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CCD photometry of the globular cluster M2: RR Lyrae physical parameters and new variables

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ABSTRACT

We report the results of CCD V and R photometry of the RR Lyrae stars in M2. The periodicities of most variables are revised and new ephemerides are calculated. Light-curve decomposition of the RR Lyrae stars was carried out and the corresponding mean physical parameters [Fe/H] = -1.47, $T_{\rm eff} = 6276$ K, $\log L = 1.63\,{\rm L}_{\odot}$ and $M_V = 0.71$ from nine RRab and [Fe/H] = -1.61, $M = 0.54\,{\rm M}_{\odot}$, $T_{\rm eff} = 7215$ K, $\log L = 1.74\,{\rm L}_{\odot}$ and $M_V = 0.71$ from two RRc stars were calculated. A comparison of the radii obtained from the above luminosity and temperature with predicted radii from non-linear convective models is discussed. The estimated mean distance to the cluster is 10.49 ± 0.15 kpc. These results place M2 correctly in the general globular cluster sequences for Oosterhoff type, mass, luminosity and temperature, all as a function of the metallicity. Mean relationships for M, $\log L/{\rm L}_{\odot}$, $T_{\rm eff}$ and M_V as a function of [Fe/H] for a family of globular clusters are offered. These trends are consistent with evolutionary and structural notions on the horizontal branch. Eight new variables are reported.

Key words: stars: horizontal branch – stars: Population II – stars: variables: other – globular clusters: individual: M2.

1 INTRODUCTION

RR Lyrae stars are of particular importance in the determination of the age and distance to ancient stellar systems, such as globular clusters. Their usefulness is based in the fact that their light curves are easily distinguishable and their high intrinsic brightness allows their detection in systems of the Local Group. Their well-defined absolute magnitude allows using them as standard candles in the cosmic distance scale (e.g. Alcock et al. 2004 for the Large Magellanic Cloud, LMC).

The RR Lyrae stars have been used in the determination of the absolute ages of globular clusters, by measuring the magnitude difference between the main-sequence turn-off point and the horizontal branch (HB), on which the RR Lyrae stars reside. This is a useful reddening-free parameter that helps in tracing the early stages of the formation of our Galaxy. This, however, requires a proper calibration of the absolute magnitude M_V for the RR Lyraes.

The pulsational behaviour of RR Lyrae stars in globular clusters has been a subject of study for decades because it offers insight on stellar evolution in the HB stages. The mean periods of fundamental pulsators (type RRab) divide globular clusters into two groups, the Oosterhoff type I (OoI) with $\langle P_{\rm ab}\rangle$ smaller than 0.6 d and the Oosterhoff type II (OoII) with $\langle P_{\rm ab}\rangle$ larger than 0.6 d (Oosterhoff 1939). Recent light-curve Fourier decomposition calculations have clearly shown that RR Lyrae stars in OoII clusters are, on average, more luminous, more massive and cooler than in OoI clusters, and that these quantities are closely correlated with the mean cluster metallicity. For example, these stars have longer periods in metal-poor clusters than in metal-rich clusters (e.g. Simon & Clement 1993; Clement & Shelton 1997; Kaluzny et al. 2000; Arellano Ferro et al. 2004; Arellano Ferro, García Lugo & Rosenzweig 2006, see their tables 8 and 9).

On the other hand, the distribution of fundamental periods ($P_{\rm ab}$ for RRab stars) and the fundamental periods calculated from the first overtone period and the period ratio (P_f for RRc stars), as well as the relative number of RRc and RRab stars, provide important insights relevant to the instability strip structure and HB structure and evolution (Castellani, Caputo & Castellani 2003). Nevertheless, such studies are strongly limited by bona fide completeness

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of the sample of RR Lyrae pulsators in a cluster. It is evident from recent works that a substantial number of RR Lyrae stars can be discovered when new image-subtraction techniques (Alard & Lupton 1998; Alard 2000; Bond et al. 2001; Bramich et al. 2005) are applied to CCD images of globular clusters (e.g. Lee & Carney 1999a, hereinafter LC99; Kaluzny, Olech & Stanek 2001; Clementini et al. 2004).

The latest CCD study of M2 (NGC 7089) was published by LC99. These authors reported 13 new RR Lyraes, for a total of 34 variables in the cluster, 30 of which are RR Lyrae stars. They calculated the ratio $n(c)/n(ab + c) = 0.40$, which approaches the mean typical value of 0.44 in OoII clusters. Hence, not many undiscovered RR Lyraes are expected. However, because these authors did not perform a light-curve decomposition analysis, we decided to supplement their *BV* data with new *VR* observations and use the two data sets to refine the ephemerides, determine the mean physical parameters of the RR Lyrae stars from the Fourier decomposition technique, compare the results with those of other similarly studied OoI and OoII clusters and, in passing, search for new variables. The effort was not fruitless.

In Section 2, we describe the observations and data reductions. In Section 3, we calculate new ephemerides, new times of the maximum, discuss individual objects and report new variables. In Section 4, we calculate the physical parameters using the light-curve decomposition method. In Section 5, we discuss the results in the wider context of other globular clusters and, in Section 6, we state our conclusions.

2 OBSERVATIONS AND REDUCTIONS

The observations used in the present work, performed using the Johnson *V* and *R* filters, were obtained from 2002 June 6 to 19 with the 0.82-m telescope of the Observatorio del Teide, Tenerife, Spain. The seeing conditions were good, with an estimated FWHM $\simeq$ 1 arcsec. The detector was a Thompson CCD of 1024 $\times$ 1024 pixels of 19 μm^2; these images are of approximately 7 $\times$ 7 arcmin^2. Exposure times were 900 and 500 s in the *V* and *R* filters, respectively. A total of 60 images in *V* and 60 in *R* were obtained. Higher resolution images for proper star identification were acquired with the 2.0-m Himalayan Chandra Telescope (HCT) of the Indian Astrophysical Observatory (IAO).

Differential photometry by the image subtraction method, described in detail by Bond et al. (2001) and Bramich et al. (2005), was performed. This procedure involves the matching of a high-quality reference image to each image in the time-series, by solving for a spatially varying convolution kernel and differential sky background function. Difference images are constructed via the subtraction of the convolved reference image from the time-series images. Photometry on the difference images yields differential fluxes for each star relative to the flux from the reference image. Conversion of the light curves to magnitudes requires an accurate measurement of the reference flux.

We measured the stellar fluxes on the reference frame using DAOPHOT (Stetson 1987). However, the point spread function (PSF) on the images was highly non-gaussian and not fully modelled by the DAOPHOT routine. The reason for the poor PSF seems to be related to some optical misalignment of the telescope at the time of our observations. Hence, our reference fluxes contain systematic errors that may affect the amplitude of the variable star light curves. Fourier decomposition and the subsequent calculation of physical parameters is mainly light-curve shape dependent, and we can use our light curves for that purpose.

The instrumental magnitudes were converted to the *V* standard system by using 168 standard stars in the interval $19.5 > V > 14.0$ listed by Stetson (2005) in the M2 field. The transformation equation had a linear form $M_{\mathrm{std}} = 0.985(\pm 0.005)M_{\mathrm{ins}} - 3.990(\pm 0.01)$, without the need of a quadratic term; moreover, the standard stars span a $B - V$ range from -3.5 to +5.0 and no significant colour term was found.

We noticed that the difference in magnitudes between our data and the LC99 light curves changes from star to star, which is likely due to poor PSF quality. Therefore, we have shifted in magnitude each of our *V* light curves in order to match the LC99 photometry. Once the correct shift is applied, both data sets agree very well, as can be seen in Fig. 1. Once the vertical matching was accomplished, we noticed a small dispersion along the time axis. Because our observations were gathered between 4 and 6 yr after those of LC99, we decided to attempt a refinement of the periods, using both data sets. The string-length method, frequency analysis and Fourier fits were used to detect and refine period values. The complete set of periods used below for the Fourier decomposition are listed in Table 1, where the newly determined periods are presented alongside the periods from LC99. The differences in the periods are small but in several cases significant when phasing the light curves. The error on the refined values of the periods is 2×10^{-6} d.

