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CCD PHOTOMETRY OF THE GLOBULAR CLUSTER M15: RR LYRAE FOURIER DECOMPOSITION AND PHYSICAL PARAMETERS[1]

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RESUMEN

Se reportan los resultados de la fotometría CCD a través de los filtros V y R de 33 estrellas RR Lyrae conocidas en M15. Los períodos de algunas variables han sido recalculados y se dan nuevas efemérides. El efecto Blazhko, reportado previamente para V12 no ha sido detectado. Con la técnica de descomposición de Fourier de las curvas de luz, se han estimado los parámetros físicos de las variables de tipos RRab y RRc. El cúmulo es del tipo Oosterhoff II y los valores determinados para el contenido de hierro y la distancia son: [Fe/H]$= -1.98 \pm 0.24$ y $d = 8.67 \pm 0.41$ kpc, respectivamente. Los valores medios de los parámetros físicos de las estrellas RR Lyrae colocan al cúmulo correctamente en las secuencias tipo de Oosterhoff — metalicidad y metalicidad— temperatura efectiva, válidas para cúmulos globulares. Se han encontrado evidencias de evolución, desde la Rama Horizontal de Edad Cero, de las estrellas RRc pero no de las RRab.

ABSTRACT

Results of CCD photometry using V and R filters are reported for 33 RR Lyrae stars in M15. The periodicities of some variables have been revised and new ephemerides are given. The Blazhko effect, previously reported in V12, was not detected. Applying the approach of Fourier decomposition of the light curves, the physical parameters of the type RRab and RRc variables were estimated. The cluster is Oosterhoff type II and the values for the iron content and distance are: [Fe/H]$= -1.98 \pm 0.24$ and $d = 8.67 \pm 0.41$ kpc, respectively. The mean values of the physical parameters determined for the RR Lyrae stars place the cluster precisely into the sequences Oosterhoff type —metallicity and metallicity— effective temperature, valid for globular clusters. Evidences of evolution from the ZAHB are found for the RRc but not for the RRab stars.

Key Words: **GLOBULAR CLUSTERS (M15) — STARS: VARIABLES: RR LYRAE — STARS: HORIZONTAL BRANCH**

1. INTRODUCTION

In 1746, while observing comet De Chéseaux, Jean-Dominique Maraldi discovered the globular cluster M15 (NGC 7078). And, in 1783, W. Herschel realized the nature of the object as a cluster of stars, being one of the most luminous and dense in the Milky Way. Its large distance from the galactic center (10.4 kpc) (Harris 1996) and large eccentricity of its galactic orbit (0.32±0.05) (Dinescu, Girard, & van Altena 1999), may have contributed to these characteristics. Its large concentration has been interpreted as a collapsed core (Djorgovski & King 1986), and the observed stellar density profile can be reproduced either if a central black hole exists (Guhathakurta et al. 1996) or if the core collapsed in the presence of a difusse dark matter (Lauer et al. 1991). Moreover, it exhibits a strong X-ray flux at its center (Giacconi et al. 1974; Grindlay & Liller 1977).

Numerous photometric studies of the cluster have been made, since the pioneering work of Brown (1951), until the most recent CCD study of RR Lyraes in the cluster, by Silbermann & Smith (1995). The Horizontal Branch (HB) is densely pop-

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ulated on both sides of the RR Lyrae region (Durrell & Harris 1993). More than 150 variables are listed in the catalogue of Clement (2002) and approximately 100 of them are RR Lyraes. M15 is one of the globular clusters with a very low metal content; the many determinations of its metallicity range between $-2.15 \leq$ [Fe/H] ≤ -1.76 (Buonanno, Corsi, & Fusi Pecci 1985).

During the last decade, the light curve Fourier decomposition technique to estimate physical parameters of RR Lyrae stars (Simon & Clement 1993; Kovács & Jurcsik 1996; 1997) has been applied to some globular clusters with a large range of metallicities (e.g., Kaluzny et al. 2000; Arellano Ferro et al. 2004, and references therein). The results of the metallicity, stellar mass, effective temperature, and luminosity, obtained from this homogeneous approach, clearly show trends that offer insights on the origin of the Oosterhoff dichotomy (Arellano Ferro et al. 2004; Lázaro et al. 2006).

Good collections of light curves of RR Lyrae stars in M15 can be found in Sandage, Katem, & Sandage (1981) and Silbermann & Smith (1995); these authors offer UBV for 60 stars and $BVRI$ photometry for 44 stars, respectively. However, the Fourier light curve decomposition technique has not been applied for RR Lyraes in M15. With the aim to include M15 in the list of clusters for which this technique has been applied to estimate fundamental physical parameters, we have obtained further VR CCD photometry of two selected fields of the cluster, and have Fourier decomposed the light curves of 23 RR Lyraes. In the following section we describe the observational material and reductions. In § 3 a detailed discussion on individual stars is given, and the Fourier decomposition and physical parameters are reported. In § 4 we calculate the iron abundance of the cluster and its distance, and we discuss the evolutionary stage of the RR Lyraes. A comparison of the mean physical parameters obtained from the Fourier light curve decomposition for several clusters is presented. § 5 summarizes the conclusions.

2. OBSERVATIONAL MATERIAL AND REDUCTIONS

In the present study, V and R images were obtained in 2000 and 2001 (see Table 1), using the 1.5 m telescope of San Pedro Mártir Observatory (SPM), in Baja California, Mexico. The telescope was equipped with a CCD Tektronix of 1024 × 1024 pixels with a size of 24 μ^2.

A total of 129 and 127 images in the V and R filters, respectively, were obtained during both seasons and distributed in two fields of the cluster as illustrated in Figures 1 and 2. Typical exposure times

TABLE 1

LOG OF OBSERVATIONS

Date	Filter	n[a] (East)	n[a] (West)
8, Aug 2000	R	2	3
	V	4	3
9, Aug 2000	R	4	4
	V	4	4
10, Aug 2000	R	5	4
	V	5	4
11, Aug 2000	R	6	5
	V	6	5
12, Aug 2000	R	2	1
	V	2	1
13, Aug 2000	R	7	6
	V	7	6
14, Aug 2000	R	1	1
	V	1	1
20, Sep 2000	R	5	5
	V	5	5
21, Sep 2000	R	6	6
	V	6	6
20, Aug 2001	R	6	5
	V	6	5
21, Aug 2001	R	5	4
	V	5	4
22, Aug 2001	R	7	5
	V	6	6
23, Aug 2001	R	6	6
	V	6	6
24, Aug 2001	R	5	5
	V	9	5

[a]n is the number of images acquired.

