Comm. in Asteroseismology
Vol. 150, 2007

Delta Scuti stars: Observational aspects

M. Breger

Institute of Astronomy, University of Vienna, 1180 Vienna, Austria

Abstract

The review concentrates on several important aspects of observational studies of δ Scuti stars. After a discussion of promising astrophysical questions we examine

- the extreme amplitude variability of the evolved star 4 CVn
- the role of rotation in determining the amplitudes of radial and nonradial modes
- the lack of constancy at the millimag level of the comparison stars: we propose that up to four photometric comparison stars are used
- the very high accuracy to which frequency values can be determined
- the problem with the sufficient frequency resolution required for the detection of close frequencies.

δ Scuti stars as astrophysical tools

The δ Scuti variables are stars of spectral type A and F in the main-sequence or immediate post-main-sequence stage of evolution. They are situated in the classical instability strip with the instability caused mainly by the HeII ionization zone. In general, the period range is limited to between 0.02 d and 0.25 d. Longer periods (gravity modes) may also be present. The stars generally pulsate with a large number of simultaneously excited radial and nonradial modes. This makes them well-suited for asteroseismological studies. The photometric amplitudes of the dominant modes in the typical δ Scuti star are only a few millimag. It is now possible to detect a large number of simultaneously excited modes with sub-millimag amplitudes in stars other than the Sun using ground-based telescopes as well as satellites. An extensive review of δ Scuti stars is available (Breger 2000) and here we concentrate on a few topics of interest.

At present, the best observed star is FG Vir, for which more than 2000 hours of high-precision photometry have revealed 75+ frequencies of pulsation (Breger et al. 2005). As in most well-studied δ Scuti stars, the excited modes are both radial and nonradial. The combination of spectroscopic and photometric techniques as well as pulsation modelling has made it possible to identify the nature of the major pulsation modes (Daszyńska-Daszkiewicz et al. 2005). Probably the main aspect of the present asteroseismological research on the δ Scuti stars is concerned with concentrating on the observed pulsation frequencies of a few chosen pulsators in order to improve the models of stellar structure, evolution, convection and pulsation to agree with more and more detailed observations.

Modes ranging from $\ell = 0$ to very high values (12+) are excited in these stars, but the mode selection mechanism is not clear. The observational problem is the following: since the number of detected modes increases dramatically as the observational threshold decreases (see FG Vir or some of the MOST results), what causes a star to select some low-degree modes to have photometric amplitudes of several hundredths of a magnitude instead of a 0.0001 mag or less? How can we determine that a particular mode is not excited, rather than present with an undetectable amplitude? For mode selection, stellar rotation (see below) is important, but can only be one of many factors.

δ Scuti pulsation also occurs among pre-main-sequence stars, e.g., eight pre-main-sequence stars were found in the clusters IC 4996 and NGC 6530 (Zwintz & Weiss 2006). The internal structure of pre-main-sequence stars differs substantially from that of post-main-sequence stars of similar luminosity and temperature. The difference should show up in the nonradial pulsation spectrum, especially when modes of different ℓ values are compared with each other. The important detection of the differences requires very detailed pulsation studies of selected pre-main-sequence stars.

Another interesting application of asteroseismology concerns the chemically peculiar stars inside the instability strip. An example is provided by the λ Boo stars, which show surface underabundances of most Fe-peak elements and solar abundances of the lighter elements (C, N, O, and S). Different theories to explain the spectra of these stars include accretion of interstellar matter, diffusion, mass loss or composite spectra of spectroscopic double stars. These effects should lead to different pulsation spectra. Paunzen et al. (2002) have reported that the average pulsation of λ Bootis stars differs from that of the average δ Scuti star in two ways: incidence and radial order of the pulsation modes. A more extensive study of the λ Boo star, HD 210111, by Breger et al. (2006) revealed no unusual pulsational behaviour. Probably both studies were not extensive enough to answer the question of possible differences between 'normal' and λ Boo-type δ Scuti stars.

A number of δ Scuti pulsators are also found in semi-detached Algol systems. This raises the question whether their pulsation is different. Some of these stars have unusually short pulsation periods, e.g., the 22-minute period of RZ Cas (Rodríguez et al. 2004). In fact, RZ Cas also shows a λ Boo-type abundance pattern (Narusawa et al. 2006). Additional studies of these close systems are very promising.

