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Spectroscopic mode identification of γ Doradus stars: frequencies, modes, rotation and wave leakage

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Abstract. The gravity modes present in γ Doradus stars probe the deep stellar interiors and are thus of particular interest in asteroseismology. The MUSICIAN programme at the University of Canterbury has been successfully identifying frequencies and pulsation modes in many γ Doradus stars using hundreds of precise, high resolution spectroscopic observations obtained with the 1.0 m telescope and HERCULES spectrograph at the Mt John Observatory in New Zealand. In this paper we present a summary of our spectroscopic frequency and mode identifications. Of particular interest from our spectroscopic analyses are: the prevalence of $(\ell, m) = 1, 1$ modes in many γ Dor stars; the importance of stellar rotation in the interpretation of the frequency and mode identification; and finally, possible evidence of wave leakage in one of these stars.

Keywords. stars: oscillations (including pulsations)

1. Introduction: Why are γ Doradus stars interesting?

The gravity modes present in γ Doradus stars probe the deep stellar interiors and are thus of particular interest in asteroseismology. As a class, γ Dor stars are slightly hotter and more massive stars than the Sun and are characterised by their high-radial order and low-degree gravity mode pulsations. These gravity modes probe the deep radiative interior of the star, sometimes as deep as the convective core that is present in these stars. Hybrid γ Dor/δ Sct stars undergo simultaneous pressure modes, which probe the relatively thin outer convective envelope. Hybrid stars therefore have great potential for asteroseismic analysis to explore their interior structure. To achieve this, mode identifications of pulsational frequencies observed in the stars must be made, a task which is far from simple. The frequencies and mode identifications require careful analysis as stellar rotational effects can significantly affect their interpretation.

Various theoretical models have indicated that rapid rotation can fundamentally effect and modify the pulsations excited inside these stars (*e.g.*Townsend, 2003) . In addition, there is the long-standing problem, associated with the γ Dor stars in particular, which is that photometric mode identification and spectroscopic mode identification rarely agree, even at the level of detecting the same frequencies of oscillation, let alone achieving consistency of the identified modes of pulsation (Brunsden *et al.* 2015).

Table 1. Summary of our spectroscopic mode identifications for γ Dor stars.

Star	$v\sin i$ ($\mathrm{km\,s^{-1}}$)	Frequency ($\mathrm{d^{-1}}$)	Spectroscopic (ℓ, m)	Reference
HD12901	64	1.3959(2)	1,1	1,2,3
		1.1862(2)	1,1	1,2,3
		1.6812(2)	1,1	2,3
		1.2156(2)	1,1	1,2,3
		1.5596(2)	1,1	2,3
HD27290 (γ Dor)	57	1.3641(2)	1,1	4,2
		1.3209(2)	3,3 or 1,1	4,2
		1.4712(3)	1,1 or 2,0	4,2
		1.8783(2)	1,1	2
HD40745	44	0.7523(5)	2,-1	5
		1.0863(7)	3,-3 or 2,-2	5
HD49434	85	$\#f$ = 31 spec	-	10
		$\#f$ = 840 phot	-	
HD55892 (QW Pup)	51	0.055972(4)	1,-1	6,7
		0.055972(4)	4,-1	6,7
		5.219398(2)	4,2	6,7
HD65526	59	2.616	1,-1	8
		1.840	1,-1	8
HD112429	116	0.0515(3)	1,-1	7
HD135825	40	1.3150(3)	1,1	2,9
		0.2902(4)	2,-2	2,9
		1.4045(5)	4,0	2,9
		1.8829(5)	1,1	2,9
HD139095	64	2.353	2±1,1±1	6
	65.3	1.2263	2,-2	8
		0.59460	2,-2	8
		1.1323	2,-2	8
		1.3871	2,-2	8
HD153580	45.4	0.6589	2,-1	8
HD189631	38	1.6774(2)	1,1	5,7
		1.4172(2)	1,1	5,7
		0.0714(2)	2,-2	5,7
		1.8228(2)	4,1 or 1,1	5,7
HD197541	21	0.71344	1,1	8
		1.0181	1,1	8
		0.82202	1,1	8

