Cluster Ages Experiment (CASE): SX Phe stars from the globular cluster ω Centauri

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ABSTRACT

We present an analysis and interpretation of oscillation spectra for all 69 SX Phoenicis stars discovered in the field of the cluster. For most of the stars we have reliable absolute magnitudes and colours. Except for one or perhaps two objects, the stars are cluster members. Their pulsational behaviour is very diverse. Multiperiodic variability with at least part of the excited modes being non-radial is most common but there are also many cases of high-amplitude, presumably radial mode, pulsators. In a number of such cases we have evidence for two radial modes being excited. Parameters of radial mode pulsators are in most cases consistent with standard evolutionary models for stars in the mass range 0.9–1.15 M⊙. However, in four cases we have evidence that the masses are significantly lower than expected. Three objects show frequency triplets that may be interpreted in terms of rotational frequency splitting of ℓ = 1 modes. Implied equatorial velocities of rotation are from 10 to over 100 km s⁻¹. Nearly all measured frequencies fall in the ranges predicted for unstable modes. Two cases of low-frequency variability are interpreted as being caused by tidal distortion induced by close companions.

Key words: stars: variables: other – globular clusters: individual: ω Cen.

1 INTRODUCTION

SX Phoenicis stars (SXPS) are Population II short-period pulsators, in most respects similar to much more numerous δ Scuti stars, which are Population I objects. Both types occupy the low-luminosity end of the Cepheid instability strip in the Hertzsprung–Russell (HR) diagram. It is not clear whether there are any systematic differences in pulsation properties between the two types. The incidence of high-amplitude pulsation once seemed much higher among SXPS but now, with improved cluster photometry, many low-amplitude SXPS are being detected (Pych et al. 2001; Kaluzny & Thompson 2003; Mazur, Krzemiński & Thompson 2003; Kaluzny et al. 2004).

What makes SXPS interesting in a wider context is that they are blue straggler stars (BSS) found in a large number in globular and old open clusters. This means that they have an unusual life history which is not well understood as it cannot be explained in terms of the standard single-star evolution scenario. The problem of the BSS origin has been debated for decades. Historically, the first explanation was that the objects are products of evolution of the mass-receiving component in close binary systems (McCrea 1964). Later scenarios involving mergers of main-sequence stars were mostly considered. The scenarios included mergers of primordial binaries after a gradual decrease of the orbit (e.g. Carney et al. 2001) and direct stellar collisions in dense cluster cores (e.g. Lombardi et al. 2002). It is not clear how much imprint of the past evolution should be left in individual BSS. This depends on the efficiency of chemical element and angular momentum mixing – processes still poorly understood in stellar interior physics. Understanding the origin and internal structure of BSS is a challenging task for stellar evolution theory. The answer is of interest not only for this field but also for globular cluster research. As emphasized by Lombardi & Rasio (2002), collisions and mergers of stars which lead to BSS formation, play an important role in the evolution of these systems.

Pulsation data on SXPS are potential sources of accurate constraints on models of BSS. Each measured frequency of an identified oscillation mode is such a constraint. Admittedly, mode identification is difficult unless we have evidence that the excited modes are radial. Double-mode radial pulsators seem quite frequent among
SXPS. The two accurately measured numbers yield strong constraints on stellar mass and heavy element content in the interior. Data on non-radial mode frequencies could be even more interesting. In particular, determination of the frequency splitting provides a certain mean value of the rotation rate in the interior. Furthermore, there are non-radial modes with frequencies that are very sensitive to the extent of the element mixing beyond the convective core boundary. Of great interest in the context of the debated BSS origin is seeking evidence for the presence of close companions manifesting themselves through cyclic period variations or tidally induced variability.

What makes SXPS interesting for stellar pulsation theory is the large diversity of their pulsation forms. In a relatively narrow period range, extending from less than 0.5 h to 2 h, we encounter both the multimode low-amplitude pulsation, typical for main-sequence dwarfs, and the monomode high-amplitude pulsation, typical for Cepheids. According to linear non-adiabatic calculations, there are many unstable modes in SXPS. However, finite-amplitude development of the instability is not understood. This is the most outstanding unsolved problem of the theory. A sample of SXPS with well-constrained mean parameters may provide key information to what makes a star become a dwarf- or a giant-type pulsator.