Amplitude variability

A presently unsolved problem concerns the origin of the amplitude and phase variability found in δ Scuti (as well as other) pulsators. This is demonstrated for an extreme case, 4 CVn, in Fig. 1. It turns out that the small-amplitude δ Scuti stars are an ideal group to search for the cause of the variability, since (unlike RR Lyrae stars and Cepheids) their light curves are sinusoidal and the nonlinear effects are considerably reduced. For the stars BI CMi and FG Vir, it could be shown that the amplitude and phase variability is caused by beating between two modes of almost identical frequencies (Breger & Pamyatnykh 2006).

Radial and nonradial modes: the role of rotation

At the present time the size of the amplitudes of δ Scuti stars cannot be predicted accurately from theory. However, from observations we can show that the most important parameter determining the size of the amplitudes is stellar rotation. This is demonstrated in Fig. 2. The picture, however, is more complex than appears at first sight, since the stars are multi-frequency pulsators.

Not surprisingly, the first δ Scuti stars to be discovered were the variables with large amplitudes of $A_V \geq 0.3$ mag. These stars are now known as high-amplitude δ Scuti stars (HADS) and were in earlier times also called Dwarf Cepheids. It was only during systematic, high-precision variability surveys that it was discovered that the HADS were not typical for the stars in the Lower Instability Strip, but that most of the stars near the main sequence have small, almost undetectable amplitudes. HADS generally rotate slowly with $v \sin i \leq 30$ km/s. This is in contrast to an average rotation $\sim$150 km/s in this part of the Hertzsprung-Russell Diagram. The assumption that the large-amplitude modes of the HADS are radial modes was confirmed by the period ratios between the radial fundamental and first overtone modes of the double-mode HADS. However, recent analyses have revealed that low-amplitude nonradial modes may also be present (e.g., V974 Oph, Poretti 2003), but not in all HADS (e.g., GSC 00144-03031, Poretti et al. 2005).

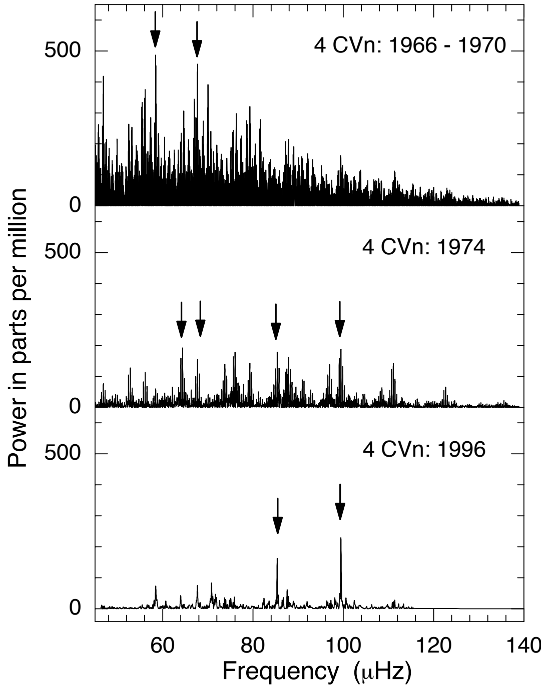

Figure 1: The power spectrum of 4 CVn in three different time periods. Arrows denote the intrinsic frequencies. The diagram shows that due to amplitude variations the same star may look like different stars in different years. The pulsation spectrum of the 2005 data (not shown here) indicates that all the peaks are still present, and no modes have disappeared but have different amplitudes.

The typical δ Scuti variable does not rotate slowly, has very low amplitudes and pulsates with mainly nonradial modes. If radial modes are detectable at all, they have very low amplitudes. An excellent example is the star FG Vir, where the radial fundamental mode at 12.15 c/d has a much smaller amplitude than the dominant ℓ=1 mode at 12.72 c/d.

The following hypothesis summarizes the present situation:

(i) Radial as well as nonradial pulsation can occur in all δ Scuti stars, irrespective of whether the star rotates quickly or slowly.

(ii) The radial modes are strongly affected by stellar rotation. They reach large amplitudes up to a magnitude only if the star rotates slowly. These stars are known as HADS and resemble the classical variables in the instability strip such as Cepheids and RR Lyrae stars.

(iii) Stars rotating faster than ~30 km/s have low amplitudes of pulsation and pulsate with a multitude of mostly nonradial modes. If radial modes can be detected photometrically at all, they have low amplitudes. An example is the star FG Vir, where the radial mode at 12.15 c/d has an amplitude of 0.004 mag in V, while the dominant $\ell = 1$ mode at 12.72 c/d reaches 0.022 mag.

