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CCD PHOTOMETRY OF THE RR LYRAE STARS IN NGC 4147[1]

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RESUMEN

Reportamos los resultados de la fotometría CCD a través de los filtros V y R de las estrellas RR Lyrae conocidas en NGC 4147. Los períodos de todas las varibles han sido recalculados y se dan nuevas efemérides. Se detectó efecto Blazhko en las variables V2 y V6. Las estrellas V5, V9 y V15, reportadas previamente como variables, no muestran variaciones. Se reporta la nueva variable, V18, que muestra un período de 0.49205 días y una amplitud de 0.15 mag. Con la técnica de descomposición de Fourier de las curvas de luz se han estimado los parámetros físicos de las variables RRab y RRc. El cúmulo es del tipo de Oosterhoff I. Los nuevos valores determinados para el contenido de hierro y la distancia; [Fe/H]$=-1.22 \pm 0.31$ y 16.8 ± 1.3 kpc colocan adecuadamente al cúmulo en las secuencias tipo de Oosterhoff-metalicidad y metalicidad-temperatura efectiva para cúmulos globulares. Una comparación con modelos de la Rama Horizontal indica que las RRab de NGC 4147 no han abandonado esa fase aún, lo que es congruente con su período promedio y la metalicidad del cúmulo.

ABSTRACT

We report the results of CCD V and R photometry of the RR Lyrae stars known in NGC 4147. The periodicities of most variables are revised and new ephemerides are calculated. The Blazhko effect has been detected in V2 and V6. Three previously reported variables; V5, V9, and V15 are found to be non-variable. A new variable V18 was discovered with a period of 0.49205 days and an amplitude of 0.15 mag. Using the approach of Fourier decomposition of the light curves, the physical parameters of the RRab and RRc variables were estimated. The cluster is of the Oosterhoff type I. With the newly values [Fe/H]$=-1.22 \pm 0.31$ and 16.8 ± 1.3 kpc, the cluster fits very well into the Oosterhoff type-metallicity and metallicity-temperature sequence found in globular clusters. A comparison with ZAHB models indicates that the RRab stars have not yet evolved off the horizontal branch, a result consistent with the mean period of the RRab variables and with the metallicity of the cluster derived in this work.

Key Words: **GLOBULAR CLUSTERS: NGC 4147 — STARS: VARIABLES: RR LYRAE**

1. INTRODUCTION

The faint cluster NGC 4147 is located at a distance of 19.3 kpc from the Sun and 21.3 kpc from the Galactic center (Harris 1996); thus, it is located in the outer regions of the Galactic globular cluster system. Its metallicity is very low; [Fe/H] = −1.83 (Harris 1996). Photographic studies of NGC 4147 can be found in the papers by Davis (1917), Baade (1930), Sandage & Walker (1955), and Newburn (1957); the 17 RR Lyrae stars discovered in these papers are reported by Clement (1997). The *HST*

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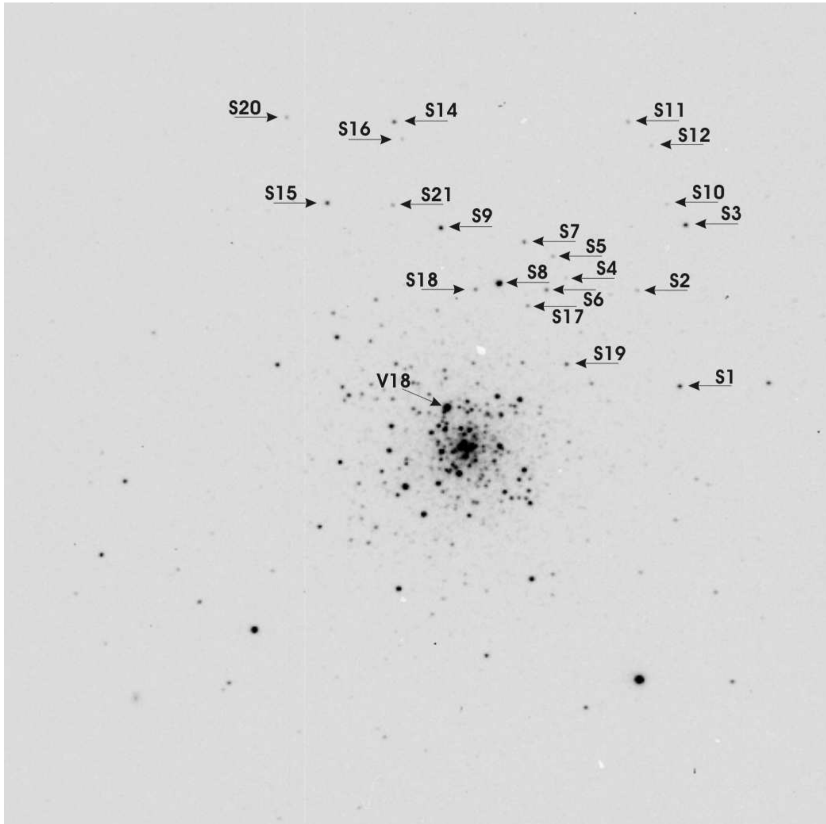

Fig. 1. Standard stars in the field of NGC 4147. The V and R values are given in Table 2. V18 is a new variable (see text for discussion).

color-magnitude diagram (Piotto et al. 2002) shows a horizontal branch with a large number of stars on the blue side of the instability strip. As low mass RR Lyrae stars evolve off the Zero Age Horizontal Branch they become brighter and bluer (Lee, Demarque & Zinn 1990; Pritzl et al. 2002), this might indicate that the RR Lyrae variables in the cluster are in the post-ZAHB. An indication that this may not always be true is suggested by the mean periods observed for RRab and RRc stars in the cluster. RR Lyraes evolved from the ZAHB should have long periods. However, the periods published for the variable stars in the globular clusters database (Clement 1997) average only $P_0 = 0.524$ days and $P_1 = 0.341$ days for the fundamental and first overtone pulsators, respectively.

