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Asteroseismology of δ Scuti and γ Doradus Stars

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Abstract. We give an overview of past and present efforts to make seismology of δ Scuti and γ Doradus stars possible. Previous work has not led to the observational detection and identification of a sufficient number of pulsation modes for these pulsators for the construction of unique seismic models. However, recent efforts including large ground-based observational campaigns, work on pre-main sequence pulsators, asteroseismic satellite missions, theoretical advances on mode identification methods, and the discovery of a star showing simultaneous self-excited δ Scuti and γ Doradus oscillations suggest that we may be able to explore the interiors of these pulsators in the very near future.

Key words. Stars: variables: δ Scuti—stars: oscillations, variables: other.

1. Introduction

The δ Scuti and γ Doradus stars are pulsating variables of spectral types A or F that are located on or near the main sequence. Although they occupy similar regions in the HR diagram (see Fig. 1), there are a number of important differences between the pulsational behaviours of these two groups of variable stars.

For instance, the δ Scuti stars pulsate with periods between about 20 minutes and 8 hours. Therefore they oscillate in pressure (p) and gravity (g) modes of low radial order. On the other hand, the pulsation periods of the γ Doradus stars range from 8 hours to 3 days, indicating that g modes of high radial order are excited. Although there is some overlap in the pulsation periods of the two classes of pulsators, they are clearly separated if the pulsation "constant" Q is considered (Handler & Shobbrook 2002).

Both the δ Scuti and γ Doradus stars contain variables that oscillate in multiple modes. This makes them interesting for asteroseismic studies and several attempts have been made to explore their interior structures by modelling their pulsation spectra. However, these attempts have not been particularly successful to date.

Consequently, the remainder of this paper is intended to give an overview of the attempts to apply asteroseismology to δ Scuti and γ Doradus stars. We first identify the areas in which problems for asteroseismic studies have been met, and then try to show how they can be overcome.

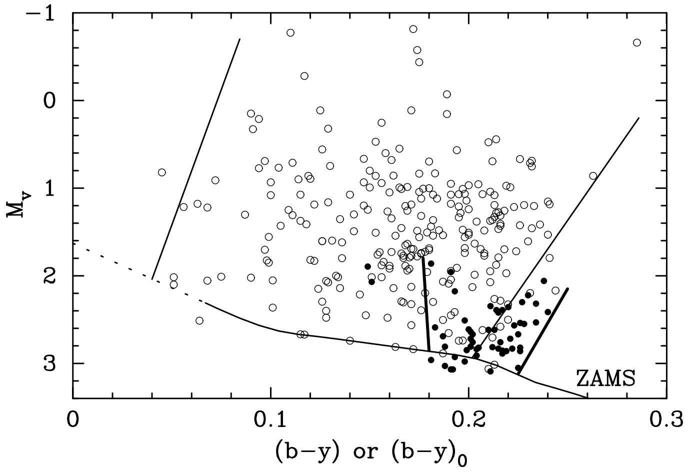

Figure 1. The location of δ Scuti and γ Doradus stars in a colour-magnitude diagram. The open circles represent all δ Scuti stars for which Strömgren colours and HIPPARCOS parallaxes are available, whereas the filled circles show all γ Doradus stars with the same information. The Zero-Age Main Sequence (ZAMS) is indicated, taken from the standard relations by Crawford (1975, 1979), and is extrapolated towards low $(b-y)$ (dotted part of the ZAMS). The observational borders of the two pulsational instability strips (Rodriguez & Breger 2001; Handler & Shobbrook 2002), with the thicker lines corresponding to the γ Doradus strip, are also shown.

2. Challenges for asteroseismology

The two main interior regions of a δ Scuti star comprise a convective core and a (mostly) radiative envelope. Both of these regions contain a specific family of pulsation modes: gravity modes are in principle located in the core, whereas pressure modes mainly propagate in the envelope. At the ZAMS, the periods of the g modes are considerably longer than those of the p modes and the two sets of mode spectra are well separated in period.

However, as a δ Scuti star evolves along the main sequence, its interior structure changes. The convective core shrinks and becomes more compact, whereas the envelope expands and its mean density decreases. This means that the g-mode periods decrease, and at the same time the p-mode periods increase. At some point, the period ranges of these two mode families begin to overlap, modes start to exchange properties (resulting in so-called mixed modes), and the avoided crossing phenomenon (e.g., see Aizenman *et al.* 1977) takes place.

This has a dramatic effect on the theoretically predicted mode spectra. Whereas a pure p-mode spectrum should be observable at the ZAMS, an ever-increasing number of mixed modes is predicted to be excited during the late- and post main sequence stages of stellar evolution (e.g., see Dziembowski & Krolikowska 1990). We illustrate this problem in Fig. 2.