TABLE 2

STANDARD STARS IN THE M15E FIELD

Star	V^a (mag)	R^a (mag)	Star	V^a (mag)	R^a (mag)
K17	15.924	15.589	S42	16.412	16.063
K19	15.824	15.483	S44	15.656	15.272
K25	15.885	15.562	S45	15.536	14.945
S2	15.788	15.425	S46	15.394	14.722
S11	15.789	15.460	S51	15.691	15.317
S14	15.967	15.616	S54	15.753	15.378
S19	14.579	13.981	S58	15.761	15.422
S20	15.255	14.598	S68	15.696	15.343
S31	14.657	14.055	S72	15.000	14.413
S38	14.083	13.542	...	...	...

[a]From Sandage (1970).

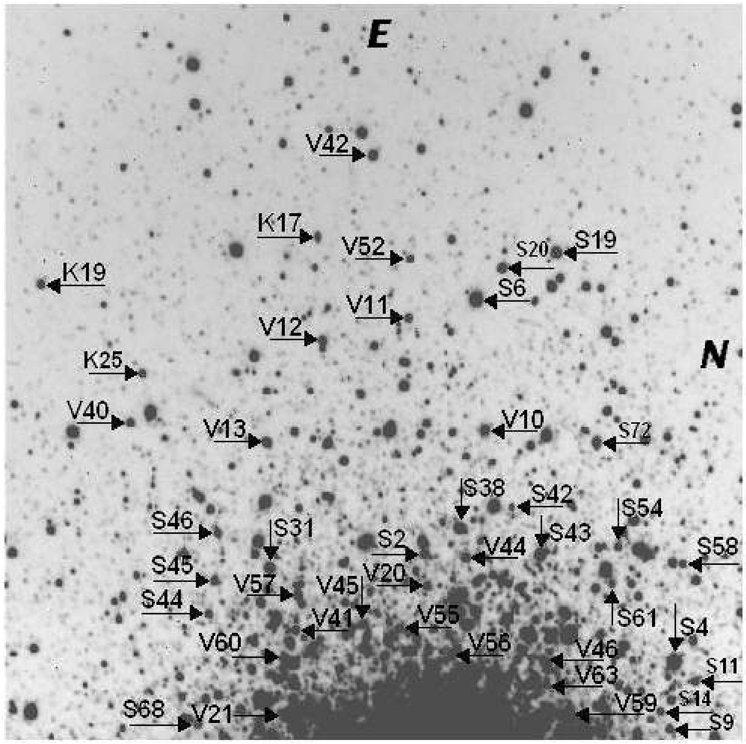

Fig. 1. A selected image of the east field of M15, obtained with the 1.5 m telescope of SPM. Identifications of known RR Lyrae stars begin with "V", otherwise they are the standard stars listed in Table 2. The image size is approximately 4×4 arcmin.

TABLE 3

STANDARD STARS IN THE M15W FIELD

Star	V^a (mag)	R^a (mag)	Star	V^a (mag)	R^a (mag)
II-10	16.067	15.724	III-52	15.695	15.367
II-11	15.790	15.464	III-67	16.199	15.428
II-23	15.713	15.363	S7	15.796	15.518
II-24	15.595	15.039	S27	15.208	14.592
II-26	15.246	14.946	S28	16.282	15.553
II-36	15.898	15.590	S29	13.457	13.036
II-64	13.228	12.822	S30	14.568	14.028
II-73	15.763	15.419	S31	15.962	15.617
II-74	15.947	15.484	S32	16.408	15.668
II-75	12.635	12.279	S33	16.785	15.920
III-5	16.512	15.725	S34	16.971	16.107
III-15	15.783	15.448	S36	15.898	15.590
III-28	15.668	15.103	S37	17.797	17.274
III-43	15.787	15.390	S38	17.797	17.274

[a]From Sandage (1970).

were 9 and 5 minutes in the V and R filters, respectively. The prevailing seeing during our observations was between 1 and 2 arc seconds.

The instrumental magnitudes were obtained using the PSF function, calculated for each frame from relatively isolated and well exposed stars, in the field of the cluster. This was achieved using the DAOPHOT tasks available in the IRAF package. After this stage, a group of programs developed locally, were used to identify and to isolate the variable and local standard stars, and to calculate the transformation equations to the standard system.

The transformation to the standard system was performed differentially, relative to a group of standard stars in the observed fields of M15, available in Sandage (1970). These stars, together with their V and R magnitudes, are listed in Tables 2 and 3 for the east and west regions, respectively, and are identified in Figs. 1 and 2. These standard stars were used to calculate the transformation equation for each image, of the form of equation (1) in order to change, from the PSF instrumental magnitudes, to the standard system. No significant quadratic or color terms were found.

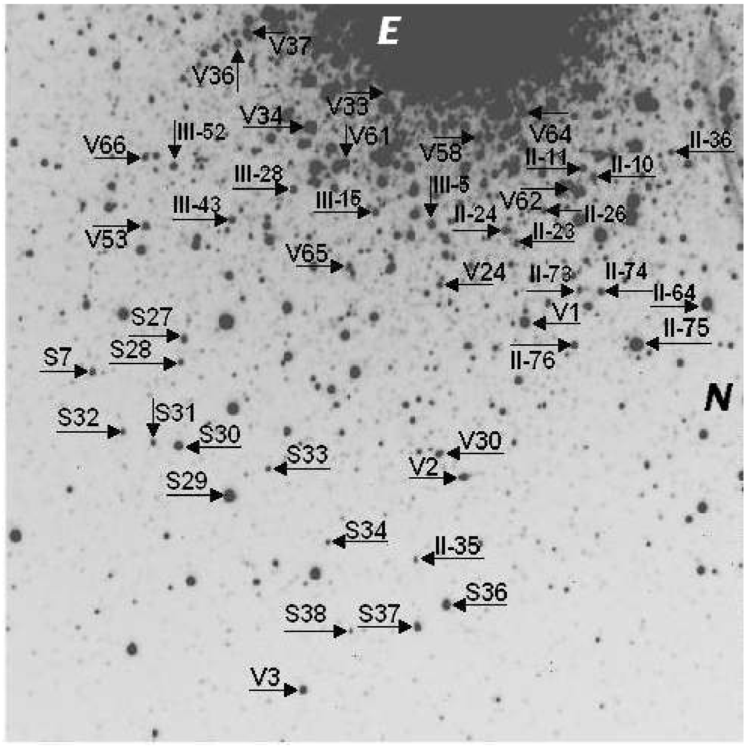

Fig. 2. A selected image of the west field of M15, obtained with the 1.5 m telescope of SPM. Identifications of known RR Lyrae stars begin with "V", otherwise they are the standard stars listed in Table 3. The image size is approximately 4 × 4 arcmin.

$$M_{std} = a\ M_{ins} + b\ . \qquad (1)$$

The light curves are displayed in Figures 4 and 5. The accuracy of the photometry was estimated by applying the above transformations to the standard stars, and comparing, for each frame, the predicted magnitudes with their nominal values. An inspection of the residuals of all the frames in our collection, indicates uncertainties of ±0.031 and ±0.019 for the V and R filters. These uncertainties are mainly due to the telescope guiding and the seeing conditions prevailing at the time of the observation.