In Figs 1 and 2, the light curves in *V* and *R* for the previously known RR Lyraes are displayed. Different symbols are used for the observations of LC99 and our own as described in the caption, which illustrates the general good agreement between the two data sets.

3 DISCUSSION OF INDIVIDUAL OBJECTS AND NEW VARIABLES

3.1 Comments on individual variables

For stars of steady amplitude (V3, V7, V9, V10, V12, V13, V27, V31 and V34), the agreement between the light curves of LC99 and those in the present work is excellent. No further discussion is needed in these cases. Other stars deserve some comments.

3.1.1 V2

V2 is labelled as a Blazhko variable in the catalogue of Clement (2002). The appearance of the light curve in Fig. 1 indeed suggests that the effect is present. The detailed plot of the light curve displayed in Fig. 3 confirms the Blazhko nature of the variable and allows an estimate of the magnitude variation of the maximum at different epochs (Table 2). With only five measurements of the maximum light momenta, it is difficult to characterize the Blazhko periodicity. Nevertheless, the frequency analysis detected a secondary peak at 1.8870 cycle d^{-1}, very close to the main peak at 1.8945 cycle d^{-1}, which suggests a Blazhko periodicity of $\sim$133 d; however, the value of the secondary peak is not fully reliable owing to the poor phase coverage of the Blazhko cycle.

3.1.2 V4, V8, V14

V4, V8 and V14 have not been noticed before as having the Blazhko effect. However, the LC99 light curves show some cycle-to-cycle variations. Moreover, our data have a different amplitude in all three cases, thus, the possibility of a long-term Blazhko effect is just plausible, but not definitely proven.

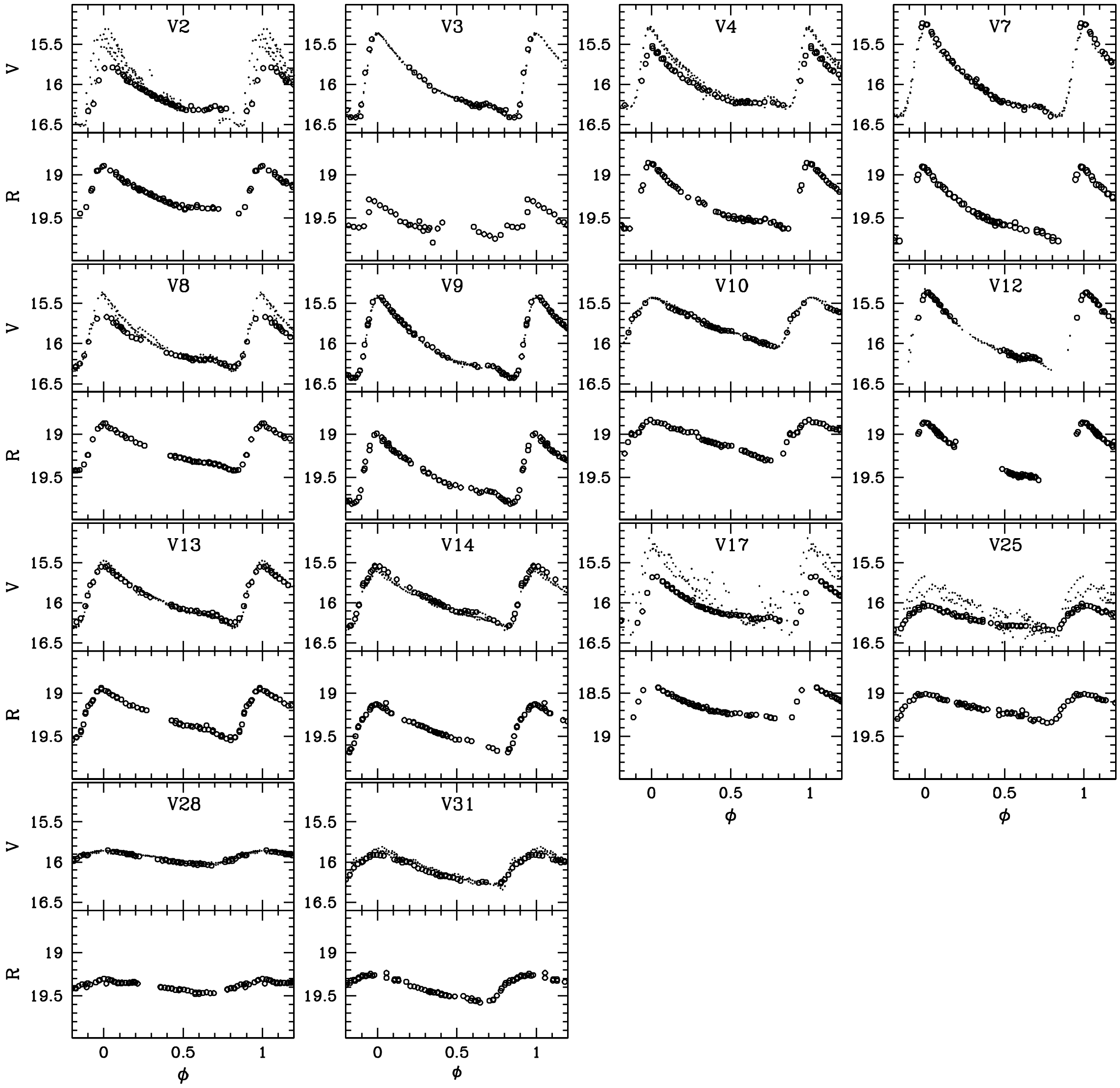

Figure 1. Light curves of known RRab stars in M2. They have been phased with the new ephemerides in Table 1. The vertical scale is the same for all the stars. Small dots represent observations from LC99. Open circles represent observations from the present work.

3.1.3 V15

The light curve in our Fig. 2 and in fig. 5 of LC99, make V15 suspected as having cycle-to-cycle variations. Because our analysis did not detect a radial double-mode pulsation, the only possibility is a Blazhko effect. Even though the time-series has large gaps, we can tentatively explain the light curve with a close doublet of frequencies ($f_1 = 3.3246$ and $f_2 = 3.2101$ cycle d^{-1} or a Blazhko period of ~8.7 d). More observations are required to define this doublet better, because it seems to be separated too much (Moskalik & Poretti 2003).

3.1.4 V17 and V25

For V17 and V25, our light curves display a lower amplitude than in LC99, but they are much more accurate and rule out the possibility of a double-mode pulsation or a Blazhko effect. Indeed, the inspection of these stars on the reference image reveal that they are blends, and hence our amplitudes are underestimated.

3.1.5 V26

V26 is suspected of being a double-mode star in the list of Clement (2002). However, when subdividing the data sets of LC99 and our own into subsets, the resulting light curves look very stable although they show considerable time shifts ranging between 0.004 and 0.062 d. Once the subsets are corrected by these shifts, a clean sinusoidal light curve is obtained with a period of 0.412 376 d. Thus, the star is not a double-mode pulsator and the shifts can possibly be explained as light-time effects if this RRc is a member of a binary system. More observations would be needed to confirm this possibility.