The number of theoretically predicted pulsation modes increases considerably as a model reaches the end of its main sequence life, and the theoretical pulsation spectrum of post main sequence models is extremely dense. For comparison, model A has a total of 24 unstable pulsation modes (8 of them being $m = 0$), model B has 80 unstable modes (24 of $m = 0$), and model C has 345 unstable modes (89 of which are $m = 0$).

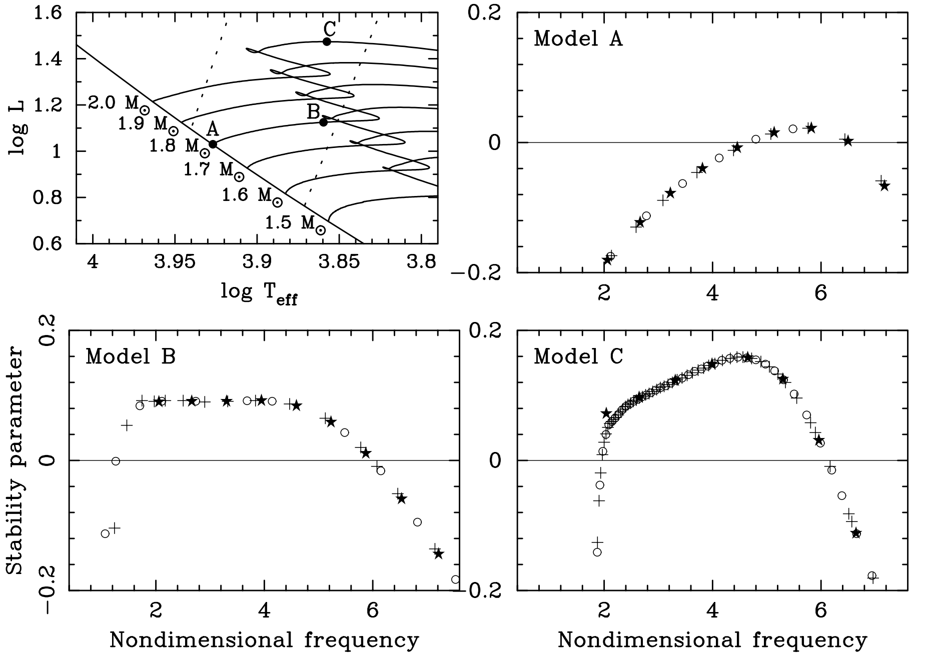

Figure 2. Upper left: a theoretical HR diagram, with some evolutionary tracks (labelled with their masses) indicated. The dotted lines are the borders of the δ Scuti instability strip. Three selected models in different evolutionary stages (ZAMS, model A; end of main sequence, model B, post main sequence, model C) are indicated. Upper right and lower two panels: pulsationally stable and unstable modes (only the $m = 0$ components are plotted) in models A, B and C. All modes with a positive stability parameter are excited in the models. Star signs indicate radial modes, open circles are $l = 1$ modes and plus signs correspond to $l = 2$ modes.

Many δ Scuti stars are also fast rotators. This means that the frequency splittings due to rotation may become large enough that their size becomes comparable to the frequency difference of consecutive radial overtones and mode coupling, leading to additional modifications of the pulsation frequencies, may also occur (see Pamyatnykh 2003).

Since ground-based observational efforts to determine the multiple pulsation frequencies of δ Scuti stars have so far revealed only a few tens of independent pulsation modes, it thus seems logical to observe unevolved pulsators that do not rotate rapidly to maximise the ratio between the number of observed and predicted pulsation modes. Such a strategy may lead to unambiguous mode identifications and hence enable seismic modelling.

Handler *et al.* (2000) followed this approach and determined a total of 22 independent pulsational mode frequencies for the δ Scuti star XX Pyxidis. This object is unevolved and about two thirds of the theoretically predicted $l \leq 2$ modes should have been detected. Still, all attempts to derive a mode identification were in vain, as no clear patterns within the mode frequencies could be detected. This example makes it clear that one needs mode identification methods to understand the pulsation spectra of δ Scuti stars.

Several of these methods exist, including photometric and spectroscopic techniques, and combinations of these (e.g., see Reed 2003 and Telting 2003 for reviews).

