ACTA ASTRONOMICA
Vol. **63** (2013) pp. 91–107

Variable Stars in the Globular Cluster M 80

G. Kopacki

Astronomical Institute, University of Wrocław, ul. Kopernika 11, 51-622 Wrocław, Poland
e-mail: kopacki@astro.uni.wroc.pl

Received March 4, 2013

ABSTRACT

We present results of a search for variable stars in the globular cluster M 80. Application of the image subtraction method to the ground-based times-series of CCD frames resulted in finding nine new RR Lyr stars, six of the RRc and three of the RRab type, and four SX Phe variables. Revised mean period of RRab stars, $\langle P\rangle_{\rm ab} = 0.68$ d, and relative percentage of RRc stars, $N_{\rm c}/(N_{\rm ab}+N_{\rm c}) = 53\%$, strongly confirm that M 80 belongs to the Oosterhoff II group of globular clusters. The mean V magnitude of the horizontal branch of M 80 based on the ten RR Lyr stars has been estimated to be $V_{\rm HB} = \langle V\rangle_{\rm RR} = 16.14 \pm 0.03$ mag. In two pulsating stars, one of the RR Lyr type and the other of the SX Phe type, oscillations with two close frequencies were detected, indicating excitation of nonradial modes in these stars. Moreover, we discovered two W UMa or ellipsoidal systems, two periodic stars of unknown type, one of which is probably a field star, and detected light variations in three red giants of the cluster.

Key words: *Stars: Population II – Stars: variables: RR Lyrae – globular clusters: individual: M 80*

1. Introduction

In the last two decades we observed a rapid increase in the number of variable stars detected in Galactic globular clusters. This was the consequence of the invention of the image subtraction method (hereafter ISM) of photometric reductions (Alard and Lupton 1998, Alard 2000) and its application to CCD data of bright globular clusters. Following the first usage of the ISM (Olech *et al.* 1999, Kopacki 2000), the method attained widespread interest and is now a standard tool in variability studies of globular clusters. The ISM makes it possible to obtain a complete inventory of bright variable stars, such as RR Lyr stars, because it works well in crowded stellar fields like cores of globular clusters. Despite numerous studies conducted until now, there are still many globular clusters not searched for variable stars with the ISM (Catelan *et al.* 2006). This implies that there are still many RR Lyr and SX Phe stars in Galactic globular clusters to be discovered. In our ongoing project aimed at completing the census of variable stars in bright Galactic globular clusters we have already published results for M 53 (Kopacki 2000), M 92 (Kopacki 2001, 2007), and M 13 (Kopacki, Kołaczkowski and Pigulski 2003, Kopacki 2005). In total, we have found or confirmed 24 RR Lyr and 9 SX Phe stars in these clusters.

As mentioned above, our project is aimed at detecting and analyzing RR Lyr and SX Phe pulsating stars in globular clusters. The overall properties of RR Lyr stars as a group are related to the intrinsic parameters of the host cluster, such as metallicity and age. This manifests in a division of Galactic globular clusters into two Oosterhoff types distinguished by the average period of their RRab stars (see Clement and Rowe 2000 and references therein). SX Phe stars, which are blue strugglers in globular clusters, are interesting because pulsating in fundamental and first overtone radial modes they follow period–luminosity relations (Nemec, Linnell Nemec, and Lutz 1994, McNamara 1995). These stars can be therefore used as independent distance indicators. However, SX Phe stars are known to pulsate both in radial and nonradial modes and because of the lack of unique method of mode identification it is difficult to define a strict relation for each radial mode. This problem can be solved with the usage of SX Phe stars pulsating simultaneously in two radial modes, because their period ratios fall in a narrow range, 0.77–0.79, for the first overtone and fundamental radial modes (Santolamazza *et al.* 2001). This approach was recently used by Cohen and Sarajedini (2012) and Kopacki and Pigulski (2012) who updated period–luminosity relations for these stars. The number of known double-mode variables of this type is rather small, thus our searches are also optimized to find such stars.

In this paper we present results of a variability survey in M 80 based on the image subtraction method. Preliminary results of this analysis were already published by Kopacki (2009).

2. The Cluster

M 80 (NGC 6093) is one of the densest Galactic globular clusters with intermediate metallicity $[\mathrm{Fe/H}] = -1.73$ (Cavallo, Suntzeff and Pilachowski 2004). Despite of being a very dense and compact object, M 80 is not regarded to be a core-collapsed cluster (Ferraro *et al.* 1999, 2003). The color–magnitude diagram of the cluster shows prominent extended blue tail along horizontal branch, very similar to what is observed for M 13 (Ferraro *et al.* 1998). In previous deep photometric studies of Alcaino *et al.* (1998) and Ferraro *et al.* (1999) the cluster was shown to contain a very large and centrally concentrated population of blue stragglers.

The Catalog of Variable Stars in Globular Clusters (CVSGC, Clement *et al.* 2001) lists 11 variable and suspected variable objects in the field of M 80 including one W Vir star, v1 (Bailey 1902), and six RR Lyr stars, v3–v5 (Sawyer 1942) and v8–v10 (Wehlau *et al.* 1984). Clement and Walker (1991) searched for double-mode RRd stars (pulsating in radial fundamental and first overtone modes) in three globular clusters including M 80, but found none.

M 80 is also famous for hosting the only certain classical nova in a globular cluster, T Sco (Nova 1860, listed in the CVSGC without a number) observed in outburst in 1860 (Luther 1860, Pogson 1860), and two dwarf novae, DN1 and DN2, found by Shara, Hinkley and Zurek (2005), which we label v11 and v12, respectively, extending the numbering scheme of the CVSGC. Using the Chandra telescope, Heinke *et al.* (2003) identified 19 X-ray sources in M 80. Two of them were classified as quiescent low-mass X-ray binaries and the other five as candidate cataclysmic variables. Heinke *et al.* (2003) suggested also that the brightest source, CX1, might be the X-ray counterpart of Nova 1860; this was subsequently confirmed by Dieball *et al.* (2010).

3. Observations and Reductions

The CCD observations presented here were obtained at the South African Astronomical Observatory (SAAO), Sutherland, Republic of South Africa, using a 40-inch telescope equipped with a STE4 detector. It is a SITe back-illuminated CCD camera with a size of 1024×1024 px ('px' stands for 'pixel'), gain of 2.8 e^-/ADU and a read-out noise of 6.5 e^-. The observations were carried out during one-week observing run in 2008, from April 9 to 15. Since our goal was a search for variable stars in M 80 and because of the short time-span of the run, we observed only through *V* filter of the Johnson *UBV* system. In total, we obtained 295 *V*-filter CCD frames of the cluster, each covering about 5.2×5.2 arcmin^2. The exposure times amounted to 300 s. The total time of continuous monitoring was equal to 29.5 h. On most nights the weather was very good but some nights were interrupted in the morning by thick mist. The seeing was in the range from 3.6 px to 9.1 px (1 px corresponding to $0\overset{''}{.}305$) with a median value of 4.4 px.

The pre-processing of the CCD frames was performed in the usual way and consisted of a subtraction of the over-scan and mean bias frame and applying flat-field correction using mean flat-field frames constructed for each night separately. The dark current was found to be negligible. Instrumental magnitudes for all stars in the observed field were derived with the DAOPHOT profile-fitting package of Stetson (1987). All images were reduced using the method described by Jerzykiewicz *et al.* (1996). We identified about 15 400 stars in the reference frame of the observed field, but could not resolve well the dense cluster core. A schematic view of the monitored field is presented in Fig. 1.

