Spectroscopic frequency and mode identification of $\gamma$ Doradus stars HD 109799 and HD 103257

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Accepted 2021 July 5. Received 2021 July 5; in original form 2020 November 18

ABSTRACT

Following frequency and mode identification of two candidate $\gamma$ Doradus stars, HD 103257 and HD 109799, both can be categorized as bona-fide members of the class. Over 250 high-resolution spectra of the two stars were collected at University of Canterbury Mount John Observatory (UCMJO) using the High Efficiency and Resolution Canterbury University Large Echelle Spectrograph (HERCULES) spectrograph. The spectra were cross-correlated with a synthetic $\delta$-function template to produce line-profiles and further augmented with high-quality photometry from the Transiting Exoplanet Survey Satellite (TESS) mission, the Wide Angle Search for Planets (WASP) archive, and HIPPARCOS catalogue for frequency and mode analysis. Frequency analysis was carried out using FAMIAS and SigSpec. Two pulsation frequencies were identified in the spectra for HD 103257: 1.22496 ± 0.00001 and 1.14569 ± 0.00002 d$^{-1}$, explaining 58.9 per cent of the variation across the line profiles. Both frequencies were characterized with best-fitting modes of $(\ell, m) = (1, 1)$. Two pulsation frequencies were identified in the spectra for HD 109799: 1.48679 ± 0.00002 and 1.25213 ± 0.00002 d$^{-1}$, explaining 32.6 per cent of the variation across the line profiles. Both frequencies also yielded individual mode fits of modes $(\ell, m) = (1, 1)$. The excellent quality photometry from TESS observations has proven complementary to the work herein, and will provide a meaningful opportunity for deeper analysis of additional stars in the HERCULES catalogue. This will be a key component in the continued development of models relating to the processes within $\gamma$ Doradus stars.

Key words: line; profiles – techniques: photometric – techniques: spectroscopic – stars: individual – stars: oscillations – stars: variables: general.

1 INTRODUCTION

A focus of modern astrophysics is the development of a deeper understanding of physics occurring within stars. While basic stellar theory is now understood, specific details pertaining to such processes as interior rotation and mixing remain unclear through the main sequence and into later evolutionary stages on the Hertzsprung–Russell (HR) diagram. A means of clarifying these unknowns is asteroseismology: observing the oscillating surface of the star to understand the interior physics (Aerts 2021), a method that relies on the identification of stellar pulsation frequencies and modes that can then be compared with theoretical models.

Asteroseismic pulsations can be characterized by the mechanisms through which it is restored: gravity (g) mode pulsations are restored by buoyancy; and pressure (p) mode pulsations are restored by pressure forces. The near-core region is typically probed by g modes, while p modes are more sensitive to the stellar envelope. For stars with moderate rotation the Coriolis force is also an important restoring force (Saio et al. 2018; Van Reeth et al. 2018). In non-radial pulsators, those in this work, these perturbations are not spherically symmetric, with the pulsation modes characterized by the radial order $n$, the degree $\ell$, and the azimuthal order $m$ (Aerts 2021).

An aspect of stellar structure and evolution which differs between models is the evolution of convective cores in intermediate-mass stars on the main sequence, where stars transition from radiative core and a convective envelope (low mass) to stars with a convective core and a radiative envelope (higher mass). Because of their location within this region, the asteroseismic study of $\gamma$ Doradus ($\gamma$ Dor) pulsators can provide an excellent means of improving structure and evolution theories for intermediate-mass stars.

$\gamma$ Dor stars are main-sequence A and F stars situated on or near to the intersection of the classical instability strip and the main sequence on the HR diagram (Kaye et al. 1999); the g-mode pulsations presenting as luminosity variations up to 0.1 mag; radial velocity variations of up to several kilometres per second (Guzik et al. 2000) and pulsation periods of 0.3 – 3 d (Handler 2013). $\gamma$ Dor stars occupy a temperature range between 7200 and 7700 K on the zero-age main sequence (ZAMS), and 6900 to 7500 K one magnitude above the ZAMS (Handler 2013). Typical observed masses and radii are 1.4 – 2 $M_{\odot}$ and 1.4 – 2.4 $R_{\odot}$ respectively (Kaye et al. 1999), although

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†This paper includes data taken at the University of Canterbury Mount John Observatory, New Zealand.