Table References:
1 Aerts, *et al.* 2004, A&A 415,1079; 2 Brunsden 2013 PhD thesis, Univ. Canterbury; 3 Brunsden *et al.* 2012a, MNRAS 427, 2512; 4 Balona *et al.* 1996 MNRAS 281, 1315; 5 Maisonneuve *et al.* 2011 MNRAS 415, 2977; 6 Wright 2008 PhD thesis, Univ. Canterbury; 7 Davie 2013 MSc thesis, Univ. Canterbury; 8 Greenwood 2012 MSc thesis, Univ. Canterbury; 9 Brunsden *et al.* 2012b MNRAS 422, 3535; 10 Brunsden *et al.* 2015 MNRAS 447, 2970

2. Observations and Analysis

The MUSICIAN programme at the University of Canterbury has been successfully identifying frequencies and pulsation modes in many γ Doradus stars using hundreds of precise, high resolution spectroscopic observations obtained at the Mt John Observatory in New Zealand. The observatory is at latitude 43°59.2' S and longitude 170°27.9' E and is 1031 m above sea level. It is near the village of Tekapo in New Zealand's South Island. Using the 1.0-m telescope and the high-resolution (R∼80,000 or R∼40,000) HERCULES spectrograph (Hearnshaw *et al.* 2002) we are able to obtain many hundreds of precise echelle spectra of our targets. Our observatory is at a useful longitude to obtain multi-site data in association with other southern hemisphere sites in Australia, South Africa and

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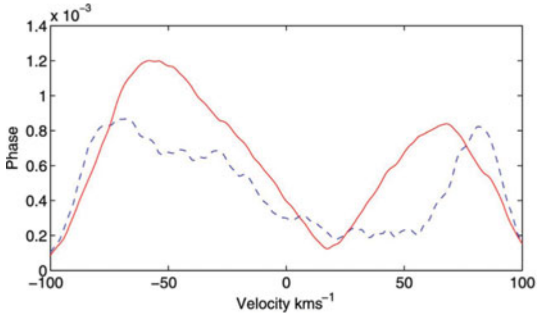

Figure 1. Average standard deviation plots of the δ Scuti-like frequencies (red, solid lines) and theγ Doradus-like frequencies (blue, dashed lines), showing the strong asymmetry of the line profile variations and the significant offset of the variations of the mean line centre.

Chile. This is an ideal set-up for undertaking long-term time-series studies of relatively bright stars ($V \gtrsim 9$).

In Table 1 we present a summary of our spectroscopic frequency and mode identifications and present the emerging patterns of the programme. Of particular interest from our spectroscopic analyses are the prevalence of 1,1 modes in many γ Dor stars and the importance of stellar rotation in the interpretation of the frequencies and the mode identifications.

3. Analysis of the hybrid γ Dor/δ Sct star, HD49434

Hybrid γ Dor/δ Sct stars have great potential for asteroseismic analysis to explore their interior structure. HD49434 is a well studied γ Dor/δ Sct hybrid candidate with a relatively high rotation rate ($v\sin i = 84$ km s^{-1}). This star was observed extensively by the photometric satellite CoRoT for 140 days, and more than 800 frequencies intrinsic to the star have been reported (Chapellier *et al.*, 2011).

We identify 31 spectroscopic frequencies in the variations of the pixels of the line profile for HD49434 using over 1400 spectra (Brunsden *et al.*, 2015). The results show almost no consistency between the frequencies found using the CoRoT photometry and the spectroscopy and no characteristic period spacings or couplings were identified in either data set.

We use a mode-identification program called FAMIAS (Zima, 2008). This program fits three parameters (the mean line profile, the amplitude of variation across the line profile and the phase of these amplitude variations across the line profile) in order to identify which non-radial pulsational mode fits the data best.

The asymmetry of the standard deviation profiles (higher amplitude in the blue wing) and the offset from the line centre (Figure 1) hinders the mode identification, prompting us to investigate possible explanations and ways to model this behaviour. HD49434 shows extreme behaviour in this respect, but lesser degrees of asymmetry and offset have been noted in our spectra of other γ Doradus stars.

