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Bright populations of the LMC cluster NGC 1978 from multicolor CCD photometry*

G. Alcaíno[1], **W. Liller**[1], **F. Alvarado**[1], **V. Kravtsov**[2], **A. Ipatov**[3], **N. Samus**[3], **and O. Smirnov**[3]

[1] Isaac Newton Institute, Ministry of Education of Chile, Casilla 8-9, Correo 9, Santiago, Chile
e-mail: inewton@reuna.cl

[2] Sternberg Astronomical Institute and Isaac Newton Institute Moscow Branch, 13, University Ave., Moscow 119899, Russia
e-mail: scorpi@sai.msu.su

[3] Institute of Astronomy of Russian Acad. Sci. and Isaac Newton Institute Moscow Branch, 48, Pyatnitskaya Str., Moscow 109017, Russia
e-mail: ipatov@inasan.rssi.ru, samus@sai.msu.su, oms@inasan.rssi.ru

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Abstract. We have carried out multicolor ($BVRI$) photometry for 3077 stars in the field of the populous cluster NGC 1978 in the Large Magellanic Cloud. We find a clear discrepancy in the zero point of our V magnitudes in NGC 1978 with earlier work (Bomans et al. 1995). A large sample of horizontal-branch stars (319 objects) has been isolated. Our study of color distributions of HB stars in different parts of the cluster reveals some variations of the shape of the distributions across the cluster face. We also find some difference in CMD positions of the lower giant branch dependent upon the position in the cluster. Thus, we do not exclude the presence of two subpopulations in NGC 1978; to explain the observations, a difference in [Fe/H] by $\sim 0.1 - 0.2$ between them would be sufficient.

Key words: galaxies: star clusters — Magellanic Clouds — clusters: globular: NGC 1978 (LMC) — HR diagram

1. Introduction

Star clusters of the Magellanic Clouds are, on average, less well studied than the bulk of the globular clusters of our Galaxy. At the same time, the rich populous clusters of the Magellanic Clouds, similar in the appearance to Galactic globulars, show a much wider range of ages, and therefore are especially interesting from the point of view of star formation and stellar evolution studies.

Among the populous star clusters in the Magellanic Clouds, of special interest are intermediate-age clusters with red horizontal branches: in our Galaxy, clusters with red horizontal branches are much older (approximately by ten billion years) and not sufficiently well-studied.

The Large Magellanic Cloud cluster, NGC 1978 ($\alpha = 5^{\rm h}28^{\rm m}44\overset{\rm s}{.}8$, $\delta = -66^\circ14'10''$, 2000.0) is a populous intermediate-age, red-horizontal-branch cluster immersed in a dense stellar field. Two detailed photometric studies have been devoted to this cluster. Olszewski (1984) published photographic BV photometry of cluster and field stars reaching slightly below the cluster main-sequence turnoff. The only multicolor CCD photometry of the cluster and surrounding field was carried out by Bomans et al. (1995). (The corresponding BV data for individual stars can be retrieved from Strasbourg Data Center as the electronic supplement to the paper of Will et al. 1995). In particular, these papers are in agreement in regard to estimates of the cluster's metallicity (-0.4 to -0.5 in [Fe/H]) and its age ($2 - 2.5$ Gyr). They also present detailed reviews of the earlier studies of the cluster.

We have obtained $BVRI$ CCD photometry of 3077 stars in a $5' \times 5'$ field including NGC 1978. In this study, we concentrate primarily on the morphology of the cluster's brighter sequences and its possible variation in different parts of the cluster field.

2. Observations and reductions

The observations reported on here were acquired on December 2 to 7, 1992, at the 2.2 m Max-Planck-Institute telescope of ESO, La Silla, with the EFOSC-2 camera. The detector was a Thompson THX 31156 CCD (1024×1024 pixels, 19×19 microns each, reduced to a 900×900 pixels window) with a readout noise of 9 e^- rms. The field covered was 5×5 arcmin, its center was positioned

Send offprint requests to: G. Alcaíno

approximately in 1.′5 north-north-east from the cluster center. A reproduction of the field can be found in Alvarado et al. (1993), Fig. 2 (Plate 96). A total of 12 frames in B light (exposure times — from 30 to 900 s), 13 frames in V (6 to 240 s), 12 frames in r (Gunn) (6 to 120 s), and 10 frames in i (Gunn) (10 to 180 s) were acquired. The seeing for most frames was from 1.0 to 1.5 arcsec.

