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The Clusters AgeS Experiment (CASE): RR Lyrae variables in the globular cluster NGC 6362

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ABSTRACT

We present *V*- and *B*-band charge-coupled device (CCD) photometry of 35 RR Lyr stars in the Southern hemisphere globular cluster NGC 6362. Fourier decomposition of the light curves was used to estimate the basic properties of these variables. From the analysis of the RRc stars we obtain a mean mass $M = 0.531 \pm 0.014\,\mathrm{M}_{\odot}$, luminosity $\log L/\mathrm{L}_{\odot} = 1.656 \pm 0.006$, effective temperature $T_{\mathrm{eff}} = 7429 \pm 20$ and helium abundance $Y = 0.292 \pm 0.002$. The mean values of the absolute magnitude, metallicity (on Jurcsik's scale) and effective temperature for 14 RRab stars with 'regular' light curves are: $M_V = 0.86 \pm 0.01$, $[\mathrm{Fe/H}] = -0.93 \pm 0.04$ and $T_{\mathrm{eff}} = 6555 \pm 25$, respectively. From the $B - V$ colours, periods and metallicities of the RRab stars we estimate the colour excess for NGC 6362 to be equal to $E(B - V) = 0.08 \pm 0.01$. Using this value we derive the colours of the blue and red edges of the instability strip in NGC 6362 to be $(B - V)_0^{\mathrm{BE}} = 0.17$ and $(B - V)_0^{\mathrm{RE}} = 0.43$. From the relations between the Fourier coefficients of RRab and RRc stars and their absolute magnitudes we estimate the apparent distance modulus to NGC 6362 to be $(m - M)_V = 14.46 \pm 0.10$. From the mean value of $\log L/\mathrm{L}_{\odot}$ of the RRc stars we obtain 14.59 ± 0.03.

The *V*-band light curves of three of the RRc stars exhibit changes in amplitude of over 0.1 mag on the time-scale of around one week. Near the radial first overtone frequency we find one or two peaks, which strongly suggests that these variables belong to the newly identified group of non-radial pulsating RR Lyr stars.

Key words: techniques: photometric – binaries: eclipsing – stars: fundamental parameters – stars: variables: other – globular clusters: individual: NGC 6362.

1 INTRODUCTION

The Clusters AgeS Experiment (CASE) is a long-term project with the main goal of determining accurate ages and distances of globular clusters by using observations of detached eclipsing binaries (Paczyński 1997). NGC 6362 was selected as one of the targets of our ongoing photometric survey aimed at identification of binaries suitable for detailed analysis (Kaluzny et al. 1999; Thompson et al. 1999). As a byproduct we obtain time-series photometry of RR Lyr stars located in the surveyed clusters (Olech et al. 1999a,b; Kaluzny et al. 2000).

NGC 6362 (C1726-670) is one of the Southern hemisphere Oosterhoff type I globular clusters. The low central concentration of the cluster and its proximity enable the measurement of reliable photometry for the majority of its stars. The Third Catalogue of Variable Stars in Globular Clusters (Sawyer Hogg 1973) contains a list of 33 variables in NGC 6362. An updated list of these stars with more precise period determinations was published by Clement, Dickens & Bingham (1995). Three objects from this list (V4, V9 and V32) were noted as non-variable stars. The nature of V1 was listed as unknown, and the other objects were classified as RR Lyr stars.

Recently Mazur, Kaluzny & Krzemiński (1999) published results of a charge-coupled device (CCD) search for short-period variables in NGC 6362. They discovered 19 new candidates, of which five were cluster RR Lyr stars, four were SX Phe stars and eight were eclipsing binaries.

The metallicity of NGC 6362 is moderately high and relatively well established. On the scale of Zinn & West (1984), $[\mathrm{Fe/H}] = -1.08$. Recently, Carretta & Gratton (1997) obtained

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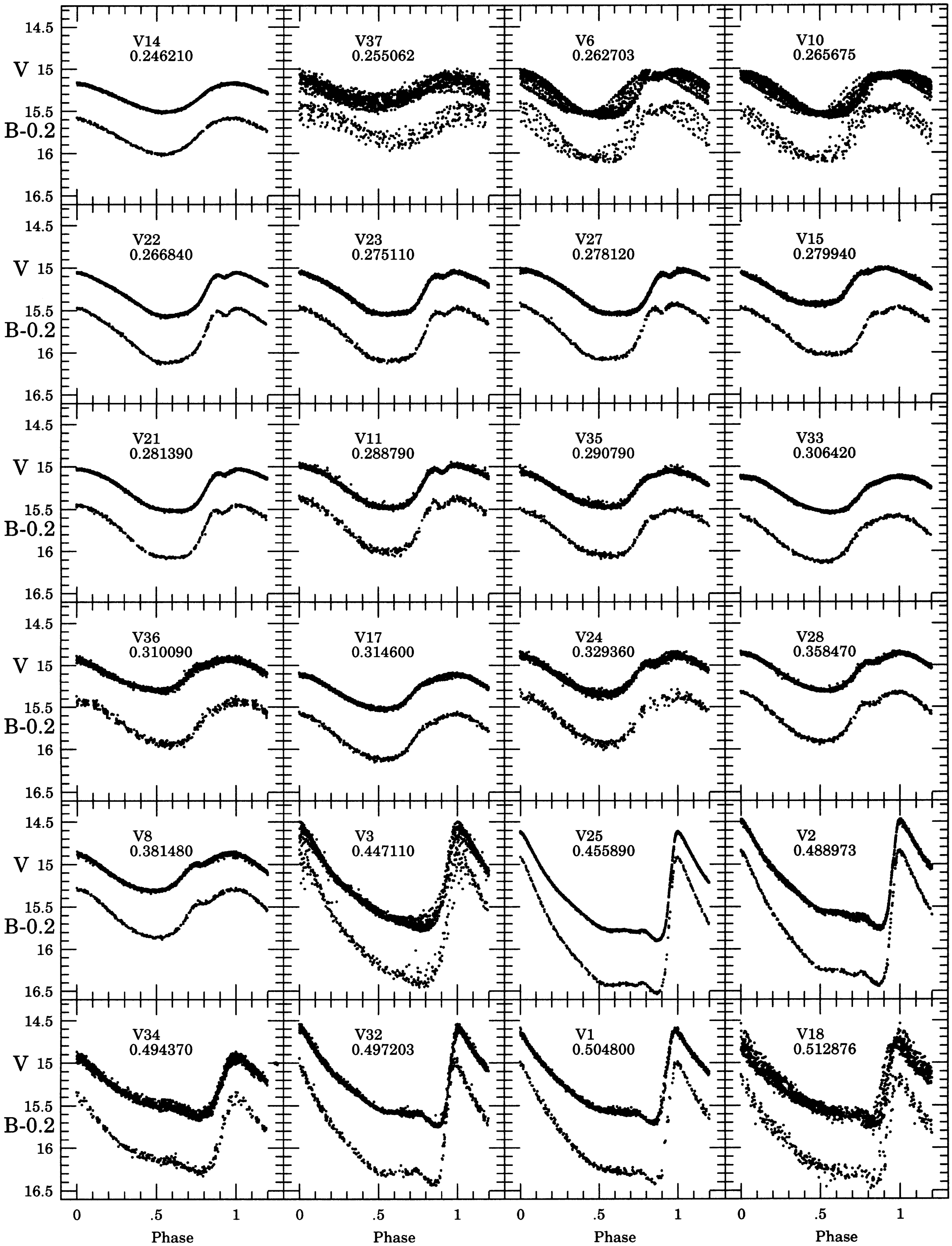

Figure 1. Light curves of RR Lyr variable stars found in NGC 6362. The stars are plotted by increasing period. The upper light curve is in the *V* band, and the lower in the *B* band. The *B* magnitude is reduced by 0.2 mag for clarity.

[Fe/H] $= -0.96$ from an analysis of echelle spectra of cluster giants, and Rutledge, Hesser & Stetson (1997) found [Fe/H] $= -0.99 \pm 0.03$ from W' calcium index.

