

LETTER TO THE EDITOR

Double mode RR Lyrae stars in Omega Centauri

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ABSTRACT

Aims. The aim of this work is to search for double mode pulsators among RR Lyr variables of globular cluster ω Cen.
Methods. We conducted a systematic frequency analysis of CASE photometry of ω Cen RR Lyr stars. We searched for periodicities using Fourier and ANOVA periodograms, combined with a consecutive prewhitening technique.
Results. We discovered six double mode pulsators, with the first overtone and a secondary mode of higher frequency simultaneously excited. These are the first double mode RR Lyr stars identified in ω Cen. In variable V10 the period ratio of the two modes is 0.80, which corresponds to pulsations in the first and second radial overtones. In V19 and V105 we found an unexpected period ratio of 0.61. Three other stars display period ratios of either ~ 0.80 or ~ 0.61 , depending on the choice of aliases.
Conclusions. While the period ratio of ~ 0.80 is easy to interpret in terms of the two lowest radial overtones, the value of ~ 0.61 cannot be explained by any two radial modes. Thus, V19 and V105 are the first members of a new class of double mode RR Lyr pulsators.

Key words. stars: oscillations – stars: horizontal-branch – Galaxy: globular clusters: individual: ω Centauri

1. Introduction

The RR Lyr type pulsating stars are one of the most interesting and most important objects in astrophysics, currently representing one of the basic rungs in the “distance ladder”. Since the moment of their discovery it was realized that their light curves were not uniform and could be divided into three classes: a, b and c (Bailey 1902). Later these classes were simplified to two types: RRab (radial pulsations in the fundamental mode) and RRc (radial pulsations in the first overtone).

For the next 75 years it appeared that these were the only forms of pulsations possible in this type of star. However, in the late 1970s and early 1980s it was found that RR Lyr stars can pulsate with both the fundamental mode and the first overtone simultaneously excited (Jerzykiewicz & Wenzel 1977; Cox et al. 1983). Later it was discovered that in addition to radial pulsations, RR Lyr stars can also display non-radial modes of similar periods (Olech et al. 1999). The possibility of pulsations in the second radial overtone was discussed in the literature as well. For example, Alcock et al. (1996) found three maxima in the period distribution of RR Lyr stars in the LMC and proposed that the shortest period maximum corresponds to the second overtone. Cluster RR Lyr stars with nearly sinusoidal, low amplitude light curves and very short periods were interpreted as second overtone pulsators, too (e.g. Walker & Nemeč 1996; Kaluzny et al. 2000). However, the presented evidence was weak, and all these stars could be pulsating in the first overtone after all. Theoretical models actually predict the existence of such short period, low amplitude RRc stars (e.g. Bono et al. 1997).

While in RR Lyr stars there is no conclusive evidence for excitation of the second overtone, such a mode is observed in many Cepheids. In the latter case, unambiguous evidence for single mode second overtone pulsations have been found only recently (Soszyński et al. 2008), but double mode Cepheids with

the first and second overtones simultaneously excited have been known for years (Mantegazza 1983; Alcock et al. 1995).

2. Data and frequency analysis

Omega Centauri (ω Cen) is the largest globular cluster of the Galaxy. It consists of about one million stars, of which almost 500 are known to be variable (Kaluzny et al. 2004; Weldrake et al. 2007). Very accurate *B* and *V* CCD photometry of ω Cen variables has recently been published by the Cluster AgeS Experiment or CASE (Kaluzny et al. 2004). The paper provides high quality photometry of 151 RR Lyr pulsators. The data were collected between February 6/7, 1999 and August 9/10, 2000 and contained from 594 to 761 points per star.

