Five colour photometry of the RRd star V372 Ser*

(Research Note)

J. M. Benkő** and S. Barcza

Konkoly Observatory of the Hungarian Academy of Sciences, P.O. Box 67, H-1525 Budapest, Hungary
e-mail: benko@konkoly.hu, barcza@konkoly.hu

Received; accepted

ABSTRACT

Aims. The first $U$-band and new $BV(RI)_C$ photometry of the RRd star V372 Ser is presented to determine some parameters of the star.

Methods. In April, May 2007 2812 $UBVRI$ frames were obtained at Konkoly and Teide Observatories, 1508 $V$ observations were collected from the literature. Fourier fitted light curves have been derived in all bands.

Results. The non-linearly coupled frequencies $f_1 = (2.121840 \pm 0.000001)$ cycles·day$^{-1}$, $f_1 = (2.851188 \pm 0.000001)$ c·d$^{-1}$, i.e. periods $P_0 = 0.4712891 \pm 0.0000002$ days, $P_1 = 0.3507310 \pm 0.0000001$ d, $P_1/P_0 = 0.7441950$, amplitudes $A_{v}^{(0)} = 0.15399$ mag, $A_{v}^{(1)} = 0.20591$ mag, and phases have been found. $A_1/A_0 = 1.319 \pm 0.008$ has been found from averaging the amplitude ratio in the different bands i.e. the first overtone is the dominant pulsation mode. From the $V$ observations upper limits are given for secular change of the Fourier parameters. The period ratio and period put V372 Ser among the RRd stars of the globular clusters M3 and IC 4499, mass, luminosity, and metallicity estimates are given.

Key words. stars: variables; RR Lyr – stars: fundamental parameters: (colours, frequencies, mass, luminosity) – stars: individual: V372 Ser

1. Introduction

Double mode pulsation plays a key role in the mass determination of RR Lyrae (RRL) variable stars because confirmed RRL type component is not known in binary systems. We have indirect methods to determine their mass (Smith 1995): for double mode RRL (RRd) stars the Petersen diagram (Petersen 1973) offers a possibility of most accurate determination. Of course, the derived values depend on theoretical input.

In spite of the importance of RRd stars there are very few observed data of their multicolour photometric behaviour. It is partially due to the moderate number of known stars until the near past: at the moment of this writing we know 30 more or less bright RRd stars ($V < 14$ mag) in the Galactic field discovered by the NSVS and ASAS all-sky variability surveys (Wils et al. 2006; Szczygiel & Fabrycky 2007; Pilecki & Szczygiel 2007; Khruslov 2007). Only two stars (GSC 4868-0831 and V372 Ser) are known with $V < 11.5$ mag. A number of fainter objects were discovered in the Galactic bulge (Mizerksi 2003) and several more in extragalactic systems allowing to draw statistically significant conclusions concerning distribution of the RRd stars in the Petersen diagram, etc (see Clementini et al. 2004 and references therein.)

To review the literature we found that AQ Leo, CU Com, two fainter Galactic, and nine extragalactic RRd stars were studied spectroscopically (Clement et al. 1991; Clementini et al. 2000; Gratton et al. 2004). Multicolour photometric time series are available for CU Com (CCD $BVRI$, Clementini et al. 2000).

Send offprint requests to: S. Barcza

* Photometric data are only available in electronic form at CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/

** Guest observer at Teide Observatory, IAC, Spain

BS Com (CCD $BVRI$, Dékány 2008) and AQ Leo (photoelectric $BV$, Jerzykiewicz & Wenzel 1977; Jerzykiewicz et al. 1982). Some multicolour CCD time series were also published for six globular clusters containing at least one RRd star (IC 4499, M15, M68, M3, NGC 6426, and NGC 2419).

The RRd character of V372 Ser (GSC 5002-0629, $\alpha = 15^h 17^m 35^s 03, \delta = -1^\circ 5^\prime 7^\prime\prime 2$) was discovered a few years ago (Garcia-Melendo et al. 2001). It is the second brightest known field RRd star (Szczygiel & Fabrycky 2007) and it is especially suited for high precision CCD photometric observations because in its vicinity there are comparison and check stars (GSC 5002-0506, GSC 5002-0525, GSC 5002-0566) approximately of the same brightness and colour.

This study presents the first $U$-band as well as new $BV(RI)_C$ time-series data for this RRd star and the fundamental parameters which could be derived from the frequencies. Sect. 2 describes the observations and reductions, Sect. 3 presents the frequency analysis and Fourier fitted colour curves. In Sect. 4 a short discussion is given and the conclusions are drawn.

