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CCD photometry of the globular cluster Palomar 13

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Abstract. A new CCD photometry of the halo cluster Palomar 13 is used to construct a color − magnitude diagram in the Thuan−Gunn and the B, V photometric systems[1]. The color−magnitude diagram of the cluster shows as already noted by Ortolani et al. (1985) an extremely poor red horizontal branch and a very sparsely populated giant branch. Seven BSS candidates are identified in the field of Palomar 13. The age of the cluster determined by fitting with the isochrones of Proffitt & Vanden Berg (1991) and Bergbusch & Vanden Berg (1992) and by a differential comparison of the color−magnitude diagram with that of Pal 5 is 12 $\pm$ 2 Gyr.

Key words: globular clusters: individual: Palomar 13 — Hertzprung — Russel diagram

1. Introduction

The study of the color-magnitude diagram of globular clusters gives a large amount of information regarding their age, composition, location and history, as well as information on the galactic evolution. In particular the study of the remote globular clusters is important to describe the actual and past structure of the outer halo of the Galaxy.

The Palomar clusters are a group of sparse, low-mass globular clusters identified by Abel (1955). They generally lie at large galactocentric distance and have a low integrated absolute magnitude, very low surface brightness, large core and tidal radii and predominantly red horizontal branch populations.

Palomar 13 is a typical representative of the Palomar class clusters. A preliminary study of the cluster was published by Ciatti et al. (1965). In 1985 Ortolani, Rosino and Sandage have published the B and V magnitudes of 122 stars which have been determined by examining plates obtained at the prime focus of the Hale telescope by means of a PDS microphotometer.

This paper presents the first CCD photometry of the central (2.0×1.5 arcmin) region of Palomar 13 performed in the BV Johnson photometric system and a photometry of the wide-field (7.7×5.1 arcmin) in the Thuan−Gunn system. The purpose of our work is to study some details of the color−magnitude diagram and to determine the absolute and differential age of the cluster.

2. Observations and data reduction

The observations of Palomar 13 were made using the 2 m RCC reflector of the Bulgarian National Astronomical Observatory. The images in Gunn system − (g, r) filters − were taken with the Focal Reduser of the Max Plank Institute for Aeronomy (Jockers et al. 1992). An EEV 576×385 CCD type $P8603/B$ was used as a detector. The telescope/reducer configuration and the CCD's square 22 μm pixels provide an image scale of 0.8 arcsec/px for an unvignetted field of about 7.7×5.1 arcmin at an effective focal ratio $f/2.86$.

The frames in B, V system were taken with the SBIG Model ST−6 camera. The detector is 375×242 pixels, the scale is 0.30×0.34 arcsec per pixel and the image size is about 2.0×1.5 arcmin. This camera was kindly granted by the EAS/ESO support of astronomy in the Central/Eastern Europe countries.

Table 1. The journal of observations

Data	Filter	Total Exp. Time (sec.)	Air mass
24.11.92	g	630	1.20
24.11.92	r	600	1.40
02.08.94	V	1500	1.20
02.08.94	B	2100	1.18

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[1] Tables 6 and 7 only available in electronic form at CDS.

During the nights of observations the seeing was stable with measured stellar PSF on the raw frames about $0.8 - 1.2$ FWHM arcsec.

A log of the observations is given in Table 1. The airmasses listed there are the mean airmasses over the duration of each exposure.

The preliminary reductions of the CCD frames including bias subtraction and flat fielding were carried out using the standard MIDAS (ver.92) data reduction package. No cosmic ray cleaning was done.

The photometry of the stars on the frames was performed by means of the point−spread function (PSF) fitting package DAOPHOT available in MIDAS (Stetson 1987). This package is widely used and there are numerous references describing the application of the package in details in addition to the description provided by Stetson. We followed closely the steps described in Smith et al. (1986) to produce a list of objects with PSF−derived magnitudes. The magnitudes were then corrected on the basis of a 10 pixels radius aperture. To determine the value of this correction we selected a range of 10 to 15 bright, relatively isolated and well−fitted stars per frame and carried out aperture photometry on the selected stars. The mean difference between the magnitudes derived by the PSF fitting and the magnitudes derived by the 10 pixels radius aperture for the selected stars was subtracted from the PSF derived magnitudes for all objects measured on the frame. We then rejected:

1. All stars which were not found on two or more independent frames in each color.
2. All stars which had values of $\chi^2 > 2$.
3. All stars with formal errors from the PSF fitting greater than 0.15 in all frames.

