Main Sequence Variables

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Abstract. The pulsators along and near the main sequence are well-suited for asteroseismology and provide a probe of the stellar interior and its changes with evolution. With the exception of rapidly oscillating Ap stars (roAp), the pulsation periods range from 0.5 h to days. This requires multisite campaigns lasting several weeks. The δ Scuti, roAp and β Cephei variables offer the greatest potential, while the longer-period g-mode pulsators (SPB – slowly pulsating B stars – and γ Doradus variables) are very difficult to study. A summary of the multiperiod structure of δ Scuti stars is given. The two best-studied stars, FG Vir and CD-24°7599, both have been WET targets. A preliminary analysis of the 1995 campaign of FG Vir has already detected 19 frequencies. The standard photometric WET technique has a high duty cycle since the variable star is observed continuously with one channel. The study of main sequence variables requires photometric stability at low frequencies. The extension of the WET technique to low frequencies and its modification are discussed.

Key words: techniques: photometric – stars: δ Scuti variables – stars: individual: FG Vir

1. Introduction

This paper is not intended to be a comprehensive review of main sequence variables, but only a discussion of asteroseismological possibilities of WET. Several recent reviews of the astrophysical properties of main sequence variables can be found in the Proceedings of the IAU Colloquium No. 155, held in 1995 at Cape Town (to be published in the ASP Conference Series). Other excellent references
During the last two decades, the discovery of additional groups of small-amplitude variables has shown that stellar pulsations can be found in almost all regions of the H-R diagram. Due to rapid progress of our knowledge, a complete summary is not possible, but Fig. 1 shows a highly personal collection of different groups of Population I pulsators hotter than the Sun.

We would like to direct the reader’s attention to five groups of pulsators on the main sequence:

(i) Among the B stars, we find the classical β Cephei variables, which pulsate mainly in low-degree p-modes. There are suggestions that these stars also show at least one radial mode.

(ii) The SPB/53 Persei stars are found on the cool side of the β Cephei variables. The long periods indicate that they pulsate with nonradial g-modes. We consider the SPB and 53 Persei type stars to be the same group of variables.

(iii) The δ Scuti variables (see Breger 1995) are pulsators inside the classical instability strip. The periods range from just under 30 min to about 8 h, where both limits are poorly defined. Most photometrically observed modes are nonradial p-modes of low-degree. Spectroscopically, sectorial modes of degree ≥ 2 can also be found (e.g. Kennelly 1995). The variability of the (few) high-amplitude δ Scuti stars with visual amplitudes in excess of 0.30 mag is dominated by the radial fundamental and first overtone modes, similar to the RR Lyrae type stars and cepheids. The vast majority of δ Scuti stars are small-amplitude variables with p-mode pulsation. g-modes exist as well, but with frequencies only slightly lower than those of the p-modes. The presence of (other) g-modes with frequencies as low as those found in the SPB or γ Doradus (see below) variables is still quite controversial and under investigation.

(iv) Among B stars, as the cool border of the β Cephei instability strip in the HR diagram is crossed, a transition from p-mode to g-mode pulsation occurs together with a change in classification from β Cephei to SPB variables. A similar transition can be found among A/F stars as the cool border of the δ Scuti instability strip is crossed. In another paper of this volume, Pawel Moskalik will explain these transitions on the basis of models of pulsational excitation. These cooler g-mode pulsators are the
Fig. 1. A subjective H-R diagram showing the positions of Population I pulsators hotter than the Sun.

Pulsation modes
R = radial  
p = nonradial acoustic  
g = nonradial gravity

Quantum numbers
n = radial  
$l$ = degree  
m = azimuthal
recently discovered \( \gamma \) Doradus variables. Alternate explanations of the observed variability in terms of surface spots became unlikely as three simultaneously present periods of 0.757, 0.733 and 0.678 d were detected in \( \gamma \) Doradus (Balona, Krisciunas & Cousins 1994). The observed period spacing makes a spot model with such large differential rotation unrealistic.

The rapidly oscillating Ap (roAp) stars are also found on and near the main sequence and overlap in luminosity and temperature with \( \delta \) Scuti stars. The two groups, however, are quite distinct in their pulsational behavior. The roAp stars are cool magnetic Ap SrCrEu stars which pulsate in high-overtone, low-degree \( p \)-modes with periods which range from just under 6 min to about 16 min. The pulsations are dominated by strong global magnetic fields. An excellent summary is given by Kurtz (1995).

