The frequency content of $\delta$ Sct stars as determined by photometry

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Abstract. The results obtained by means of the photometric approach to the study of $\delta$ Sct stars are extensively discussed. The different frequency contents of the three best candidates for asteroseismological studies (FG Vir, 4 CVn and XX Pyx) are presented and compared; the importance of the amplitude variations and of the combination terms is emphasized. The analysis of other multiperiodic variables shows how a large variety of nonradial modes are excited; in some cases, modifications of the power spectrum can be observed over a few years and new modes can be seen to grow. Among monoperiodic pulsators, constant as well as variable amplitudes can be observed. The difficulty of identifying an oscillation yielding quantum numbers is emphasized; the possibilities offered by $\delta$ Sct stars belonging to binary systems and open clusters are discussed. In this respect, combining the photometric and the spectroscopic approaches could lead to a solution. A comparison is also made between low- and high-amplitude pulsators, finding similarities.

The use of a reliable Period–Luminosity–Colour relationships toward the shortest periods can greatly help mode identification in the galactic stars; moreover, it could provide an independent verification of extragalactic distances.

1. Introduction

$\delta$ Sct variables are now a well-defined class of stars. They are located on or just above the zero-age main sequence, in the lowest part of the classical instability strip. $\delta$ Sct stars have masses between 1.5 and 2.5 $M_\odot$ and they are close to the end of the core hydrogen burning phase (Breger & Pamyatnykh 1998). The presence of convective zones and related phenomena such as convective overshooting, make them very interesting objects for the understanding of stellar evolution. The investigation of pulsational properties of pre-main sequence stars allowed their instability strip in the H-R diagram to be defined (Marconi & Palla 1998); some of these stars showing $\delta$ Sct variability were discovered (Kurtz & Muller 1999).

Photometric monitoring is the most practiced approach to study the properties of $\delta$ Sct stars and several stars have been deeply investigated. However, the spectroscopic approach tells us that many modes that are not photometri-
cally detectable are actually excited. Rotation acts as an important factor in the increase of the number of excited modes.

The observed frequencies are between 5 and 35 cd$^{-1}$ and multiperiodicity is very common; only a few stars show a monoperiodic behaviour above the current limit of the detectable amplitude from ground, i.e., $\sim$1 mmag. The observed modes are in the domain of pressure ($p$) modes; there is no observational evidence that gravity ($g$) modes are excited in $\delta$ Sct stars, even if some cases are suggested. At the moment, $g$-modes seem to be present only in the $\gamma$ Dor stars, which in turn do not show $p$-modes.

The great observational effort made by several teams allows us to handle a well-defined phenomenological scenario of the $\delta$ Sct variability. This contribution tries to summarize the results obtained in the past years by means of extended photometric time series. The paper is structured as follows:

2. The best candidates for asteroseismological studies
   2.1 FG Vir: 24 independent modes
   2.2 XX Pyx: strong and rapid amplitude changes
   2.3 4 CVn: presence of combination terms and amplitude variations
   2.4 Comparison between FG Vir, XX Pyx and 4 CVn

3. Other stars studied by the Merate Group
   3.1 44 Tau: variable amplitude and recurrent ratio 0.77
   3.2 BH Psc: variable amplitude and rich pulsational content
   3.3 V663 Cas: growth of new modes
   3.4 The help of the spectroscopic approach

4. Monoperiodic pulsators

5. $\delta$ Sct stars in binary systems

6. $\delta$ Sct stars in open clusters

7. The frequency content of high amplitude $\delta$ Sct stars

8. Summing-up and Conclusions

9. The future: the exportation of the results on galactic stars to extragalactic research

In what manner the photometric results can be used to identify modes (i.e., to classify the oscillation in terms of quantum numbers $n$, $\ell$ and $m$) is discussed by Garrido (2000). Some improvements, both observational and theoretical, are probably necessary to make new, substantial steps forward. A better connection between theory and observation will allow us to really progress in the asteroseismology of these stars.
2. The best candidates for asteroseismological studies

The studies and the related papers on δ Sct stars follow a recurrent paradigm in the process of the determination of the frequency content. In most cases a first solution, often wrongly considered a “good” solution, is obtained on the basis of a few, fragmented nights. At this stage, the observations are hardly useful for a significant analysis. However, since the complicated light behaviour of our stars always leaves some unclear facts, the same authors or another team plan a second run. As a consequence, it appears that the solution proposed in the first paper was indeed preliminary. A very interesting result often obtained while doing this refinement is the detection of variations in amplitude and/or in frequency for the excited modes. Therefore, more observations are requested and, in general, they are never sufficient . . . We can however obtain more and more satisfactory results from the observational works on δ Sct stars by delving deeper and deeper in this process, even if it involves stronger and stronger efforts. The three cases reported below are probably the best examples that the δ Sct community can offer.