The reductions of CCD photometry were performed at the Institute of Astronomy (Moscow) using the software described by us earlier (Samus et al. 1995) and based upon the DAOPHOT II ALLSTAR application (Stetson 1991). We reduced the photometric data to the standard $BV(RI)_{\rm C}$ system. The formulas taking into account the color terms of photometric reductions were derived by us using observations of the standard sequence in NGC 1978 itself (Alvarado et al. 1993).

The formulas used in this study are:

$$V = v + 0.083(\pm 0.014)(b - v) - 0.008(\pm 0.009),$$

$$V = v + 0.048(\pm 0.021)(v - i) - 0.014(\pm 0.021),$$

$$B - V = 1.349(\pm 0.014)(b - v) + 0.032(\pm 0.010),$$

$$V - R = 1.170(\pm 0.032)(v - r) - 0.051(\pm 0.015),$$

$$V - I = 1.031(\pm 0.010)(v - i) - 0.012(\pm 0.010).$$

These formulas are derived from observations of 7 stars covering a wide range of colors (-0.16 to 1.71 in $B-V$; -0.13 to 0.81 in $V-R$; -0.05 to 1.51 in $V-I$). The photoelectric magnitudes of the standards are well reproduced by our CCD data; this can be seen from Table 1 presenting photoelectric magnitudes and colors of the standard sequence along with residuals for our CCD values, expressed in the sense (Phe–CCD). Our first formula agrees well with the corresponding formula derived, for the same photometer, by Buonanno et al. (1993) (their $(b-v)$ coefficient is 0.084). However, the formula for $(B-V)$ following from Buonanno et al. would have a different $(b-v)$ coefficient (1.197). The reason for the discrepancy is not clear, taking into account the small error associated with our formula.

The internal accuracy of our magnitudes, for most stars, is: for $V \le 18$, $\sigma_B < 0.03$, $\sigma_V \approx \sigma_R \approx \sigma_I < 0.01$; for $V > 18$, $\sigma_B < 0.06$, $\sigma_V \approx \sigma_R \approx \sigma_I < 0.04$.

We have identified 332 stars of our sample with stars measured photographically by Olszewski (1984). Figure 1 shows the comparison of photometries. The agreement of V magnitudes is reasonably good, taking into account typical accuracy of photographic photometry. However, one can see systematic deviations in $B-V$ color, especially for blue stars. We also find some systematic trends of ΔV values with $B-V$, despite the abovementioned excellent agreement of our reduction formula for V with that from Buonanno et al. (1993).

Our investigation is the second $BVRI$ CCD study of NGC 1978, and a detailed comparison with photometry from Will et al. (1995) is of considerable interest. To compare photometric results, we used the data deposited in the Star Data Center in Strasbourg. Unfortunately, only V magnitudes and $B-V$ color indices are available for Will et al. (1995) photometry in NGC 1978 accessible electronically, whereas $BVRI$ photometry is discussed in Bomans et al. (1995). We have identified 1899 stars in common with Will et al. The comparison of photometries is illustrated by Fig. 2. Its striking feature is a large

Table 1. Data for photoelectric standards

Star	V	$B-V$	$V-R$	$V-I$
C	13.62	1.71	0.81	1.51
	+0.03	−0.02	+0.02	−0.01
E	13.92	0.08	0.05	0.20
	+0.02	−0.02	+0.01	−0.02
F	14.52	−0.16	−0.13	−0.10
	+0.01	+0.02	−0.04	+0.02
G	14.60	−0.08	−0.03	−0.05
	−0.02	+0.00	+0.03	−0.02
H	14.73	−0.02	0.06	0.18
	−0.01	−0.01	−0.01	−0.00
I	14.82	1.56	0.75	1.42
	−0.00	+0.02	+0.02	+0.01
J	15.33	—	0.75	1.64
	−0.08	—	−0.03	+0.00

