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RR Lyrae in M15: Fourier Decomposition and Physical Parameters

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Abstract. The V and R light curves for 30 RR Lyrae stars in M15 were used to calculate their physical parameters. The Blazhko effect, previously reported in V12, was not detected. The determined values of the iron content and distance of the cluster are: [Fe/H] = -1.98 ± 0.24 and d = 8.67 ± 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.

Keywords. Globular Clusters-M15, Variable Stars-RR Lyrae.

1. Introduction

M15 (NGC 7078) is one of the most luminous and dense clusters in the Milky Way. Numerous photometric studies of the cluster have originated, from the pioneering work of Brown (1951) to the most recent CCD study of RR Lyrae in the cluster by Silbermann & Smith (1995). More than 150 variables are listed in the catalogue of Clement (2002) and approximately 100 of them are RR Lyrae. M15 is one of the globular clusters with a very low metal content; the many determinations of its metallicity range between -2.15 $\leqslant$ [Fe/H] $\leqslant$ -1.76 (Buonanno *et al.* 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.* 2005).

The Fourier light curve decomposition technique has not been applied to RR Lyrae 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 30 RR Lyrae.

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2. Observational Material and Reductions

In the present study, 129 V and 127 R images, distributed in two fields of the cluster as illustrated in Figures 1 and 2, were obtained in 2000 and 2001, 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.

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). The accuracy of the photometry was estimated as ± 0.031 and ± 0.019 for the V and R filters, respectively.

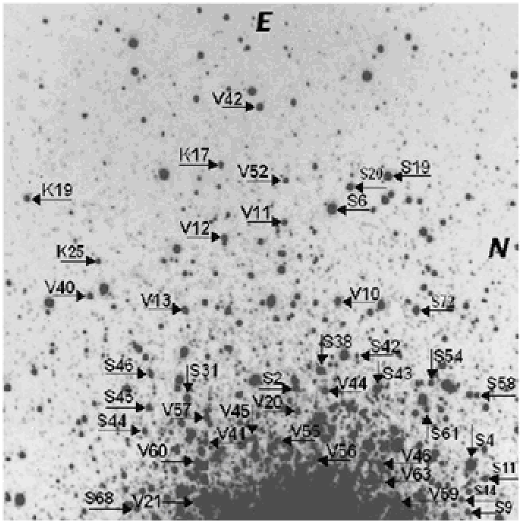

Figure 1. A selected image of the east field of M15, obtained in this work. Identifications of known RR Lyrae stars begin with "V", otherwise they are standard stars.

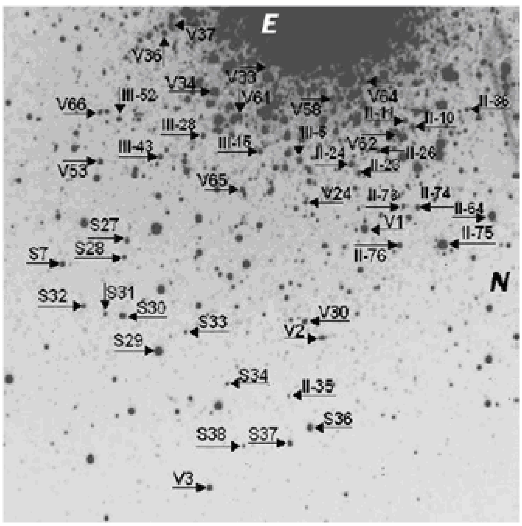

Figure 2. A selected image of the west field of M15, obtained in this work. Identifications of known RR Lyrae stars begin with "V", otherwise they are standard stars.

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3. The RR Lyrae stars in M15

In Clement's (2002) database of variables stars, a total of 158 variable stars are known, from which approximately 104 are RR Lyrae type stars. In this work, 30 known RR Lyrae stars, identified in Figures 1 and 2, have been studied. For all the stars, a new time of maximum light has been calculated; for some, the period also has been calculated, either because it was not reported in the list of variables of Clement (2002) or, because it has been noticed that the reported period does not produce a coherent light variation.