3.1.6 V28

V28 seems to be rather peculiar, displaying a lower amplitude light curve than the other RRab stars. It is the longest period RR Lyrae variable in M2 (see Table 1), and its physical parameters are clearly discordant with those of the other RRab stars, with a particularly

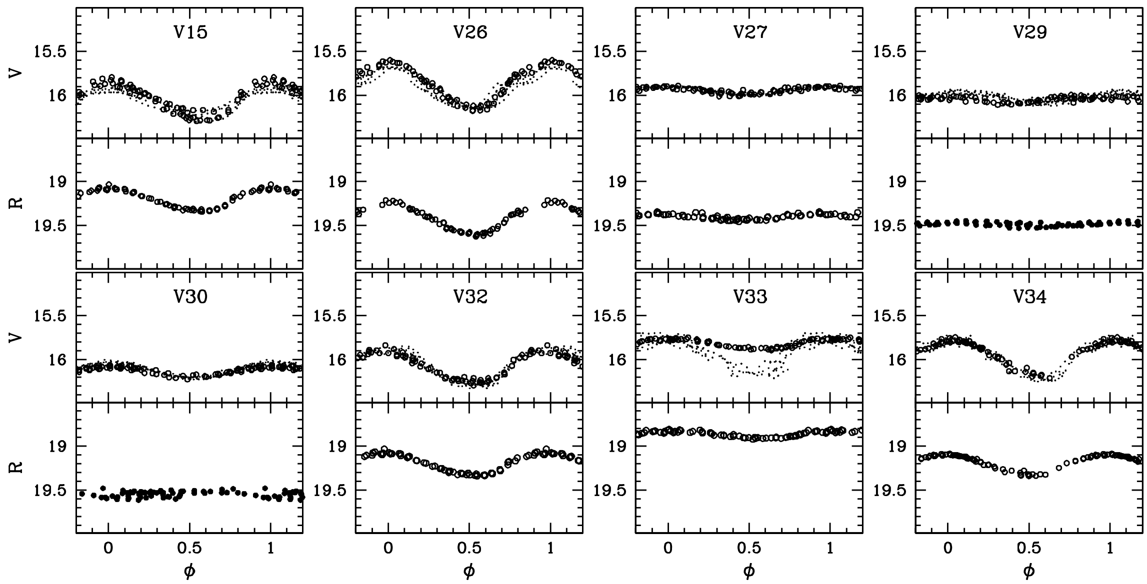

Figure 2. Light curves of previously known RRc stars in M2. Symbols are as in Fig. 1.

Table 1. Update of periods and epochs for the RR Lyrae stars in M2.

Variable	Type	Old period (days)	New period (days)	New epoch (+ 240 0000)
V2	ab	0.527 8619	0.527 840	52445.561
V3	ab	0.619 7084	0.619 713	52445.165
V4	ab	0.564 2512	0.564 243	52445.629
V7	ab	0.594 8665	0.594 868	52445.347
V8	ab	0.643 7059	0.643 690	52445.287
V9	ab	0.609 2938	0.609 295	52445.582
V10	ab	0.875 7413	0.875 744	52445.090
V12	ab	0.665 6063	0.665 607	52445.248
V13	ab	0.706 6260	0.706 619	52445.074
V14	ab	0.693 7767	0.693 788	52445.442
V15	c	0.300 7852	0.300 785	52445.586
V17	ab	0.636 4715	0.636 444	52445.474
V25	ab	0.728 7186	0.728 720	52445.466
V26	c	0.419 5213	0.412 376	52445.461
V27	c	0.314 1578	0.314 158	52445.473
V28	ab	0.823 7775	0.823 797	52445.210
V30	c	0.272 8723	0.272 871	52445.582
V31	ab	0.788 7144	0.788 715	52445.005
V32	c	0.361 9382	0.367 021	52445.655
V34	c	0.391 4157	0.391 414	52445.639

low $T_{\rm eff}$ and a large luminosity and radius. The possibility of an unseen blend affecting its light curve can not be discarded. The star could be an anomalous Cepheid, but its mean V magnitude ($V = 15.945$) is quite normal for an RR Lyrae variable. Owing to this peculiar behaviour, we did not include its physical parameters in Table 6.

3.1.7 V30

V30 is also suspected of being a double-mode star in the list of Clement (2002). However, we find it to be monoperiodic with a period of 0.272 871 d. The scatter in the observations of both LC99 and our own is a bit large.

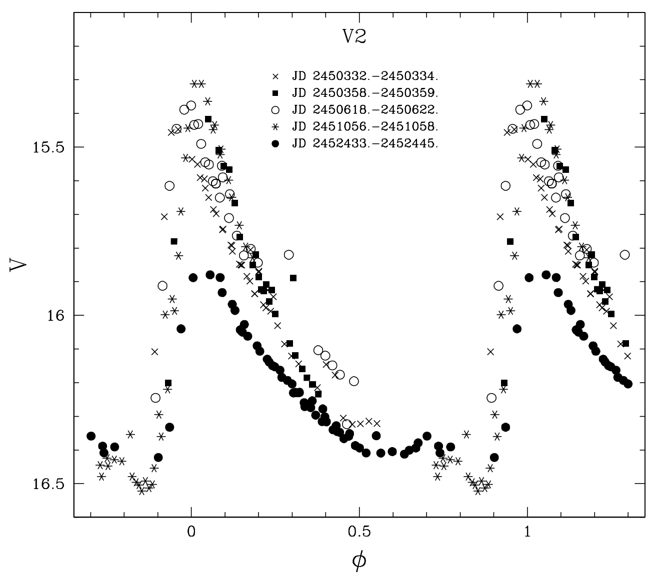

Figure 3. Blazhko effect in V2.

Table 2. V magnitude of maximum light variations in V2.

$V_{\rm max}$	HJD
15.532	245 0333.667
15.309	245 0358.476
15.374	245 0622.921
15.309	245 1057.877
15.878	245 2436.609

3.1.8 V32

For V32, the LC99 data show some scatter but no traces of a second periodicity have been found performing a frequency analysis. However, when splitting the time-series into different subsets, we clearly evidenced the same light curve displaced in time. Therefore, a light-time effect is plausible for this star. The light curve displayed in Fig. 2 has been corrected for this effect.

3.2 Negative detections

3.2.1 V16

V16 is reported as variable in the catalogue of Clement (2002) and it is identified in the map of LC99. However, we find no star in the position marked by these authors nor variability in nearby stars. Therefore, we have not included this star in Fig. 1 or in the subsequent analysis.

3.2.2 V18–21

V18–21 were not in the field of our CCD images.

3.2.3 V22–24

V22–24, convincingly variables as reported by LC99, were identified in our images, but no significant light variations were detected in either the *V* or *R* filters despite not being in particularly crowded regions.

3.2.4 V29, V33

V29 and V33 are a blend in our images and the resulting amplitudes are very small. Our data are not useful to improve LC99 results.

3.3 Newly discovered variables

We have detected clear light variations in eight stars in the field of M2, not previously reported as variables. The corresponding identifications are shown in Figs 4 and 5. In Table 3, we report the period and epoch of maximum light, and the Bailey type for each new variable. The error on the periods of the new variables is 4×10^{-4} d.

The light curves of the new variables are shown in Fig. 6. Due to the problem with the PSF of our images described in Section 2 and the fact that these new variables are all blends to some degree (see Fig. 5), we cannot assign a standard magnitude for the new variables. The light curves are therefore displayed as differential fluxes in units of ADU s^{-1}. Fourier decomposition and the subsequent calculation of physical parameters are mainly light-curve shape dependent, and we can use the light curves for some of the new variables for that purpose. The new variables follow.

3.3.1 V35

The RRc variable V35 appears in the *V* images as a blend with another brighter star by about two magnitudes and it is not detected in the *R* images. This star will not be considered for physical parameter calculations.

3.3.2 V36 and V42

V36 and V42 are new RRc variables.

3.3.3 V37, V38, V39 and V40

V37, V38, V39 and V40 show clear light curves of the RRab type. V37 is not detected in the *R* images.

3.3.4 V41

V41 is a strong blend not resolved in our images. The variability in the difference images has a small offset relative to the centre of the contaminating brighter star. The variable is of type RRab.

