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Variable stars in the globular cluster M 13

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Abstract. Results of a search for variable stars in the central region of the globular cluster M 13 are presented. Prior to this study, 36 variable and suspected variable stars were known in this cluster (Osborn 2000; Clement et al. 2001). Of these stars, five were not observed by us. We find v3, v4, v10, v12, and v13 to be constant in light. Surprisingly, only two out of the ten variable star candidates of Kadla et al. (1980) appear to be variable. Both are RRc variables. Additionally, three RR Lyrae stars and one SX Phoenicis variable are discovered. Three close frequencies are detected for an RRc star v36. It appears that this variable is another multi-periodic RR Lyrae star pulsating in non-radial modes. Light curves of the three known BL Herculis stars and all known RR Lyrae stars are presented. The total number of known RR Lyrae stars in M 13 is now nine. Only one is an RRab star. The mean period of RRc variables amounts to 0.36 ± 0.05 d, suggesting that M 13 should be included in the group of Oosterhoff type II globular clusters. Mean V magnitudes and ranges of variation are derived for seven RR Lyrae and three BL Herculis variables. Almost all observed bright giants show some degree of variability. In particular, we confirm the variability of two red giants announced to be variable by Osborn (2000) and in addition find five new cases.

Key words. stars: population II – stars: variables: RR Lyr – stars: variables: Cepheids – globular clusters: individual: M 13

1. Introduction

This is the third paper in a series devoted to the CCD photometry of variable stars in bright globular clusters of the northern sky. In the first two papers (Kopacki 2000, 2001) the results of the search for variables in M 53 and M 92 were presented. Application of the image subtraction method allowed us to confirm variability of 11 RR Lyrae stars and discover ten new variables: eight RR Lyrae and two SX Phoenicis stars. In the present paper we give the results of the photometric study of yet another cluster, M 13. An announcement of this work was given by Kopacki et al. (2002).

M 13 (NGC 6205, C1639+365) is an intermediate metallicity globular cluster. Its metallicity on the Zinn's (1985) scale is [Fe/H] = −1.65. The cluster is located relatively far from the Galactic plane. In consequence, its reddening is small; $E(B-V)$ = 0.02 mag according to Schlegel et al. (1998). Many colour–magnitude diagrams of this cluster have been published. As far as we are aware, the most recent CCD photometric study of M 13 is that of Rey et al. (2001). All these works show that the horizontal branch of M 13 is predominantly blue.

In the next section we give an account of the previous work on variable stars in M 13. In subsequent sections we present our observations and the results of our search for variable stars in the central region of the cluster using the Image Subtraction Method of Alard & Lupton (1998). We also comment on variability of all observed suspected variable stars. For stars proved by us to be variable we determine periods and plot the light curves.

2. Variable stars in M 13

The latest version of the Catalogue of Variable Stars in Globular Clusters (CVSGC, Clement et al. 2001) lists 33 variable and suspected variable stars in M 13. Hereafter, the numbering system of this catalogue will be used. There are, however, other stars in M 13 suspected to be variable but not included in the CVSGC. In these cases the numbering scheme of Ludendorff (1905) will be used, and star numbers of this system will be prefixed with the letter 'L'.

Below we give chronological description of variable star history in M 13. One should note, however, that the numbering system of the CVSGC does not follow exactly the discovery order.

Altogether, three Cepheids of the BL Herculis type (v1, v2, and v6) and four RR Lyrae stars (v5, v7, v8, and v9) are known in the cluster. The remaining variable stars are mainly semiregular red giants.

The first variable stars in M 13, v1 and v2, were discovered in 1898 by Bailey (1902). Barnard (1900a, 1900b), after hearing about the findings of Bailey, rediscovered v2 and determined its period to be 5.1 d. For v1 Barnard (1909) derived a period of 6.0 d. It appeared that both these variables were Cepheids. The next variable star to be discovered in the cluster, now known as v7, was found by Barnard (1914). He also reported L258 and L682 as probable variable stars. The vari-

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ability of v7 was confirmed by Shapley (1915b). Subsequently, Shapley (1915a) identified four additional stars (v3 – v6) as variable, for which he suspected short periods.

The earliest version of the CVSGC (Sawyer 1939) listed seven variable or suspected variable stars in M 13, v1 – v7. Sawyer (1940) found four additional variables, v8 – v11. She could not resolve v9 and v5 (see Fig. 1). In the following paper, Sawyer (1942) gave light curves for four variables and classified v1, v2, and v6 as Cepheids, and v8 as an RR Lyrae variable. She confirmed Barnard's (1909) period of v2 and determined a correct period of 1.45899 d for v1. For the third Cepheid, v6, she derived a period of 2.11283 d. Although she could not resolve v5 and v9, she concluded that these two variables are probably RR Lyrae stars. As to the suspected variables v10 and v11, Sawyer (1942) considered them to be bright irregular variables.

Kollnig-Schattschneider (1942) extended the list of variable stars in M 13 with three new suspects, v12 – v14. For 11 variables (v1 – v8, v12 – v14) she derived periods and presented light curves. Although she classified v3, v4, v12, v13, and v14 as RR Lyrae stars with unusually short periods in the range 0.13 – 0.24 d, inspection of her light curves for these stars hardly indicates any variation. She determined also a period of about 0.75 d for an RRab variable v8.

The next variable star in M 13, v15, was found by Arp (1955a, 1955b). In the first paper, Arp (1955a) showed light curves of v1, v2, and v6, in the second (Arp 1955b) he published light curves for two certain RR Lyrae stars, v7 and v8. For v7 Arp (1955b) derived a very short period of 0.2388 d. The second edition of the CVSGC by Sawyer (1955) lists 15 objects in M 13, v1 – v15. However, variability of v3, v4, v12, v13, and v14 was questioned on the basis of unpublished material of Arp and Sawyer. Tsoo (1967) found two suspected variable stars, of which only one, v16, was included in the CVSGC.

Osborn (1969a) studied period changes of v1, v2, v6, and v8. He also determined periods for two RR Lyrae stars, v5 and v9 (Osborn 1969b, 1973). Demers (1971) presented *UBV* photographic photometry of v1, v2, v6, v7, v8, and v11. He established that v11 is a long-period variable with period equal to 92.5 d. Ibanez & Osborn (1973) corrected Arp's (1955b) period of v7 to 0.312929 d. Furthermore, Osborn & Ibanez (1973) reobserved v16 and found this star to be constant. Osborn et al. (1973) examined new photographic observations of v3 and concluded that this star is most likely non-variable. Russev (1973) investigated eight variable stars in M 13, v1, v2, v5 – v8, v11, and v15. He derived a period of 91.77 d for v11 and a period of 140.3 d for v15. Moreover, he detected variations in three red giants, L334, L414, and L917.

