

# Spectroscopy of $\gamma$ Doradus stars

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**Abstract.** The MUSICIAN programme at the University of Canterbury has been successfully identifying pulsation modes in many  $\gamma$  Doradus stars using hundreds of ground-based spectroscopic observations. This paper describes some of the successful mode identifications and emerging patterns of the programme. The hybrid  $\gamma$  Doradus/ $\delta$  Scuti star HD 49434 remains an enigma, despite the analysis of more than 1700 multi-site high-resolution spectra. A new result for this star is apparently distinct line-profile variations for the  $\gamma$  Doradus and  $\delta$  Scuti frequencies.

**Keywords.** line: profiles, techniques: spectroscopic, stars: individual (HD 135825, HD 12901,  $\gamma$  Doradus, HD 49434), stars: variables: other, stars: oscillations (including pulsations)

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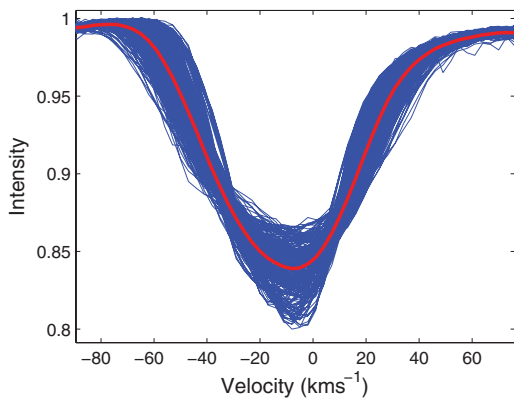
## 1. Introduction

Spectroscopic mode identification of individual pulsating stars is a challenging and time-consuming task. The  $\gamma$  Doradus class of pulsators make for particularly awkward targets due to their characteristic 1 – 3 d<sup>-1</sup> frequencies. These frequencies have significant aliasing problems due to ground-based observing cycles and long beat periods. To overcome these problems the MUSICIAN programme at the University of Canterbury has been targeting  $\gamma$  Doradus stars in frequent observing runs over several months to years. Typically 100 to 400 spectra are acquired for each star from Mt John University Observatory's 1-m McLellan telescope with the High Efficiency and Resolution Canterbury University Large Échelle Spectrograph (HERCULES). Data are then combined with spectra from other sites where possible for analysis. Successful mode identifications have now been made for a number of stars, four of which are described here.

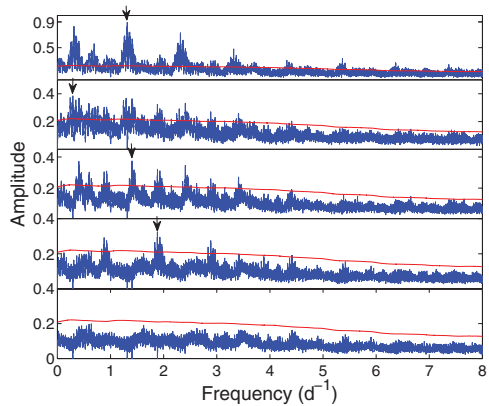
## 2. Data reduction and analysis techniques

This section comprises of a brief overview of the currently used methods for data reduction and analysis. More detail can also be found in Brunsden *et al.* (2012b). Spectra acquired are reduced using the standard reduction packages offered for each spectrograph. Cross-correlation of up to 5000 lines per spectrum is performed, avoiding regions of telluric and strong hydrogen lines. The cross-correlation is performed independently for each site, which produces representative line profiles for each observation. An example of the profiles generated for HD 135825 is given in Fig. 1.

Frequency and mode identification using the representative line profiles is performed in FAMIAS (Zima 2008). Frequencies are calculated using the moment method (Balona 1986a,b, Balona 1987, Aerts *et al.* 1992) and using the individual pixels across the line profile (Mantegazza 2000). Fourier spectra of the pixel frequencies detected in HD 135825

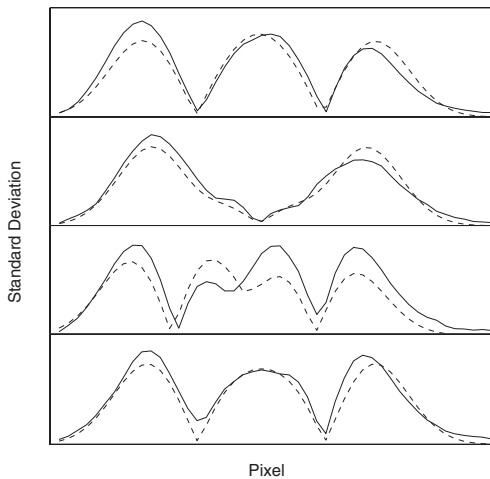


**Figure 1.** Representative line profile of 295 observations of HD 135825. Pulsations can be clearly seen deforming lines from the mean line profile.