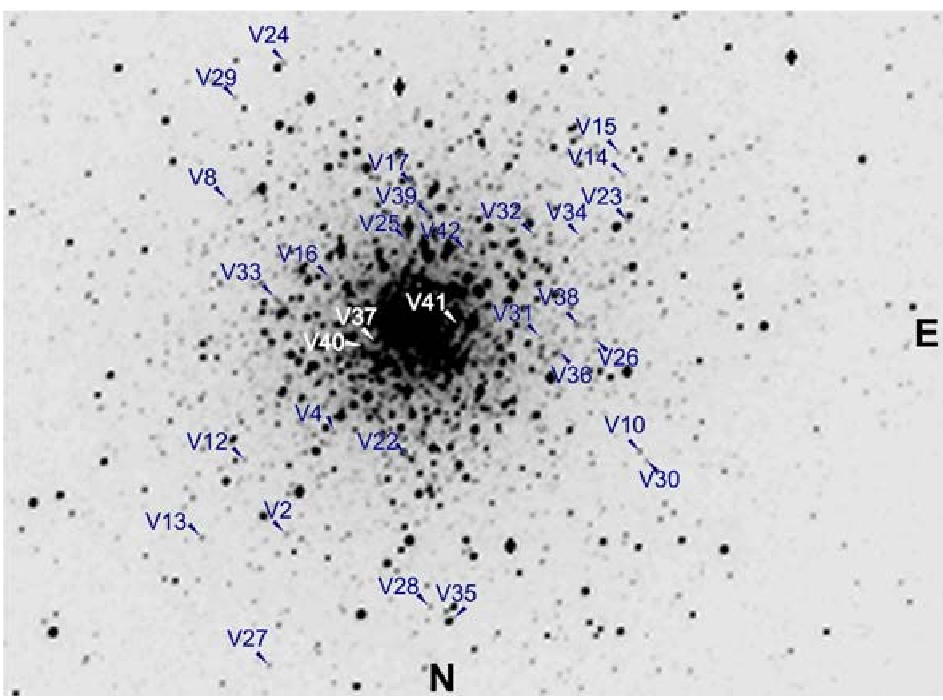

Figure 4. Variables in M2. Individual image stamps for the new variables can be found in Fig. 5. The image was obtained at the 2.0-m HCT of the IAO. The size of the image is approximately 6×6 arcmin^2.

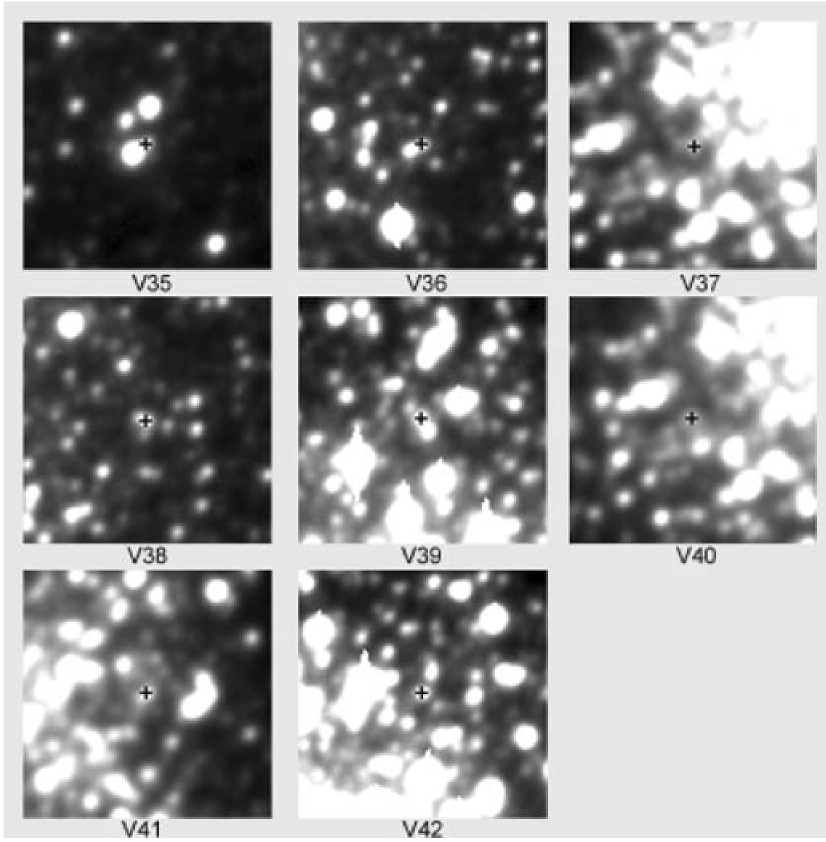

Figure 5. Detailed identifications of new variables in M2. The size of the stamps is 17 × 17 arcsec. As in Fig. 4, north is down and east is to the right.

Table 3. Bailey types, (α, δ) (2000) coordinates, periods and epochs for the newly detected variables.

Variable	Type	α (h m s)	δ (° ′ ″)	Period (days)	Epoch (+240 0000)
V35	c	21 33 28.0	−0 47 31	0.325 57	52445.517
V36	c	21 33 30.7	−0 49 12	0.270 78	52445.562
V37	ab	21 33 26.0	−0 49 18	0.566 68	52445.709
V38	ab	21 33 31.1	−0 49 23	0.807 35	52445.519
V39	ab	21 33 27.3	−0 50 06	0.607 81	52445.467
V40	ab	21 33 25.6	−0 49 15	0.751 73	52445.447
V41	ab	21 33 28.0	−0 49 24	0.605 32	52445.663
V42	c	21 33 28.3	−0 49 51	0.328 01	52445.497

4 FOURIER LIGHT-CURVE DECOMPOSITION AND PHYSICAL PARAMETERS

The mathematical representation of the light curves is of the form:

$$m(t) = A_0 + \sum_{k=1}^{N} A_k \cos\left[\frac{2\pi}{P} k\,(t - E) + \phi_k\right], \tag{1}$$

where $m(t)$ are magnitudes at time t, P is the period and E is the epoch. A linear minimization routine is used to fit the data with the Fourier series model, deriving the best-fitting values of E and of the amplitudes A_k and phases ϕ_k of the sinusoidal components.

The fits are not shown in Figs 1, 2 and 6 for simplicity and clarity. From the amplitudes and phases of the harmonics in equation (1), the Fourier parameters, defined as $\phi_{ij} = j\phi_i - i\phi_j$ and $R_{ij} = A_i/A_j$, were calculated. The mean magnitudes A_0 and the Fourier light-curve fitting parameters of the individual RRab and RRc type stars in V are listed in Table 4. The mean dispersion about the fits is about ±0.022 mag. These parameters will be used below to estimate the physical parameters of the stars.

The realization that light-curve shapes and physical parameters are related, traces back to the paper of Walraven (1953). The relation between the pulsation of RR Lyrae variables and their physical parameters is obtained from hydrodynamic pulsation models of defined physical parameters, which are used to generate theoretical light curves. These curves are then fitted to obtain the corresponding Fourier parameters. Simon & Clement (1993) used hydrodynamic pulsation models to calibrate equations for the effective temperature $T_{\rm eff}$, a helium content parameter Y, the stellar mass M and the luminosity L, in terms of the period and Fourier parameter ϕ_{31} for RR Lyrae stars of the Bailey type RRc (see equations 2, 3, 4 and 5). Recently, Morgan, Wahl & Wieckhorst (2005) have found several [Fe/H] − $\log P - \phi_{31}$ relations for RRc variables and we have adopted their equation (5) (see equation 6 below), with a quoted standard deviation of ±0.21, to derive the [Fe/H] values given in Table 5. M_V for the RRc stars can be estimated through the calibration given by Kovács (1998) (equation 7). For the sake of clarity, all the equations used are listed below:

$$\log M/{\rm M}_{\odot} = 0.52 \log P - 0.11\, \phi_{31}^{(c)} + 0.39, \tag{2}$$

$$\log L/{\rm L}_{\odot} = 1.04 \log P - 0.058\, \phi_{31}^{(c)} + 2.41, \tag{3}$$