In the third edition of the CVSGC, Sawyer-Hogg (1973) listed 16 variables in M 13, v1 – v16. In a paper on infrared photometry of M 13, Russev (1974) mentioned the variability of one red giant, v17 (L973). His observations of L414 indicated that this star is indeed variable. Subsequently, Fuenmayor & Osborn (1974) confirmed the variability of v17 and derived a period of about 39 d, but did not detect any light variation of L414. In their photometric study of the central region of M 13, Kadla et al. (1976) found some evidence of variability for three stars, L194, L598, and L222; the first two were subsequently designated as v19 and v24.

The next variable red giant in M 13, v20 (L70), was found by Pike & Meston (1977) in their photometric study of the cluster pulsating stars. At about the same time, Osborn & Fuenmayor (1977) presented photographic *B* photometry for v2, v10, v11, and v15, as well as for two suspected red variables, v17 and L414. They showed that v11, v15, and v17 are semiregular variables with mean periods of 92.42, 39.23, and 39.14 d, respectively, but could not confirm the variability of v10 and L414. Bisard & Osborn (1977) modified the period of the RR Lyrae star v7 to 0.3126626 d.

Meinunger (1978) announced finding three suspected variable stars. Russev & Russeva (1979a) analyzed archival and new observations of v17 and determined a period of about 43 d for this red giant. The same authors, Russev & Russeva (1979b), investigated once again the variation of v11 and concluded that its light curve is probably subject to periodic changes. A more thorough study of v1, v2, v4, v6 – v8, v11, v12, and v15 by Russev & Russeva (1979c) resulted in deriving periods of 0.298827 and 5.21753 d for v4 and v12, respectively, the two stars previously regarded constant (Sawyer-Hogg 1973). These authors suggested that v4 is an RRc variable.

Additional three suspected variable red giants in M 13, L72, L240, and L261, were found by Russeva & Russev (1980). Of these stars, L72 is listed in the CVSGC as v18. Russeva & Russev (1980) confirmed the variability of v19 and derived periods of 35.62, 39.23, 41.25, 44.48, and 64.26 d for v10, v15, v18, v19, and v20, respectively. Kadla et al. (1980) searched the core of M 13, and discovered ten new suspected variable stars. These variables were included in the CVSGC with designations v21 – v23 and v25 – v31 (v24 has been discovered earlier by Kadla et al. 1976). Because of their photometric parameters, variables v27 – v31 were supposed by Kadla et al. (1980) to be of the RR Lyrae type.

Subsequently, White (1981) reported the discovery of light variations of three asymptotic branch giants in M 13, L687, L773, and L961. Five stars in the cluster were investigated for variability by Russeva et al. (1982). These authors found L66 and v24 undoubtedly variable. The new variable L66 was denoted in the CVSGC as v32. For the remaining three stars, L526, L761, and L1067, Russeva et al. (1982) did not detect any variability. The period changes of short-period variable stars in M 13 were studied by Russeva & Russev (1983). They suggested that M 13 belongs to the Oosterhoff type I globular clusters.

A large sample of bright red giants in M 13, including all previously suspected to be variable, was checked for variability by Welty (1985). The result was the confirmation of variation for v11, v17 – v20, and the detection of light changes in a new suspected variable, v33 (L954), which was considered constant by White (1981). Recently, Osborn (2000) presented *UBVRI* photometry for variable stars in M 13. He found v3, v4, v10, v12, v13, v15, and v18 to be most probably constant in light and detected variability in two red giants, L629 and L940. Moreover, Osborn (2000) checked White's (1981) three possible red variables (L687, L773, L961) and Russeva & Russev's

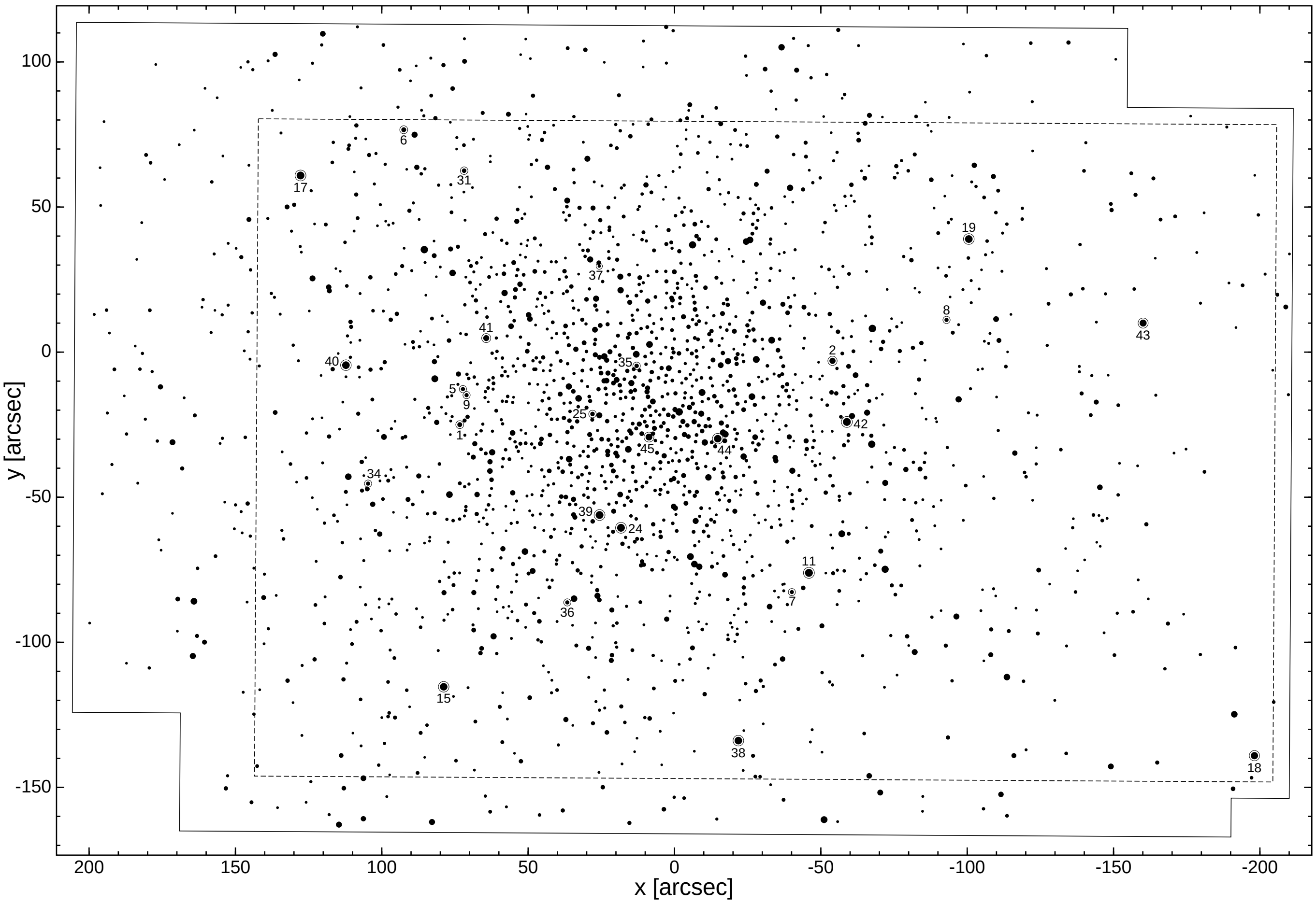

Fig. 1. Schematic view of the observed field of M 13. The rectangle drawn with dashed lines denotes the region which was searched for variable stars using the image subtraction method. For clarity, only stars brighter than 17 mag in V are shown. All observed variable stars are marked with open circles and are labeled with their numbers given in Tables 1 or 2. Positions (x, y) are in the reference frame of the CVSGC. North is up, East to the left.