The cluster NGC 4147 was chosen because the number of known RR Lyrae variables in it is small, no recent searches for new variables are available, no photometric studies of the cluster in the CCD era have been done and no previous Fourier decomposition of the light curves of RR Lyrae stars in the cluster exists. Since the expected incompletness factor in the detection of RR Lyrae stars in globular clusters is 30% (Kaluzny, Olech, & Stanek 2001), there are good opportunities to find new variables that would make the study of the pulsating stars in this cluster more complete. Also several of the periods of the RR Lyrae variables determined by Newburn (1957) are suspected to be uncertain and probably incorrect (Clement 2000). The purpose of this paper is to study the known RR Lyrae variables in the cluster based on CCD photometry, to establish new ephemerides, to use the light curve Fourier decomposition (see Simon & Clement 1993; Kovács & Jurcsik 1996; 1997; Olech et al. 1999), to estimate their fundamental physical parameters, and also to search for Blazhko effect and to detect new variables. The physical parameters derived from the light curves are to be compared with equivalent results in other globular clusters.

2. OBSERVATIONS AND REDUCTIONS

The observations used in the present work were obtained from three observatories. From January 12 to 16, 2003, B, V, and R images were secured us-

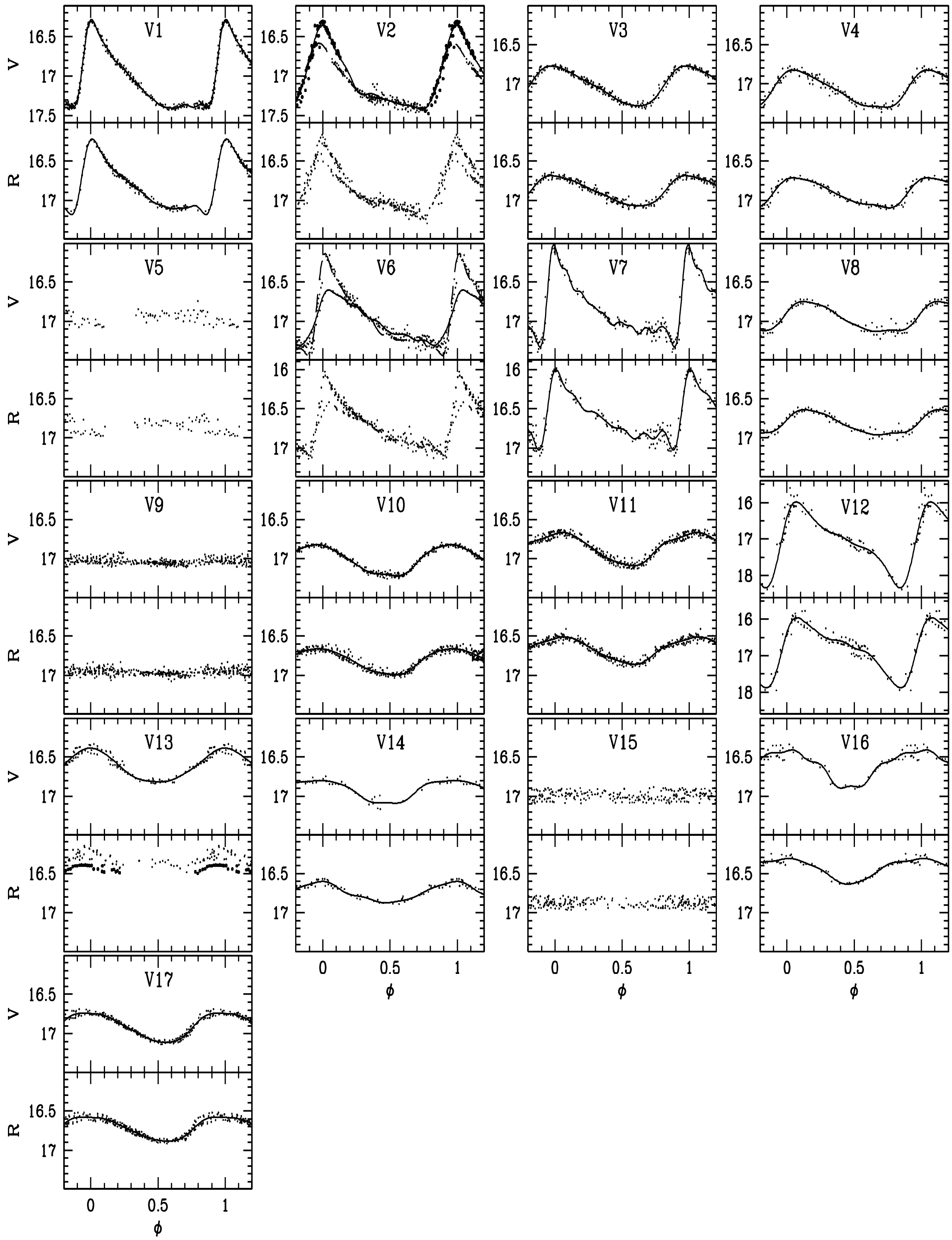

Fig. 2. Light curves and fits of 17 know RR Lyrae stars in NGC 4147. They have been phased with the ephemerides in Table 3. Except for V12 that displays a very large amplitude, the vertical scale is the same for all the stars, so as to appreciate relative amplitudes and mean brightness differences.

TABLE 1

LOG OF OBSERVATIONS IN 2003

Date	Filter	N	Exp. Time (sec)	Observatory
12, Jan	R	26	20	SPM
	V	31	30	SPM
	B	9	60	SPM
13, Jan	R	14	25	SPM
	V	13	30	SPM
	B	13	60	SPM
14, Jan	R	12	25	SPM
	V	11	30	SPM
	B	12	60	SPM
15, Jan	R	10	25	SPM
	V	8	30	SPM
	B	9	60	SPM
16, Jan	R	15	25	SPM
	V	14	40	SPM
7, May	R	14	20	IAO
	V	15	30	IAO
8, May	R	21	25	IAO
	V	23	30	IAO
	B	21	60	IAO
9, May	R	25	25	IAO
	V	28	30	IAO
10, May	R	11	25	IAO
	V	11	30	IAO
31, May	R	13	300	OT
	V	10	400	OT
1, Jun	R	7	400	OT
	V	7	600	OT
2, Jun	R	14	300	OT
	V	15	600	OT
5, Jun	R	14	300	OT
	V	7	600	OT
20, Jun	R	14	300	OT
	V	9	600	OT
21, Jun	R	14	300	OT
	V	7	600	OT
22, Jun	R	14	300	OT
	V	10	600	OT
23, Jun	R	14	300	OT
	V	6	600	OT
24, Jun	R	14	300	OT
	V	6	600	OT
26, Jun	R	14	300	OT
	V	6	600	OT
27, Jun	R	14	300	OT
	V	21	600	OT
28, Jun	R	14	300	OT
	V	8	600	OT
29, Jun	R	14	300	OT
	V	25	600	OT
1, Jul	R	14	300	OT
	V	5	600	OT
2, Jul	R	14	300	OT
	V	3	600	OT