(iv) There exists a region with stars in which both $\ell = 0$ (radial) and $\ell = 1$ (nonradial) modes may reach amplitudes in excess of 0.05 mag (peak-to-peak). Examples are stars such as 1 Mon and 44 Tau (projected rotational velocities of 14 and 2 km s^{-1}, respectively), which are both studied by the Delta Scuti Network at the present time.

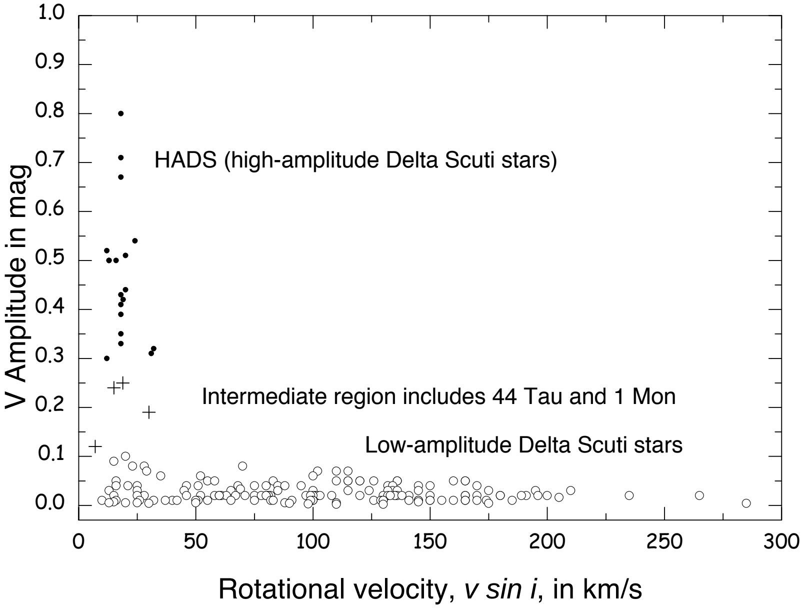

Figure 2: Relationship between the measured projected rotational velocity, *v* sin *i*, and amplitude of pulsation. The diagram shows that large amplitudes (mostly radial modes) require slow rotation. However, nonradial modes with small amplitudes are detected in δ Scuti stars of all rotational velocities.

An observational necessity: comparison stars

In order to study variability on the millimag level of photometric accuracy, it is necessary to also observe comparison stars. This holds for ground-based photomultiplier and CCD photometry, and also for satellite measurements. Because of observational limitations, the choice of comparison stars is limited. Recent extensive photometric campaigns by the Delta Scuti Network have corroborated the suspicion that constant comparison stars are very rare, especially at the millimag level. This can be demonstrated by the results for the δ Scuti star 44 Tau. Two of the four carefully chosen comparison stars of spectral type F were detected to be variable with long periods (see Fig. 3).

This demonstrates that great care needs to be taken in choosing constant comparison stars. The popular techniques of avoiding A stars (since they probably also are δ Scuti variables) and choosing F stars is a good one. Nevertheless, most of the F stars studied by us show low-frequency peaks and may be γ Dor variables, whose instability strip extends to somewhat lower temperatures than previously known. We advise that campaigns should choose more than two comparison stars.

Frequency precision vs. frequency resolution

The knowledge to what precision a frequency can be determined is important. It is required to interpret measured period changes, possibly of evolutionary nature. Also, many amplitude variations are actually caused by the beating of close frequencies: consequently, knowledge of the frequency resolution is required.

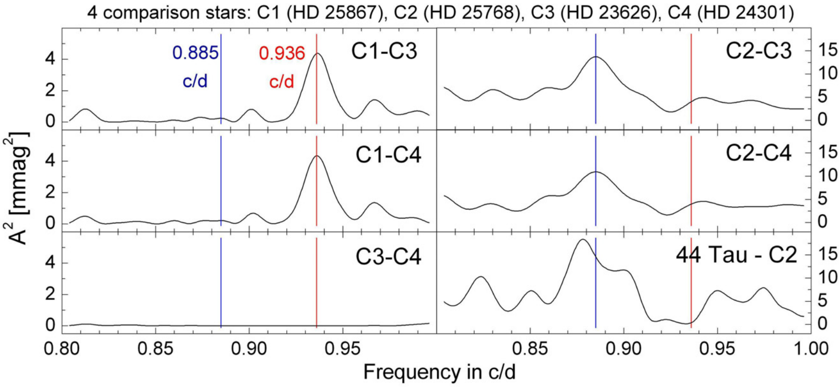

Figure 3: The problem with small-amplitude variability of comparison stars is demonstrated by examining four (!) comparison stars used for the study of 44 Tau. The panels show the power spectra of the difference between two comparison stars in the 0.8 to 1.0 c/d frequency region. The top two left panels indicate that the 0.936 c/d peak is present in both (C1-C3) and (C1-C4), but absent in (C3-C4). This shows that the peak originates in C1. Similarly, the 0.885 c/d peak originates in C2. Stars C3 and C4 appear to be constant most of the time.