(1980) two other suspects (L240, L261) and found them constant in light.

3. Observations and reductions

The CCD observations presented here were carried out at the Białków station of the Wrocław University Observatory with the same equipment as that described by Kopacki & Pigulski (1995). A 6×4 arcmin^2 field of view covering the core of the cluster was observed through V and I_C filters of the Johnson-Kron-Cousins $UBV(RI)_C$ system. The observed field was chosen to include as many as possible of the known variable stars in M 13.

The observations were carried out on 23 nights between 2001 February 27 and August 1. In all, we collected 324 and 342 frames in the I_C and V bands, respectively. Usually, the exposure times amounted to 300 s for the V-filter frames and 200 s for the I_C-filter frames. On most nights the weather was very good. On some nights, however, the sky brightness was rather high due to the bright Moon; on some others the sky transparency was affected by thin cirrus clouds. The seeing varied over a rather wide range, between 1.7 and 3.9 arcsec, with a typical value of 2.4 arcsec.

The pre-processing of the frames was performed in the usual way and consisted of subtracting bias and dark frames and applying the flat-field correction. Instrumental magnitudes for all stars in the field were computed using the DAOPHOT profile-fitting software (Stetson 1987). All images were reduced in the same way as described by Jerzykiewicz et al. (1996). We identified 3124 stars in the observed field. A finding chart for the monitored field is shown in Fig. 1.

Our average instrumental V-magnitudes were transformed to the standard ones using the recent BV photometric data of Rey et al. (2001). To do this, we obtained on two nights, 2002 February 13/14 and 14/15, 12 I_C-filter and 11 V-filter CCD frames of an additional field shifted about 2.5 arcmin to the east in respect to the main observed field. Thirty six stars in common with Rey et al. (2001) were found, and the following transformation equation was obtained:

$$V - v = +0.074\,(v - i) + 13.474, \qquad \sigma = 0.027,$$

Table 1. Types of variability, corrected positions (x, y) relative to the cluster centre, periods (P) and epochs of light-maximum ($T_{\rm max}$ = HJD$_{\rm max}$ − 2400000) of the short-period pulsating stars in the observed field of M 13. Coordinates are given in the reference frame of the CVSGC.

Var	Type	x [″]	y [″]	P [d]	$T_{\rm max}$
v1	BL Her	73.43	−24.96	1.459033	52000.120
v2	BL Her	−53.88	−3.00	5.110818	51999.600
v5	RR Lyr	72.37	−12.59	0.38180	52000.330
v6	BL Her	92.52	76.65	2.112918	51999.812
v7	RR Lyr	−40.02	−82.56	0.31269	51999.984
v8	RR Lyr	−92.78	11.04	0.750316	51999.785
v9	RR Lyr	70.86	−15.03	0.39278	52000.194
v25	RR Lyr	28.05	−21.19	0.42956	52000.195
v31	RR Lyr	71.73	62.48	0.31930	51999.995
v34	RR Lyr	104.69	−45.25	0.38933	51969.139
v35	RR Lyr	13.09	−4.88	0.32003	52000.003
v36	RR Lyr	36.93	−86.03	0.31584 P_1	52023.214
				0.30441 P_2	52023.158
				0.33497 P_3	52023.086
v37	SX Phe	25.70	29.62	0.04941	52000.002

where uppercase letters denote standard magnitudes and lowercase letters, the instrumental ones; σ is the standard deviation from the fit.

Using the above given equation, instrumental V-filter magnitudes of the variable stars were transformed to the standard system in the same way as described by Kopacki (2001).

In order to search for variable stars in the core of the cluster we reduced our CCD frames using the Image Subtraction Method (ISM) package developed by Alard & Lupton (1998). This method allows obtaining very good quality light-curves even in very crowded fields and is now in common use. The same procedure of reductions as in Kopacki (2000) was followed; we refer the reader to this paper for details.

In the next step for each variable-star candidate detected in the ISM variability map we computed the AoV periodogram of Schwarzenberg-Czerny (1996) in the frequency range from 0 to 30 d^{-1}. To identify variable and constant stars we checked visually these periodograms as well as light curves.

4. Results of the variability survey

Out of the 33 variable and suspected variable stars listed in the CVSGC, five were outside the field investigated by us. These were v14, v16, v20, v32, and v33. Moreover, the field we observed included two suspected variable red giants of Osborn (2000). We found v3, v4, v10, v12, and v13 to be constant in light. Our conclusion is in agreement with Osborn's (2000) less accurate photometry for these stars. It should be mentioned that v4 was classified in the CVSGC as an RRc star for which Russev & Russeva (1979c) derived a period of 0.298827 d.

For the three BL Herculis stars known in the cluster, v1, v2, and v6, light-curves with good phase coverage were obtained. The V- and $I_{\rm C}$-filter light-curves of these three stars are plotted in Fig. 2. Our light-curves of v1 and v6 show clearly bumps on the ascending branches. This feature for v1 was previously

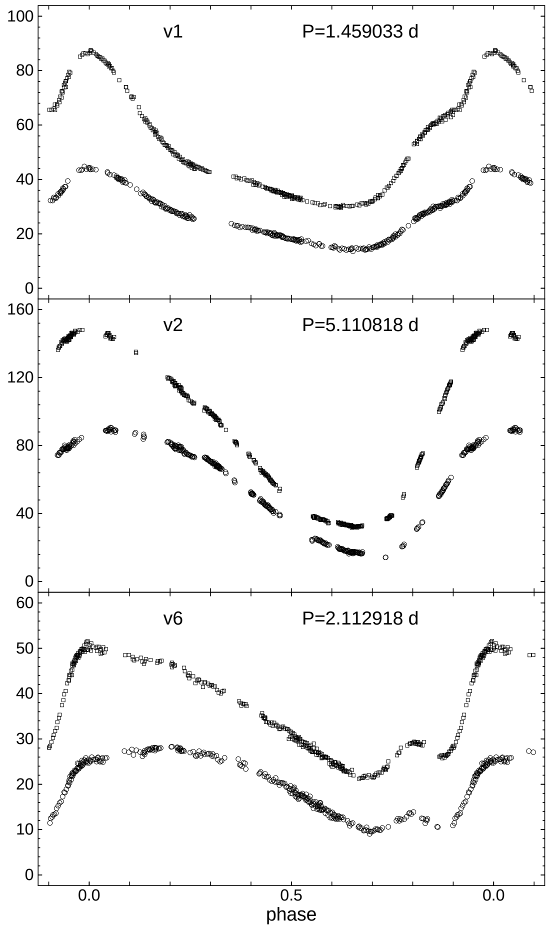

Fig. 2. V-filter (squares) and $I_{\rm C}$-filter (circles) light-curves of the three BL Herculis variables. Ordinate is expressed in arbitrary flux units. Note the differences in the ordinate scales.

suggested by Osborn (1976 and references therein) and now is definitely confirmed.