Alcaino & Liller (1986) obtain a distance modulus $(m-M)_V = 14.74$ and a reddening $E(B-V) = 0.10$. Piotto et al. (1999) obtained $(m-M)_V = 14.67 \pm 0.20$ and $E(B-V) = 0.06 \pm 0.03$ from an analysis of *Hubble Space Telescope* data. Recently, Brocato et al. (1999), performing a global fitting with the

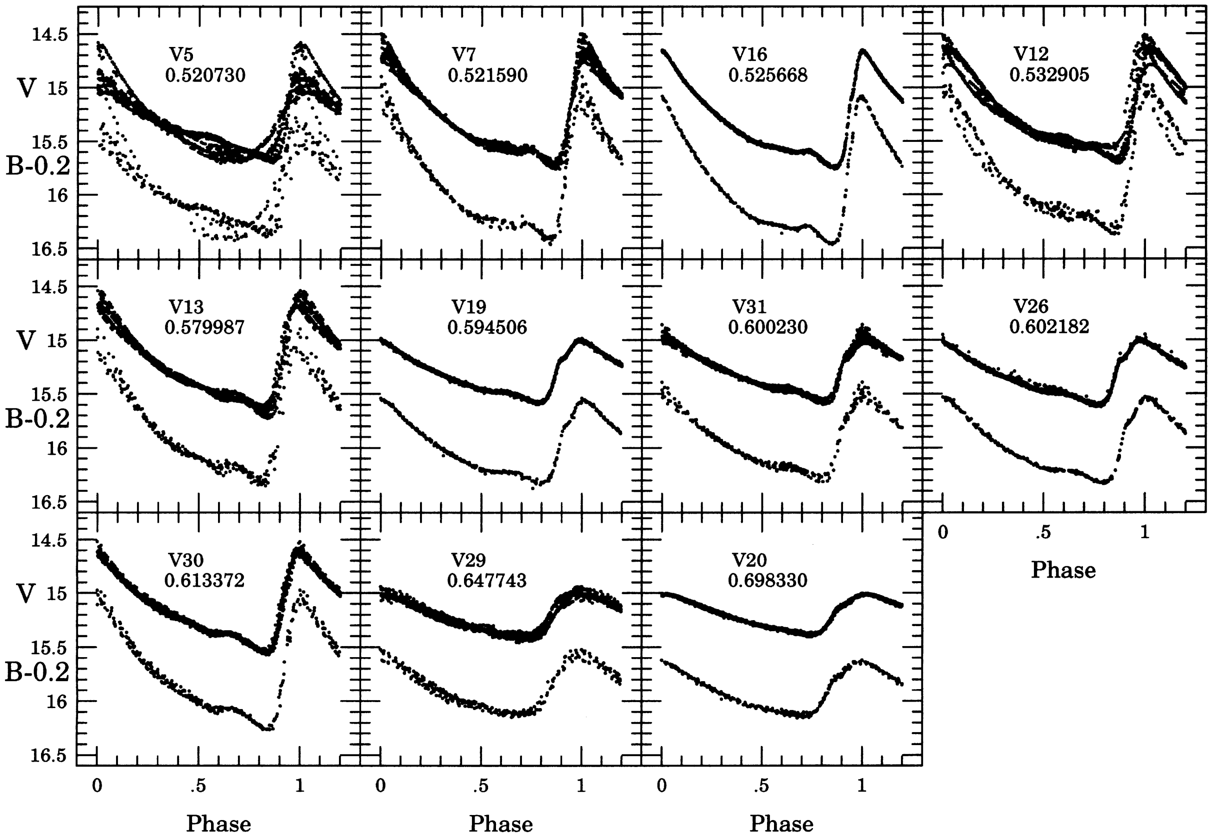

Figure 1 – *continued.*

theoretical isochrones and zero-age horizontal branch, found an age of 12 ± 1 Gyr, together with $(m-M)_V = 14.68$ and $E(B-V) = 0.08$.

2 OBSERVATIONS AND DATA REDUCTION

Time-series photometry of NGC 6362 was obtained during the interval 1999 April 17–August 22 with the 1.0-m Swope telescope at Las Campanas Observatory. We used the backside-illuminated SITE3 2048×4096 CCD, with a pixel scale 0.435 arcsec pixel^{-1}. A 2048×3150 subsection of the CCD was used, giving a field of view of 14.8×22.8 arcmin^2. Photometry presented in this paper is based on 1088 *V*-band images and 259 *B*-band images, which were collected on 42 nights. Exposure times were adjusted on every night – depending on the seeing – to assure unsaturated images for stars from the horizontal branch of the cluster. For the *V* band these ranged from 180 to 300 s.

Instrumental photometry was extracted using DOPHOT (Schechter, Mateo & Saha 1993). We used DOPHOT in the fixed-position mode, with the stellar positions measured on 'template' images constructed by averaging the three best exposures obtained for each filter. The instrumental photometry was transformed to the standard *BV* system using observations of standard stars from Landolt (1992). We estimate that systematic errors of the zero points of the final *BV* photometry do not exceed 0.03 mag.

3 RESULTS

Our search for pulsating variable stars in NGC 6362 has identified 35 RR Lyrae stars. All these variables were previously known (Clement et al. 1995; Mazur et al. 1999 – we use the nomenclature from these papers). The periods *P*, the *V* filter peak-to-peak amplitudes A_V, the *B* filter peak-to-peak amplitudes A_B, the intensity-averaged $\langle V \rangle$ and $\langle B \rangle$ magnitudes and the types of these stars are presented in Table 1. The phased light curves of these stars are shown in Fig. 1. Crowding prevented the classification of V1 and V32 by Clement et al. and Mazur et al. The light curves in Fig. 1 indicate that both are RRab stars.

We compared our photometry with the observations of Mazur et al. (1999). For 18 RR Lyr stars in common, the mean difference $\langle V \rangle_{\rm our} - \langle V \rangle_{\rm Mazur} = 0.001 \pm 0.006$.

In Fig. 2 we present a colour–magnitude diagram for RR Lyr variables in NGC 6362. Open circles denote the RRc stars, and open triangles correspond to the RRab variables. The periods of the cluster RRc stars are between 0.2462 and 0.3815 d with a mean value of 0.295 d. The periods of the RRab variables are between 0.4471 and 0.6983 d with a mean value of 0.538 d. These values are in very good agreement with the mean values of periods of RRc and RRab stars in NGC 6362 of 0.296 and 0.556 d, respectively, obtained by Clement et al. (1995). These mean values are also similar to those obtained for the Oosterhoff type I clusters NGC 6171 and 6732 with characteristics resembling NGC 6362 (Sandage 1993).

We fitted our *V*-band light curves with Fourier sine series of the form:

$$V = A_0 + \sum_{j=1}^{12} A_j \sin(j\omega t + \phi_j), \qquad (1)$$

where $\omega = 2\pi/P$. To find the values of ω, A_j and ϕ_j we employed the method developed by Schwarzenberg-Czerny (1997) and Schwarzenberg-Czerny & Kaluzny (1998). To demonstrate the

Table 1. Elements of the pulsating variables in NGC 6362.

Star	P (d)	A_V	A_B	$\langle V\rangle$	$\langle B\rangle$	Type
V1	0.504800	1.09	1.41	15.274	15.657	RRab
V2	0.488973	1.27	1.60	15.243	15.595	RRab
V3	0.447110	1.14	1.41	15.266	15.598	RRab
V5	0.520730	0.74	0.96	15.332	15.741	RRab
V6	0.262703	0.47	0.59	15.288	15.547	RRc
V7	0.521590	1.03	1.31	15.276	15.664	RRab
V8	0.381480	0.44	0.56	15.087	15.362	RRc
V10	0.265675	0.47	0.60	15.296	15.552	RRc
V11	0.288790	0.50	0.64	15.219	15.475	RRc
V12	0.532905	1.02	1.35	15.230	15.581	RRab
V13	0.579987	1.00	1.25	15.211	15.573	RRab
V14	0.246210	0.34	0.43	15.337	15.588	RRc
V15	0.279940	0.43	0.56	15.221	15.540	RRc
V16	0.525668	1.08	1.38	15.299	15.706	RRab
V17	0.314600	0.42	0.54	15.308	15.639	RRc
V18	0.512876	0.96	1.20	15.306	15.706	RRab
V19	0.594506	0.59	0.77	15.318	15.794	RRab
V20	0.698330	0.38	0.50	15.206	15.713	RRab
V21	0.281390	0.49	0.62	15.267	15.558	RRc
V22	0.266840	0.51	0.65	15.317	15.582	RRc
V23	0.275110	0.49	0.63	15.303	15.574	RRc
V24	0.329360	0.46	0.57	15.109	15.432	RRc
V25	0.455891	1.28	1.63	15.407	15.722	RRab
V26	0.602182	0.61	0.79	15.327	15.789	RRab
V27	0.278120	0.51	0.65	15.280	15.545	RRc
V28	0.358470	0.44	0.59	15.074	15.406	RRc
V29	0.647743	0.42	0.55	15.218	15.688	RRab
V30	0.613372	0.94	1.22	15.137	15.542	RRab
V31	0.600230	0.60	0.79	15.294	15.739	RRab
V32	0.497203	1.14	1.44	15.277	15.659	RRab
V33	0.306420	0.42	0.54	15.318	15.636	RRc
V34	0.494370	0.68	0.88	15.326	15.723	RRab
V35	0.290790	0.43	0.54	15.254	15.576	RRc
V36	0.310090	0.38	0.51	15.107	15.475	RRc
V37	0.255062	0.28	0.37	15.273	15.478	RRc

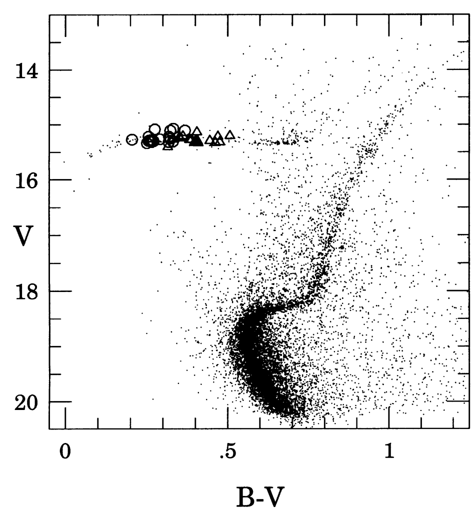

Figure 2. Colour–magnitude diagram of NGC 6362. The open triangles denote RRab stars and open circles correspond to RRc variables.

precision of our light curves, in Fig. 3 we plot the observed light curve of RRab variable V25 together with the Fourier sine series with $j = 15$. The observational points are plotted using grey open circles of diameter 0.06 mag, equal to 10 standard deviations. The solid black line corresponds to the fit based on equation (1).

