Hybrid pulsators among A/F-type stars

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Abstract. This article reviews the present knowledge on oscillating main sequence A/F stars that belong to more than one class of pulsator. Due to recent results of asteroseismic space missions, we now know of many δ Scuti/γ Doradus stars. However, γ Doradus variability was also detected in a rapidly oscillating Ap star, and solar-like oscillations were discovered in a δ Scuti star. The astrophysical information that can be gained from these pulsators is discussed, and confronted with what is believed to be known about pulsational driving.

1. Introduction

Over the last 40 years, our knowledge about pulsating stars has greatly expanded. The ever increasing accuracy in stellar observations and advances in theory have revealed a large number of previously unknown classes of variable star. Figure 1 compares the knowledge on the positions of pulsating stars in the HR diagram over this time span.

The most striking difference between the two panels in this figure is that the HR Diagram nowadays is well filled with pulsating variables. This has the important consequence that stellar oscillations can be utilized to sound the interiors of stars in many different evolutionary stages, and over wide ranges of mass and chemical composition. Besides better defined locations of the pulsating stars over the last 40 years, another new feature is obvious: several of the different instability strips overlap.

These instability strips contain stars with different pulsational behaviour, or in other words, with different types of mode excited. Consequently, it can be suspected that stars possessing more than a single set of mode spectra exist. Ground based observations have shown that they do, and the history of their study has been reviewed elsewhere (e.g., Handler 2009).

The most complicated region in the HR Diagram in terms of overlap of different classes of pulsating star is where the lower classical instability strip intersects the main sequence, at spectral types of A and F. There one finds:

- δ Scuti stars, pulsating in radial and nonradial pressure and mixed modes of low radial order with periods between 20 minutes and 6 hours, driven by the classical κ mechanism in the He I/H ionization zone (Baker & Kippenhahn 1962)

- rapidly oscillating Ap (roAp) stars, high-order pressure modes pulsators governed by a global magnetic field, with periods of 5 - 20 minutes, believed to be driven by the κ mechanism in the He I/H ionization zone (Balmforth et al. 2001)
Figure 1. Left: classes of pulsating star known in the late 1960’s. Right: a selection of classes of pulsating star known to date. Areas hatched from lower right to upper left depict domains of g-mode pulsators, areas hatched from lower left to upper right delineate domains of p-mode pulsators; overlapping areas may contain "hybrid" pulsators. Parts of model evolutionary tracks for main sequence, horizontal branch and post-AGB stars are shown as dashed-dotted lines for orientation.

- $\gamma$ Doradus stars that oscillate in high-order g modes with periods between 0.3 - 3 days, and likely driven by blocking of flux at the base of the envelope convection zone (Guzik et al. 2000)

- solar-like oscillations with periods around 10 - 40 minutes are theoretically predicted to be present and driven by surface convection (Houdek et al. 1999)

The present article reviews the present knowledge on hybrid pulsators in this domain in the light of recent results of asteroseismic space missions. There will be a strong focus on Kepler data, not only because they have the best quality, but for the practical reason that the author is involved in their analysis.

2. **Delgam Scudor stars**

When searching for $\delta$ Scuti pulsations in $\gamma$ Doradus stars, Bob Shobbrook invented the term "Delgam Scudor stars" for such hybrids. The asteroseismic observations by the Kepler satellite (Gilliland et al. 2010) revealed a large number of such variables. An example light curve is shown in Fig. 2.

The presence of multiperiodic pulsation with both long and short periods is quite obvious thanks to the excellent data quality. First analyses of Kepler data (Grigahcène et al. 2010, Uytterhoeven et al. 2011) revealed that $\delta$ Scuti/$\gamma$ Doradus hybridity is quite
Hybrid pulsators among A/F-type stars

Figure 2. Upper four panels: three weeks of Kepler data of a Delgam Scudor star. Light variations due to beating of multiperiodic g mode pulsations are clearly visible. Lower panel: zoom into a one-day segment of these measurements, highlighting the simultaneously present short-period p mode oscillations.

common (with an incidence of about 1/4) among A/F type stars, a result consistent with findings from CoRoT (Hareter et al. 2010).

Of course, better data also provide new challenges. It was noticed that the instability domains of δ Scuti and γ Doradus stars, and consequently, such hybrids, are larger than previously thought. This is in general not a surprise, but the apparent presence of hybrids all over the δ Scuti instability strip (Grigahcène et al. 2010, Uytterhoeven et al. 2011), and beyond, is. However, it must be kept in mind that the effective temperatures and surface gravities of these faint stars are not yet known to high accuracy. Work is in progress to improve this situation.

Another new result from the space missions is that the g and p mode domains in many Delgam Scudor stars are not nicely separated in frequency, as to be expected from their defining pulsational behaviour. Several stars appear to have a continuum of pulsation frequencies excited, filling the gap between high-order g modes and low order p and mixed modes.

This is a problem for models of pulsational mode excitation, which predict just such a clear separation (e.g. cf. Fig. 2 of Grigahcène et al. 2010) between the two types of mode. How can the frequency gap be filled?

Two scenarios appear viable. The first has been proposed long ago by Balona & Dziembowski (1999, their Fig. 1). Modes with high spherical degrees (l ≥ 6) can fill
G. Handler

Figure 3. Upper four panels: schematic theoretical $l = 2$ mode spectrum of a Delgam Scudor star rotating with 20 km/s. The g modes are clustered at low frequency, the p modes occupy the domain $> 10 \text{c/d}$. In consequent panels, the model rotates faster and faster. At rotational velocities approaching 200 km/s the frequency gap between the two sets of mode spectra becomes filled.