Surprisingly, only two out of the ten suspected variable stars of Kadla et al. (1980), viz. v25 and v31, appear to be variable. All eight remaining stars show no evidence of variability in our data. We classify v25 and v31 as RRc variables. The V- and $I_{\rm C}$-filter light-curves of these two RR Lyrae stars, as well as those of the four previously known variables of this type are shown in Fig. 3.

In addition, four new short-period pulsating stars have been found in the cluster. Three of them are of RR Lyrae type, the fourth is an SX Phoenicis star. Extending the numbering scheme of the CVSGC for M 13, we designate these new variables as v34 through v37. Their V- and $I_{\rm C}$-filter light-curves are shown in Fig. 4. As can be seen in this figure, the scatter of observations in the light curve of the RRc star v36 is much larger than for other RRc variables. This variable deserves more detailed analysis and will be discussed separately.

Positions relative to the cluster centre, types of variability, adopted periods, and computed epochs of light-maximum of the short period variable stars we observed are given in Table 1. Coordinates are given in the reference frame of the

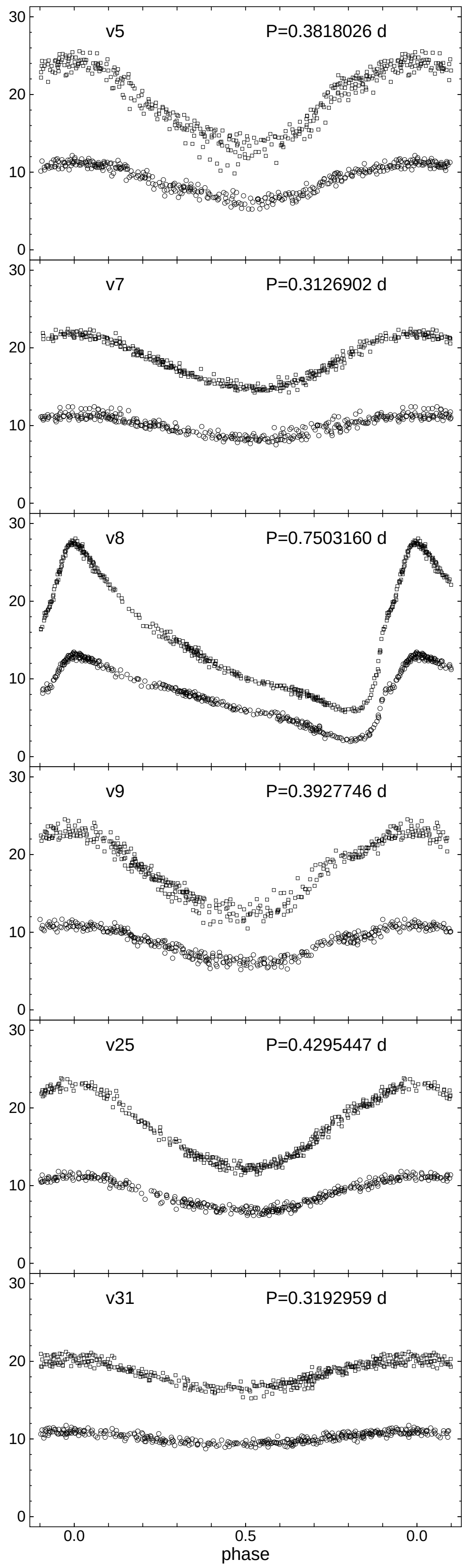

Fig. 3. V-filter (squares) and I_C-filter (circles) light-curves of the observed RR Lyrae stars listed in the CVSGC. The variables are arranged according to their numbers in that catalogue. Ordinate is expressed in the same flux units as in Fig. 2.

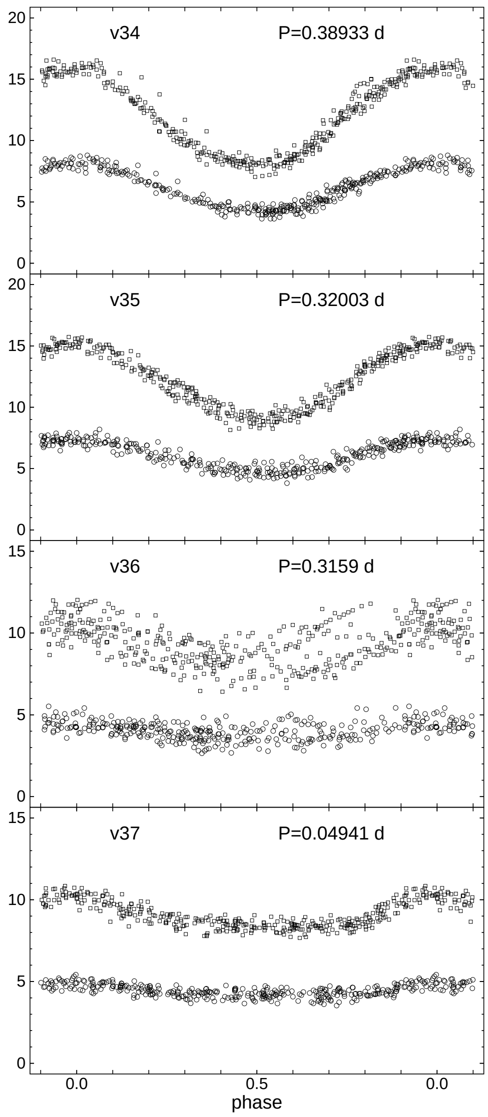

Fig. 4. V-filter (squares) and I_C-filter (circles) light-curves of four new variable stars: three RR Lyrae stars (v34 – v36) and an SX Phoenicis star, v37. Ordinate is expressed in the same flux units as in Fig. 2. Note the differences in the ordinate scales.

CVSGC, but were redetermined using positions of 16 stars in the CVSGC. All these variables are also indicated in Fig. 1.

The periods of the BL Herculis stars and the RRab variable v8 given in Table 1 were taken from the CVSGC. For all previously known RRc variables, v5, v7, and v9, we determined revised periods using our observations only. These new periods produced smoother light-curves than the old ones. Other periods listed in Table 1 were derived for the first time from our data alone using multi-harmonic AoV periodogram method of Schwarzenberg-Czerny (1996).