Our instrumental *V* magnitudes were transformed to standard ones using 20 stars in common with the updated Stetson's (2000) photometric database for M 80. Having observations in one passband only, we were able to use a simple transformation without a color term. The following equation was obtained:

$$V = v + (3.22 \pm 0.03)$$

where *V* denotes standard magnitude and v, instrumental one. Comparing our standard *V* magnitudes with those of Alcaino *et al.* (1998) we found a large systematic

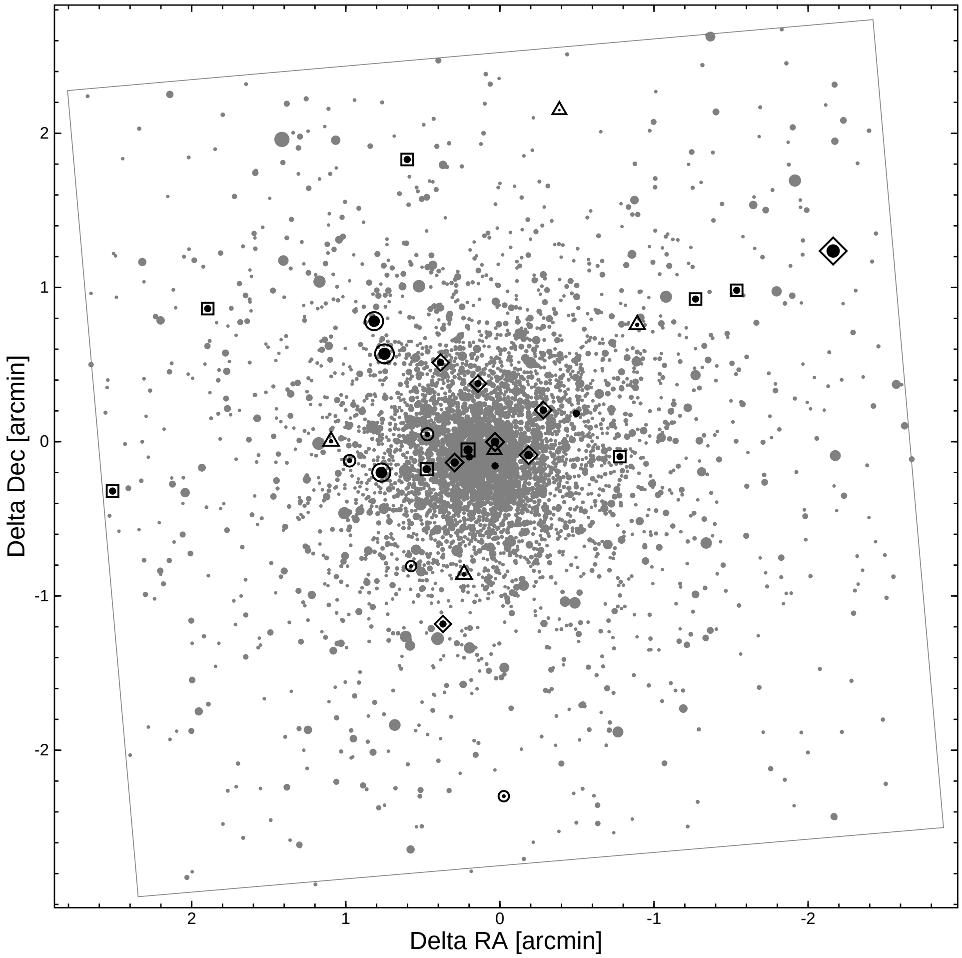

Fig. 1. Schematic view of the observed field of M 80 covering 5.2×5.2 arcmin^2. Variable stars are indicated with different symbols, a W Vir star (the most western one) and RRab variables, with diamonds, RRc stars, with squares, SX Phe stars, with triangles, and stars of other types (W UMa stars, variable red giants), using open circles. The SX Phe star at the very center of the cluster is v33. Positions of the Nova T Sco and the two dwarf novae, v11 and v12, are indicated with black dots. T Sco is the easternmost of them. The $(0,0)$ coordinates correspond to $\alpha = 16^{\rm h}17^{\rm m}02^{\rm s}$, $\delta = -22°58'30''$.

shift between them amounting to $\langle V_{\rm Stetson} - V_{\rm Alcaino}\rangle = 0.61 \pm 0.04$ mag. A similar difference was obtained from the comparison of our standard magnitudes with those of Brocato *et al.* (1998). It should be noted that both Stetson (2000) and Brocato *et al.* (1998) photometries are tied directly to the Landolt (1992) standards while this is not the case for Alcaino *et al.* (1998) magnitudes.

Fig. 2 shows the scatter in the light curves of all observed stars with reliable photometry, that is stars located outside the cluster core, as a function of the mean V magnitude. The scatter is measured as a standard deviation of individual observations from the mean value. The cluster core is defined as a circular area around cluster center with a radius of $50''$. Our differential photometry has an accuracy of about 9 mmag for the brightest stars, decreasing to 30 mmag for stars with $V = 20$ mag.

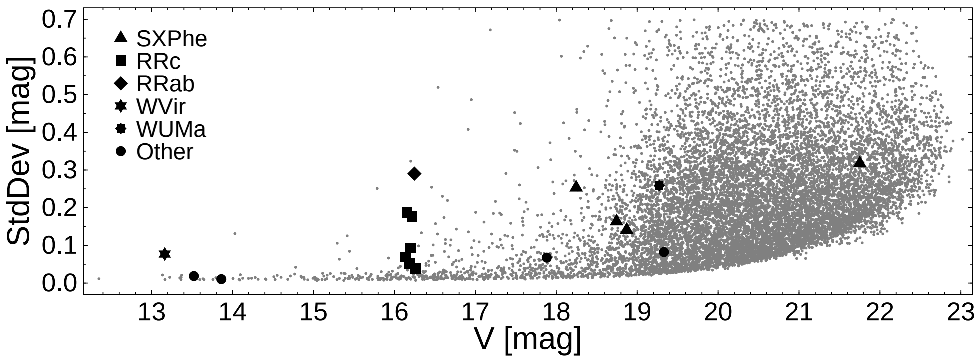

Fig. 2. Standard deviation as a function of the average V magnitude for light curves of stars located outside cluster core (with distance from cluster's center $r > 50''$). Variable stars are indicated with different black symbols. Note a group of RR Lyr stars at $V \approx 16.2$ mag.

In order to search for variable stars in M 80, we reduced our CCD frames with the ISM. In general, the same procedure of reductions as in Kopacki (2000) was followed. However, the CCD frames showed very significant effect of the optical deformation which manifested through non-circular shape of stellar profiles. In combination with a large range of seeing, it turned out that all frames cannot be reduced satisfactorily using the same set of parameters of the method. Eventually, we found that an adequate image subtraction required adjusting the radius of the convolution kernel, in the sense that for larger seeing this radius should also be larger. We computed difference images and derived the final profile photometry from them using two settings of the size of the convolution kernel: 15 px for frames with seeing smaller than 6 px and 18 px for frames with seeing larger than 6 px. For all frames we used the same reference frame constructed from the best-seeing low-background images; its seeing was 3.9 px. This approach significantly improved the quality of the photometry, especially for stars located in the cluster core or in the neighborhood of bright stars.