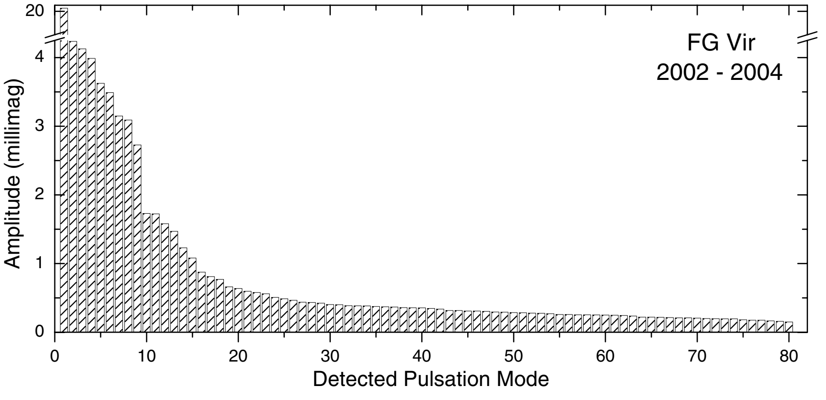

Figure 3. The number of frequencies found in the light curves of the δ Scuti star FG Vir depending on the detection threshold. Used with permission from Breger *et al.* (2005).

Unfortunately, their application also seems to be problematic for δ Scuti stars (e.g., Balona 2000), because some apparently independent methods are redundant and because the shallow surface convection zones of these stars seem to make mode discrimination ambiguous.

Summarising, we can state that the two major problems for seismology of δ Scuti stars are the detection of a sufficient number of pulsation modes and their unambiguous identification with the pulsational quantum numbers k, the radial order, l, the spherical degree and m, the azimuthal order. These difficulties must be overcome before detailed theoretical seismic studies can commence.

Turning now briefly to the γ Doradus stars, we face a similar situation. In fact, it is even more difficult to detect and identify the individual pulsation modes of these stars, since their pulsation periods are of the same order as their rotation periods, leading to considerable overlap of neighbouring mode multiplets, and complicating the theoretical treatment of rotation. In addition, the longer pulsation periods themselves require even larger quantities of data to be obtained with the most stable equipment.

Taking the discussion above at face value, it seems that asteroseismology of δ Scuti and γ Doradus stars is extremely difficult from the observational point of view. In fact, several researchers (including the present author) have stopped their work on these problems. However, such an attitude may be too pessimistic.

3. Light at the end of the tunnel?

3.1 *δ Scuti stars*

Fortunately, the continued efforts of several groups of researchers, including the advent of asteroseismic satellite missions have brought some important advances in both observation and theory. For instance, Breger *et al.* (2005) carried out extensive multisite ground-based photometric observations of the star FG Vir over several consecutive seasons, leading to the detection of a total of 67 independent pulsation modes (see Fig. 3).

The position of FG Vir in the HR diagram is close to that of our model B from the previous section that had a total of 80 unstable pulsation modes. Consequently, it is possible that a sufficient number of modes has been detected for seismic modelling of this star, unless a significant fraction of the observed modes is $l > 2$.

The study of pre-main sequence (PMS) δ Scuti stars also bears some seismic promise. Since the interior structure of these objects (e.g., Suran *et al.* 2001) is presumed to be relatively simple, it may also be possible to decipher their pulsational mode spectra more easily. Recent searches for PMS pulsators have brought the number of known objects up to two dozen (K. Zwintz, private communication), increasing the chances to find promising targets considerably. In fact, multisite observations of PMS δ Scuti stars have already revealed as many as 19 pulsation frequencies (T. Kallinger, private communication) for an individual star.

The biggest advances in observational asteroseismology of δ Scuti and γ Doradus stars can however be expected from present and future satellite missions. The high measurement accuracy from space will allow the detection of an unprecedented number of pulsation modes, as can also be expected from Fig. 3 where the number of detected oscillations increases sharply with decreasing detection limit.

The MOST (Microvariability and Oscillations of STars, Walker *et al.* 2003) satellite is already delivering data, with excellent performance (Matthews, these proceedings). The COROT (Convection, Rotation, and planetary Transits, e.g., Baglin 2003) mission is due to be launched in mid 2006. It contains a larger telescope than MOST (27 *vs.* 15 cm aperture), will monitor its targets over a longer time baseline (~ 150 d *vs.* ~ 40 d), and has several δ Scuti stars as primary targets. Consequently, it can be expected that COROT will deliver even better data after a successful launch.

However, it should be clearly pointed out that the advent of space asteroseismology will not make ground-based observations unnecessary. First, the satellites are strongly limited in terms of target brightness and observable region in the sky. Second, the length of the data sets obtained from space is usually not sufficient to resolve the frequencies of all the possibly excited pulsation modes in, e.g., δ Scuti stars (see Handler 2004 for a discussion). Third, the use of mode identification methods is not implemented in the present asteroseismology satellite setups. The larger flexibility of ground-based measurements will thus still make them an asset for future asteroseismic observations.

Having mentioned mode identification methods, it is noted that considerable progress has been made on the theoretical side concerning δ Scuti stars. Daszyńska-Daszkiewicz *et al.* (2003) showed that if time-resolved multicolour photometry of such a pulsator in at least three filters is available, it can be used both to infer the type of the pulsation mode as well as to obtain constraints on surface convection.

