DOING RESEARCH WITH SMALL TELESCOPES:

Frequency Analysis of Multiperiodic δ Scuti Stars

E. PORETTI, Osservatorio Astronomico di Brera, Milano, Italy
L. MANTEGAZZA, Università di Pavia, Italy

1. A Preliminary Approach to the Problem

δ Scuti variables (hereafter DSCT variables, following the *General Catalogue of Variable Stars* notation) are a numerous class of pulsating stars located in the lower region of the instability strip; they are Pop. I, A–F main-sequence or giant stars and they are now clearly separated from the Pop. II objects, currently named SX Phe stars. The presence of many non-radial modes simultaneously excited in some of these stars renders them very interesting from the point of view of asteroseismology, making possible in principle to resolve their internal structure. Moreover, most of them have very high apparent luminosities and the task of obtaining the needed data can be achieved in a very economic way by using small-size telescopes. In spite of this, Kurtz (1988) emphasized that multimode DSCT pulsators for which a successful frequency analysis is available are very few and restricted to high amplitude cases (AC And, VZ Cnc, 1 Mon, δ Sct, AI Vel) with the only exception of the small amplitude case of θ^2 Tau; his recommendation was "to obtain complete frequency solutions for as many multimode pulsators as possible". The main reason for this difficulty is the complex mixture of radial and non-radial modes often observed in this class of variable stars: we will meet cases for which six periods are not sufficient to solve the light curve. Moreover, the problem of the stability of the mode amplitudes was recently reviewed with the analyses of datasets spanning several observing seasons.

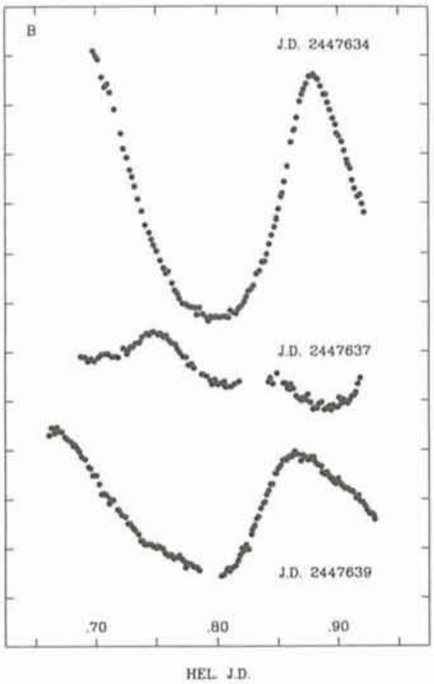

Figure 1: *The light curves of V974 Oph on three close nights: the strong changes in the shape are the largest in amplitude ever observed in a DSCT star. Ticks on the vertical axis are separated by 0.10 mag.*

At Merate Observatory, the study of DSCT stars began in the sixties and spectroscopic and photometric campaigns were continuously undertaken in order to clarify the controversial points. As an obvious extension of the research, the observation of DSCT stars was proposed for telescope-time allocation at ESO, in order to take advantage of the ESO facilities and of the considerably better sky of La Silla. After some observing runs devoted to a search for variability in open clusters, we monitored some faint stars with an amplitude greater than 0.4 mag and classified as DSCT stars. The observations, carried out at the ESO 1-m telescope, were planned to increase the sample of stars for which Fourier parameters are available, but they led us to the unpleasant discovery that a lot of the stars classified as DSCT or SXPHE by the GCVS are actually eclipsing variables (see LeBorgne et al., 1989 for the case of CK Aqr). Remarkable exceptions are KU Cen (Poretti et al., 1990) and V974 Oph (Poretti and Antonello, 1988). Fourier decomposition of high-amplitude DSCT stars opened some interesting questions about further subdivision of their photometric features, as for example the existence of a subclass characterized by light curves with a descending branch steeper than the ascending one. Moreover, the multimode nature of V974 Oph became evident only after a second 7-day observing run at the 1-m telescope, but on that occasion we could not obtain a satisfactory solution because of a bad spectral window. Indeed, the light curve of this star is actually much more complicated than that described in the preliminary analysis (Poretti and Antonello, 1988). This case showed us that a multimode pulsation is also present in very large amplitude stars (V974 Oph reaches an amplitude of 0.5 mag in B-light and Figure 1 shows an example of the dramatic changes occurring over a short time baseline) and the collection of larger and longer datasets became a fixed step in the study of all the DSCT stars.

2. A More Rigorous Approach

All this considered, the study of DSCT stars constitutes a stimulating challenge which requires not only a careful choice of the programme stars, but also the set-up of a powerfull method of frequency analysis, of an error-minimizing observing procedure and the readiness to spend many nights at the telescope.