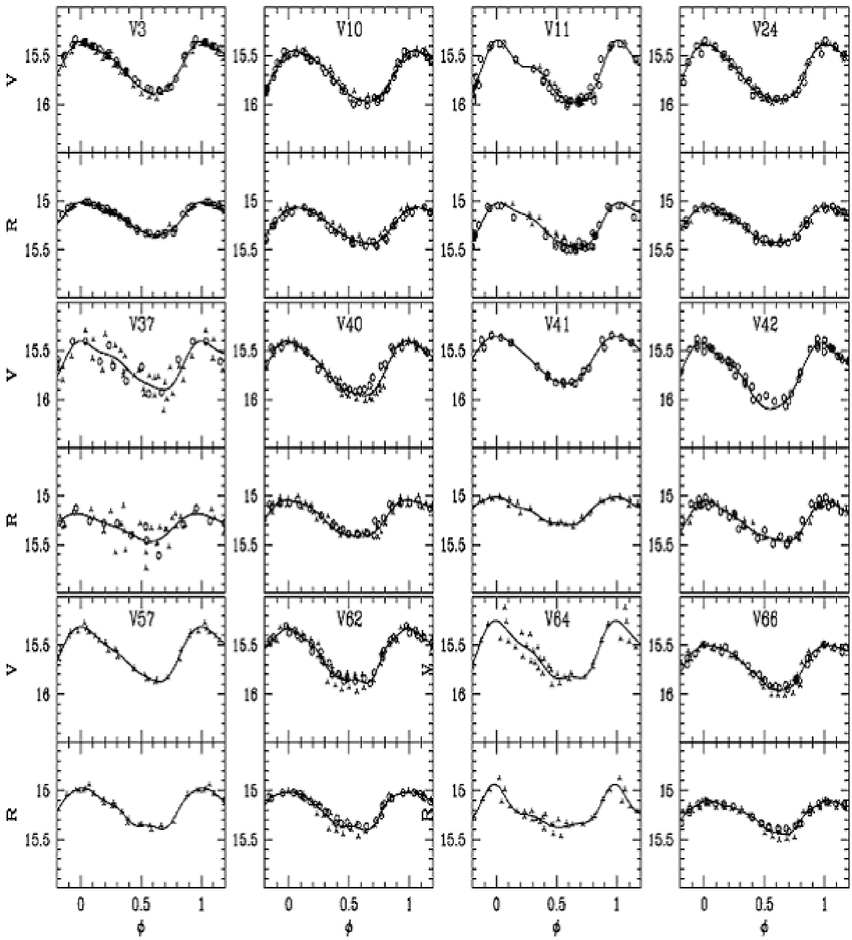

Figure 3. Light curves and Fourier fits of 12 know RRc Lyrae stars in M15.

3.1. *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:

$$f(t) = A_0 + \sum_{k=1}^{n} A_k cos((2\pi k(t - E)/P) + \phi_k) \tag{3.1}$$

The solid curves in Figures 3 and 4 are the Fourier fits represented by Equation (3.1).