The globular cluster ω Centauri houses the largest number of SXPS of all systems in our Galaxy (Kaluzny et al. 2004). Having a large number of objects with well-determined luminosities is an obvious advantage. The fact that the stars cannot be assumed to be coeval and of the same chemical composition (Rey et al. 2000) is a complicating factor. The cluster is atypical. Data on SXPS may prove useful in disentangling its evolution.

In the next section we survey observational data on all SXPS in ω Cen which includes frequency analysis. In Section 3 we compare mean photometric parameters of SXPS with the corresponding values calculated for standard evolutionary models. We also provide information on pulsation properties of these models based on a linear non-adiabatic analysis. Section 4 is a star by star analysis of individual objects in which we compare their observational properties with theoretical models. In Section 5 we summarize our results.

2 PHOTOMETRY

ω Centauri contains the most numerous population of variable stars among globular clusters of the Galaxy (Clement et al. 2001). However, until the mid-1990s there was only one SX Phe-type variable known in the field of the cluster. It was V65, which in fact turned out later to be a foreground star. However, not much later Kaluzny et al. (1996, 1997) reported a discovery of 25 SXPS, most of which must be members of the cluster. Subsequent work performed by Kaluzny et al. (2004) increased the number of SXPS in the field of ω Centauri to 69, making it the richest in these variables among all globular clusters of our Galaxy.

Kaluzny et al. (2004) provide extensive photometry for 61 SXPS collected over 2 yr. This photometry contains from 532 to 755 V and over 150 B measurements for each variable. It is an excellent data base for analysing multimode behaviour and extracting information on physical properties of individual objects.

In addition, ω Cen is the first globular cluster for which the CASE project (Thompson et al. 2001) determined the distance. The analysis of photometric and spectroscopic data for an eclipsing binary OGLE GC17 yielded an apparent distance modulus of $(m-M)_V=14.09\pm0.04$ mag (Kaluzny et al. 2002). It is the most precise and reliable distance determination for this cluster and will be used in our work for calculating the absolute magnitudes of SXPS belonging to ω Cen. We will also use the mean colour data dereddened with the colour excess $E(B-V)=0.13$ mag (Schlegel, Finkbeiner & Davis 1998) to place individual objects in the HR diagram.

The full list of SXPS located in the field of ω Centauri containing main periods, amplitudes, mean magnitudes and colours is provided in Table 1. Fig. 1 shows the colour–magnitude diagram around the blue stragglers region of ω Cen. Points and open circles denote constant stars and SXPS, respectively. Not all stars in the SXPS region are variables. This is hardly surprising, as we have the same situation in the δ Scuti domain. Presumably, these apparently constant objects are very low-amplitude pulsators.

3 FREQUENCY ANALYSIS

Many SX Phe stars exhibit multiple periods hence their analysis poses specific challenges. Arguably, the most advanced project in terms of both the extent of its photometry and the multitude of detected periods, the Whole Earth Telescope (WET), employed either the pre-whitening or synthesis methods in their analysis (Kepler 1993). From the statistical point of view the two methods correspond to Gauss–Seidel (GS) and Newton–Raphson (NR) solutions of the least-squares problem (LSQ). On one hand, a current astronomical practice favours the synthesis (NR) method, employing the covariance matrix with large extra-diagonal coefficients. The presence of close frequencies and/or their combinations in the synthesis method yields nearly singular normal equations and may produce large nearly cancelling terms in the solution, creating the $\infty - \infty$ problem and yielding solutions with excess amplitudes. On the other hand, the method recommended to deal with singularity in least-squares fitting is by means of the singular-value decomposition (SVD, e.g. Press et al. 1986). In the SVD procedure the nearly singular terms of the covariance matrix are set small, resulting in the choice of the solution with the minimum norm (minimum amplitudes in the present context). This resembles somewhat the pre-whitening method, where implicitly all extra-diagonal terms are set to zero (Gray & Desikachary 1973). We are unaware of any paper comparing the merits of the pre-whitening and synthesis methods in rigid mathematical (statistical) terms.

