rotation causes the period spacing to vary with frequency. These effects have been observed in Kepler data for a number of γ Dor stars (Bedding et al. 2014; Van Reeth et al. 2015a,b).

For KIC 10080943, we used long-cadence data (29.4-minute sampling) from the full Kepler mission, spanning 1470.5 d (4.0 y). The Fourier spectrum (Fig. 1) shows pulsations in both the g-mode and p-mode frequency regions. These regions are clearly separated, with the g-mode region below approximately 6 d^{-1} and the p-mode region above approximately 8 d^{-1}.

At low frequency there is a peak at 0.065209 d^{-1} with a long series of harmonics. Such harmonic series are often seen in binary stars. The inverse of this frequency is 15.335 d, which we take as the binary orbital period. KIC 10080943 was already established as a binary by Tkachenko et al. (2013), and was selected for spectroscopic observations to determine the orbital parameters of the system. Those are presented in Schmid et al. (2015).

To analyse the pulsation content, we sequentially extracted the 250 strongest peaks in the frequency range from zero to the Nyquist frequency (24.47 d^{-1}) using PERIOD04 (Lenz & Breger 2004, 2005). Non-linear least-squares fitting was implemented during extraction. Although we were interested in the g modes, the p modes were also extracted because the spectral windows of the p and g modes overlap. We also checked that the extracted peaks were not Nyquist aliases using the method outlined by Murphy, Shibahashi & Kurtz (2013).

In the range 0.6 to 1.7 d^{-1} we identified six series of pulsation modes. Each is approximately equally spaced in period, consistent with a series of overtones with a common ℓ and m value. Furthermore, some of the series are separated from others by a fixed frequency, suggesting rotational splitting. Given that KIC 10080943 is a binary system, we were led to identify two sets of g modes with slightly different period spacings, one from each component of the binary. This is shown in Figs 2 and 3, where we have arbitrarily labelled the components of the binary as Stars A and B. In Star A we see rotationally split doublets, while Star B has triplets in which the central component is weak. There is also a sequence with slightly lower period spacing (asterisks) that we tentatively identify with ℓ = 2 modes. Note that Bed-
The peaks are plotted in échelle format in Fig. 4 for the two stars, with symbol size indicating amplitude. The frequencies and amplitudes for the six g-mode series are given in Tables 1 to 3. Importantly, all significant peaks in this frequency range have been identified with modes. The number of points in the échelle diagram (Fig. 4) is greater than the number in the period spacing diagram (Fig. 2), since the latter require two neighbouring modes for each period spacing, but some modes are missing. Values of $m$ could still be assigned to modes in incomplete multiplets by tracing their period spacings.

2.1 Combination Frequencies

Kurtz et al. (2015) showed recently that the Fourier spectra of some g-mode pulsators are dominated by combination frequencies. We have checked whether any peaks in the main g-mode region of KIC10080943 (0.6 to 1.7 d$^{-1}$) are
2.2 Rotational Splittings

As discussed above, we identified two series of rotationally split \( \ell = 1 \) multiplets, one in each component of the binary – see Fig. 3. The triplets in Star B \((m = 0, \pm 1)\) have frequency splittings of about \(0.07 \, \text{d}^{-1}\) and are slightly asymmetric, as shown in the lower panel of Fig. 6. The asymmetry is small, at about 0.5 per cent, and is presumably caused by second-order effects (see Murphy 2014 for a discussion of non-equal rotational splittings in A stars in the \textit{Kepler} era). The implied rotation period at the edge of the convective core is about 7 d.

The doublets in Star A, which presumably correspond to azimuthal orders \(m = \pm 1\), have a frequency splitting of \(0.091 \, \text{d}^{-1}\). This varies slightly with frequency, as shown in the upper panel of Fig. 6. This variation cannot be explained by radial differential rotation because the g-modes all probe the same region outside the core. Instead, it reflects the fact that the Ledoux constant \(C_{n,1}\) has a small dependence on radial order, \(n\) (Bedding et al., in prep.). Star A is a particularly good example of this phenomenon. Its core rotation period is about 11 d.
Figure 5. Additive combination frequencies in KIC 10080943. The upper plot shows the g-mode region of the amplitude spectrum while the lower plot shows a higher-frequency section of exactly the same length, with an offset of $f_{3,3} = 3.34 \text{ d}^{-1}$. Coloured symbols have the same meanings as in previous figures, with the addition that those in the lower panel indicate combination frequencies. Note the different amplitude scales in the two panels.

3 CONCLUSION

KIC 10080943 is a binary system with two pulsating components, making it particularly interesting for asteroseismology. The combined oscillation spectrum is complicated because the two sets of g modes partially overlap in frequency. However, it was possible to disentangle them by identifying rotationally split doublets in Star A and triplets in Star B. The identification was helped by the presence of additive combination frequencies in Star A and not Star B. The rotational splittings of the g-mode multiplets imply core rotation periods of about 11 d and 7 d in Stars A and B, respectively. Analysis of the p modes, together with models of the oscillation frequencies, are presented by Schmidt et al. (2015) and in future papers.