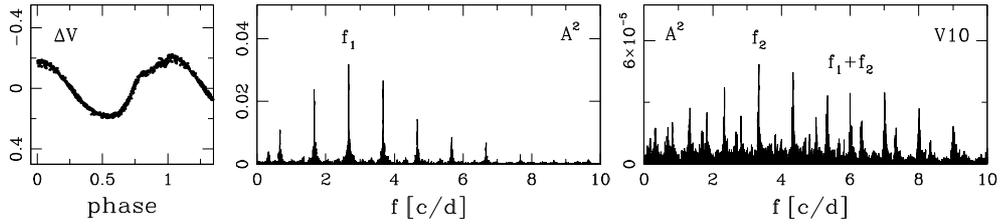
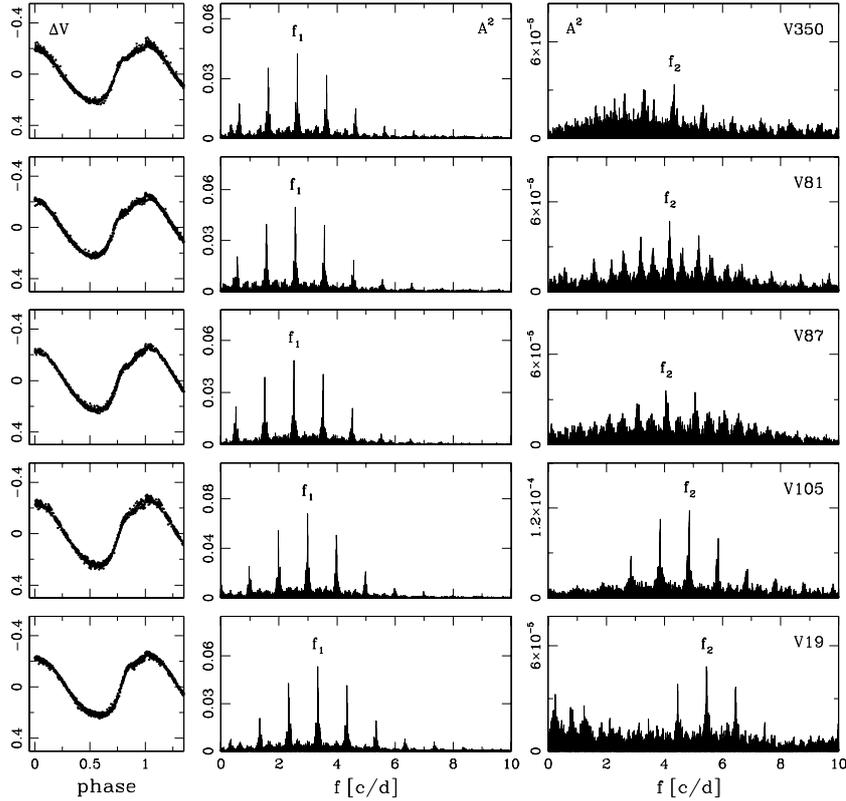
We conducted a systematic frequency analysis of all RR Lyr stars observed by the CASE project. This was done with two different methods. In both cases we used the standard consecutive prewhitening technique (Moskalik et al. 2004). In the first approach, the data were first fitted with the single frequency Fourier sum of the form:

$$m(t) = A_0 + \sum_k A_k \sin(2\pi k f_0 t + \phi_k) \quad (1)$$

where the primary pulsation frequency $f_0 = 1/P_0$ was also optimized in the fitting process. The fit Eq. (1) was then subtracted from the data and the residuals were searched for secondary periodicities. This was done with the Fourier power spectrum computed over the range of 0–10 c/d. If any additional signal was detected, a new Fourier fit with all frequencies identified so far and with their linear combinations was performed. All frequencies were optimized anew. The new fit was subtracted from the original time-series data and the residuals were searched again for additional periodicities. The process was repeated until no new frequencies appeared. At this stage we performed data clipping,

Table 1. Pulsation frequencies of V10, V350, V81, V87, V105 and V19.

Star		P_1 [day]	P_2 [day]	P_2/P_1	A_1 [mag]	A_2 [mag]	σ [mag]
V10	1st sol.	0.3749759(5)	0.299176(9)	0.79785	0.1831(4)	0.0067(4)	0.0071
V10	2nd sol.	0.3749758(5)	0.230126(6)	0.61371	0.1825(5)	0.0064(5)	0.0074
V350	1st sol.	0.3791074(3)	0.230632(5)	0.60836	0.2126(6)	0.0062(6)	0.011
V350	2nd sol.	0.3791077(4)	0.303810(9)	0.80138	0.2117(6)	0.0058(6)	0.011
V350	3rd sol.	0.3749758(5)	0.230126(6)	0.61371	0.1825(5)	0.0064(5)	0.011
V81	1st sol.	0.3893907(3)	0.238990(4)	0.61375	0.2214(5)	0.0072(5)	0.010
V81	2nd sol.	0.3893907(3)	0.314313(7)	0.80719	0.2217(5)	0.0065(6)	0.010
V87	1st sol.	0.3964889(3)	0.246584(4)	0.62192	0.2314(6)	0.0063(5)	0.010
V87	2nd sol.	0.3964884(3)	0.320542(8)	0.80845	0.2322(6)	0.0055(6)	0.010
V105		0.3353278(2)	0.205811(2)	0.61376	0.2465(6)	0.0125(6)	0.010
V19		0.2995510(2)	0.183302(2)	0.61192	0.2279(5)	0.0071(5)	0.010

