Core overshoot and convection in δ Scuti and γ Doradus stars

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Abstract. The effects of rotation on pulsation in δ Scuti and γ Doradus stars are poorly understood. Stars in this mass range span the transition from convective envelopes to convective cores, and realistic models of convection are thus a key part of understanding these stars. In this work, we use 2D asteroseismic modelling of 5 stars observed with the *Kepler* spacecraft to provide constraints on the age, mass, rotation rate, and convective core overshoot. We use Period04 to calculate the frequencies based on short cadence *Kepler* observations of five γ Doradus and δ Scuti stars. We fit these stars with rotating models calculated using MESA and adiabatic pulsation frequencies calculated with GYRE. Comparison of these models with the pulsation frequencies of three stars observed with *Kepler* allowed us to place constraints on the age, mass, and rotation rate of these stars. All frequencies not identified as possible combinations were compared to theoretical frequencies calculated using models including the effects of rotation and overshoot. The best fitting models for all five stars are slowly rotating at the best fitting age and have moderate convective core overshoot. In this work, we will discuss the results of the frequency extraction and fitting process.

1 Introduction

One of the theoretical challenges presented by δ Scuti stars is determining which stars should be pulsating. Although all the stars in the δ Scuti instability strip are predicted to show pulsations, observations show that less than half of the stars in this region actually pulsate ([1, 2]). This difference between theory and observation is not presently understood. It has been suggested that nonlinear mode coupling may stabilize the pulsations ([7]), or the opacity driving mechanism could be saturated ([13]). Unfortunately, testing these predictions requires nonlinear models of nonadiabatic nonradial pulsations, which do not currently exist.

Additionally, space-based observations, such as with CoRoT ([11]) and *Kepler* (e.g., [5, 9]), have found that a number of δ Scuti stars are observed to pulsate with γ Dor-type frequencies, and these are usually described as hybrid stars. Hybrid stars are particularly interesting asteroseismic targets, as the g modes sample deeper regions of the star than the p modes. Hybrid stars, γ Dor and δ Scuti stars collectively span the mass range $1.4 - 2.5 M_{\odot}$, where the interior structure transitions from a convective envelope and radiative core in the lower mass stars to higher mass stars with convective cores and radiative envelopes. Studies of stars in this mass range with *Kepler* have found more hybrid star candidates than expected by current stellar pulsation theory ([18]). The leading explanation for

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Table 1. Literature parameters. All parameters are taken from the KIC.

KIC #	T_{eff} (K)	$\log g$ (± 0.4)	Magnitude (K_p)
5466537	6979 ± 221	4.141	10.34
6131093	6629 ± 180	4.358	9.25
9962653	7254 ± 220	4.277	10.11
10451090	7577 ± 152	4.134	9.21
11649699	7182 ± 202	4.211	10.14

this discrepancy is that the interaction between convection and pulsation in both the deeper layers (γ Dor, g modes) and upper layers (δ Scuti, p modes) is not fully understood.

In this work, we study the pulsation characteristics of 5 γ Doradus and δ Scuti stars, including candidate hybrid stars. The frequency analysis described here will provide the foundation for modelling these stars, providing us with constraints on their interior convection and rotational properties. In Section 2 we describe the observations, and in Section 3 we describe the results of our frequency extraction. Our preliminary conclusions are summarized in Section 4.

2 Observations

Observations were made with the *Kepler* spacecraft ([3]) as part of a Guest Observer project (GO 20022, PI J. A. Guzik) to observe δ Scuti, γ Doradus, and solar-type variables. Based on previous observations, 14 bright stars were chosen with masses between 1.0 and $1.8 M_{\odot}$. Bright targets were selected to give the best quality data possible, and the resulting signal-to-noise ratio is very high. These targets were then observed in short-cadence mode (1 point integrated every minute) for 30 days. All of these stars have been previously observed through other programs, and all available short-cadence data were used to extract frequencies. For most of the stars, this consisted of two sets of observations separated by several hundred days. Two of the stars (KIC 9962653 and KIC 10451090) have been observed for 4 and 5 sets of 30 days, respectively. The available data covers a total of about 600 days for each star, although the coverage is incomplete. Processed light curves were downloaded from the Mikulski Archive for Space Telescopes (MAST). Stellar parameters for these stars are primarily taken from the *Kepler* Input Catalogue (KIC, [6]), with updates for some of the parameters for three of the stars ([4, 16, 18]).

3 Results

All five stars proved to have very rich Fourier spectra, with close to 100 frequencies with $\text{SNR} > 4$ in all cases. The details of the frequency analysis for each star are described below. The literature parameters for each star are summarized in Table 1.