$$\log T_{\rm eff} = 3.775 - 0.1452 \log P + 0.0056\, \phi_{31}^{(c)}, \tag{4}$$

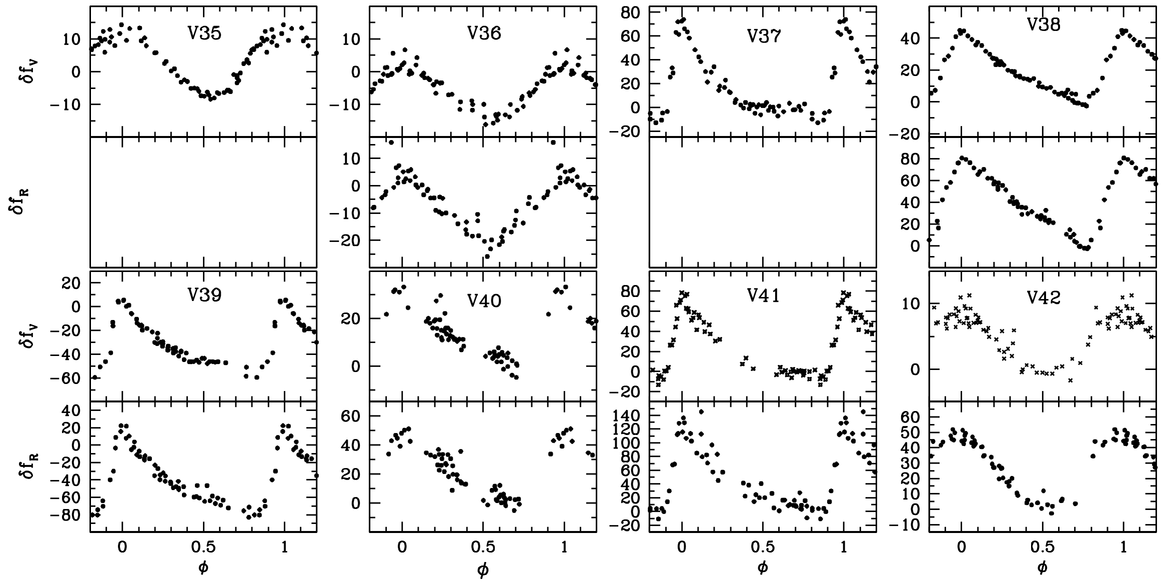

Figure 6. Light curves of the new variables. For identifications, refer to Figs 5 and 6. The vertical scales are differential fluxes in ADU s^{-1}. Thus the amplitudes are artificial and not comparable between different filters and stars.

Table 4. Fourier fitting parameters for *V* light curves.

Star (*N*)	A_0	A_1	A_4	ϕ_{21}	ϕ_{31}	ϕ_{41}
V3 (9)	16.007	0.362	0.084	4.03	2.05	0.17
V7 (8)	15.995	0.391	0.084	3.95	1.91	6.14
V9 (8)	16.038	0.356	0.077	3.98	1.99	0.10
V10 (8)	15.753	0.246	0.019	4.48	3.06	1.27
V12 (8)	15.957	0.349	0.075	4.17	2.29	0.64
V13 (6)	15.952	0.275	0.045	4.19	2.33	0.61
V17 (8)	16.056	0.196	0.052	3.89	1.72	5.98
V25 (5)	16.211	0.118	0.011	4.03	2.18	0.26
V27 (1)	15.954	0.047				
V28 (2)	15.945	0.079		4.79		
V30 (1)	16.126	0.079				
V31 (4)	16.074	0.184	0.013	4.48	3.06	1.66
V32 (4)	16.085	0.201	0.005	4.66	3.50	2.70
V34 (4)	15.983	0.213	0.013	5.38	4.50	3.23
V36 (2)	–	0.077		4.36		
V37 (7)	–	0.123	0.040	3.61	1.51	5.59
V38 (4)	–	0.107	0.008	4.39	2.63	0.89
V39 (6)	–	0.097	0.017	3.96	2.09	6.10
V41 (4)	–	0.048	0.014	4.03	2.31	0.06
$\langle\sigma_{\rm RRab}\rangle$	±0.002	±0.003	±0.003	±0.07	±0.11	±0.18
$\langle\sigma_{\rm RRc}\rangle$	±0.002	±0.004	±0.004	±0.24	±0.37	±0.66

N: number of harmonics used to fit the light curve.
A_0: after shifting our data to fit the LC99 magnitude scale.
V17 and V25: light-curve fitting on our data only.

$$\log Y = -20.26 + 4.935 \log T_{\rm eff} - 0.2638 \log M/{\rm M}_\odot + 0.3318 \log L/{\rm L}_\odot, \tag{5}$$

$$[{\rm Fe/H}] = 3.702(\log P)^2 + 0.124\left[\phi_{31}^{(c)}\right]^2 - 0.845\phi_{31}^{(c)} - 1.023\phi_{31}^{(c)} \log P - 2.620, \tag{6}$$

$$M_V = 1.261 - 0.961P - 0.044\phi_{21}^{(s)} - 4.447A_4. \tag{7}$$

For the RRab stars, we have used the equation (3) of Jurcsik & Kovács (1996) for [Fe/H] (our equation 8), equation (2) in Kovács & Jurcsik (1996) for M_V (our equation 9), and equations (5) and (11) in Jurcsik (1998) for $(V-K)_0$ and $\log T_{\rm eff}$ (our equations 10 and 11). The explicit formulae are:

$$[{\rm Fe/H}] = -5.038 - 5.394P + 1.345\phi_{31}^{(s)}, \tag{8}$$

$$M_V = 1.221 - 1.396P - 0.477A_1 + 0.103\phi_{31}^{(s)}, \tag{9}$$

$$(V-K)_0 = 1.585 + 1.257P - 0.273A_1 - 0.234\phi_{31}^{(s)} + 0.062\phi_{41}^{(s)}, \tag{10}$$

$$\log T_{\rm eff} = 3.9291 - 0.1112(V-K)_0 - 0.0032[{\rm Fe/H}]. \tag{11}$$

The luminosity is derived through M_V and the bolometric correction *BC*, adopting the relation of Sandage & Cacciari (1990)

$$BC = 0.06[{\rm Fe/H}] + 0.06, \tag{12}$$

with

$$M_{\rm bol} = M_V + BC \text{ and } \log L/{\rm L}_\odot = -0.4(M_{\rm bol} - 4.75). \tag{13}$$

In the previous equations, $\phi_{jk}^{(c)}$ and $\phi_{jk}^{(s)}$ are phase shifts with assumed cosine and sine Fourier series respectively: they are related by $\phi_{jk}^{(s)} = \phi_{jk}^{(c)} - (j-k)\frac{\pi}{2}$.

A thorough discussion of the uncertainties in the physical parameters, as obtained from the above mentioned calibrations, can be found in the work of Jurcsik (1998). The estimated uncertainties for $\log L$, $\log T$, $\log M$ and [Fe/H] are ±0.009, ±0.003, ±0.026 and ±0.14 dex, respectively.

We have carried out the Fourier decomposition of RRab stars using the combined data of LC99 and our own, except in those stars where the Blazhko effect is confirmed or suspected, i.e. in V2, V4, V8, V14 and V15. Moreover, V31, V40 and V41 data are less reliable owing to high scatter and/or gaps in the phase coverage: also these stars have been not considered. Tables 5 and 6 list the physical parameters we obtained.

Table 5. Physical parameters for the RRc stars.

Star	[Fe/H]	T_{eff}	M_V	$\log(L/\mathrm{L}_{\odot})$	Y	$M/\mathrm{M}_{\odot}$	$\log(R/\mathrm{R}_{\odot})$ (LT)	$\log(R/\mathrm{R}_{\odot})$ (PRZ)	D (kpc)
V32	−1.798	7202	0.75	1.754	0.26	0.60	0.713	0.710	10.71
V34	−1.422	7228	0.66	1.725	0.28	0.48	0.673	0.728	10.64
Mean	−1.61	7215	0.71	1.74	0.27	0.54	0.69	0.68	10.67
σ	±0.27	±18	±0.06	±0.02	±0.01	±0.08	±0.03	±0.04	±0.05

Table 6. Physical parameters for the RRab stars.

Star	[Fe/H]	T_{eff}	M_V	$\log(L/\mathrm{L}_{\odot})$	$\log(R/\mathrm{R}_{\odot})$ (LT)	$\log(R/\mathrm{R}_{\odot})$ (PRZ)	D (kpc)
V3	−1.398	6380	0.72	1.622	0.729	0.767	10.49
V7	−1.452	6424	0.72	1.621	0.720	0.756	10.40
V9	−1.421	6384	0.73	1.618	0.727	0.762	10.58
V10	−1.421	6084	0.52	1.702	0.808	0.854	10.22
V12	−1.323	6320	0.68	1.634	0.744	0.785	10.40
V13	−1.490	6231	0.67	1.645	0.758	0.800	10.47
V37	−1.824	6287	0.85	1.579	0.714	0.744	–
V38	−1.630	6049	0.64	1.660	0.790	0.833	–
V39	−1.280	6331	0.87	1.561	0.705	0.762	–
Mean	−1.47	6276	0.71	1.63	0.75	0.79	10.42
σ	±0.16	±124	±0.10	±0.04	±0.03	±0.04	±0.11

We notice that the average value of [Fe/H] we derived from our RRab sample (−1.47) is in close agreement with that reported by Kovács & Walker (2001; [Fe/H] = −1.43 ± 0.15). Also when including the two RRc stars (as Kovács & Walker did), the average value ([Fe/H] = −1.50 ± 0.17) is within the error bars.

