HYBRID $\gamma$ DORADUS–$\delta$ SCTI PULSATORS: NEW INSIGHTS INTO THE PHYSICS OF THE OSCILLATIONS FROM KEPLER OBSERVATIONS

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ABSTRACT

Observations of the pulsations of stars can be used to infer their interior structure and test theoretical models. The main-sequence $\gamma$ Doradus (Dor) and $\delta$ Scuti (Sct) stars with masses $1.2–2.5 M_\odot$ are particularly useful for these studies. The $\gamma$ Dor stars pulsate in high-order $g$-modes with periods of order 1 day, driven by convective blocking at the base of their envelope convection zone. The $\delta$ Sct stars pulsate in low-order $g$- and $p$-modes with periods of order 2 hr, driven by the $\kappa$ mechanism operating in the He ii ionization zone. Theory predicts an overlap region in the Hertzsprung–Russell diagram between instability regions, where “hybrid” stars pulsating in both types of modes should exist. The two types of modes with properties governed by different portions of the stellar interior provide complementary model constraints. Among the known $\gamma$ Dor and $\delta$ Sct stars, only four have been confirmed as hybrids. Now, analysis of combined Quarter 0 and Quarter 1 Kepler data for hundreds of variable stars shows that the frequency spectra are so rich that there are practically no pure $\delta$ Sct or $\gamma$ Dor pulsators, i.e., essentially all of the stars show frequencies in both the $\delta$ Sct and the $\gamma$ Dor frequency range. A new observational classification scheme is proposed that takes into account the amplitude as well as the frequency and is applied to categorize 234 stars as $\delta$ Sct, $\gamma$ Dor, $\delta$ Sct/$\gamma$ Dor or $\gamma$ Dor/$\delta$ Sct hybrids.

Key words: space vehicles: instruments – stars: variables: delta Scuti

1. INTRODUCTION

Many stars oscillate in multiple simultaneous modes during some portion of their evolution. The frequency range, spacing, amplitude, or other properties can be used to infer the interior structure of these stars and test the input physics and predictions of theoretical models, a process called asteroseismology. The $\gamma$ Doradus (Dor) and $\delta$ Scuti (Sct) stars that pulsate in many simultaneous frequencies are particularly useful for asteroseismic studies. These stars are core hydrogen burning and somewhat more massive than the Sun, at $1.2–2.5 M_\odot$. However, unlike the Sun, they have convective cores, shallower convective envelopes, and often rapid rotation.

While helioseismologists have been searching for solar $g$-modes (e.g., García et al. 2007), stellar astronomers have found them in several groups of pulsating stars including the $\gamma$ Dor variables. The $\gamma$ Dor $g$-modes have periods of the order of 1 day, making them difficult to observe continuously from the ground. In addition, the $g$-modes reach the stellar surface with small amplitudes which make their detection a challenge.
From a pulsational point of view, there is a clear distinction between δ Sct and γ Dor stars. The former are short-period pulsating stars, with periods between 0.014 and 0.333 days, while the latter are long-period pulsators, with periods between about 0.3 and 3 days. The distinction is even clearer if one considers the pulsation constant $Q$ (Handler & Shobbrook 2002); the δ Sct stars have $Q < 0.055$ days whereas for γ Dor stars $Q > 0.24$ days. When the γ Dor variables were first recognized as a new group (Balona et al. 1994; Kaye et al. 1999), their position on the Hertzsprung–Russell diagram (HRD) already suggested some relationship with the δ Sct group. The γ Dor stars lie in a zone close to the cool border of the classical instability strip, partially overlapping with the δ Sct pulsators. This latter property led astronomers to investigate the possible existence of hybrid stars exhibiting both types of pulsations (Breger & Beichbuchner 1996).

These hybrid objects are of great interest because they offer additional constraints on stellar structure. The γ Dor stars pulsate in g-modes, giving us the opportunity to probe the stellar core, while the δ Sct stars pulsate in p-modes, that help to probe the stellar envelope. Moreover, since γ Dor stars pulsate in high-order g-modes, the asymptotic approximation can be used, where we can benefit from an analytical solution of the equations (Smeyers & Moya 2007). Hence, the existence of hybrid stars provides a unique opportunity to extend this advantage to δ Sct stars (Handler & Shobbrook 2002).

Furthermore, in the same region of the HRD where the δ Sct and γ Dor instability strips overlap, solar-like oscillations are also predicted to occur for δ Sct stars (Houdek et al. 1999; Samadi et al. 2002). So far, no detections of solar-like oscillations in such hot stars have been reported (Antoci et al. 2009), which is probably due to the detection limits imposed by earthbound measurements. Stochastic excitation as an excitation mechanism in γ Dor stars has also been sought (e.g., see Pereira et al. 2007), but so far not confirmed. Kepler data are expected to reach the precision needed to observe stochastically excited pulsation. A positive or a significant null detection would set strong constraints on the parameterization of the convective envelopes.

