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A CCD BVI color-magnitude study of the metal-rich globular cluster NGC 5927⋆,⋆⋆

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Abstract. — We present for the globular cluster NGC 5927 the first multicolor CCD photometry that reaches below the cluster's main sequence turnoff. The turnoff is located approximately at $V_{\rm TO} = 20\overset{\rm m}{.}1$, $(B-V)_{\rm TO} = 1\overset{\rm m}{.}18$, $(V-I)_{\rm TO} = 1\overset{\rm m}{.}30$. There is a hint of horizontal branch morphology variations with distance from the cluster center. Using the isochrones of VandenBerg & Bell (1985), we derive the cluster age to be about 15 Gyr.

Key words: globular clusters: individual: NGC 5927 — HR diagram

1. Introduction

The solution of one of the most fundamental astrophysical problems, that of the Galaxy's formation, is tightly connected with a thorough study of globular clusters of the disc, especially such properties as their ages and composition. Such clusters also provide an important test of evolution theory for old metal-rich populations. However, for a number of reasons, studies of these objects using precise CMDs, potentially an extremely important source of information, are rather scanty. Even now, after a number of careful photometric studies of disc globulars (Armandoff 1988; Friel & Geisler 1991; Ortolani et al. 1990, 1992; Bica et al. 1994; Sarajedini & Norris 1994, and others), such objects, with a possible exception of 47 Tuc, remain considerably more poorly studied compared to halo clusters. This is especially true for age determinations.

This paper is devoted to an investigation of the disc globular cluster NGC 5927 ($\alpha_{1950} = 15^{\rm h}24\overset{\rm m}{.}4$; $\delta_{1950} = -50°29'$; $l = 326\overset{\circ}{.}6$; $b = +4\overset{\circ}{.}9$) on the basis of deep CCD BVI photometry. According to Zinn & West (1984), this is one of the most metal-rich ([Fe/H] $= -0.3$) disc clusters. Its first photographic photometry by Menzies (1974) and Alcaino (1979) revealed features of the CMD typical of metal-rich globulars: a flat giant branch, an extremely red horizontal branch overlapping the giant branch, and principal sequences showing large scatter, probably partially due to reddening variations. Sarajedini & Norris (1994) improved the values of the cluster's metallicity and reddening using their method of simultaneous determination from the CMD. They also determined the difference of V magnitudes between the horizontal branch and the red giant branch clump. We present in this paper the first CCD photometry of NGC 5927 reaching the cluster's main sequence and the results of its age determination; we also show evidence for and discuss suspected radial variations of the cluster's horizontal branch morphology.

2. Observations and reductions

Observations were made on 4 nights in February, 1988 (13/14, 14/15, 16/17, 20/21) at the Cassegrain focus of the 2.2 m Max-Planck-Institut telescope at ESO/La Silla. The CCD was an RCA laminated thinned back-illuminated chip, Type SID 501EX, consisting of 512×320 pixels. The telescope's $f/8$ beam provides a scale of $11.7''$/mm, and with pixel size 30×30 μm (0.36×0.36 arcsec), the total field is 3.1×1.9 arcmin. The center of the measured field (for all frames) is approximately in $1\overset{'}{.}6$ to the east and $0\overset{'}{.}4$ to the south of the cluster center. The seeing during the best night (February 20/21) was about $1''$, on the rest

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⋆Based on observations collected at the European Southern Observatory

⋆⋆Table 3 completely available in electronic form via anonymous ftp 130.79.128.5

of nights the seeing was variable and reached about 2″. The log of observations is presented in Table 1.