3. THE RR LYRAE STARS IN M15

In Clement's (2002) data base of variables stars, a total of 158 variable stars are known, from which approximately 104 are RR Lyrae type stars. In this work, 33 known RR Lyrae stars, identified in Figs. 1 and 2 and listed in Table 4, have been studied. For all the stars in Table 4, a new time of maximum light has been calculated. For some stars, the period also has been calculated because it was not reported in the list of variables of Clement (2002), or because the reported period did not produce a coherent light variation. The periods for the double mode RRd stars have been refined.

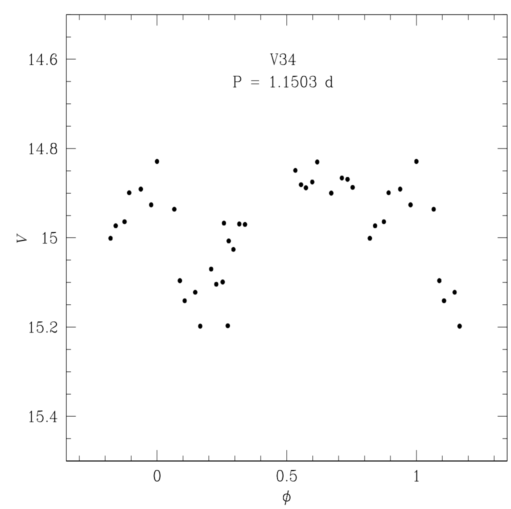

Fig. 3. Light curve obtained for star V34 in 2000. The star is suspected to be an eclipsing binary or an anomalous cepheid.

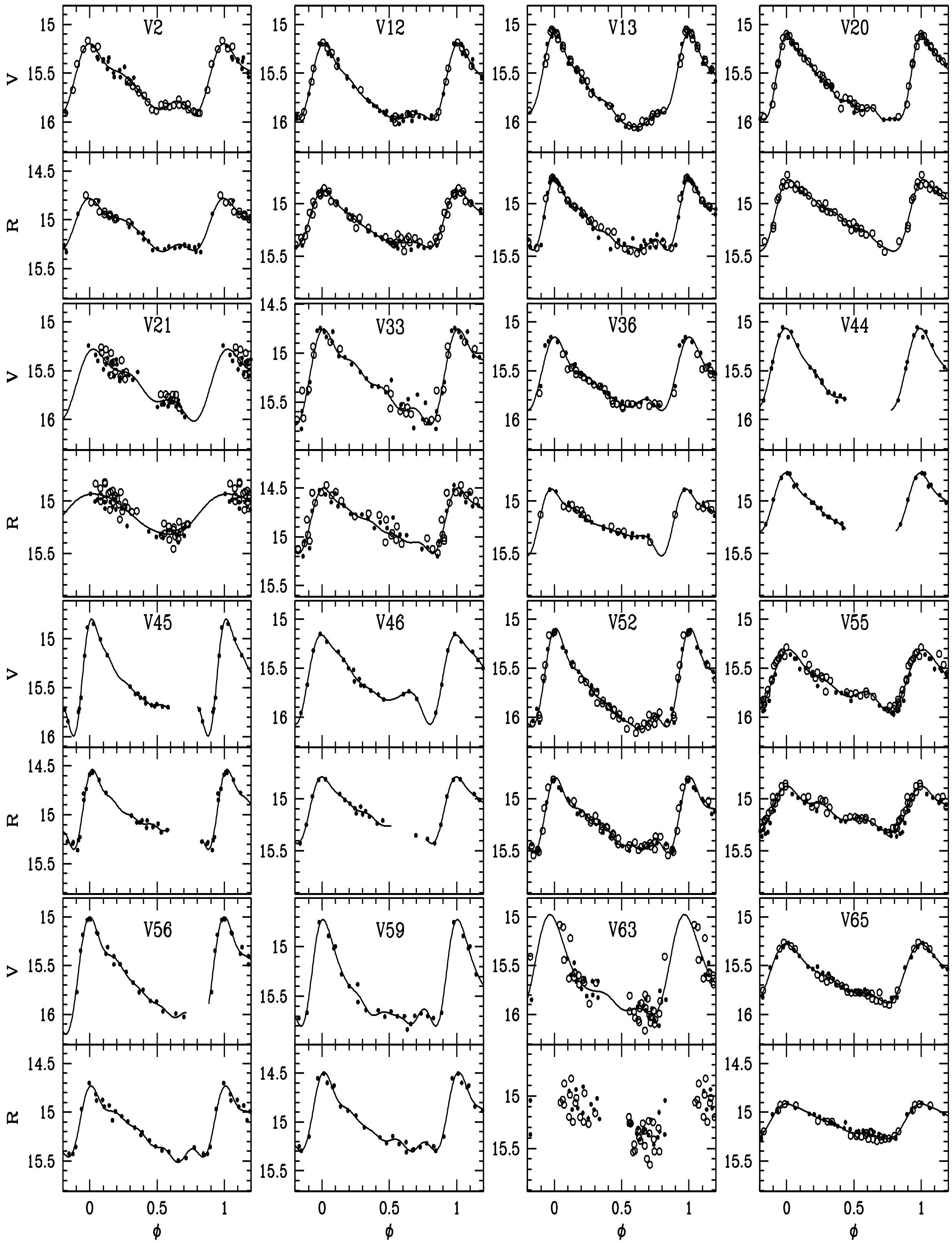

Fig. 4. Light curves and Fourier fits of 16 known RRab Lyrae stars in M15, phased with the ephemerides given in Table 4. Dots are data taken in 2001 and circles in 2000.