Table 1: *List of the DSCT stars observed at Merate and ESO. The number of measurements N and the total length of the monitoring are relative to the programme star, while the standard deviation S.D. is relative to its comparison stars.*

Star	Site	Observing period	Nights	N	Survey [hours]	Filter	S.D. [mag]
V356 Aur	Merate	Jan. 1986	6	462	32	B, V	0.0090
HR 1225	ESO	Nov. 1987	7	705	38	b	0.0033
o^1 Eri	ESO	Nov. 1987	7	710	38	b	0.0033
HR 547	ESO	Nov. 1987	8	462	22	b	0.0050
SAO 4710	Merate	Dec. 1988 – Jan. 1989	10	1131	54	B	0.0081
HD 101158	ESO	Apr. 1989	13	1234	62	B	0.0033
V974 Oph	ESO	Apr. 1989	13	1329	64	B	0.0060
X Cae	ESO	Nov. 1989	10	1013	54	V	0.0044
44 Tau	Merate	Dec. 1989 – Feb. 1990	25	2434	117	V	0.0087
BD+2°1867	ESO	Jan. – Feb. 1991	14	1392	100	V	0.0046
BD+2°1867	Merate	Jan. – Feb. 1991	10	708	43	V	0.0094
BD–3°5741	ESO	Sep. – Oct. 1991	20	2649	120	B	0.0044
HD 18878	Merate	Nov. 1991 – Jan. 1992	25	2900	150	V	0.0056

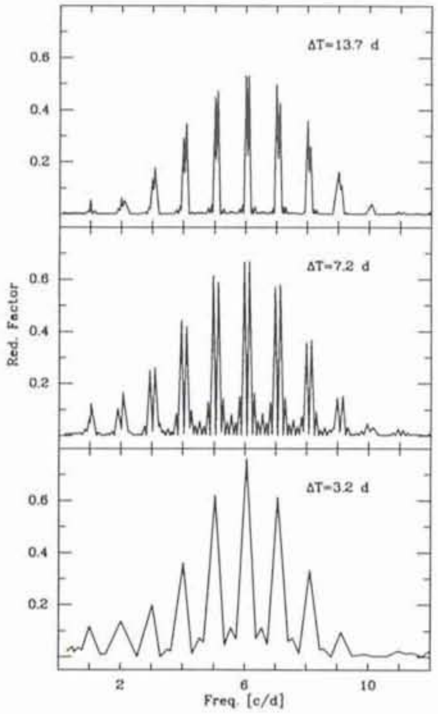

Figure 2: *When dealing with a close doublet of frequencies, an insufficient length of the observing run can lead to an unresolved peak (lower panel) or to wrong identifications (middle panel). The right power spectrum is shown in the upper panel.*

How can the task be tackled? The past schedules indicated that the ESO 50-cm telescope was more suitable than the 1-m telescope for observing runs longer than a week. With respect to the problems described above, the time resolution offered by long observing runs with a very performing instrument such as the ESO 50-cm was an astronomical facility that it would have been silly not to exploit fully.

We therefore put in our observing programme DSCT stars showing cycle-to-cycle variations and, possibly, an amplitude larger than 0.05 mag in order to have a better signal-to-noise ratio. In Table 1 we report the list of DSCT stars observed at Merate and at ESO for which at least a preliminary analysis is available. The measurements were performed in a differential manner, always using two close comparison stars having the same B – V (or b – y) index as the variable: this procedure allows us to minimize the errors introduced by changes in the sky transparency, crucial at the low height above sea level of Merate Observatory, but of some importance also at La Silla. For each variable star, the last column of Table 1 lists the standard deviations observed between the comparison stars. Generally, the measurements obtained in this way are separated by a very short time interval (about 0.002 on the average) and they allow us to reconstruct the light curve in a very faithful way, leaving no ambiguity on the sense of variation or on the reality of small features: this is particularly important in view of the expected complicated light curves. If necessary, uvbyß magnitudes are calculated by observing some standard stars located near the variable star.