The *frequency precision* is sometimes estimated to be 1/ΔT, where ΔT is the length of observation. This is incorrect: under many conditions the precision is much higher. If we fit a sine curve to the data, then the uncertainty can be computed in the standard manner, viz., $\sigma(\mathrm{f}) = \sqrt{6/N}\, \sigma(\mathrm{m})/(\pi a \Delta \mathrm{T})$, where m is the brightness in mag, a is the amplitude, N is the number of observations. There are some hidden assumptions here that there is only white noise, essentially no aliasing, multiple frequencies do not affect each other, and that there exists little or no amplitude variation. These assumptions are not always met.

The calculation of the frequency precision can be improved by Monte Carlo simulations to the data, e.g., as performed in our statistical package PERIOD04 (Lenz & Breger 2005). Let us apply the Monte Carlo simulations to the 80 frequencies of FG Vir and the 1992 – 2004 data (Breger et al. 2005). We note that 80 frequencies take up 241 degrees of freedom (80 frequencies, 80 amplitudes, 80 phases and 1 zero-point). This presents no problem, since there are more than 10 000 independent data points in the sample.

For the dominant frequency of FG Vir at 12.72 c/d, the Monte Carlo simulations result in $\sigma(\mathrm{f}) = 1.678 \times 10^{-7}$ c/d, (or 1.9 pHz, or one part in 10^{-8}). This value is only slightly higher than that given by the standard formula, but a factor of a thousand better than given by 1/ΔT.

The conditions to obtain this precision were listed above. If the star has close frequency doublets, the conditions are not met and the precision is lowered significantly due to the 'interaction' between the two frequencies. Now the frequency resolution becomes important.

It is also not quite correct to state that the *frequency resolution* is given by 1/ΔT. In fact, Loumos & Deeming (1978) showed that the frequency resolution is only 1.5/ΔT! For a two-month observing run, the detectable frequency separation would be larger than 0.025 c/d. A typical ground-based observing campaign by the Delta Scuti Network covers several years or decades: for a three-season campaign with ΔT ∼ 30 months, the frequency resolution by the Loumos & Deeming criterion would be would be 0.0017 c/d or 19 nHz.

The situation may, in fact, be better than this, since the quality of the measurements during the time ΔT as well as the amplitudes of two close frequencies need to be considered. After all, if the measurements were continuous and error-free (infinite signal/noise ratio), two independent frequencies of any separation could hypothetically be determined. Consequently, the question of what is meant by frequency resolution becomes important. Numerical simulations with *realistic* data are required to determine the probability of a correct discovery and determination of the frequency doublet. In particular, effects such as aliasing, non-white noise and the presence of additional frequencies need to be considered. Our experience with proving that close frequency pairs in FG Vir exist (Breger & Pamyatnykh 2006) advises caution: we only solved the problem by obtaining a coverage much longer than required by statistical predictions.

Conclusions

In the paper we have highlighted several aspects of δ Scuti star research with considerable asteroseismological potential. We also examined several observational problems which may not be generally known. The difficulties can be overcome in the planning stages of future observational campaigns.

Acknowledgments. This investigation has been supported by the Austrian Fonds zur Förderung der Wissenschaft. We are grateful to P. Reegen for assistance with the APT measurements of 44 Tau and its four comparison stars and W. Weiss as well as T. Kallinger for interesting discussions.

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DISCUSSION

Dziembowski: The correlation between the rotational velocities and amplitudes of the δ Scuti stars has a common cause. The large-amplitude stars are all evolved objects and they rotate more slowly. But there may be another connection, namely that the amplitudes have to do with resonances. Rotation gives you more options for radial modes to undergo resonances and therefore you can estimate that there is a significant influence of rotation.

Breger: I think your point about the evolutionary status is a very good one. I have repeated this diagram for stars near the ZAMS and for evolved stars. One expects that main sequence stars have smaller amplitudes and evolved stars larger ones. But "fortunately" the correlation still exists, even if you only plot evolved objects.

Kepler: Are the amplitude variations you see due to close frequencies or are they intrinsic amplitude modulations?

Breger: Whereever there exist enough data to distinguish between the two explanations, for δ Scuti stars the amplitude variations are caused by the beating of close frequencies.

Michel Breger and Chris Sterken taking a deserved break.