Poretti et al. (2009), using data from the French-led CoRoT mission, show that over most of the periodograms of HD 292790 ($V = 9.5$), the amplitude of the noise level is 0.01 mmag for an observational time span of 57 days. In Kepler observations of the combined Quarter 0 and Quarter 1 data of a 9.5 mag star (time span of 44 days), the amplitude of the noise level is 0.001 mmag. The noise level in Kepler observations is therefore approximately 10 times smaller than in CoRoT observations.

The large number of stars to be studied by Kepler will also allow for control of long-term (low-frequency) instrumental changes; understanding these is important for confident identification of the low-frequency g-modes. Most importantly, the 3.5-year time span of the mission will give data with unprecedented frequency resolution. This is known to be necessary from ground-based studies that show closely spaced frequencies in data sets spanning years.

2. CURRENT OBSERVATIONAL STATUS

Among the hundreds of known δ Sct stars and several dozen confirmed γ Dor variables, only four have been previously observationally identified as hybrids and interpreted afterward using theoretical models (Bouabid et al. 2009).

One of the major contributions came from the Canadian Space Mission Microvariability and Oscillations of Stars (MOST; Matthews 2007), while CoRoT (Auvergne et al. 2009) is expected to add new confirmed cases in the near future, especially since the preliminary results indicate the possible detection of hybrid γ Dor and δ Sct pulsators in the exofield (Mathias et al. 2009).

The known hybrid pulsators are depicted, together with single-type pulsators, in Figure 1. The first case recorded was HD 209295 (Handler & Shobbrook 2002), but it turned out afterward that this star is a close binary and the long-period modes could be tidally excited (Handler et al. 2002). Following this work, Henry & Fekel (2005) discovered both γ Dor and δ Sct-type pulsations in the single Am star HD 8801 (Handler 2009).

MOST found two additional hybrid pulsators: HD 114839 (King et al. 2006) and BD+18 4914 (Rowe et al. 2006). Both of these are also Am stars. In preparation for the CoRoT mission, Uytterhoeven et al. (2008) identified HD 49434 as a candidate hybrid pulsator.

It is very interesting to note that three of the four known hybrids show Am-type peculiarities, even though Am stars are less likely to show pulsational variability than A/F-type main-sequence stars (Kurtz 1989). Increasing the number of hybrids is expected to shed light on the relationship between hybrid pulsation and Am chemical peculiarity.

3. THEORETICAL EXPECTATIONS AND MODELING

It is well known that the $\kappa$-mechanism operating in the He i ionization zone is responsible for the pulsational driving of δ Sct stars (Chevalier 1971). With this mechanism, the theoretical blue edge of the δ Sct instability strip is predicted correctly with linear non-adiabatic models for radial as well as for non-radial modes. But determining the theoretical red edge is more difficult, because it requires a time-dependent treatment of the interaction between convection and pulsation. In this stage of their evolution, cool δ Sct stars have relatively deep surface convection zones which typically extend beyond the location of the second stage of helium ionization, the principal driving region of δ Sct pulsations. Consequently, mode stability is
corresponding to typical \( \delta \) fluxes (e.g., Deupree 1977; Baker & Gough 1979; Gonzi 1982; only by means of a time-dependent treatment of the turbulent

The location of the red edge can be described theoretically near the red edge of the classical instability strip in the HRD.

Models have \( Z = 0.02, \alpha_{\MLT} = 2.0, \alpha_c = 0.2 \). The vertical line corresponds to the effective temperature of the Kepler target: \( \text{KIC11445913} \) (\( T_{\text{eff}} = 7200 \pm 200 \text{ K} \)).

\[ \begin{align*}
\text{Frequency (d}^{-1}) & \\
\log T_{\text{eff}} & \\
3.865 & 3.865 \quad 3.865 \quad 3.864 \quad 3.845 \quad 3.840 \\
0.1 & 1.0 \quad 10.0
\end{align*} \]

\[ \begin{align*}
\delta \text{ Sct} & \\
\gamma \text{ Dor} & \\
1.55 M_\odot & 1.50 M_\odot & 1.45 M_\odot \\
1.60 M_\odot & 1.65 M_\odot & 1.70-1.75 M_\odot
\end{align*} \]

Figure 2. Hybrid theoretical instability domain for \( \ell = 0 - 3 \ g \) - and \( p \)-modes. Models have \( Z = 0.02, \alpha_{\MLT} = 2.0, \alpha_c = 0.2 \). The vertical line corresponds to the effective temperature of the Kepler target: KIC11445913 (\( T_{\text{eff}} = 7200 \pm 200 \text{ K} \)).