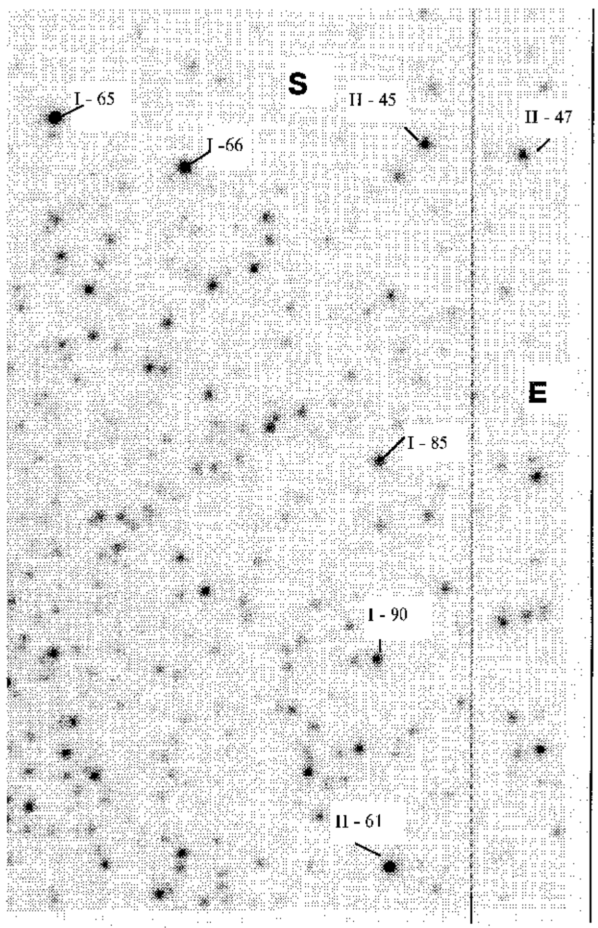

Fig. 1. A V frame of NGC 5927, with photoelectric standards marked

The majority of deep B and I frames were taken under very good weather conditions while the sequence of V frames were taken during variable seeing. Consequently, we decided to use the single deepest V frame, taken in moderately good seeing, for subsequent analysis in order to avoid deterioration of results caused by crowding problems owing to the poorer seeing.

In the reductions, we used photoelectric standards from Alvarado et al. (1995). As usual for CCD studies of the Isaac Newton Institute, we employed a photoelectric sequence established in the program field itself. Figure 1 reproduces a V frame of the measured field, with standards marked; the magnitudes and colors of the standards are listed in Table 2.

The reductions were done using the DAOPHOT II package in the frame of the system pcIPC, as described in our earlier publication (Samus et al. 1995). To convert our instrumental magnitudes and colors to the standard BVI_{C} system, we used reduction formulae derived from our data (for V magnitudes) and determined earlier (for colors; cf. Alcaíno et al. 1990) for the same telescope, CCD camera, and filters. The final formulae were:

$$V = v - 0.058(\pm 0.025) + 0.100(\pm 0.027)(b - v);$$

$$V = v - 0.042(\pm 0.035) + 0.081(\pm 0.035)(v - i);$$

$$B - V = 1.16(b - v) - 0.142;$$

$$V - I = 1.04(v - i) + 0.06.$$

The mean internal accuracy of our photometry for brighter cluster stars ($14 - 16^{\mathrm{m}}V$) is about $0\overset{\mathrm{m}}{.}02$ in all filters, gradually deteriorating to about $0\overset{\mathrm{m}}{.}08$ for the faintest stars.

Figure 2a, b shows the comparison (based on about 90 common stars) of our photometry with photographic photometry published by Menzies (1974). Slight systematic trends are noticeable for V magnitudes, those published by Menzies being, as a rule, brighter than ours; the

Table 1. Log of CCD observations

Filter	Exposure time (s); Number of exposures	Air mass
B	20; 3	1.11–1.39
	30; 3	
	60; 3	
	180; 3	
	540; 2	
	1080; 3	
V	20; 4	1.12–1.24
	60; 3	
	180; 3	
	540; 2	
	1080; 2	
I	5; 3	1.09–1.21
	10; 3	
	20; 3	
	60; 3	
	180; 2	
	540; 2	
	1080; 2	

Table 2. Data for photoelectric standards

Star	V	$B-V$	$V-I$
I–65	13.28	0.65	0.81
I–66	13.94	0.80	1.03
I–85	14.89	0.72	0.84
I–90	14.81	0.96	1.02
II–45	14.62	1.51	1.64
II–47	14.84	0.76	0.98
II–61	13.77	0.74	0.88