We employ the pre-whitening and synthesis methods in parallel to analyse our SX Phe light curves. We employed no more than six harmonics in pre-whitening and in most cases just two or three harmonics for the $f_0$ mode and one harmonic for other modes. The values of (fundamental) frequencies were adjusted by non-linear iterations, their harmonics/combinations were tied to the base frequencies. The resulting frequencies are listed in Table 2. Both methods yielded consistent frequencies for all strong detections, corresponding to the analysis of variance (ANOVA) statistics $\Theta > 15$. We observed no adverse effect such as the reappearance of the frequencies once pre-whitened. Ambiguity, if any, arose occasionally due to aliasing and it manifested with equal strength in both the pre-whitening and synthesis methods. Such cases are marked in Table 2 with a superscript 1.

The novelty in our approach, as compared with WET, is in use of the multiharmonic ANOVA periodogram (Schwarzenberg-Czerny 1996). It employs orthogonal functions and is able to combine power from harmonics ($NH = 2$ harmonics were combined in practice). The importance of the use of orthogonal functions in period searches was argued by Lomb (1976), Ferraz-Mello (1981), Scargle (1982) and Foster (1994). The advantage in combining harmonics is twofold: they contribute extra power for the base frequency and at the same time reduce power in the residuals. Any method sensitive to the harmonics (e.g. phase folding and binning and the present
case of Fourier fitting) is prone to producing subharmonics in the periodogram. The subharmonics pose little problem in practice as they are easily identified by tight packing of aliases. There exist exact relations between the power in the data, the root-mean square (rms) of the residuals and the ANOVA statistics θ employed in the present case (e.g. Schwarzenberg-Czerny 1999). Detection of frequencies poses a special case of hypothesis testing in statistics. In our case the detection criterion θ ≡ θc ≥ 8 roughly corresponded to the mode amplitude exceeding its standard deviation by a factor of 4, A > 4σA. Any frequencies near/below that detection limit are deemed unsable and indicated with a superscript 2 in Table 2. The purpose of listing these marginal detections (15 > θ > 8) is solely to indicate deviations of residuals from pure noise and not to ponder on frequencies.

An example of our results for NV324 is shown in Fig. 2. The panels show ANOVA periodograms (Schwarzenberg-Czerny 1996). The uppermost panel is computed for the original data and reveals the dominant peak with its aliases. The remaining ones are computed for the data after subtraction of all thus far identified frequencies and significant combinations thereof. Fig. 3 shows the light curves of NV324 associated with all six periods found. Each light curve, phased with the particular period, was pre-whitened with the five remaining periods and their harmonics. Note the asymmetry of the three upper light curves, which is typical for pulsating stars. The