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Dor-like pulsations have been modelled in pre-main sequence stars up to 2.5 M⊙ (Bouabid et al. 2010).

The internal structure of γ Dor stars is three-layered, containing a convective core, a radiative zone, and an outer convective envelope, with the oscillations driven by convective flux blocking (Guzik et al. 2000), Grassitelli et al. (2015) and Xiong et al. (2016) have also suggested that oscillations in γ Dor stars could be damped by turbulent thermal convection. This gives γ Dor stars excellent utility in probing the convection boundary (Guzik et al. 2000; Dupret et al. 2005b; Grigahcéne et al. 2010) and the ability to yield observational constraints that can be utilized in modelling (e.g. Ouazzani et al. 2016; Mombarb et al. 2019; Li et al. 2020; Mombarb, Van Reeth & Aerts 2021; Sekaran et al. 2020).

The utility of space-based telescopes for the identification of γ Dor stars has been established, with the nature of many γ Dor stars initially determined from the HIPPARCOS mission (Perryman et al. 1997; Aerts, Eyer & Kestens 1998; Eyer & Aerts 2000), with the subsequent Corot (Auvergne et al. 2009) and Kepler (Koch et al. 2010) missions adding hundreds of additional candidates. The number of members of this class is therefore expected to rise through an influx of data from NASA’S Transiting Exoplanet Survey Satellite (TESS) (Ricker et al. 2015; Antoci et al. 2019).

Photometric and spectroscopic studies are complementary, and the characterization of stellar pulsations within this analysis makes use of data from both. This work discusses the analysis of two stars, HD 109799 and HD 103257 selected due to indications of variability based on previous analysis of HIPPARCOS data (Handler 1999; Koen & Eyer 2002). Thorough analysis was undertaken for this work utilizing spectroscopic and photometric data obtained over 20 yr. Section 2 outlines the stars in this paper, while Section 3 describes the observations and data treatment. Section 4 discusses the methods of frequency analysis and mode identification, while the results are outlined and discussed in Sections 5 and 6, respectively.

2 TARGETS

HD 103257 is a moderately bright ($V = 6.62$) candidate γ Dor star of spectral type F2V (Kahraman Alicavus et al. 2016) located at a distance of 61.52 ± 0.15 pc according to GAIA GDR2 parallax measurements (Gaia Collaboration 2018) via Bailer-Jones et al. (2018). HD 103257 was designated as a γ Dor candidate in a search for γ Dor stars in the HIPPARCOS database (Handler 1999), with two photometric periods of 0.817 (1.224 d⁻¹) and 0.873 d (1.145 d⁻¹) found. HD 103257 was later categorized as an unsolved variable with a frequency of 1.22459 d⁻¹ by Koen & Eyer (2002), but no additional frequencies were confirmed.

HD 109799 is another moderately bright ($V = 5.45$) candidate γ Dor star of spectral type F2V (Kahraman Alicavus et al. 2016), located at a distance of 34.01 ± 0.12 pc according to GAIA GDR2 parallax measurements (Gaia Collaboration 2018) via Bailer-Jones et al. (2018). HD 109799 was also designated as a γ Dor candidate in a search for γ Dor stars in the HIPPARCOS data (Handler 1999), with a single photometric period, 1.058 d (0.945 d⁻¹) found.

Table 1 provides a summary of the literature values for the properties of both HD 103257 and HD 109979.

3 OBSERVATIONS

All spectra were acquired under the auspices of the MUSICIAN program (Pollard et al. 2014) and collected over several observing runs from 2009 to 2017 at (UCMJO). The details of these observations are presented in Table 4. Spectra were collected using the 1 m McLellan Telescope, which is connected to the High Efficiency and Resolution Canterbury University Large Echelle Spectrograph (HERCULES), with a resolving power of $R \sim 41000$ when using a 100 ūm diameter fibre (Hearnshaw et al. 2002).