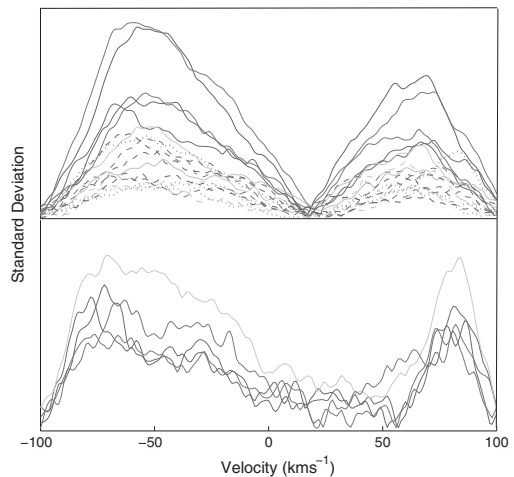


**Figure 2.** The Fourier spectrum showing frequencies found using the pixel-by-pixel technique and successive prewhitening. The smooth line shows the significance level from FAMIAS.

with each prewhitening stage are shown in Fig. 2. Mode identifications are performed in FAMIAS using the pixel-by-pixel technique (Zima 2009). This method fits the variations of the line profiles to a grid of models to identify the pulsation modes. A  $\chi^2$  minimisation routine is used to identify the best modes. As an example, the standard deviation profiles of the four frequencies identified in HD 135825 are shown in Fig. 3 with their mode fits.



**Figure 3.** The fit (dashed line) of the mode identification to the standard deviation profile and phase (solid line) of the four identified frequencies in HD 135825.



**Figure 4.** Standard deviation profiles of the  $\delta$  Scuti (top) and  $\gamma$  Doradus (bottom) range frequencies detected in HD 49434.

### 3. Summary of results

The frequencies and mode identifications of several  $\gamma$  Doradus stars are given in Table 1 of Pollard *et al.* (these proceedings), including the three described in this paper.

HD 135825 was found to have a single dominant, high-amplitude frequency and three lower amplitude frequencies. It is confirmed that HD 135825 is a true  $\gamma$  Doradus star.

Considering the prior studies (Aerts 2004, Moya 2005), all of the candidate frequencies and modes found for HD 12901 are well supported. The occurrence of five (1, 1) modes in this star suggests they may be the same low degree ( $l$ ) for sequential values of  $n$  (Tassoul 1980). This led to an investigation into the period spacings of the identified frequencies which showed no consistent spacings.

The frequencies found in the analysis of  $\gamma$  Doradus were almost identical to those found in previous spectroscopic and photometric studies (Balona 1994, Balona *et al.* 1996, Dupret *et al.* 2005a, Tarrant *et al.* 2008). Two frequencies have been shown to be stable over twenty years since their first identification by Cousins (1992).  $\gamma$  Doradus shows an excellent agreement between the frequencies and modes found in photometry and spectroscopy giving independent confirmation of the modes detected in FAMIAS.

A prevalence of (1, 1) modes in  $\gamma$  Doradus stars is beginning to emerge. This could be explained by considering the selection bias of ground-based targets. The stars selected for our ground-based observational work are bright targets ( $V < 8$  for spectroscopy) with high-amplitude pulsations. The  $l = 1$  modes are expected to have the highest amplitude in these stars due to the large surface area covered in each segment of the mode. In addition, stars with high inclinations ( $i$  close to  $90^\circ$ ) will have higher observed amplitudes for sectoral modes and those with low inclinations, higher-amplitude tesseral and zonal modes (Schrijvers *et al.* 1997, Reese *et al.* 2013). For rotating stars, the presence of an equatorial wave-guide (Townsend 2003) would suppress the tesseral modes and thus only the stars with sectoral modes would be classified as  $\gamma$  Doradus stars.

#### 4. The special case of HD 49434

The presence of both  $\gamma$  Doradus and  $\delta$  Scuti-range frequencies suggests that HD 49434 may be a hybrid star of the two classes. This classification was made by Uytterhoeven *et al.* (2008) based on the frequencies found and the proximity of the star in the intersection of the pulsation groups in the Hertzsprung-Russell diagram. The star was also monitored by the *CoRoT* mission with more than 800 frequencies identified (Chapellier *et al.* 2011). The addition of 1100 spectra to the 700 analysed in Uytterhoeven *et al.* (2008) refined the spectroscopic picture of this star, with 31 frequencies extracted. These frequencies match very poorly those detected by *CoRoT*. Upon inspection of the standard deviation profiles, two distinct shapes were observed (Fig. 4). These two groups corresponded to the frequencies in the  $\delta$  Scuti range and in the  $\gamma$  Doradus range of expected frequencies.

The classification of the shapes of the line profiles of the frequencies suggests physical differences between the two groups of frequencies and two groups of modes. The shift of the centre of the standard deviation profile with respect to the centre of the line profile is currently being investigated.

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