TABLE 4

EPHEMERIS OF THE RR LYRAE STARS IN M15 USED IN THE PRESENT WORK

RR Lyrae	Type	Epoch (+240 0000)	P_0 (Days)	P_1 (Days)
V2	ab	51807.806	0.684300	
V3	c	52143.828	0.388746	
V10	c	51767.972	0.386383	
V11	c	52145.024	0.343267	
V12	ab	51766.970	0.592848	
V13	ab	51766.983	0.574910	
V20	ab	51766.995	0.697021	
V21	ab	52142.827	0.648800	
V24	c	51766.949	0.369693	
V30[a]	d	51764.952	0.5446230	0.4059826
V33	ab	52144.841	0.583945	
V34[a]	ceph?	52143.908	1.1503?	
V36	ab	52142.865	0.624151	
V37[a]	c	52142.972	0.28775	
V40	c	51769.976	0.377350	
V41[a]	c	51766.985	0.392177	
V42	c	52143.006	0.360166	
V44	ab	52143.518	0.595580	
V45	ab	52143.935	0.677399	
V46	ab	52141.966	0.691500	
V52	ab	51765.992	0.575640	
V53[a]	d	51808.754	0.553770	0.414096
V55	ab	52142.799	0.748596	
V56	ab	52143.028	0.570400	
V57[a]	ab	52145.909	0.537481	
V58	d	51765.347	0.545909	0.407685
V59	ab	52143.474	0.554792	
V60[a]	ab	52141.844	0.73124	
V61[a]	d	51767.946	0.5277880	0.39880995
V62[a]	d	52142.927	0.5084324	0.37731720
V63[a]	ab	51766.850	0.658332	
V64	c	51767.958	0.364200	
V65	ab	51765.952	0.718196	
V66	c	51769.879	0.379350	

[a] Periods calculated in the present work. Otherwise taken from Clement (2002) or Cox et al. (1983) for V58.

3.1. *Notes on Individual RRab and RRc Stars*

V12. This star is listed by Clement (2002) as a Blazhko variable. Nevertheless, with the present data, an amplitude variation of the light curve is not observed. Therefore, a Blazhko effect in this star is not confirmed.

V34. The possible variability of this star was first discussed by Notni & Oleak (1958) after whom the star is reported by Clement (2002) as a probable variable, but no ephemeris is suggested. After the work of Notni & Oleak (1958), the star has not been included in other photometric studies. The star is heavily blended with a fainter star, making difficult a precise photometry. For the 2001 season, we could not resolve the pair. In 2000, the sky conditions were better and the star could be separated from the blend in all our images. Although noisy, the light curve phased with a period of about 1.15 days is shown in Figure 3. As seen, the star is indeed variable and brighter than the RR Lyrae stars in the cluster by about 0.5 mag. Thus, the star is suspected to be an anomalous cepheid (see Clement et al. 2001) or an eclipsing binary. Nevertheless, further observations, under optimal whether conditions and a larger resolution optics, are necessary in order to classify this star.

V37. The period 0.237 *d*, listed in Clement (2002), does not produce a smooth light curve but a rather dispersed cloud of points. Although our estimate of a 0.28775 *d* period phases the observations reasonably well, the light curve is noisy (see Fig. 5) due to the proximity of the star to the central region of the cluster, were the accuracy of our photometry is smaller. Therefore, this star shall not be used in the calculation of the physical parameters of RRc stars.

V41. The star is listed as a double mode by Cox et al. (1983). These authors noted the peculiarly large P_1/P_0 ratio. We find the refined value of the period 0.392177 *d*, but we are unable to find traces of a second periodicity. Therefore, we do not confirm the double mode nature of this star. In our opinion the star is an RRc.

V57. This star is listed by Clement (2002) as a probable double mode with $P_1 = 0.3496144$ *d*. We are unable to find that period, neither in our data set alone nor in combination with the data of Sandage et al. (1981). We find instead that the alias $P_0 = 0.537481$ *d*, phases the data reasonably well. We do not confirm the double mode nature of the star and in our opinion it is an RRab. Due to this ambiguity, it will be excluded from the estimate of the physical parameters.

V60. This star does not have a known period in the catalogue of Clement (2002). Performing a period analysis of our data, we found a value of 0.731237 *d*. This is an RRab star and its light curve is shown in Figure 6. The alias period 0.42286 *d* produces a more scattered light curve but, at the moment, it cannot be ruled out. The