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Table 1. A least-squares fit of the g-mode $\ell = 1$ doublets in Star A (as shown in Fig. 3) for KIC 10080943. The uncertainties were determined by non-linear least-squares fitting.

| $m$  | Frequency (d$^{-1}$) | Amplitude (mmag ± 0.007) |
|------|---------------------|--------------------------|
| −1   | 0.701089 ± 0.000011 | 0.237                    |
| −1   | 0.740343 ± 0.000003 | 0.726                    |
| −1   | 0.761387 ± 0.000002 | 1.314                    |
| −1   | 0.783179 ± 0.000002 | 1.163                    |
| 1    | 0.874151 ± 0.000003 | 0.762                    |
| −1   | 0.806578 ± 0.000006 | 0.440                    |
| 1    | 0.897602 ± 0.000006 | 0.415                    |
| −1   | 0.831815 ± 0.000002 | 1.414                    |
| 1    | 0.922896 ± 0.000002 | 1.436                    |
| −1   | 0.858849 ± 0.000002 | 1.263                    |
| 1    | 0.949902 ± 0.000003 | 0.971                    |
| −1   | 0.886926 ± 0.000002 | 1.679                    |
| 1    | 0.978058 ± 0.000002 | 1.239                    |
| −1   | 0.916677 ± 0.000002 | 1.401                    |
| 1    | 1.007856 ± 0.000002 | 1.379                    |
| −1   | 0.948214 ± 0.000002 | 1.474                    |
| 1    | 1.039429 ± 0.000003 | 0.731                    |
| −1   | 0.982322 ± 0.000005 | 0.511                    |
| 1    | 1.073596 ± 0.000002 | 1.493                    |
| −1   | 1.059381 ± 0.000012 | 2.169                    |
| 1    | 1.150806 ± 0.000001 | 1.956                    |
| −1   | 1.110715 ± 0.000004 | 0.709                    |
| 1    | 1.195443 ± 0.000003 | 0.815                    |
| 1    | 1.238138 ± 0.000002 | 1.455                    |
| 1    | 1.341122 ± 0.000004 | 0.671                    |
Table 2. A least-squares fit of the g-mode $\ell = 1$ triplets in Star B (as shown in Fig. 3) for KIC 10080943. The uncertainties were determined by non-linear least-squares fitting.

| $m$ | Frequency (d$^{-1}$) | Amplitude (mmag) ± 0.007 |
|-----|----------------------|--------------------------|
| −1  | 0.889276 ± 0.000051  | 0.048                    |
| −1  | 0.920191 ± 0.000009  | 0.286                    |
| −1  | 0.953444 ± 0.000003  | 0.926                    |
| −1  | 0.989185 ± 0.000015  | 0.173                    |
| −1  | 1.027054 ± 0.000005  | 0.516                    |
| 0   | 1.097305 ± 0.000029  | 0.82                     |
| 1   | 1.168167 ± 0.000035  | 0.71                     |
| −1  | 1.067338 ± 0.000004  | 0.665                    |
| 0   | 1.137748 ± 0.000018  | 0.145                    |
| 1   | 1.208489 ± 0.000005  | 0.484                    |
| −1  | 1.110715 ± 0.000004  | 0.709                    |
| 0   | 1.181141 ± 0.000013  | 0.202                    |
| 1   | 1.252003 ± 0.000004  | 0.655                    |
| −1  | 1.158160 ± 0.000005  | 0.483                    |
| 0   | 1.228640 ± 0.000016  | 0.151                    |
| 1   | 1.299529 ± 0.000004  | 0.619                    |
| −1  | 1.210161 ± 0.000017  | 0.153                    |
| 0   | 1.280615 ± 0.000030  | 0.082                    |
| 1   | 1.351545 ± 0.000005  | 0.512                    |
| −1  | 1.267386 ± 0.000012  | 0.215                    |
| 1   | 1.408809 ± 0.000006  | 0.398                    |
| 1   | 1.473037 ± 0.000008  | 0.312                    |
| 1   | 1.545034 ± 0.000016  | 0.158                    |

Table 3. A least-squares fit of the series of g-modes of KIC 10080943 marked with black asterisks in Figs 2 to 4. These peaks are tentatively labelled as having $\ell = 2$ and belonging to Star B. The uncertainties were determined by non-linear least-squares fitting.

| Frequency (d$^{-1}$) | Amplitude (mmag) ± 0.007 |
|----------------------|--------------------------|
| 1.271255 ± 0.0000010 | 0.254                    |
| 1.315665 ± 0.0000050 | 0.051                    |
| 1.362751 ± 0.0000015 | 0.173                    |
| 1.412779 ± 0.0000007 | 0.369                    |
| 1.466406 ± 0.0000007 | 0.378                    |
| 1.524018 ± 0.0000012 | 0.214                    |
| 1.585784 ± 0.0000050 | 0.050                    |
| 1.653745 ± 0.0000015 | 0.170                    |

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