| Star | Period | Amp. | \(\langle V \rangle\) | \(B - V\) | \(M_V\) | \(\langle B - V \rangle_0\) |
|------|--------|------|-----------------|----------|--------|-----------------|
| NV294 | 0.01773351 | 0.02 | 17.292 | 0.328 | 3.202 | 0.198 |
| NV295 | 0.01823177 | 0.01 | 17.283 | 0.357 | 3.193 | 0.227 |
| NV296 | 0.02126444 | 0.03 | 16.946 | 0.365 | 2.856 | 0.235 |
| NV297 | 0.0398566 | 0.02 | 16.628 | 0.301 | 2.538 | 0.171 |
| NV298 | 0.0335889 | 0.08 | 17.410 | 0.354 | 3.320 | 0.224 |
| NV299 | 0.0444009 | 0.04 | 17.342 | 0.323 | 3.355 | 0.302 |
| NV300 | 0.037301 | 0.02 | 17.484 | 0.363 | 3.394 | 0.233 |
| NV301 | 0.034434 | 0.07 | 16.974 | 0.439 | 2.844 | 0.309 |
| NV302 | 0.0355192 | 0.04 | 17.081 | 0.349 | 3.265 | 0.219 |
| NV303 | 0.0359503 | 0.01 | 16.932 | 0.322 | 2.842 | 0.192 |
| NV304 | 0.0351405 | 0.03 | 17.236 | 0.421 | 3.146 | 0.291 |
| NV305 | 0.035672 | 0.04 | 17.384 | 0.391 | 3.294 | 0.261 |
| NV306 | 0.0344044 | 0.06 | 17.528 | 0.370 | 3.438 | 0.240 |
| NV307 | 0.035032 | 0.07 | 16.099 | 0.519 | 2.979 | 0.389 |
| NV308 | 0.039852 | 0.05 | 17.278 | 0.382 | 3.188 | 0.252 |
| NV309 | 0.0397455 | 0.04 | 16.591 | 0.362 | 2.501 | 0.232 |
| NV310 | 0.0401776 | 0.02 | 16.791 | 0.415 | 2.701 | 0.285 |
| NV311 | 0.0414132 | – | – | – | – | – |
| NV312 | 0.0433272 | 0.06 | 16.394 | 0.390 | 2.304 | 0.266 |
| NV313 | 0.0418484 | 0.16 | 17.678 | 0.348 | 3.588 | 0.218 |
| NV314 | 0.0412200 | 0.10 | 17.986 | 0.386 | 2.996 | 0.256 |
| NV315 | 0.0428118 | 0.10 | 16.392 | 0.518 | 3.202 | 0.388 |
| NV316 | 0.0424004 | 0.03 | 17.326 | 0.326 | 3.236 | 0.409 |
| NV317 | 0.0426396 | 0.05 | 16.968 | 0.453 | 2.878 | 0.323 |
| NV318 | 0.0437006 | 0.02 | 17.709 | 0.472 | 2.709 | 0.342 |
| NV319 | 0.0489421 | 0.10 | 17.239 | 0.465 | 1.349 | 0.335 |
| NV320 | 0.0471936 | 0.08 | 17.294 | 0.440 | 3.204 | 0.310 |
| NV321 | 0.0474854 | 0.10 | 16.409 | 0.316 | 2.319 | 0.066 |
| NV322 | 0.0479562 | 0.08 | 17.096 | – | 3.006 | – |
| NV323 | 0.0495457 | 0.03 | 16.638 | 0.436 | 2.548 | 0.307 |
Table 2. The frequencies found in the light curves of SX Phe variables in the field of \( \omega \) Cen.

| Star  | \( f_0 \)  | \( f_1 \)  | \( f_2 \)  | \( f_3 \)  | \( f_4 \)  | \( f_5 \)  | \( f_6 \)  |
|-------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| V65   | 15.943(2) | 20.228(1) | 21.218(2) | 24.519(8) | 36.172(8) | –         | –         |
| V194  | 21.196(1) | 27.163(5) | 43.793(9) | 20.747(6) | 22.146(2) | –         | –         |
| V195  | 15.269(2) | 15.274(5) | 15.266(6) | –         | –         | –         | –         |
| V197  | 21.219(2) | 21.390(4) | 21.312(9) | 27.183(8) | –         | –         | –         |
| V198  | 20.754(8) | –         | –         | –         | –         | –         | –         |
| V199  | 16.054(8) | –         | –         | –         | –         | –         | –         |
| V200  | 20.193(5) | 26.530(5) | –         | –         | –         | –         | –         |
| V204  | 20.250(5) | 26.155(5) | –         | –         | –         | –         | –         |
| V217  | 18.775(5) | –         | –         | –         | –         | –         | –         |
| V218  | 22.862(5) | 27.000(6) | 43.686(9) | –         | –         | –         | –         |
| V219  | 25.861(6) | 26.620(8) | 28.253(8) | 3.283(6)  | –         | –         | –         |
| V220  | 18.908(2) | 24.316(5) | 23.845(7) | –         | –         | –         | –         |
| V221  | 27.674(9) | 26.915(3) | 32.884(5) | 27.686(6) | 27.663(9) | –         | –         |
| V222  | 20.560(2) | 26.415(5) | 26.821(6) | –         | –         | –         | –         |
| V223  | 28.614(9) | 24.373(2) | 26.790(6) | 30.974(9) | –         | –         | –         |
| V225  | 26.294(3) | 51.607(3) | –         | –         | –         | –         | –         |
| V226  | 26.678(4) | 27.126(9) | 27.350(7) | 36.696(6) | 30.576(7)| –         | –         |
| V227  | 23.369(1) | 24.116(2) | 15.416(7) | 25.452(8) | –         | –         | –         |
| V228  | 20.250(9) | 26.155(5) | –         | –         | –         | –         | –         |
| V229  | 25.861(6) | 26.620(8) | 28.253(8) | 3.283(6)  | –         | –         | –         |
| V230  | 18.596(3) | 24.316(5) | 23.845(7) | –         | –         | –         | –         |
| V231  | 27.674(9) | 26.915(3) | 32.884(5) | 27.686(6) | 27.663(9) | –         | –         |
| V232  | 20.560(2) | 26.415(5) | 26.821(6) | –         | –         | –         | –         |
| V233  | 28.614(9) | 24.373(2) | 26.790(6) | 30.974(9) | –         | –         | –         |
| V234  | 26.294(3) | 51.607(3) | –         | –         | –         | –         | –         |