2.1. FG Vir: 24 independent modes

FG Vir can be considered a cornerstone in the development of our knowledge of δ Sct stars. After a few nights of observations by López de Coca et al. (1984), it was studied first by Mantegazza, Poretti, & Bossi (1994) on the basis of a single-site campaign carried out at the European Southern Observatory, Chile. These authors proposed seven certain frequencies and a possible eighth one; they also claimed the presence of undetected terms, owing to the relatively high level of noise in some parts of the power spectrum. A successive multisite campaign (Breger et al. 1998) confirmed the seven frequencies, demonstrating how a single site observing run can be successful in the detection of the main components of a multiperiodic pulsator. However, the eighth, small-amplitude frequency was an alias and the misidentification originated from the combination of the spectral window with the noise. A search for the presence of the hitherto previously undetectable terms was undertaken and the number of frequencies increased to at least 24. However, new campaigns on this star are considered necessary to improve the frequency resolution and a time baseline of several months is requested.

The light curves obtained in a multisite campaign look quite fine and they bear witness to the efforts made by the δ Sct researchers to improve the quality and the quantity of the data; Fig. 1 shows the very dense \( v \) and \( y \) light curves obtained on a baseline spanning 20 days, a subset of the 1995 campaign. Considering all the frequencies now known in the light curve, it seems that the pulsation of FG Vir is much more stable than that of XX Pyx and 4 CVn: the amplitude variability is very limited and the frequency values seem to be stable over a baseline of decades. The frequencies are mainly distributed in two subgroups: the first ranges from 9.2 to 11.1 cd\(^{-1}\), the second from 19.2 to 24.2 cd\(^{-1}\). An isolated peak is found at 16.1 cd\(^{-1}\) and a few between 28.1 to 34.1 cd\(^{-1}\). Contrasting with the 22 independent frequencies found, only 2 combination terms have been detected. It should be noted that the identification was accepted at an amplitude S/N limit of 4.0 for an independent term and 3.5 for a combination frequency.
Figure 1. Roughly a half of the $y$ (filled circles) and $v$ (open circles) measurements obtained during the 1995 multisite campaign on FG Vir are shown. The fits of the 24 frequency solutions derived by Breger et al. (1998) are represented as solid curves

Kuschnig et al. (1997) supply a theoretical basis for these assumptions. The combination terms are related to the $f_1$ term, which has an amplitude 5 times larger than the other ones. This term also displays an asymmetric shape, since the $2f_1$ harmonic is also observed ($R_{21} = A_{2f_1}/A_{f_1} = 0.04$).

Photometric measurements are adequate to perform mode identification by means of the phase shifts in different colours. Viskum et al. (1998) and Breger et al. (1999a) agree that the dominant mode can be identified with $\ell=1$ and the 12.15 cd$^{-1}$ mode with the radial fundamental. Considering the sophisticated pulsational modeling proposed by Breger et al. (1999a), FG Vir looks as a very good candidate to match theory and observations.

2.2. XX Pyx: strong and rapid amplitude changes

Our knowledge on XX Pyx has rapidly grown in the last years, following the paradigm described above. Its variability was discovered with the Whole Earth Telescope (Handler et al. 1996) and then the first solution of the light curve (based on 116.7 hours of photometry) was already very good: 7 frequencies between 27.01 and 38.11 cd$^{-1}$ were unambiguously found. However, a second campaign was planned to match the requirements of stellar seismology. Not only was the number of frequencies increased to 13 (Handler et al. 1997), but, as noted above, the possibility of comparing different observing seasons immedi-
Figure 2. The three main pulsation modes of XX Pyx. The rapid variability of their amplitude is detected by subdividing the measurements in different subsets. White histograms indicate upper limit values for the amplitude.

ately evidenced the variability of the amplitudes. The three dominating modes change their photometric amplitude within one month at certain times, while the amplitudes can remain constant at other times (Handler et al. 1998): Fig. 2 shows the behaviour of these modes. The investigation about the nature of these variations considered various hypotheses: oblique pulsator, precession of the pulsational axis, beating of closely spaced frequencies. However, none of them can explain satisfactorily the amplitude changes. It is important to note that no change in the pulse shape of the $f_1$ mode seems to accompany the amplitude variations, while changes are expected in case of frequency beating. In the same way, evolutionary effects, binarity, magnetic field cannot explain period changes.

The distribution of the frequencies is clearly shifted toward high values. A $2f_1$ harmonic term is observed; Handler et al. (1996) suggested the presence of very small combination terms as a representation of nonlinearities originating in the outer part of the star’s envelope, but they are very close to the significance limit.

As a last step, a pulsational model of XX Pyx was undertaken, but a unique solution could not be proposed (Pamyatnykh et al. 1998). The presence of a frequency spacing of $\approx 26 \mu$Hz was used to analyze different possibilities, but the seismic modeling was unable to match the observed frequencies since the mean departures exceed the mean observational frequency by at least one order of magnitude. Unfortunately, this star is very faint ($V=11.5$) and line-profile variations, which could help in the mode identifications, are very difficult to measure with the requested accuracy. An improvement is expected from the results of a new multisite campaign (Arentoft et al. 2000), perpetuating the observational paradigm of $\delta$ Sct stars.
2.3. 4 CVn: presence of combinations terms and amplitude variations

Several campaigns were organized on this bright ($V = 6.1$) star, allowing the determination of a set of reliable frequencies on nine occasions over 30 years. They are mostly free from the 1 cd$^{-1}$ alias problem and are accurate to 0.001 cd$^{-1}$. Breger et al. (1999b) propose a solution of the light curve composed of 18 independent frequencies and 16 combination terms $f_i \pm f_j$; the residual rms is decreased to the level expected for the noise.