A fundamental point is to understand the importance of an adequate resolution in order to perform an accurate frequency analysis. To show it, we generated a synthetic dataset containing a signal which is the sum of two sinewaves with $f_1=6.00$ c/d and $f_2=6.10$ c/d, amplitude 0.020 mag and phase difference of 2.0 rad; no noise was added. The signal was sampled in time in the same manner as the measurements of HD 101158 (see Table 2 in Poretti for further details). Then we performed a frequency analysis on the basis of the whole dataset ($\Delta T=13.7$ d), the first 7 nights ($\Delta T=7.2$ d) and the first 4 nights ($\Delta T=3.2$ d). We used either a Fourier Transform method or a least squares method (for a comparison between the two methods, see Antonello et al., 1986): the results were the same and they are shown in Figure 2, where the least squares power spectra form was preferred. In the upper power spectrum the two peaks are separated and the frequencies (i.e. 6.00 c/d and 6.10 c/d) are exactly identified; in the medium panel the two peaks are separated, but the tops occur at 5.96 c/d and 6.14 c/d, i.e. at wrong values; in the lower power spectrum the two peaks are not resolved and instead one large peak centred at 6.04 c/d is visible. Even if these discrepancies could be predicted by evaluating the interaction of the main peak corresponding to one periodicity with the sidelobes related to the other, they are a demonstration of the conspicuous gain in the handling of data that is achieved by increasing the length of an observing run.

3. Observational Results

For some of the stars listed in Table 1, Figure 3 summarizes the identified frequencies with the respective amplitudes. The frequency spectra of HR 1225 and HR 547 display an abrupt decrease between the first two (HR 1225) or three (HR 547) highest amplitudes to the others, while o^1 Eri represents the most unfavourable case where a rather high amplitude value (0.06 mag)

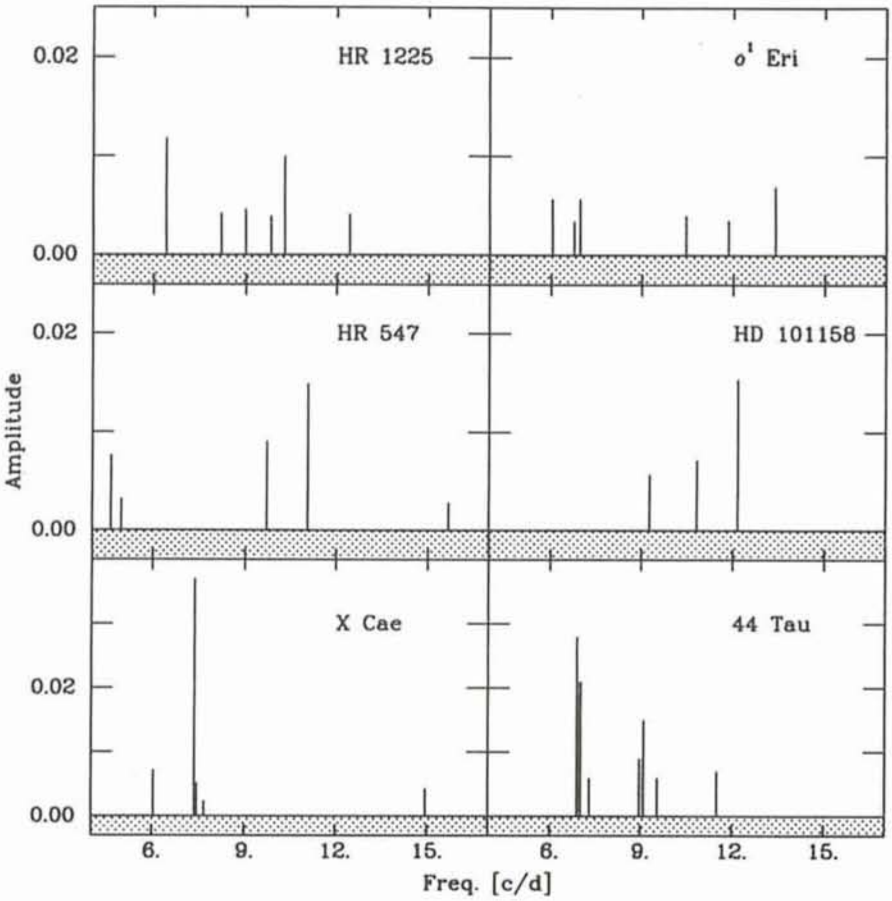

Figure 3: *Graphical description of the frequency identifications in the power spectra of some of the DSCT stars discussed in the text. Note the close doublet frequency near 7.4 c/d in the spectrum of X Cae.*

is the sum of many small-amplitude terms. In all these cases the collected measurements are not sufficient to solve completely the light curve (since at least six frequencies are necessary to reduce the rms residual to the level of the observational error and they cannot be all determined unambiguously), but together with uvbyß photometry they furnish the possibility to discriminate between radial and non-radial pulsation modes (Poretti, 1989). The amplitude spectrum of X Cae is similar to the previous ones: we observe a single dominant frequency and a group of terms with an amplitude from 5 to 15 times smaller. In spite of this, the high-precision measurements allowed us to evidence non-linear coupling terms and possible resonance effects and a satisfactory solution with 8 sine-waves could be proposed (Mantegazza and Poretti, 1992). The non-linear coupling terms are also evidenced in the frequency spectra of BD+2°1867. Thanks to its equatorial position, this star was also observed at Merate Observatory in a double-site simultaneous campaign which allowed us to reduce the aliases at ± 1 c/d and to perform a more accurate analysis. Figure 4 shows one of the longest strings of measurements: the multimode pulsation nature is evident. These objects are a good example of the difficulties inherent in the frequency analysis of DSCT stars. However, it was always possible to search for periodicities down to very small amplitude values and to give a satisfactory picture of the modal content.