A total of 150 and 128 spectra were collected respectively for HD 109799 and HD 103257 at UCMJO between March 2009 to February 2017. Typically, 1200 s exposures were used for both HD 109799 and HD 103257, providing sufficient temporal resolution for γ Dor pulsations.

Both stars benefitted from the use of photometric data to aid in identifying the pulsation frequencies. Photometry was from three sources: TESS, the HIPPARCOS catalogue (Perryman et al. 1997), and the WASP archive (Pierux Maxted, private communication, 2017).

TESS, launched in 2018 April, uses the transit method to search for planets in orbit around nearby stars (Ricker et al. 2015). The high quality, near continuous photometric data provided by the mission is well suited to asteroseismology (Antoci et al. 2019) enabling detailed studies of stellar pulsations. The satellite produces Full-Frame Images (FFI) data every ~30 min (10 min from cycle 3 onwards), with further 2-min (short cadence) images for approximately 200,000 targets. It is these latter data that are used in this paper. Over 15000 photometric measurements were available for both HD 109799 and HD 103257, consisting of observations made during orbits 27 and 28 of the TESS mission (Sector 10). These observations extend from the 26th of March to the 22nd of April 2019.

The WASP instruments, located at the Observatorio del Roque de los Muchachos, La Palma and at Sutherland Observatory, South Africa, each consist of eight wide-field cameras (Kirkby-Kent et al. 2016). For HD 103257, over 49000 photometric measurements were available in the WASP archive, collected from 6th January 2013 to 16th July (Pollacco et al. 2006; Smith & WASP Consortium 2014).

The HIPPARCOS spacecraft used a single Schmidt telescope, with an aperture of 29 cm (Perryman et al. 1997). The data contained 101 observations for HD 103257 and 77 for HD 109799.

TESS, WASP, and HIPPARCOS data were already reduced using the standard mission pipelines, however, raw spectroscopic data from UCMJO had to be reduced for frequency analysis and mode identification. This was carried out through two MATLAB pipelines (Wright 2008; Brunsden 2013). This pipeline calibrates and standardizes the wavelength of each order across all of observations for each star; performs a barycentric correction (Skuljan 2004) and a manual continuum fit and merges the stellar orders to produce a normalized stellar spectrum. Each spectrum is then cross-correlated with a synthetic δ-function template (Wright 2008) to produce radial-velocity line-profiles for each observation.

By cross-correlating multiple spectral lines, the S/N is increased while retaining the periodic line-profile variation for the analyses of periodicities and mode identification. Cross-correlating telluric lines would reproduce the barycentric motion of the Earth due to their terrestrial origin, so these sections of the spectra are removed. Broad hydrogen lines ($\text{H}α$, $\text{H}β$, and $\text{H}γ$) and weak lines (small equivalent widths) were also removed, leaving approximately 3500 stellar spectral lines. Fig. 1 shows the cross-correlated line-profiles for HD 109799 and HD 103257, indicating the variations from the mean line profiles in each case.

4 FREQUENCY ANALYSIS AND MODE IDENTIFICATION - METHODS

Spectroscopic frequency analysis for each of the stars was performed on the cross-correlated line-profiles using the software FAMIAS (Zima 2006, 2008). FAMIAS operates on the basis that pulsational
Frequency peaks were only present in the range 0 to 5 d\(^{-1}\) for both stars.

To extract the frequencies the highest-amplitude frequency is then pre-whitened using optimized parameters (frequency, zero-point, amplitude, and phase) for each pixel calculated from a least-squares fit. Pre-whitening is a technique whereby a time-series is made more uniform through the removal of the most prominent sources of non-uniformity – in this case the highest peak frequencies in the periodogram (see Fig. 2). This process was iterated until significant peaks were no longer found above the noise floor of each periodogram. A signal-to-noise ratio (S/N) > 4 corresponds approximately to a 99.9 per cent confidence (Aerts, Christensen-Dalsgaard & Kurtz 2010). The 1\(\sigma\) uncertainty for the spectroscopic frequencies were derived using the method outlined by Montgomery & Odonoghue (1999). While this yields an underestimate of the actual uncertainty, the formula is valuable as an indicator of the theoretical limitations of the data.