The frequency content of 4 CVn is characterized by the grouping of all the 18 independent frequencies in the interval $4.749–8.595$ cd$^{-1}$. In the 1996 campaign, 5 have an amplitude larger than 9 mmag; 5 others have an amplitude between 6.4 and 3.2 mmag. After a single peak at 1.6 mmag, the other terms (also including the combination terms) have an amplitude smaller than 1 mmag. However, the main result of the survey of 4 CVn is the large variability of the amplitude. This is surely not an effect of the noise distribution, since the most relevant changes also occur in the largest amplitude terms. Fig. 3 shows 6 cases of such variations: note the decrease in the amplitude of the 5.05 cd$^{-1}$ term and the corresponding increase in that of the 8.59 cd$^{-1}$ term. Other terms, such as the 6.98 cd$^{-1}$ term, show a more stable value for the amplitude. It is quite impossible to discern a rule in the behaviour of the amplitudes. A complete discussion of the amplitude changes in the light curves of 4 CVn is given by Breger (2000a).

The presence of a large number of combination terms is another important aspect; they flank the set of the independent frequencies. The sums $f_i + f_j$ are more numerous than the differences $f_i - f_j$: this should be a selection effect since the signal at low frequencies is more difficult to detect owing to the presence of a higher level of noise.

The pulsational modes of 4 CVn have also been investigated for the variability of the period: some results have been obtained (Breger & Pamyatnykh 1998), but the matter has to be investigated further, probably considering also the high-amplitude $\delta$ Sct stars (Szeidl 2000). The lack of a well-defined trend in the observed changes is the main difficulty to face when proposing an explanation.

From a methodological point of view, it is important to notice the relevant contribution of the measurements performed by the 0.75 m Automatic Photometric Telescope “Wolfgang” located at Washington Camp in Arizona, USA (Breger & Hiesberger 1999). As a matter of fact, the data are of excellent quality (standard deviation 3 mmag in $B$ and $V$ light), even if a variation in the brightness differences between the two comparison stars (about 2 mmag) was observed. It coincides with the two subsets (each lasting 4 weeks) in which the measurements are separated by a gap of two weeks. According to the authors, the sudden variation is probably a consequence of instrumental problems of the APT and it is not due to the variation of the comparison stars. The solution of this kind of problem can in the future ensure the collection of a large quantity of good-quality data by means of robotic telescopes, a new frontier for the study of $\delta$ Sct stars.
Photometry of δ Sct stars

Figure 3. 4 CVn: the variability of the amplitude is evident for several modes. All the available datasets are shown here.

2.4. Comparison between FG Vir, XX Pyx and 4 CVn

Figure 4 shows the frequency content of the well-studied pulsators described in this section; the combination terms are omitted. At first glance, it also appears that their content is completely different: high frequencies only for XX Pyx, low frequencies only for 4 CVn, two groups of intermediate frequency values for FG Vir. The obvious conclusion is that δ Sct stars are very complicated pulsators and that a general recipe cannot be used to predict their mode excitation.

As regards the similarities between δ Sct stars it should be noted that the frequency content of 4 CVn matches very closely that of HD 2724 (Mantegazza & Poretti 1999): at least 7 frequencies have almost the same value. Among the high-amplitude terms in 4 CVn, only the 5.05 cd$^{-1}$ term has no correspondence in HD 2724. The combination frequencies, very numerous in 4 CVn, are not seen in the light curve of HD 2724. This can be due both to the smaller amplitude of the modes excited in HD 2724 and to the lack of a powerful tool such as a multisite campaign, not yet exploited on HD 2724. The physical parameters of the two stars are very similar, too. So, it seems that we can have the possibility to group stars and not only to observe a different behaviour for every star.
The variations of the amplitudes are a further complication, even if we can argue that the disappearance or the damping of some terms can enhance or make discernible other modes, increasing the number of known frequencies. The cause of the amplitude variability is not clear: it can either be intrinsic or originate from the beating of two close frequencies. Both in the case of XX Pyx and 4 CVn the intrinsic damping is considered by the respective authors as a more satisfactory explanation since the other hypothesis could not match some observations.

3. Other stars studied by the Merate Group

In our effort to reveal the pulsational behaviour of δ Sct stars the Merate group regularly performed some campaigns on selected objects. At the beginning (second half of the eighties) there was no well-studied object and the main goal of our studies was to monitor different variables and try to solve the light curves as satisfactorily as possible. As a matter of fact, the history of the worldwide
photometry of δ Sct stars

observations of FG Vir started with our campaign in 1992 (Mantegazza et al. 1994).