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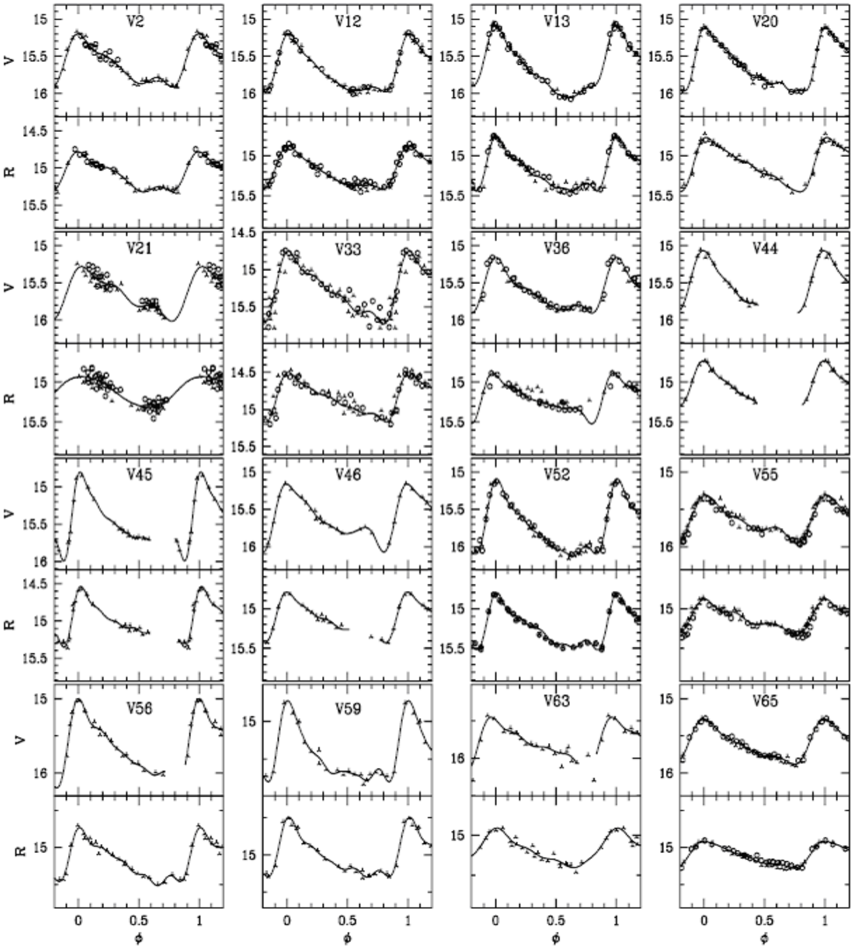

Figure 4. Light curves and Fourier fits of 16 know RRab Lyrae stars in M15.

From the amplitudes and phases of the harmonics in Equation (3.1), the Fourier parameters, defined as $\phi_{ij} = \phi_i - i\phi_j$ and $R_{ij} = A_i/A_j$, were calculated.

3.2. *The physical parameters of the RR Lyrae stars from their light curves*

For RR Lyrae stars of Bailey's type RRc stars, Simon & Clement (1993) applied hydrodynamic pulsation models to calibrate equations for the effective temperature Teff, a helium content parameter Y, the stellar mass M, and the luminosity $\log L$, in terms of the period and Fourier parameter ϕ_{31}. Their work has been extended to RRab stars by Jurcsik & Kovács (1996, JK96), Kovács & Jurcsik (1996, KJ96; 1997), and Jurcsik (1998, J98). We have adopted Morgan *et al.* (2005) calibration for RRc type stars. These parameters are summarized in Tables 1 and 2.

4. Discussion

4.1. *The iron abundance of M15*

The calibrations mentioned above are strong 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

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Table 1. Physical parameters for the RRab stars in the globular cluster M15.

Star	[Fe/H]*	$\log(T_{\rm eff})$	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 ± 0.24	3.795 ± 0.006	0.67 ± 0.03

* From the calibration of Jurcsik & Kovács (1996).

Table 2. Physical parameters for the RRc stars in the globular cluster M15.

Star	$M/M_\odot$	$\log(L/L_\odot)$	Y	M_V	$\log(T_{\rm eff})$	[Fe/H]*
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
V41	0.78	1.836	0.23	0.73	3.848	-2.29
V42	0.82	1.819	0.24	0.74	3.852	-2.15
V57	0.74	1.785	0.25	0.77	3.855	-1.99
V66	0.62	1.774	0.25	0.72	3.855	-1.93
Mean:	0.75 ± 0.08	1.809 ± 0.028	0.24 ± 0.01	0.73 ± 0.03	3.852 ± 0.003	-2.11 ± 0.16

* From the calibration of Morgan *et al.* (2005).

to keep the physical parameter calculations limited to those stars with well defined light curves. These stars and their physical parameters are listed in Tables 1 and 2.