We used two methods to search for variable stars in the set of difference images produced with the ISM. Both these methods were based on the determination of light curves for a fixed positions in the reference frame and a search for periodic signal among them using Fourier analysis. In the first method, we derived differential flux curves for all stars detected in the reference frame using DAOPHOT package and for all brightenings found in the variability map (defined as an average of the absolute values of the best-seeing difference frames) and computed Fourier spectra of these light curves in the frequency range from 0 to 50 d^{-1}. To identify variable stars we checked manually all stars showing a significant peak ($\mathrm{S/N} > 4$) in the periodograms of their light curves. The results of this approach are summa-

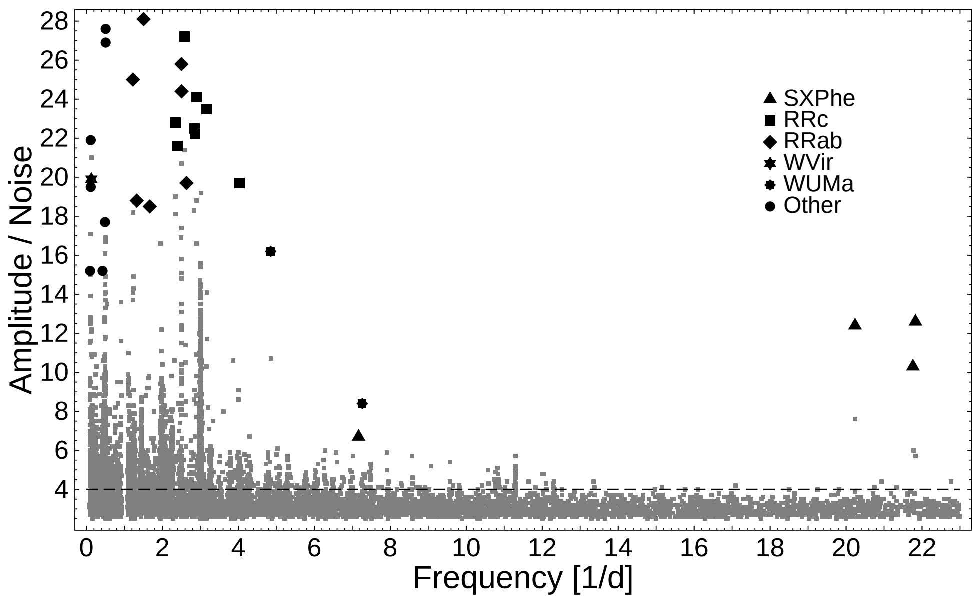

Fig. 3. The amplitude-to-noise ratio of the highest peak in the power spectrum plotted against the peak's frequency. Each point corresponds to one star detected in the reference frame. Different types of variable stars are indicated with various symbols.

rized in Fig. 3. This figure shows the plot of the S/N of the highest peak in the amplitude spectrum as a function of the corresponding frequency for all stars detected in the reference frame. We detected 27 variable stars, among which 20 are new discoveries.

To check if we did not miss faint large-amplitude variable stars (especially in the crowded cluster core) we also performed the so called pixel photometry on difference frames. This approach assumes that a star is centered at a given pixel and the light curves are derived for all positions covering the whole area of the detector with a 1 px resolution. The method was successfully applied by Kopacki (2005, 2007) to search for SX Phe stars in the cores of M 13 and M 92. We confirmed the already obtained results but found no other variable stars in the field.

4. Results of the Variability Survey

Out of eleven variable or suspected variable stars listed in the CVSGC for M 80, two were outside the field observed by us. These were v6 and v7, also known as S and R Sco, respectively. According to the CVSGC, they are long-period variables not belonging to the cluster. Star v2 was found to be constant in our data, but it is a long-period variable (Wehlau, Sawyer Hogg and Butterworth 1990) and it is possible that the variability was not detected due to the short length of our run. This star is located at the tip of the red giant branch in the cluster color–magnitude diagram (see Fig. 10). The only Type II Cepheid known in the cluster, v1, was also in our field of view. The period of this star given in the CVSGS is 16.3042 d and our week-long observations cover only about a half of the pulsation cycle. The *V*-filter light curve for v1 is shown in Fig. 4. It should be noted that we are not able to derive light curves expressed in magnitudes for all observed variable stars. To keep the presentation of our results consistent, all light curves will be shown as derived from the ISM reductions, that is in the flux units.

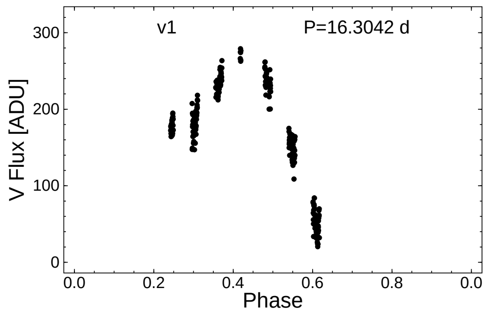

Fig. 4. *V*-filter light curve of a W Vir star v1.The period was adopted from CVSGC.

We observed all six RR Lyr stars previously known in M 80 and found nine other stars of this type in the dense core of the cluster. Extending the numbering scheme of the CVSGC for M 80, we denote these new variable stars v13 through v21. The *V*-filter light curves of all RRab and RRc stars we observed are shown in Figs. 5 and 6, respectively. Since all RR Lyr stars in a given globular cluster have approximately the same mean brightness, differences in flux amplitude of observed RR Lyr variables strictly reproduce differences in amplitude expressed in magnitude. The higher scatter of observations in the light curves of v19 and v20 is very likely of instrumental origin and is caused by imperfections of image subtraction at the cluster core, as described in Section 3. However, one RRc star (v16) shows clearly a modulation of the light curve. This star will be discussed separately later.

In addition, we have found eight other periodic variable stars, which we designate v22 through v29. Four of them, v22–v25, we classify as SX Phe stars. The variable v25 has a period rather long for an SX Phe star (but still acceptable) and a very small amplitude of the flux variations. It is therefore possible that our classification is incorrect and the star is a W UMa or an ellipsoidal binary system. Moreover, v25 is about 3 mag fainter than the other SX Phe stars in M 80 (see Fig. 2). If our tentative classification is correct, this implies the star is not a cluster member. The *V*-filter light curves of the observed SX Phe stars are presented in Fig. 7. All these stars, except v24, exhibit single-period oscillations. Multiperiodic variable v24 will be discussed separately.