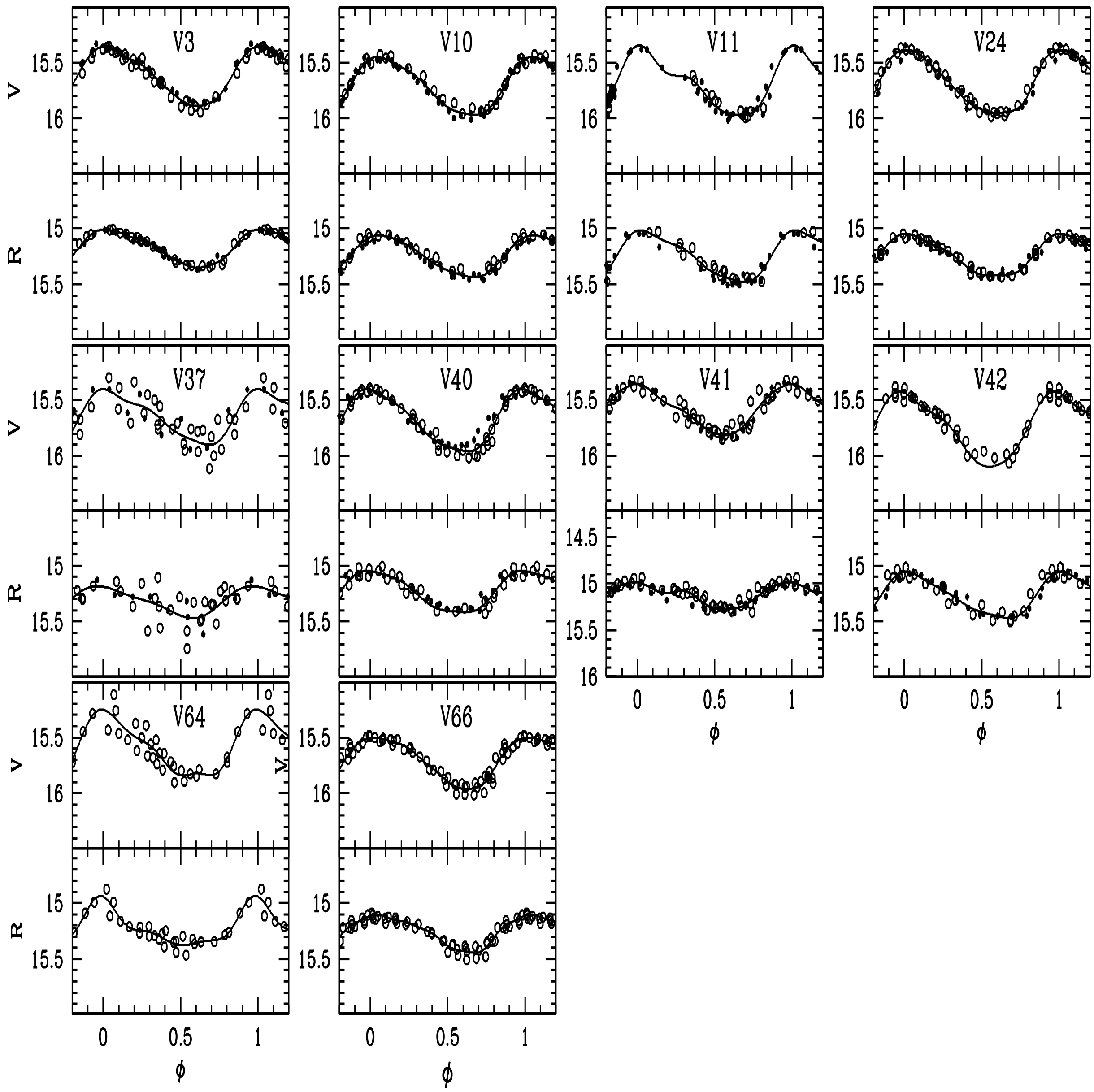

Fig. 5. Light curves and Fourier fits of 10 known RRc Lyrae stars in M15, phased with the ephemerides given in Table 4. Symbols are as in Fig. 4.

star being very close to the central bulge of the cluster, and having nearby bright companions, the scatter is large. Therefore, this star also has been excluded for the estimate of the physical parameters.

V63. Clement (2002) does not report a period for this star. Our estimated period is 0.658332 *d*. From the period value and the shape of the light curve, the star is most likely an RRab. Being in a very crowded region, the light curve is relatively noisy and will not be used for the estimate of the physical parameters.

3.2. *Notes on Individual RRd Stars*

The analysis of the double mode stars was performed using the combination of the data of Sandage et al. (1981) and the data of the present work, which reduces the uncertainties in the determination of the periods.

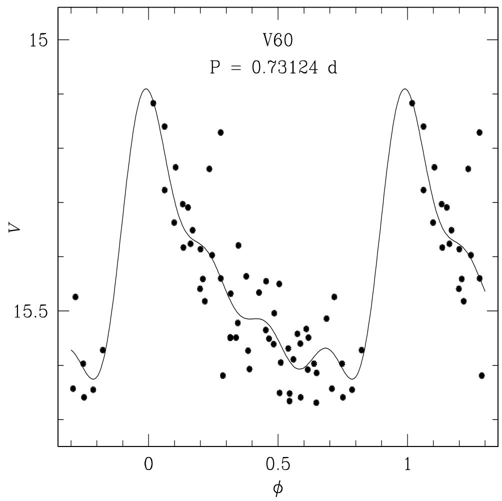

Fig. 6. Light curve obtained for star V60 phased with its newly found period. See text for discussion.

V30. Based on the high dispersion of its light curve, this star was considered by Sandage et al. (1981) as a double mode or RRd pulsator. Cox et al. (1983) reported the ratio $P_1/P_0 = 0.7454$ with $P_1 = 0.405977\,d$. The newly determined periods are given in Table 4.

V53. We confirm the double mode nature of the star. The new periods given in Table 4 represent an improvement over the ones given by Cox et al. (1983).

V58 It is listed by Cox et al. (1983) as a double mode pulsator or RRd type star with $P_1 = 0.407685\,d$ and $P_1/P_0 = 0.7468$. We confirm the double mode nature of the star; however, since our data are noisy, probably due to contamination by neighboring stars, we are not able to refine the periods.

V61. We have improved the periods of this double mode star. The new periods are reported in Table 4.

V62. The star is listed in Clement (2002) as a probable double mode star. We confirm the double mode nature of this star, with periods given in Table 4.

3.3. *Fourier Parameters of the Light Curves*

In order to estimate the Fourier parameters of the light curves, the data were fitted using the harmonic decomposition technique according to the following equation:

TABLE 5

FOURIER FITTING PARAMETERS FOR *V* LIGHT CURVES

Star	A_0	A_1	A_4	ϕ_{21}	ϕ_{31}	ϕ_{41}
			RRc			
V3	15.629	0.256	0.005	4.87	2.46	6.23
V10	15.727	0.281	0.007	4.45	2.45	0.99
V11	15.694	0.278	0.017	4.89	2.31	0.43
V24	15.700	0.286	0.007	4.16	2.38	0.98
V40	15.686	0.290	0.025	4.43	3.42	0.86
V41	15.590	0.214	···	4.75	0.54	···
V42	15.285	0.195	0.012	4.31	2.24	1.92
V64	15.597	0.281	0.009	4.25	1.97	1.58
V66	15.719	0.231	0.005	5.24	3.42	1.57
			RRab			
V2	15.626	0.288	0.030	3.91	2.08	0.35
V12	15.720	0.319	0.046	3.71	1.52	5.80
V13	15.688	0.408	0.058	4.09	1.25	5.65
V20	15.655	0.337	0.047	4.02	2.23	2.23
V36	15.642	0.276	0.046	3.84	1.62	5.82
V44	15.624	0.351	0.048	3.80	1.52	5.81
V45	15.518	0.331	0.109	3.83	1.65	5.71
V46	15.645	0.283	0.057	3.79	2.19	0.80
V52	15.777	0.392	0.082	3.93	1.55	5.80
V55	15.663	0.215	0.025	4.03	2.48	0.81
V56	15.699	0.408	0.098	4.20	2.29	0.43
V57	15.591	0.265	0.022	4.67	2.54	2.50
V59	15.478	0.368	0.106	3.51	0.96	4.87
V65	15.627	0.235	0.010	4.15	2.22	0.66

$$f(t) = A_o + \sum_{k=1}^{N} A_k cos(2\pi k(t-E)/P + \phi_k) \ . \quad (2)$$

The solid curves in Figs. 4 and 5 are the Fourier fits represented by Eq. (2). From the amplitudes and phases of the harmonics in Eq. (2), the Fourier parameters, defined as $\phi_{ij} = j\phi_i - i\phi_j$ and $R_{ij} = A_i/A_j$, were calculated. In Table 5 we report the mean magnitudes A_0, and the values of the Fourier decomposition parameters for each RR Lyrae star from the V light curves. The mean uncertainties in the amplitudes A_i, and shifts ϕ_{ij}, are ±0.012 mag. and ±0.19 rad., respectively. The mean dispersion about the fits is ±0.034 mag.