The mean values are [Fe/H]= -1.87 ± 0.24 for the RRab stars and [Fe/H]= -2.11 ± 0.16 for the RRc stars. Our overall average for [Fe/H] is then -1.98 ± 0.24 for M15.

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 2 have first been 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 $M_{\rm bol} = 4.75$.

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 1, 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 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 from 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 percent closer than the adopted distance in Harris (1996). In the present work, both values of the luminosity and the absolute magnitude of the RR Lyrae stars, have also been obtained with Fourier's technique. Nevertheless, as seen in Tables 3 and 4, these values produce a coherent sequence of physical parameters with metallicity, within the Oosterhoff type of the cluster, as will be discussed in the following subsection.

4.3. *Physical parameters of globular clusters as a function of metallicity*

Tables 3 and 4 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 [Fe/H] value. It is easy to confirm that the mass and luminosity increase while the temperature and helium parameter decrease with increasing 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] = -2.11 ± 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 bracketed by the several independent determinations listed by Buonanno *et al.* (1985), that range from -2.15 to -1.76.

Table 3. Mean physical parameters obtained from RRab stars in globular clusters.

Cluster	Oo Type	N	[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	0.81
NGC 1851[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
M2[6]	II	20	-1.52	6687	0.71
M55[7]	II	3	-1.56	6325	0.68
M92[8]	II	5	-1.87	5596	0.67
M15	II	11	-1.87	6237	0.67

1. Clement & Shelton (1997), 2. Arellano Ferro *et al.* (2004), 3. Walker (1999), 4. Kaluzny *et al.* (2000), 5. Kaluzny *et al.* (1998), 6. Lázaro *et al.* (2005), 7. Olech *et al.* (1999), 8. recalculated in this work from the data in Marin (2002), 9. this work. N is the number of stars studied.

5. Conclusions

V- and R-band CCD photometry for 30 known RR Lyrae variables in M15 have been presented. The Blazhko variation in V12 is not confirmed. The stars V30, V58, and V60 are found to be double-mode pulsators or RRd type variables. For the star V34, whose

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Table 4. Mean physical parameters obtained from RRc stars in globular clusters.

Cluster	Oo Type	[Fe/H]	N	$M/M_\odot$	$\log(L/L_\odot)$	$T_{\rm eff}$	Y
NGC 6171	I	-0.68	6	0.53	1.65	7447	0.29
NGC 4147[1]	I	-1.22	9	0.54	1.69	7334	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[6]	I	-1.47	5	0.59	1.71	7315	0.27
M2[4]	II	-1.52	11	0.60	1.71	7320	0.28
M9	II	-1.72	1	0.60	1.72	7299	0.27
M55[5]	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[6]	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	-2.26	6	0.73	1.80	7136	0.25
M15	II	-2.11	9	0.75	1.81	7112	0.24

Data taken from Clement & Shelton (1997), except: 1. Arellano Ferro *et al.* (2004), 2. Kaluzny *et al.* (2000), 3. Kaluzny *et al.* (1998), 4. Lázaro *et al.* (2005), 5. Olech *et al.* (1999), 6. recalculated in this work from the data in Marin (2002), 7. this work. N is the number of stars studied.

variability has been questioned in the past (Notni & Oleak 1958), we find authentic variations but a peculiar and scattered light curve that precludes classifying the star's variable type.

From the Fourier parameters derived from the light curves of RRab and RRc stars, and the physical parameters calibrations available in the literature, we estimate for the RRc stars the mean mass and effective temperature as 0.75 ± 0.08 $M_\odot$ and $\log(T_{\rm eff}) = 3.852 \pm 0.003$, respectively; [Fe/H] = -2.11 ± 0.16, $\log(L/L_\odot) = 1.809 \pm 0.028$, 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 ± 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 ± 0.34 and 8.67 ± 0.41 kpc, respectively. This estimate of the metallicity is in agreement with previous determinations, although the cluster appears 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 foreseen by Clement & Shelton (1997), in the sense that Oosterhoff type II 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. An extensive and detailed version of this work can be found in Arellano Ferro *et al.* (2006).

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