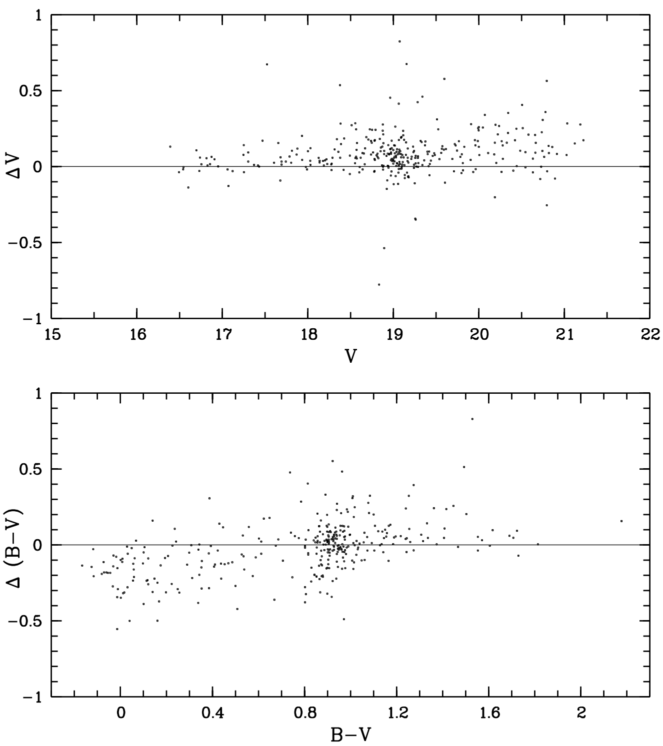

Fig. 1. Comparison of our photometry with that from Olszewski 1984. **a)** ΔV (present paper minus Olszewski) vs. V (present paper); **b)** $\Delta(B-V)$ (present paper minus Olszewski) vs. $B-V$ (present paper)

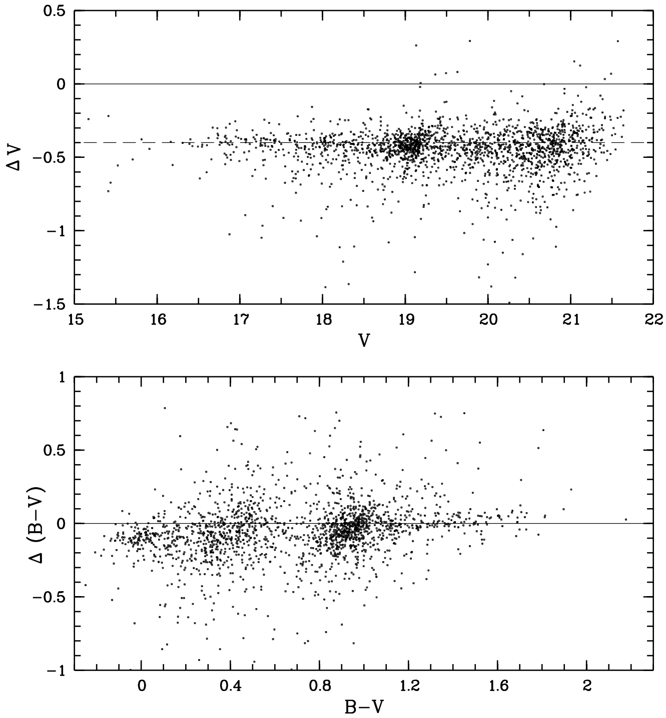

Fig. 2. Comparison of our photometry with that from Will et al. 1995. **a)** ΔV (present paper minus Will et al.) vs. V (present paper); **b)** $\Delta(B-V)$ (present paper minus Will et al.) vs. $B-V$ (present paper)

