Bulgarian Journal of Physics **28** Nos 3/4 (2001) 175–184

VARIABLE STARS IN THE OUTER-HALO GLOBULAR CLUSTER PALOMAR 3

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Abstract. We present the time-series V and I photometry of the outer-halo globular cluster Palomar 3, which has been obtained with a purpose of providing the extensive CCD variability study of this cluster. As a result, we have confirmed the variability of the RR Lyr star candidate of Burbidge and Sandage (1958), the RR Lyr star suspected by Gratton and Ortolani (1984) and the Population II Cepheid. Seven new suspected variables are presented. For the first time we determine the period $P = 3.402$ days and the light curve of the Population II Cepheid. As well known, Population II Cepheids are usually found in clusters with well-developed blue-HB tails only, so their presence in such a red-HB cluster as Palomar 3 is extremely puzzling.

PACS number: 97.30.-b

1. Introduction

Obtaining complete samples of RR Lyr variables in Galactic globular clusters is a very important observational task. The pulsation characteristics of these variables reflect the values assumed by their underlying physical parameters (mass, luminosity, temperature, chemical composition), and thus provide a sensitive tool to analyze the physical properties of horizontal-branch (HB) stars. Moreover, knowledge of the "real" number of RR Lyr variables in a globular cluster is required for the computation of the HB morphology parameters, such as $(B - R)/(B + V + R)$, which are usually employed in the analysis of the second-parameter problem.

Palomar 3 is an outer-halo $R_{GC} \simeq 89.9$ kpc, metal-intermediate [Fe/H] $\simeq -1.66$, red-HB (Dickens type 6), loose $c \simeq 1.0$, and relatively faint $M_V \simeq -5.5$ cluster (see [5]). A preliminary study of Palomar 3 has been published by Burbidge and Sandage [1]. They have found one variable star. Gratton and Ortolani [4] identified three RR Lyr stars and one possible Population II cepheid. They were not able to confirm the variability of the Burbidge-Sandage star. Later on 1999 Stetson et al [12] confirmed the variability status of Burbidge-Sandage and Gratton-Ortolani variable stars and suspected other 4 RR Lyr stars.

The limited number of variability studies for this cluster has ecouraged us to undertake a new survey of Palomar 3 to search for short-period variables. Special motivation for our study was provided by the noted possible presence of a Population II Cepheid in a red-HB cluster such as Palomar 3. As well known, Population II Cepheids are usually found in clusters with well-developed blue-HB tails only (see e. g. [10, 13]).

2. Observations and Data Reduction

Our analysis was based on approximately 50 CCD frames obtained during 6 nights: three in January 1997 at the 1.54 m telescope operated by the Steward Observatory, University of Arizona (1024×1024 pixels CCD, scale 0.38 arcsec/px), one night in February 1997 at the 2 m telescope of NAO "Rozhen", Bulgaria (375×242 pixels CCD, scale 0.32 arcsec/px), one in April 1999 at Steward Observatory and one in April, 2000 at NAO "Rozhen". The frames were obtained through V and I filters, and the exposure times for the frames varied between 6 and 15 minutes. The photometric reductions ware carried out using the DAOPHOT/ALLSTAR package [11] available in IRAF. Approximately 350 stars were identified on each frame and their instrumental magnitudes were determined. Following the method described in [3], we have selected one of the frames as a reference. The magnitudes determined for the other frames were converted by a first order least-squares fit to the reference frame system. The instrumental values were transformed to the standard (V, I) system by observing the standard field of M67 [2]. The errors from photometry and calibration are smaller than 0.07 for magnitude interval between 19 and 21 in V and I filters.

3. Search for Variable Stars

In our search for undetected variables we have used the following different methods.

3.1. Method of Kadla and Gerashchenko

The method proposed by Kadla and Gerashchenko [6] is based on the analysis of the color-magnitude diagram obtained from measurements of two images taken within a time interval that is much shorter than the variability period. Thus the variables are at nearly identical phases and have to be located in the RR Lyr "gap". This method is suitable for the identification of RR Lyr candidates only. Applying this technique we confirmed the variability of the Burbidge and Sandage [1] candidate RR Lyr star (hereafter BS) and found five new suspected variables, all within 1 arcmin from the cluster center.