We also note that the stability of modes in the gap decreases as degree \( \ell \) increases. This is due to the fact that the Lamb frequency \( S^2_{\ell} \propto (\ell + 1) \), so the size of the propagation cavity, of \( g \)-modes increases with \( \ell \) for a given frequency.

Therefore, the direct comparison of the observed frequency spectrum with models is a test of the excitation models and can improve our knowledge about important physical characteristics of the stars, including the age, chemical composition, etc.

Another more general problem in stellar pulsation modeling is connected with the effects of rotation on eigenfrequencies and eigenfunctions. The commonly adopted approach is perturbation theory which assumes that oscillation frequencies are much larger than the angular rotation rate \( \Omega \) and that the star is not significantly deformed by the centrifugal force (\( \Omega \ll \Omega_{\text{crit}} \equiv \sqrt{GM/R^3} \) (Reese et al. 2008). This assumption is violated for many \( \delta \) Sct and \( \gamma \) Dor stars, due to their relatively rapid rotation. This implies that rotation will significantly affect the pulsation frequency spectrum and surface amplitude distribution. This in turn will affect how limb darkening and light cancellation affects the pulsation mode visibility and radial velocity variations.

Hybrids can be extremely useful when investigating the internal rotation profile of stars. In Suárez et al. (2006), the authors examine the effect of rotation on the oscillation spectrum for intermediate-mass rotating stars. Significant effects for both \( p \)- and mixed modes (very low radial order \( g \)- and \( p \)-modes) are predicted. Analysis of hybrid stars will allow us to constrain the modeling of their rotation profiles. Better constraints on the internal rotation profile will help us better understand angular momentum transport processes in the stellar interior.

Neither \( \delta \) Sct stars nor hybrid stars are expected to pulsate in asymptotic \( p \)-mode oscillations. However, recently García-Hernández et al. (2009) found regular spacings in the oscillation spectrum of the CoRoT \( \delta \) Sct star HD 174936. Analysis of the 422 detected oscillation frequencies revealed a spacing periodicity of around 52 \( \mu \)Hz. Although the modes considered were not in the asymptotic regime, a comparison with stellar models confirmed that this signature may stem from a quasi-periodic pattern similar to the so-called large separation in solar-like stars. Other frequency spacings have also been observed in other stars using ground-based observations (e.g., Handler et al. 2000; Breger et al. 2009). From numerical results, this approximate asymptotic behavior has been found to hold for \( p \)-modes of low order (e.g., Christensen-Dalsgaard 2000). The presence of such spacings in hybrid stars may allow us to analyze simultaneously \( p \)- and \( g \)-modes with some characteristics of the asymptotic regime and even solar-like oscillations, if detected.

Interestingly, asteroseismology of hybrid stars can also benefit from techniques used for analyzing and interpreting the oscillation spectra of both types of pulsations. For instance, if \( g \)-modes in the asymptotic regime are detected, techniques based on the asymptotic properties of \( g \)-modes can be applied, namely the Frequency Ratio Method (FRM; Moya et al. 2005; Suárez et al. 2005). The FRM is particularly adapted for obtaining asteroseismic information on \( \gamma \) Dor pulsating stars showing at least three pulsation frequencies. The method provides an identification of the radial order \( n \) and degree \( \ell \) of observed frequencies and an estimate of the integral of the buoyancy frequency (Brunt-Väisälä) weighted over the stellar radius along the radiative zone. Miglio et al. (2008) also considered high-order \( g \)-modes to probe the properties of convective cores in slowly pulsating B and \( \gamma \) Dor stars.
Table 1

| Class            | Number | Percent | (log $T_{\text{eff}}$) |
|------------------|--------|---------|------------------------|
| $\delta$ Sct     | 67     | 27      | 3.885 ± 0.003          |
| $\delta$ Sct/\gamma$ Dor | 32     | 14      | 3.883 ± 0.006          |
| $\gamma$ Dor/\delta$ Sct | 19    | 9       | 3.868 ± 0.006          |
| $\gamma$ Dor     | 116    | 50      | 3.853 ± 0.005          |

Note. For each class, the mean values of the effective temperature are given.