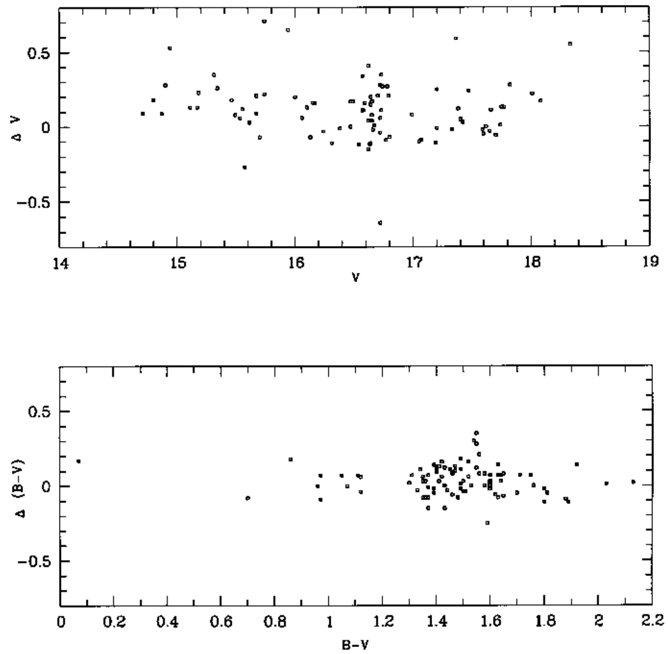

Fig. 2. Comparison with photographic photometry by Menzies (1974). **a)**: ΔV (Samus et al. minus Menzies) versus V (Samus et al.); **b)**: $\Delta(B-V)$ (Samus et al. minus Menzies) versus $(B-V)$ (Samus et al.)

agreement of $(B-V)$ color indices is very good. It is not possible to compare our photometry directly to that published by Sarajedini & Norris (1994) because their CCD field does not overlap with that measured by us. However, Fig. 9 in their paper (comparison of their photometry with Menzies) reveals quite the same effects as our Fig. 2, thus providing evidence for good agreement between our photometry and photometry by Sarajedini and Norris.

3. The CMD and its radial variations

The total number of measured stars (Table 3 [1]) is 4136. Since we used V magnitudes from a single frame, we present in Fig. 2 the $V-(B-I)$ diagram, prefering not to use the V band in the color index. However, it should be noted that the effects to be discussed below appear for any combination of magnitudes and color indices.

Figure 3a, b presents CMDs for two fields within the measured cluster area, with differing mean distance from the cluster center (the second field being more peripheral). Figure 3c is the combined CMD for all measured stars. Comparison of these diagrams shows that, when approaching the cluster center, the stars of the turnoff region and on the giant branch become systematically bluer. A similar effect was noted for the cluster NGC 6528 by Ortolani et al. (1992). They compared $V-(B-V)$ diagrams for the fields of this cluster situated at $\sim 1'$ and $\sim 3'$ distance from the center and found that the sequences of the first field were bluer than those of the second one by $\Delta(B-V)$ about $0\overset{m}{.}1$. The cited authors attributed this color difference to variations of reddening across the cluster field. The same effect found by us for another cluster raises doubts on such an interpretation (though the presence of reddening variations is quite possible for both clusters). The most natural explanation for the revealed phenomenon, in our opinion, would be photometric effects due to increased crowding towards the centers of the clusters. The behavior of the horizontal branch of NGC 5927 has the opposite pattern: the morphology of the horizontal branch changes depending on the distance from the cluster center; its red boundary, when approaching the cluster center, shifts towards the giant branch and probably overlaps it, the redder horizontal-branch stars being slightly fainter than the bluer ones. There is a hint of a

[1]Completely available in electronic form via an anonymous ftp copy at the CDS; data are represented here only for the first 30 stars, as a sample. For identification, note that, in the system of Table 3, the standards II-45 and II-47 have coordinates $x = 239.762$, $y = 77.709$, and $x = 295.709$, $y = 84.065$, respectively.