The frequencies confirmed using TESS light curves were similarly found using FAMIAS and then confirmed using SigSpec. SigSpec performs a Fourier analysis on the 2D data-set, selecting frequencies based upon significance and a false-alarm probability (Reegen 2007). Without careful monitoring SigSpec can be prone to over estimation of frequencies, however, in this case SigSpec was used only as a means to confirm the two dominant frequencies for each star. Estimates of the photometric frequencies uncertainties obtained via SigSpec were calculated following Kallinger, Reegen & Weiss (2008).

The frequencies for each star were then screened to identify those arising from stellar pulsations. The task of identifying these frequencies was complicated by the presence of aliasing. A regular sampling pattern of one cycle-per-day can also introduce frequencies that become convoluted with the genuine stellar pulsations. This can be an issue when the frequencies exist near 1 d\(^{-1}\), as is the norm for the g modes in these stars (Brunsden 2013). This effect can be mitigated by taking data irregularly throughout the year, or many data points per day. While SigSpec simultaneously inspects multiple stages of pre-whitening to remove alias frequencies, FAMIAS lacks inbuilt protocols for the detection of aliases and non-exact harmonic frequencies. As such, each frequency found in FAMIAS was examined to ascertain which were data sampling artefacts and those which were genuine. This included careful inspection of the frequency range spectral windows to visually identify aliases (see Fig. 2), as well as removing frequencies with asymmetric amplitudes in the standard deviation profile. The percentage of the overall variation explained by a given frequency was also used as a method of alias detection, with the alias frequencies usually accounting for a smaller percentage of variation than genuine frequencies. Finally, frequency peaks found below a S/N of 4 were removed. It is also worth noting that the model star within FAMIAS is spherically symmetric, with a slow uniform rotation – meaning that in this case the effects of the Coriolis force are neglected.

### Table 1. Literature parameters found for HD 103257 and HD 109799. Entries with * are values derived from spectroscopy and entries with † are estimates from HIPPARCOS photometry.

| star         | \(T_{\text{eff}}\) (K) | \(\log g\) \((\text{cm s}^{-2})\) | \(\text{v} \sin i\) \((\text{km s}^{-1})\) | \(\text{Fe}/H\) \((\text{dex})\) | \(\text{Radius}\) \((R_\odot)\) | \(\text{Mass}\) \((M_\odot)\) |
|--------------|------------------------|----------------------------------|---------------------------------|------------------|------------------|------------------|
| HD 103257    | 7100 ± 200\(^{1}\)     | 4.0 ± 0.2\(^{1}\)               | 70 ± 2\(^{1}\)                 | −0.39\(^{2}\)    | 1.51 ± 0.09\(^{3}\) | 1.50 ± 0.12\(^{3}\) |
| HD 109799    | 7000 ± 100\(^{1}\)     | 4.0 ± 0.1\(^{1}\)               | 39 ± 2\(^{1}\)                 | −0.24\(^{2}\)    | 1.62 ± 0.10\(^{3}\) | 1.53 ± 0.12\(^{3}\) |

Note. \(^{1}\)Kahraman Alicavus et al. (2016)*; \(^{2}\)Holmberg, Nordström & Andersen (2009)*; \(^{3}\)Allende Prieto & Lambert (1999)†.
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Figure 2. PBP Fourier periodograms indicating the final selected frequencies for HD 103257 and HD 109799 using UCMJO spectroscopic data. The shift in relative intensity scale emphasizes the drop towards the noise floor. The dashed red line represents the significance level at a signal-to-noise ratio of 4. The arrows indicate the extracted frequency.

Following frequency identification, the pulsation modes were identified in FAMIAS following Zima (2006). The Fourier Parameter Fit (FPF) method was used in this work due to its suitability when applied to spectral line profiles in relatively fast rotating stars \( (v\sin i > 30 \text{ km s}^{-1}) \) (Brunsden 2013). The FPF technique, developed by Zima (2006) employs a genetic algorithm to explore a user-defined parameter space, searching until the parameters with the best fit are discovered. Varying permutations of azimuthal number \( m \) and degree \( \ell \) were fitted to the amplitude and phase profiles for individual frequencies, with the phase, inclination, and velocity amplitude additionally set as free parameters. When the best fitting solution for each frequency was identified, these parameters were then set as fixed parameters - a final fit with the inclination as the only variable then being performed to ascertain whether the inclination converged for each frequency.