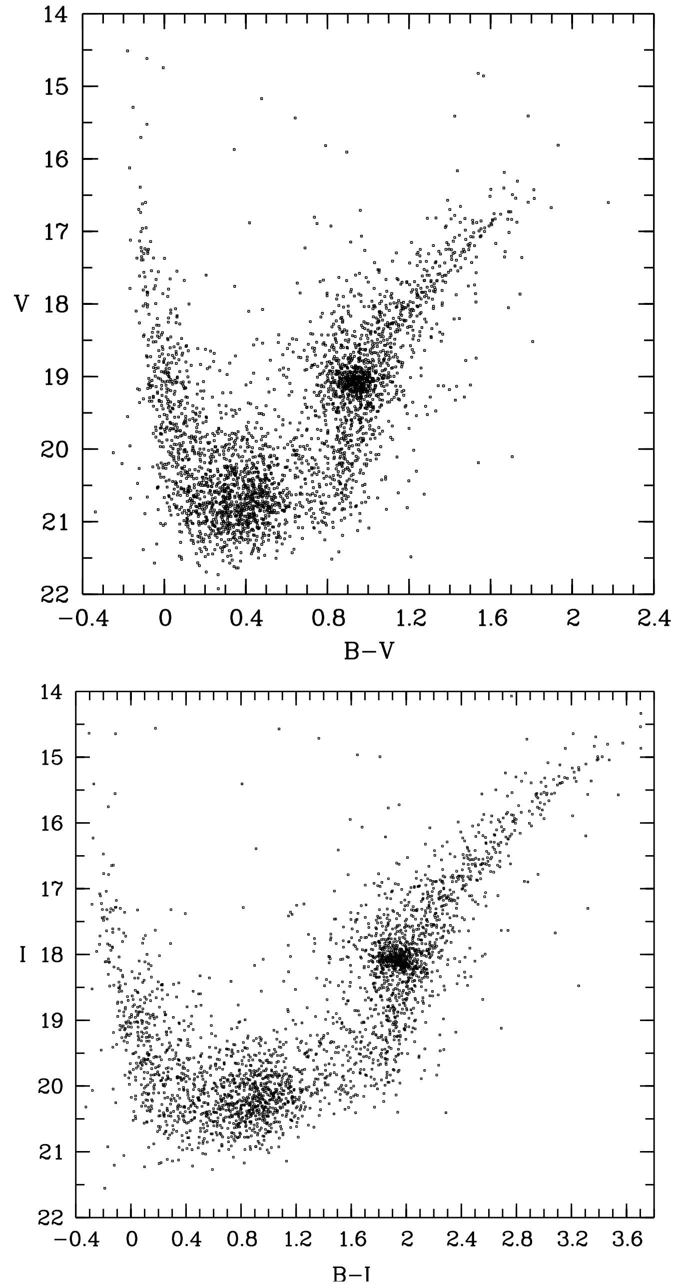

Fig. 3. a) The $V-(B-V)$ diagram and **b)** $I-(B-I)$ diagram based on our photometry of 3077 stars in the $5' \times 5'$ field around NGC 1978

difference of zero point in V magnitude, at least by $0\overset{\mathrm{m}}{.}4$, despite the photometry of Will et al. being based upon the photoelectric standards of Alcaíno & Alvarado (1988), created with the same equipment as the standards used by us (Alvarado et al. 1993). The standard "J" from Alvarado et al. (1993), with photoelectric $V = 15.33$, has $V = 16.140$ in the CCD data by Will et al. Taking into account our overall agreement with Olszewski (1984) in the magnitude zero point, we tend to attribute the revealed disagreement to a calibration error in Will et al. (1995). A systematic error could be introduced into our data because we use photoelectric, and thus aperture, magnitudes for the standard stars, located in a crowded field, along with our PSF CCD data. But this error is not expected to exceed several hundredths of a magnitude. The distribution of stars in Fig. 2a is rather asymmetric, with more stars scattering below the average line than above it. This may be due to errors in both studies. In $B-V$ color, our data show systematic effects resembling those revealed in comparison with Olszewski (1984).

