V470 Cas and GSC 2901-00089, Two New Double-mode Cepheids

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Abstract We present a photometric study of two new double-mode Cepheids, pulsating in the first and second overtones modes: V470 Cas and GSC 2901-00089. For the search of the double-mode variability, we used all available observations from the ROTSE-I/NSVS and SuperWASP online public archives. Our multicolour CCD observations in the $B$, $V$ and $R$ bands in Johnson’s system confirm the double periodicity of these variables. We study period variations of the two stars; variations of the first overtone periods were reliably detected. In addition, we consider the Petersen diagram for the Galactic 1O/2O Cepheids.

Key words: techniques: photometric — stars: variables: Cepheids — stars: individual: V470 Cas, GSC 2901-00089

1 INTRODUCTION

Classical Cepheid are radially pulsating periodic variable stars. Pulsations of single-period Cepheids occur in the fundamental mode (F) or in the first overtone mode (1O). In addition, several examples of possible second overtone (2O) Cepheids are known. The double-mode Cepheids (or beat Cepheids) pulsate simultaneously in two radial pulsation modes: in the fundamental mode and in the first overtone mode (F/1O) or in the first and second overtone mode (1O/2O). The period ratio is a good indicator of the excited modes. Characteristic period ratios are $0.69 < P_1/P_0 < 0.73$ and $P_2/P_1 = 0.80$. The mass of the Cepheid can be derived using the two pulsation periods only. The first results based on the linear theory of stellar pulsations were obtained by Petersen (1973). For recent results of non-linear modelling of double-mode Cepheids, see Smolec & Moskalik (2010).

Double-mode Cepheids are known for more than half a century. Oosterhoff (1957) was the first to detect a group of $\delta$ Cephei variable stars with a large scatter in their photoelectric phased light curves, because of superposition of two oscillations. Later, double periodicity oscillations in the fundamental mode and first overtone were confirmed for most of these stars. To date, a little more than 30 F/1O Cepheids are known.
The first Cepheid pulsating in the first and second overtones was discovered by Mantegazza (1983). It was CO Aur, which long remained the only 1O/2O Cepheid. The next variables of this type in our Galaxy were V1048 Cen (Beltrame & Poretti 2002), V767 Sgr and V363 Cas (Hajdu et al. 2009).

In 2009–2012, 12 new 1O/2O Cepheids were detected by one of the authors (Khruslov 2009a, 2009b, 2010a, 2010b, 2012) from data of the ASAS-3 and NSVS surveys. Of these, three short-period variables (GSC 6567-01616, TYC 0717 01091 1, and GSC 6558-01290) were originally classified as double-mode RR Lyrae stars. Later, we changed the classification of these three stars due to their small galactic latitude (respectively $b = +3^\circ.0$, $-6^\circ.2$, and $+2^\circ.0$). 1O/2O RR Lyrae stars at large distances from the Galactic plane are not known, so we consider these stars along with 1O/2O Cepheids. Other examples of such stars are V1719 Cyg, considered an RRC variable in the GCVS according to Mantegazza & Poretti (1986) ($P_1 = 0.2673$ days, $P_2/P_1 = 0.7998$, $b = +2^\circ.6$), and V798 Cyg, a double-mode HADS star according to Musazzi et al. (1998) ($P_1 = 0.1948$ days, $P_2/P_1 = 0.8010$, $b = +4^\circ.6$).

The OGLE-III project discovered seven more 1O/2O Cepheids near the galactic center (Soszynski et al. 2011a, 2011b; Pietrukowicz et al. 2013); three of them also have very short periods in the $0^d.24 - 0^d.29$ range. In addition, Khruslov (2013) reported a possible first and second overtone double periodicity of MS Mus and TYC 8308 02055 1.

According to the OGLE-III survey, double-mode Cepheids are well represented in the Large (LMC) and Small (SMC) Magellanic Clouds: in the LMC, there are 61 F/1O and 203 1O/2O Cepheids; in the SMC, there are 59 F/1O and 215 1O/2O Cepheids (Soszynski et al. 2008b, 2010).

Also, two triple-mode stars with periods in the Cepheid range are known in the Galaxy: AC And (Florya 1937, Fitch & Szeidl 1976) and V823 Cas (Antipin 1997); they show F/1O/2O pulsations. In the Magellanic Clouds, several triple-mode Cepheids are known (Soszynski et al. 2008a, 2010).