Table 2. Summary of calibration observations

Data	24.11.92	02.08.94
seeing (Arcsec)	1.2	0.8
No. standards	3	11
$g - r$ Slope	0.037	–
g Color Term	0.023	–
$B - V$ Slope	–	1.092
V Color Term	–	0.017
σ (g)	0.023	–
σ ($g - r$)	0.017	–
σ (V)	–	0.016
σ ($B - V$)	–	0.020

The instrumental values were corrected for extinction and transformed to the standard B, V and g, r systems using a technique similar to that described by Christian & Heasley (1986) − the instrumental magnitudes m were converted to the standard scale M by means of the equation:

$$M = m + a - bX + c(B - V) \tag{1}$$

where a is a constant, X is the airmass and $(B - V)$, res. $(g - r)$ is the color of the object. The coefficients (Table 2) were determined by reducing the frames of the standard fields in NGC 7006 (Christian et al. 1985) and the three standard stars selected from the list of Thuan & Gunn (1976), using an aperture photometry algorithm. The rms. deviations of the reduced CCD photometry from the standard values are 0.016 in V, 0.02 in B, 0.023 in g and 0.017 in r over the range of standards. A certain inaccuracy of the zero point in the g, r system is possible due to the insufficient number of the used standards. This inaccuracy was however estimated to be within the standard photometry error and thus could not seriously affect the results of our study.

Tables 6 and 7 (available in electronic form) list our final photometric results for 80 stars in the central field of Palomar 13 in the B, V system and 175 stars in the g, r system. The star identifications in these tables are as follows: identification number; x, y - the $(x,\ y)$ positions give the locations of the stars in pixel terms. Columns g, $g - r$, V and $B - V$ are the weight averaged magnitudes and colors taken from all available data.

Table 3. The mean standard deviations

Magnitude	g	r	V	B
14−15	0.017	–	–	–
15−16	0.017	0.012	–	–
16−17	0.021	0.015	0.012	0.015
17−18	0.023	0.017	0.014	0.018
18−19	0.032	0.021	0.020	0.025
19−20	0.035	0.025	0.023	0.027
20−21	0.044	0.025	0.027	0.031
21−22	0.044	0.031	0.035	0.039

Table 3 lists the derived mean standard deviations for successive intervals of one magnitude in the g, r, V and B frames.

3. Comparison with previous works

Two previous photometric studies of Palomar 13 are available in the literature: a preliminary study of the cluster published by Ciatti et al. (1965) and photographic data published by Ortolani et al. (1985). In order to check our data for any systematic variations the photometry of

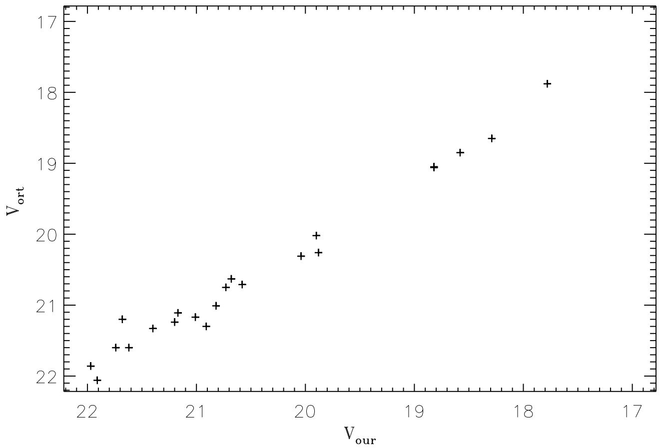

Fig. 1. Comparison between V magnitudes derived here and photometry of Ortolani et al. (1985)