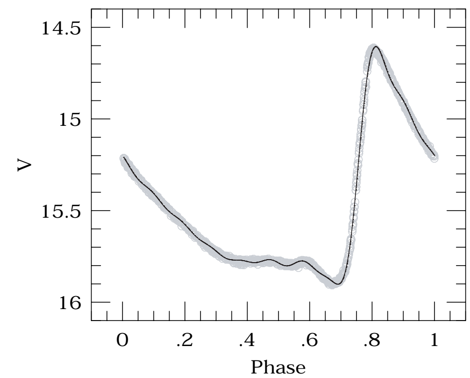

Figure 3. The phased light curve of variable V25. The observational points are plotted with grey open circles. The size of these circles is 10 times larger than the photometric errors. The solid black line corresponds to the fit computed from equation (1).

Table 2. Fourier elements of the RRab variable V25 from NGC 6362.

A_1	σA_1	A_2	σA_2	A_3	σA_3
0.4401	0.0003	0.2118	0.0003	0.1576	0.0003
A_4	σA_4	A_5	σA_5	A_6	σA_6
0.1010	0.0003	0.0737	0.0003	0.0508	0.0003
A_7	σA_7	A_8	σA_8	A_9	σA_9
0.0320	0.0003	0.0211	0.003	0.0173	0.0003
A_{10}	σA_{10}	A_{11}	σA_{11}	A_{12}	σA_{12}
0.0137	0.0003	0.0097	0.0003	0.0059	0.0003
A_{13}	σA_{13}	A_{14}	σA_{14}	A_{15}	σA_{15}
0.0035	0.0003	0.0029	0.0003	0.0022	0.0003
ϕ_1	$\sigma\phi_1$	ϕ_2	$\sigma\phi_2$	ϕ_3	$\sigma\phi_3$
5.169	0.001	0.041	0.002	1.506	0.002
ϕ_4	$\sigma\phi_4$	ϕ_5	$\sigma\phi_5$	ϕ_6	$\sigma\phi_6$
3.007	0.003	4.538	0.005	6.129	0.007
ϕ_7	$\sigma\phi_7$	ϕ_8	$\sigma\phi_8$	ϕ_9	$\sigma\phi_9$
1.327	0.010	2.674	0.016	4.080	0.019
ϕ_{10}	$\sigma\phi_{10}$	ϕ_{11}	$\sigma\phi_{11}$	ϕ_{12}	$\sigma\phi_{12}$
5.556	0.024	0.875	0.034	2.362	0.055
ϕ_{13}	$\sigma\phi_{13}$	ϕ_{14}	$\sigma\phi_{14}$	ϕ_{15}	$\sigma\phi_{15}$
3.683	0.094	5.198	0.117	0.100	0.155

Table 2 presents the amplitudes A_j and phases ϕ_j and their errors. For RRab stars with amplitudes of 1.25 mag we can determine values of A_j up to $j = 14$ with relative error smaller than 10 per cent. The relative error of A_{15} is equal to 14 per cent.

The values of the peak-to-peak amplitudes A_V and periods P presented in Table 1 are used to plot the period–amplitude ($\log_{10} P$ versus A_V) diagram shown in Fig. 4. Open circles denote RRc stars, filled triangles RRab stars with $D_{\rm m} < 3$ (for definition of $D_{\rm m}$ see Section 3.3) and open triangles RRab variables with $D_{\rm m} > 3$. The solid line represents a linear fit to RRab variables in M3 (Kaluzny et al. 1998), another Oosterhoff type I globular cluster.

Clement & Shelton (1999) have suggested that for RRab stars the V amplitude at a given period is not a function of metal abundance, but rather only a function of the Oosterhoff type. We see in Fig. 4 that the majority of our RRab variables lie below the

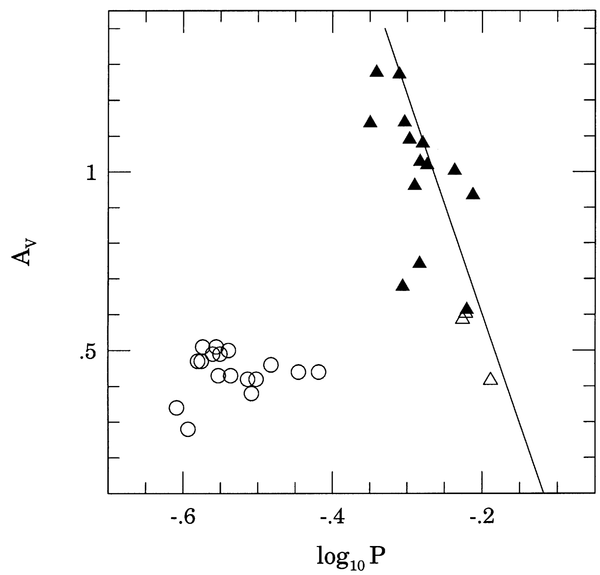

Figure 4. Period–amplitude diagram for RRab stars with $D_m < 3$ (solid triangles), RRab stars with $D_m > 3$ (open triangles) and RRc stars (open circles). The solid line represents a linear fit to RRab variables in M3 (Kaluzny et al. 1998).

mean line for Oosterhoff type I clusters, as defined by the RRab stars in the globular cluster M3. A similar result is also found by Kaluzny et al. (2000) for the cluster M5 and by Wehlau, Slawson & Nemec (1999) for the cluster NGC 7006. These results suggest that, while there is a clear correlation of Oosterhoff type with metallicity (see Table 4), within at least the Oosterhoff type I clusters there is an additional dependence of V amplitude at a given period upon metallicity, with the more metal-rich stars having lower V amplitudes, i.e. the period shift between M3 and NGC 6362 is almost certainly due to a difference in luminosity as a function of metallicity for Oosterhoff type I clusters.

3.1 Fourier analysis of the RRc stars

Simon & Clement (1993) showed that the Fourier decomposition of the light curves of RRc variables is a very useful technique for estimating the physical parameters of these stars. The equations of Simon & Clement (1993) are:

$$\log M = 0.52 \log P_1 - 0.11\phi_{31}^* + 0.39, \quad (2)$$

$$\log L = 1.04 \log P_1 - 0.058\phi_{31}^* + 2.41, \quad (3)$$

$$\log T_{\rm eff} = 3.265 - 0.3026 \log P_1 - 0.1777 \log M + 0.2402 \log L, \quad (4)$$

$$\log Y = -20.26 + 4.935 \log T_{\rm eff} - 0.2638 \log M + 0.3318 \log L, \quad (5)$$

Table 3. Parameters for the RRc variables in NGC 6362.