**Fig. 1.** Double mode RR Lyr variable V10. **a)** light curve phased with the primary period P_1 ; **b)** power spectrum of original light curve; **c)** power spectrum of prewhitened light curve.**Fig. 2.** Same as Fig. 1, but for double mode RR Lyr variables V350, V81, V87, V105 and V19.

by rejecting all measurements deviating from the fit by more than 5σ , where σ is dispersion of the residuals. After removing deviating datapoints, the entire frequency analysis was repeated.

Our second approach differed in the treatment of residuals. We started with the ANOVA periodogram (Schwarzenberg-Czerny 1996) of the raw time-series data and searched it for the peak frequency. The data were then prewhitened with the frequency just identified. Depending on the amplitudes,

we removed up to 15 harmonics of the frequency from the *prewhitened data* of the previous stage. Next, we recomputed the ANOVA periodogram for the residuals and the whole procedure was repeated until no feature exceeding an ANOVA value of 15 appeared.

Both methods yielded the same results within statistical errors. The only discrepancies appeared when a true frequency and its alias had similar amplitudes and the first method preferred

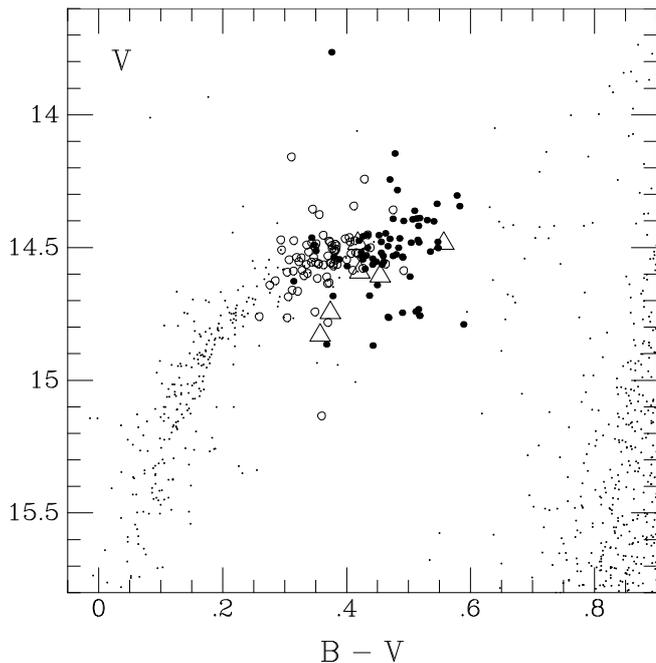


Fig. 3. Color-magnitude diagram for the horizontal branch of ω Cen. Filled and open circles correspond to RRab and RRc star, respectively. Nonvariable stars are displayed with dots. Triangles mark double mode RR Lyrae variables of Table 1

one peak while the second method preferred the other. In such cases we chose the frequency that yielded a fit with lower σ .

3. Results

3.1. Periods and period ratios

In the course of our analysis we identified many RR Lyrae variables with secondary periodicities close to the primary (radial) pulsation frequency. These objects, commonly referred to as Blazhko RR Lyrae stars, are discussed elsewhere (Moskalik & Olech 2008, 2009). In six of the RRc variables we detected multiperiodicity of a different kind – a secondary mode appeared at a frequency much higher than the primary one. These stars are listed in Table 1.