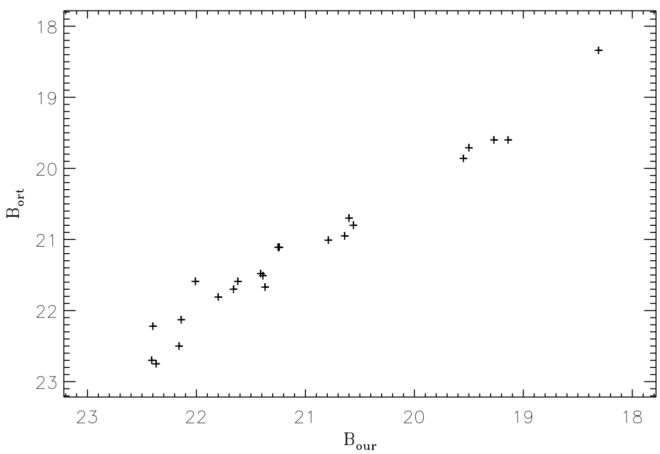

Fig. 2. Comparison between B magnitudes derived here and photometry of Ortolani et al. (1985)

Ortolani et al. (1985) has been used. Figures 1 and 2 show a comparison of the V and B magnitudes in our CCD photometry with those obtained with Ortolani et al. (1985). No systematic magnitude shift in the B and V have been found. There are significant differences for the faintest stars only (the stars No. 77 and No. 61 in list of Ortolani et al. 1985).

To outline the bright parts of the CMD still better we added the RGB, SGB and the turnoff stars from the study of Ortolani et al. (1985) to our B, V photometry. This was done by calculating the coefficients of a linear transformation on the basis of all common stars and then applying this transformation to all stars in Ortolani's list that were to be added to our photometry. The mean standard deviations of this transform are $\sigma(V) = 0.18$ and $\sigma(B-V) = 0.09$.

4. Color − magnitude diagrams

4.1. Color − magnitude diagram in B, V system

The V, $B-V$ color-magnitude diagram for Palomar 13 derived in this study is shown in Fig. 3. The stars within 24 arcsec of the cluster center (1 core radii, Djorgovski 1993) are presented by crosses. The core of the cluster was well resolved and all stars down to $V = 21.5$ mag ($n = 47$) were measured.

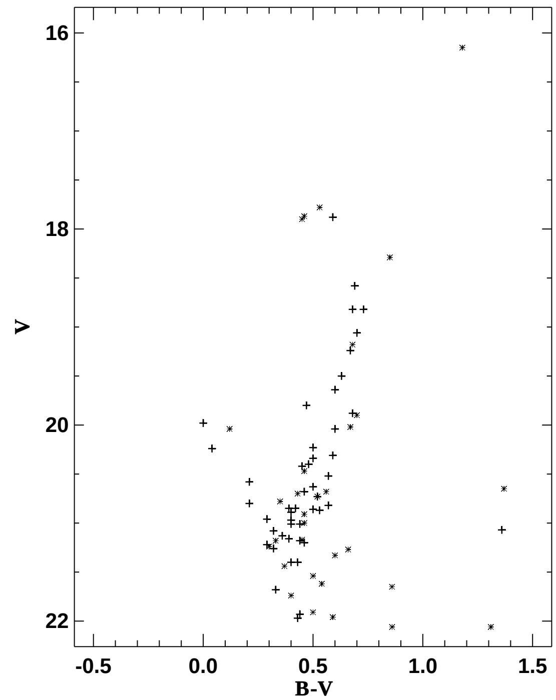

Fig. 3. The observed V vs. $B-V$ color-magnitude diagram of Palomar 13 based on all stars listed in Table 6. The stars within 1 core radii are represented by crosses

In Fig. 4. is shown the composed CMD based on our CCD data (crosses) and the photographic data of Ortolani et al. (1985) transformed to our photometric system. It contains 154 stars, covering 5×5 arcmin area around the cluster.

The basic characteristics of the CMD are:

1. An extreme poorness of the horizontal branch (HB) which is populated by only one star ($V = 17.78$ mag) in addition to the three RR Lyr variables in our field.
2. A sparsely populated, moderately steep red giant branch (RGB) and a full lack of the red giants in the cluster's core (see Fig. 3). All bright giants are located at a distance $r > 1$ arcmin from the center of the of the cluster.
3. A well defined subgiant branch and upper main sequence turnoff region. As can be seen in the Fig. 3 the subgiants are the brightest stars in the core of the cluster.