2. Delta Scuti stars

A large number of multiple periods and the associated small amplitudes in the millimag range make the observational determination of the multiple periods and mode identifications difficult. In order to limit the effects of aliasing, photometric multisite campaigns around the globe have given the most promising answers. Out of more than 350 \( \delta \) Scuti stars discovered so far, less than two dozen nonradially pulsating stars can be regarded as being observed well enough for the multiperiod structure to be regarded as known. Future work should probably concentrate on a few stars with some very large campaigns utilizing telescopes on several continents in order to detect more of the large number of excited pulsation modes.

Figs. 2 and 3 summarize the status of our knowledge of multiple pulsation modes of \( \delta \) Scuti stars and have been updated to August 1995. The criteria for inclusion into the present group are: (1) the number of reliably detected frequencies must be \( \geq 4 \), (2) information of reasonable quality on the basic stellar parameters such as \( T_{\text{eff}} \), \( \log g \) and \( M_V \) must exist, and (3) stars with variable amplitudes were included only when the variability was judged to be intrinsic to the star rather than caused by incomplete multifrequency solutions. For variable amplitudes, an average amplitude was calculated for each frequency. To correct for different stellar radii, the frequency scales for individual stars have been normalized by the value of the pulsation constant, \( Q \). This makes it possible to show the predicted values for the four low-order radial modes. The observationally determined
Fig. 2. Multiple pulsation modes detected for well-studied δ Scuti stars. For each star, the frequency scale has been normalized by the value of the pulsation constant, $Q$. The theoretically computed frequencies for low-order radial modes are shown for comparison.
Fig. 3. Continuation of Fig. 2
Q values are uncertain to about 18% even for stars with excellent $uvby\beta$ values (see Breger 1990a). Consequently, small horizontal shifts are still possible. Most of the stars shown in the diagrams are not radial pulsators. Nevertheless, since the frequency separations between successive radial orders of nonradial modes are similar to those of radial modes, the lines drawn can be an important diagnostic tool for mode identification.

The three $\delta$ Scuti stars with the most frequencies known are FG Vir, CD $-24^\circ 7599$ and BH Psc. FG Vir and CD $-24^\circ 7599$ are previous WET targets. For FG Vir, the 1993 WET campaign allowed the determination of ten frequencies between 106 and 385 $\mu$Hz (Breger et al. 1995). The identification with pulsation models computed by Dziembowski for FG Vir, however, was not unique. The power spectrum of the residuals (after prewhitening of ten frequencies) shows that additional frequencies are excited in FG Vir. Consequently, during March and April of 1995, a large multisite campaign covering more than 600 hours was carried out. The top panel of Fig. 2 shows the 19 frequencies detected so far in a preliminary analysis of part of the photometric data. The new campaign was carried out with the $v$ and $y$ filters, to obtain information on phase shifts. Line-profile analyses are also available, so that mode identifications should be possible.

The data for CD $-24^\circ 7599$ are also preliminary and based on multisite campaigns carried out as follow-ups to a very successful WET campaign (Handler et al. 1995). For BH Psc, the data were taken from a preprint by Mantegazza, Poretti & Bossi (1995). The other stars in the figure have the following references: FM Com (Paparo et al. 1993, Bax, Wehlau & Sharpe 1995), $\theta^2$ Tau (Breger et al. 1989), GX Peg (Michel et al. 1992), BU Cnc (Breger et al. 1993, Belmonte et al. 1994), BN Cnc (Belmonte et al. 1994, Kovacs 1981), UU Ari (Ostermann et al. 1991), 21 Mon (Stobie et al. 1977), AI Vel (Walraven, Walraven & Balona 1992), HD 18878 (Mantegazza & Poretti 1993), HD 224639 (Mantegazza, Poretti & Zerbi 1995), BI CMi (Mantegazza & Poretti 1994), X Cae (Mantegazza & Poretti 1994), 4 CVn (Breger 1990b), 44 Tau (Poretti et al. 1993).