Star	A_0	A_1	ϕ_{21}	ϕ_{31}	M	$\log L$	$T_{\rm eff}$	Y	$M_V^{\rm Ko}$	M_V
V6	15.304	0.244	3.166	6.476	0.526	1.613	7544	0.305	0.825	0.753
	±0.000	±0.003	±0.105	±0.190	±0.025	±0.011	±18	±0.006	±0.014	
V8	15.096	0.217	4.182	7.778	0.460	1.706	7267	0.282	0.657	0.520
	±0.000	±0.001	±0.084	±0.032	±0.004	±0.002	±2	±0.001	±0.006	
V10	15.311	0.242	3.151	6.154	0.574	1.637	7500	0.295	0.818	0.693
	±0.000	±0.002	±0.070	±0.136	±0.020	±0.008	±13	±0.004	±0.009	
V11	15.234	0.254	3.315	6.614	0.534	1.648	7454	0.294	0.762	0.665
	±0.000	±0.001	±0.017	±0.027	±0.004	±0.002	±2	±0.001	±0.005	
V14	15.343	0.169	3.047	6.090	0.561	1.606	7577	0.305	0.881	0.770
	±0.000	±0.000	±0.015	±0.068	±0.010	±0.004	±6	±0.002	±0.001	
V15	15.234	0.219	2.959	6.201	0.583	1.657	7448	0.289	0.804	0.643
	±0.000	±0.000	±0.016	±0.027	±0.004	±0.002	±2	±0.001	±0.005	
V17	15.316	0.210	3.172	7.267	0.473	1.648	7425	0.298	0.788	0.665
	±0.000	±0.001	±0.033	±0.044	±0.005	±0.003	±4	±0.001	±0.005	
V21	15.281	0.253	3.173	6.398	0.557	1.648	7461	0.293	0.775	0.665
	±0.000	±0.000	±0.009	±0.013	±0.002	±0.001	±1	±0.000	±0.000	
V22	15.317	0.254	3.156	5.972	0.603	1.649	7478	0.290	0.790	0.663
	±0.000	±0.000	±0.007	±0.017	±0.003	±0.001	±1	±0.000	±0.000	
V23	15.305	0.253	3.134	6.086	0.595	1.656	7456	0.288	0.779	0.645
	±0.000	±0.000	±0.013	±0.021	±0.003	±0.001	±1	±0.001	±0.001	
V24	15.121	0.231	3.329	7.303	0.480	1.667	7379	0.292	0.740	0.618
	±0.000	±0.001	±0.054	±0.064	±0.008	±0.004	±6	±0.002	±0.005	
V27	15.296	0.261	3.091	6.195	0.582	1.655	7455	0.289	0.773	0.648
	±0.000	±0.001	±0.014	±0.022	±0.003	±0.001	±2	±0.001	±0.004	
V28	15.085	0.221	3.684	7.562	0.470	1.690	7313	0.286	0.692	0.560
	±0.000	±0.001	±0.045	±0.031	±0.004	±0.002	±2	±0.001	±0.005	
V33	15.328	0.215	3.161	7.022	0.497	1.651	7429	0.296	0.796	0.658
	±0.000	±0.000	±0.020	±0.029	±0.004	±0.002	±2	±0.001	±0.001	
V35	15.267	0.217	3.038	6.525	0.548	1.656	7438	0.291	0.803	0.645
	±0.000	±0.001	±0.021	±0.033	±0.005	±0.002	±3	±0.001	±0.005	
V36	15.113	0.189	3.178	7.113	0.488	1.651	7425	0.296	0.788	0.658
	±0.000	±0.001	±0.044	±0.058	±0.007	±0.003	±5	±0.002	±0.005	
V37	15.277	0.138	2.034	4.061	0.956	1.740	7343	0.252	0.904	0.435
	±0.000	±0.003	±0.199	±5.529	±1.339	±0.321	±520	±0.010	±0.016	

Table 4. Mean parameters for RRc stars in globular clusters after Kaluzny et al. (1998, 2000).

Cluster	Oosterhoff type	[Fe/H]	No. of stars	Mean mass	Mean $\log L$	Mean $T_{\rm eff}$	Mean Y
NGC 6171	I	−0.68	6	0.53	1.65	7447	0.29
NGC 6362	I	−1.08	14	0.53	1.66	7429	0.29
M5	I	−1.25	14	0.54	1.69	7353	0.28
M3	I	−1.47	5	0.59	1.71	7315	0.27
M9	II	−1.72	1	0.60	1.72	7299	0.27
M55	II	−1.90	5	0.53	1.75	7193	0.27
NGC 2298	II	−1.90	2	0.59	1.75	7200	0.26
M68	II	−2.03	16	0.70	1.79	7145	0.25
M15	II	−2.28	6	0.73	1.80	7136	0.25

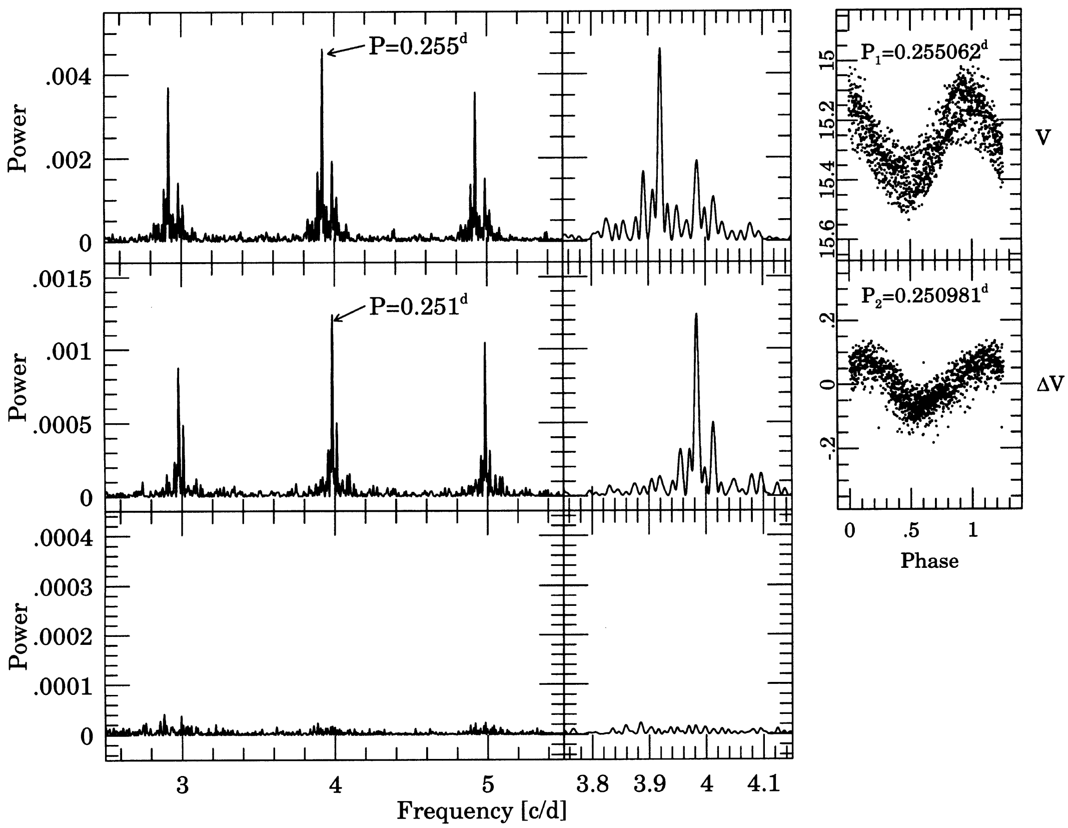

Figure 5. The power spectrum of the real (top), prewhitened (middle) and twice prewhitened (bottom) light curve of variable V37. The prewhitened light curves phased with periods P_1 and P_2 are shown on the right.

where M is the mass of the star in solar units, P_1 is the first overtone pulsation period in days, L is the luminosity in solar units, $T_{\rm eff}$ is the effective temperature in kelvin, Y is the relative helium abundance and $\phi^*_{31} = \phi^*_3 - 3\phi^*_1$. The phases marked by asterisks are obtained from a cosine Fourier series (used by Simon & Clement 1993) and differ from our phases, which were obtained from a sine series (cf. equation 1). For ϕ_{31} we have $\phi_{31} = \phi^*_{31} + \pi$.

In addition, using the formula of Kovács (1998) we may estimate the absolute magnitude $M_V^{\rm Ko}$ of RRc stars directly:

$$M_V^{\rm Ko} = 1.261 - 0.961P_1 - 0.004\phi_{21} - 4.447A_4. \qquad (6)$$

From equations (2)–(6) we compute masses, luminosities, effective temperatures, relative helium abundances and absolute magnitudes of RRc stars in NGC 6362. These are presented in Table 3 together with the values of A_0, A_1, ϕ_{21} and ϕ_{31}. The errors presented in Table 3 are calculated from the formal errors of the Fourier coefficients using the error propagation law.

We exclude from our sample the variables V6, V10 and V37 because of their irregular light curves and large errors of ϕ_{31} (see Section 3.2). The mean values of the mass, luminosity, effective temperature and helium abundance for the remaining 14 RRc stars are $0.531 \pm 0.014\,{\rm M}_\odot$, $\log L/{\rm L}_\odot = 1.656 \pm 0.006$, $T_{\rm eff} = 7429 \pm 20$ and $Y = 0.292 \pm 0.002$, respectively. The mean $\log P_1$ is equal to -0.525 ± 0.014 and the mean ϕ^*_{31} is equal to 3.582 ± 0.162.

By comparing the physical parameters of the RRc stars from different clusters, Clement & Shelton (1997) revealed several correlations. Specifically, an increasing mean mass corresponds to an increasing luminosity and a decreasing effective temperature and relative helium abundance. It is clearly visible from Table 4 taken from Kaluzny et al. (1998, 2000) that NGC 6362 fits this sequence rather well.