Table 3. CCD photometry in NGC 5927

No.	x	y	V	$B-V$	$V-I$
1	4.776	346.859	18.348	–	0.809
2	4.817	268.494	19.171	–	0.300
3	4.840	401.956	19.715	–	0.978
4	4.908	53.604	20.421	–	1.015
5	4.921	130.503	19.694	–	0.793
6	4.982	308.469	18.975	–	0.350
7	5.096	468.275	18.789	–	0.630
8	5.185	354.422	19.020	–	0.757
9	5.240	233.287	18.870	–	0.902
10	5.423	207.035	20.116	–	0.969
11	5.435	403.704	19.926	–	1.181
12	5.452	416.021	18.757	–	1.068
13	5.459	389.213	17.440	0.234	2.479
14	5.476	32.780	17.636	–	1.096
15	5.486	272.083	19.398	–	0.928
16	5.499	315.291	20.200	–	1.097
17	5.575	365.747	18.684	–	1.612
18	5.618	189.768	20.222	–	1.355
19	5.664	227.465	20.252	–	1.116
20	5.719	86.419	19.496	0.999	1.703
21	5.745	69.488	21.130	–	1.244
22	5.781	94.019	22.369	–	1.523
23	5.802	196.843	20.115	–	1.031
24	5.927	136.143	21.070	–	1.236
25	6.012	360.139	18.552	–	1.246
26	6.181	285.467	19.727	–	0.902
27	6.257	258.284	19.190	1.315	0.925
28	6.276	242.682	19.367	–	0.813
29	6.302	298.971	19.780	–	0.929
30	6.334	158.635	16.516	–	1.720