It should be noted that recently Thomson *et al.* (2010) conducted a variability survey of M 80 using sparse far-ultraviolet data from the ACS on-board the HST and besides the two RR Lyr stars found by us (v17 and v19), they discovered yet

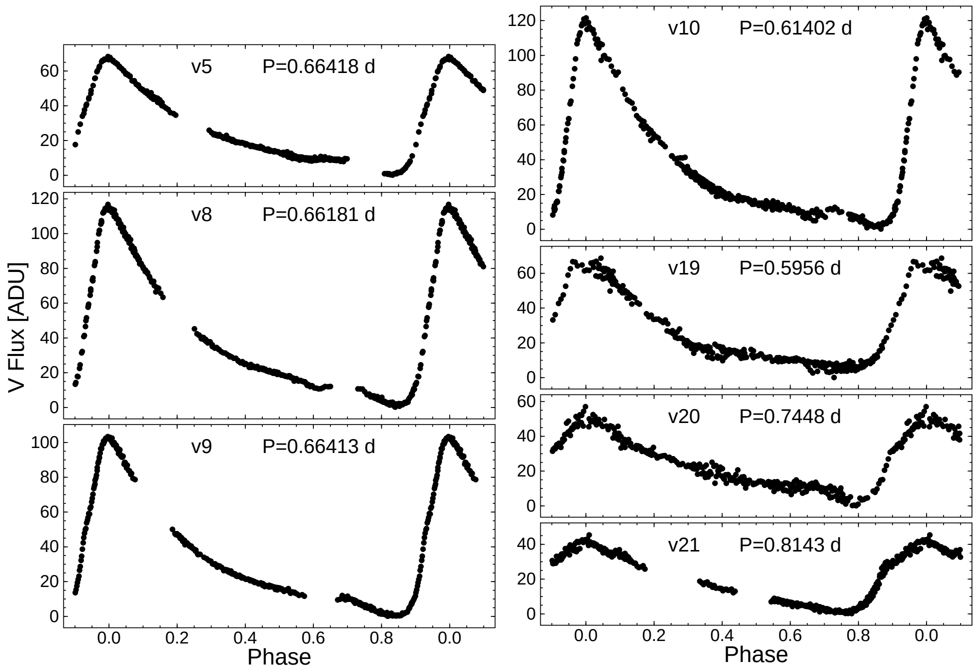

Fig. 5. *V*-filter light curves of RRab stars in M 80. Variables v19, v20 and v21 were discovered in this work. The ordinate scale is the same in all panels.

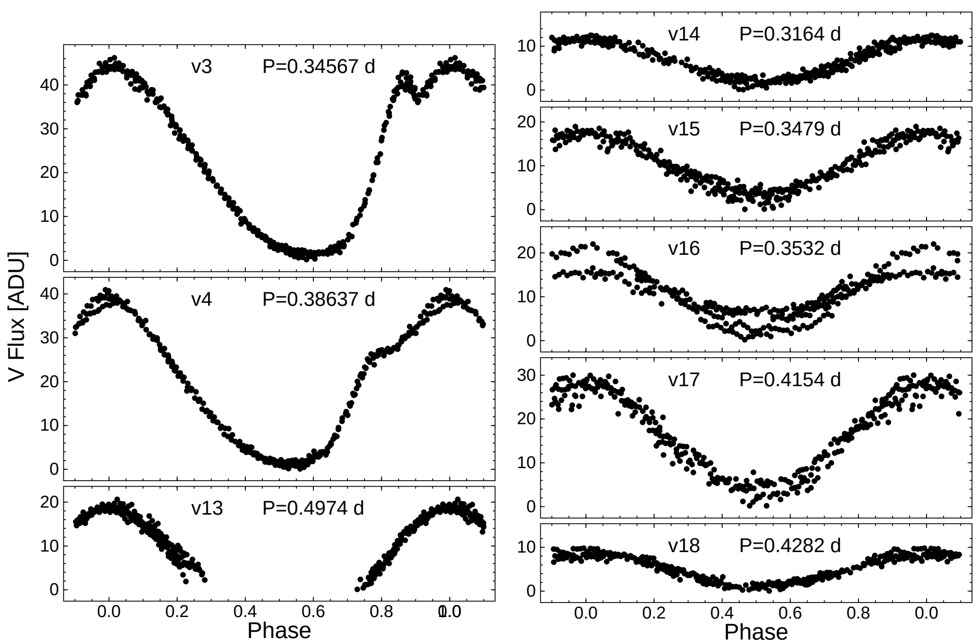

Fig. 6. *V*-filter light curves of RRc stars in M 80. All they, except v3 and v4, were discovered to be variable in this work. The ordinate scale is the same in all panels.

another SX Phe star in the central region of the cluster. We name this star v33. Although the star falls into our field of view, we could not derive reliable time-series photometry for it. Actually, all SX Phe stars discovered by us are located outside the cluster's core (see Fig. 1) and we suspect that our inability to detect v33 and other potential SX Phe stars in the cluster core was caused by the imperfections of the image subtraction described in Section 3.

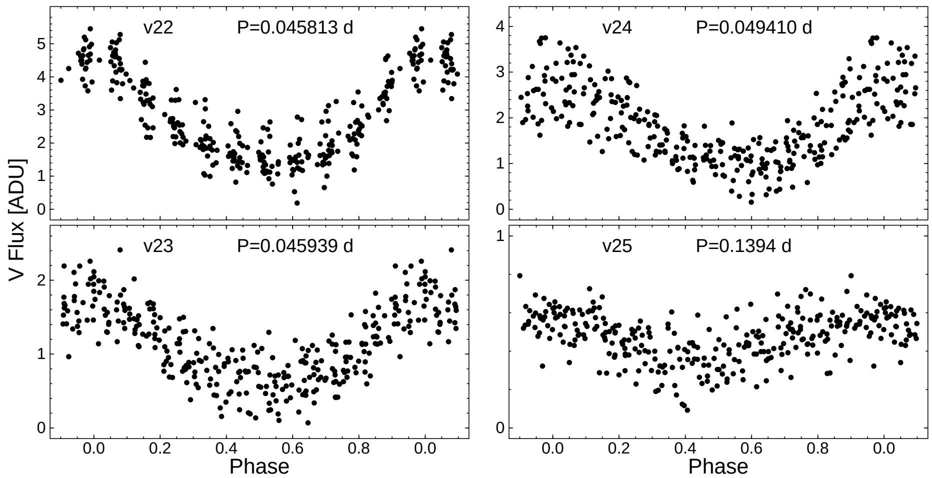

Fig. 7. *V*-filter light curves of SX Phe stars in M 80. They have all been discovered in this work.

The other periodic stars we found are the two W UMa eclipsing binaries, v26 and v27, and two stars of unknown type, v28 and v29, with periods of about 2 d. One of the latter stars (v29) is a field star, as indicated in Fig. 10. The light curves of these variables are shown in Figs. 8 and 9.

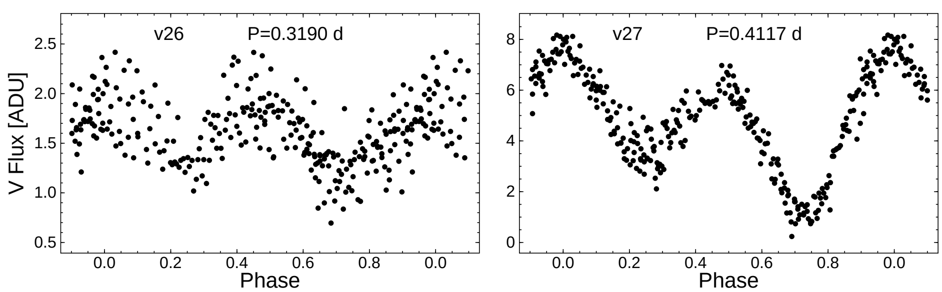

Fig. 8. *V*-filter light curves of two stars suspected to be of the W UMa or ellipsoidal type.