TABLE 2

STANDARD STARS IN THE FIELD OF NGC 4147

Star	V	R	Star	V	R
S1	16.824	16.34	S11	18.569	17.72
S2	18.303	17.86	S12	18.979	18.58
S3	16.773	16.30	S14	16.989	16.67
S4	18.986	18.59	S15	18.029	17.59
S5	18.214	17.80	S16	16.891	16.48
S6	17.663	16.9	S17	18.770	18.35
S7	17.464	17.01	S18	17.410	17.40
S8	15.081	14.52	S19	17.993	17.09
S9	16.424	16.00	S20	16.780	16.70
S10	18.982	18.57	S21	18.709	17.83

ing the 0.84 m telescope of San Pedro Mártir Observatory (SPM), México. It is equipped with a CCD SITE1 of 1024×1024 pixels of 24 square microns size. From May 7 to 10, 2003, V and R observations were obtained with the 2.0 m telescope of the Indian Astrophysical Observatory in Hanle (IAO), India. Two CCDs were used at this telescope, a 1024×1024 pixels of 19 square microns size for the first two nights and a 2048×2048 of 15 square microns size for the rest of the run.

From May 30 to July 2, 2003 V and R images were obtained with the 0.82 m telescope of the Observatorio del Teide (OT) Izaña, Tenerife, Spain. The detector here was a Thompson CCD of 1024×1024 pixels of 19 square microns size. Table 1 contains the log of the observations. A total of 43 in B, 208 in V, and 192 in R observations were obtained.

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

The transformation to the standard system was done differentially relative to a group of standard stars in the field of NGC 4147 available in Patterson (2003). These stars are identified in Figure 1 and listed in Table 2 with their V and R standard values.

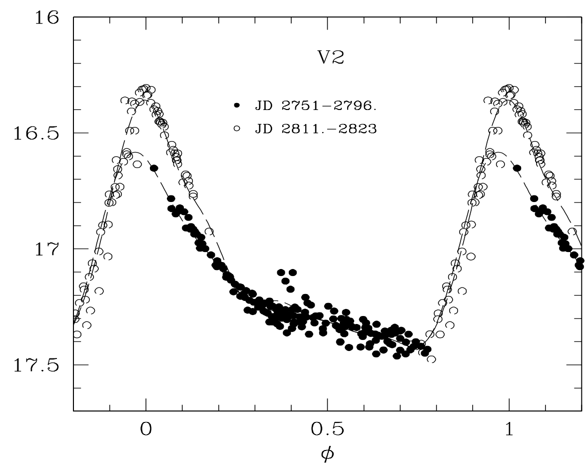

Fig. 3. Blazhko effect in V2

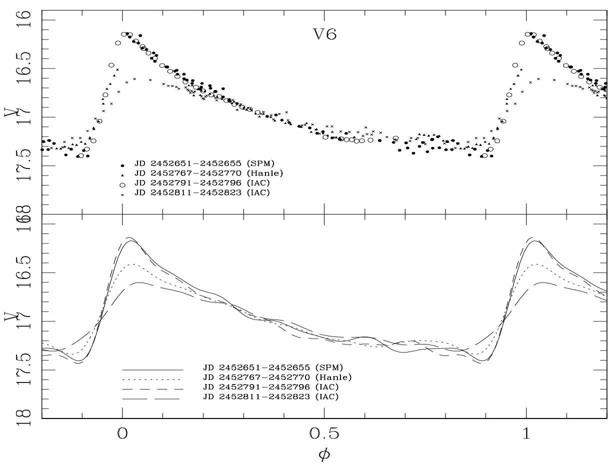

Fig. 4. Blazhko effect in V6. The upper pannel shows the light curves in three seasons during 2003. The lower pannel shows the corresponding fittings. A clear modulation of the maximum is present, while the minimum remains at the same level as it is typical of Blazhko modulations. The wavy pattern of the lower part of the fittings is due to the sampling. The estimated periodicity of the Blazhko effect is about 68 days.

These standard stars were used to calculate the transformation equations of the form of equation (1) to change from the PSF instrumental magnitudes to the standard system. No quadratic or colour terms were found to be significant.

$$M_{std} = a\ M_{ins} + b. \tag{1}$$

The above transformation was then used to convert the instrumental magnitudes of the RR Lyrae stars to the standard V and R magnitudes for each image. The results can be obtained from the first author. The accuracy of the photometry was estimated from the scatter in the transformation equations. We found ± 0.046, ± 0.034 mag for V and R respectively for SPM, ± 0.023, ± 0.016 mag for IAO and $\pm 0.012, \pm 0.011$ mag for OT. These uncertainties are mainly defined by the seeing conditions prevailing at the time of the observation.

The search for new variables was performed using the image subtraction method first described by Alard & Lupton (1998) and Alard (2000). The program and data pipeline used were those described in the implementation of the method by Bond et al. (2001) and Bramich (2004). One new variable was found as will be described in the following section.

3. THE RR LYRAE STARS IN NGC 4147

In the list of variables in the updated Catalogue of Sawyer-Hoag (Clement 1997), many periods are indicated as dubious. In phasing our observations we discovered that many periods, in fact, seem incorrect or imprecise. Thus, before using the light curves for estimates of the physical parameters, we chose to revise the ephemerides of the RR Lyrae stars.