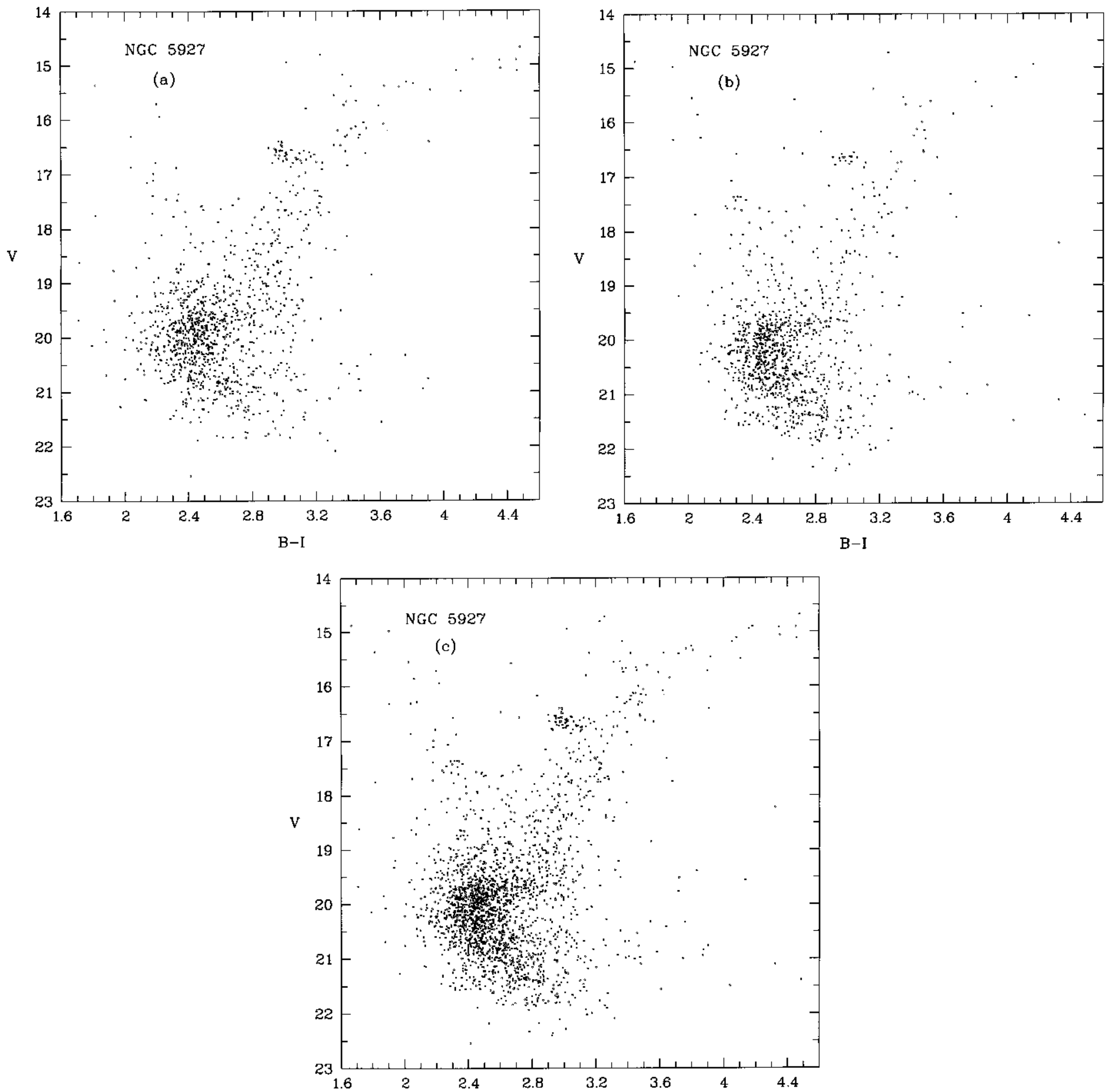

Fig. 3. Color-magnitude diagrams of the globular cluster NGC 5927: **a)** — for the western half of the field covered with CCD frames, closest to the cluster center; **b)** — for the eastern half of the field, more distant from the cluster center; **c)** — combined

bimodal distribution of stars along the horizontal branch. If we determine the red edge of what we will call the bluer "mode", at $B-I=3.07$ (see Fig. 3b), then the number ratio of red mode to blue mode stars is 2:14 for the peripheral half of the field and 11:30 for the inner half of the field. Included in the counts were stars within $\pm0\overset{\text{m}}{.}2$ of the mean level of the horizontal branch estimated as $V=16.7$, and with $B-I$ colors from approximately $2\overset{\text{m}}{.}9$ to the red boundary of the horizontal branch (its position is rather evident from the combined $V-(B-I)$ diagram, Fig. 3c, approximately at $B-I=3.2$). Note also that bright red giants are much better represented in the central part of the field.

In Fig. 3b the horizontal branch appears parallel to the abscissa, and there exists a gap separating it from the giant branch. But in Fig. 3a the horizontal branch shows a slope, and the gap disappears. While some of the detailed differences of the horizontal-branch behavior might be due to insufficient statistics, we stress the most important point: the nearer the cluster center, the redder becomes the horizontal branch of NGC 5927. Compare this to the above-mentioned opposite trend in colors of other sequences. The visual inspection of CMDs from Armandoff (1988) argues for this effect being real. The cited paper presents CMDs separately for inner and outer parts for several disc globulars. At least for 3 clusters (NGC 6316, 6342, and 6760), the horizontal branch in the central part of the corresponding cluster appears systematically redder, like for NGC 5927. Note that, according to Harris (1994), these clusters have the concentration parameter c from 1.55 to 2.50, whereas the three clusters not showing this effect (NGC 6496, 6539, and Pal 8) have c in the range from 0.70 to 1.60. The value of c for NGC 5927 is 1.60.

The effects revealed here could not arise from the contamination of the CMD with field stars. Though we have no measurements of comparison fields at our disposal, and the existing models of galactic populations are not very reliable at low galactic latitudes (where two neighboring fields can show drastically different densities of field stars), our estimates of field star densities using a code (J. Bahcall, private communication to Dr. O. Malkov), based essentially on the models by Bahcall & Soneira (1980), indicate that we cannot expect more than 1 field star in the whole CMD region occupied by the horizontal branch. This agrees with the visual impression from the CMD.

Sarajedini & Norris (1994) derived a relation between the horizontal branch mean color $< B-V >_0$ and metallicity from CCD photometry of 6 disc globulars. They note that the field horizontal branch stars with metallicities similar to those of the globular clusters are systematically redder. This might mean that the horizontal branch stars in the central regions of sufficiently concentrated disc globular clusters are photometrically more similar to field horizontal branch stars than the stars in outer cluster regions.