Bright red giants in globular clusters usually show small-amplitude irregular variability (Welty 1985). In M 53 and M 13, for example, almost all stars at the tip of the red giant branch are variable (Kopacki 2000, 2003). In contrast, no variable red giants were found in M 92 (Kopacki 2001). From our observations of M 80 we find all red giants at the very tip of red giant branch to be non-variable. However,

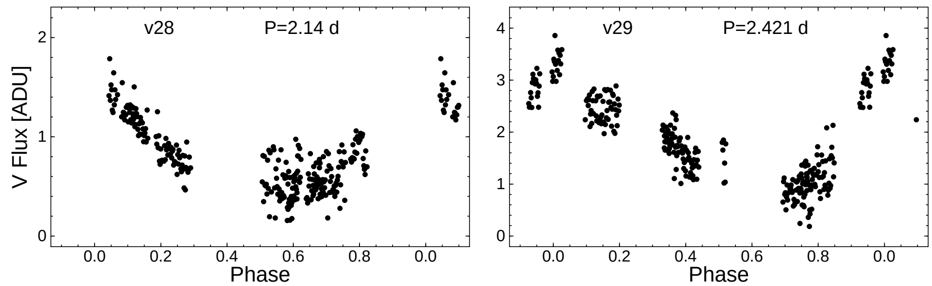

Fig. 9. *V*-filter light curves of the two periodic stars of unknown type.

one of these stars is v2, which was shown in previous studies to exhibit small-amplitude long-period light changes. Instead, we detected irregular light variation in three fainter giants, which we designate v30 through v32. Two of them are indicated in the color–magnitude diagram of the cluster (Fig. 10).

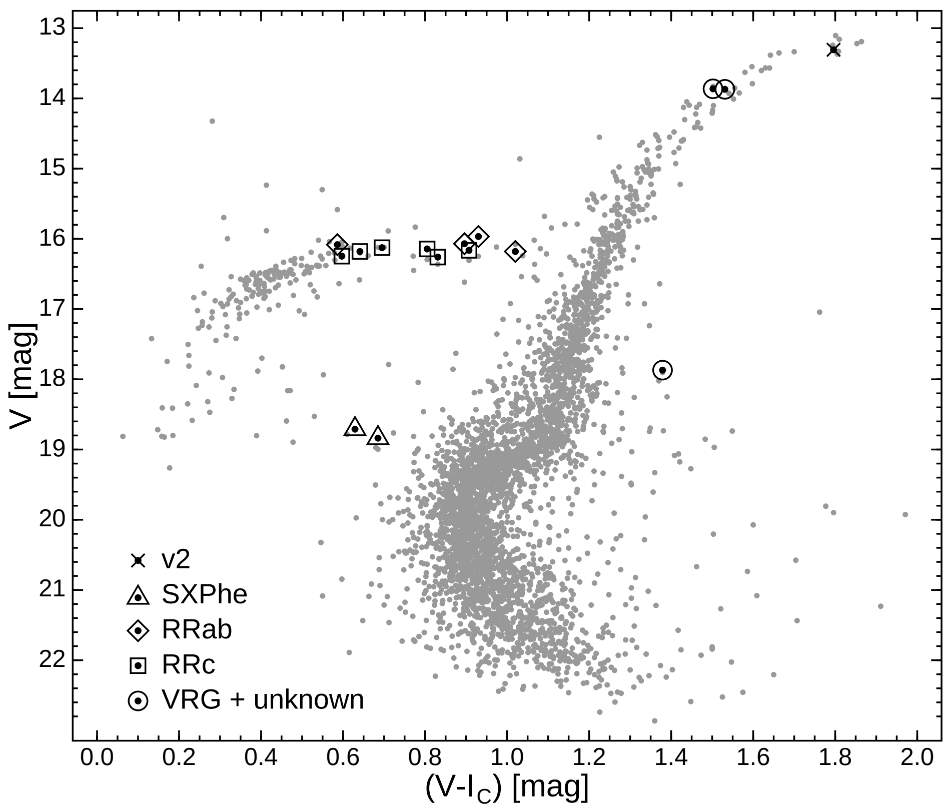

Fig. 10. The *V vs.* $V-I_C$ color–magnitude diagram for M 80 constructed from photometric data of Alcaino *et al.* (1998). For variable stars intensity-weighted mean *V* magnitudes derived in this paper were used. *V* magnitudes of other stars were shifted by adding 0.61 mag (see text). SX Phe stars are indicated with triangles, RRc variables with open squares and RRab stars with diamonds. Star v2 is shown with a cross.

The classical nova T Sco and the two dwarf novae known in the cluster deserve a comment. These stars are very faint at quiescent phase and are below the detection threshold of our photometry. Most known dwarf novae experience a 2–5 mag outbursts every few weeks or months, whereas classic novae brighten even by 12 mag (Schaefer 2010). This opens a possibility of detecting these object in our data provided they are accidentally in eruption. We thus derived light curves for them using their equatorial coordinates transformed to the rectangular positions in our field of view. Positions of T Sco, v11 and v12 are indicated in Fig. 1. As can be seen from Fig. 1, T Sco is located very close to the RRc star v17. Because of that, the light curve we derived mimics the variations of v17 and is therefore useless. Light curves of v11 and v12 show no signs of variability.

The V *vs.* $(V-I_{\rm C})$ color–magnitude diagram for M 80, constructed using the photometric data of Alcaino *et al.* (1998) is shown in Fig. 10. V magnitudes were shifted by 0.61 mag to match the photometric system of Stetson (2000). All observed variable stars which could be identified in the photometry of Alcaino *et al.* (1998) are indicated with different symbols. For these stars we used mean V magnitudes derived in this paper instead of shifted magnitudes from Alcaino *et al.* (1998). Since the Alcaino *et al.* (1998) data are not cycle-averaged colors, there is a greater than expected scatter of RRab stars along horizontal branch of the cluster. The most severe example is v9, which is located at the blue edge of the instability strip. This is a consequence of the large amplitudes and non-sinusoidal shapes of the light curves for this type of pulsating stars. But still, as expected, RRc stars occupy the hotter part of the classical instability strip. The two SX Phe stars, v22 and v23, are found among the blue straggler population of the cluster.

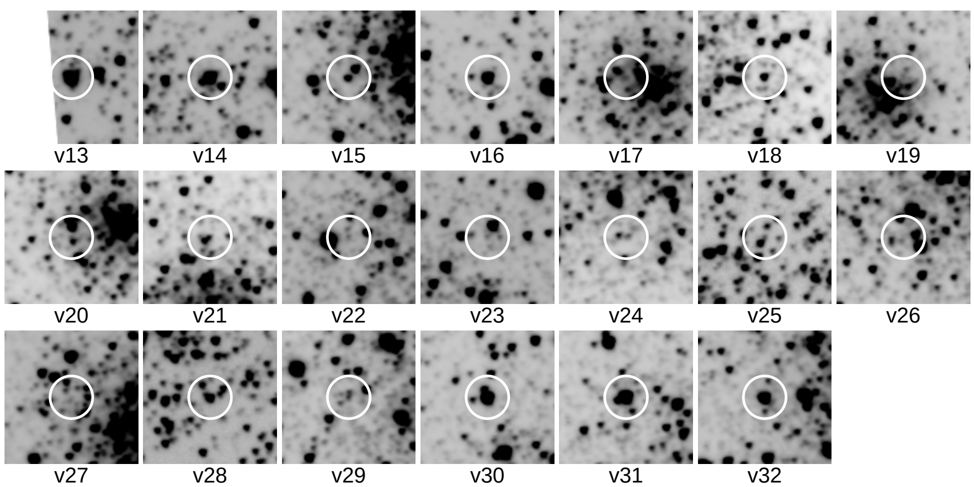

Fig. 11. Finding charts for new variable stars found in M 80. The size of each chart is 30×30 arcsec^2. North is up and East to the left.