3.1. *Period Determination*

The periods of the known RR Lyrae variables (Clement 1997), listed in Table 3, are from Mannino (1958) for variables V1-3, V10-11, and V17 and from Newburn (1957) for variables V4-8 and V12-16. The observations in the present work have been used to revise the periods. The string-length method, which searches for minima in the light curve dispersion, and a program of our own were used for this purpose. The method was applied independently to the V and R data and the results were averaged. Once the periods were calculated we estimated the time of maximum light to establish new ephemerides. In Table 3 we list the times of maximum light and the newly determined periods, as well as the old values from Newburn and Mannino for comparison.

In general. the agreement of the new and old periods is good, except for stars V8, V13, V14 and V16, for which the differences are substantial. The new periods produce smoother light curves as shown in Figure 2.

3.2. *Notes on Individual Stars*

V1. The observed periodicity of this RRab variable is consistent with the one reported by Mannino (1958), but a significant shift of the maximum is noted relative to the old epoch. We have obtained a slightly different value for the period and a new time of maximum brightness.

TABLE 3

UPDATE OF PERIODS, EPOCHS, AND AMPLITUDES FOR THE RR LYRAE STARS IN NGC 4147

Variable	Type	Old Period (days)	New Period (days)	Epoch (+ 240 0000)	A_V (mag)	A_R (mag)
V1	ab	0.500386	0.50038	52791.468	1.11	0.88
V2	ab	0.49306	0.49325	52637.404	1.10[a]	1.00[a]
V3	c	0.280542	0.28058	52767.280	0.51	0.38
V4	c	0.30097	0.29922	52652.052	0.47	0.38
V5		0.34125:	not variable			
V6	ab	0.61860	0.60975	52639.072	1.13[a]	1.00[a]
V7	ab	0.51294	0.51439	52767.309	1.22	0.99
V8	c	0.3897:	0.27861	52651.933	0.38	0.32
V9		prob. not var.	not variable			
V10	c	0.352314	0.35233	52651.971	0.40	0.33
V11	c	0.38739	0.38745	52651.971	0.42	0.35
V12	ab	0.5:	0.50461	52651.933	2.52	1.92
V13	c	0.3759:	0.40813	52653.991	0.47	···
V14	c	0.5255:	0.25950	52769.274	0.32	0.27
V15		0.3354:	not variable			
V16	c	0.2775:	0.3694	52767.317	0.47	0.32
V17	c	0.37473	0.37494	52651.916	0.37	0.30

[a]Maximum amplitude but there is evidence of Blazhko effect.

V2. This is a RRab variable. The reported period by Mannino (1958), 0.49306 days, does not phase our data properly. The revised period is 0.49325 days. The light curve clearly shows the presence of the Blazhko effect (see Figure 3). However our data are insufficient to estimate the periodicity of the effect. The two continuous lines in the figure are independent fits to the two major groups in our data suitably splitted in time, as indicated by the symbols.

V3. Our observations are consistent with the period reported by Mannino (1958) for this RRc variable.

V4. For this RRc variable we have refined the period and estimated a new time of maximum.

V5. This star does not show variations in our data. Thus we do not confirm the variable nature of the star reported by Newburn (1957) from blinking pairs of plates.

V6. The period of this RRab variable has been slightly modified. A significant shift of the maximum is noted relative to the old epoch. This star shows a clear Blazhko effect. In Figure 4 the four versions of the light curve, as obtained in different seasons during 2003, are displayed. The modulation of the maximum is evident. Five times of maximum brightness were determined and they are plotted in Figure 5 together with the modulation model which suggest a Blazhko period of about 68 days. A competing period is 39 days (not illustrated). With only five points, however, we cannot favour one of these two periods.

V7. The old ephemerides for this RRab star is consistent with our observations.

V8. The proposed period 0.3897 days by Newburn (1957) is incompatible with our observations. We found instead that a period of 0.27861 days produces a smoother light curve.

V9. This star does not show variations in our data, confirming the non-variable nature reported in the database of Clement (1997).

V10. A slight modification of the period and a new epoch were required for this RRc variable.

V11. As for V10 the old period was revised and slightly modified. A new epoch was also calculated for this RRc variable.

V12. The old estimate of the period was 0.5 days. We have refined the period and found the value

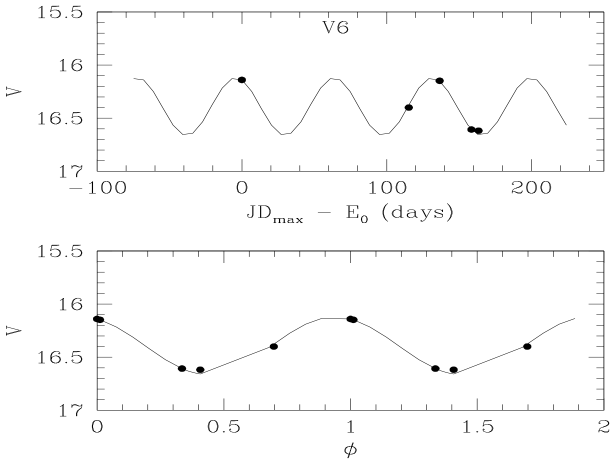

Fig. 5. Times of maximum light in V6 observed in 2003 are modulated by the Blazhko effect. The solid curve has a periodicity of 67.9 days. In the top pannel the time axis is the difference of julian day of maximum minus the epoch of the ephemerides. In the lower pannel the the modulation is represented in phase. An alternative period of about 39 days is not illustrared. (See text).

0.50461 days and a new epoch. The light curve has a peculiar shape and a much larger amplitude than the other RR Lyrae stars in the cluster. The star needs further observations to confirm its peculiarities and we have not included it in the calculation of physical parameters.

V13. The V data are displayed in Figure 6. The data from different observatories show clear variations of the maximum brightness, while around minimum light the data mingle well. The best period found from the V data is 0.408129 days. This period was adopted for the R data from Hanle since SPM and IAC data do show larger scatter. Still, the R light curve looks scattered. While this star could be a double mode RRd star or a Blazhko-type RRc, like those reported by Kovács et al. (2000) and Olech et al. (1999), our observations are insufficient to decide.