The most interesting case is variable V10. Its primary period of $P_1 = 0.3749759$ days and its light curve are typical for RRc pulsator. Prewhitening led to discovery of the second frequency, corresponding to the period of $P_2 = 0.299176$ days. The resulting period ratio of $P_2/P_1 = 0.79785$ is characteristic of simultaneous pulsation in the first and second overtone (FO/SO double mode variable).

The light curve of V10, its Fourier power spectrum and power spectrum of the prewhitened light curve are shown in Fig. 1. Both f_2 and the combination peak $f_1 + f_2$ are clearly visible. We note that the spectral window is not very good and it is possible that the true secondary frequency is at the 1-day alias of the highest peak. If this is the case, then $P_2 = 0.230126$ days, giving a period ratio of $P_2/P_1 = 0.61371$. This solution is listed in the second line of Table 1. It yields a higher dispersion of the least-square fit, but it cannot be definitely excluded. Nevertheless, the most likely period ratio in V10 is ~ 0.80 , which makes this star a strong candidate to be the first FO/SO double mode pulsator among RR Lyrae variables.

We found five more double mode pulsators with high frequency secondary modes. Their properties are summarized in

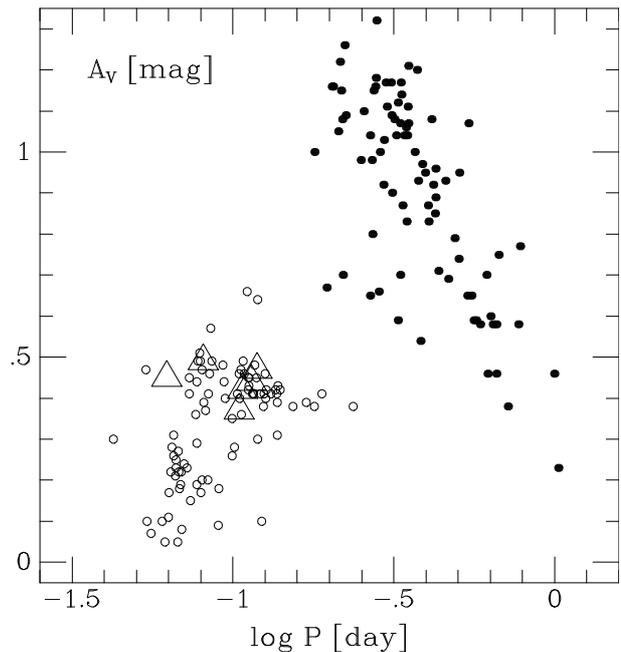


Fig. 4. Period-amplitude diagram for RR Lyrae stars of ω Cen. Same symbols as in Fig. 3

Table 1. In Fig. 2 we display light curves, original power spectra and power spectra of prewhitened light curves of these stars. Judging from the shapes of their light curves, there is no doubt that in all five stars the primary frequency corresponds to the first overtone. There is also no doubt that the secondary frequencies are real. The first three stars: V350, V81 and V87, are similar to V10: they display period ratios of either ~ 0.80 or ~ 0.61 , depending on the choice of the alias. This time, selecting the true alias is not possible, however, because both choices lead to least-square fits of the same quality. We were initially tempted to reject the period ratio of ~ 0.61 as unphysical. As it turned out, this would be unjustified.

The most surprising result was found for the other two double mode pulsators, V105 and V19. For these two variables we derived a period ratio of $P_2/P_1 \sim 0.61$ and it was *the only acceptable possibility*. This puzzling value does not correspond to any two radial modes. Thus, variables V105 and V19 constitute a new type of double mode RR Lyrae pulsator.

3.2. Color-magnitude diagram

Figure 3 presents the $V - (B - V)$ color-magnitude diagram for the horizontal branch of ω Cen. It is worth noting that the RRc and RRab regions overlap significantly. There is a clear scatter in mean V magnitude of the horizontal branch stars, which is most likely caused by differences in their chemical composition. It is known that stars of ω Cen can differ in metallicity by factor of up to 100 (Sollima et al. 2005). Six double mode variables discussed in the previous section are displayed with filled triangles. Because they are strongly dominated by the first overtone, we will compare them with the RRc stars. Five of the double mode variables are located on the cooler side of the RRc region, but without any significant trend or clumping. The clear exception is V350, which seems to be as red as the reddest fundamental mode pulsators. This variable is a new detection made by Kaluzny et al. (2004) with the image subtraction technique. It