The observed variable stars in M 80 are indicated in Fig. 1. In addition, finding charts for those discovered by us are presented in Fig. 11. The photometric parame-

Table 1

Photometric data for variable stars in M 80

Var	α_{2000}	δ_{2000}	$\langle V\rangle$ [mag]	V [mag]	$V-I_C$ [mag]	ΔV [mag]	P [d]	Type
v1	$16^h16^m52\overset{s}{.}62$	$-22°57'16\overset{''}{.}1$	13.365	–	–	–	16.3042	W Vir
v2	$16^h17^m04\overset{s}{.}22$	$-22°58'53\overset{''}{.}8$	–	12.698	1.796	–	–	const
v3	$16^h17^m10\overset{s}{.}23$	$-22°57'38\overset{''}{.}0$	16.144	15.685	0.805	0.498	0.34567	RR Lyr
v4	$16^h16^m56\overset{s}{.}48$	$-22°57'34\overset{''}{.}2$	16.164	15.698	0.907	0.430	0.38637	RR Lyr
v5	$16^h17^m03\overset{s}{.}59$	$-22°59'40\overset{''}{.}4$	16.180	15.468	1.020	0.931	0.66418	RR Lyr
v8	$16^h17^m00\overset{s}{.}76$	$-22°58'17\overset{''}{.}1$	16.070	16.007	0.896	1.097	0.66181	RR Lyr
v9	$16^h17^m03\overset{s}{.}66$	$-22°57'58\overset{''}{.}7$	16.833	14.974	0.586	0.927	0.66413	RR Lyr
v10	$16^h17^m01\overset{s}{.}17$	$-22°58'34\overset{''}{.}6$	–	–	–	–	0.61402	RR Lyr
v13	$16^h17^m12\overset{s}{.}94$	$-22°58'49\overset{''}{.}3$	16.247	15.486	0.597	0.291	0.4974	RR Lyr
v14	$16^h16^m55\overset{s}{.}32$	$-22°57'30\overset{''}{.}9$	16.180	15.591	0.641	0.134	0.3164	RR Lyr
v15	$16^h17^m04\overset{s}{.}04$	$-22°58'40\overset{''}{.}2$	–	–	–	–	0.3479	RR Lyr
v16	$16^h17^m04\overset{s}{.}61$	$-22°56'40\overset{''}{.}0$	16.126	15.522	0.695	0.181	0.3532	RR Lyr
						0.061	0.3339	
						0.021	0.590	
v17	$16^h17^m02\overset{s}{.}88$	$-22°58'32\overset{''}{.}6$	–	–	–	–	0.4154	RR Lyr
v18	$16^h16^m58\overset{s}{.}60$	$-22°58'35\overset{''}{.}3$	16.260	15.752	0.831	0.089	0.4282	RR Lyr
v19	$16^h17^m02\overset{s}{.}11$	$-22°58'29\overset{''}{.}5$	–	–	–	–	0.5956	RR Lyr
v20	$16^h17^m03\overset{s}{.}26$	$-22°58'37\overset{''}{.}5$	–	–	–	–	0.7448	RR Lyr
v21	$16^h17^m02\overset{s}{.}60$	$-22°58'06\overset{''}{.}9$	15.967	15.639	0.930	0.494	0.8143	RR Lyr
v22	$16^h17^m06\overset{s}{.}76$	$-22°58'29\overset{''}{.}4$	18.710	18.099	0.629	0.298	0.045813	SX Phe
v23	$16^h16^m58\overset{s}{.}11$	$-22°57'44\overset{''}{.}1$	18.838	18.385	0.685	0.112	0.045939	SX Phe
v24	$16^h17^m02\overset{s}{.}99$	$-22°59'21\overset{''}{.}1$	18.259	–	–	0.099	0.049410	SX Phe
						0.055	0.048409	
v25	$16^h17^m00\overset{s}{.}33$	$-22°56'20\overset{''}{.}9$	21.821	–	–	0.340	0.1394	SX Phe
v26	$16^h17^m04\overset{s}{.}49$	$-22°59'17\overset{''}{.}9$	19.280	–	–	0.147	0.3190	W UMa
v27	$16^h17^m04\overset{s}{.}02$	$-22°58'26\overset{''}{.}5$	–	–	–	–	0.4117	W UMa
v28	$16^h17^m01\overset{s}{.}89$	$-23°00'47\overset{''}{.}7$	19.306	–	–	0.166	2.14	unknown
v29	$16^h17^m06\overset{s}{.}22$	$-22°58'36\overset{''}{.}9$	17.870	17.295	1.379	0.115	2.421	unknown
v30	$16^h17^m05\overset{s}{.}54$	$-22°57'42\overset{''}{.}6$	13.864	13.219	1.502	0.027	–	VRG
v31	$16^h17^m05\overset{s}{.}24$	$-22°57'55\overset{''}{.}3$	13.520	–	–	0.037	–	VRG
v32	$16^h17^m05\overset{s}{.}33$	$-22°58'41\overset{''}{.}5$	13.871	13.253	1.531	0.029	–	VRG
v33	$16^h17^m02\overset{s}{.}16$	$-22°58'33\overset{''}{.}2$	–	–	–	–	0.0385	SX Phe

ters of observed variables are given in Table 1. For each star we provide the adopted designation, equatorial coordinates, (α,δ), and if available, average V magnitude, $\langle V\rangle$, V magnitude and $(V-I_C)$ color index taken from Alcaino *et al.* (1998), the range of variability, ΔV, period(s), P, and type of variability. The equatorial coordinates were derived from astrometric transformation of our rectangular positions using 955 stars in common with the NOMAD catalog (Zacharias *et al.* 2004). The standard deviations of the derived astrometric equations are $0\overset{''}{.}57$ for right ascention and 0.″62 for declination. The mean magnitudes $\langle V \rangle$ are intensity-weighted averages in the case of pulsating stars and arithmetic means for other variable stars. The intensity-weighted mean magnitudes and the ranges of variability of periodic stars were computed from the fit of the truncated Fourier series to our instrumental V magnitudes and only for stars having reliable DAOPHOT photometry. $\langle V \rangle$ and ΔV may be uncertain for v13 because it has light curve not completely covered in phase (Fig. 6). For the variable red giants (VRGs) we give the range of the mean nightly magnitudes. Periods are given with an accuracy resulting from a non-linear least-squares fit of truncated Fourier series to the observations. For each star we used the smallest possible number of harmonic components which described reasonably well the observed light curve. For multiperiodic stars, v16 and v24, we provide ranges of variability and periods of all detected terms. The equatorial coordinates and the period of v33 were taken from Thomson *et al.* (2010). The novae, T Sco, v11 and v12 are not included in Table 1. It should be also noted that the numbering scheme for the new variable stars adopted here is slightly different from designations used in our previous paper on M 80 (Kopacki 2009).

Altogether, the V-filter light curves expressed in flux units have been obtained for 27 variable stars. They can be downloaded from the *Acta Astronomica Archive (ftp://ftp.astrouw.edu.pl/acta/2013/kop_91)*. Moreover, for stars having reliable DAOPHOT photometry we provide light curves with differential fluxes transformed to magnitudes and shifted to the standard system. For each variable we give a list of HJD of the frame mid-exposure and the corresponding differential flux from the ISM reductions and (if available) magnitude with their formal error.