V14. A new period of 0.25950 was found from SPM and Hanle data in the R filter. This was adopted for the V Hanle data. These clean curves were then used to calculate the Fourier fits.

V15. This star does not show variations in our data. Thus we do not confirm the variable nature of the star reported by Newburn (1957) from blinking pairs of plates.

V16. This star was suspected to be a double mode RRd. However we have found that the old period of 0.2775 days was incorrect. The period 0.3694 days fits the data much better and the star can be classified as an RRc.

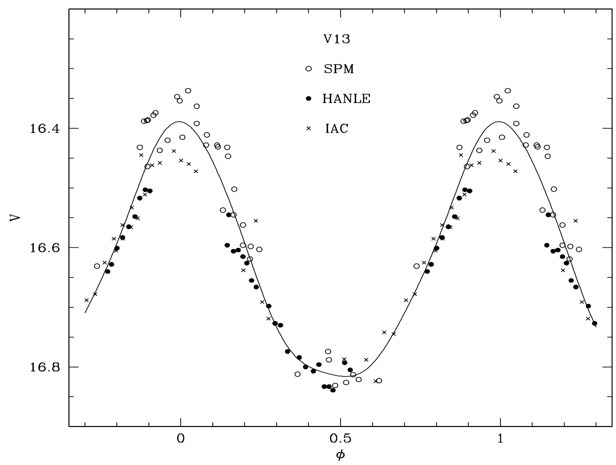

Fig. 6. V light in V13 clear shows variations of maximum brightness for different epochs as seen in the figure, while the data at minimum are well mixed. This suggests the presence of Blazhko effect. (See text for details).

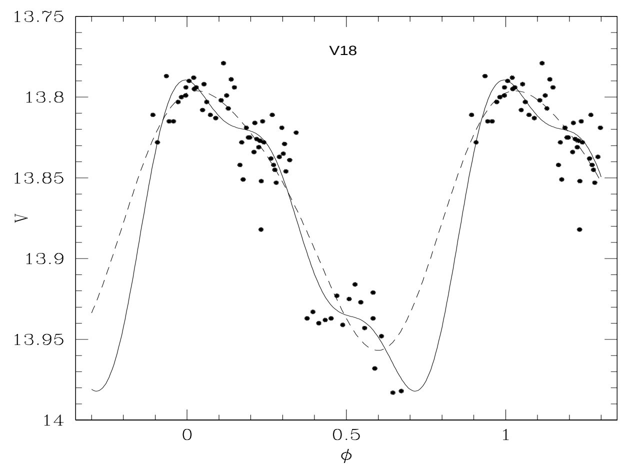

Fig. 7. V light in V18 show clear variations. The period is 0.49205 days. The star is likely a foreground RR Lyrae star. (See text for discussion).

V17. We have found that a slight modification of the old period of this RRc star, as given in Table 3, improves the quality of the fit.

V18. We have discovered the variability of this star. The light curve is presented in Figure 7 phased with a period of 0.49205 days. The amplitude of the variation is 0.15 mag and the mean magnitude is 13.870±0.003, i.e., about half the amplitude of the RRc stars in the cluster and 4.43 magnitudes brighter than other cluster RR Lyrae stars. The V amplitude being small, the R amplitude is expected to be even smaller. The variations are not clearly detected in our R CCD photometry. The star seems to be a foreground RR Lyrae star projected against the central regions of NGC 4147, see Fig. 1 for the star identification. Two fits are shown in Fig. 7; for 2 (dashed curve) and 3 (solid curve) harmonics. The later suggests the star being an RRab, which would also be consistent with its period. We have not used this star for the cluster physical parameters discussion.

3.3. *Fourier Parameters of the Light Curves*

To estimate the Fourier parameters of the light curves described in the previous section, these were fitted using the harmonic decomposition technique according to an equation of the form:

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

The light curves and their fits phased with the ephemerides of Table 3 are displayed in Fig. 2.

From the amplitudes and phases of the harmonics in Eq. 2, the Fourier parameters, defined as $\phi_{ij} = \phi_i - i\phi_j$, and $R_{ij} = A_i/A_j$, were calculated. In Table 3 we also report the values of the full amplitudes in V and R while in Tables 4 and 5 we report the mean magnitudes A_0, and the values of the Fourier decomposition parameters for each RR Lyrae star from the V and R light curves, respectively.

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

The realization that light curve shapes and physical parameters are related can be traced 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 with 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 log L, in terms of the period and Fourier parameter ϕ_{31} (see their Eqs. 2, 3, 6, and 7) for RR Lyrae stars of Bailey type RR*c*. Their work has been extended to RR*ab* stars by Jurcsik & Kovács (1996) (JK96), Kovács & Jurcsik (1996 (KJ96); 1997), and Jurcsik (1998) (J98). The equations that we have used are Eq. 3 in JK96 for [Fe/H], Eq. 2 in KJ96 for M_V, and Eqs. 3 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 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 made use of the calibrations in the above mentioned papers to estimate the corresponding physical parameters for the stars in NGC 4147, which are summarized in Tables 6 and 7.

4. DISCUSSION

4.1. *Oosterhoff Type and Consistency Tests*

The averages of the new periods listed in Table 3 for the RRc and RRab stars are; $< P_c >= 0.323 \pm 0.060$ days and $< P_{ab} >= 0.524 \pm 0.048$; these values make NGC 4147 an Osterohoff type I cluster.

A standard test of consistency between the mean magnitudes of the RR Lyrae stars and their derived luminosities or absolute magnitudes obtained from the empirical calibrations, is done by plotting $\rm A_0$ versus log L and $\rm A_0$ versus $\rm M_V$ for the RRc and RRab stars, where ideally one should find linear correlations. These plots for the RR Lyrae stars in NGC 4147 are shown in Figures 8a and 8b. In Fig. 8a the lines have a slope of 0.4 and are separated by the estimated uncertainty in log $L/L_\odot$ of 0.04. In Fig. 8b the slopes are 1.0 and the lines are separated by the estimated uncertainty 0.1 mag in M_V. The distribution of points is not correlated with the distance of the stars to the cluster center; the stars are labeled and their position in the cluster can be seen in the chart of Sandage & Walker (1955); thus the scatter is not caused by inaccuracy in the photometry while dealing with crowded regions of the cluster, as suggested by Simon & Clement (1993). Similar scattered plots have been found by Kaluzny et al. (2000) for M5 and Olech et al. (1999) for M55. An explanation in terms of inadequate treatment of convection and radiative transfer in the atmospheres and unknown physics in the pulsation of these stars as the sources of discrepancy between models and observations has been suggested by Olech et al..