Our photometry in NGC 1978 is available upon request from the authors (N. Samus).

3. The color-magnitude diagram

Figure 3ab presents the $V-(B-V)$ and $I-(B-I)$ diagrams based on our photometry of 3077 stars in the field of NGC 1978. Similar to earlier studies, we find numerous field stars as well as a moderately well-populated giant branch and a rich red horizontal branch. In all investigations, the scatter of stars around the giant branch of NGC 1978 was found to be considerable, probably due not only to crowding and field-star contamination but also to intrinsic reasons. Also, the intrinsic widths of the sequences are suspiciously broad in galactic globular clusters with red horizontal branches, and they are not always easily explained by crowding, differential reddening, contribution of field stars (see, for example, CMDs in Armandroff

1988; Ortolani et al. 1992; Sarajedini & Norris 1994). As for NGC 1978, some broadening of the upper giant branch may be, besides crowding, due to the contribution of stars on the asymptotic branch which must be quite close to the main giant branch in the CMD.

Contrary to the metal-richest galactic globulars, where the reddest part of the giant branch curls back in itself and becomes fainter in V light than the giants at somewhat lower color index (see, for instance, Ortolani et al. 1992), the reddest giants of NGC 1978 are apparently the brightest ones, both in our photometry and in earlier studies.

4. Horizontal branch

4.1. The sample of horizontal-branch stars

To study the horizontal branch (HB), we first had to identify the stars belonging to this evolutionary sequence. We note that in the $I-(B-I)$ diagram (Fig. 3b) the HB is indeed more or less horizontal. We judge that the luminosity limits of the HB, from this CMD, are $I = 17.8$ and $I = 18.3$. Using the advantages of multicolor photometry, we can separate HB stars from the stars of the giant branch more reliably. On one hand, HB stars show the largest difference in color from giant-branch stars in both $B-I$ and $B-R$. The color-magnitude diagrams with these color indices show no significant overlap of these sequences. On the other hand, we selected only those stars which are located within the HB range, adopted from visual inspection of the CMDs, simultaneously for $B-R$, $B-I$, and $V-I$ colors [$1.250 < B-R < 1.500$, $1.760 < B-I < 2.028$, $0.914 < V-I < 1.070$]. A total of 319 stars satisfy these color criteria as well as the I luminosity criterion.

To determine the mean V and I magnitudes of the horizontal branch, we used a still smaller sample of 201 most probable cluster members, within the ellipse with $a = 1\farcm9$. The mean $V_{\rm HB}$ value, from this sample, is 19.057 ± 0.008 (the error quoted is the rms error of the average). The mean $I_{\rm HB}$ value is 18.056 ± 0.007.

Because NGC 1978 is decidedly elliptical in shape, our subsequent analysis of HB subsamples refers either to elliptical zones or to zones limited, in the radial direction, by similar ellipses of different sizes. We adopt the ellipticity parameter value $e = (a-b)/a$, where a and b are the semi-major and semi-minor axes of the ellipse, equal to 0.3 for NGC 1978 (Fischer et al. 1992). We also adopt the position angle of the major axis PA $= 145^\circ$, which lies within the range of this parameter in Fischer et al. and close to the value they find for the peripheral zone of the cluster. We adopt the position of the cluster center based upon the brighter ($I < 17.8$) giants which clearly show concentration towards the cluster center.

From luminosity profiles, Fischer et al. (1992) found that the semimajor axis of NGC 1978 is at least 55 pc in V light and 65 pc, in B light (i.e. $\sim 4\farcm5$ at the LMC distance of 50 kpc). We have adopted the B-light value as the cluster size. Thus, the field studied by us is almost completely within the body of the cluster.

4.2. Horizontal branches of two parts of the cluster

One of the possible explanations of the significant ellipticity of the cluster is the formation of NGC 1978 as a merger of two clusters (see, for instance, Fischer et al. 1992). Having a rather large sample of HB stars, we can compare stellar populations in two parts of the cluster. A natural separation line between the two parts of the cluster is its minor axis. In the following, we will compare the color distributions of HB stars in two fields (quadrants) of NGC 1978, both situated to the northeast of the cluster's major axis and separated by the semi-minor axis. We shall subsequently call the zone to the north of the cluster center "quadrant A", and the zone to the east of the cluster center, "quadrant B".