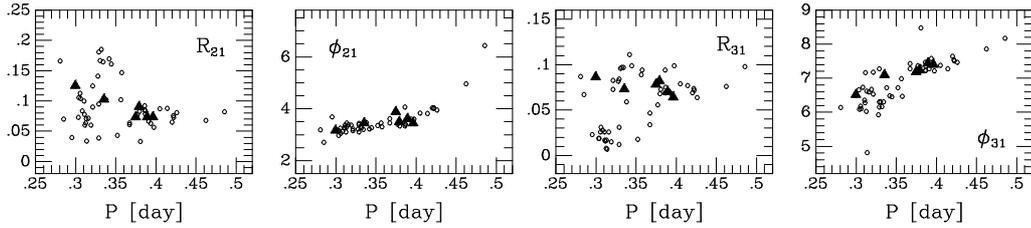


Fig. 5. The amplitude ratios R_{j1} and phase differences ϕ_{j1} vs. first overtone period P for all RRc variables of our sample. Triangles mark double mode pulsators of Table 1.

is located in a very crowded region, where significant blending can affect both the mean magnitude of the star and its color.

3.3. Period-amplitude diagram

Typical period-amplitude diagrams for RR Lyr stars of a globular cluster show a roughly linear trend for RRab stars, with smaller amplitudes at longer periods, and a clump of RRc stars with no clear structure. Some investigators try to divide this clump by amplitude into two subgroups, containing the first and second overtone pulsators, respectively (e.g. Clement & Rowe 2000). This is not well justified, as the shortest period first overtone pulsators can have very small amplitudes as well (Bono et al. 1997).

The period-amplitude diagram for RR Lyr stars of ω Cen is shown in Fig. 4. The double mode pulsators are plotted with filled triangles. All of them are located firmly among RRc variables. We note, however, that they all have high pulsation amplitudes, one of the highest among overtone pulsators.

3.4. Fourier coefficients

Fourier coefficients (amplitudes A_j , amplitude ratios R_{ij} and phase differences ϕ_{ij}) could be used to characterize the shape of the pulsation light curves and to discriminating between different modes of pulsation. We decided to compare Fourier coefficients of our six double mode variables with those of the RRc pulsators. The results are shown in Fig. 5. In all cases, the position of the double mode stars is typical for RRc variables, without any trend or clumping. It confirms the conclusions drawn from visual inspection of the light curves of the variables. They look typical for RRc stars, without any significant peculiarity, indicating that the influence of the secondary mode is weak and this mode does not affect the global shape of the light curve. The only surprising thing is the large pulsation amplitude which was mentioned in the previous paragraph.

4. Conclusions

Systematic frequency analysis of RR Lyr stars of the globular cluster ω Cen resulted in discovery of six RRc variables, which in addition to the dominant first radial overtone, also display a weak secondary mode of higher frequency. These are the first double mode RR Lyr stars identified in this cluster. In variable V10 the most probable period ratio of the two modes is 0.80. This value points towards pulsations in the first and second radial overtones. In three other stars, the period ratios are either ~ 0.80 or ~ 0.61 , depending on the choice of aliases. Finally, in

the last two stars (V19 and V105) an unambiguous period ratio of 0.61 was found. Such a period ratio cannot be explained by two radial modes, which implies that the secondary mode must be nonradial (cf. Moskalik & Kołaczkowski 2009, for discussion of this point). Thus, V19 and V105 belong to a new class of double mode RR Lyr pulsators. We recall that a similar period ratio of ~ 0.61 was also discovered in the LMC first overtone Cepheids (Moskalik & Kołaczkowski 2008; Soszyński et al. 2008) and in the field double mode RR Lyr star AQ Leo (Gruberbauer et al. 2007).

Discovery of RR Lyr stars pulsating in the first and second overtones has been claimed previously in the LMC (Alcock et al. 2000). However, Soszyński et al. (2003) have shown that all these objects are about 1 mag brighter than typical RR Lyr stars in the LMC, and suggested that they might be short-period Cepheids instead. In contrast, all six double mode variables discovered in ω Cen belong to the RR Lyr population of the cluster without any doubt. Thus, V10 is the first reliable candidate FO/SO double mode RR Lyr pulsator.

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