Table 1. Candidate variables: Kadla and Gerashchenko method

Name	X (arcsec)	Y (arcsec)	V	$V-I$	R (arcmin)
V1	−3.2	−2.3	20.27	0.75	0.06
V2	15.8	4.1	20.73	0.75	0.27
V3	−57.3	14.2	20.34	0.81	0.98
V4	25.7	18.6	20.61	0.78	0.53
V5	−60.7	35.0	20.62	0.87	1.17
BS	−28.4	−5.0	20.25	0.82	0.48

The candidate variables are given in (Table 1). In columns 2 and 3 of Table 1 the coordinates in arcsec of the new possible variables in the Sawyer-Hogg [9] system are listed. The next two columns give V and $V-I$ values, determined by only one image pair. R is the projected radial distance (in arcmin) from the cluster center.

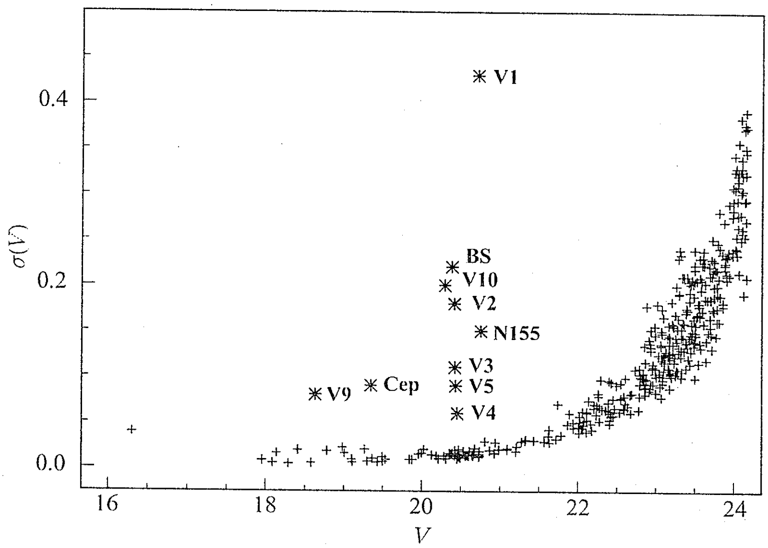

Fig. 1. Plot of the standard deviation vs. mean V magnitude
Possible variable stars are plotted as asterisks and the nonvariables as crosses

3.2. Comparison of the Brightness Variations

We determined the mean magnitudes and their standard deviations for the entire sample of stars. Naturally, the variables are expected to show much larger variations than the non-variable stars with the same brightness (Fig. 1). We found four additional candidates, including the Population II Cepheid, and the RR Lyr (No 155) suspected by Gratton and Ortonali [4]. The 4σ criterion would reject V4 and V5, found by the previous method. Table 2 lists the mean magnitudes and their variation for all the candidates, and for comparison, the typical observational uncertainties for the relevant magnitude interval. A plot of the standard deviation versus mean magnitude is shown in Fig. 1.

Table 2. Candidate variables: standard deviations of the magnitudes

Name	$\langle V \rangle$ "variables"	σ	$\langle V \rangle$ "normal stars"	σ
V1	20.71	0.43	20.5-21.0	0.03
V2	20.41	0.18	20.0-20.5	0.02
V3	20.42	0.11	20.0-20.5	0.02
V4	20.45	0.06	20.0-20.5	0.02
V5	20.43	0.09	20.0-20.5	0.02
BS	20.38	0.22	20.0-20.5	0.02
No 155	20.75	0.15	20.5-21.0	0.03
Pop. II Ceph.	19.34	0.09	19.0-19.5	0.01
V9	18.63	0.08	18.5-19.0	0.01
V10	20.29	0.20	20.0-20.5	0.03

3.3. Night-to-night Variations in the V Magnitude

As a further attempt to test the variability of the suspected stars we analyze night-to-night variations in the V magnitude. In Table 3 are given the mean magnitudes for the possible variables from three sets of observations. These stars present variations which are much larger than the variations of nonvariable stars of similar magnitude.