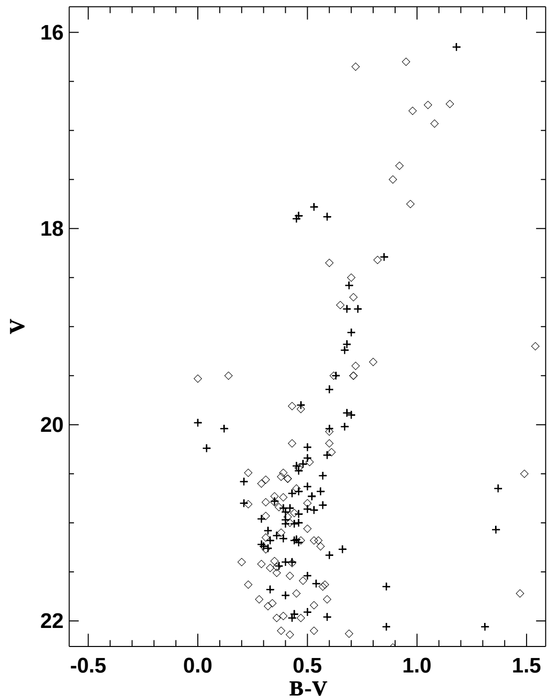

Fig. 4. The observed V vs. $B-V$ color-magnitude diagram of Palomar 13 based on stars listed in Table 6 (crosses) and stars added from study of Ortolani et al. (1985) (open squares)

Table 4. BSS candidates

No	x	y	V	$B-V$	g	$g-r$	Distance (arcmin)
1	218.0	150.1	20.04	0.12	19.73	−0.22	0.6
2	273.7	180.7	20.24	0.04	19.62	−0.22	0.3
3	263.0	190.0	20.58	0.21			0.3
4	281.0	239.0	20.80	0.21			0.3
5	309.7	212.3	19.98	0.00	19.42	−0.40	0.1
6*	246.8	256.0			19.67	−0.14	0.4
7*	67.6	315.9			19.68	−0.13	0.4

* the coordinates are in the g, r coordinate system.

4. A number of stars form an extension of the main sequence up to about 1.5 mag brighter than TO point. These are possible blue straggler stars (BSS). Seven BSS candidates are identified in our field. Careful checks was made to ensure that the internal errors of the BSS candidates are the same as those of the subgiants at the same level. According to the galaxy model of Ratnatunga & Bahcall (1985) the predicted number of field stars (0.2 stars at $19 < V < 21$ and $(B-V) < 0.8$) is not sufficient to explain this population. Ortolani et al. (1985) don't mention the presence of BSS candidates but two of them can be seen on their color−magnitude diagram. The BSS candidates lie at $r < 38$ arcsec from the cluster center and four of them are in the core of the cluster. It is obvious that the BSS candidates present a marked tendency to populate the central part of the cluster. Comparison with other clusters of Palomar group (Pal4, Pal5, Pal14 and Pal15 − Fusi Pecci et al. 1992) shows that Palomar 13 can be included in class BS1 (Fusi Pecci et al. 1992). Data for BSS candidates in Palomar 13 − magnitudes, colors and distances from the cluster center are separately listed in Table 4.
5. The main sequence turnoff is found to be at $V_{\rm TO} = 21.15 \pm 0.06$ and $(B-V)_{\rm TO} = 0.35 \pm 0.04$. The magnitude level of the HB determined as the magnitude of the nonvariable star is $V_{\rm HB} = 17.78 \pm 0.02$ (the error is the internal error of the photometry). The magnitude level of the HB determined as mean magnitude of the RR Lyr variable stars is $V_{\rm HB} = 17.88 \pm 0.012$. Lee et al. (1990) found that the mean V magnitude of the red HB would be $0.1-0.2$ mag. brighter then that of the RR Lyrae variables. The agreement between the apparent magnitude of the horizontal branch determined as a magnitude of the nonvariable star and mean magnitude of the RR Lyr stars is good. This implies a magnitude difference between the HB and the TO $\Delta V_{\rm TO}^{\rm HB} = 3.37 \pm 0.1$.
6. There are no Palomar 13 stars in the asymptotic giant branch (AGB) phase of evolution.