In Figure 8c the distribution of RRc stars in the log P - V amplitude plane is consistent with the locus (the solid straight line in the figure) derived for RRc stars in M3 (Kaluzny et al. 1998), another cluster of Oosterhoff type I.

4.2. *Comparison with other Globular Clusters*

The mean parameters for RRc and RRab stars are compared for several clusters in Tables 8 and 9. The clusters in these tables are ordered according to their Oosterhoff type and their [Fe/H] value. It can be seen that the values obtained in this work for NGC 4147 put the cluster in the right place in the

TABLE 4

FOURIER FITTING PARAMETERS FOR V LIGHT CURVES

Star	A_0	σ_{A_0}	A_1	σ_{A_1}	ϕ_{21}	$\sigma_{\phi_{21}}$	ϕ_{31}	$\sigma_{\phi_{31}}$	ϕ_{41}	$\sigma_{\phi_{41}}$	R_{21}	$\sigma_{R_{21}}$
V1	17.072	0.002	0.435	0.003	3.848	0.023	1.655	0.033	5.792	0.046	0.391	0.023
V2	17.126	0.004	0.326	0.006	3.775	0.037	1.627	0.089	5.777	0.149	0.518	0.020
V2	17.075	0.009	0.411	0.008	3.670	0.084	1.141	0.199	5.631	0.339	0.523	0.036
V3	17.034	0.002	0.241	0.003	4.469	0.062	2.628	0.219	1.361	0.476	0.235	0.014
V4	17.085	0.004	0.230	0.006	4.421	0.119	2.356	0.229	1.374	0.625	0.207	0.025
V6	16.981	0.005	0.402	0.006	3.858	0.044	1.933	0.061	6.099	0.088	0.522	0.018
V6	17.002	0.004	0.285	0.010	4.213	0.062	2.539	0.101	0.526	0.217	0.376	0.020
V7	16.857	0.008	0.358	0.012	3.852	0.092	1.668	0.137	5.772	0.169	0.528	0.038
V8	16.966	0.005	0.192	0.007	3.833	0.217	2.298	0.398	0.643	0.613	0.201	0.039
V10	17.027	0.001	0.200	0.002	4.276	0.101	3.406	0.151	2.638	0.220	0.102	0.009
V11	16.873	0.002	0.206	0.003	5.701	0.309	4.628	0.175	3.064	0.394	0.048	0.015
V12	17.080	0.003	0.778	0.005	4.840	0.116	3.439	0.214	2.123	0.579	0.614	0.062
V13	16.634	0.005	0.212	0.006	2.980	0.226	5.381	3.318	4.253	1.276	0.141	0.029
V14	16.936	0.009	0.157	0.016	5.939	0.731	3.290	0.833	2.698	1.147	0.102	0.098
V16	16.630	0.008	0.231	0.012	0.234	0.273	0.005	1.019	2.495	1.603	0.203	0.052
V17	16.917	0.002	0.191	0.003	4.960	0.098	3.469	0.219	1.375	0.328	0.144	0.013

TABLE 5

FOURIER FITTING PARAMETERS FOR R LIGHT CURVES

Star	A_0	σ_{A_0}	A_1	σ_{A_1}	ϕ_{21}	$\sigma_{\phi_{21}}$	ϕ_{31}	$\sigma_{\phi_{31}}$	ϕ_{41}	$\sigma_{\phi_{41}}$	R_{21}	$\sigma_{R_{21}}$
V1	16.842	0.001	0.346	0.004	3.922	0.034	1.735	0.048	5.934	0.067	0.422	0.012
V2	...	...	...	...	...	...	...	...	...	...	...	...
V3	16.886	0.003	0.185	0.004	4.589	0.096	2.672	0.281	0.967	0.433	0.227	0.020
V4	16.912	0.004	0.181	0.005	4.264	0.125	2.912	0.221	1.482	0.578	0.246	0.028
V5	...	...	...	...	...	...	...	...	...	...	...	...
V6	...	...	...	...	...	...	...	...	...	...	...	...
V7	16.624	0.008	0.302	0.012	4.152	0.112	2.367	0.152	4.671	0.201	0.466	0.042
V8	16.823	0.005	0.157	0.007	3.750	0.259	1.906	0.498	0.351	0.676	0.191	0.044
V9	...	...	...	...	...	...	...	...	...	...	...	...
V10	16.826	0.002	0.168	0.003	4.797	0.186	3.671	0.290	2.935	0.566	0.093	0.016
V11	16.680	0.002	0.167	0.003	5.735	0.346	4.813	0.187	3.452	0.647	0.049	0.017
V12	16.822	0.020	0.676	0.035	0.676	0.096	3.748	0.200	2.281	0.577	0.586	0.051
V13	...	...	...	...	...	...	...	...	...	...	...	...
V14	16.752	0.004	0.126	0.006	3.429	0.408	5.622	0.591	1.271	0.728	0.129	0.053
V16	16.451	0.005	0.156	0.007	0.136	0.274	5.142	1.916	1.900	0.761	0.180	0.047
V17	16.724	0.002	0.158	0.003	4.948	0.142	3.437	0.248	1.392	0.572	0.145	0.020