In this paper, we present a photometric study of two new double-mode Cepheids, pulsating in the first and second overtone modes: V470 Cas and GSC 2901-00089.

2 OBSERVATIONS AND DATA REDUCTION

To search for double-mode variability, we used all available observations from the ROTSE-I/NSVS (Wozniak et al. 2004) [http://skydot.lanl.gov/nsvs] and SuperWASP (Butters et al. 2010) [http://wasp.cert-scinform.com] online public archives. The SuperWASP observations are available as FITS tables, which were converted into ASCII tables using the OMC2ASCII program as described by Sokolovsky (2007); we also used the SuperWASP FITS to ASCII lightcurve conversion service ([http://scan.sai.msu.ru/swasp_converter]). We reliably classified GSC 2901-00089 as a 1O/2O Cepheid and reported preliminary results in Khruslov (2013). Possible double-mode variability of V470 Cas was suspected by us using ROTSE-I/NSVS and SuperWASP data.
Table 1  Comparison and check stars.

| Variable | V470 Cas | GSC 2901–00089 |
|----------|----------|-----------------|
| Comparison star | | |
| Name | GSC 3678–00722 | GSC 2901–00493 |
| Coordinates, J2000.0 | 01h32m12.75 +56°30′40″.0 | 04h45m06.34 +42°57′50″.9 |
| $V$ mag | 13.937 | 12.827 |
| $B$ mag | 14.755 | 13.326 |

| Check star | | |
| Name | GSC 3678–01408 | USNO-B1.0 1329–0132855 |
| Coordinates, J2000.0 | 01h31m51.71 +56°27′53″.6 | 04h44m59′.64 +42°57′25″.5 |

To confirm the double-mode variability of these stars, we started multicolor CCD observations in 2013. Our CCD observations in the Johnson $B$, $V$ and $R$ bands were performed at the Tien Shan Astronomical Observatory of the V.G. Fesenkov Astrophysical Institute, at the altitude of 2750 m above the sea level. The observatory has two Zeiss 1000-mm telescopes. Most of our observations were performed with the eastern Zeiss 1000-mm reflector (the focal length of the system was $f = 13380$ mm before JD 2456500 and 6650 mm after this date; the detector was an Apogee U9000 D9 CCD camera; the chip was cooled to $-40^\circ$ C). The time interval of the observations for GSC 2901–00089 is JD 2456364–2456963 (March 12, 2013 – November 1, 2014); for V470 Cas, it is JD 2456575–2456964 (October 9, 2013 – November 2, 2014). Additionally, for observations of V470 Cas during two nights (JD 2456899 and 2456959), we used the newly introduced western Zeiss 1000-mm reflector (the focal length of the system was $f = 13250$ mm, the detector being an Apogee F16M CCD camera); during one night, JD 2456584, we used the 360-mm Ritchey–Chretien telescope designed by V.B. Sekirov (the focal length of the system is 1440 mm; the detector was an ST-402 SBIG CCD camera; the chip was cooled to $-20^\circ$ C).

Reductions were performed using the MaxIm DL aperture photometry package. For GSC 2901–00089, we obtained a homogeneous observations set. For V470 Cas, exposures of different lengths were used, and we obtained a non-homogeneous observations set. In addition, the small amplitude of the second oscillation, $2O$, requires minimal observation errors. Therefore, we averaged individual values over time intervals of nearly the same duration, each point being an average of 3–6 individual observations.

Information on the comparison stars and check stars for the two Cepheids, used in our CCD photometry, is presented in Table 1. Magnitudes of the comparison stars (in Johnson’s $B$ and $V$ bands) were taken from the AAVSO Photometric All-Sky Survey (APASS, [http://www.aavso.org/download-apass-data](http://www.aavso.org/download-apass-data)) catalog. The $R$-band observations could be presented only as magnitude differences with respect to the comparison star. For GSC 2901–00089, the magnitudes differences $\Delta R$ in the $R$ band are $\Delta R = m_{\text{var}} - m_{\text{comp}}$; for V470 Cas, $\Delta R = m_{\text{var}} - m_{\text{comp}} + 1^m.916$.