Table 2. Frequencies discovered using UCMJO data above a S/N of 4 for HD 103257 and HD 109799. The estimated uncertainty was derived using the method outlined by Montgomery & Odonoghue (1999), using \( \Delta t = 2889 \text{ d} \) for HD 103257 and \( \Delta t = 2861 \text{ d} \) for HD 109799.

| Frequency Uncert. | S/N | Cumulative variation |
|-------------------|-----|----------------------|
| (d\(^{-1}\)) | (d\(^{-1}\)) | (per cent) |
| HD 103257 | | |
| \( f_{a1} \) | 1.2249 6 | 0.000 01 | 18.9 | 32.4 |
| \( f_{a2} \) | 1.145 69 | 0.000 02 | 15.5 | 58.9 |
| \( f_{a3} \) | 0.673 08 | 0.000 04 | 7.8 | 66.6 |
| \( f_{a4} \) | 0.128 30 | 0.000 04 | 7.1 | 68.2 |
| \( f_{a5} \) | 1.063 16 | 0.000 04 | 5.3 | 76.0 |
| \( f_{a6} \) | 1.224 44 | 0.000 05 | 4.4 | 77.0 |
| HD 109799 | | |
| \( f_{b1} \) | 1.486 79 | 0.000 02 | 7.2 | 11.8 |
| \( f_{b2} \) | 1.252 13 | 0.000 02 | 8.2 | 32.6 |
| \( f_{b3} \) | 1.028 31 | 0.000 03 | 5.2 | 66.7 |
| \( f_{b4} \) | 0.155 22 | 0.000 03 | 8.4 | 48.2 |
| \( f_{b5} \) | 0.013 60 | 0.000 03 | 4.2 | 58.1 |
| \( f_{b6} \) | 0.921 84 | 0.000 04 | 4.5 | 64.7 |

The best fit is established through the minimization of the reduced \( \chi^2 \) for every fit. \( \chi^2 = 0 \) demonstrates an ideal fit, while a meaningful result is normally \( \chi^2 \gtrsim 1 \). In reality, however, the \( \chi^2 \) for the stars discussed here exceeds 1 due to the imperfect fitting of phase and amplitude within FAMIAS and inherent data uncertainties. The final product is an indication of the best-fitting mode.

Consideration of the physicality of a model was a key concern during the identification of modes, with a parameter space constrained to exclude regions that are non-physical, i.e.: models with inclination values that result in a rotational velocity exceeding the Keplerian breakup velocity. This then places a lower limit on the inclination values of the star.

5 RESULTS

5.1 Frequencies

Table 2 shows the highest amplitude frequencies found for both HD 103257 and HD 109799 using UCMJO data. Frequency peaks found below a S/N of 4 were removed. The PBP mean Fourier periodograms for HD 103257 and HD 109699 are reproduced in Fig. 2 for the final frequencies selected after vetting. Here, we discuss the identification of frequencies for both stars.

5.1.1 HD 103257

The Fourier periodograms in Fig. 2 illustrate the frequency spread across all pixels. Six candidate frequency peaks were identified above S/N = 4 in the spectroscopic data for HD 103257 including a one cycle-per-day alias frequency (\( f_{a5} \)). Frequencies \( f_{a1} \) and \( f_{a2} \) dominate, accounting for 32.4 and 26.5 per cent of the total variation of the star, respectively. The percentage of the overall variation explained by a given frequency was established by calculating the percentage reduction of the mean standard deviation after the removal of a particular frequency from the line profiles during the pre-whitening process. The two selected peaks, and their one day aliases, are clearly visible in Fig. 2. These dominant frequencies are confirmations of the periods found in the HIPPARCOS data by Handler (1999) and Koen & Eyer (2002), 0.817 (1.224 d\(^{-1}\)) and 0.873 d (1.145 d\(^{-1}\)).
Table 3. The frequencies found in the UCMJO data (S/N > 4) for which there are corresponding TESS, HIPPARCOS, and WASP frequencies for HD 103257 and HD 109799. Estimated uncertainties are given in brackets and derived using the method outlined by Montgomery & Odonoghue (1999).