2. Observations and reduction

2.1. Observations

The observational material of V372 Ser was collected in the spring of 2007 with two telescopes (see Table I for details). The 1-m RCC telescope is mounted at Piskéstető Mountain Station of the Konkoly Observatory. It was used with the UV-enhancement coating Versarray 1300B camera constructed by Princeton Instruments. This device contains a back illuminated EEV CCD36-40 1340×1300 chip that corresponds to a 6.6×6.8 field of view (FOV) with 0′′.303 pixel$^{-1}$ resolution. The camera was driven by QPAsO, a TcI based observing software running

[Note: The rest of the text is not transcribed as it appears to be incomplete or corrupted.]
Table 1. Logbook of the observations of V372 Ser.

| HJD−2 400 000 | No. of frames | quality\(^a\) | Telescope     |
|--------------|---------------|---------------|--------------|
| 54217.3745−5945 | 305           | 2             | RCC          |
| 54220.4249−4670 | 55            | 3             | RCC          |
| 54221.3889−5685 | 250           | 3             | RCC          |
| 54222.3767−5986 | 310           | 2             | RCC          |
| 54223.3726−5865 | 300           | 2             | RCC          |
| 54242.3355−5162 | 202           | 2             | RCC          |
| 54244.3418−3808 | 48            | 3             | RCC          |
| 54245.3971−6290 | 223           | 2             | IAC80        |
| 54245.3915−6535 | 165           | 1             | IAC80        |
| 54249.4283−6746 | 250           | 1             | IAC80        |
| 54250.4068−6728 | 270           | 1             | IAC80        |
| 54251.4152−6580 | 224           | 1             | IAC80        |

\(^a\) Quality of the night is characterized by the extinction coefficient \(k\_V\) in units \(V\text{mag}(\text{airmass})\): 1: stable and \(k\_V < 0.25\), 2: stable and \(0.25 \leq k\_V < 0.5\), 3: \(k\_V > 0.5\) or unstable and \(k\_V > 0.5\) and interruptions because of clouds.

2.3. Transformation into the standard system

The instrumental magnitudes were transformed into the \(UBV(RI)C\) Johnson-Cousins system. The standard sequence published by Landolt (1973) was used as a source of standard magnitudes. Our standard \(UBV(RI)C\) magnitudes for stars A, B, C were determined on the nights HJD−2 454 200−23 and 48. Within the error our values were identical to those of García-Melendo et al. (2001), therefore, we used the weighted mean (giving half weight to our measurements of 2 454 223).

Table 2 gives our accepted magnitudes and colour indices. Each night colour differences \(u_A - u_B\), ..., \(b_A - b_B\), ..., were determined from all frames and correlated with \(U_A - U_B\), ..., \(B_A - B_B\), ..., where \(u, b, ...\) are the instrumental magnitudes of stars A, B, C. Since almost perfect linear relations and random scatter were found the magnitude differences of V372 Ser were transformed to the standard \(UBV(RI)C\) magnitudes by the formulae

\[
U = U_A + 1.016(u_A - u_B) + 0.012, \\
B = B_A + 1.018(b_A - b_B) + 0.011, \\
V = V_A + 1.005(V_A - V_B) + 0.001, \\
R_C = R_{C_A} + 1.001(r_A - r_B) + 0.002, \\
I_C = I_{C_A} + 0.981(i_A - i_B) + 0.013,
\]

where the asterisk indicates V372 Ser. Between HJD−2 454 245−0.3971−5280 we have simultaneous observations with the telescopes RCC and IAC80. Zero point corrections -0.043, -0.025, -0.034, -0.019, +0.004 were added to the RCC \(U, B, V, (R, I)C\) magnitudes in order to obtain congruence of the RCC and IAC80 light curves.

The typical errors of individual observations were between 0.01–0.02 mag in \(B, V, (R, I)C\) and 0.03 mag in \(U\).

The construction of our observational database is simple: the file includes the heliocentric Julian date (HJD) and magnitudes in the Johnson-Cousins reference \(U, B, V, R_C, I_C\), respectively. In the last column of the table a quality flag is given, it indicates the 13 frames as well which were excluded from the analysis because of bad atmospheric conditions (e.g. sudden transparency loss exceeding 1.5 mag).