This frequency gap. It has hitherto been assumed that such modes cannot be seen in disk-integrated photometric measurements, but with the highly improved quality thanks to space observations, this assumption must be abandoned. Daszyńska-Daszkiewicz et al. (2002) have shown that, for instance, the photometric amplitude of an $l = 8$ mode still is 0.3% of a radial mode with the same intrinsic amplitude. Such modes can therefore fill the frequency gap.

Another possibility to fill the gap is rapid rotation, illustrated in Fig. 3. At low rotation speeds, the g and p mode spectra are well separated. However, with increasing rotation, the g mode regions extends and the p modes become rotationally split predominantly to lower frequency. Because of the small vertical amplitude of the g modes, they hardly experience the centrifugal force and prograde modes increase in frequency with rotation. On the other hand, the mostly vertically moving p modes feel the centrifugal force and retrograde modes attain lower and lower frequencies. For clarity of presentation, the current example was restricted to $l = 2$ modes; the effect becomes stronger for higher $l$ and with inwardly increasing rotation rate (Dziembowski & Pamyatnykh 2008).

We are only at the beginning of the exploration of the scientific information present in the stellar mode spectra provided from the new high-quality measurements. There are several questions that require further thought and investigations, such as: what are the decisive quantities that separate hybrid pulsators from “pure” oscillators of a single class? What are the signals in the gap between the g and p/mixed mode domains?

Of general importance is the following question: are all the variability frequencies we see in these stars due to normal pulsation modes or are there other causes? Rotational modulation of light curves can generate signals with frequencies in the $\gamma$ Doradus domain. In fact, a close connection between rotation and $\gamma$ Doradus pulsation has recently been proposed (Balona et al. 2011b). Another possibility is the presence of $r$ modes in some oscillation spectra (Kurtz et al. 2011).
Given the presence of stellar surface convection in stars within the $\delta$ Scuti instability strip, Kallinger & Matthews (2010) proposed that granulation noise may be observed in the amplitude spectra of stars with apparently "too many" pulsation frequencies. Amplitude/phase modulation of pulsation modes may also generate spurious signals in frequency analyses. Because of the many possible previously unobserved phenomena in stellar light variations, it remains to be discussed whether or not there is much point in keeping the designations of variable star classes as they are.

2.1. Chemically peculiar Delgam Scudor stars

As the first Delgam Scudor stars were discovered, there was the hypothesis that their nature could be related to chemical peculiarity, as several of these seemed to be Am stars (Matthews 2007). Recent spectroscopic analyses (Hareter et al. 2011) argue against this hypothesis.

The Kepler mission also revealed some Delgam Scudor stars among Ap stars and candidates. The detections of the oscillations are quite convincing, what remains to be proven is whether these objects are true Ap stars (Balona et al. 2011a); spectroscopic observations need to be obtained.

3. New types of hybrid pulsators

Recently, a hybrid between a $\gamma$ Doradus and a roAp star has been reported and modelled (Balona et al. 2011). Unfortunately the presumed $\gamma$ Doradus mode spectrum is sparse, wherefore utilizing both types of mode is not yet possible.

Kepler observations also supplied the first detection of solar-like oscillations in the $\delta$ Scuti star HD 187547 (Antoci et al. 2011). The light variations of the star are dominated by low-order p mode pulsations, whereas at higher frequencies the comb-like structure of high radial overtone oscillations is observed. Figure 4 shows a comparison of the temporal behaviour of a $\delta$ Scuti mode, a stochastically driven pulsation and a solar mode. The similarity between the latter two is striking.

The importance of the detection of these oscillations lies not only in the possibility to sound different interior regions of the star asteroseismically. It also implies that stellar surface convection can still be efficient in stars about twice as massive as the Sun, where the superficial convection zones are as thin as 1% of the stellar radius. The solar-like mode amplitudes and lifetimes can be used to constrain convection models in a hitherto observationally unexplored domain of physical parameter space, and it will be interesting to see how this result can be reconciled with others implying non-efficient surface convection in $\delta$ Scuti stars (Lenz et al. 2008).

4. Summary and discussion

The $\delta$ Scuti stars, the roAp stars, the $\gamma$ Dor stars and solar like oscillators all overlap at the intersection of the classical instability strip and the main sequence. Each of these classes of pulsating star are driven in different regions of the star. To date, we know hybrid pulsators between: $\delta$ Scuti and $\gamma$ Dor stars, roAp stars and $\gamma$ Dor stars as well as $\delta$ Scuti stars and solar-like oscillators. The other three possible combinations of two classes of pulsator have not yet been observed.
This status makes sense from the point of view of pulsational driving (as we believe to understand it to date), because the mechanisms operating in the known hybrids, or their basic physical characteristics, do not affect each other negatively. On the other hand, the absence of roAp/solar-like hybrids is also not a surprise, as the strong magnetic fields of Ap stars are believed to suppress surface convection. Similar arguments may be invoked to explain the non-detection of roAp/δ Scuti hybrids: the diffusion and settling of chemical elements is supposed to deplete the driving zone for δ Scuti oscillations of the required Helium, and slow wave leakage due to strong magnetic fields is believed to provide additional damping.

What about γ Doradus/solar-like hybrids? Such stars have not been reported to date, but the author believes this is only a question of time. Along those lines, given the large fraction of Delgam Scudor stars, one may also expect the existence of δ Scuti/γ Doradus/solar-like hybrids, which would be another goldmine for asteroseismology of main sequence stars.

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Hybrid pulsators among A/F-type stars

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