3.2 *γ Doradus stars*

As opposed to the δ Scuti stars, the γ Doradus stars are known to be pulsating variables only for a few years (Kaye *et al.* 1999), and hence they are not that well investigated. On the other hand, their long pulsation periods make them well suitable for measurements with automated photometric telescopes. Such searches (most recently Henry *et al.* 2005) have increased their number to a total of 54, four times as many as were known only five years ago!

Figure 4 shows a colour-magnitude diagram of the γ Doradus stars, where it becomes clear that about half of them are located within the δ Scuti instability strip as well. There

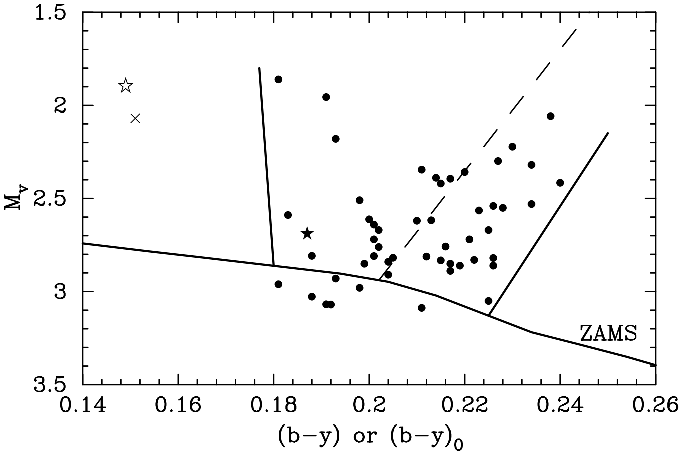

Figure 4. A colour-magnitude diagram of the bonafide γ Doradus stars (filled circles), similar to Fig. 1. The dashed line is the cool border of the δ Scuti instability strip. The open star symbol corresponds to HD 209295, whose γ Doradus pulsations are likely to be tidally excited, the cross is for HD 221866, a binary with a γ Doradus component, and the filled star symbol is HD 8801, both a γ Doradus and a δ Scuti star.

are also two prominent outliers to the blue edge of the γ Doradus region: HD 209295 is a 3-day binary in an eccentric orbit with an unknown companion that exhibits both δ Scuti and γ Doradus pulsations, but the latter are probably excited by tidal interaction (Handler *et al.* 2002). HD 221866 is also a binary, consisting of an Am star and an F2 dwarf (Kaye *et al.* 2004), and it is therefore suspected that the pulsations originate from the F2 star whereas the system's colours are dominated by the earlier-type companion.

In any case, the stars that are located in both instability domains are particularly interesting for asteroseismology as they may show self-excited pulsations of both types. Unfortunately, searches for such stars (Handler & Shobbrook 2002) were unsuccessful—until recently. Henry & Fekel (2005) reported the discovery of simultaneous δ Scuti and γ Doradus pulsations in the apparently single Am star HD 8801. Although only a few pulsation modes were detected for this object, it is important to know that both types of pulsation can exist in the same star. It is hoped that more such objects will be discovered in the near future, since they offer the possibility to study their innermost regions, and to sound their envelopes at the same time.

In this context it is interesting to note that the γ Doradus stars (as well as the cooler δ Scuti stars) occupy a region in the HR diagram where solar-like oscillations are also predicted (Zerbi *et al.* 2000) and high-precision radial velocity observations as well as space photometry could reveal both types of variability. This would be particularly exciting as one of the unsolved questions of helioseismology is just the reverse: the presence of *g* modes in the sun.

4. Summary and conclusions

To date, it has not been possible to perform detailed asteroseismic studies of δ Scuti and γ Doradus pulsators. From the observational point of view, the main problems to be overcome are the detection of a sufficient number of pulsation modes, and their unique match with the pulsational quantum numbers k, l and m. The γ Doradus stars pose additional complications due to their longer pulsational time scales that make observations and mode identifications even more difficult and that also make the theoretical treatment of rotation more elaborate.

However, some recent studies of δ Scuti stars turned out to be quite encouraging: large numbers of pulsation modes are detectable from the ground if the stars are observed persistently, pre-main sequence objects may have pulsation spectra simple enough for mode identification via pattern recognition, and some mode identification methods have matured to a point where they may be applied reliably and could even yield additional constraints on surface convection for stellar modelling. High-precision space observations will soon be available for a number of objects and it is reasonable to expect that a significantly larger number of pulsation modes will be detected as compared to ground-based measurements (which can however not be replaced by the satellite data).

There is also considerable progress in the study of the γ Doradus pulsators: we know now more than 50 such objects, and the first star that shows both self-excited γ Doradus and δ Scuti oscillations has been discovered. In addition, it also seems possible that solar-like oscillations can be present in some γ Doradus and some cooler δ Scuti stars.

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