The finding charts of the two Cepheids are displayed in Fig. 1.

We analyzed the time series using Deeming’s method ([Deeming 1975](#)) implemented in the WinEfk code written by V.P. Goranskij.
3 RESULTS

Our two program variable stars are new double-mode Cepheids, pulsating in the first and second overtone modes. We studied brightness variations of these stars using NSVS and SWASP data and our CCD observations, identified periods of 1O and 2O pulsations, and found period variations.

3.1 V470 Cas

3.1.1 Earlier studies

The variability of V470 Cas = S8459 (α = 01h 32m 18.16s, δ = +56°29'58.0'', J2000) was discovered by Hoffmeister (1964). The variable was classified as a short-periodic variable (possibly eclipsing), the variability range was 12m.5 – 13m.0. The first study of the variability of V470 Cas was published by Meinunger (1968) who classified the star as an eclipsing variable with the light elements:

\[ \text{MinI (JD)} = 2429231.369 + 0^d.444692 \times E. \]

The variability range is 13m.0 – 13m.5.

Gessner & Meinunger (1973) confirmed these light elements but remarked on their being not quite certain. Eight times of light minima were reported. The variable was included in General Catalog of Variable Stars (Samus et al. 2007-2015) based on this publication.
Fig. 2 Light curves and power spectra of V470 Cas according to NSVS data. The light curves in upper panels: raw data; those in the lower panels: the folded light curves with the other oscillation pre-whitened. Under the light curves, we present power spectra, for the raw data and after subtraction of the first overtone oscillations.

Agerer et al. (1996) performed CCD-observations of V470 Cas and studied plates of the Sonneberg Sky Patrol. It was found that the star was not an eclipsing variable. V470 Cas is a possible RR Lyrae variable star with a long period and small amplitude. The amplitude of variability in the instrumental system (without filters) is $0^m.35$. Asymmetry of the light curve is more typical for classical Cepheids ($M - m = 0^P.35$). During the interval of observations (photographic observations: JD 2436200 – 2448862, CCD observations: JD 2449170 – 2450013), the period of variability changed. Therefore, Agerer et al. (1996) gave two systems of the light elements:

for JD 2436200 – 2445000: HJD (max) = 2436200.588 + $0^d.874356 \times E$;

for JD 2445000 – 2450013: HJD (max) = 2449170.518 + $0^d.8744654 \times E$. 

3.1.2 Analysis of NSVS and SWASP data

We suspected double-mode variability of V470 Cas from NSVS and 1SWASP data. The second frequency was detected sufficiently reliably in the NSVS data (for this analysis, we excluded data with the errors $err > 0^m.05$); its detection in the 1SWASP data is much less certain. The light curves and power spectra are displayed in Figs. 2 and 3.

Our classification of V470 Cas is confirmed with its small galactic latitude ($b = -5^\circ.9$) and color indices $J - K = 0.48$ (2MASS), $B - V = 0.94$ (Tycho2), and $B - V = 0.84$ (APASS), typical for Cepheids.

3.1.3 CCD observations

Our CCD observations completely confirmed the double-mode nature of V470 Cas: this star is a double-mode Cepheid, pulsating in the first and second overtone modes. The period ratio $P_2/P_1 = 0.8029$ is typical of the double-mode 1O/2O variables.
Table 2  Light elements of V470 Cas.

| Data   | $P_1$, days | Epoch$_1$, HJD | $P_2$, days | Epoch$_2$, HJD | $P_{2+1}$, days |
|--------|-------------|----------------|-------------|----------------|-----------------|
| NSVS   | 0.8744      | 2451510.732    | 0.7023      | 2451510.914    | –               |
| 1SWASP | 0.8745      | 2454390.438    | 0.7025      | 2454390.425    | –               |
| CCD    | 0.87454     | 2456789.16     | 0.70217     | 2456789.67     | 0.389467        |

Fig. 4  CCD observations: light curves in $B$, $V$ and $R$ bands for V470 Cas; raw data for the 1O period.

The light elements of the two pulsations for all data sets are presented in Table 2. Semi-amplitudes of the individual oscillations and variability ranges in individual bands are collected in Table 3. Besides the first and second overtone frequencies, we detected one interaction frequency, $f_2 + f_1$, of V470 Cas in our CCD data.