3.4. *The Physical Parameters of the RR Lyrae Stars from their Light Curves*

Walraven (1953) was first to realize that there was a dependency between the shape of the light curve and the physical parameters of the star. To calibrate key physical parameters of structural and evolutionary relevance in terms of the Fourier terms of the light curve decomposition, theoretical and semiempirical approaches have been undertaken in the past decade. For RR Lyrae stars of Bailey's type RRc, Simon & Clement (1993) applied 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 $\log L$, in terms of the period and the Fourier parameter ϕ_{31} (see their Eqs. 2, 3, 6, and 7). Their work has been extended in a semiempirical way to RRab stars by Jurcsik & Kovács (1996) (JK96), Kovács & Jurcsik (1996 (KJ96); 1997), and Jurcsik (1998) (J98). The equations that we have applied are Eq. (3) in JK96 for [Fe/H], Eq. (2) in KJ96 for M_V, Eqs. (5) and (11) in J98 for $V-K$ and $\log T_{\rm eff}$, respectively.

A thorough discussion of the uncertainties in the physical parameters, as obtained from the above mentioned calibrations, can be found in the work of J98. The estimated uncertainties for $\log L$, $\log T$, $\log M$, and [Fe/H] are $\pm0.009, \pm0.003, \pm0.026$, and ±0.14 dex, respectively.

Recently, Morgan, Wahl, & Wieckhorst (2005) offered a semiempirical calibration of [Fe/H] as a function of the pulsating period and the Fourier parameter ϕ_{31} for RRc type stars, which complements the calibration of JK96 for RRab stars.

The calibrations mentioned in the above paragraphs have been applied in order to estimate the corresponding physical parameters for the observed RR Lyrae stars in M15. These parameters are summarized in Tables 6 and 7, and discussed further in the remaining sections.

4. DISCUSSION

4.1. *The Iron Abundance of M15*

There are two calibrations of the Fourier decomposition parameters to calculate the iron abundance, [Fe/H] for the RR Lyrae stars in a cluster, namely, for the RRab stars that of JK96, and for the RRc stars that of Morgan et al. (2005). Both calibrations are strongly dependent on ϕ_{31}. Hence, if the dispersion of the light curve is large, ϕ_{31} is uncertain and the value of [Fe/H] is unreliable. We decided to keep the physical parameter calculations limited to those stars with well defined light curves. Due to this fact, from Fig. 4, the RRab stars V21, V33, V56, V59, V60, and V63, have been omitted; and from Fig. 5, the RRc stars V37, V41, and V62 also were omitted. These stars are very close to the central bulge of the cluster and their measurements suffer contamination due to crowdiness. The remaining stars and their physical parameters are listed in Tables 6 and 7.

TABLE 6

PHYSICAL PARAMETERS FOR THE RRab STARS

Star	[Fe/H][a]	$\log T_{\rm eff}$	M_V
V2	−1.70	3.794	0.67
V12	−1.97	3.800	0.72
V13	−2.23	3.800	0.68
V20	−1.77	3.784	0.64
V36	−1.99	3.797	0.71
V44	−1.99	3.800	0.70
V45	−2.25	3.793	0.61
V46	−1.60	3.792	0.67
V52	−1.84	3.804	0.71
V55	−1.51	3.789	0.65
V65	−1.70	3.789	0.66
Mean	−1.87	3.795	0.67
σ	±0.24	±0.006	±0.03

[a]From the calibration of JK96.

The mean values are [Fe/H]$=-1.87\pm0.24$ for the RRab stars and [Fe/H]$=-2.12\pm0.16$ for the RRc stars. Our overall average for [Fe/H] is then -1.98 ± 0.24 for M15. Although the calibration of Morgan et al. (2005) seems to render iron values slightly smaller and less dispersed than the calibration of JK96, they are consistent within the uncertainties.

4.2. *The Distance to M15*

An important fact is that the above results can be used to estimate the distance to the cluster. For the RRc stars, the luminosity values in Table 7 have been firstly transformed into M_V. In doing so, we have adopted the expression for the bolometric correction BC = 0.06 [Fe/H] + 0.06 (Sandage & Cacciari 1990) and $M_{\rm bol\odot}=4.75$. To obtain the true distance modulus we have adopted $E(B-V)=0.08$ (Sandage et al. 1981) and a total-to-selective absorption ratio $R=3.2$. For the RRab stars the M_V values in Table 6, obtained from the calibrations, have been used to calculate the distance modulus. We find the mean true distance moduli 14.72 ± 0.05 mag and

TABLE 7

PHYSICAL PARAMETERS FOR THE RRc STARS

Star	$M/M_\odot$	$\log(L/L_\odot)$	Y	M_V	$\log\ T_{\rm eff}$	[Fe/H][a]
V3	0.81	1.841	0.23	0.72	3.848	−2.29
V10	0.81	1.839	0.23	0.73	3.848	−2.28
V11	0.79	1.793	0.24	0.71	3.855	−2.02
V24	0.80	1.822	0.24	0.76	3.851	−2.19
V40	0.62	1.771	0.26	0.66	3.855	−1.91
V42	0.82	1.819	0.24	0.74	3.852	−2.15
V64	0.88	1.840	0.23	0.76	3.849	−2.21
V66	0.62	1.774	0.25	0.72	3.855	−1.93
Mean	0.76	1.812	0.24	0.72	3.852	−2.12
σ	±0.08	±0.028	±0.01	±0.03	±0.003	±0.16

[a]From the calibration of Morgan et al. (2005).