The total number of known RR Lyrae stars in M 13 equals now nine. Only one of them is an RRab star. The mean period of RRc variables amounts to 0.36±0.05 d, suggesting that M 13 should be included in the Oosterhoff type II group of globular clusters.

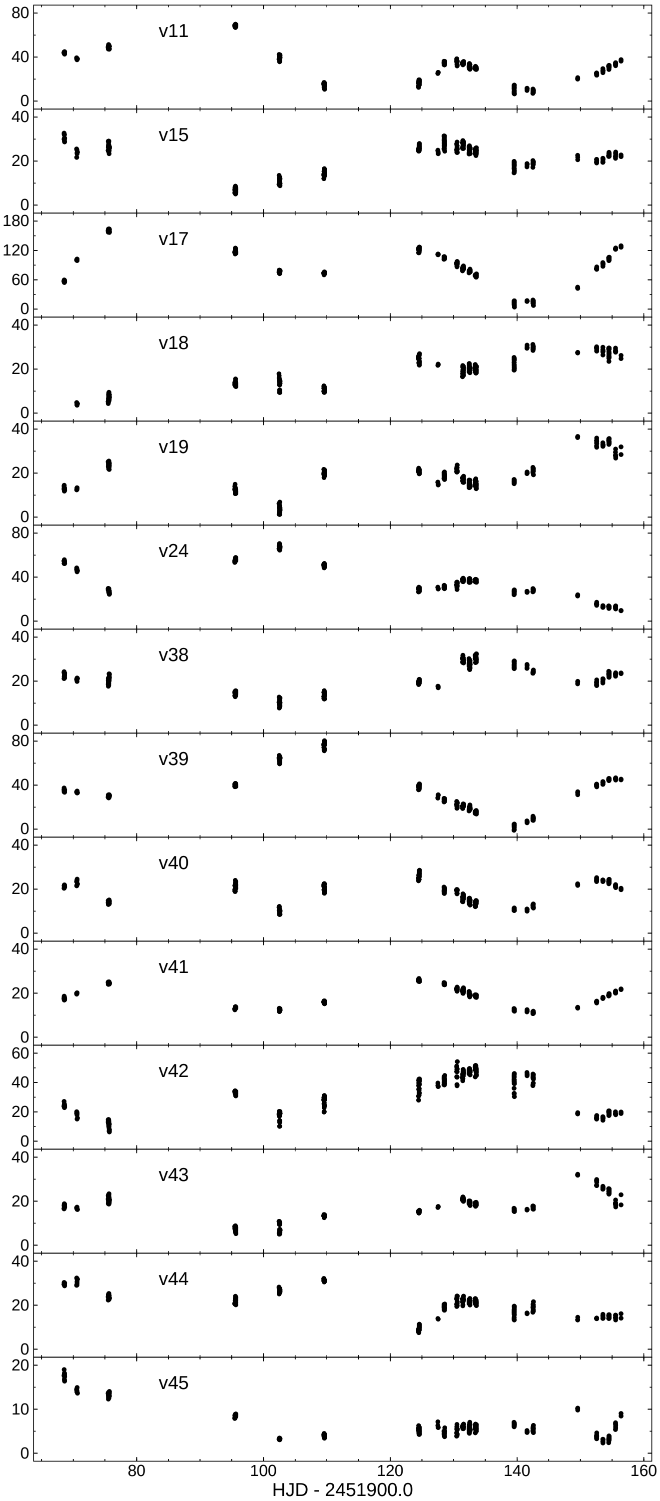

Fig. 5. V-filter light-curves of the observed variable red giants. Except v41, they all exhibit irregular brightness variations. Ordinate is expressed in the same flux units as in Fig. 2. Note the differences in the ordinate scales.

Bright giants in globular clusters usually show some degree of variability. In M 53, for example, seven giants are known to be variable (Kopacki 2000). On the other hand, no variable red giant was found by Kopacki (2001) in M 92.

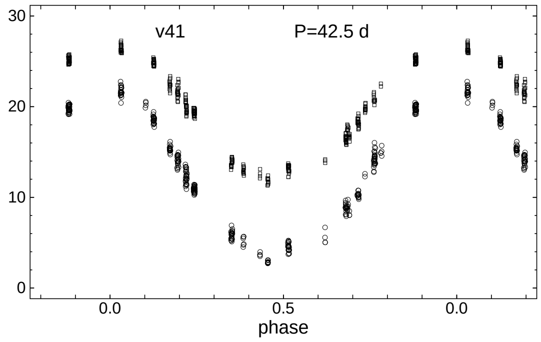

Fig. 6. V-filter (squares) and I_C-filter (circles) observations of the new variable red giant, v41, phased with the period of 42.5 d. Ordinate is expressed in the same flux units as in Fig. 2.

Table 2. Positions (x, y) relative to the cluster center, average V-brightnesses, $\langle V\rangle$, and the ranges of variability, ΔV, of the observed red-giant variables. Coordinates are given in the reference frame of the CVSGC.

Var	x [″]	y [″]	$\langle V\rangle$ [mag]	ΔV [mag]
v11	−45.81	−76.07	11.928	0.13
v15	78.88	−115.40	12.139	0.09
v17	127.86	60.97	11.976	0.38
v18	−197.67	−138.87	12.319	0.11
v19	−100.31	38.88	12.066	0.09
v24	18.46	−60.42	12.005	0.24
v38	−21.69	−133.88	12.118	0.07
v39	25.63	−56.05	11.980	0.22
v40	112.03	−4.25	12.075	0.08
v41	64.49	4.92	13.155	0.11
v42	−58.83	−24.04	11.940	0.10
v43	−159.92	9.96	12.470	0.07
v44	−14.74	−29.64	–	–
v45	8.89	−29.27	–	–

CVSGC lists ten suspected red variables in M 13, of which we observed seven. Except for v10, the other six above-mentioned red giants show light variations. We confirm also the variability of the Russev's (1973) suspect, L414, as well as the two red giants of Osborn (2000), L629 and L940. Since these three variables are not included in the CVSGC, we name them with consecutive numbers as v38, v39, and v40, respectively. Moreover we discovered five new variable red giants which we designate v41 through v45. Positions of all red giants we found variable, computed in the same way as for RR Lyrae stars, together with the average V-filter brightnesses and ranges of variability are given in Table 2. Fig. 5 shows the light curves of these variables. All variable red giants are also indicated in Fig. 1.

Almost all red variables seem to be semi- or irregular. In particular, we could not confirm any period determined earlier for these variables (see Sect. 2). The only red giant showing a periodic variation, at least over the time covered by our observations, is v41. For this variable we derived a period of 42.5 d.

Observations of v41, phased with this period, are presented in Fig. 6.