Our contribution to the field was guaranteed by the extensive campaigns carried out in Merate (as a rule one target was observed for several weeks) and at ESO, in both cases using a 0.5-m telescope. Breger (2000b) reports on the list of our campaigns. Here we would like to discuss some interesting cases.

3.1. 44 Tau: variable amplitude and recurrent ratio 0.77

This star has an important place in the development of the studies performed by the Merate group. The intensive survey carried out in 1989 allowed us to verify for the first time the variability of the amplitude of some modes; this fact drove a change in our approach to the study of δ Sct stars. It was realized that a few nights on an object cannot constitute a significant improvement on the knowledge of the pulsational behaviour and therefore the planning of an observational campaign must satisfy critical parameters such as frequency resolution (i.e., a long baseline), alias damping (long nights or, better, multisite observations), evaluation of observational errors and spectral window effects, . . .

Several datasets were available on 44 Tau and a comparison among them led to the detection of amplitude variations (Poretti, Mantegazza, & Riboni 1992). However, this bright star ($V = 5.5$) was considered a good target for other teams also; Akan (1993) and Park & Lee (1995) provided other intensive datasets and the verification of the amplitude variations was an important goal of their studies. Figure 5 summarizes the results: the three papers quoted above supply the three values around 1990. The $6.90 \text{ cd}^{-1}$ term is always the dominant one even if a slight decrease has been observed in the last years, in correspondence with an increase in the amplitude of the $7.01 \text{ cd}^{-1}$ term. Note also the similar behaviour of the $9.12$ and $9.56 \text{ cd}^{-1}$ terms and the stability of the other ones. The general look of Fig. 5 suggests a real variation in the amplitudes rather than the effect of uncertainties in the amplitude determination.

The frequency detected in the light curve of 44 Tau also emphasizes how complicated it is to type the modes. In several old papers the 0.77 ratio between two modes was considered as a clear fingerprint of the pulsation in the fundamental and first overtone radial modes, as happens in high-amplitude δ Sct stars. However, several examples of ratios in the range 0.76-0.78 can be found among the seven terms: 6.90/8.96, 7.01/8.96, 6.90/9.12, 7.01/9.12, 7.30/9.56, 8.96/11.52 . . . As a consequence, it is quite evident that nonradial modes can also show the same ratio even in a small bunch of terms (only seven here) and that trying to find two frequencies showing a 0.77 ratio to type them as radial modes is naive and misleading.

As a final remark, it should be noted that 44 Tau is probably a unique case in the δ Sct scenario owing to the very small $v \sin i$ value, i.e., 4 km s$^{-1}$. In a certain sense, it proves that a multimode pulsation can be found in a slow rotator or in a pole-on star.

3.2. BH Psc: variable amplitude and rich pulsational content

BH Psc was observed by our group in 1989, 1991, 1994 and 1995 at the European Southern Observatory, Chile. The analysis of the first two campaigns showed a very complex light variability resulting from the superposition of more than 10
pulsation modes with frequencies between 5 and 12 cd$^{-1}$ and semi-amplitudes between 17 and 3 mmag (Mantegazza, Poretti, & Zerbi 1995). The fit left a high r.m.s. residual 2.3 times greater than that measured between the two comparison stars. A second photometric campaign was carried out in October and November 1994; we hoped to reveal more terms and to check the stability of their amplitudes. The analysis of the new data allowed us to single out 13 frequencies (Mantegazza, Poretti, & Bossi 1996). They are concentrated in the region 5–11.5 cd$^{-1}$: this distribution is slightly larger than that observed for 4 CVn, but they can be considered very similar. However, more terms should be present, with an amplitude below 3 mmag, since a good 15% of the variance could not be explained with the detected terms and the noise. Moreover, the standard deviation around the mean value was considerably higher in 1991 than in 1994 (26 mmag against 18 mmag); considerations about the amplitudes of the modes confirmed that the pulsation energy in 1994 was lower than in 1991. BH Psc constitutes another example of a δ Sct star showing strong amplitude variations.

Figure 5 shows the fit of the 13-term solution to the $B$ measurements in some nights: undetected terms are the more probable explanations for the sys-
Photometry of δ Sct stars

3.3. V663 Cas: growth of new modes

The solution of the light curve of V663 Cas=HD 16439=SAO 4710 was not an easy task. At the beginning it was considered as a monoperiodic pulsator with \( f_1 = 17.13 \text{ cd}^{-1} \) (Sedano, Rodríguez, & López de Coca 1987), but an observing campaign in the winter of 1988–89 evidenced a second peak at 10.13 \text{ cd}^{-1} \) (Mantegazza & Poretti 1990). The amplitude of this second peak is only 3 mmag, so we considered that this term was not detected by Sedano et al. owing to their limited dataset. The panels in the left column of Fig. 7 show the detection of these terms in the 1988–89 dataset. The analysis of the original data allowed us to identify the \( f_1 \) term (top panel). Then the frequency of this term (but neither its amplitude or its phase) was introduced as a known constituent (k.c.)
Figure 7. V663 Cas: comparison between the power spectra obtained in the analysis of the 1988–89 data (left column) and of the 1994–95 ones (right column). Each spectrum is obtained by considering the terms detected in the previous ones as known constituents (k.c.). The appearance of a new term is clearly visible comparing the two bottom panels.

in the subsequent iteration, in which the $f_2$ term was detected (middle panel). Once more, these two terms were introduced as k.c.’s: in this case no significant third term was revealed (bottom panel).