3.4. Variable Search Technique of Welch and Stetson

The availability of CCD observations in two filters separated by one month allowed us to apply the search technique of Welch and Stetson [14]. As described by these authors, "... the largest fraction of the flux change from a pulsating variable is due to the change in surface brightness-effective temperature, and hence the change in magnitude and color between any two epochs is correlated". *Nonvariable stars* have to be located near the origin in the diagram $V_1 - V_2$ versus $I_1 - I_2$ (where indices 1 and 2 indicate the values measured in two different epochs), with dispersion equal to the errors of observations. The *variable stars*, on the other hand, have to be correlated in such a diagram.

Table 3. Candidate variables: night-to-night variations in V

Name	JD 244+		
	50466.59	50467.53	50490.54
V1	21.06	20.38	20.27
V2	20.22	20.62	20.73
V3	20.26	20.56	20.34
V4	20.45	20.44	20.61
V5	20.48	20.48	20.62
BS	20.25	20.66	20.25
No 155	20.82	20.71	20.62
Pop. II Ceph.	19.26	19.41	19.44
V9	18.63	18.70	18.72
V10	20.13	20.54	20.44

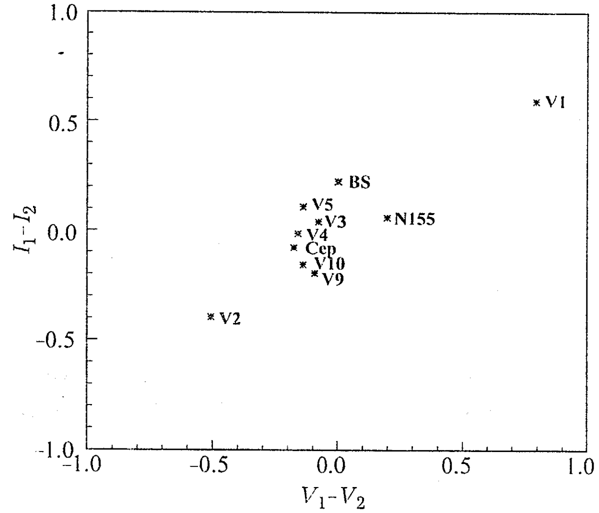

Fig. 2. The plot of $V_1 - V_2$ vs. $I_1 - I_2$
The indices 1 and 2 indicate the observations in January and February 1997, respectively

The magnitude differences $V_1 - V_2$ versus $I_1 - I_2$ for all possible variables of Palomar 3 are shown in Fig. 2. The indices 1 and 2 stand for the observations from January and February 1997, respectively. We have found that magnitude differences $V_1 - V_2$ and $I_1 - I_2$ of the candidate variables do seem to be correlated, although the correlation is not very strong. The locations of V3 and V4 are very close to $V_1 - V_2 = 0$ and $I_1 - I_2 = 0$, the region populated by nonvariable stars.

As a further attempt to test the variability of the stars we calculated the variability index I and variability ratio R of Welch and Stetson [14] for all stars in common between the two epochs. The variability index I is connected with changes in the brightness of the star in the two bandpasses and should be averaged zero for *nonvariable stars*. Each variable star will produce a variability index with a constant value, related to the amplitude of variation. Additional information of the nature of variation gives variability ratio R which is connected with temperature amplitude of the star.

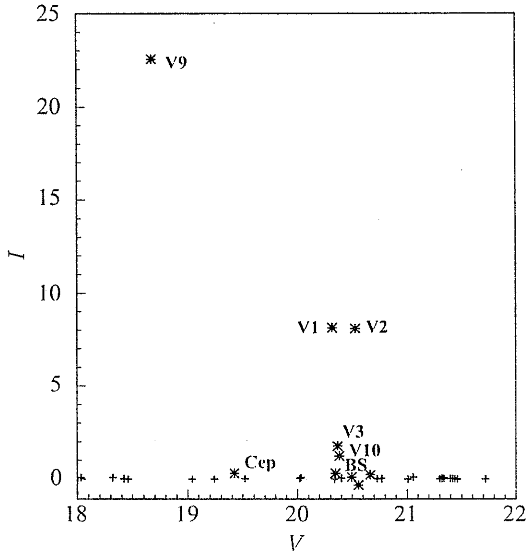

Fig. 3. A plot of the variability index I as a function of the average V magnitude The possible variable stars are plotted as asterisks and the nonvariables as crosses

Unfortunately, because of the small field of the CCD in our February 1997 run we have only 30 stars in common between two epochs. A plot of the variability index I as a function of the average V magnitude is shown in Fig. 3. The mean V magnitude, variability index I, variability ratio R and values of $I\sin(\arctan R)$, $I\cos(\arctan R)$ [14] for all suspected variable stars are given in Table 4. As can be seen, there are differences in the variability index and ratio of possible variables and nonvariable stars. The mean threshold of the nonvariable stars is $I = 0.2$ and $R = 0.1$.