4.1. Multiperiodic Variable Stars

Two pulsating stars, v16 (Fig. 6) and v24 (Fig. 7), show long-period modulation of the light-curve shape, which in the case of RR Lyr stars is refereed to as the Blazhko effect (see, *e.g.*, Kolenberg *et al.* 2010, Benkő *et al.* 2010). This behavior is an indication of multiperiodicity. We shall now discuss the two stars in more detail.

The Fourier spectrum of the original observations of RRc star v16 is shown in Fig. 12a. The highest peak occurs at a frequency $f_1 = 2.831$ d^{-1}. Periodogram of the residuals obtained after prewhitening the original data with the frequency f_1 is presented in Fig. 12b. The highest peak is found at frequency $f_2 = 2.995$ d^{-1}, which is close to the main frequency f_1. Moreover, this frequency is also not far from 3 d^{-1}. The third significant frequency, $f_3 = 1.695$ d^{-1}, can be seen in Fig. 12c, after removing f_1 and f_2 from the original data. No more periodic terms are found in the light curve of v16, which is testified by the flat periodogram obtained after prewhitening the data with all the detected frequencies (see Fig. 12d). Phase diagrams for all three components are shown in the right panels of Fig. 12.

A very small separation between the two main components, $\Delta f = f_2 - f_1 = 0.164$ d^{-1}, suggests that one of them, most probably that with the smaller ampli-

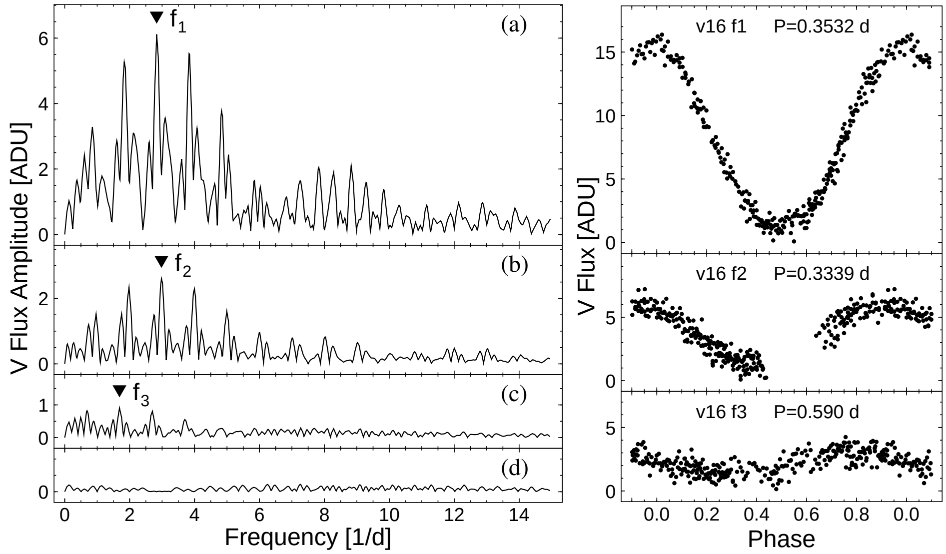

Fig. 12. *Left panels:* Amplitude spectra of the RR Lyr star v16: (a) for the original *V*-filter observations, (b) after prewhitening with frequency $f_1 = 2.831$ d^{-1}, (c) after removing frequencies f_1 and $f_2 = 2.995$ d^{-1}, (d) after prewhitening with frequencies f_1, f_2, and $f_3 = 1.695$ d^{-1}. The ordinate scale is the same in all panels. *Right panels:* Separated light curves of v16 for the f_1, f_2, and f_3 components (from *top* to *bottom*) phased with appropriate periods. Arbitrarily chosen initial epoch is the same for all light curves. The ordinate scale is the same in all panels.

tude, corresponds to a nonradial mode of pulsation. The ratio of the primary and the tertiary periods amounts to $P_1/P_3 = f_3/f_1 = 0.599$. This value is close to the expected period ratio of the second overtone and the fundamental radial modes, $P_{\rm SO}/P_{\rm F}$. However, this interpretation would require that fundamental mode in V16 has amplitude much smaller than the second overtone ($A_1/A_3 = 8.6$). This seems very unlikely. Several RR Lyrae stars are known to exhibit F/SO double-mode pulsations (Moskalik 2013), but they are all of the RRab type. Moreover, first overtone modes excited in those stars have very small amplitudes.

The other multiperiodic star we found is the SX Phe variable v24. The Fourier spectrum of the *V*-filter data of this star is presented in Fig. 13a. The highest peak is found at frequency $f_1 = 20.239$ d^{-1}. The asymmetric shape of this periodic component is manifested by the presence of the peak at $2f_1$. After removing the frequency f_1 with its harmonics from original observations, we obtain residuals for which the periodogram is shown in Fig. 13b. Another significant peak appears at the frequency $f_2 = 20.657$ d^{-1}. Additionally, the combination term, $f_1 + f_2$, can be seen. The spectrum of the residuals obtained after prewhitening with both detected frequencies (Fig. 13c) is practically flat with some higher signal at low frequencies that can be attributed to the instrumental effects. Phase diagrams of the two components are shown in the right panels of Fig. 13. The two frequencies found in the light variation of v24 form a closely spaced pair with a period ratio of $f_1/f_2 = 0.98$. We conclude that at least one of the modes is nonradial.

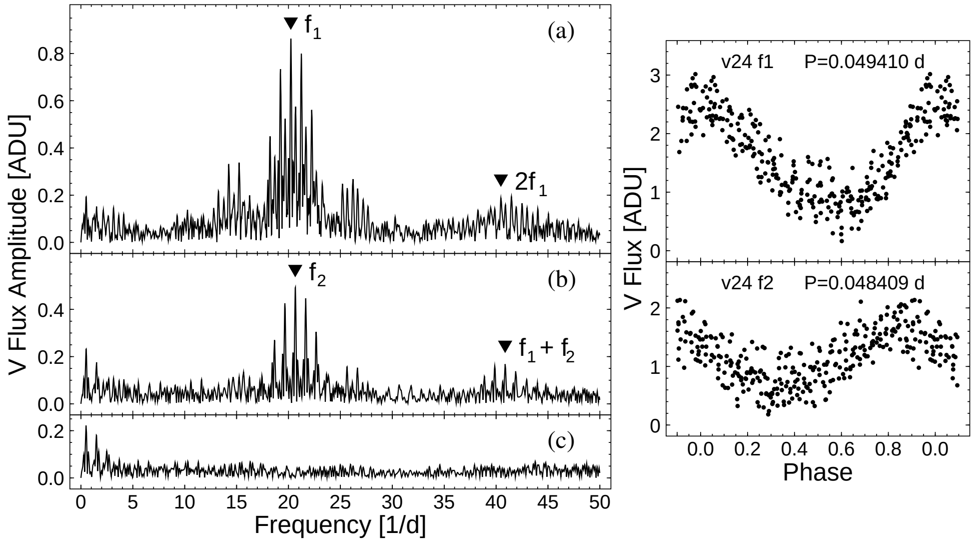

Fig. 13. *Left panels:* Amplitude spectra of the SX Phe star v24: (a) for the original *V*-filter observations, (b) after prewhitening with frequency $f_1 = 20.239$ d^{-1} and its harmonics, (c) after removing frequencies f_1, $f_2 = 20.657$ d^{-1} and the combination frequency $f_1 + f_2$. The ordinate scale is the same in all panels. *Right panels:* Separated light curves of v24 for the f_1 and f_2 components (from *top* to *bottom*) phased with appropriate periods. Arbitrarily chosen initial epoch is the same for all light curves. The ordinate scale is the same in all panels.