3. Analysis of the light curves

3.1. Pulsation frequencies

We performed standard Fourier frequency analysis on our time series data using the facilities of the program package MuFrAn (Kollath 1990). The frequencies of the fundamental and first overtone modes \((f_0 = 2.121841 \text{ d}^{-1}, f_1 = 2.851189 \text{ d}^{-1})\) and their ±1, ±2, ... daily aliases were clearly observed. With the first approximation of these two frequencies and some harmonics a simultaneous nonlinear fit was carried out. Then the light curves were whitened out by subtracting the result of the fit. The Fourier spectra of the residual light curves contain strong peaks which can be identified with the coupling term \(f_0 + f_1\) and its aliases. Their appearance is an unambiguous signal of strong nonlinear coupling in the stellar pulsation. In order to identify further frequency components, a successive prewhitening procedure was performed. The subsequently found frequencies were fitted simultaneously with all previously identified ones and their overall contribution was subtracted from the original data set. This iterative method increases the signal detection probability by eliminating the strong alias structure in the vicinity of a frequency

\(^1\) The 0.82m IAC80 Telescope is operated on the island Tenerife by the Instituto de Astrofisica de Canarias in the Spanish Observatorio del Teide

\(^2\) IRAF is distributed by the NOAO, operated by the Association of Universities for Research in Astronomy Inc., under contract with the NSF

\(^3\) Available also at the webpage http://www.konkoly.hu/staff/benko/pub.html
To determine the final set of frequencies we investigated the CCD $V$ data set observed in the years 1997-1998 by Garcia-Melendo et al. (2001). Performing the above described frequency search we obtained a Fourier solution with 12 elements of very similar parameters to our previous ones, both for the frequencies ($f_0 = 2.12250$ d$^{-1}$, $f_1 = 2.85083$ d$^{-1}$) and the amplitudes. Differences between periods are 3.78 and 12.64 seconds for $f_0$ and $f_1$, respectively: the frequency content of the light variations seems to be unchanged within the last ten years. To verify this conjecture we tried to make a common fit of all the available $V$ data. We remark that because of the lack of data for 10 years to unify and handle the two data sets in a common Fourier analysis is not practical due to the very unfavourable references between periods are 3.78 and 12.64 seconds for $f_0$ and $f_1$, respectively: the frequency content of the light variations seems to be unchanged within the last ten years. To verify this conjecture we tried to make a common fit of all the available $V$ data. We remark that because of the lack of data for 10 years to unify and handle the two data sets in a common Fourier analysis is not practical due to the very unfavourable window function. None of the further determined Fourier parameters (frequencies, amplitudes and phase) based only either of data sets gave us an acceptable fit for the unified data. Therefore,
we refined the frequency analysis by a successive approximation on the combined data, where the residuals of the non-linear fit were minimized while the structure of the decomposition (number of harmonics and linear combinations) was fixed and the two frequencies were independently changed in their limiting intervals. As a result of this process we could fit the total light curve at the frequencies $f_0 = 2.121840 \text{ d}^{-1}$, $f_1 = 2.851188 \text{ d}^{-1}$ with the rms accuracy of 0.014 mag.

Since the frequencies were found to be stable we can employ the spectrum averaging method (SAM) as implemented by Nagy & Kovács (2006) to find additional peaks which remained hidden in the individual spectra. The two spectra were added weighted inversely with their variances. The morphology of the summed spectrum confirmed again that the frequencies were really constant within their errors. We subtracted non-linear fit of the accurate frequencies and their harmonics from both light curves separately, then the Fourier spectra of residuals were summed again to find the next frequency and so on. At the end of this process we achieved a spectrum without any significant additional peaks at 6σ level (for the definition of significance level of a peak see Alcock et al. 2000). Our conclusion is that additional signal has not been found: the Fourier decomposition of our data revealed all significant frequencies.

### 3.2. Fourier amplitudes and phase

Using the obtained frequencies, their harmonics and linear combinations non-linear fits were computed determining amplitudes and phase for all bands. We assumed the light curves $m(t)$ in the form

$$m(t) = A_0 + \sum_{jk} A_{jk} \sin[2\pi j t + \phi_{jk}],$$

where $c = U, B, V, R_C, I_C$, $v_{jk} = jf_0 + kf_1$, $j,k = 0, \pm 1, \pm 2, \ldots$, and the epoch of an arbitrarily chosen phase was $t_0 = 2450539$. The results are given in Table 3. These parameters allowed us to construct synthetic light curves. As an example the synthetic and observed V light curves are shown in Fig. 1. The residual rms scatters of the fits are 0.012, 0.015, 0.015, 0.018 for $B, V, R_C, I_C$ bands, respectively, and it is 0.028 for $U$. These values of scatter are compatible with the observational accuracy. For the unified $V$ filter data (García-Melendo et al. [2001] and ours) we also found a fit with rms=0.014, similar amplitudes, and phase as given in Table 3. It indicates, that on 10 years scale not only frequencies and amplitudes were stable but phase as well. Folded $V$ light curves are given in Fig 2.