Analysis of Table 4 shows that V1, V2, V9, V10, BS and the Population II Cepheid are as strong candidates, and leaves V4 and V5 bellow the 4σ statistical limit.

Table 4. Candidate variables: variability index I (Welch and Stetson)

Name	$\langle V \rangle$	I	R	$I\sin(\arctan R)$	$I\cos(\arctan R)$
V1	20.32	8.12	0.33	2.59	7.69
V2	20.54	8.08	1.60	6.85	4.28
V3	20.36	1.77	2.07	1.59	0.77
V4	20.49	0.12	23.68	0.12	0.00
V5	20.55	−0.31	1.21	−0.23	−0.19
BS	20.34	0.32	1.74	0.27	0.15
No 155	20.66	0.23	3.03	0.22	0.07
Pop. II Ceph.	19.42	0.31	2.14	0.28	0.13
V9	18.67	22.55	0.72	13.22	18.27
V10	20.38	1.23	1.13	0.92	0.82

According to Welch and Stetson [14] R ratio contains information about the contamination of stellar flux by fainter objects. They pointed that while a contamination by an object bluer than the variable would not change the R, a contamination by a redder one would increase the R. In our case there is no contamination of the Population II Cepheid by unresolved faint object. The variability ratio of most of the possible RR Lyr stars fall in the range from 1.13 to 2.07. The variable star V4 has a very large R value. We have no explanation for this result. The large R value for star No 155 can be explained with contamination by an unresolved companion.

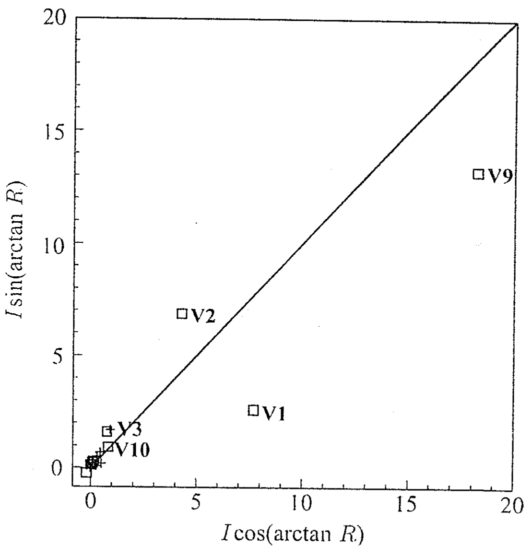

Fig. 4. A plot of $I\sin(\arctan R)$ vs. $I\cos(\arctan R)$ for all stars in common between the two epochs Possible variable stars are shown as squares

Figure 4 shows a plot of $I\sin(\arctan R)$ vs. $I\cos(\arctan R)$ which reveals probable variability and classification information directly. The nonvariable stars are concentrated near the origin of the plot. The position of V9 in this diagram suggests that this star may be a red variable.

4. Light Curves

We searched the periods using a least-squares periodogram analysis by means of the phase dispersion minimization (PDM) task available in IRAF and a period-finding program based on Lafler and Kinman's [8] "theta" statistic. For the first time we have obtained the light curves and periods for 3 variable stars in Palomar 3: the Population II Cepheid has period $P = 3.402$ days, V1 and RR Lyr star No 155 from Gratton and Ortolani have periods $P = 0.567184$ and $P = 0.624152$, respectively. Unfortunately, the small number of CCD frames and very irregular time intervals did not permit us to obtain representative light curves and periods for the remaining suspected variables.

The V light curves are displayed in Figs 5 and 6.