4.2. Color − magnitude diagram in g ,r system

The g, $g-r$ color−magnitude diagram for 175 stars measurable on the Focal Reducer of the Max Plank Institute of Aeronomy CCD images is presented in Fig. 5. Because of the smaller scale of the Reducer only 25 stars have been measured in the core of the cluster. The CMD in g, $g-r$ verified the main features of the V, $B-V$ CMD and especially:

1. Ortolani et al. (1985) noted that the existence of some “evaporated” HB stars can not be excluded. In our field -7.7×5.1 arcmin we have not found such stars. There is only one star (No. 46 in Table 7) above the HB in our g, $g-r$ diagram which has an uncertain status.
2. No more BSS candidates have been identified in this region. There are two stars on the diagram which fall in the region of the BSS candidates. One of them (No. 83 in Table 7) is a contact star and its photometry is poor, another (No. 164 in Table 7) is located too far from the center of the cluster ($r = 3.9$ arcmin) so we mean that it is more probable a field star. There is some discrepancy of the status of two of the BSS candidates listed in Table 7 (No. 168 and Ort 24). According g, r photometry they are subgiant stars. More precise photometry is needed for these stars.
3. The main sequence turnoff is found to be at $g_{\rm TO} = 21.12 \pm 0.05$ and $(g-r)_{\rm TO} = -0.14 \pm 0.02$. The magnitude level of the HB determined as the magnitude of the nonvariable star is $g_{\rm HB} = 17.84 \pm 0.03$ (the error is the internal error of the photometry). The magnitude level of the HB determined as the

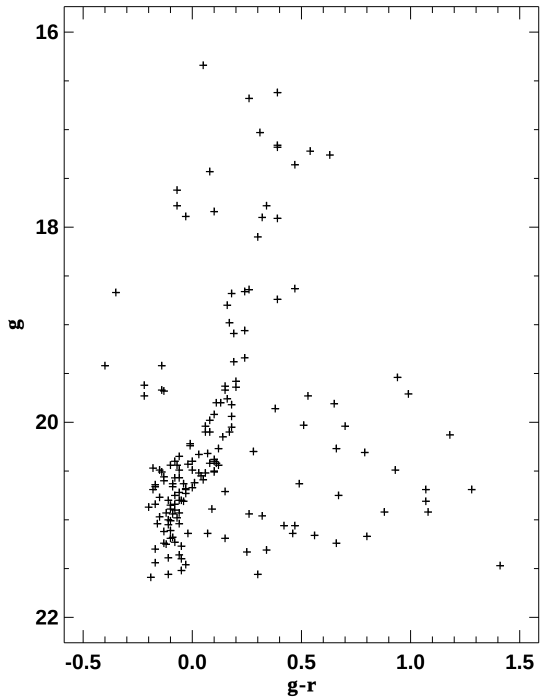

Fig. 5. The observed g vs. $g - r$ color−magnitude diagram of Palomar 13 based on all stars listed in Table 7

mean magnitude of the RR Lyr variable stars is $g_{\rm HB} = 17.76 \pm 0.12$.

The models of Ratnatunga & Bahcall (1985) have been used to estimate how many field stars are predicted in the region of Pal 13. The observed CMD has been statistically decontaminated by applying the procedure described in Ferraro et al. (1995). The analysis of the CMDs for Palomar 13 in the two photometric system allows us to separate 158 cluster members brighter than $V = 22$ mag, including 4 variable stars and 51 field stars.

The fiducial lines of the main branches of Pal 13 have been determined from the statistically corrected CMD by dividing the various sequences into bins and computing in each bin the mode of the distribution color.