3.2 Non-radial pulsations of RRc stars

Three of the RRc variables presented in Fig. 1, namely, V37, V6 and V10, show clear modulation of their light curves. The amplitudes and shapes of the light curves change on the time-scale of days. This is not the Blazhko effect, which is observed mainly in RRab stars as a modulation of the amplitude on a time-scale of tens of days. The other possible explanation is that these stars are bimodal pulsators (RRd stars) with pulsation in both the fundamental mode and the first overtone. To check this possibility we calculated the power spectra of these variables. The power spectrum of the light curve of V37 is presented in the upper panel of Fig. 5. The highest peak is detected at a frequency of $f_1 = 3.920\,615\,\mathrm{cycle\,d^{-1}}$ ($P_1 = 0.255\,0V62$ d). The light curve of this star phased with P_1 is shown in the third plot in the upper panel. One can see that the light curve is noisy. The power spectrum shows a secondary peak at frequency $f_2 = 3.984\,365$ ($P_2 = 0.250\,981$ d). We prewhitened our original light curve removing the main period P_1 with its harmonics. The power spectrum of the prewhitened light curve is shown in the middle panel of Fig. 5. There is no trace of the main frequency f_1 and the highest and only significant peak is f_2. The third plot in the middle panel presents the prewhitened light curve phased with the period P_2. Again we prewhitened this light curve now removing period P_2 with its harmonics, and the resulting power spectrum shows no further significant frequencies (see the lower panel of Fig. 5). We conclude that both frequencies correspond to real modes of pulsation. For ordinary double-mode pulsators the ratio of the first overtone period to the fundamental period is approximately 0.745. In our case the ratio P_2/P_1 is equal to 0.98 and thus it is clear that if P_1 corresponds to the radial first overtone pulsations then P_2 in V37 corresponds to a non-radial mode.

Another variable with a 'noisy' light curve is V6. The power spectrum of its raw light curve is presented in the upper panel of Fig. 6. The highest peak has frequency $f_1 = 3.806\,580\,\mathrm{cycle\,d^{-1}}$ ($P_1 = 0.262\,703$ d). The power spectrum reveals the presence of other components. We prewhitened the light curve of V6 using P_1,

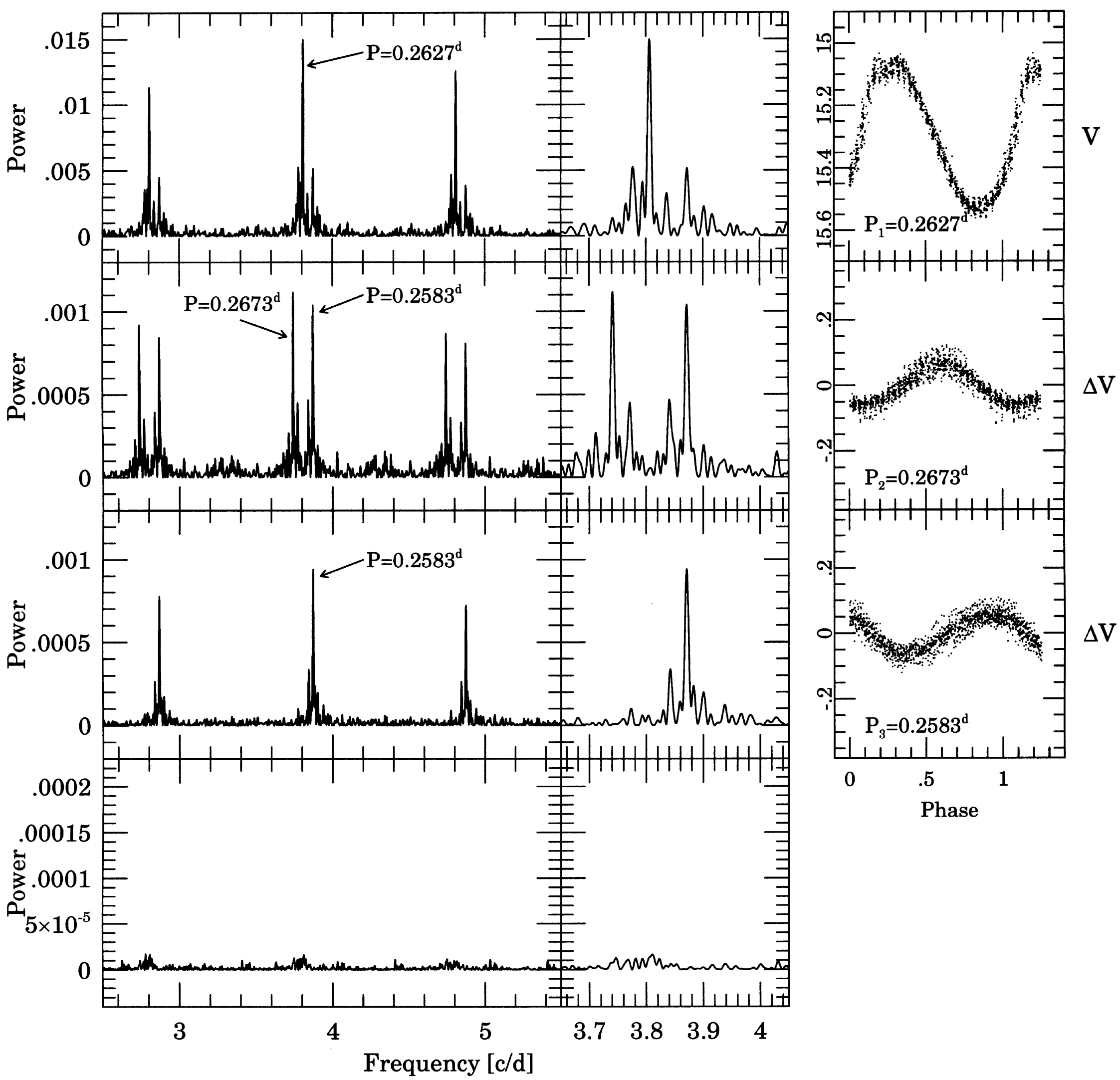

Figure 6. The power spectrum of the real (top), prewhitened (upper middle), twice prewhitened (lower middle) and three times prewhitened (bottom) light curve of variable V6. The prewhitened light curves phased with periods P_1, P_2 and P_3 are shown on the right.

and the power spectrum of this prewhitened light curve is presented in the second panel of Fig. 6. There are two high peaks with frequencies of $f_2 = 3.740\,961$ ($P_2 = 0.267\,311$ d) and $f_3 = 3.871\,003$ cycle d^{-1} ($P_3 = 0.258\,331$ d) in this plot. We again prewhitened our light curve using the period P_2 and its harmonics, and the power spectrum of the twice prewhitened light curve is presented in the third panel of Fig. 6. The only peak that is left is f_3. After removing P_3 with its harmonics we obtained a power spectrum clean of any significant features, presented in the lower panel in Fig. 6.

The frequencies f_3 and f_2 lie symmetrically above and below f_1, with $f_3 - f_1 = 0.0644$ and $f_1 - f_2 = 0.0656$. This symmetry suggests that P_2 and P_3 are signatures of the amplitude modulation with a period equal to $1/(f_1 - f_2) = 1/(f_3 - f_1) \approx 15$ d. This resembles the Blazhko effect. Although the Blazhko effect is common among RRab stars, it is seldom observed in RRc stars. In particular, in a sample of 46 stars with known Blazhko periods there are only three RRc stars, and the shortest Blazhko period is 10.9 d (Smith 1995). However, the difference $(f_1 - f_2) - (f_3 - f_1) = 0.0012$ is large compared to the accuracy of our frequency determinations. Since the separate light curves phased with periods P_1, P_2 and P_3 shown in Fig. 6 display stable amplitudes, they could correspond to pulsations in three different modes of which two are non-radial, similar to the one non-radial mode in V37.

A similar analysis was performed for variable V10 with the results presented in Fig. 7. In this case we also detected three periods. The most significant is $P_1 = 0.265\,675$ d ($f_1 = 3.763\,997$) and other two are $P_2 = 0.257\,573$ d ($f_2 = 3.882\,395$) and $P_3 = 0.274\,262$ d ($f_3 = 3.646\,148$). Again the differences of frequencies $f_2 - f_1$ and $f_1 - f_3$ are similar and equal to 0.1184 and 0.1178, respectively. The corresponding beat period $1/(f_2 - f_1) = 1/(f_1 - f_3) \approx 8.5$ d. If we assume that the amplitude modulation is the Blazhko effect, the corresponding Blazhko period would be the shortest known! For V10 the difference $(f_2 - f_1) - (f_1 - f_3)$ is equal to 0.0006 and, given the stable light curves in Fig. 7, we suggest that the periods P_2 and P_3 are real and correspond to non-radial pulsations.