3.1 KIC 5466537

KIC 5466537 has 132 identified frequencies, of which 23 frequencies were not considered to be combinations. One of these 23 frequencies is 1.39 c/d, consistent with γ Doradus pulsations, while the remaining 22 frequencies are between 9 and 28 c/d, as expected for δ Scuti variables. This is consistent with the previous identification of this star as a hybrid ([5]).

Figure 1. An echelle diagram for observed frequencies in KIC 5466537. The large spacing was found to be 2.81 c/d using the Dirac's comb method ([8]) based on 23 frequencies.

Although δ Scuti stars are not expected to obey an asymptotic frequency spacing, there are patterns in the frequency spectrum that can be detected ([8, 14]). We used the Dirac's comb method ([8]) to look for periodic spacing in the detected frequencies. Although we only used 23 frequencies, we were able to detect a spacing pattern at 2.81 c/d. This results in the echelle diagram shown in Figure 1. Since only one of the non-combination frequencies was in the g -mode region, no attempt to analyze patterns in the g modes has been made.

3.2 KIC 6131093

KIC 6131093 has been previously identified as a flare star with a rotation period of 8.028 d ([2]). We identified 65 significant frequencies in this star, mainly g modes expected in a γ Doradus star. We used the techniques for determining significance described in [19] rather than a strict signal-to-noise ratio criterion. We looked for patterns in the period spacings and found upward trends, as shown in Figure 2. This is consistent with an identification of $m = -1$ for these modes ([19]). We also observe dips in the period spacing pattern which indicates there is a chemical discontinuity within the core of the star ([12]). To determine the location of the chemical discontinuity, we need to identify the radial orders of the modes, which has not been done at this time. The effects of rotation will further complicate the frequency spectrum, making it more difficult to interpret. Even at relatively low rotation rates, the resulting splitting can be comparable in size to the period spacing. Spectroscopic mode identification may be required in order to interpret the observed frequency spectrum.

3.3 KIC 9962653

KIC 9962653 was previously identified as a γ Doradus star ([1]). We identified nearly 100 significant frequencies in this star, primarily in the range 1-4 c/d, consistent with the identification as a γ Doradus star. We find multiple lines in the period spacing pattern, all with the upward slope expected for

Figure 2. A section of the period spacing diagram for KIC 6131093. The upward trend suggests the majority of the observed frequencies are retrograde ($m = -1$) modes. The dips in the period spacing at 0.65 d and 1 d indicate that there are chemical discontinuities in the star.

retrograde ($m = -1$) modes. As for KIC 6131093, there are visible dips in this pattern, indicating a chemical discontinuity within the star.

3.4 KIC 10451090

KIC 10451090 was previously identified as a δ Scuti star based on long cadence observations, which identified many frequencies in the range 10-20 c/d ([5]). In our short cadence data, we found a large number of frequencies (108), primarily in the range 29-38 c/d, with no detected frequencies between 10 and 20 c/d. The frequencies detected in the long cadence data were probably reflections of frequencies above the Nyquist frequency (24.5). This effect has been shown to occur in other stars ([10]). We also detected a few very low frequencies (0.03-0.05 c/d), but these are relatively low amplitude and are likely the result of combinations of real frequencies. Using the same techniques as for KIC 5466537, we were able to find a large frequency separation of 2.27 c/d, resulting in two ridges in the echelle diagram.

3.5 KIC 11649699

No previous studies of this star have been performed. We identified nearly 100 significant frequencies in this star. As for KIC 6131093 and KIC 9962653, the modes are tentatively identified as $m = -1$ based on the patterns visible in the period spacings. The majority of the detected frequencies in this star are low, consistent with γ Doradus pulsation. However, a few low-amplitude frequencies have been detected between 5-10 c/d. These are likely combination frequencies, but may suggest that KIC 11649699 is also a hybrid star.

4 Conclusions

We present preliminary frequency analysis for 5 δ Scuti and γ Doradus stars observed with *Kepler*. A large number of significant frequencies has been detected in each of the five stars. Two of the stars (KIC 5466537, KIC 10451090) have been identified as δ Scuti stars based on the range of observed frequencies. For these two stars, we have been able to identify the large frequency separation by taking the Fourier transform of the Dirac comb produced by the observed frequencies. In both cases, the large separation can be used to make an echelle diagram showing two ridges. We have not yet identified the ℓ of these ridges.

The other three stars in our sample are all consistent with γ Doradus pulsations. Plotting the period separation against the observed period produces regular patterns, and these have been used to tentatively identify the modes as primarily retrograde ($m = -1$) modes. All three stars also show dips in the period spacing pattern, which indicates the presence of a chemical discontinuity inside the star.

Now that the observed frequencies and patterns have been extracted, we will compare the observed frequencies to theoretical models calculated with MESA ([15]) and GYRE ([17]). These theoretical models will be used to constrain the interior rotation and convection properties of the stars.

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