4.3. Metallicity and distance modulus

The cluster metallicity can be estimated by means of an appropriate calibration of RGB observations. $(B - V)_{0,\rm g}$, the intrinsic RGB color at the level of the HB in the Zinn & West (1984) calibration gives [Fe/H] $= -1.52 \pm 0.23$. The observed color $(B - V)_{\rm g}$ is 0.86 ± 0.05 where the error has been estimated by combining the error made in merely locating the point with the photometric error. We have adopted 0.05 at $E(B - V)$ (Harris & Racine 1979). The derived metal abundance by Ortolani et al. (1985) is between -1 and -1.5, a result consistent with our estimate.

We estimate the distance modulus of Palomar 13 by assuming the calibration of Lee (1990): $M_V^{\rm HB} = 0.19$ [Fe/H] $+ 0.97$. For [Fe/H] $= -1.52$ this gives $M_V^{\rm HB} = 0.681$. The apparent magnitude of the HB is $V = 17.78 \pm 0.02$ and thus the apparent distance modulus is $(m - M)_V = 17.10 \pm 0.02$ (internal uncertainty only). As can be seen below the distances derived from the isochrone fitting are quite consistent with this estimate.

5. The age of Palomar 13

The determination of globular cluster ages continues to be an active field of research. There are two widely applied methods used to estimate cluster ages − isochrone fitting and differential measures through careful comparisons of the location of the principal stellar sequences on the CMD.

For the isochrone fitting we used the isochrones computed by by Proffitt & Vanden Berg (1991) using a [O/Fe] ratio of between 0.75 and 0.40, which include the effect of He diffusion and the isochrones by Bergbusch & Vanden Berg (1992), which adopted a [O/Fe] ratio between 0.75 and 0.23. We also compared the Bell & Vanden Berg (1987) theoretical isochrones with the CMD morphology of the turnoff region in g, r system.

The ψ^2 parameter of Flannery & Johnson (1982) was used as a fitting statistics and we calculated this parameter for $E(g - r)$ between $(0.01 - 0.1)$, 16.5 $< (m - M)_0 <$ 17.5, $-2.27 <$ [Fe/H] < -1.27 and age between $(10 - 16)$ Gyr.

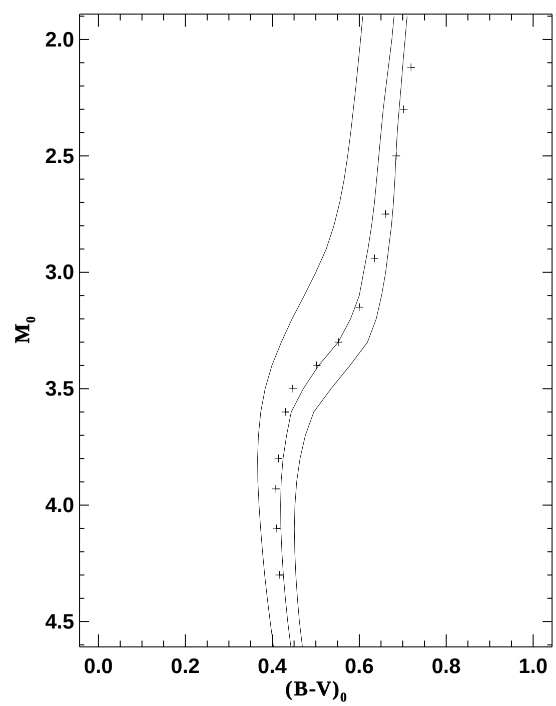

Fig. 6. Comparison of the Proffitt & Vanden Berg (1991) theoretical isochrones (solid curves) with fiducial line of Palomar 13 (crosses) for [Fe/H] $= -2.26$, -1.66 and -1.26 for an age of 12 Gyr. Palomar 13 data have been corrected for a distance modulus of 17.23 mag and reddening 0.05

The best statistics was reached for a cluster age of 12 Gyr, with metallicity [Fe/H] $= -1.66$ at the isochrones by Proffitt & Vanden Berg (1991). The implied distance modulus derived from the comparison with the isochrones is 17.23 with $E(B-V) = 0.05$. The best fit isochrones are shown in Fig. 6. There is a large disagreement between the theoretically calculated isochrones and the red giant branch.