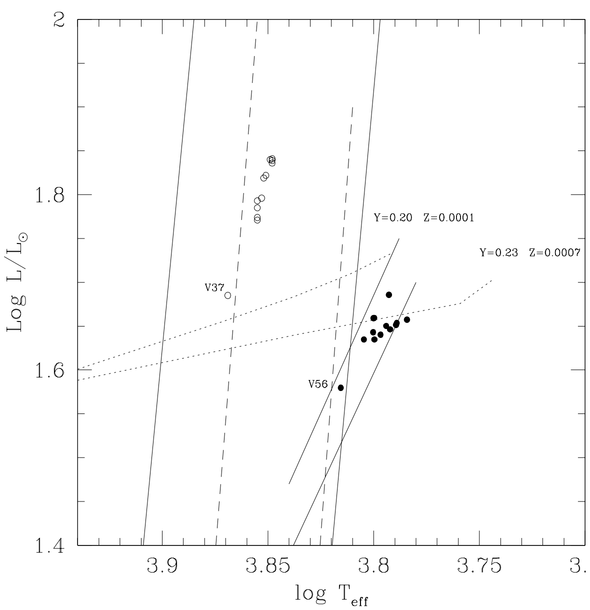

Fig. 7. Solid and open circles represent RRab and RRc stars, respectively. The solid lines are the extrapolation from the cepheid instability strip of Sandage & Tammann (1969). The dashed lines define the theoretical instability strip of Marconi & Palla (1998). The short solid lines indicate the empirical bounds found by Jurcsik (1998) from 272 RRab stars. Two models of the ZAHB (Lee & Demarque 1990) are shown and labeled with the corresponding metallicities. Even though the model for $Y = 0.24$ does not exist, we can infer from the trend of the two displayed models that the RRab stars lie near the ZAHB. The discrepant RRc V37 and RRab V56, which exhibit large scatter and poor coverage of the light curve, respectively, are labeled. See text for discussion.

14.87 ± 0.15 for the RRab and RRc stars, respectively. The average of these moduli corresponds to a distance of 8.67 ± 0.41 kpc, where the uncertainty is the standard deviation of the mean from individual stars. This value of the cluster distance is to be compared with 10.3 kpc listed in the catalogue of Harris (1996), 10.11 ± 0.46 kpc, derived from the reported distance modulus by Cox et al. (1983), and with the dynamical estimate of 9.98 ± 0.47 kpc obtained by McNamara et al. (2004), from the proper motion and radial velocity dispersion of 237 stars.

As for NGC 4147 (Arellano Ferro et al. 2004), the Fourier decomposition approach places M15 about 17% closer than the adopted distance in Harris (1996). In the present work, both the values of the luminosity and the absolute magnitude of the RR Lyrae stars have been obtained with Fourier's technique. Nevertheless, as seen in Tables 8 and 9, these values produce a coherent sequence of physical parameters with metallicity within the Oosterhoff type of the cluster, as it will be discussed in the following subsection.

4.3. *Globular Clusters Physical Parameters as a Function of Metallicity*

Tables 8 and 9 are updates of Tables 3 and 6 of Kaluzny et al. (2000), with new clusters added to the list. In these tables the clusters are ordered according to their Oosterhoff type and their [Fe/H] value. It is easy to confirm that the mass and the luminosity increase while the temperature and helium parameter decrease with decreasing metallicity. These trends were first foreseen by Simon & Clement (1993) (see also Clement & Shelton 1997). It can be seen that the mean values of the physical parameters of the RR Lyrae stars in M15, obtained in this work, locate the cluster in the expected place in the general sequences. In particular, our average values [Fe/H] =−2.12 ± 0.16 for the RRc and [Fe/H] =−1.87 ± 0.24 for the RRab stars make the rest of the parameters consistent with the general sequences. The above [Fe/H] values are consistent, within the uncertainties, with the generally accepted value of [Fe/H] =−2.26 (Harris 1996) and are bracketted by the several independent determinations listed by Buonanno et al. (1985), that range from −2.15 to −1.76.

4.4. *On the Evolutionary Stage of RR Lyrae Stars in M15*

In Figure 7, the position of the RRab and RRc stars are shown in the HR diagram along with three versions of the instability strip. The long solid lines

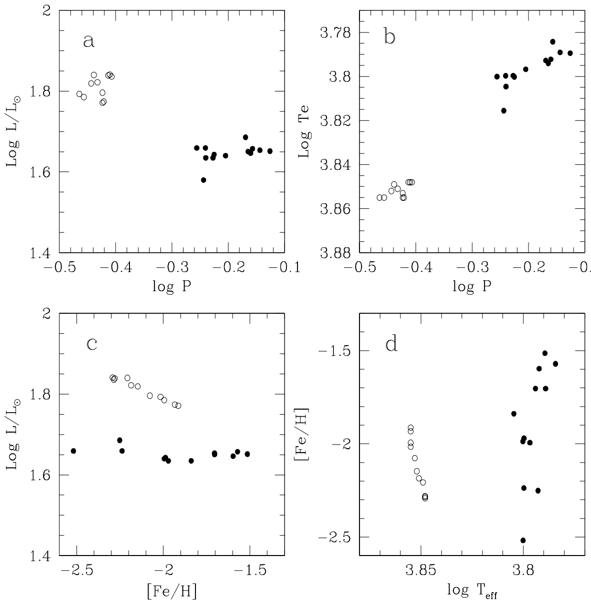

Fig. 8. Interrelations of physical parameters for the RR Lyrae stars in M15. Solid and open circles represent RRab and RRc stars, respectively. The discrepant RRc V37 and RRab V56 in Fig. 7 have been omitted. See text for discussion.

are an extrapolation towards lower luminosities of the cepheid instability strip of Sandage & Tammann (1969). The dashed lines are the predicted strip of the models of Marconi & Palla (1998). The short continuous lines are the empirical fundamental mode instability strip found by J98 from 272 RRab stars; and, as pointed out in that work, the band is very narrow and more inclined than that predicted by hydrodynamical model calculations. J98 attributes the discrepancy to poorly selected parameter combination of the evolutionary models and/or defects of the convection treatment in the hydrodynamical models. The theoretical zero age horizontal branch (ZAHB) is also shown from the RRab models of Lee & Demarque (1990) for two chemical mixtures, ($Y = 0.20; Z = 0.0001$) and ($Y = 0.23; Z = 0.0007$).

The RRab stars fall within the bounds of the empirical fundamental mode instability strip, and the bulk of these stars match an extrapolation of the ZAHB models for $Y = 0.24$ calculated for the RRc stars. This suggests that the RRab stars have not yet evolved from the ZAHB.