The pulsation modes that can be identified with these observed frequencies of $\delta$ Scuti stars are low-order $p$-modes with values of $n$ from 1 to 7. It can be also seen in the figures that for some stars the detected frequencies are too low to be fit by $p$-modes. It is very tantalizing to explain these in terms of g-modes and the pulsation models, including these modes, have already been calculated by the
Dziembowski group. Probably the most obvious property of the δ Scuti stars is the variety of behavior from star to star, or even in the same star from one decade to the next. At the moment, no relationship between temperature and luminosity has been detected. Also there is a question, which frequencies are excited to a photometrically observable level. The answers may be found by more detailed studies of individual stars such as FG Vir.

### 3. Extending the WET technique to lower frequencies

The WET technique is optimized to study periods shorter than 20 minutes (830 μHz), but the pulsation periods of main-sequence stars hotter than the Sun are usually longer than 30 min. Investigations of such long periods require a photometric stability in the range of 0.1 % over one hour or longer. This creates some difficulties, since one- or two-star photometers usually do not reach this level of stability due to atmospheric changes and detector drifts. Consequently, comparison stars need to be measured. The new WET three-star photometers, which measure the variable star, a close comparison star and the sky background simultaneously with three separate detectors, should eliminate the problems caused by changes of the sky transparency. Extensive tests should determine whether detector drift is still a source of photometric uncertainty. With the new three-star photometers, one problem remains: often it is difficult to find a reliable comparison star of constant brightness in the same (small) field of view.

The long-term stability is the strength of the three-star technique, which has been described by Breger (1993). With this technique, measurements with the same channel and filter are alternated between the variable and two comparison stars, C1 and C2, respectively. This cycling, which takes about 5 minutes, eliminates not only transparency changes of the atmosphere, but also equipment drifts. These drifts can be quite large and are artificially removed during the standard WET reductions. The three-star technique separates intrinsic and observational low-frequency variations.

The difficulty of extending the WET technique to lower frequencies was the subject of a paper by Breger & Handler (1993) presented at the last WET workshop. The photometric stability provided by the three-star technique is not free: the movement of the telescope and the measurement of three different stars lead to a relatively low duty cycle for measurements of the variable star. Furthermore, the
Fig. 4. Reduction of the noise in the power spectrum achieved by increasing the number of observations of a comparison star with the same channel.
required movement of the telescope to a different star every two minutes can cause severe strain to the observer. Consequently, the question of a hybrid technique providing the advantages of both the WET and the three-star techniques becomes important. In our previous analysis it was shown that observing the variable star continuously with a comparison star every hour makes the low-frequency noise lower, but this may be dangerous because atmospheric variations sometimes take place on semi-regular time scales close to one hour.

Here we would like to report the results of an experiment to help answer the following question: how often a comparison star must be observed to reduce the low-frequency noise below a certain limit? Strictly speaking, the results of the experiment pertain only to the 14 clear nights of March 1995 at CTIO. However, the results may also indicate the situation at other observatories. Fig. 4 shows power spectra of HD 105912 observed by Wolfgang Zima. The measurements were obtained through the $y$ filter on the 0.6 m telescope and cover about 30 s every 10 min. Note the low duty cycle for the data, which, however, is sufficient to demonstrate the effect of more frequent observation of a comparison star.

The top panel shows the raw data of HD 105912. Not surprisingly, at low frequencies the power is quite high. However, observing a comparison star once every hour significantly reduces the noise. We note that for frequencies higher than 200 $\mu$Hz, observing a comparison star more often is not really needed, at least for the data used here. The low-frequency noise can be reduced further by observing a comparison star every 30, or even 10 minutes.

This experiment demonstrates the usefulness of observing comparison stars regularly when studying periods in the range of one or more hours, e.g. for $\delta$ Scuti and $\beta$ Cephei stars.

An interesting aspect concerns the very low frequency region around 10 $\mu$Hz (about 1 cycle per day). This region is important for the study of SPB and $\gamma$ Doradus variables. The figure shows for HD 105912 that diligent observations of a single comparison star do not eliminate the noise near 10 $\mu$Hz. Such low-frequency peaks have already been seen in power spectra of some other stars used as comparison stars. Could small-amplitude variations with periods from one to several days be fairly common or such peaks are signs of instrumental and observational errors?

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