The 31 spectroscopic frequencies identified have standard deviation profiles suggesting multiple modes sharing (ℓ, m) in the δ Sct frequency region (see Figure 2 top) and several skewed modes sharing the same (ℓ, m) in the γ Doradus frequency region (see Figure 2 bottom). According to Townsend (2000), such line asymmetries can only arise from wave leakage (see Figure 3, Townsend's figure for line profile variations due to g-mode leakage from a B star) or from extremely non-adiabatic pulsations, which are not expected in the majority of stars (Unno *et al.*1989). If wave leakage is the reason for the extreme

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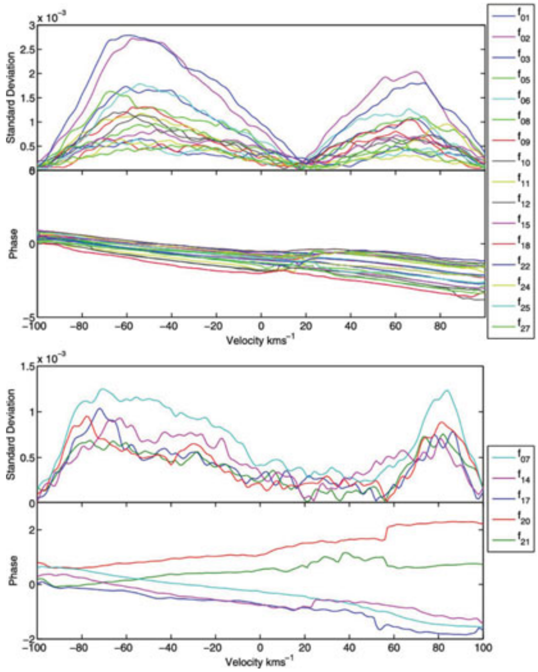

Figure 2. Standard deviation plots of (top) the δ Scuti-like frequencies and (bottom) the γ Doradus-like frequencies.

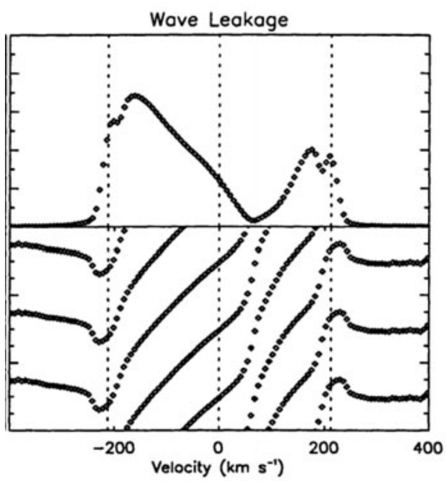

Figure 3. Figure from Townsend (2000), showing the typical line profile variations due to g-mode leakage from a B star.

line asymmetry and offset seen the line profiles, the next question to ask is: why is this star so extreme? A low inclination, and thus a very fast rotation of HD 49434, would explain some of the effects seen, such as finding no gap between the frequency domains (Handler 2012) and could even explain some of the difference between the photometric and spectroscopic frequency spectra.

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4. Summary

We have identified a significant number of spectroscopic frequencies and pulsation modes in γ Doradus stars. This is credited to extensive, high-resolution datasets and careful analysis techniques. We can contribute these and further results to constrain stellar structure and seismic models of γ Doradus stars. We hope to further refine our analysis methods, and thus our inputs to the stellar structure models, through including a better understanding of the effects of rotation on stellar pulsations and also investigating the possible effects of wave leakage, which is a possible explanation for the line asymmetries and offsets we have seen in the hybrid star HD49434. However, the puzzle of the inconsistency between photometrically and spectroscopically frequencies remains for the majority of stars investigated using both methods. With the advent of access to impressive and unprecedented satellite data sets of single band photometric data, this is a spur for us investigate what may be the underlying physical reasons for these discrepancies.

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