Non-radial pulsations in RR Lyr stars were first discovered by Olech et al. (1999a) in three RRc variables in the globular cluster M55. This discovery was quickly followed by Olech et al. (1999b) who found one non-radial pulsating RRc star in M5, by Kovács et al. (2000) who reported a few such RRc stars in the MACHO

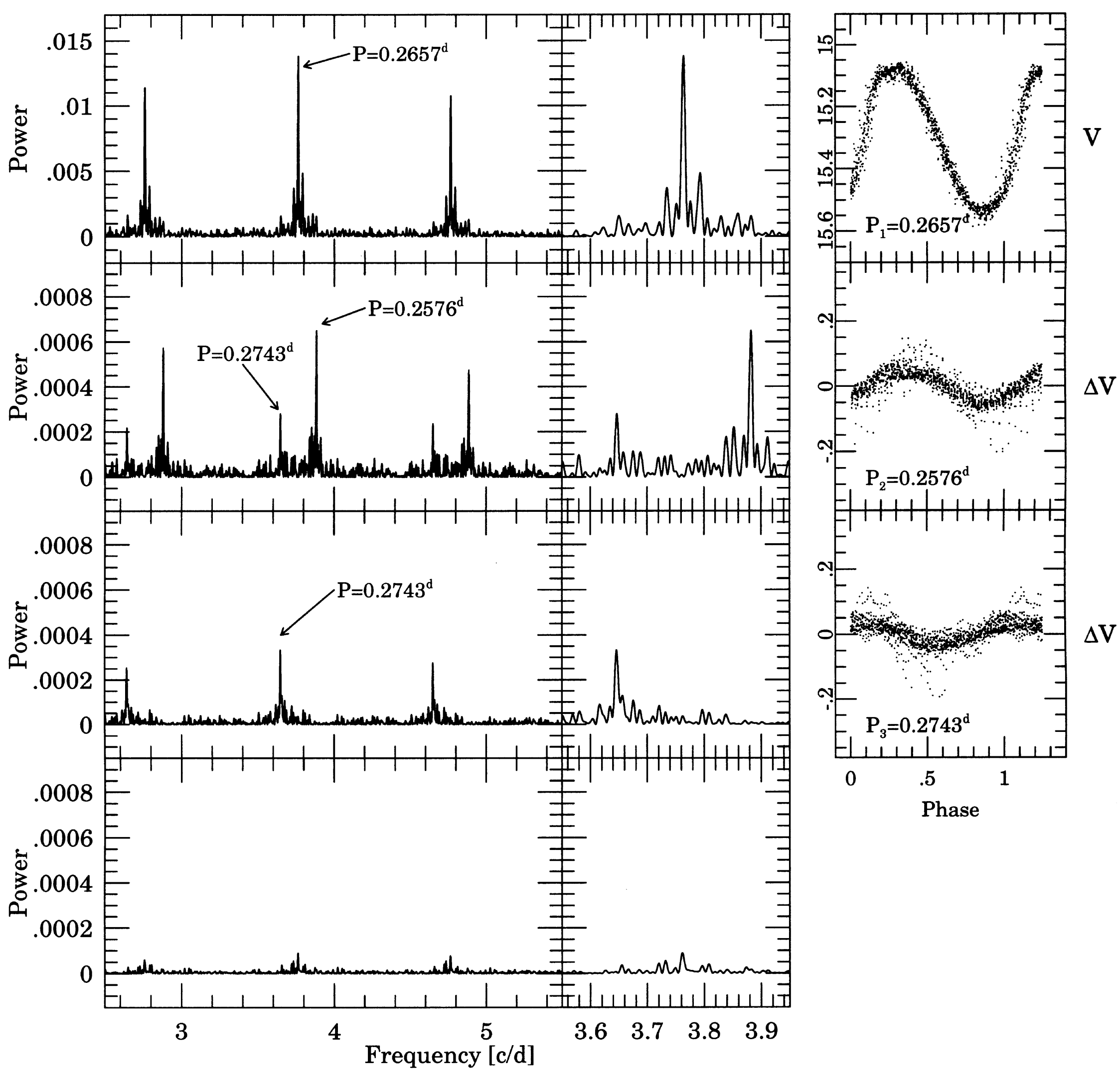

Figure 7. The power spectrum of the real (top), prewhitened (upper middle), twice prewhitened (lower middle) and three times prewhitened (bottom) light curve of variable V10. The prewhitened light curves phased with periods P_1, P_2 and P_3 are shown on the right.

data, and by Moskalik (2000) who discovered six non-radial RRc and RRab pulsators in the OGLE data.

A theoretical investigation of non-radial pulsations in RR Lyr stars was presented by Dziembowski & Cassisi (1999). They showed that the largest growth rates are seen for radial modes and strongly trapped unstable modes with large values of l. The latter do not explain our observations because it is difficult to detect pulsations with such large values of l ($l = 7$–10) in photometric data. The third group of modes with quite large growth rates are non-radial pulsations with $l = 1$ laying in the vicinity of the unstable first overtone mode (see fig. 2 of Dziembowski & Cassisi 1999). The most unstable $l = 1$ modes always have high frequencies (short periods), which is in good agreement with our observations. In NGC 6362 there is only one monoperiodic RRc star with a period shorter than the periods of the RRc stars with non-radial pulsations. The remaining 13 monoperiodic RRc stars have longer periods. A similar situation was observed by Olech et al. (1999a) in M55. Among nine RRc stars there is only one star with a period shorter than the period of the three non-radially pulsating variables.

Dziembowski & Cassisi (1999) showed also that the relative frequency separation $\Delta f/f$ is largest for the $l = 1$ modes in the vicinity of the first overtone pulsations. For the shortest periods $\Delta f/f$ is around 0.01, which is in good agreement with our observations, which give 0.016, 0.017 and 0.031 for V37, V6 and V10, respectively.

The $B - V$ colour range for RRc variables in NGC 6362 is between 0.21 and 0.33. The colours of V37, V6 and V10 are 0.21, 0.26 and 0.26, respectively, placing these stars near the blue edge of the instability strip. The same result was obtained by Olech at al (1999a) who found three non-radial pulsating RRc stars in M55 with $B - V$ colours between 0.31 and 0.32. The $B - V$ colours of the RRc stars in M55 are between 0.31 and 0.39.

3.3 Fourier analysis of the RRab variables

Recently Jurcsik (1995) and Kovács & Jurcsik (1996, 1997) have derived formulae that estimate the absolute magnitudes, metallicities, intrinsic colours and temperatures of RRab stars from the periods, amplitudes and phases as measured from a Fourier analysis of the light curves. These equations are:

$$[\mathrm{Fe/H}] = -5.038 - 5.394P_0 + 1.345\phi_{31}, \tag{7}$$

$$M_V = 1.221 - 1.396P_0 - 0.477A_1 + 0.103\phi_{31}, \tag{8}$$

$$V_0 - K_0 = 1.585 + 1.257P_0 - 0.273A_1 - 0.234\phi_{31} + 0.062\phi_{41}, \tag{9}$$

$$\log T_{\mathrm{eff}} = 3.9291 - 0.1112(V_0 - K_0) - 0.0032[\mathrm{Fe/H}], \tag{10}$$

where $\phi_{41} = \phi_4 - 4\phi_1$ (cf. equation 1).

These equations are valid only for RRab stars with regular light curves, i.e. variables with a deviation parameter D_{m} smaller than 3

Table 5. Parameters for the RRab variables in NGC 6362.

Star	P (d)	A_0	A_1	ϕ_{31}	ϕ_{41}	M_V	[Fe/H]	T_{eff}	D_{m}
V1	0.504800	15.321	0.376	5.015	1.412	0.859	−1.015	6572	1.64
		±0.001	±0.001	±0.009	±0.013	±0.084	±0.022		
V2	0.488973	15.309	0.422	5.040	1.357	0.861	−0.897	6637	1.83
		±0.001	±0.001	±0.008	±0.012	±0.084	±0.022		
V3	0.447110	15.322	0.449	5.013	1.293	0.904	−0.707	6726	2.38
		±0.001	±0.002	±0.020	±0.038	±0.082	±0.035		
V5	0.520730	15.354	0.290	5.220	1.554	0.899	−0.825	6556	2.49
		±0.002	±0.003	±0.061	±0.089	±0.090	±0.084		
V7	0.521590	15.323	0.361	5.113	1.580	0.852	−0.974	6549	1.58
		±0.001	±0.001	±0.017	±0.024	±0.087	±0.028		
V12	0.532905	15.278	0.361	5.063	1.487	0.831	−1.103	6521	1.49
		±0.002	±0.002	±0.027	±0.040	±0.086	±0.040		
V13	0.579987	15.253	0.362	5.241	1.864	0.784	−1.118	6454	1.76
		±0.001	±0.001	±0.018	±0.026	±0.090	±0.031		
V16	0.525668	15.346	0.359	5.105	1.547	0.847	−1.007	6541	0.80
		±0.000	±0.000	±0.004	±0.006	±0.087	±0.018		
V18	0.512876	15.351	0.344	5.141	1.541	0.876	−0.890	6571	1.50
		±0.002	±0.003	±0.040	±0.055	±0.087	±0.056		
V19	0.594506	15.332	0.220	5.522	2.378	0.860	−0.818	6402	15.26
		±0.000	±0.000	±0.010	±0.020	±0.096	±0.033		
V20	0.698330	15.212	0.163	5.974	3.459	0.790	−0.769	6227	4.71
		±0.000	±0.000	±0.019	±0.058	0.107	±0.060		
V25	0.455891	15.478	0.440	4.849	1.181	0.879	−0.976	6662	1.51
		±0.000	±0.000	±0.004	±0.005	±0.080	±0.024		
V26	0.602182	15.343	0.227	5.575	2.507	0.852	−0.788	6395	2.08
		±0.000	±0.001	±0.011	±0.024	±0.097	±0.035		
V29	0.647743	15.226	0.184	5.738	2.314	0.826	−0.814	6366	15.76
		±0.001	±0.001	±0.052	0.114	0.102	±0.081		
V30	0.613372	15.170	0.316	5.379	2.075	0.773	−1.111	6396	2.12
		±0.001	±0.001	±0.012	±0.018	±0.094	±0.029		
V31	0.600230	15.308	0.223	5.617	2.421	0.861	−0.720	6419	13.89
		±0.001	±0.001	±0.019	±0.036	±0.098	±0.043		
V32	0.497203	15.330	0.380	5.040	1.422	0.870	−0.941	6596	1.50
		±0.001	±0.001	±0.012	±0.018	±0.085	±0.024		
V34	0.494370	15.349	0.263	5.273	1.658	0.954	−0.612	6599	2.64
		±0.001	±0.002	±0.031	±0.071	±0.090	±0.047		