| Mode | UCMJO  (d^{-1}) | TESS  (d^{-1}) | HIPPARCOS (d^{-1}) | WASP  (d^{-1}) |
|------|-----------------|----------------|-------------------|----------------|
| HD 103257 | | | | |
| fa_1 | 1.224 96(1) | 1.224 80(7) | 1.224 56(3) | 1.225 19(3) |
| fa_2 | 1.146 69(2) | 1.143 38(6) | 1.145 12(4) | 1.145 75(3) |
| HD 109799 | | | | |
| fb_1 | 1.486 79(2) | 1.4837(4) | – | – |
| fb_2 | 1.252 13(2) | 1.2524(2) | – | – |

Table 4. Individual mode identifications for the two selected frequencies of HD 103257 and HD 109799, with their associated χ² and modelled inclination.

| Mode | χ² | Inclination (°) |
|------|----|----------------|
| HD 103257 |     |                |
| fa_1 | 14.0 | 1, 1 |
| fa_2 | 8.4 | 1, 1 |
| HD 109799 |     |                |
| fb_1 | 6.7 | 1, 1 |
| fb_2 | 8.7 | 1, 1 |

Of note in the six frequencies identified in the spectra is the apparent duplication between fa_1 = 1.224 96 and fa_6 = 1.224 44 d^{-1} with the latter likely presenting residual power from the removal of the former. To test the veracity of fa_6 as a frequency in its own right, the two frequencies were pre-whitened individually to observe what effects, if any, the removal of each frequency had on the other. Removal of fa_6 prior to the removal of fa_1 distorted the standard deviation profile for the latter, suggesting that they are not independent and, hence, aliases.

The dominant frequencies found within the WASP and TESS data were, again, confirmations of the two frequencies found by Handler (1999) and reflective of the two dominant spectroscopic frequencies. These frequencies are shown in Table 3. In both the TESS and WASP data, further significant frequencies were found above the noise floor, indicating additional frequencies present in the star not detected in the spectroscopic data. Follow up work will look at the relationship between these photometric frequencies and those found in the spectroscopy.

Only the two highest amplitude frequencies were ultimately considered viable for modal analysis, with visual inspection of fa_1 and fa_5 indicating a lack of the characteristic line-profile symmetry indicative of a true pulsation frequency and needed for mode identification. This poor symmetry may be due to noise in the data, phase gaps, or misidentification.

5.2 Mode identification

The parameters in Table 1 were used to model the modes of HD 103257 and HD 109799. Table 4 summarizes the individual best-fitting modes for the highest amplitude frequencies of each star, with their associated χ² values, inclination, and radius.

5.2.1 HD 103257

For HD 103257 the vsini was fit at 71.5 km s^{-1}, within the uncertainty expected by the literature value of 70 ± 2 km s^{-1} (Kahraman Alicavus et al. 2016). The Keplerian breakup velocity and associated minimum inclination, i, were calculated using the literature values for radius and mass R = 1.51 R_⊙ and M = 1.50 M_⊙ (Allende Prieto & Lambert 1999) and the derived vsini. A theoretical critical velocity and lower limit for inclination were calculated to be 435.2 km s^{-1} and 9.45°, respectively.

Due to the status of HD 103257 as a candidate γ Dor star, the typical parameter space for the class was searched, consisting of modes from 0 < ℓ < 3 and −3 < m < 3. Fig. 3 shows the best-fitting amplitude and phase profiles for the two analysed frequencies.

The strongest frequency (f_2 = 1.224 96 d^{-1}) was best fit with a reduced χ² of 14.0 for an identified mode of (ℓ, m) = (1, 1). The best fit yielded an inclination of i = 81.3°.

Analysis of f_2 = 1.145 69 d^{-1} yielded a best fit reduced χ² value of 8.4 for an identified mode of (ℓ, m) = (1, 1). This best fit yielded an inclination of i = 89.9°.