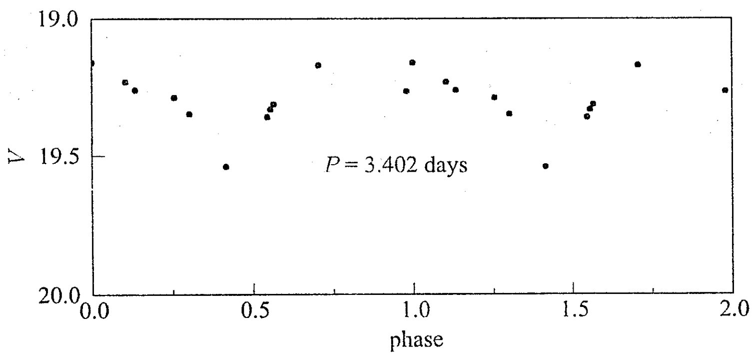

Fig. 5. The light curve of the Population II Cepheid

5. Summary

Using different techniques to search for variable stars in the globular cluster Palomar 3, we have reached the following conclusions:

- the RR Lyr star candidate from Burbidge and Sandage [1] was confirmed;
- we confirm the variability of the Population II Cepheid and determine the period $P = 3.402$ days;
- the RR Lyr star suspected by Gratton and Ortolani [4] has period $P = 0.624125$ days and is RRab Lyr type of star;
- the star V1 is also RRab Lyr type of star and has period $P = 0.567184$ days;
- V9 is probably a red variable;
- the status of V3, V5 and V10 remains uncertain.

The finding chart for the possible variables is shown in Fig. 7.

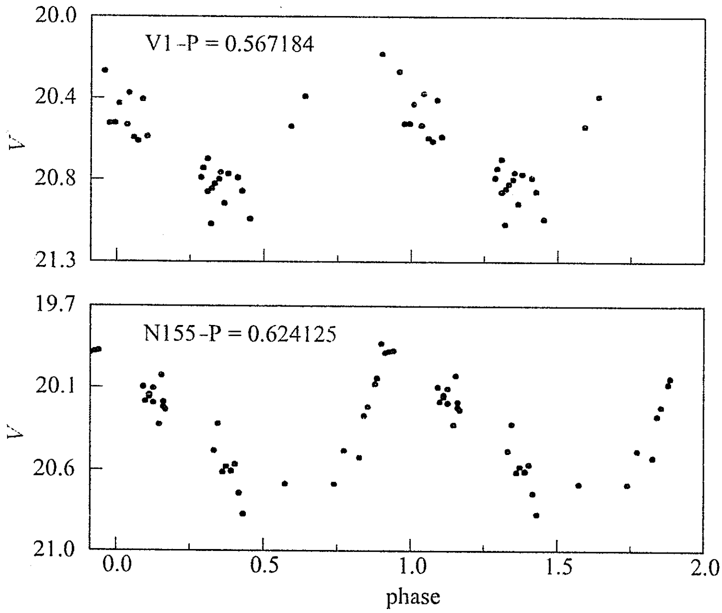

Fig. 6. The light curves of the V1 and No 155

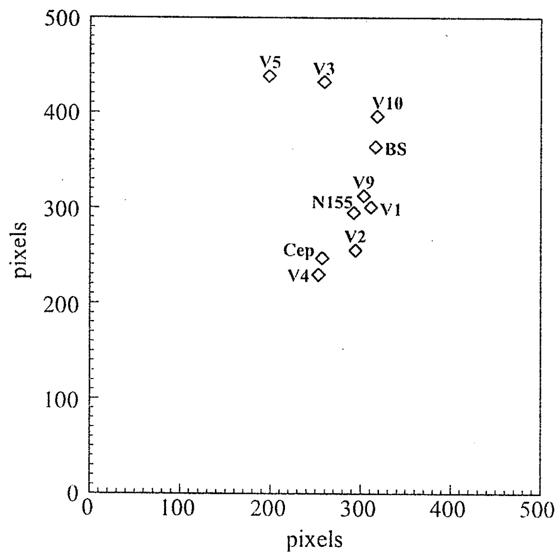

Fig. 7. Finding chart of the possible variable stars in the globular cluster Palomar 3
The size of the field is 3.98 arcmin. North is down and East is to the right

Acknowledgements

This research was supported in part by the Bulgarian National Science Fund grant under contract No F-812/1998 with the Bulgarian Ministry of Education and Sciences.

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