4. Age of NGC 5927

In order to avoid possible influence of crowding on photometric accuracy, we use for isochrone analysis the CMDs for the more distant parts of the cluster field. For the level of the horizontal branch we adopt $V = 16.7 \pm 0.1$. The diagrams $V-(B-V)$, $V-(V-I)$, $V-(B-I)$ with superimposed VandenBerg & Bell (1985) isochrones are shown in Figs. 4–6. (We would have used our more reliable $V-(B-I)$ diagrams with the more recent oxygen-enhanced isochrones from Bergbusch & VandenBerg (1992), but this color combination was not available.) All these diagrams lead to the position of the turnoff point close to $V = 20.1 \pm 0.1$. Thus, the

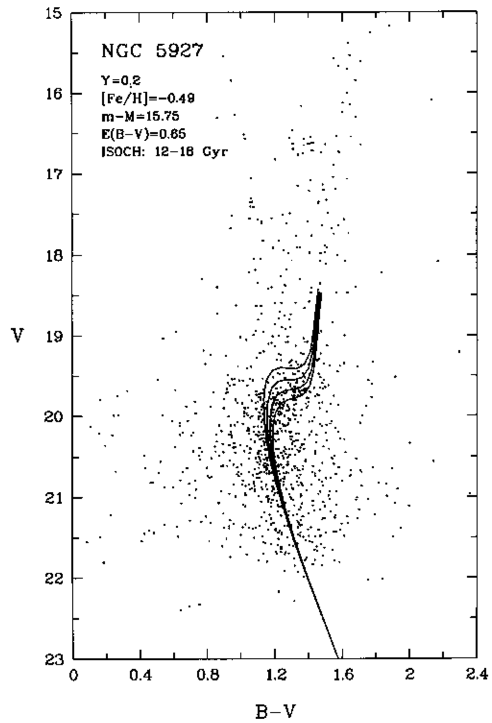

Fig. 4. The $V-(B-V)$ diagram of NGC 5927, with superimposed isochrones for [Fe/H] $= -0.49$, $Y = 0.2$, $m-M = 15.75$, and $E(B-V) = 0.65$, corresponding to age values 12, 14, 16, and 18 Gyr

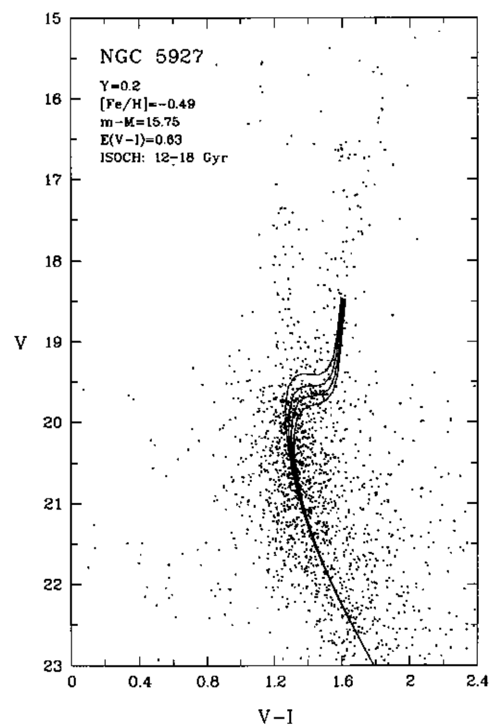

Fig. 5. The $V-(V-I)$ diagram of NGC 5927, with superimposed isochrones for $E(V-I) = 0.63$; the rest of the parameters are the same as in Fig. 4

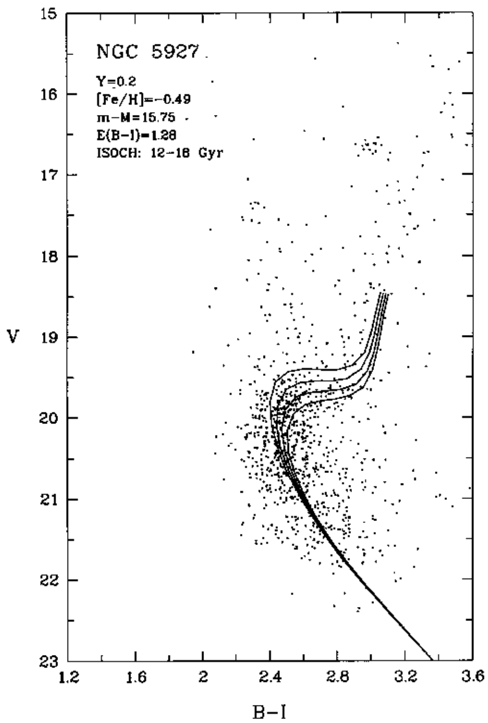

Fig. 6. The $V-(B-I)$ diagram of NGC 5927, with superimposed isochrones for $E(B-I)=1.28$; the rest of the parameters are the same as in Fig. 4