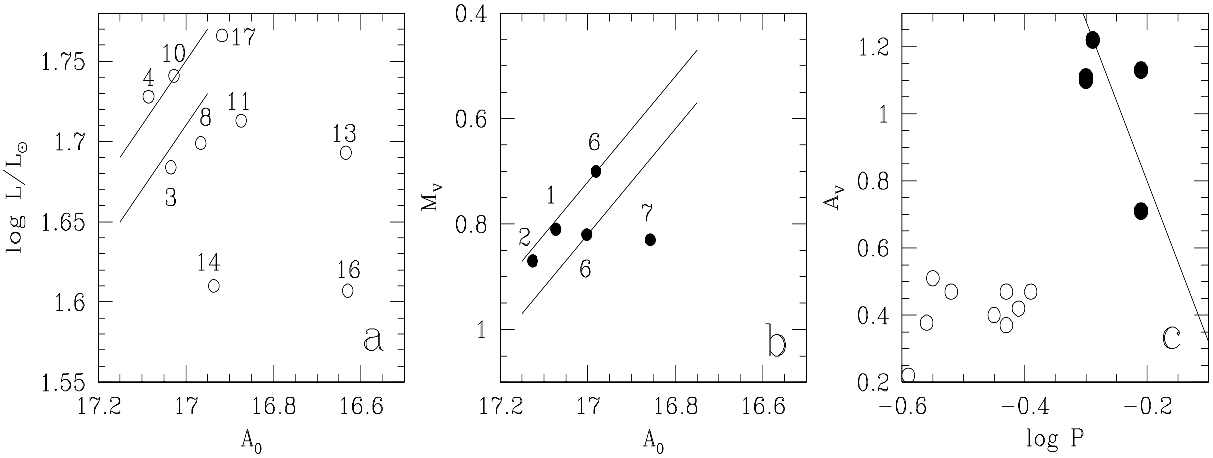

Fig. 8. Solid circles represent RRab stars and open circles RRc. In panels (a) and (b) a comparison is performed of the mean observed magnitude A_0 with the luminosity and absolute magnitudes derived from the calibrations. In panel (a) the lines have a slope of 0.4 and are separated by the estimated uncertainty in log $L/L_{\odot}$ of 0.04. In panel (b) the slopes are 1.0 and the lines are separated by the estimated uncertainty in 0.1 mag in M_V. In panel (c), A_V in the vertical axis is the full amplitude of the V light curve. The solid line is the mean locus of RRc stars in M3 estimated by Kaluzny et al. (1998).

general sequence. In particular [Fe/H]=−1.22±0.31, makes the rest of the parameters more consistent than they would be with [Fe/H]=−1.83 (Harris 1996) for the RRc stars.

4.3. *The Distance to NGC 4147*

The above results can be used to estimate the distance to the cluster. For the RRc stars, the luminosity values in Table 6 have been first transformed into M_V, also included in the last column of Table 6. In doing so, we have adopted the expression for the bolometric correction BC = 0.06[Fe/H]+0.06 (Sandage & Cacciari 1990) and taken ${M^{bol}}_{\odot} = 4.75$. To obtain the true distance modulus we have adopted $E(B-V) = 0.02$ (Harris 1996) and a total to selective absorption ratio R = 3.2. For the RRab star the M_V values in Table 7 obtained from the calibrations have been used to calculate the distance modulus. We find true distance moduli of 16.14 mag for the RRab star and 16.12 for the RRc stars, the average of which corresponds to a distance of 16.8±1.3 kpc, where the uncertainty is the standard deviation of the mean from individual stars. Our results place the cluster closer than the value 19.3 kpc reported by Harris (1996).

4.4. *On the Evolutionary Stage of RRab Stars in NGC 4147*

In Figure 9 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 are an extrapolation to lower luminosities of the Cepheid instability strip of Sandage & Tammann (1969). The dashed lines are the strip predicted by the models of Marconi & Palla (1998). The short continuous lines are the empirical fundamental mode instability strip found by Jurcsik (1998) from 272 RRab stars, and as pointed out by her, the band is very narrow and more inclined than that predicted by hydrodynamical model calculations. The discrepancy is attributed to poorly selected parameter combination and defects of the convection treatment in the hydrodynamical models. The 5 RRab stars in NGC 4147 fall within its bounds. For the Blazhko variable V6 two positions have been plotted, for two Blazhko phases of different amplitudes. The low amplitude case (asterisk in the figure) is clearly standing out from the rest of the RR ab stars. The theoretical zero age horizontal branch (ZAHB) is also shown from the RRab models of Lee, Demarque, & Zinn (1990) for two chemical mixtures, $(Y = 0.20; Z = 0.0001)$ and $(Y = 0.23; Z = 0.0007)$. These two ZAHB's lie above the RRab stars; however, the estimated value of the relative abundance of helium for our RRab sample is $Y = 0.28$, for which a model is not available. Since the luminosity of the ZAHB decreases with increasing Y, an extrapolation of Lee et al.'s (1990) models to larger values of Y would make the ZAHB match the distribution of RRab stars. This implies that these RRab stars have not yet evolved from the ZAHB. According to Jurcsik (1998), the

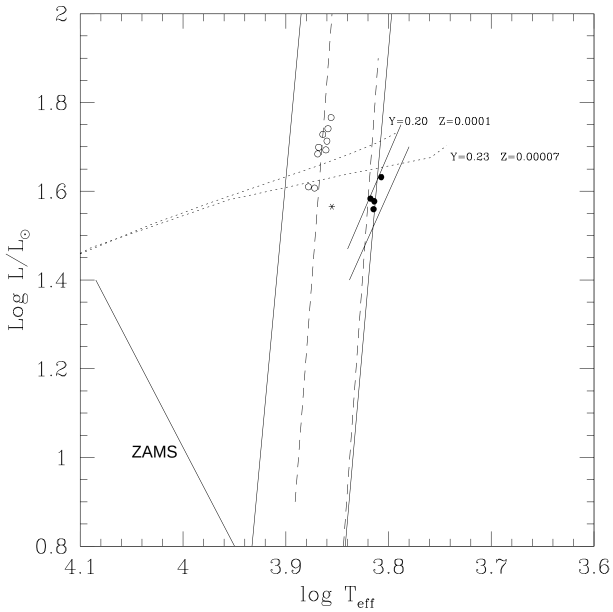

Fig. 9. Solid circles represent RRab stars and open circles RRc stars. The solid lines are the extrapolation from the Cepheid instability strip of Sandage & Tammann (1969). The dashed lines define the theoretical instability strip of Marconi & Palla (1998). The short solid lines indicate the empirical bounds found by Jurcsic (1998) from 272 RRab stars. Two models of the ZAHB (Lee et al. 1990) are shown and labeled with the corresponding metallicities. An extrapolation of these models to values of $Y = 0.28$ would place the RRab stars near the ZAHB. The ZAMS is also shown as reference (see text for discussion).

most extreme metal defficient globular clusters show RRab stars evolved from the ZAHB and therefore having longer periods. However the mean period for RRab in NGC 4147 is 0.524 days, consistent with its Oosterhoff type I, the milder metal defficiency found in this paper ([Fe/H] = −1.22±0.31) and the non-evolved nature of the RRab stars.