To make the two quadrants approximately equal in area and the field of the cluster more or less symmetrical relative to its minor axis, we artificially imposed a western border at $x = 150$, an eastern border at $x = 850$, and a northern border at $y = 700$ (200 pixels correspond to approximately $1\farcm1$). Outer border is imposed at $a_{\rm ext} \approx 3\farcm3$ from the cluster center. We excluded the densest part of the cluster inside $a_{\rm int} \approx 0\farcm8$.

The subsamples contain 78 stars for quadrant A and 77, for quadrant B. Their color ($B-V$, $B-R$, $B-I$) distributions are shown in Figs. 4a,b,c. The dashed line is the distribution of stars from quadrant A; the dotted line, that of stars from quadrant B. The distribution of 319 HB stars from the whole cluster field is presented by the solid line. For each of the three color indices, we reveal systematic differences among distributions of stars in the two parts of the cluster. The distribution for quadrant B seems to be more symmetrical, with a maximum near the distribution center, whereas the distribution for quadrant A shows a deficiency of stars in the center of distribution compared to quadrant B, with maybe a slight excess at the red end compared to B. As can be seen from Figs. 4a,b,c, these differences are characteristic not only of the two restricted fields (quadrants) but they are traced in corresponding color distributions (solid line) of the whole sample of the HB stars. These differences are apparent for colors formed using B magnitudes, but are practically absent for $V-I$.

5. Giant branch

If the stars of NGC 1978 really have inhomogeneous parameters (age or chemical abundance), the inhomogeneity should reveal itself not only for the horizontal branch. We cannot be sure, however, that the differences can be

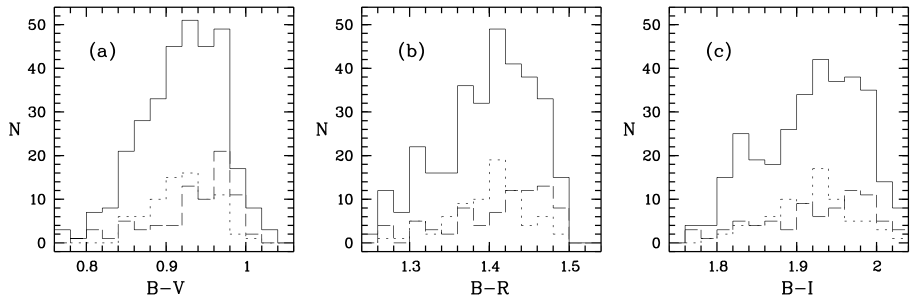

Fig. 4. The color [$B-V$ – **a**); $B-R$ – **b**); $B-I$ – **c**)] distributions of the horizontal branch in different zones of NGC 1978: the dashed line, for quadrant A (see text); the dotted line, for quadrant B; the solid line, for the complete sample of HB stars. See text for details