It must be noticed that M_V derived from equations (7) and (9) for RRc and RRab stars, respectively, agree very well. However, the luminosities for RRc stars derived from equation (3) seem to be too large when compared with those for RRab variables (derived from equations 9, 12 and 13). This can be appreciated in Fig. 8, later (open circles and crosses). The possibility that this is the result of the temperature dependence of the bolometric correction, *BC*, can be ruled out as it does not explain the difference in $\log L/\mathrm{L}_{\odot}$. Alternatively, if equation (12) is used to transform the M_V values, obtained with equation (7), into $\log L/\mathrm{L}_{\odot}$, both RRc and RRab stars have similar luminosities (crosses in Fig. 8, later). Moreover, the A_0 values of the RRc stars reported in Table 4 (V27, V30, V32 and V34) are quite similar to those of the RRab stars. Therefore, some inconsistency seems to exists between the zero-points of equations (3) and (7) for the RRc stars. This problem has been noticed and commented on by Cacciari, Corwin & Carney (2005) whom opted for decreasing the magnitude scale derived from equation (7) by 0.20 mag.

5 DISCUSSION

5.1 Oosterhoff type and RR Lyrae statistics

Including the three new variables, the average value of the period for the RRc stars is 0.327 ± 0.044 d. Comparing with the mean values for seven clusters reported by Clement & Rowe (2000), M2 fits better among the OoI type, although considering the standard deviations, the difference from the value in OoII type clusters of 0.36 d is not significant. For the RRab stars, including the five new variables, we find an average period of 0.674 ± 0.093 d, which is typical of OoII type clusters (average 0.65 d). Therefore, it seems that M2 is a borderline case between OoI and OoII type clusters.

After LC99 reported 13 new RR Lyraes, for a total of 30 in the cluster, the ratio $n(c)/n(ab+c) = 0.40$ approached the mean typical value of 0.44 in OoII clusters and argued that not many undiscovered RR Lyraes are expected. We have found eight new variables and a new value $n(c)/n(ab+c) = 0.41$ (negative detections excluded as variables). We see no reason for not finding yet more RR Lyraes in this cluster if adequate monitoring is performed.

5.2 RR Lyrae radii

Given $\log(L/\mathrm{L}_{\odot})$ (M_V for RRab) and T_{eff} in Tables 5 and 6, one can derive the stellar radii. These radii depend fully on the semi-empirical relations and the hydrodynamical models used to calculate the luminosity and temperature, and they are included in Tables 5 and 6 under the name $\log(R/\mathrm{R}_{\odot})$ (LT). Recently, Marconi et al. (2005) have offered period–radius–metallicity (PRZ) relationships for the RR Lyrae based on the non-linear convective models of Bono et al. (2003, and references therein). In these relations, the mean radius can be obtained from the pulsation period and the metallicity parameter *Z*. We have used these calibrations to calculate the radii of the RR Lyrae in M2 and compare them with the radii obtained independently from the light-curve Fourier decomposition. In doing so, we have converted the [Fe/H] parameter into *Z* making use of the equation $\log \mathrm{Z} = [\mathrm{Fe/H}] - 1.70 + \log(0.638 f + 0.362)$, where f is the α-enhancement factor with respect to iron (Salaris, Chieffi & Straniero 1993), which we adopt as $f = 1$. The radius can be estimated using the individual values of [Fe/H] in Table 6 or the average value −1.543. We have found that the differences in the estimated radii are not significant. Thus we report in Tables 5 and 6 the radii from *P* and *Z*, labelled $\log(R/\mathrm{R}_{\odot})$ (PRZ) using the average [Fe/H].

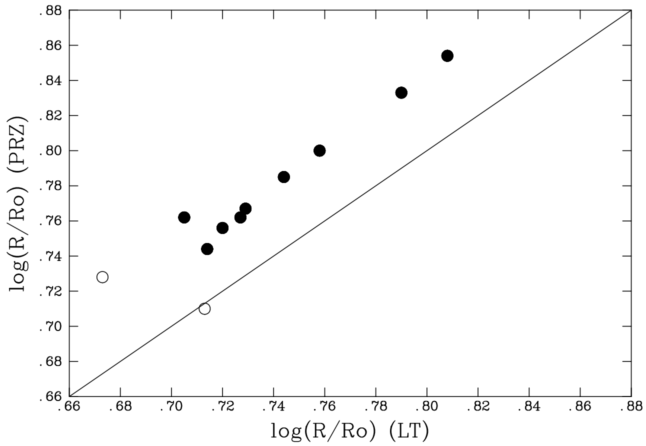

Figure 7. Comparison of radii from the Fourier decomposition parameters L and $T_{\rm eff}$ with those obtained from the Marconi et al. (2005) calibration from P and Z. Solid circles represent RRab stars and open circles RRc stars.

In Fig. 7, the comparison of $\log(R/\mathrm{R}_\odot)$ (LT) and $\log(R/\mathrm{R}_\odot)$ (PRZ) is shown. As seen in Tables 5 and 6, and Fig. 7, the $\log(R/\mathrm{R}_\odot)$ (PRZ) values are systematically larger than $\log(R/\mathrm{R}_\odot)$ (LT) by about 0.04. However, given that both radii determinations are based on different models, methods and calibrations, and the sensitivity of radii to the opacity and other ingredients in the stellar models, both determinations can be considered quite consistent.

5.3 Distance to M2

To calculate the distance to the cluster, we have calculated the distance moduli ($A_0 - M_V$) for each star, using the absolute magnitudes M_V, given in Tables 5 and 6, derived from the Fourier parameters listed in Table 4. The total to selective extinction ratio $R = A_V/E(B-V) = 3.1$, with $E(B-V) = 0.06$ (Harris 1996), was adopted to correct for interstellar extinction. For the RRab stars, the M_V values were obtained from the calibration of Kovács & Jurcsik (1996), while for the RRc stars, the relation of Kovács (1998) was used to derive M_V.

We find a mean distance of 10.42 ± 0.12 kpc for the RRab and 10.67 ± 0.05 kpc for the RRc stars, respectively. The uncertainty in these values is the standard deviation of the mean from individual stars. Our mean value of the distance to M2, 10.49 ± 0.15 kpc, from 11 RRab and RRc variables, is to be compared with the previous estimates of 11.5 and 11.2 kpc reported by Harris (1975, 1996), respectively.

5.4 On the evolutionary stage of the RR Lyrae stars

From the values in Tables 5 and 6, we can place the RRc and RRab stars in the HR diagram in Fig. 8. Two versions of the instability strip are shown. The vertical boundaries are the fundamental (continuous lines) and first overtone (dashed lines) instability strips from Bono, Caputo & Marconi (1995), $M = 0.65\,\mathrm{M}_\odot$, $Y = 0.24$ and $Z = 0.001$. As shown in the figure, the RRab variables populate the fundamental mode band in a narrow region in $T_{\rm eff}$ near the red edge of the theoretical instability strip, whereas the two RRc stars are located close to the first overtone blue edge. The small number of RRc variables in our diagram does not allow for the discussion of the suggestion of Bono et al. (1995) that in OoII clusters the transition between RRc and RRab variability occurs near the first overtone red edge, while in the OoI clusters the transition is found closer to the fundamental blue edge. The short continuous tilted lines are the empirical fundamental mode instability strip found by Jurcsik (1998) from 272 RRab stars of different metallicity, including variables from Galactic field stars, many globular clusters and the Sculptor dwarf galaxy. It seems rather surprising that the empirical instability band is much narrower that the modelled one from Bono et al. (1995), even if it is defined from a very inhomogeneous sample of RRab variables. It is also clear that the location of the RRab stars in M2 follows closely the empirical strip both in slope and width.