<sup>1</sup>Problems with aliasing, <sup>2</sup>close to the detection limit.
window function is a concept associated with the power spectrum. Strictly speaking, it does not apply for the ANOVA periodogram. However, in Fig. 2 numerous window-like structures are present around principal frequencies.

We refrain here from a discussion of amplitudes. On one hand, theoretical results on amplitudes are unreliable (Section 4), but, on the other hand, LSQ fits of multifrequency light curves often suffer from large correlations between parameters, indicating large error ellipses despite small variances. We address this problem only indirectly here by relying in our analysis on a large sample of stars with very extensive coverage of observations. Application of two independent reduction methods benefited us in that we checked against any computation errors and gained insight into the repeatability and reliability of our results.

4 EVOLUTIONARY MODELS AND THEIR OSCILLATION PROPERTIES

Model calculations were made with the Warsaw–New Jersey stellar evolution code which is a modern version of the Paczyński (1970) code developed mainly by M. Kozłowski and R. Sienkiewicz to include new opacity and equation of state (EOS) data,\(^1\) the mean effect of rotation and overshooting. Oscillation properties were calculated with the modernized version of Dziembowski’s (1977) code, which includes the effects of rotation.

Our default hypothesis is that stellar structure is adequately described by standard stellar models, i.e. that there are no imprints of mass exchange or merging in their current structure. When discussing individual objects we ask whether the data are consistent with this hypothesis. The test is possible if we have a plausible identification of at least one peak in the oscillation spectra with a radial mode. If a measured period is found to be longer than that of the fundamental mode in the model consistent with the star position in the HR diagram and this position also excludes driving of g-modes,

\(^1\) Both from the OPAL project (Iglesias & Rogers 1996; Rogers, Swenson & Iglesias 1996, respectively).
then we may suspect that the object has lower mass than is implied by its luminosity.

We consider the interpretation of three close frequencies in terms of rotational splitting of $\ell = 1$ mode frequencies. The self-consistency of the hypothesis is checked by comparing the observed and calculated multiplet structures. The frequency distance between the extreme components is a measure of the mean rotation rate, which is mode-dependent because different modes probe different parts of the star. The consistency test is possible if nearly uniform rotation is assumed. Then we can evaluate the departure from symmetry induced by the higher-order effects of rotation and compare the result with observations.

Even if we cannot identify individual peaks in oscillation spectra, still we can compare the frequency ranges where the peaks occur with the range of unstable modes in the models. This is of interest because the presence of oscillations left of the blue edge may indicate a substantial helium enhancement, which is expected in certain models of BSS formation.

Peaks at frequencies much lower than that of the fundamental radial mode are of our interest too. These could be attributed to high order g-modes. It is now a debated problem whether such modes may be excited in $\delta$ Scuti stars (Handler 1999; Breger et al. 2002; Dupret et al. 2004). An even more interesting possibility is that such peaks represent tidally induced changes (Aerts et al. 2002; Handler et al. 2002).

Fig. 4 shows evolutionary tracks and positions of SXPS from $\omega$ Cen in the colour–magnitude diagram. Tracks were calculated with two sets of the chemical composition parameters ($Z = 0.002$, $X = 0.74$) and ($Z = 0.0002$, $X = 0.75$). The range of $Z$ values is consistent with metal abundances observed among the stars belonging to the cluster (Rey et al. 2000). The range of masses, which is given in the caption, was chosen to cover the range of stellar $B - V$ and $M_V$ values. The tracks were converted from the log $T_{\text{eff}}$–log $L$ to the ($B - V$)–$M_V$ diagram with the use of Kurucz’s (1998) tabular data based on his stellar atmosphere model calculations.