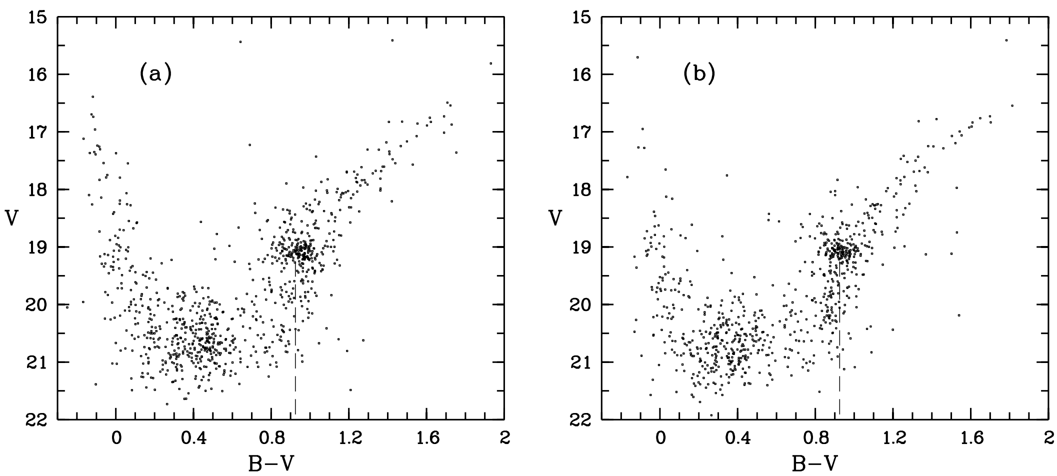

Fig. 5. The $V-(B-V)$ diagrams for the northwestern half [panel **a**)] and for the southeastern half [panel **b**)] of the cluster field. The dashed reference line corresponds to $B-V=0.925$

noticed for given photometric accuracy, sample size, etc. Figs. 5a and 5b present the $V-(B-V)$ diagrams for two parts of the symmetrical NGC 1978 field described in the previous section, separated by the cluster's minor axis: the northwestern half (NWH) and the southeastern half (SEH), respectively. To facilitate comparison, we show, in both figures, the vertical dashed reference line at $B-V=0.925$. A somewhat different appearance of the two diagrams can be suspected. First of all this concerns a slightly different visible position of the giant branch (GB) at the level of HB stars and below it, down to $V\sim 20.5$ (in the most probable color range of the GB, $0.80<B-V<1.05$). Most GB stars in these magnitude and color ranges in the CMD of the cluster's SEH are located to the left of the reference line as opposed to those in the CMD of the cluster's NWH. Also, there is a hint that in the turnoff region ($V>20.0$ and $0.2<B-V<0.6$) the NWH stars are systematically redder than the SEH ones. Again, the differences for lower giants are apparent for colors formed using B magnitudes, but are practically absent for $V-I$. Note that the described difference between visible CMD positions of the GB stars in the cluster's NWH (which includes quadrant A, see the previous section) and SEH (which includes quadrant B) resembles qualitatively that between color distributions of HB stars in CMDs of the two quadrants.

6. The color-position diagram

Another useful tool revealing the differences discussed in two previous sections is the color-position diagram (CPD). Figure 6 presents the plot of the color $B-V$ versus position (X, in pixels) of stars along the major axis of NGC 1978. Positive and negative values of X correspond to the NWH and the SEH of the cluster, respectively. We have excluded stars which lie, on the CMD, above the adopted upper luminosity limit of the HB stars and to the right of the sequence of field stars ($I<17.8$ and $B-V>0.2$). Two reference lines are shown in the figure. The vertical one is the same as in Fig. 5; the horizontal one, at $X=0$, separates the stars of the cluster's NWH and SEH. It is apparent that, in the color range $0.80<B-V<1.05$, most of the HB and GB stars with $X<0$ are to the left of the vertical reference line, in contrast to the position of such stars having $X>0$. As it follows from Figs. 4a, 5, and 6, the maximum difference in $B-V$ color between both HB stars and lower giants in

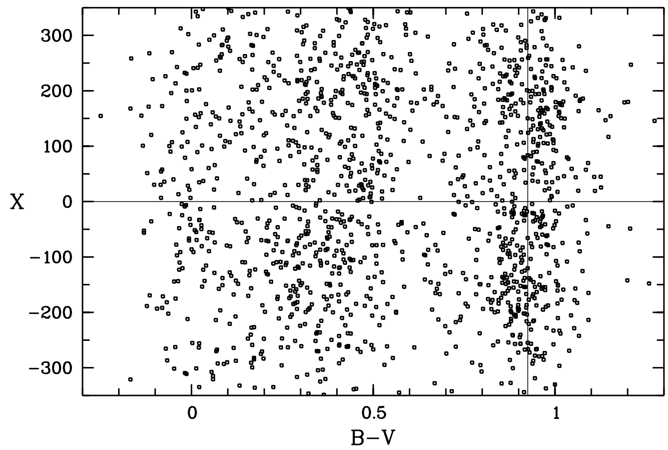

Fig. 6. The color-position diagram for stars (see text for details) from the cluster field shown in Fig. 1. It presents the plot of color $B-V$ versus position (X, in pixels) of stars along the major axis of NGC 1978. Positive and negative values of X correspond to NWH and SEH of the cluster. Stars near the vertical reference line ($B-V=0.925$) are the HB stars and the lower giants