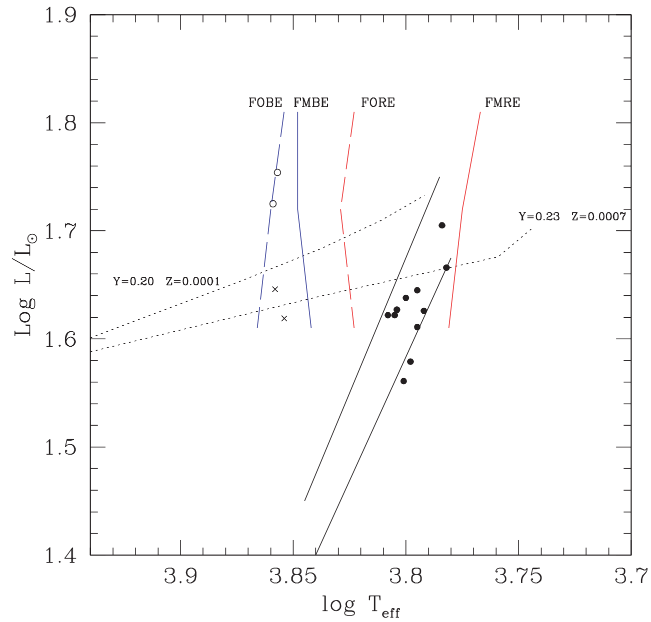

Figure 8. Solid circles represent RRab stars, open circles RRc stars with $\log(L/\mathrm{L}_\odot)$ calculated from equation (3) and crosses RRc stars with $\log(L/\mathrm{L}_\odot)$ calculated from M_V. The solid tilted lines indicate the empirical bounds found by Jurcsik (1998) from 272 RRab stars. The vertical boundaries are the fundamental (continuum lines) and first overtone (dashed lines) instability strips from Bono et al. (1995) for $0.65\,M/\mathrm{M}_\odot$. Two models of the ZAHB (Lee & Demarque 1990) are shown and labelled with the corresponding metallicities. An extrapolation of these models to the value of $Y = 0.27$ (found from the RRc stars) would place the RRab stars near the ZAHB.

Two values for the luminosity of the two RRc stars are plotted in Fig. 8. The upper values (open circles) correspond to the values obtained from equation (3). The lower values are those obtained from the M_V values from equation (7) and transformed into luminosity by equations (12) and 13. While the apparent and absolute magnitudes of the RRc stars agree with those of the RRab stars, it is clear that the luminosity predicted from equation (3) is large. We shall retain these large values for further comparison, in Section 5.5, with RRc stars in other globular clusters studied by the Fourier decomposition technique.

The theoretical zero-age horizontal branch (ZAHB) from the RRab models of Lee & Demarque (1990) for two chemical mixtures, ($Y = 0.20$; $Z = 0.0001$) and ($Y = 0.23$; $Z = 0.0007$), are also shown in Fig. 8. These two ZAHBs lie above the RRab stars. However, the estimated value of the relative abundance of helium for our RRc sample is $Y = 0.27$, for which a model is not available. Because the luminosity of the ZAHB decreases with increasing Y, an extrapolation of Lee & Demarque (1990) models to larger values of Y would make the ZAHB match the distribution of RRab stars.

5.5 Physical parameter trends in globular clusters

The mean parameters for the RRc and RRab stars are compared for several clusters in Tables 7 and 8. These tables contain only those clusters for which their mean parameters have been obtained from the technique of RR Lyrae light-curve Fourier decomposition and are updated versions of equivalent tables previously published by Kaluzny et al. (2000) and Arellano Ferro et al. (2004, 2006).

Figs 9 and 10 show the trends of physical parameters as a function of metallicity for RRc and RRab stars, respectively. The dependences on metallicity are clear in all cases, especially for $\log L/\mathrm{L}_\odot$ and T_{eff}. The straight lines in the figures are the least-square fits to the point distribution. The relationships representing the lines are as follows.

For the RRc stars:

$$\log M/\mathrm{M}_\odot = -(0.105 \pm 0.019)[\mathrm{Fe/H}] - (0.381 \pm 0.032), \quad (14)$$

$$\log L/\mathrm{L}_\odot = -(0.111 \pm 0.009)[\mathrm{Fe/H}] + (1.554 \pm 0.016), \quad (15)$$

$$\log T_{\mathrm{eff}} = +(0.013 \pm 0.001)[\mathrm{Fe/H}] + (3.882 \pm 0.002). \quad (16)$$

The uncertainties in $\log M/\mathrm{M}_\odot, \log L/\mathrm{L}_\odot$ and $\log T_{\mathrm{eff}}$ in the above calibrations are: 0.029, 0.014 and 0.002, respectively.

For the RRab stars:

$$\log T_{\mathrm{eff}} = +(0.032 \pm 0.006)[\mathrm{Fe/H}] + (3.852 \pm 0.008), \quad (17)$$

$$M_V = +(0.191 \pm 0.037)[\mathrm{Fe/H}] + (1.032 \pm 0.054). \quad (18)$$

The uncertainties in $\log T_{\mathrm{eff}}$ and M_V are 0.004 and 0.031, respectively.

The relationship between $\log L/\mathrm{L}_\odot$ and [Fe/H] for the RRc stars (equation 15) is very tight and can be transformed into an M_V–[Fe/H] relationship with the bolometric correction. Adopting the BC–[Fe/H] relation of Sandage & Cacciari (1990) and $M_{\mathrm{bol},\odot} = 4.75$, we derive the relation

$$M_V = +(0.22 \pm 0.03)[\mathrm{Fe/H}] + (0.86 \pm 0.05). \quad (19)$$

This relation, shown as a dashed line in the lower panel of Fig. 10, has a small zero-point difference with the average relationship obtained from several methods by Chaboyer (1999): $M_V = (0.23 \pm 0.04)$ [Fe/H] + (0.93 ± 0.12). Equation 19 can be used to estimate an average $M_V = 0.53 \pm 0.08$ at [Fe/H] $= -1.50$. This result is in good agreement with the weighted average of $M_V = 0.58 \pm 0.04$ obtained by Cacciari (2003) from various methods, or with the weighted average of $M_V = 0.61 \pm 0.11$ of seven clusters obtained by Chaboyer (1999), both for [Fe/H] $= -1.50$. Thus, the zero-point predicted by the luminosities of equation (3) (Simon & Clement

Table 7. Mean physical parameters obtained from RRc stars in globular clusters.

Cluster	Oo type	[Fe/H]	No. of stars	$M/\mathrm{M}_\odot$	log $(L/\mathrm{L}_\odot)$	T_{eff}	Y
NGC 6171	I	−0.68	6	0.53	1.65	7447	0.29
NGC 4147[a]	I	−1.22	9	0.55	1.693	7335	0.28
M5	I	−1.25	7	0.58	1.68	7338	0.28
M5[b]	I	−1.25	14	0.54	1.69	7353	0.28
M3[c]	I	−1.47	5	0.59	1.71	7315	0.27
NGC 6934[d]	I	−1.53	4	0.63	1.72	7300	0.27
M2[e]	II	−1.61	2	0.54	1.739	7215	0.27
M9	II	−1.72	1	0.60	1.72	7299	0.27
M55[f]	II	−1.90	5	0.53	1.75	7193	0.27
NGC 2298	II	−1.90	2	0.59	1.75	7200	0.26
M92[g]	II	−1.87	3	0.64	1.77	7186	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
M15[h]	II	−2.12	8	0.76	1.81	7112	0.24

Data taken from Clement & Shelton (1997), except: [a]Arellano Ferro et al. (2004), [b]Kaluzny et al. (2000), [c]Kaluzny et al. (1998), [d]Kaluzny et al. (2001), [e]this work, [f]Olech et al. (1999), [g]recalculated in this work from the data of Marín (2002), [h]Arellano Ferro et al. (2006).

Table 8. Mean physical parameters obtained from RRab stars in globular clusters.