Still following the paradigm of the study of the δ Sct stars, a second intensive campaign was performed in the winter of 1994–95 (Poretti, Mantegazza, & Bossi 1996). The results of the frequency analysis are shown in the panels of the right column of Fig. 7. After the easy detection of the $f_1$ term (top panel), the second spectrum looks different: the structure at about 10 cd$^{-1}$ is more complex than the one observed in the 1988–89 dataset (to compare the two middle panels). Indeed, after considering the $f_2$ term, a new $f_3$ term was revealed at 10.48 cd$^{-1}$ and the noise around 18 cd$^{-1}$ was higher than in the 1988–89 dataset (bottom panel).

Since the time baseline, the number, and the standard deviation of the measurements are the same for the two observing seasons, this fact cannot be related to a sampling problem. Moreover, the amplitude of the $f_1$ term has slightly decreased from 15.9 to 14.0 mmag in $B$ light. By comparing the two observing seasons we can discern the growth of new modes in the light curve of V663 Cas.
3.4. The help of the spectroscopic approach

It is quite evident that every star carries a brick with which to build our castle of knowledge about δ Sct pulsations, and results on one star have consequences for the analysis of the next one. However, mode identification from photometric data always leaves some uncertainties. For this reason we turned toward spectroscopy: independent constraints on mode typing and detection of low and high degree ℓ modes can be obtained from the analysis of the time series of the individual pixels defining the line profiles. Moreover, trying to fill the gap between the output of the observations and the inputs for a reliable pulsational model, we tried to discriminate between different modes through a direct fit of pulsational model to spectroscopic and photometric data. Such a synergic approach is described by Mantegazza (2000).

4. Monoperiodic pulsators

It is a quite accepted concept that detecting as many frequencies as possible in the light curves is mandatory in order to make progress in the field of asteroseismology. Only in this way is it possible to compare the values predicted by the theoretical models with the observed ones. Consequently, the observation of monoperiodic stars has been put aside in the last decade. However, even these variables display a wide variety of intriguing behaviour.

Beta Cas: It is probably the best known monoperiodic pulsator, also included in the secondary target list of the MONS satellite. Riboni, Poretti, & Galli (1994) proved that a constant value of the frequency cannot fit the times of maximum brightness collected since 1965; on the other hand, a constant value (9.897396 cd$^{-1}$) can fit all the datasets since 1983. Hence, a probable variation of the period occurred between 1965 and 1983. On the other hand, the amplitude has remained stable ($\Delta V = 0.03$ mag) over a 25-year baseline since no significant variation could be inferred. Considering the value of the period (0.101 d), this behaviour is typical for a high-amplitude δ Sct star rather than for a small amplitude one.

AZ CMi: The light curve of AZ CMi is asymmetrical ($R_{21}=0.13$ in $V$ light; Poretti 2000) and very stable in shape and amplitude ($\Delta V=0.055$ mag); hints of a possible decreasing value of the amplitude need more observations to be confirmed. $B$ and $V$ photometry is available: the measured phase shift is $\phi_{B-V} - \phi_V = -9\pm9$ degrees. Since it is negative, such a value slightly suggests a nonradial mode, but the error bar hampers a definite identification (Poretti et al. 1996).

The examples reported above seem to suggest that monoperiodic stars are simple and stable pulsators even if the ambiguity between radial or nonradial modes cannot be solved. However, the analysis of other cases complicates the scenario a little:

BF Phe: All the measurements available on this star are well satisfied by the single term $f=16.0166$ cd$^{-1}$ (Poretti et al. 1996). The reality of a secondary peak was discussed and, at the end, rejected. The amplitude observed in 1991 in $V$ light is very similar to that observed in 1993 in $y$ light. However, in $b$
light the amplitude observed in 1989 (25 mmag) is larger than that observed in 1993 (16 mmag) and this discrepancy cannot be explained by errors in the measurements; unfortunately BF Phe was measured in 1989 in the $b$-light only. Hence, this monoperiodic pulsator shows an amplitude that has changed by a factor of 1.7 in two years, if we consider the amplitude was the same in 1991 and 1993.

28 And: Rodríguez et al. (1993) demonstrated that 28 And=GN And is a monoperiodic pulsator. They carried out a frequency analysis on the datasets available in the literature and when the main frequency is prewhitened the resulting periodograms do not show any trace of another significant peak. New \textit{uvby} photometric data were acquired in 1996 (Rodríguez et al. 1998); the observed amplitude of the light curves is very small compared with any other previous dataset. More precisely, the amplitude was about 19 times smaller than that observed five years before. In this new dataset a second term was detected; however, the reality of this term is not well-established, since it is marginally significant ($S/N=4.1$ and other smaller peaks are visible in the power spectrum). Further observations are requested to verify if 28 And will display a pulsational behaviour similar to that of V663 Cas, with new frequencies slowly growing to a detectable level.