CCD light curves of V470 Cas in the $B$, $V$, and $R$ bands are displayed in Figs. 4 and 5. The power spectra according to CCD observations are displayed in Fig. 6. The structure of the power spectra leaves no doubt that $f_2$ is a real frequency.
Table 3  Semi-amplitudes and variability ranges of V470 Cas.

| Band     | $A_1$ | $A_2$ | $A_{2+1}$ | $\text{mag}$ |
|----------|-------|-------|-----------|--------------|
| NSVS (R) | 0.137 | 0.026 | –         | 11.95–12.40  |
| 1SWASP   | 0.189 | 0.015 | –         | 11.92–12.42  |
| $B$      | 0.3327| 0.0364| 0.0176    | 12.82–13.54  |
| $V$      | 0.2447| 0.0252| 0.0116    | 12.03–12.58  |
| $R$      | 0.1910| 0.0185| 0.0092    | 0.42         |

Fig. 5  CCD observations: light curves in $B$, $V$, and $R$ bands for V470 Cas; the folded light curves for the 2O period with the other oscillation pre-whitened.

3.1.4 Period variations

Period variations of the first overtone oscillation ($P_1$) can be represented by an $O-C$ diagram, see Fig. 7. The parabolic shape of this diagram is typical of secular period variations of classical Cepheids. Figure 6 is based on linear light elements for the middle of the time interval:

$\text{HJD (max)} = 2446000.633 + 0^d.874434 \times E$.

Before JD 2449000, all points are times of high brightness according to photographic photometry; after JD 2449000, all points are CCD maxima. We used the data from Agerer et al. (1996), Agerer & Huebscher (2002), Huebscher (2005), Huebscher et al. (2005), Huebscher et al. (2006), Huebscher et al. (2009), Huebscher et al. (2010), Huebscher & Lehmann (2012), and data from our study.
Fig. 6 Power spectra of V470 Cas for the frequencies $f_1$ and $f_2$ according to CCD observations in the $V$ band. Upper panel: raw data; lower panel: the first overtone oscillation pre-whitened.

Fig. 7 $O - C$ diagram for the period of the first overtone oscillation of V470 Cas.

3.2 GSC 2901-00089

3.2.1 Earlier studies

The variability of GSC 2901-00089 ($\alpha = 04^{h}45^{m}23^{s}.89, \delta = +42^{\circ}55^{\prime}20^{\prime\prime}.0$, J2000) was reported by Hoffman et al. (2009) from ROTSE-I/NSVS data (NSVS 4346946). The variable was classified as an RR Lyrae star with the period of 0.53391 days.
Later, we classified GSC 2901-00089 as a 1O/2O double-mode Cepheid (Khruslov 2013) using all available observations from the ROTSE-I/NSVS and SuperWASP online public archives. In the cited paper, we presented the preliminary results. The paper contained only the two periods and the new classification, CEP(B) variability type in the GCVS classifications system (Samus et al. 2007-2015). Now we have re-analysed NSVS and SuperWASP data and our CCD observations, confirmed the 1O/2O double periodicity of GSC 2901-00089, and improved its light elements.
3.2.2 Analysis of NSVS and SWASP data

The light curves and power spectra from NSVS and SuperWASP data are displayed in Figs. 8 and 9. For the analysis of NSVS data, we excluded data with the errors $err > 0^{m}.1$; for the analysis of SWASP data, we excluded data with $err > 0^{m}.05$. The ROTSE data with photometric correction flags (usually rejected) were kept for the analysis.

Our classification is confirmed by the small galactic latitude $b = -1^{\circ}.7$ and by the color indices $J - K = 0.54$ (2MASS), $B - V = 1.05$ (APASS).

3.2.3 CCD observations

Our CCD observations completely confirmed the double-mode nature of GSC 2901-00089: this star is a $1O/2O$ double-mode Cepheid. The period ratio $P_2/P_1 = 0.8036$ is typical of variables of this type. Besides the first and second overtone frequencies, we detected two interaction frequencies of GSC 2901-00089, $f_2 + f_1$ and $f_2 - f_1$, in our CCD data.
The light elements of the two pulsations for all data sets are presented in Table 4: the first-overtone period $P_1$ and epoch, the second-overtone period $P_2$ and epoch, periods for the frequencies $f_2 + f_1$ and $f_2 - f_1$. The periods and epochs are given for all individual data sets. Semi-amplitudes of the individual oscillations and the variability ranges in different bands are collected in Table 5. For the $R$ band, we give the full variability amplitude (peak to peak).