The suspects not included in the CVSGC deserve a comment. Firstly, we identified three suspected variable stars of Meinunger (1978). Her star a is L765 and is outside the field we observed. Star b could not be found in the Ludendorff's list. In our CCD frames it forms a blend of two faint stars situated close to L956. The equatorial coordinates of the brighter component are given in Table 3. Both these stars are constant in light. The third suspect, star c, can be safely identified as L993, which is known UV-bright object in M 13 (Zinn et al. 1972). On the basis of radial velocity and proper motion measurements (Zinn 1974, Cudworth & Monet 1979) the star was regarded as a cluster member. It shows no evidence of variability in our data.

Of all other suspected variable stars in M 13 we observed the blue straggler L222 and two red giants, L261 and L334. We found these three stars constant in light. L222 also known as Barnard 29 (Barnard 1914) is a very interesting object, which is now believed to be hot cluster post-AGB star (Conlon et al. 1994).

Altogether, the light curves have been obtained for 13 variable stars in the Cepheid instability strip and for 14 variable red giants. The observations are available in electronic form from CDS in Strasbourg via anonymous ftp to `cdsarc.u-strasbg.fr` (or `130.79.128.5`). For each variable we give a list of HJD of frame mid-exposure along with V and I_C magnitudes and ISM fluxes, their errors, and air masses.

Using 200 reference stars from the HST Guide Star Catalog, Version 2.2.01 we transformed our DAOPHOT rectangular coordinates of all observed variable and suspected variable stars in M 13 into J2000.0 equatorial coordinates. These positions are given in Table 3. We found our coordinates shifted systematically 0.58 ± 0.02 arcsec east and 0.24 ± 0.02 south in respect to those derived by Osborn (2000) based on 39 stars in common. Undoubtedly these differences result from Osborn's use of a different reference star catalogue, the USNO-A2.0. All objects under consideration were also cross-identified with stars in Ludendorff's (1905) list. The Ludendorff's numbers are given in the second column of Table 3. It should be noted that Kadla et al. (1980) erroneously identified v28 as L569. Using their coordinates for this star we found it to be in fact L519.

Table 3. Equatorial coordinates of all observed variable and suspected variable stars in M 13. L is a Ludendorff's number and 'RG' denotes variable red giant. Stars a and b are Meinunger's suspects.

Var	L	Type	α_{2000} [$^{\rm h\ m\ s}$]	δ_{2000} [$^\circ\ '\ ''$]
v1	816	BL Her	16 41 46.45	36 27 27.7
v2	306	BL Her	16 41 35.88	36 27 48.3
v5	806β	RR Lyr	16 41 46.35	36 27 39.9
v6	872	BL Her	16 41 47.95	36 29 09.6
v7	344	RR Lyr	16 41 37.10	36 26 28.8
v8	206	RR Lyr	16 41 32.64	36 28 02.0
v9	806α	RR Lyr	16 41 46.24	36 27 37.8
v11	324	RG	16 41 36.61	36 26 35.3
v15	835	RG	16 41 46.98	36 25 57.3
v17	973	RG	16 41 50.89	36 28 54.2
v18	72	RG	16 41 24.06	36 25 30.6
v19	194	RG	16 41 31.98	36 28 29.8
v24	598	RG	16 41 41.91	36 26 51.5
v25	630	RR Lyr	16 41 42.68	36 27 31.0
v31	807	RR Lyr	16 41 46.25	36 28 55.2
v34	918	RR Lyr	16 41 49.06	36 27 07.7
v35	571	RR Lyr	16 41 41.43	36 27 47.1
v36	–	RR Lyr	16 41 43.45	36 26 26.0
v37	–	SX Phe	16 41 42.45	36 28 21.8
v38	414	RG	16 41 38.65	36 25 37.7
v39	629	RG	16 41 42.51	36 26 56.0
v40	940	RG	16 41 49.66	36 27 48.6
v41	782	RG	16 41 45.67	36 27 57.4
v42	289	RG	16 41 35.49	36 27 27.2
v43	96	RG	16 41 27.08	36 28 00.2
v44	445	RG	16 41 39.15	36 27 21.9
v45	554	RG	16 41 41.09	36 27 22.7
v3	135	const	16 41 29.75	36 28 07.2
v4	322	const	16 41 36.17	36 28 51.5
v10	487	const	16 41 39.96	36 26 41.3
v12	187	const	16 41 31.54	36 28 44.1
v13	327	const	16 41 36.65	36 27 20.8
v21	216	const	16 41 33.43	36 27 10.7
v22	568	const	16 41 41.27	36 28 13.0
v23	575	const	16 41 41.60	36 27 38.4
v26	748	const	16 41 45.08	36 27 37.2
v27	254	const	16 41 34.50	36 27 52.3
v28	519	const	16 41 40.44	36 27 29.9
v29	717	const	16 41 44.27	36 28 31.7
v30	743	const	16 41 44.97	36 27 04.0
–	222	const	16 41 33.64	36 26 07.6
–	261	const	16 41 34.74	36 27 59.3
–	334	const	16 41 36.77	36 26 30.1
b	–	const	16 41 49.79	36 28 20.9
c	993	const	16 41 52.05	36 26 28.8

4.1. The case of v36

RRc variable v36 exhibits much larger scatter in the light curve than other variables of this type (see Fig. 4). A closer look at the individual nights indicates modulation of the amplitude on time scale of several days.

The Fourier spectrum of the original V-filter data of v36 is presented in Fig. 7a. Two close peaks with almost the same height are seen in this figure. The highest peak occurs at frequency $f_1 = 3.1661$ d^{-1} ($P_1 = 0.31584$ d). The periodogram of the I_C-filter observations (not given here) shows the same pattern of highest peaks. Periodogram of the residuals obtained after prewhitening the V-filter observations with the main frequency f_1 is shown in Fig. 7b. The highest peak is seen at frequency $f_2 = 3.2850$ d^{-1} ($P_2 = 0.30441$ d). In Fig. 7d we show the periodogram of the V-filter residuals obtained after removing the f_1 and f_2 frequencies. As can be seen, another significant peak appears at frequency $f_3 = 2.9853$ d^{-1} ($P_3 = 0.33497$ d). It should be noted that this frequency is almost equal to 3 d^{-1} and at present we cannot be sure that it is real. After prewhitening the data with the f_1, f_2, and f_3, we obtain resid-