Cluster	Oo type	No. of stars	[Fe/H]	T_{eff}	M_V
NGC 6171[a]	I	3	−0.91	6619	0.85
NGC 4147[b]	I	5	−1.22	6633	0.80
NGC 1851[c]	I	7	−1.22	6494	0.80
M5[d]	I	26	−1.23	6465	0.81
M3[e]	I	17	−1.42	6438	0.78
NGC 6934[f]	I	24	−1.53	6450	0.81
M55[g]	II	5	−1.48	6352	0.71
M2[h]	II	9	−1.47	6276	0.71
M92[i]	II	5	−1.87	6160	0.67
M15[j]	II	11	−1.87	6237	0.67

[a]Clement & Shelton (1997), [b]Arellano Ferro et al. (2004), [c]Walker (1998), [d]Kaluzny et al. (2000), [e]Kaluzny et al. (1998), [f]Kaluzny et al. (2001), [g]Olech et al. (1999), [h]this work, [i]recalculated in this work from the data of Marín (2002), [j]Arellano Ferro et al. (2006).

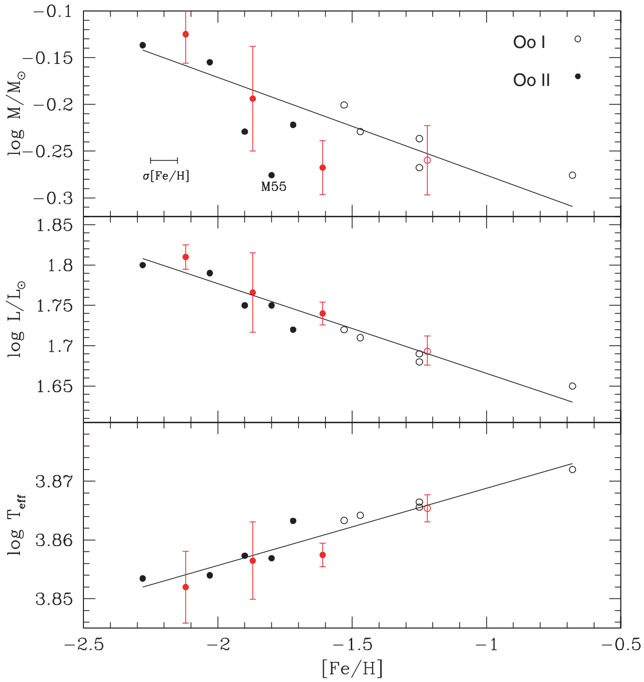

Figure 9. General trends of relevant physical parameters in globular clusters as a function of metallicity. All these parameters have been calculated by the RRc stars light-curve Fourier decomposition technique. The error bars are the standard deviation of the mean divided by the square root of the number of stars included in each cluster. The horizontal error bar in the metallicity is a mean uncertainty calculated using the expression from Jurcsik & Kovács (1996, their equation 4). Error bars have only been calculated for those clusters studied by our team. The labelled dot has not been included in the fit.

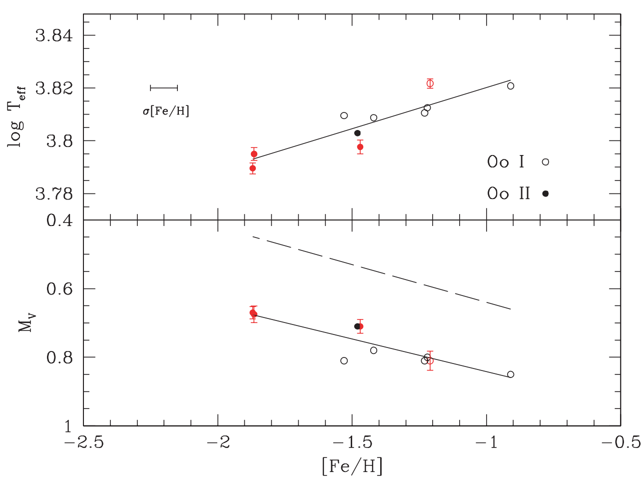

Figure 10. Same as Fig. 9 but for the RRab stars. The dashed line corresponds to equation (19). This indicates that equation (3) makes the RRc stars appear brighter than the RRab stars by about 0.20 mag. See text in Section 4 for discussion.

1993) is in agreement with the above independent estimates, but it is about 0.20 mag too bright relative to the zero-point predicted by the calibrations of equations (7) and 9 for the RRc and RRab stars (Kovács 1998; Kovács & Jurcsik 1996, respectively).

We do not find the discontinuity in the M_V–[Fe/H] relation claimed by Lee & Carney (1999b) but find rather a smooth transition between OoI and OoII clusters.

The above equations represent general laws for the HB position and structure as a function of metallicity and seem to hold for globular clusters at a wide range of Galactocentric distances and metallicities.

The trends given by equations (15), (18) and (19) agree with previous studies in that the RR Lyrae variables are more luminous (hence more evolved) in lower metalicity (hence older) clusters.

The relationship between M_V and [Fe/H] has been widely discussed in the literature. Some evidence of the non-linearity of the M_V–[Fe/H] relationship has been offered from empirical (Caputo et al. 2000; Demarque et al. 2000) and theoretical arguments (Cassisi et al. 1999; Ferraro et al. 1999; VandenBerg et al. 2000).

Of particular interest is the $\log M/M_\odot$ versus [Fe/H] relation for the RRc variables. It is evident that RRc stars in OoII clusters have systematically larger masses than in OoI clusters. However, Clement & Rowe (2000), in a study of RRc variables in the clusters ω Cen, M55 and M3 reached the opposite conclusion. They found an increase of mass with luminosity within each of the Oosterhoff groups, but a discontinuity at the transition between the OoI and OoII clusters. They derived lower masses and higher luminosities for the OoII RRc variables in ω Cen and M55 than the OoI RRc variables in ω Cen and M3, and a similar behaviour for the RRab variables. It seems that this conclusion could have been strongly influenced by the low value of $\log M/M_\odot$ for the cluster M55. However, our Figs 9 and 10 (see also Tables 7 and 8), based on a larger number of clusters, suggest a continuous trend with metallicity and do not support any significant discontinuity between OoI and OoII variables.

The trends in Figs 9 and 10 and the related equations support the general scheme that OoII clusters are older and less metallic than OoI clusters, with their RR Lyrae being more massive, more luminous and having longer periods. This would be expected if the mass loss at the tip of the red giant branch is diminished for smaller metallicities; thus in older clusters, at the time of reaching the HB stage, the stars turn into slightly more massive RR Lyrae variables with lower $T_{\rm eff}$ but larger luminosity, as expected from models of HB stars. This is consistent with the hypothesis that the origin of the Oosterhoff dichotomy is age: in OoII, the stars are more massive, older and more evolved off the HB. The conclusion that, on average, metal-poor clusters (OoII group) are older than the richer clusters has been made in different studies (e.g. Lee & Carney 1999b).

6 CONCLUSIONS

Physical parameters of astrophysical relevance have been derived for the RR Lyrae stars in M2 using the Fourier decomposition of their light curves. The estimates of the stellar radii for RRab stars from the above approach are about 5 per cent smaller than radii derived from period–radius–metallicity relations obtained from non-linear convective models, i.e. a completely different set of pulsational models and approach. The agreement for the RRc is generally good but the dispersion is markedly larger.

Previously recognized trends between the cluster mean values of $\log(M/M_\odot)$, $\log(L/L_\odot)$, $\log T_{\rm eff}$ and M_V against [Fe/H], obtained from RRc stars, have been established for a sample of seven OoII and five OoI clusters. We extended the study of the trends for RRab stars in four OoII and five OoI clusters.

Our analysis, based on a larger data set than previous studies, allows one to quantify the relations (see equations 14–19 and Figs 9 and 10). In particular, much has been discussed about the relation between luminosity (or M_V) and metallicity for the RR Lyrae variables. Our equations (15), (17) and (19) are in very good agreement with the slopes of M_V–[Fe/H] relations solidly determined and available in the literature. However, the zero-points indicate that the luminosities for the RRc and RRab stars, as calculated from equation (3) (Simon & Clement 1993) and those derived from equations (7) and (9) (Kovács 1998; Kovács & Jurcsik 1996) respectively, differ by the equivalent to 0.2 mag. This suggests these calibrations need to be revised.

RR Lyrae Fourier light-curve decomposition produces a zero-point of the RR Lyrae distance scale consistent with those from other methods. When the light-curve decomposition technique is used on families of OoI and OoII globular clusters, it provides physical parameters, as a function of the metal content of the cluster, that are consistent with general notions of stellar evolution in the HB and of early stages of Galactic formation.

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