difference of V magnitudes between the turnoff point and the horizontal branch is $\Delta V = 3.4 \pm 0.14$ agreeing well with usually accepted values. The turnoff point colors are: $B-V=1.18$, $V-I=1.30$, $B-I=2.47$.

Zinn & West (1984) give for NGC 5927 [Fe/H] $= -0.3 \pm 0.09$, while from Washington photometry, Friel & Geisler (1991) find [Fe/H] $= -0.25 \pm 0.25$. A somewhat lower value, -0.41 ± 0.07, was found by Sarajedini & Norris (1994). We adopt the cluster's metallicity [Fe/H] $= -0.35$. The distance modulus, $m-M=15.75$, follows from the position of the horizontal branch and its absolute magnitude derived for the adopted metallicity using the relation from Harris (1994). The set of VandenBerg & Bell (1985) isochrones closest in metallicity is for [Fe/H] $= -0.49$.

Whereas the metallicity of NGC 5927 is known with sufficient confidence, the problem of helium abundances in metal-rich globular clusters is not solved yet. Bergbusch & VandenBerg (1992) adopt $Y=0.2454$ for their highest-metallicity isochrones ([Fe/H] $= -0.47$). The set of VandenBerg & Bell (1985) isochrones used in Fig. 3 has the value $Y=0.2$, somewhat closer to the above value than the alternative possibility, $Y=0.3$.

Having fixed the distance modulus, we find the values of color excess leading to the best CMD fit (providing the best agreement between the observed subgiant branch and the upper part of the isochrones) to be $E(B-V)=0.65$, $E(V-I)=0.63$, $E(B-I)=1.28$.

To estimate the cluster age, we use, first, the fact that the preferred isochrone is the one closest to that region of the CMD with the largest density of data points. However, a known important additional age indicator is the color range between the turnoff point and the lower giant branch. This means that, independent of the particular values of the distance modulus and reddening, we are able to select, from the set of isochrones with [Fe/H] and Y values most appropriate for the cluster, the isochrone best reproducing the "width" of the transition from the main-sequence turnoff to the lower giant branch.

Despite the large scatter of the presented CMDs, we find that the isochrone for the age value of 16 ± 2 Gyr seems to describe the observed sequences best for all our CMDs. The quoted error corresponds to the internal accuracy; it is a subjective estimate of the confidence level of the isochrone fit. It is difficult to determine accurately the influence of numerous other sources of error (of the chemical abundance uncertainties, errors in the distance modulus, uncertainties of the theory, etc.) upon the resulting age estimates.

Recently Minniti (1995) concluded that the mean helium abundance in the galactic bulge is $Y=0.28 \pm 0.02$, and the metal-rich globulars have similar Y values. Taking this into account, we also considered VandenBerg and Bell isochrones for $Y=0.3$. Their fit to the CMDs of NGC 5927 gives age estimates close to 14 Gyr. Keeping in mind the problem of the helium abundance, we suggest 15 Gyr as the most probable age estimate for NGC 5927.

5. Conclusions

1. We have obtained, for the first time, deep multicolor CCD photometry for the disc globular cluster NGC 5927. The main sequence turnoff is located approximately at $V_{\rm TO} = 20\overset{\rm m}{.}1$, $(B-V)_{\rm TO} = 1\overset{\rm m}{.}18$, $(V-I)_{\rm TO} = 1\overset{\rm m}{.}30$.

2. We find a hint of horizontal branch morphology variations with the distance from the cluster center: the horizontal branch becomes redder when approaching the cluster center.

3. The age derived for NGC 5927 from VandenBerg & Bell (1985) isochrones is about 15 Gyr. Thus, from our data we do not see any direct evidence that the age of the metal-rich disc cluster NGC 5927 is significantly lower than the ages of other globulars studied by us.

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