4. KEPLER’S FIRST OBSERVATIONS

The main result from the inspection of these first Kepler data is that there are practically no pure $\delta$ Sct or $\gamma$ Dor pulsators. This finding raises a new problem: why is it that there is a clear distinction between the two types of pulsators in ground-based observations but not in Kepler observations? Part of the answer could be that in ground-based photometric observations the modes of highest visibility are modes of low degree whereas at the photometric precision of Kepler many more modes of high degree are now visible.

Now we must consider whether we can construct a classification scheme that allows us to retain the useful $\delta$ Sct/\gamma$ Dor categories. It is important to note that relying only on the mode frequencies, Kepler’s data show that all stars with variability in these frequency ranges are hybrids. The use of amplitude in addition to frequency can help by potentially filtering out the high-degree modes that generally would be expected to have a lower photometric amplitude. Considering both amplitude and frequency, we propose a new observational classification scheme for $\delta$ Sct and $\gamma$ Dor stars.

1. $\delta$ Sct: most of the frequencies are $\geq$5 day$^{-1}$, and the lower frequencies are of relatively low amplitude.

Figure 3. Theoretical HRD showing classification of Kepler target stars. Filled circles represent $\delta$ Sct, open circles $\delta$ Sct/\gamma$ Dor, crosses $\gamma$ Dor/\delta$ Sct, and plus signs represent $\gamma$ Dor. The solid lines show the zero-age main sequence, the radial fundamental red and blue edges (1R, 1B), and the fourth overtone radial red and blue edges (4R, 4B) of the $\delta$ Sct instability strip (Dupret et al. 2005). The dashed lines are the red and blue edges of the $\gamma$ Dor instability strip ($\ell = 1$ and mixing length $\alpha_{\text{MLT}} = 2.0$) (Dupret et al. 2005).

Figure 4. Frequency spectra of the long-cadence data obtained by Kepler for the stars KIC 9775454 and KIC 11445913 that display hybrid pulsations in the $\gamma$ Dor region (below 5 day$^{-1}$) and in the $\delta$ Sct region (above 12 day$^{-1}$). The details of the spectra at higher frequencies require short-cadence data to be confirmed and analyzed.
2. δ Sct/γ Dor hybrid: most of the frequencies are \(\geq 5 \text{ day}^{-1}\), but there are some lower frequencies which are of comparable amplitude.

3. γ Dor: most of the frequencies are \(\leq 5 \text{ day}^{-1}\), and the higher frequencies are of relatively low amplitude.

4. γ Dor/δ Sct hybrid: most of the frequencies are \(\leq 5 \text{ day}^{-1}\), but there are some higher frequencies which are of comparable amplitude.

We apply this scheme to a sample of 554 stars selected from the Kepler working group targets, where we have excluded stars that are constant or eclipsing variables. Among them, 234 show γ Dor or δ Sct frequencies and have an effective temperature near the instability strips for these types of pulsation. Table 1 summarizes the categorization and mean properties for these stars. The same stars are shown in the theoretical HRD in Figure 3 using the \(T_{\text{eff}}\) and radii derived from the Kepler Input Catalogue (KIC). Also shown are calculated red and blue edges overcame difficulties with mode identification, and the detection range associated with ground-based photometric campaigns. γ frequency spectra coupled with unprecedented photometric precision between \(\delta\) and \(\gamma\) Sct/γ Dor hybrids, whereas theory predicts the existence of hybrids in only a small overlapping region of the instability strips? What is the connection between Am chemical peculiarity and hybrid behavior? Why are modes observed between the \(\delta\) Sct and γ Dor frequency ranges, where theory predicts a frequency gap? Will we be able to confirm stochastic excitation or other pulsation driving mechanisms? Can the high-photometric precision of Kepler detect higher-degree modes (\(\ell > 2\)) that could fill in the frequency gap? Will these stars help us to distinguish between explanations for the red edge of the δ Sct instability strip? Will we be able to discern rotational frequency splittings and derive internal differential rotation rates for these stars?

Perhaps just as important are the many Kepler targets that lie within the γ Dor or δ Sct instability strips that show no periodic variations at micromagnitude photometric precision levels obtainable by Kepler. Monitoring over several years with Kepler will provide insight into amplitude limiting and mode selection mechanisms for these stars that is not possible with ground-based observations.

The analysis presented here of the first and second Quarter data obtained by Kepler confirms its capability to provide very high-quality data that will allow us to study hybrid pulsators of the δ Sct/γ Dor type. Moreover, the very rich frequency spectra of these stars lead us to propose a new classification scheme to overcome the ambiguity of the older, pure frequency-based scheme. The close frequency spacing of relatively short-period modes in δ Sct stars requires short-cadence data. We expect to obtain short-cadence data for selected targets of mixed character in the near future.

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