The CCD light curves in the $B$, $V$, and $R$ bands for GSC 2901-00089 are displayed in Figs. 10 and 11. The power spectra according to CCD observations are shown in Fig. 12. The structure of the power spectra leaves no doubt that $f_2$ is a real frequency.

**Table 4** Light elements of GSC 2901-00089.

| Data   | $P_1$, days | Epoch1, HJD | $P_2$, days | Epoch2, HJD | $P_{2+1}$, days | $P_{2-1}$, days |
|--------|-------------|-------------|-------------|-------------|-----------------|-----------------|
| NSVS   | 0.53394     | 2451450.380 | 0.42905     | 2451450.390 | --              | --              |
| 1SWASP | 0.53389     | 2453700.227 | 0.42905     | 2453700.333 | 0.23796         | --              |
| CCD    | 0.533824    | 2456650.325 | 0.428983    | 2456650.288 | 0.237848        | 2.1843          |

**Fig. 10** CCD observations: light curves in $B$, $V$, and $R$ bands for GSC 2901-00089; raw data for the 1O period.
Table 5  Semi-amplitudes and variability ranges of GSC 2901-00089.

| Band  | $A_1$  | $A_2$ | $A_{2+1}$ | $A_{2-1}$ | mag  |
|-------|--------|-------|-----------|-----------|------|
| NSVS  | 0.119  | 0.029 | –         | –         | 12.9 – 13.35 |
| 1SWASP| 0.179  | 0.044 | 0.017     | –         | 12.74 – 13.37 |
| $B$   | 0.2349 | 0.0418| 0.0154    | 0.0115    | 13.98 – 14.63 |
| $V$   | 0.1626 | 0.0289| 0.0114    | 0.0094    | 13.11 – 13.54 |
| $R$   | 0.1278 | 0.0209| 0.0091    | 0.0075    | 0.34 |

Fig. 11  CCD observations: light curves in $B$, $V$, and $R$ band for GSC 2901-00089; the folded light curves for the 2O period with the other oscillation pre-whitened.

3.2.4 Period variations

The periods of the first and second overtone oscillations vary significantly, see Table 4. We can claim it beyond doubt for $P_1$ (progressive decrease). The diagram of the period variations of GSC 2901-00089 is displayed in Fig. 13.

4 CONCLUSIONS

In this paper we presented a photometric study of two new double-mode Cepheids, pulsating in the first and second overtones mode. From our multicolor CCD observations in the Johnson’s $B$, $V$ and $R$ bands, we found the light elements of two oscillations and detected interaction frequencies for each of the stars. We study period variations of the stars; variations of the first overtone periods were reliably detected.
Fig. 12 Power spectra of GSC 2901-00089 for the frequencies \( f_1 \) and \( f_2 \) according to CCD observations in the \( B \) band. Upper panels: raw data; lower panels: the first overtone oscillation pre-whitened.

Fig. 13 The period variations of GSC 2901-00089.

It is more difficult to find 1O/2O Cepheids in our Galaxy compared to the Magellanic Clouds, and each new case is of considerable interest. It is already possible to use known Cepheids of this kind, including those identified by the author, to plot the Petersen diagram and to compare the Galactic sample of the 1O/2O Cepheids to that of the 1O/2O Cepheids in the Magellanic Clouds.
Figure 14 presented the Petersen diagram for Galactic 1O/2O Cepheids compared to 1O/2O Cepheids in the LMC. Solid circles represent known 1O/2O Galactic Cepheids; open circles are the two 1O/2O Galactic Cepheids suspected by Khruslov (2013); the solid squares are the two Cepheids of this study; solid triangles are three-modal Galactic Cepheids; open triangles, 1O/2O Cepheids in the LMC (Soszynsky et al. 2008). In addition, the figure also shows two 1O/2O stars classified not as double-mode Cepheids but actually very similar to them: V798 and V1719 Cygni.

It appears from this diagram that the two samples differ considerably, probably because of chemical-composition differences between the galaxies.
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