(see Kovács & Kanbur 1998). In our sample, only three variables do not satisfy this condition. Table 5 summarizes the results obtained from equations (7)–(10). The mean values of the absolute magnitude, metallicity and effective temperature for 14 stars with $D_m < 3$ are $M_V = 0.86 \pm 0.01$, $[Fe/H] = -0.93 \pm 0.04$ and $T_{eff} = 6555 \pm 25$, respectively.

In their original paper Jurcsik & Kovács (1996) introduced the D_m parameter to distinguish RRab variables with regular light curves ($D_m < 3$) from those with irregular light curves, i.e. those showing Blazhko behaviour ($D_m > 3$). In our sample of RRab stars, V5, V7, V12 and V13 exhibit clear amplitude modulations. Surprisingly, the D_m parameter for these stars is less than 3. This may be a result of the large number of observational points in our light curves. The Blazhko effect is then averaged over many cycles and the fit given in equation (1) is not able to detect the modulation since the light curve seems to be regular.

The estimated mean metallicity $[Fe/H] = -0.93 \pm 0.04$ is in very good agreement with the estimates of Zinn & West (1984) $[Fe/H] = -1.08$ and Carretta & Gratton (1997) $[Fe/H] = -0.96$. However, the metallicity computed from equation (7) is on the scale of Jurcsik (1995), which is connected with the scale of Zinn & West by the formula:

$$[Fe/H]_{Jurcsik} = 1.431[Fe/H]_{ZW} + 0.880. \qquad (11)$$

If we take $[Fe/H] = -1.08$ from Zinn & West (1984), then equation (11) gives $[Fe/H] = -0.67$ on the Jurcsik (1995) scale. The reason for this discrepancy is unknown. Previous estimates of [Fe/H] using equation (7) have produced results in broad agreement with other estimates (see Kaluzny et al. 1998, 2000; Olech et al. 1999a).

3.4 Variable V18

The light curve of RRab variable V18 shown in Fig. 1 is quite noisy. The scatter is observed not only around maximum as in Blazhko variables (e.g. V5, V7, V12, V13) but along the whole light curve. This may indicate that this variable pulsates in two modes. The non-radial pulsations discovered in RRc stars (Olech et al. 1999a; this paper) were also observed in RRab stars (Moskalik 2000) and the presence of non-radial modes in V18 could explain the scatter in the light curve.

Inspection of the raw light curve suggests an amplitude modulation of 0.1 to 0.2 mag on a time-scale of around 40 d, perhaps indicating a beating effect. In our opinion there is another possible explanation.

The power spectrum shown in Fig. 8 displays a maximum frequency at $f_0 = 1.949\,79$ cycle d^{-1}, which corresponds to $P_0 = 0.512\,876$ d. There are also many aliases of f_0 placed at $f_0 \pm 1$, $f_0 + 2$ and $f_0 + 3$. The analysis-of-variance spectrum for three harmonics also shows a clear variation at f_0 with weak peaks at $f_0 \pm 1, f_0/2, f_0/3, f_0/4$ and $(f_0 + 1)/2$.

Both these periodograms are in agreement with a single frequency f_0 but this does not explain the scatter in the light curve of V18. One can notice that the doubled period ($2P_0 = 1.026$ d) differs only 0.026 d from one day and thus at each 38 d around midnight we observe only the flat part of the light curve, which is close to the mean brightness of the star. After 20 d around midnight we observe the largest change of the amplitude. Thus the modulation of the amplitude might not be real but might be caused by observing different parts of the light curve at each night.

The prewhitening of the raw light curve with f_0 and five harmonics gives a noisy light curve with a standard deviation of 0.07 mag, much larger than the photometric errors. The power spectrum of the prewhitened light curve shows many peaks with the highest at f_0 and $f_0/2$ with amplitudes of approximately 0.03 mag.

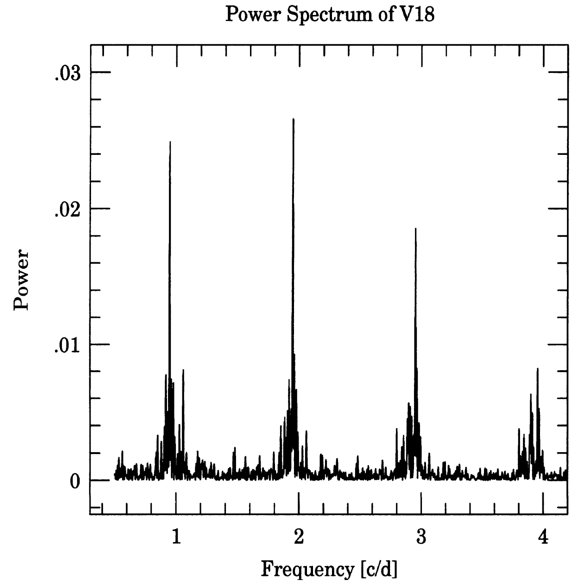

Figure 8. The power spectrum of RRab variable V18.

We conclude that there is no evidence for multiperiodic behaviour of V18. It is possible that the enhanced scatter detected in the light curve of this star is partially caused by the Blazhko effect, but this is difficult to check as a result of the proximity of P_0 to half a day.

3.5 Reddening and instability strip of NGC 6362

The reddening of RRab variables can be calculated from the metallicity, expressed in terms of ΔS (Preston 1959). From Blanco (1992) we have the relation:

$$E(B-V) = \langle B-V \rangle_{\Phi(0.5-0.8)} + 0.01222\Delta S - 0.00045(\Delta S)^2 - 0.185P - 0.356, \qquad (12)$$

where $\langle B-V \rangle_{\Phi(0.5-0.8)}$ is the observed mean colour in the 0.5–0.8 phase interval and P is the fundamental period. Based on the globular cluster metallicity scale adopted by Zinn & West (1984), Suntzeff, Kinman & Kraft (1991) derived the following ΔS versus [Fe/H] relation:

$$[Fe/H] = -0.408 - 0.158\Delta S. \qquad (13)$$

Using equation (13) and adopting $[Fe/H] = -1.0$ for NGC 6362, we obtain $\Delta S = 3.75$.

The average value of $E(B-V)$ calculated in this way for all 18 of our NGC 6362 RRab stars is $E(B-V) = 0.08 \pm 0.01$. This value is consistent with a recent determination of Piotto et al. (1999) who obtained $E(B-V) = 0.06 \pm 0.03$, slightly smaller than the value of Alcaino & Liller (1986) who obtained $E(B-V) = 0.10$, and in excellent agreement with the value of Brocato et al. (1999) who derived $E(B-V) = 0.08 \pm 0.02$.

Knowing the colours of RR Lyr variables and the reddening we are able to estimate the boundaries of the instability strip in NGC 6362. Our coolest variable is V20 with $\langle B \rangle - \langle V \rangle = 0.51$ and T_{eff}

computed from equation (10) equal to 6227 K. The hottest variable is V14 with $\langle B\rangle - \langle V\rangle = 0.25$ and $T_{\rm eff}$ computed from equation (4) equal to 7577 K (we exclude V37 with $\langle B\rangle - \langle V\rangle = 0.21$ because of its noisy light curve). Adopting a colour excess of $E(B-V) = 0.08$, we measure the blue and red edges of the instability strip in NGC 6362 to be at $(B-V)_0^{\rm BE} = 0.17$ and $(B-V)_0^{\rm RE} = 0.43$. These values are consistent with estimates made for other globular clusters (Smith 1995). One can however note a considerable overlap between variable and non-variable stars in the horizontal branch. Owing to this, the uncertainties in our determinations of the blue and red edges of the instability strip in NGC 6362 are around 0.03 mag.

3.6 Distance modulus to NGC 6362

Piotto et al. (1999) estimate the apparent distance modulus to NGC 6362 to be $(m-M)_V = 14.67 \pm 0.20$, based on a measured mean magnitude of the horizontal branch (HB) and the average of a number of calibrations of the relation between the absolute magnitude of the zero-age horizontal branch and the cluster metallicity.