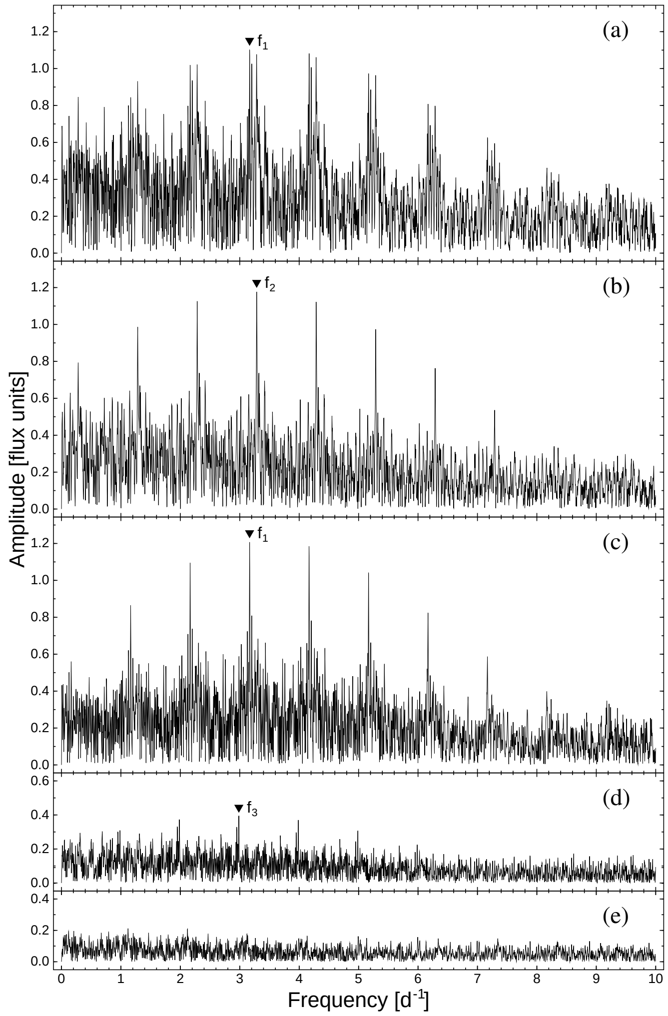

Fig. 7. Fourier periodograms of the RRc variable v36: **a**) for original V-filter data, **b**) after prewhitening with frequency f_1 = 3.166 d^{-1}, **c**) after removing frequency f_2 = 3.285 d^{-1} only, **d**) after prewhitening with both f_1 and f_2 frequencies, and **e**) after prewhitening with f_1, f_2, and f_3 = 2.985 d^{-1}. Ordinates are expressed in the same flux units as in Fig. 4.

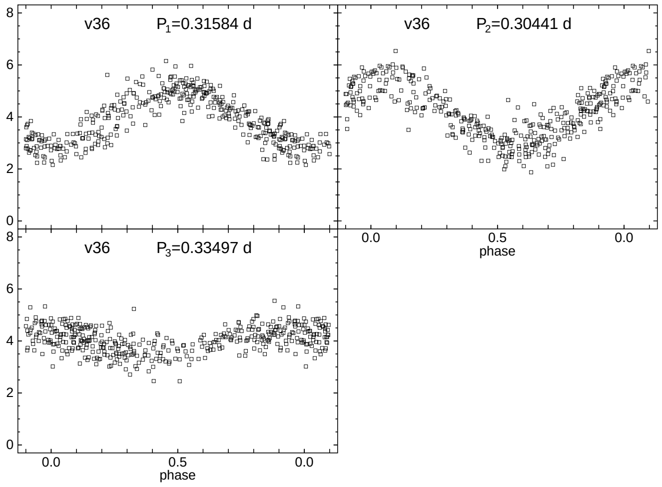

Fig. 8. V-filter light-curves of the RRc variable v36. The upper left panel shows the data prewhitened with f_2 and f_3 and phased with the period P_1. The upper right panel shows the residuals obtained after removing the f_1 and f_3 components, and phased with the period P_2. The lower panel shows the data prewhitened with f_1 and f_2 and phased with the period P_3. Initial epoch was chosen arbitrarily, but it is the same for all light curves. Ordinate is expressed in the same flux units as in Fig. 4.

uals for which a power spectrum is practically flat (Fig. 7e). Prewhitened light-curves phased with periods P_1, P_2, and P_3, respectively, are shown in Fig. 8.

Thus, for v36 we get three close frequencies with a small separations, $f_2 - f_1 = 0.12$ d^{-1} and $f_1 - f_3 = 0.18$ d^{-1}. Our conclusion is that v36 belongs to the new group of the multi-mode RRc stars discovered by Olech et al. (1999a, 1999b). The frequencies of these variables are so closely spaced that the ratios of periods are higher than 0.95 and could be as large as 0.999 (Alcock et al. 2000). For ratios of this order it is clear that if the main period is the first overtone radial mode then the other ones are non-radial modes. However, in the case of v36 it is not possible to unambiguously indicate which frequency corresponds to the radial mode, because f_1 and f_2 have almost the same amplitude. Among the RRc stars in M 13, the periods of v36 are the shortest ones.

Table 4. RR Lyrae stars in globular clusters for which non-radial modes have been found.

Cluster	[Fe/H]	Variables	Source
M 5	−1.25	v104	Olech et al. (1999b)
M 13	−1.65	v36	this paper
M 55	−1.90	v9, v10, v12	Olech et al. (1999a)
M 92	−2.24	v11	Kopacki (2001)
NGC 6362	−1.08	v6, v10, v37	Olech et al. (2001)

At present, nine RR Lyrae stars for which non-radial mode(s) have been detected are known in globular clusters; they are listed in Table 4.

5. Light-curve parameters

Mean brightnesses of variable stars were derived both as the intensity- and magnitude-weighted averages in the same way as in Kopacki (2001). However, instead of using DAOPHOT light-curves we used ISM light-curves transformed to the magnitude scale. The conversion of the ISM light-curves was accomplished by using all available DAOPHOT magnitudes. For each variable star the following equation

$$m_i - m_0 = -2.5 \log (1 + \Delta f_i / f_0)$$

was solved by the method of the least-squares to find two parameters, reference point in magnitude, m_0, and reference point in the flux, f_0. Above, m_i denote DAOPHOT magnitudes and Δf_i ISM relative fluxes. Knowing m_0 and f_0 we transformed ISM light-curves into instrumental magnitudes and subsequently into the standard magnitudes. In this way, the quality of the derived light-curves (measured with the standard

Table 5. Average intensity-weighted, $\langle V \rangle_i$, and magnitude-weighted, $\langle V \rangle_m$, V brightnesses, and the ranges of variability, ΔV, for seven RR Lyrae stars and three BL Herculis variables, all located well outside the cluster core. Additionally, ΔV range, derived from the ISM photometry is shown for two other RR Lyrae stars, v25 and v35, situated in the central area of the cluster. σ_V denotes the r.m.s. error of the average brightness derived from the best fit Fourier decomposition of the light curve.

Var	$\langle V \rangle_i$ [mag]	$\langle V \rangle_m$ [mag]	ΔV [mag]	σ_V [mag]
v1	14.086	14.138	1.041	0.001
v2	13.012	13.054	0.870	0.001
v5	14.767	14.777	0.425	0.002
v6	14.078	14.095	0.600	0.001
v7	14.925	14.930	0.305	0.001
v8	14.850	14.880	0.836	0.001
v9	14.819	14.829	0.434	0.002
v31	14.432	14.433	0.113	0.001
v34	14.828	14.834	0.320	0.001
v36	14.809	14.810	0.056 f_1	0.001
			0.064 f_2	0.001
			0.024 f_3	0.001
v25	–	–	0.44	0.01
v35	–	–	0.25	0.01

deviation of the magnitudes from the best finite Fourier series fit) was on average improved by a factor of 1.6. It should be mentioned that most authors derive reference points only from one frame, usually ISM reference image. However, it was already pointed out by Benkő (2001) that in order to obtain reliable transformations of the ISM fluxes into magnitudes, the reference magnitudes have to be known with a high accuracy.