The cases of genuine monoperiodic $\delta$ Sct stars as BF Phe and (probably) 28 And yield the observational evidence that in these pulsators also the amplitudes of the excited modes are affected by variations. Moreover, a multiperiodic pulsator as V663 Cas can show a different pulsational content in different seasons, greatly complicating observational investigation. As a matter of fact we proved that the changing amplitude is not a prerogative of pulsators with a large number of excited modes (as observed in XX Pyx, 4 CVn and 44 Tau). It is also possible to find a $\delta$ Sct pulsator displaying a single period with a very small amplitude: the light curve of HD 19279 has a full amplitude of only 4.2 mmag (Mantegazza & Poretti 1993).

Moreover, the detection of a single frequency in the light curve is not an indication of radial pulsation for $\delta$ Sct stars of low amplitude. Table 1 lists the physical parameters as determined by means of Hipparcos parallaxes and Strömgren photometry: as can be noticed, these stars display a large variety of pulsational constants $Q$’s and, hence, different excited modes.

| Star | HIP   | $T_{\text{eff}}$ [K] | log $g$ | $M_{\text{bol}}$ | $Q$ [d$^{-1}$] |
|------|-------|---------------------|--------|------------------|----------------|
| AZ CMi | 37705 | 7800                | 3.6    | 0.8              | 0.020          |
| BF Phe | 117515 | 7500                | 4.1    | 2.5              | 0.034          |
| 28 And | 2355  | 7500                | 3.7    | 1.4              | 0.018          |
| $\beta$ Cas | 746    | 7000                | 3.6    | 1.2              | 0.020          |
5. δ Sct stars in binary systems

In principle, the study of δ Sct stars belonging to binary systems can supply useful suggestions to understand the physics of the pulsation driving. The complications introduced by the companion are much less important than the measurable parameters we can attain. Lampens & Boffin (2000) provide a review on δ Sct stars in stellar systems. Here we would like to draw attention to a few binary systems:

θ² Tau: It is the component of a wide binary \( P=140.728 \) d and there is no interaction between the two stars. However, it is a well-studied pulsator. Breger et al. (1989) determined five frequencies, very close to each other (from 13.23 to 14.62 cd\(^{-1}\)), without regular spacing among them. Such a very close (much closer than in the case of 4 CVn), isolated multiplet is not usual in the solution of light curves. The amplitudes of the modes seem to be very stable, even if recently Zhiping, Aiying, & Dawei (1997) claimed to have evidence of amplitude variations; further campaigns could be useful to clarify the matter.

θ Tuc: This double line spectroscopic binary is located near the South Celestial Pole, which makes it very suitable for long-term monitoring. The orbital period is 7.1036 d; a regular spacing is observed among the 10 detected frequencies, which take place in the interval 15.8–20.3 cd\(^{-1}\) (Paparó et al. 1996). Low-frequency terms have been observed and they are ascribed to the orbital period. The mode identification was performed by Sterken (1997) using the Strömgren photometry: the results are not conclusive for most of the frequencies, but the \( f=20.28 \) cd\(^{-1}\) is reconcilable with a radial mode. De Mey, Daems, & Sterken (1998) confirmed this result and they also found that the system has a very low mass ratio, \( q=0.09 \). The possibility that the regular spacing is related to the slow rotation of the δ Sct star deserves further attention. De Mey et al. (1998) also found \( 1.7 < R_1 < 2.7 R_\odot \) for the radius \( R_1 \) of the δ Sct star. A rotational period of 7.1036 d is not plausible since it should imply \( 12 < v_1 < 19 \) km s\(^{-1}\) \( v_1 \) sin \( i \). In fact, during the primary eclipse we can see about 20% of the disk of the pulsating star. Unfortunately, the observational uncertainties do not allow one to discriminate between radial and nonradial modes by using the changes in the amplitude caused by the progress of the eclipse. Other considerations suggest a fundamental radial mode.

AB Cas: AB Cas is an eclipsing binary with \( P_{\text{orb}}=1.367 \) d; the primary component is also a monoperiodic pulsator with \( P_{\text{puls}}=0.058 \) d (Fig.8); there is no connection between the two periods (Rodríguez et al. 1998). The light and colour curves are quite normal for this variable: perhaps its main peculiarity is its monoperiodicity. It should be noted that the pulsation period is among the shortest observed in δ Sct stars. The pulsation seems to disappear when the secondary star transits across the disk of the primary: this is due to the large depth of the primary eclipse. However, when the curve due to binarity is removed, the pulsation is visible in the residuals. In fact, during the primary eclipse we can see about 20% of the disk of the pulsating star. Unfortunately, the observational uncertainties do not allow one to discriminate between radial and nonradial modes by using the changes in the amplitude caused by the progress of the eclipse. Other considerations suggest a fundamental radial mode.
Figure 8. The pulsation of the primary component of AB Cas is superimposed on the light curve caused by eclipses

57 Tau: Paparó et al. (2000) indicated 57 Tau as a pulsator showing simultaneously gravity and pressure modes. However, the discovery of its duplicity (Kaye 1999) explains the low-frequency terms as due to the orbital effect \( P_{\text{orb}} = 2.4860 \) d; the first example of a pulsator combining the \( \gamma \) Dor (gravity) and \( \delta \) Sct (pressure) modes has so far not been found. The promising case of BI CMi (Mantegazza & Poretti 1994) is still awaiting closer investigation.