5. CONCLUSIONS

We have presented V and R-band CCD photometry for 18 RR Lyrae variables in NGC 4147, 17 of which were previously reported as variables (Clement 1997). We find however that V5, V9, and V15 do not show variations in the course of our observations. We have discovered a new variable, V18, for which we have determined a period of 0.49205 days, but it is 4.43 magnitudes brighter than the expected value for a cluster RR Lyrae star, and thus it may be a foreground RRc variable projected against the cluster.

The Blazhko effect has been encountered in the variables V2 and V6 and is most likely present in

TABLE 6

PHYSICAL PARAMETERS FOR THE RRc STARS

Star	$M/M_\odot$	$\log(L/L_\odot)$	T_{eff}	Y	M_V
V3	0.65	1.684	7404.	0.28	0.76
V4	0.72	1.728	7310.	0.26	0.74
V8	0.71	1.699	7380.	0.27	0.77
V10	0.60	1.741	7236.	0.26	0.69
V11	0.46	1.713	7250.	0.28	0.60
V13	0.39	1.693	7266.	0.29	0.72
V14	0.53	1.610	7553.	0.31	0.71
V16	0.31	1.607	7439.	0.33	0.83
V17	0.61	1.766	7177.	0.26	0.65
Mean	0.55	1.693	7335.	0.28	0.72
σ	±0.14	±0.054	±119	±0.02	±0.07

TABLE 7

PHYSICAL PARAMETERS FOR THE RRab STARS

Star	$[Fe/H]$	T_{eff}	M_V
V1	−1.285	6571	0.81
V2	−1.285	6526	0.87
V6	−1.501	6414	0.70
V6[a]	−0.687	7164	0.82
V7	−1.343	6516	0.83
Mean	−1.220	6633	0.80
σ	±0.311	±257.	±0.06

[a]Two solutions from two Blazhko phases of distinct amplitudes.

V13. For V6, the several times of maximum observed indicate a time scale of about 62 days for the Blazhko amplitude modulation.

We find NGC 4147 to be of Oosterhoff type I. From the Fourier parameters of 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 0.54 $M_\odot$ and 7334 K respectively, $\log(L/L_\odot) = 1.694$ and a mean relative abundance of helium $Y = 0.28$. For the RRab we find $T_{\rm eff} = 6633$ K, [Fe/H] $= -1.22$ and $M_V = 0.81$. The metallicity and distance of the cluster are thus estimated as [Fe/H] = −1.22±0.31 and 16.8±1.3 kpc, i.e., less metal defficient and closer than previously

TABLE 8

MEAN PHYSICAL PARAMETERS OBTAINED FROM RRc STARS IN GLOBULAR CLUSTERS

Cluster	Oosterhoof Type	[Fe/H]	Number of Stars	$M/M_\odot$	$\log(L/L_\odot)$	$T_{\rm eff}$	Y	M_V
NGC 6171	I	−0.68	6	0.53	1.65	7447	0.29	0.65
NGC 4147[a]	I	−1.22	9	0.54	1.694	7334.	0.28	0.72
M5	I	−1.25	7	0.58	1.68	7338	0.28	0.61
M5	I	−1.25	14	0.54	1.69	7353	0.28	
M3	I	−1.47	5	0.59	1.71	7315	0.27	0.55
M9	II	−1.72	1	0.60	1.72	7299	0.27	0.33
M55	II	−1.90	5	0.53	1.75	7193	0.27	
NGC2298	II	−1.90	2	0.59	1.75	7200	0.26	0.47
M68	II	−2.03	16	0.70	1.79	7145	0.25	0.38
M92[b]	II	−1.87	3	0.64	1.77	7186	0.26	0.68
M15	II	−2.28	6	0.73	1.80	7136	0.25	0.37
M15[c]	II	−1.96	10	0.74	1.80	7139	0.25	0.71

[a]This work;[b] Martín (2002); [c] García (2004), otherwise from Kaluzny et al. (2000).

TABLE 9

MEAN PHYSICAL PARAMETERS OBTAINED FROM RRab STARS IN GLOBULAR CLUSTERS

Cluster	Oosterhoof Type	Number of Stars	$[Fe/H]$	$T_{\rm eff}$	M_V
NGC 6171	I	3	−0.91	6619	0.85
NGC 4147[a]	I	5	−1.22	6633	0.81
NGC 1851	I	7	−1.22	6494	0.80
M5	I	26	−1.23	6465	0.81
M3	I	17	−1.42	6438	0.78
M55	II	3	−1.56	6325	0.68
M92[b]	II	5	−1.87	5596	0.67
M15[c]	II	15	−1.96	5500	0.89

[a]This work;[b] Martín (2002); [c] García (2004), otherwise from Kaluzny et al. (2000).

reported. Furthermore, when compared with other globular clusters, both RRab and RRc stars place NGC 4147 at the correct place in the sequences first forseen by Clement & Shelton (1997), in the sense that Oosterhoff type I clusters are less metalic than those of type II and the mean temperature increases with decreasing iron content.

The temperatures and luminosities for the RRab stars are consistent with those found by Jurcsik (1998) for the large sample of 272 RRab stars. A comparison with the ZAHB models of Lee et al. (1990), suggest that these stars have not yet evolved from the horizontal branch, which is consistent with the Oosterhoff type I of the cluster and the mean metallicity derived from the Fourier decomposition of their light curves.

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