The light-curve parameters are given in Table 5. Only variable stars for which a reliable DAOPHOT profile photometry could be obtained are included in this table. For v36 we give full-amplitudes of all three detected modes. As can be seen in Table 5, the RR Lyrae star v31 is about 0.4 mag brighter than the other RR Lyrae variables. We supposed that it is most probably caused by the presence of a close companion unresolved in our CCD frames. Our suspicion has been confirmed by investigation of the recent HST pictures of M 13, where v31 is clearly seen as a close pair of stars.

The mean V magnitude of the horizontal branch, $\langle V_{HB} \rangle_i$, estimated using intensity-weighted mean magnitudes of six RR Lyrae stars listed in Table 5 (we excluded v31 for the reason given above), is equal to 14.83 ± 0.02 mag.

As discussed in detail by Kopacki (2001) and Benkő (2001), the ISM of Alard & Lupton (1998) does not allow one to derive light curves expressed in magnitudes without knowing at least one reference magnitude corresponding to some ISM relative flux. This additional parameter is usually derived from the DAOPHOT photometry and is lacking for stars located in the crowded core of the globular cluster. However, we expect all RR Lyrae stars in the cluster to have very similar average brightness, and this average brightness may be used as a reference magnitude, although exclusively for RR Lyrae variables.

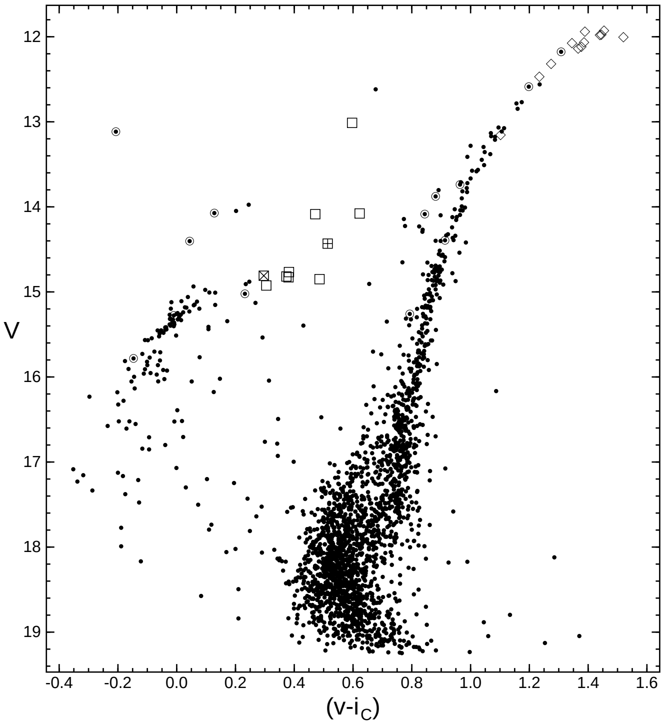

Fig. 9. The V vs. $(v - i_C)$ colour-magnitude diagram for M 13. Only stars with the distance from cluster centre greater than 1.8 arcmin and the error in $(v - i_C)$ smaller than 0.1 mag are included. RR Lyrae and BL Herculis stars are shown with open squares and are represented by their intensity-weighted mean V brightness and magnitude-weighted mean $(v - i_C)$ colour index. Multi-periodic RRc star v36 is additionally marked with the 'x' sign. Semiregular variable red giants are plotted as open diamonds. Some suspected variable stars listed in the CVSGC, which turned out to be constant, are also shown with symbols enclosed within circles. Note the unusual position of an RRc variable v31 (indicated with the plus sign), caused by the presence of a close companion unresolved in our CCD frames.

Using several RR Lyrae stars for which both reliable DAOPHOT and ISM light-curves were obtained we determined linear transformation between the flux measured by DAOPHOT and differential flux of the ISM. Assuming that RR Lyrae stars lying in the cluster central region have the same intensity-weighted average brightness, equal to the average magnitude of the horizontal branch, $\langle V_{HB} \rangle_i$, we were able to compute ΔV ranges of these stars. ΔV ranges of the two RR Lyrae variables, v25 and v35, derived in this way, are listed in Table 5.

6. The colour-magnitude diagram

The V vs. $(v - i_C)$ colour-magnitude diagram for M 13 is shown in Fig. 9. Only stars with distance from the cluster center greater than 1.8 arcmin and having an error in the colour-index smaller than 0.1 mag are plotted. Variable stars are represented by their intensity-weighted mean $\langle V \rangle_i$ brightness and instrumental magnitude-weighted mean $\langle v - i_C \rangle_m$ colour index.

The colour-magnitude diagram shows a well-defined red giant branch, asymptotic giant branch, and the predominantly blue horizontal branch. There is a clear separation between the variable and constant stars and also between one RRab star and RRc variables. One should note an unusual position of the RRc variable v31, which is brighter and redder than all other RR Lyrae stars in the cluster. As we already pointed out, it is caused by blending with another star.

In the colour-magnitude diagram the multi-periodic non-radial pulsating RRc variable v36 is situated at the blue edge of the instability strip. The same result was obtained by Olech et al. (1999a) for three non-radial pulsating RRc stars in M 55, by Olech et al. (2001) in the case of also three RRc variables in the cluster NGC 6362, and by Kopacki (2001) for one such variable in M 92.

Thirteen suspected variable stars for which reliable photometry was obtained but did not show evidence of variations are also shown in Fig. 9. Three of them, v4, v12, and v29, occupy the blue part of the horizontal branch and lie outside the RR Lyrae instability strip. The bright blue star is L222, the famous blue straggler also known as Barnard 29 (Barnard 1931). v27 and L993 seem to be field stars, although L993 is a known UV-bright object classified as a cluster member on the basis of radial velocity and proper motion measurements. The remaining seven, v3, v10, v13, v21, v30, L261, and L334, are red giants, with v13 and v21 being most probably asymptotic branch objects.

7. Summary

We presented two-colour photometric study of variable stars in globular cluster M 13. The search for new variable stars resulted in the discovery of three RR Lyrae stars and one SX Phoenicis variable. Since the image subtraction method was used, our search is complete as far as RR Lyrae stars are concerned. It appears that M 13 is relatively poor in RR Lyrae stars. Apparently, it contains nine variables of this type with only one being an RRab star. Among RRc stars we found one variable (v36) which pulsates in at least two modes with closely-spaced frequencies. It is therefore an RR Lyrae star with nonradial mode(s) excited. Moreover, we found that all cluster red giants brighter than about 12.5 mag in V are variable. Only one variable red giant exhibits periodic variations and all remaining ones are semi- or irregular.

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