A combined fit was performed for both frequencies, allowing the modes (ℓ, m), and the inclination, i, to vary. This combination resulted in a best fit with an inclination of i = 86.4° and a χ² of 10.1. It is clear the inclination is best fit in the 85 to 90° range, indicating the star is viewed almost equator-on. Using this inclination range, and the derived vsini (71.5 km s^{-1}), a probable rotational velocity range of v = 71.5 – 71.8 km s^{-1} is indicated, well below the estimated Keplerian break-up limit of 435.2 km s^{-1}.

5.2.2 HD 109799

For HD 109799 the vsini fit converged at 40.2 km s^{-1} with a χ² of 24.3 – in agreement with the literature value of 39 ± 2 km s^{-1} (Kahraman Alicavus et al. 2016). The Keplerian breakup velocity and associated minimum inclination, i, were calculated using the literature values for radius and mass R = 1.62 R_⊙ and M = 1.53 M_⊙ (Allende Prieto & Lambert 1999) and the derived vsini. A theoretical critical velocity and lower limit for inclination were calculated to be 424.3 km s^{-1} and 5.44°, respectively.
The best-fitting amplitude and phase profiles for the two highest amplitude frequencies of HD 103257, indicating $f_{a1} = (1, 1)$ (a) and $f_{a2} = (1, 1)$ (b). The solid black line is the observed profile, the dashed red line is the best-fitting synthetic profile, and the green represents the mean of the two.

As with HD 103257, a parameter space typical for the class was searched, consisting of modes from $0 < \ell < 3$ and $-3 < m < 3$. Mode identification was performed individually to find the best fit for each of the frequencies, shown in Fig. 4.

The highest amplitude frequency ($f_{b1} = 1.48679 \text{ d}^{-1}$) was best fit with a reduced $\chi^2$ of 6.7 for an identified mode of $(\ell, m) = (1, 1)$, while next lowest $\chi^2$ (17.3) corresponded to a $(\ell, m) = (3, 0)$ mode. The best fit yielded an inclination of $67.1^\circ$.

The second highest amplitude ($f_{b2} = 1.48679 \text{ d}^{-1}$) yielded a best-fitting $\chi^2$ of 9.3 for an identified mode of $(\ell, m) = (1, 1)$, while the next lowest $\chi^2$ (22.92) corresponded to a mode of $(\ell, m) = (3, -2)$. The best fit yielded an inclination of $69.9^\circ$.

As can be seen in Table 4, the modes for $f_{b1}$ and $f_{b2}$ agree closely with respect to mode and inclination. A combined fit was performed for both frequencies, allowing the modes $(\ell, m)$, and the inclination, $i$ to vary. This resulted in a best combined fit with an inclination of $66.7^\circ$ and a $\chi^2 = 7.9$. This combined fit demonstrates excellent agreement for $f_{b1}$ and $f_{b2}$, affirming that both frequencies are genuine $(\ell, m) = (1, 1)$ modes. It is clear the inclination is best fit in the $65^\circ$ to $70^\circ$ range. Using this range, and the derived $v \sin i$ of $40.2 \text{ km s}^{-1}$, a probable rotational velocity range of $v = 42.8 - 44.4 \text{ km s}^{-1}$ is indicated, well below the Keplerian break-up limit of $424.3 \text{ km s}^{-1}$.

6 DISCUSSION

The two highest amplitude frequencies extracted from each data-set are the most robust, appearing with clarity in each set of results – spectroscopic and photometric. This, in combination with their appearance in the literature (Handler 1999) made them ideal candidates for mode identification. Beyond these first two frequencies, however, there is some disagreement between the photometric and spectroscopic frequencies. It is apparent that HD 109799 has as a substantial amount of line-profile variation remaining after pre-whitening of the two frequencies in each of the three data-sets, with a maximum of $67.4$ per cent variation remaining. It is highly likely that several frequencies remain undetected beneath S/N limits of the...
presented spectroscopic data for both stars. This is to be expected given the propensity of $\gamma$ Dor stars to exhibit potentially dozens of frequencies in photometry (Van Reeth et al. 2015b). Similarly, in both the TESS and WASP data, several significant frequencies were found above the noise floor for both stars that were not detected in the spectroscopic data. It is also worth noting that the spectroscopy seems to miss prominent frequencies present in the photometric data (and vice versa) – a phenomenon that may arise through geometric cancellation (Van Reeth et al. 2015a). Follow up work will look at the relationship between these photometric frequencies and those found in the spectroscopy.