The blue edge was determined by means of our linear stability analysis. In this plot, we chose the first overtone because this mode is most frequently excited in the stars considered. The fundamental mode blue edge is redder by some 0.022 mag in $B - V$ and that of the second overtone is bluer by 0.014 mag relative to that of the first overtone. These lines depend on the mode frequency but not on the degree $\ell$. The adopted red edge is empirical and is based on $\delta$ Scuti data (Rodriguez, López-González & López 2000).

We see in Fig. 4 that the blue edge is sensitive to the assumed metal content. Not surprisingly, the sensitivity to helium content is even stronger. After all, it is helium that does most of the mode driving. Increasing the helium abundance from $Y = 0.25$ to 0.50 causes a blueward shift of the first overtone blue edge by 0.05–0.06 mag.

Note that most of our stars fall within the instability strip. However, there are few objects which are redder than the red edge but admittedly their positions are quite uncertain. It may depend on metallicity. There is only one star (NV321, not shown in the plot) which is far bluer than the blue edge but, as we comment in the next section, its colour is very uncertain. Thus, we see no evidence for a substantial helium enhancement in stellar outer layers.

The period–luminosity (PL) relations calculated for the first overtone along the tracks are shown in Fig. 5. Similar relations for other radial modes are obtained by the shifts given in the caption. The relations depend on the colour and metal content. Thus, application of SXPS as standard candles seems problematical.

We will use the plots shown in Figs 4 and 5 to discuss the parameters of individual objects and their mode identification.

Fig. 6 shows the period ratios for consecutive radial mode pairs as functions of the longer period in the pair (hereafter PRP diagram). The relation for the first two radial modes is known as the Petersen diagram. We may see that, just as in the case of double-mode Cepheids, the $Z$ value is important but the pattern of the period–period ratio relation is more complicated.

![Figure 4](https://example.com/fig4.png)

**Figure 4.** The HR diagram showing evolutionary tracks in the mass range 1.0–1.2 with a 0.05 $M_\odot$ step at $Z = 0.002$ (dashed line) and 0.85–1.05 at $Z = 0.0002$ (solid line). Straight lines show the corresponding positions of the first overtone blue edge. The dotted straight line shows the empirical red edge of the instability strip. The open circle shows stellar values taken from Table 1.

![Figure 5](https://example.com/fig5.png)

**Figure 5.** The theoretical period–luminosity relation for the first overtone pulsation and the same models as in Fig. 4. The one for the fundamental mode is shifted by +0.1 and that for the second overtone by −0.06 in log $P$. Straight lines show corresponding positions of the first overtone blue edge.
5 INDIVIDUAL STARS

For each object, the first question we asked is whether any of the peaks in the frequency spectrum could be identified with any of the radial modes. Stars that have two radial modes excited are of special interest for constraining stellar parameters. With this in mind we first asked whether in our sample we find objects with period ratios that are consistent with the expected values for consecutive radial modes. Fig. 7, which is similar to fig. 5 of Poretti (2003) for the high-amplitude $\delta$ Scuti stars, shows that we have many candidates for two radial mode pulsators. However, since the ranges for each period ratio are rather wide, we cannot use Fig. 7 alone as a tool for a definite mode identification. The width of the band for the specific period ratio arises from the uncertainty in metal abundance, in mass and in the effective temperature. How these parameters affect the period is shown in Fig. 6. Thus, both figures must be used jointly.

The agreement with the model values was regarded as a hint. If none of the period pairs gave a ratio consistent with the values seen in the PRP diagram, we concluded that at most only one peak in the oscillation spectrum may be associated with a radial mode. The case of high-amplitude pulsation was considered as another hint for the radial mode identification. It was then checked using the position of the star in the HR and PL diagrams. If there were no high-amplitude peaks, we checked only whether the frequency of any of the peaks in the power spectrum agreed with any frequency of an unstable radial mode (or its close non-radial neighbour) in the model.