As a concluding remark on this subject, the connection between pulsation and duplicity does not seem to be well-exploited in current research on \( \delta \) Sct stars. It is quite obvious that simultaneous photometry and spectroscopy of a pulsator in an eclipsing system can help mode typing. One of the main difficulties met in the combined use of photometric and spectroscopic data on \( \delta \) Sct stars (the synergic approach described in Sect. 3.4) is to put constraints on the inclination angle. The possibility of determining this angle and the rotational period (as obtained from the orbital solution, assuming synchronous rotation and equatorial orbits) greatly simplifies mode identification by reducing the number of admissible modes. Lampens & Boffin (2000) report on many other candidates to study the connection between duplicity and pulsation.
6. δ Sct stars in open clusters

δ Sct stars belonging to an open cluster offer a very good opportunity to delve deep into the models thanks to the more precise information available on metallicity, distance and age. The common origin of all the stars allows closer comparisons between the results found on each of them. Interesting results were found by Hernández (1998) by analyzing the data collected by the STEPHI observational network on δ Sct stars located in the Praesepe cluster. Unfortunately all these stars are very complicated pulsators and it is very difficult to define a clear picture of their frequency content.

Alvarez et al. (1998) discussed a set of frequencies for two of them, BQ and BW Cnc. In particular, BW Cnc displays two pairs of very close frequencies; inspection of the light curves showed how two close frequencies can disappear or be misidentified in the presence of bad time resolution. These authors recommend long time baselines for campaigns on δ Sct stars, i.e., much longer than 1 week. Also considering the results described below, this requirement has to be considered as mandatory for further works. BQ Cnc is a binary system, but only three frequencies were identified; one of them could be a $g$-mode and further investigations are requested. Interesting results on the Praesepe pulsating stars were also obtained by Arentoft et al. (1998), who successfully used defocussed CCD images. The number of detected frequencies was limited, but the possibility of using the Praesepe metallicity leads the analysis toward deriving reliable physical stellar parameters. Peña et al. (1998) also re-analyzed photometric time series of δ Sct stars in Praesepe proposing mode identifications on the basis of the physical properties of the cluster. Unfortunately, the uncertainties due to the effects of rotation and convective overshooting limit these conclusions somewhat.

The STACC network monitored some northern open clusters (NGC 7245, NGC 7062, NGC 7226, NGC 7654) searching for δ Sct stars (Viskum et al. 1997). As a result, they found that the fraction of these variables is much lower than among field stars and in other open clusters. This observational fact suggests that some parameters are working in the selection of the pulsation excitation and future efforts should be undertaken to discover what they are.

7. The frequency content of high amplitude δ Sct stars

After examining the complex phenomenological scenario of low amplitude δ Sct stars, it is interesting to verify what happens in the domain of the high amplitude δ Sct stars (HADS). Rodríguez et al. (1996) analyzed the multicolour data (Strömgren and Johnson systems) for monoperiodic HADS. The results indicate that all these stars, both Pop. I and Pop. II objects, are fundamental radial pulsators. This conclusion was obtained on the basis of the phase shifts and amplitude ratios between light and colour variations.

Moreover, Rodriguez (1999) analyzed all the reliable photometric datasets of a selected sample of monoperiodic HADS to study the stability of the light curves. In this manner more than 22000 measurements were scrutinized for seven stars (ZZ Mic, EH Lib, BE Lyn, YZ Boo, SZ Lyn, AD CMi, DY Her).
The conclusion was that no significant long-term changes of amplitude occurred for any of these stars.

The impression is that the HADS are very stable fundamental radial pulsators, with a few exceptions represented by double-mode HADS. Can such an idyllic scenario resist the observational effort made in the last few years? It seems it does, since a large homogeneity was found by Morgan, Simet, & Bardenquast (1998) analyzing the HADS contained in the OGLE database. We note here that the subgroup with an anomalous $\phi_{31}$ parameter seems to be an artifact (Poretti, in preparation).

However, we can single out a few interesting cases among the HADS.

**V1162 Ori:** Arentoft & Sterken (2000) discuss the time series collected on V1162 Ori. After a period break and a significant decrease in amplitude (about 50%; Hintz, Joner, & Kim 1998), they also found that the period was no longer valid in early 1998 and that the period changed again during March–April 1998. The latter change was accompanied by an increase in amplitude of the order of 10%; such a phenomenology calls to mind the behaviour of some low-amplitude $\delta$ Sct stars. A new campaign is in progress to clarify the reasons for these changes.