5. Summary and Conclusions

Our variability survey resulted in the discovery of 20 new variable stars in globular cluster M 80. Of these, nine are RR Lyr stars, four are SX Phe stars, two show W UMa-type or ellipsoidal light variation, and the other three are irregular red giants. Since we probed cluster crowded core with the ISM, we suppose that our search revealed all RR Lyr stars belonging to the cluster.

The total number of RR Lyr stars known in M 80 is now 15. Seven of them are RRab stars, the remaining eight are of the RRc type. Nine RR Lyr stars were discovered in this work. With this more than twofold increase in the number of RR Lyr stars in the cluster, the Oosterhoff type of M 80 can be much better established. Revised mean period of RRab stars, $\langle P\rangle_{\rm ab} = 0.68$ d, and relative percentage of RRc stars, $N_{\rm c}/(N_{\rm ab}+N_{\rm c}) = 53\%$, confirm that M 80 belongs to the Oosterhoff II group of globular clusters. This result is also in accordance with the low metallicity of the cluster.

The mean *V* magnitude of the horizontal branch for M 80 determined from the intensity-weighted mean magnitudes of the ten RR Lyr stars is equal to $V_{\rm HB} = \langle V\rangle_{\rm RR} = 16.14 \pm 0.03$ mag. Within the errors this value is equal to the *V* brightness of the cluster's horizontal branch given in the latest version of the Harris'

(1996) catalog. It is also consistent with the RR Lyr based relation $M_V(\mathrm{HB}) = 0.22\,[\mathrm{Fe/H}] + 0.89$ from Gratton *et al.* (2003), which predicts $V_{\mathrm{HB}} = 16.09$ mag, assuming apparent distance modulus $(m-M)_V = 15.58 \pm 0.12$ from Brocato *et al.* (1998).

Among the RR Lyr stars we found only one variable, v16, showing Blazhko effect. This RRc star pulsates in at least two modes, closely spaced in frequency, one of which is thus nonradial. We also checked if any SX Phe star we observed shows radial double-mode pulsations. We found one variable, v24, showing bi-periodic variability. Unfortunately, the two detected periods are too close to each other to be both radial modes.

Acknowledgements. We acknowledge the support from the NCN grant no. 2011/03/B/ST9/02667. This paper uses observations made at the South African Astronomical Observatory.

REFERENCES

Alard, C. 2000, *A&AS*, **144**, 363.
Alard, C., and Lupton, R.H. 1998, *ApJ*, **503**, 325.
Alcaino, G., Liller, W., Alvarado, F., Kravtsov, V., Ipatov, A., Samus, N., and Smirnov, O. 1998, *AJ*, **116**, 2415.
Bailey, S.I. 1902, *Annals of the Astronomical Observatory of Harvard College*, **38**, 1.
Benkő, J.M., *et al.* 2010, *MNRAS*, **409**, 1585.
Brocato, E., Castellani, V., Scotti, G.A., Saviane, I., Piotto, G., and Ferraro, F.R. 1998, *A&A*, **335**, 929.
Catelan, M., *et al.* 2006, *Memorie della Societa Astronomica Italiana*, **77**, 202.
Cavallo, R.M., Suntzeff, N.B., and Pilachowski, C.A. 2004, *AJ*, **127**, 3411.
Clement, C.M, and Walker, I.R. 1991, *AJ*, **101**, 1352.
Clement, C.M., and Rowe, J. 2000, *AJ*, **120**, 2579.
Clement, C.M., *et al.* 2001, *AJ*, **122**, 2587.
Cohen, R.E., and Sarajedini, A. 2012, *MNRAS*, **419**, 342.
Dieball, A., Long, K.S., Knigge, C., Thomson, G.S., and Zurek, D.R. 2010, *ApJ*, **710**, 332.
Ferraro, F.R, Paltrinieri, B., Pecci, F.F., Rood, R.T., and Dorman, B. 1998, *ApJ*, **500**, 311.
Ferraro, F.R, Paltrinieri, B., Rood, R.T., and Dorman, B. 1999, *ApJ*, **522**, 983.
Ferraro, F.R., Sills, A., Rood, R.T., Paltrinieri, B. and Buonanno, R. 2003, *ApJ*, **588**, 464.
Gratton, R.G., Bragaglia, A., Carretta, E., Clementini, G., Desidera, S., Grundahl, F., and Lucatello, S. 2003, *A&A*, **408**, 529.
Harris, W.E. 1996, *AJ*, **112**, 1487.
Heinke, C.O., Grindlay, J.E., Edmonds, P.D., Lloyd, D.A., Murray, S.S., Cohn, H.N., and Lugger, P.M. 2003, *ApJ*, **598**, 516.
Jerzykiewicz, M., Pigulski, A., Kopacki, G., Mialkowska, A., and Niczyporuk, S. 1996, *Acta Astron.*, **46**, 253.
Kolenberg, K., *et al.* 2010, *ApJ*, **713**, L198.
Kopacki, G. 2000, *A&A*, **358**, 547.
Kopacki, G. 2001, *A&A*, **369**, 862.
Kopacki, G. 2005, *Acta Astron.*, **55**, 85.
Kopacki, G. 2007, *Acta Astron.*, **57**, 49.
Kopacki, G. 2009, *AIPC*, **1170**, 194.

Kopacki, G., Kołaczkowski, Z., and Pigulski, A. 2003, *A&A*, **398**, 541.
Kopacki, G., and Pigulski, A. 2012, arXiv:1211.5465.
Landolt, A.U. 1992, *AJ*, **104**, 340.
Luther, E. 1860, *Astron. Nachr.*, **53**, 293.
McNamara, D.H. 1995, *AJ*, **109**, 1751.
Moskalik, P. 2013, *Stellar Pulsations, Astrophysics and Space Science Proceedings*, **31**, 103.
Nemec, J.M., Linnell Nemec, A.F., and Lutz, T.E. 1994, *AJ*, **108**, 222.
Olech, A., Woźniak, P.R., Alard, C., Kaluzny, J., and Thompson, I.B. 1999, *MNRAS*, **310**, 759.
Pogson, N.R. 1860, *MNRAS*, **21**, 32.
Santolamazza, P., Marconi, M., Bono, G., Caputo, F., Cassisi, S., and Gilliland, R.L. 2001, *ApJ*, **554**, 1124.
Sawyer, H.B. 1942, *Publ. David Dunlap Obs.*, **1**, 241 było 12.
Schaefer, B.E. 2010, *ApJS*, **187**, 275.
Shara, M.M., Hinkley, S., and Zurek, D.R 2005, *ApJ*, **634**, 1272 było 1271.
Stetson, P.B. 1987, *PASP*, **99**, 191.
Stetson, P.B. 2000, *PASP*, **112**, 925.
Thomson, G.S., Dieball, A., Knigge, C., Long, K.S., and Zurek, D.R. 2010, *MNRAS*, **406**, 1084.
Wehlau, A., Gannon, P., Rice, P., and Hogg, H.S. 1984, *IBVS*, 2586.
Wehlau, A., Sawyer Hogg, H., and Butterworth, S. 1990, *AJ*, **99**, 1159.
Welty, D.E. 1985, *AJ*, **90**, 2555.
Zacharias, N., Monet, D.G., Levine, S.E., Urban, S.E., Gaume, R., and Wycoff, G.L. 2004, *BAAS*, **36**, 1418.