A comparison of the colour–magnitude diagram of NGC 6362 presented in Fig. 2 with that of Piotto et al. (1999) shows a small but significant shift in *V* magnitude. Piotto et al. (1999) present a histogram of the distribution in *V* for the HB stars in the colour interval $0.5 < B-V < 0.7$. From this histogram they obtained a mean visual magnitude for the HB of $V_{\rm HB} = 15.45 \pm 0.03$. Fig. 9 shows similar histograms (we decided to increase the range of colours to $0.0 < B-V < 0.85$) for all colour–magnitude diagrams of the cluster found in the literature. The panels correspond to the work of (from top to bottom) Alcaino & Liller (1986), Mazur et al. (1999), Piotto et al. (1999) and this work. All histograms, except that of Piotto et al., show that the mean *V* magnitude of the HB is equal to 15.33. The 0.12-mag difference between the Piotto et al. estimate and the other data sets in Fig. 9 suggests that the value of apparent distance modulus to NGC 6362 from the Piotto et al. work should be $(m-M)_V = 14.55 \pm 0.20$ instead of $(m-M)_V = 14.67 \pm 0.20$.

Knowing the values of A_0 and $M_V^{\rm Ko}$ for RRc stars (see Table 3) we can compute the apparent distance modulus to NGC 6362. It is equal to $(m-M)_V = 14.46 \pm 0.02$, quite consistent with our corrected value of Piotto's determination. On the other hand one should remember that the equation for $M_V^{\rm Ko}$ is calibrated using Baade–Wesselink luminosities, which give faint absolute magnitudes for RR Lyr stars. We can also use the values of $\log L/{\rm L}_\odot$ of RRc stars to compute the distance modulus. The absolute magnitudes M_V (presented in the last column of Table 3) were calculated assuming a value of 4.79 for $M_{\rm bol}$ of the Sun and using a bolometric correction BC = 0.06[Fe/H] + 0.06, adopted from Sandage & Cacciari (1990). The resulting distance modulus is equal to $(m-M)_V = 14.59 \pm 0.03$, in excellent agreement with the value presented above. This agreement suggests that the theoretical models constructed by Simon & Clement (1993) produce the correct values of luminosities of RRc stars.

A similar estimate can be made for the RRab stars. Using the data given in Table 5 (14 RRab stars with $D_{\rm m} < 3$) we obtain $(m-M)_V = 14.46 \pm 0.10$. It is exactly the same value as we obtained using Kovács' expression for $M_V^{\rm Ko}$ of RRc stars (see Section 3.1). The agreement is expected since both equations (6) and (8) were calibrated using Baade–Wesselink luminosities.

Table 6 summarizes the distance and reddening determinations for NGC 6362. The values of the distance modulus based on the mean magnitude of the HB and that measured from $\log L/{\rm L}_\odot$ of RRc stars are very consistent. It is known that theoretical models of RR Lyr stars favour the *long* distance scale and thus large values of distance modulus. On the opposite side stand the statistical parallaxes and Baade–Wesselink luminosities of RR Lyr stars, which give faint values of absolute magnitudes of RR Lyr stars and thus values of the distance modulus that are smaller by 0.2–0.3 mag.

The final conclusion of this section is that the distance modulus to NGC 6362 is around 14.45 mag if we prefer the *short* distance scale and around 14.6 if we prefer the *long* distance scale.

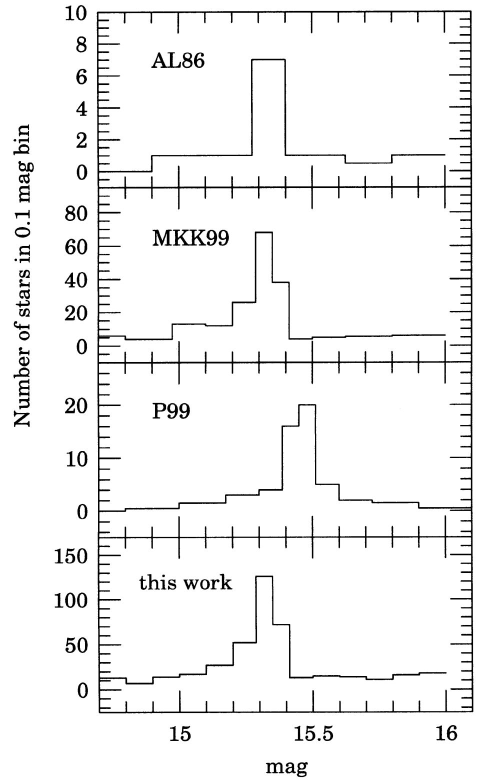

Figure 9. Histograms of the distribution in *V* of the HB stars in the colour interval $0.0 < B-V < 0.85$ based on colour–magnitude diagrams obtained by (top to bottom) Alcaino & Liller (1986), Mazur et al. (1999), Piotto et al. (1999) and this work.

Table 6. The distance and reddening determinations for NGC 6362.

Distance modulus $(m-M)_V$	Colour excess $E(B-V)$	Source
14.74	0.10	Alcaino & Liller (1986)
14.67 ± 0.20	0.06 ± 0.03	Piotto et al. (1999)
14.68 ± 0.05	0.08 ± 0.02	Brocato et al. (1999)
14.55 ± 0.20	–	Piotto corrected
14.46 ± 0.02	–	$M_V^{\rm Ko}$ of RRc stars
14.59 ± 0.03	–	$\log L/{\rm L}_\odot$ for RRc stars
14.46 ± 0.10	0.08 ± 0.01	RRab stars

4 CONCLUSIONS

We have presented a comprehensive study of 35 RR Lyr variables in the globular cluster NGC 6362. Our *V*-band light curves contain over 1000 measurements and our *B*-band light curves around 260 measurements. The periods of the cluster RRc stars are between 0.2462 and 0.3815 d with a mean value of 0.295 d. The periods of the RRab variables are between 0.4471 and 0.6983 d with a mean value of 0.538 d.

The period–amplitude ($\log_{10} P$ versus A_V) diagram for NGC 6362 shows that RRab variables from this cluster do not fit the $\log_{10} P$ versus A_V relation for M3, another Oosterhoff type I globular cluster, suggesting that the V amplitude for a given period is a function of metallicity rather than Oosterhoff type alone.

Fourier decomposition of the light curves was used to estimate the basic properties of these variables. From the analysis of the RRc stars we obtain a mean mass $M = 0.531 \pm 0.014\,M_\odot$, luminosity $\log L/L_\odot = 1.656 \pm 0.006$, effective temperature $T_{\rm eff} = 7429 \pm 20$ and helium abundance $Y = 0.292 \pm 0.002$. The mean values of the absolute magnitude, metallicity (Jurcsik's scale) and effective temperature for 14 RRab stars with 'regular' light curves are $M_V = 0.86 \pm 0.01$, $[\mathrm{Fe/H}] = -0.93 \pm 0.04$ and $T_{\rm eff} = 6555 \pm 25$, respectively.

Using the $B - V$ colours, periods and metallicities of the RRab stars, we estimate the value of the colour excess for NGC 6362 to be equal to $E(B - V) = 0.08 \pm 0.01$. From this colour excess we derive the unreddened colours of the blue and red edges of the instability strip in NGC 6362 to be $(B - V)_0^{\rm BE} = 0.17$ and $(B - V)_0^{\rm RE} = 0.43$.

The apparent distance modulus of NGC 6362 calculated from the sample of 14 RRab stars is $(m - M)_V = 14.46 \pm 0.10$. An analysis of the RRc stars based on Kovács' expression for $M_V^{\rm Ko}$ leads to a value of $(m - M)_V = 14.46 \pm 0.02$. This agreement is expected since both derivations rely on Baade–Wesselink luminosities, giving faint magnitudes for RR Lyr stars and a *short* distance scale. On the other hand, a larger value of the distance modulus is determined from estimates of $\log L/L_\odot$ of the RRc stars: $(m - M)_V = 14.59 \pm 0.03$. This result is also expected because theoretical models of RR Lyr stars produce large values of distance moduli and prefer a *long* distance scale. These latter distance determinations are consistent with the value of $(m - M)_V = 14.55 \pm 0.20$ derived from the mean magnitude of the zero-age horizontal branch.

Three of the RRc variables presented in Fig. 1 (V37, V6 and V10) show a clear modulation of their light curves. The power spectra of the light curves of these stars show the highest peaks for the first overtone radial pulsations. In the case of V37 we detect another peak in the vicinity of the main frequency, which cannot be connected with radial pulsations. In the case of V6 and V10 we detect two non-radial modes in the vicinity of the main frequency. Our conclusion is that these variables belong to the newly discovered group of non-radial pulsating RR Lyr stars (Olech et al. 1999a,b; Kovács et al. 2000; Moskalik 2000). We have also noticed that the non-radial pulsation RRc stars lie near the blue edge of the instability strip, consistent with the results of Olech et al. (1999a) for RRc stars in the globular cluster M55.

The light curves presented in Fig. 1 are available from http://www.camk.edu.pl/~jka/.

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