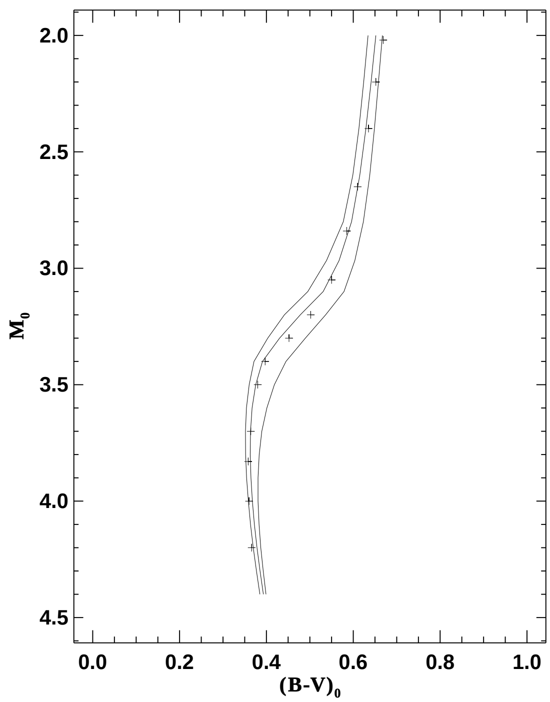

Fig. 7. Comparison of the Bergbusch & Vanden Berg (1992) theoretical isochrones (solid curves) with fiducial line of Palomar 13 (crosses) for [Fe/H] $= -1.78$, -1.66 and -1.48 for an age of 12 Gyr. Palomar 13 data have been corrected for a distance modulus of 17.19 mag and reddening 0.05

Figure 7 shows a comparison between the theoretical isochrones of Bergbusch & Vanden Berg (1992). The best statistics was reached for a cluster age of 12 Gyr, with metallicity [Fe/H] $= -1.66$, [O/Fe] $= +0.63$. The implied distance modulus derived from the comparison with the isochrones is 17.19 with $E(B-V) = 0.05$.

When was made a comparison between the different sets of isochrones it was found that the diffusive isochrones did not fit the observations as well as the nondiffusive ones.

The similar result -12 Gyr, [Fe/H] $= -1.52$, $(M-m) = 17.20$ and $E(g-r) = 0.07$ was found by using isochrones of Bell & Vanden Berg (1987) calculated in g, r system (Fig. 8).

Due to some uncertainties in the locations of the fiducial points, $E(B-V)$ and [Fe/H] the total external uncertainty at this method is 3 Gyr (Bolte 1990).

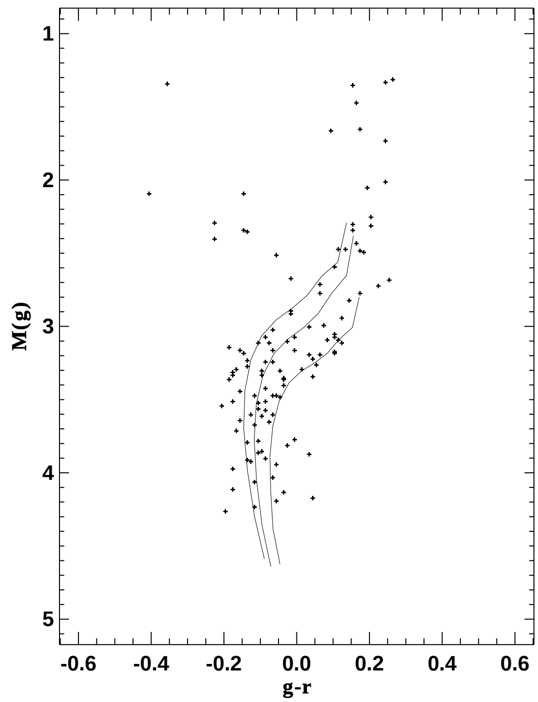

Fig. 8. Comparison of the Vanden Berg & Bell (1987) theoretical isochrones (solid curves) with the color−magnitude diagram of Palomar 13 (crosses) for metal abundance [Fe/H] of -2.27, -1.77 and -1.27 for age of 12 Gyr. Palomar 13 data have been corrected for a distance modulus of 17.20 mag and reddening 0.07