J98 has shown that, at a given metallicity, RRab stars with longer periods are more evolved from the ZAHB, and that the more evolved post-ZAHB objects are found among the most metal-poor variables. Searching for evidences of evolution of the RR Lyraes from the ZAHB, we have plotted in Figure 8 interrelations of effective temperature, luminosity, pulsation period, and metallicity. It is evident that neither for RRc nor for RRab stars there is a dependence of the luminosity on the period, as would be the case if evolutionary effects were present (see panels a and b of Fig. 8). The mild trend of $\log T_{\rm eff}$ with log P is a natural consequence of the tilt of the ZAHB relative to the lines of constant period, (i.e., hotter stars having longer periods), and not an evidence of evolution off the ZAHB.

On the other hand, for the RRab stars no correlation exists between the luminosity or the temperature with metallicity (see panels c and d of Fig. 8). These trends, evident for RR Lyrae stars from clusters of different metallicities (see Tables 8 and 9), are not seen within the RR Lyrae stars of M15. The scatter in [Fe/H] for both RRab and RRc stars is most likely due to uncertainties in the Fourier decomposition of the light curves due to incomplete coverage and to the intrinsic uncertainty carried by the applied calibrations to calculate [Fe/H] of JK96 and Morgan et al. (2005), respectively.

It is worth noticing that the correlation between the mean period of RR Lyraes and the metallicity, does exist within Oosterhoff type I clusters but it does not exist for Oosterhoff type II (Clement et al. 2001). Thus, in the case of M15, despite the low metallicity of its RR Lyrae stars, the mean period for the RRab stars, 0.637 d (Clement et al. 2001), is typical of an Oosterhoff II type cluster and no signs of evolution of the RRab stars are evident.

However, for the RRc stars there is a clear correlation between the luminosity and the temperature with metallicity (see panels c and d of Fig. 8), in the sense that more metal deficient stars are more luminous and cooler. The mean period of the RRc stars studied in this work is 0.386 d, which is slightly larger than the nominal value (0.36 d) for Oosterhoff II type clusters. These results suggest evolutionary effects in the RRc stars of M15.

5. CONCLUSIONS

V- and R-band CCD photometry for 33 known RR Lyrae variables in M15 is presented. The Blazhko variation in V12 is not confirmed. The double mode nature of several stars reported by Cox et al. (1983) was confirmed and their periods have been refined. For the star V34, whose variability has been questioned in the past (Notni & Oleak 1958), we find authentic variations with a period of about 1.15 d and a long term brightness change. The star might be an anomalous cepheid but our data are too scarce to classify the star's variable type.

TABLE 8

MEAN PHYSICAL PARAMETERS OBTAINED FROM RRab STARS IN GLOBULAR CLUSTERS

Cluster	Oo Type	No. of Stars	$[Fe/H]$	$T_{\rm eff}$	M_V
NGC 6171[1]	I	3	−0.91	6619	0.85
NGC 4147[2]	I	5	−1.22	6633	0.80
NGC1851[3]	I	7	−1.22	6494	0.80
M5[4]	I	26	−1.23	6465	0.81
M3[5]	I	17	−1.42	6438	0.78
NGC 6934[6]	I	24	−1.53	6450	0.81
M55[7]	II	3	−1.48	6352	0.71
M2[8]	II	11	−1.54	6257	0.71
M92[9]	II	5	−1.87	6160	0.67
M15[10]	II	11	−1.87	6237	0.67

[1]Clement & Shelton (1997); Å§[2]Arellano Ferro et al. (2004); [3]Walker (1999); [4]Kaluzny et al. (2000); [5]Kaluzny et al. (1998); [6]Kaluzny et al. (2001); [7]Olech et al. (1999); [8]Lázaro et al. (2006); [9]recalculated in this work from the data of Marín (2002); [10]this work.

TABLE 9

MEAN PHYSICAL PARAMETERS OBTAINED FROM RRc STARS IN GLOBULAR CLUSTERS

Cluster	Oo Type	[Fe/H]	No. of Stars	$M/M_\odot$	$\log(L/L_\odot)$	$T_{\rm eff}$	Y
NGC 6171	I	−0.68	6	0.53	1.65	7447	0.29
NGC 4147[1]	I	−1.22	9	0.55	1.693	7335	0.28
M5	I	−1.25	7	0.58	1.68	7338	0.28
M5[2]	I	−1.25	14	0.54	1.69	7353	0.28
M3[3]	I	−1.47	5	0.59	1.71	7315	0.27
NGC 6934[4]	I	−1.53	4	0.63	1.72	7300	0.27
M2[5]	II	−1.78	2	0.61	1.76	7177	0.26
M9	II	−1.72	1	0.60	1.72	7299	0.27
M55[6]	II	−1.90	6	0.53	1.75	7193	0.27
NGC 2298	II	−1.90	2	0.59	1.75	7200	0.26
M92[7]	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[8]	II	−2.12	8	0.76	1.81	7112	0.24

[a]Data taken from Clement & Shelton (1997), except:

[1]Arellano Ferro et al. (2004); [2]Kaluzny et al. (2000); [3]Kaluzny et al. (1998); [4]Kaluzny et al. (2001); [5]Lázaro et al. (2006); [6]Olech et al. (1999); [7]recalculated in this work from the data of Marín (2002); [8]this work.

From the Fourier parameters of the light curves of RRab and RRc stars and from the physical parameters calibrations available in the literature, we estimate for the RRc stars the mean mass and effective temperature as $0.76 \pm 0.08\ M_{\odot}$ and $\log T_{\rm eff} = 3.852 \pm 0.003$, respectively; [Fe/H]$=-2.12 \pm 0.16$, $\log(L/L_{\odot}) = 1.812 \pm 0.028$, and a mean relative abundance of helium $Y = 0.24 \pm 0.01$. For the RRab, we find $\log T_{\rm eff} = 3.795 \pm 0.006$, [Fe/H]$=-1.87 \pm 0.24$, and $M_V = 0.67 \pm 0.03$. The average metallicity and distance of the cluster are thus estimated as [Fe/H]$=-1.98 \pm 0.24$ and 8.67 ± 0.41 kpc, respectively. This estimate of the metallicity is in agreement with previous determinations, although the cluster appears to be closer to the Sun. Furthermore, when compared with other globular clusters, both RRab and RRc stars place M15 in the correct place in the sequences first forseen by Clement & Shelton (1997), in the sense that Oosterhoff II type clusters are more metal deficient than those of type I and the mean temperature of their RR Lyrae stars decreases with a decreasing iron content.

The temperatures and luminosities for the RRab stars are consistent with those found by J98 for the large sample of 272 RRab stars. Evidences of evolution from the ZAHB are found for the RRc stars but not for the RRab stars.

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