**V974 Oph:** The case of V974 Oph is more intriguing. This faint ($V=11.8$) variable was observed twice at ESO (July 1987 and April 1989). It was first considered a HADS similar to V1719 Cyg (Poretti & Antonello 1988), but the second run clearly demonstrated that it is a multiperiodic star: at least 4 independent frequencies were detected ranging from 5.23 to 6.66 cd$^{-1}$. Three of them have a half-amplitude larger than 0.04 mag; harmonic and combination terms are also observed. The latter result ruled out the simple model of a binary star composed of two HADSs. The strong changes in the shape are the largest observed in the amplitude of a HADS (Poretti 2000). Maybe V974 Oph can be considered as a link between the multiperiodic low amplitude $\delta$ Sct stars and the stable fundamental radial HADS pulsators.

8. **Summing-up and Conclusions**

In our travel through the observational scenario we met many objects which teach us something about the pulsation of $\delta$ Sct stars. The high frequencies shown by XX Pyx, the intermediate frequencies displayed by FG Vir and the low frequencies found in the case of 4 CVn are leading toward the idea that the mode excitation is really complex and unpredictable. In this respect, the close similarity between 4 CVn and HD 2724 is comfortable. Probably the multiperiodic behaviour of the high-amplitude $\delta$ Sct star V974 Oph can also be seen as a simplification of the phenomenology, demonstrating that we can observe a multimode excitation even when a large pulsational energy is involved. To complete the similarities in the opposite direction, we observe monoperiodic pulsators with a very small amplitude (HD 19279 and $\beta$ Cas). What the excited mode is should be investigated in order to understand if a selection effect acts for these low-amplitude monoperiodic stars and what difference there is with a star such as AZ CMi, which displays an asymmetrical light curve.
The amplitude variations are observed in a large variety of stars, both multiperiodic (XX Pyx, 4 CVn, 44 Tau) and monoperiodic (28 And and BF Phe). The observations of mode growth in the light curve of a relatively simple pulsator such as V663 Cas clarifies what can happen in much more complicated ones: some modes can be damped and then re-excited. There are some observational facts which make this explanation preferable even if the model of a beating between two close frequencies with similar, constant amplitude cannot be ruled out. In this context the continuous survey of δ Sct stars which will be performed by space missions could greatly improve the situation; in the case of intrinsic variations, the time-scale of such variations could be determined.

The better focusing of the phenomenological scenario is not the only result. The effort made by the observers in the last years allowed us to detect a large number of frequencies in stars such as FG Vir, XX Pyx, 4 CVn and BH Psc. By means of multisite campaigns we are able to detect terms with amplitudes less than 1 mmag; in these conditions ground-based observations can be successfully complementary to space missions. The mode identification techniques are based on both the phase shifts and amplitude ratios of the light and colour curves and the synergic approach performed by considering spectroscopic curves. Their full exploitation should guarantee an important role for our research in stellar physics.

9. The future: the exportation of the results on galactic stars to extragalactic research

There is always a bit of confusion about the taxonomy of short-period pulsating stars: in the Galaxy they are called δ Sct stars if Pop. I objects and SX Phe stars if Pop. II objects. The old definitions “dwarf Cepheids” or RRs or AI Vel stars are currently avoided in the dedicated literature, but they turn up again in papers on extragalactic researches. However, the definition currently used by stellar researchers, i.e., high-amplitude δ Sct stars (HADS), seems to be irrespective of which Population they belong to and we are coming back to old definitions with new names. Moreover, the phenomenology previously described warns us that the separation between high- and low-amplitude δ Sct stars is not so obvious and that the amplitude cannot be considered a good physical criterion to separate variable stars.

Mateo, Hurley-Keller, & Nemec (1998) reported on the discovery of 20 pulsating stars in the Carina dwarf Spheroidal Galaxy. Their periods range from 0.048 d to 0.077 d and their amplitude is below 0.30 mag in V-light. Poretti (1999) improved the period values first determined by Mateo et al. (1998), obtaining a more clear picture of the Period–Luminosity–Metallicity relationships (Fig. 9).

The observed stars are monoperiodic and their periods are usually shorter than the periods observed in galactic HADS. An extended effort was made to understand the properties of the Fourier parameters of galactic HADS (Morgan et al. 1998), particularly to use them as a mode discriminant. In the case of an external galaxy the approach to the analysis of HADS light curves is the opposite: the Period–Luminosity relationships allow us to separate in a straightforward way the pulsation modes. Then we could have the tool to investigate
Figure 9. The short-period variable stars in the Carina dwarf Spheroidal galaxy. The Period–Luminosity–Metallicity relationships for fundamental mode (lower line) and first overtone (upper line) pulsators are shown together with the frequency values. Dashed lines indicate error bars.

the differences thus driven, always using the Fourier decomposition. In this direction, the results described by Poretti (1999) are quite preliminary, but we can be confident that in the near future we will be able to expand the horizon of HADS studies to extragalactic topics.

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