The amplitudes of all detected frequencies increase towards shorter wavelengths and the amplitudes of the linear combination frequency components are smaller than those of their constituent frequencies. All of the detected coupling terms are at positive linear combination frequencies of the modes except for $f_0 - f_1$. This seems to be in agreement with model results of Antonello & Aikawa (1998). According to their non-linear transient double-mode Cepheid models, frequency terms of positive linear combinations have always larger amplitudes than those of negative linear combination.

To estimate the accuracy of the parameters in Table 3 Monte Carlo simulations were carried out. 1000 artificial time series were constructed for data in each band with the help of the determined Fourier parameters, Gaussian noise and sampling according to the real observations. The epochs of the beginning of data sampling were randomly chosen for the first trial then they were shifted by 0.01 day for each subsequently produced synthetic time series. As it was stressed by Benkő et al. (2006) this is important for the interpretation of possible amplitude variations such as mode changes. The accuracies were found to be between 0.0025 and 0.0007 mag for all amplitudes. The highest errors are for the filter $U$ data and the smallest ones are for filters $R_C$ and $I_C$. Typical errors of the phase are between 0.01 and 0.004 radians for the two main frequencies.

### 4. Discussion and conclusions

Table 4 summarizes the relevant data of V372 Ser derived from our Fourier analysis. The average of the amplitude ratios

$$A_{0.51}^{\text{obs}} / A_{1.0}^{\text{obs}} = 1.319 \pm 0.008, m = U, B, V, R_C, I_C$$

shows that the amplitude ratio is independent of colours at 3σ level.

From the point of view of frequencies and amplitudes V372 Ser is a double mode RR Lyrae star: the period ratio 0.7441951 is in the canonical range given by non-linear theoretical values expected for RR Lyrae stars (Cox et al. 1983). The first overtone is the dominant mode. In different bands identical frequency content has been found: the atmosphere is grey from the point of view of transmitting pulsation frequencies.

The magnitude-averaged colour indices obtained by fitting the date with Eq. (2) are given in Table 5; they differ slightly from those of García-Melendo et al. (2001): $(B-V) = 0.38, (V-R_C) = 0.26$, except for $(V-I_C) = 0.57$. We attribute this differ-
Table 4. Summary of the relevant data of V372 Ser.

| $P_1$(days) | 0.3507310 ± 0.0000001 |
| $P_1$(hours) | 0.4712891 ± 0.0000002 |
| $P_1/P_0$ | 0.7441950 |
| $(V) = A(0)$ | 11.264 |
| $(U - B) = A(B) - A(0)$ | -0.026 |
| $(B - V) = A(B) - A(0)$ | 0.411 |
| $(V - R_C) = A(0) - A(0)$ | 0.233 |
| $(V - I_C) = A(0) - A(0)$ | 0.443 |
| $A(0)$ | 20.059 |
| $A(0)$ | 15.34 |
| $A(0)/A(0)$ | 1.326 |
| $A(0)/A(0)$ | 1.377 |
| $A(0)/A(0)$ | 1.299 |
| $A(0)/A(0)$ | 1.318 |

gives $M = 0.65 M_\odot$ and luminosity $\log L \approx 1.72$. Turbulent convection and more sophisticated hydrodynamic treatment are added to the above model assumptions in Szabó et al. (2004). Interpolation in their diagrams and tables gives $|M| \approx -1.7$, $M > 0.7 M_\odot$ and $\log L \approx 1.60$.

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Fig. 3. Observed $U$ light curves of a medium, large, and small ascending branch.

ence to their much smaller sampling of the $B, R_C, I_C$ bands and to a possible misprint in their $R_C - I_C = 0.29$ instead of 0.19. V372 Ser has reddish colours even if they are dereddened by $(U - B)$, both are moderately metal deficient globular clusters approximately equal to those of the RRd stars of M3 and IC 4499, both are moderately metal deficient globular clusters ($|M| = -1.57, -1.50$, respectively). Interpolating $P_1/P_0, P_0$ in the Petersen diagram of Bono et al. (1996) (derived from nonlinear, non-local, time dependent models with the new opacities)