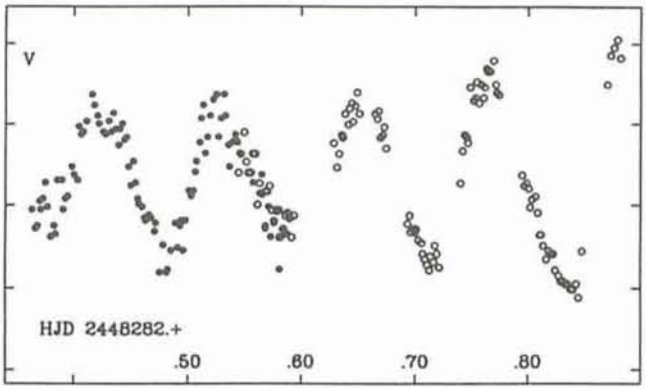

Figure 4: *A light curve of BD + 2°1867. Dots: Merate measurements; open circles: ESO measurements. Ticks on the vertical axis are separated by 0.03 mag.*

Multi-site campaigns are often invoked to solve the most complicated light curves; this is undoubtedly right, but our intensive observations of 44 Tau show that single-site monitorings can be very productive if they take full advantage of the greater availability of telescope time. The light curve solution 44 Tau (Poretti et al., 1992) is important for another reason: if we look at its very rich power spectrum reported in Figure 3, at first sight we can think that it originated from the work of rotational splitting. The presence of the second-order coefficients can destroy the equidistant structure and generate groups of unequally spaced frequencies. 44 Tau is a very slow rotator (v sin i=5 km/s) and our analysis concluded that the seven identified frequencies are independent from each other: we also noted that the two largest amplitude frequencies differ by only 0.11 c/d. Therefore this close doublet and more generally the whole spectrum should be ascribed to physical reasons that are different from rotational splitting.

We must also mention that there are DSCT stars with a much less complicated light curve, such as SAO 4710≡HD 16439, HD 37819 and HD 101158. This type of stars is the most suitable for single-site observations and perhaps for the study of variability in mode amplitudes. The double-mode stars SAO 4710 and HD 37819 were observed at Merate and we note again the presence of a factor of 4–5 between the amplitude of the dominant frequency and the second term. In the light curve of HD 101158 (observed at ESO) three pulsation modes can be identified (Fig. 3). Our solution is different from a previous one reported by Lampens and Rufener (1990), but it fits their measurements satisfactorily. This fact emphasizes the necessity of having light curves with a good coverage at our disposal (as they result from a continuous monitoring during the night described in the previous section) because in this case we can obtain a solution only leaving the uncertainties related to the ± 1 c/d alias problem. The technique of measuring a DSCT star once every 10–15 minutes generates datasets for which many solutions are possible, each giving slightly different rms residuals. From a mathematical point of view, this means that in the least-squares parameter space the objective function has a very smoothed behaviour and many parameter combinations can be picked up with only marginal differences on the goodness of the fit.

4. Implications for the Future

The frequency analysis here summarized can be regarded as pictures of the complicated multimode pulsation of the stars in the lower part of the instability strip. If the variability in mode amplitudes will be confirmed by new observations of other DSCT stars the scenario will be even more complicated. To solve the matter it will be necessary to get well sampled datasets in the future. Therefore, the possibility to do precise photometry with a small telescope on a baseline of 10–15 nights can establish some experimental evidences in agreement with the theoretical requests, as testified by our activity.

For these reasons we look at the ESO policy in the near future with great worry. Even in the case where the "streamlining" of La Silla would not involve a reduction of the efficiency of the ESO facilities, we are not able to find a scientific justification to the strong reduction in the ESO photo-electric instrumentation (after 1996 only the 1-m telescope will be equipped part-time with a photometer; Cristiani 1991). In our opinion, the possibility to obtain a high time-resolution is a requirement in many research fields and it is a facility which should be maintained at the disposal of the scientific community since it is based on the same attitude as the one that, for example, drives technologists to plan sophisticated instruments to improve spatial resolution of data analysts to develop software packages to better extract the signal from the noise.

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