The confirmed modes identified for the two identified frequencies of HD 103257 were $fa_1(\ell, m) = (1, 1)$, $fa_2(\ell, m) = (1, 1)$. The confirmed modes identified for the two frequencies of HD 109799 are $fb_1(\ell, m) = (1, 1)$ and $fb_2(\ell, m) = (1, 1)$. These are the first mode identifications for pulsations within these stars and are in the typical $\gamma$ Dor range of $0.3 - 3$ d$^{-1}$. These results indicate that HD 103257 and HD 109799 are both typical $\gamma$ Dor stars with variations of low harmonic degree, $\ell$. Based on these results, HD 103257 and HD 109799 can be categorized as bona-fide members of the $\gamma$ Dor class.

The modelled inclination, $i = 86.4^\circ$ indicates that HD 103257 is viewed almost equator-on. This inclination sets the rotational velocity in the region of $v = 71.8 - 71.5$ km s$^{-1}$; while the calculated rotational velocity for HD 109799 was in the range of $v = 42.8 - 44.4$ km s$^{-1}$. Both of these velocity ranges place the stars within reasonable bounds for an F-type star (McNally 1965; Augustsson et al. 2012).

The prevalence of $(\ell, m) = (1, 1)$ modes in this analysis both stars align with that of $\gamma$ Dor stars in general (e.g. Dupret et al. 2005a; Maisonneuve et al. 2011; Brunsden et al. 2018). This may be indicative of sequencing of the $n$-values, or the number of interior shells within the stars.

TESS continues to provide high-precision photometric data, with initial results from the mission proving consistent with those herein (Antoci et al. 2019). Going forward, many of the MUSICIAN targets continue to be observed in both full frame images (10-min cadence, reduced from 30) and shorter 2-min cadence. These data will prove invaluable in the continued testing of the consistency between spectroscopic and photometric results, and will allow us to develop our insights into these stars. Avenues to be pursued include the potential for the two observing regimes to probe different optical depths within the star – a potential source of both the mild disparity between the dominant frequencies in the different observing methods.

It was also noted that, without careful monitoring, SigSpec and other extraction pipelines can be prone to over extraction of frequencies. While in this study SigSpec was used only as a means to confirm the two dominant frequencies for each star, future work will examine this over extraction and address the validity of photometric frequencies found in this way.

Finally, recent developments also indicate that many $\gamma$ Dor stars may be $\delta$ Scuti hybrids, demonstrating both p and g modes (Grigahcène et al. 2010; Balona & Dziembowski 2011), although pulsators that are uniquely $\gamma$ Dor do exist (Li et al. 2018). This apparent prevalence of hybrids remains broadly unexplained and will be a rich topic for further investigation.

ACKNOWLEDGEMENTS

Thanks to the referee for their kind and useful comments.

Many of the UCMJO spectra analysed herein were collected by the author in 2016 thanks to a Royal Astronomical Society (RAS) grant. The remaining observations were carried out by others as part of the MUSICIAN program, with particular thanks going to Mr. Fraser Gunn. The authors also acknowledge the assistance of staff at UCMJO.

Mode identification results obtained with the software package FAMIAS. We acknowledge Dr Emily Brunsden and Dr Duncan Wright for the MATLAB scripts used for processing the UCMJO data.

Finally, gratitude to Dr Pierre Maxted for providing WASP data used in frequency confirmations.

DATA AVAILABILITY

This paper includes data collected by the TESS mission, which were obtained from the Mikulski Archive for Space Telescopes (MAST) at the Space Telescope Science Institute. The specific observations analysed can be accessed via https://doi.org/10.17909/t9-czhh-0492.

The MUSICIAN data used in this article will be shared on reasonable request to the corresponding author. The WASP data underlying this article will be shared on request to the corresponding author with permission of Dr. Pierre Maxted.

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