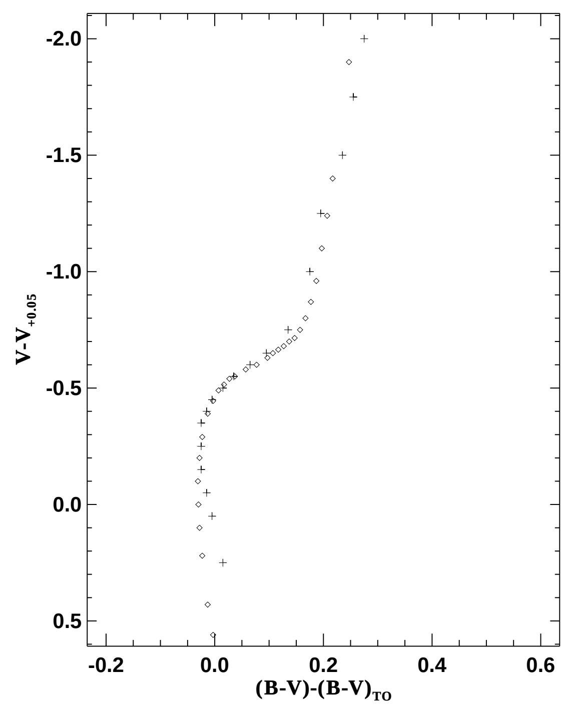

Fig. 9. Fiducial sequences for Palomar 13 (crosses) and Palomar 5. The clusters were shifted to a common reddening and distance

A second approach to determine an age of Palomar 13 was made using calibration of Chaboyer et al. (1992) (see their formula 1). Assuming [Fe/H] $= -1.52$ and $\Delta V_{\rm TO}^{\rm HB} = 3.37$ we have calculated $t_9 = 11.94 \pm 1.7$.

Table 5. Δt consistency test for Palomar 13

ref. cl.	[Fe/H]	Δ	δ	$\Delta \log t_9(\Delta)$	$\Delta \log t_9(\delta)$
MPC	−2.00	0.18	0.039	0.101	−0.11
M 3	−1.70	0.16	−0.004	0.093	0.011
NGC 362	−1.30	0.05	−0.008	0.058	0.026
Rup 106	−1.90	−0.17	−0.002	−0.025	0.005
Arp 2	−1.84	0.02	0.002	0.007	−0.005
Pal 5	−1.47	0.03	−0.004	0.011	0.013

According to resent work of Buonanno et al. (1993), Buonanno et al. (1995a, b) we used the "vertical" method, based on the magnitude difference between the horizontal branch and the main sequence turnoff and the "horizontal" method based on the color difference between the base of RGB and the main sequence turnoff. We will consider the same reference clusters as Buonanno et al. (1995) for Arp 2. The necessary data for all objects are listed in Table 5. The TO−to−RGB color difference for Palomar 13 is 0.25 ± 0.02 The error was computed using the procedure suggested by Vanden Berg et al. (1990) in which parabolic arcs are fit to stars in appropriate boxes in the color − magnitude diagram. The comparison with M 3, NGC 6752, Rup 106, Arp 2 and MPC − the metal−poor clusters in the table produces inconsistent age differences. Consistent differential ages are obtained in comparison with Pal5 (Smith et al. 1986) (Fig. 9). The estimated error is approximately 2 Gyr.

6. Conclusions

We have presented g, r, B and V CCD observations of the halo globular cluster Pal 13.

The cluster is very sparsely populated and the horizontal branch is extremely peculiar. A sequence of candidates for blue stragglers can be seen on the color−magnitude diagrams.

An age of 12 ± 2 Gyr has been found using various methods. This estimate puts Palomar 13 in group of so−called "young" globular clusters like Pal 12 (Gratton & Ortolani 1988; Stetson et al. 1989), Ruprecht 106 (Buonnano et al. 1990; Buonnano et al. 1993), Terzan 7 (Buonnano et al. 1995b), Arp 2 (Buonnano et al. 1995a). Further photometry extended to fainter magnitudes is necessary to confirm this.

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