A star by star detailed description and analysis is given in the Appendix.2

The pulsational behaviour of the stars from the analysed sample is very diversified. Multiperiodic variability with at least part of the excited modes being non-radial is most common but there are also many cases of high-amplitude, presumably radial mode, pulsators (for example, V199 or V217). In a number of such cases we have evidence for two radial modes being excited (for example, V194). Three objects (V197, NV309 and NV317) show frequency triplets that may be interpreted in terms of rotational frequency splitting of $\ell = 1$ modes. Implied equatorial velocities of rotation are from 10 to over 100 km s$^{-1}$. Nearly all measured frequencies fall in the ranges predicted for unstable modes. Two cases (V219 and V233) of low-frequency variability are interpreted as being caused by tidal distortion induced by close companions.

6 CONCLUSIONS

In most cases the observed properties of SXPS in $\omega$ Centauri may be explained in terms of standard evolutionary models and their linear non-adiabatic properties. In a number of cases, where the observational evidence pointed to radial mode excitation, we derived the masses of the objects. They all fall into the range 0.90–1.15 M$_\odot$. The implied evolutionary status covers both the main-sequence and early post-main-sequence evolutionary phases.

Only in four cases were the observed parameters inconsistent with the standard models and could be reconciled with the undermassive objects. Such objects could arise in several situations. They can appear as a result of mergers, if there is a mass loss or element mixing. They could also arise as the result of mass exchange in binary systems. This possibility may be contemplated only in the case of very large mass loss on the lower red giant branch. Applicable models would have rather low mass ($\sim 0.2$ M$_\odot$), most of which is
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contained in the helium core. Such models were once considered by Dziembowski & Kozlowski (1974) for high-amplitude \(\delta\) Scti stars, then called Dwarf Cepheids.

We found two cases of stars with long periodicities that may be interpreted as being due to tidally induced distortion. This could be indirect evidence for binarity. Possible implications for the mechanism of BSS formation are interesting. Therefore, the two objects deserve further studies to check the interpretation. This could be performed by searching for induced pulsation period changes (current data do not allow one to reject nor confirm the proposal) or by means of radial velocity measurements.

Our search for rotationally split triplets resulted in three plausible cases. For NV309 the inferred equatorial velocity would be \(\sim 60 \text{ km s}^{-1}\), and for NV317 it would be \(\sim 80\) or \(120 \text{ km s}^{-1}\), depending on the three frequency peaks involved. For V197 the interpretation of all three close peaks as \(\ell = 1\) triplet results in an equatorial rotational velocity of \(\sim 10 \text{ km s}^{-1}\).

We found considerable diversity in pulsational behaviour ranging from that typical for main-sequence \(\delta\) Scti stars characterized by low-amplitude and multimode variability to high-amplitude Cepheid-like monomode pulsations. This is quite amazing bearing in mind the fact that the spread in \(V\) brightness is only approximately 1 mag. To give the picture of the observed diversity, Fig. 8 shows the phased light curves of the monoperiodic pulsators from our sample.

Examples of \(\delta\) Scti-like behaviour are objects such as V219, NV294, NV295 and NV296. These are among the faintest and the hottest stars in our sample. Amongst the faintest objects there are also some relatively high-amplitude pulsators (V198, V249 and NV313) but all of them are suspected of being undermassive.

The star V199, the light curve of which resembles those of Cepheids or RR\(ab\) stars, is amongst the most luminous objects. Other high-amplitude objects are multiperiodic. Among them there are five classical double-mode pulsators i.e. stars with the fundamental and the first overtone excited. These objects were crucial for deriving constrains on masses and metallicities. In three of them we detected additional, apparently non-radial modes. Coexistence of high-amplitude radial modes with low-amplitude non-radial modes was first seen by Walraven, Walraven & Balona (1992) in the \(\delta\) Scti star AI Vel (see also Poretti 2003). In some of our cases the non-radial modes are located close to radial modes in the frequency spectrum but not in all, just as in AI Vel.

Three clean cases of spectra consisting of a dominant peak surrounded by close low-amplitude peaks are V195, V197 and NV321. These are possible analogues of Blazhko RR\(ab\) stars.

Figure 8. Phased light curves of monoperiodic SXPS in \(\omega\) Centauri.

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SUPPLEMENTARY MATERIAL

The following supplementary material is available for this article online.

Appendix A. Individual stars.

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