the cluster's NWH and their counterparts in the cluster's SEH may be as large as $0\overset{m}{.}05-0\overset{m}{.}07$. Similar behavior of stars of the cluster turnoff region may also be suspected in the CPD.

7. Discussion

We find differences in CMD (as well as in CPD) positions for HB stars and lower giants (at the level of HB stars and below it) in two parts of NGC 1978, in several colors (all of them including B magnitudes). However, the upper giants show no obvious differences in the CMD positions for the NWH and SEH of the cluster. Do these features reflect real properties of the star population in the cluster field? We cannot exclude the photometric errors to have influenced the result. But, in this case, photometric errors should be rather specific because they influence only B magnitudes and have almost abrupt change just near the position of the cluster's minor axis. If the stars of NGC 1978 really have nonuniform parameters (chemical abundance, age), what range of them could explain the differences discussed? To answer this question, we considered isochrones by Bertelli et al. (1994) and Yale isochrones by Demarque et al. (1996) with values of parameters (age and [Fe/H]) close to those of NGC 1978. In spite of a number of sensible differences between isochrones (with similar or close values of age, [Fe/H], and Y) of the two sets, it is possible to conclude the following (cf. Fig. 7).

Because there is no obvious variation, if any, of the turnoff magnitude in the two parts of the cluster, an age spread cannot be significant and, consequently, it cannot cause the differences under consideration. A metallicity spread might play an important role, especially taking into account that isochrones of both sets show that metallicity variations lead to a shift of the *lower giants* in $B-V$ greater than that in $V-I$ at least by a factor of $\sim 1.5-2.0$. But it is not the case for the upper parts of the GB, especially for the GB tip where a shift in $V-I$ may be even greater than in $B-V$.

The isochrones by Bertelli et al. (1994), reproducing the position of the clump of the HB stars, indicate that, similar to the lower giants, the clumps of the HB stars with different metallicity are closer to each other in $V-I$ than in $B-V$ color.

To explain the observed variations, the difference in metallicity between stars in the NWH and SEH of NGC 1978 should be as large as Δ[Fe/H] $\sim 0.1-0.2$, the stars of the cluster's NWH being more metal-rich. Also, stars of the cluster's NWH still may be slightly younger (by a few tenths of a Gyr) than those of the cluster's SEH. The permitted age difference between the two subpopulations (so that their turnoff magnitudes remain indistinguishable in the CMD) depends on the possible difference of the helium content.

Thus, we cannot exclude the existence of a real inhomogeneity of the stellar content in NGC 1978, presumably a result of merging. But it has to be noted that studies of dynamics and of surface brightness isophotes do not provide evidence for merging in NGC 1978 (Fischer et al. 1992). To verify our results and to make more definite conclusions, an additional multicolor photometric study of NGC 1978 with high accuracy in a large magnitude range is needed.

8. Conclusions

1. We have carried out multicolor ($BVRI$) photometry for more than 3000 stars in the field of the LMC populous cluster NGC 1978. We find reasonably good agreement of our photometry with Olszewski (1984) but note a discrepancy of zero points of V magnitudes, by approximately $0\overset{m}{.}4$, between our CCD photometry and the CCD photometry by Bomans et al. (1995).

2. Our study of color distributions of HB stars in different parts of the cluster does not exclude the presence of two subpopulations in the cluster. The same follows from the positions of lower-giant-branch stars in the color-magnitude diagrams for different cluster zones. Comparison with isochrones shows that, to explain the observations, a difference in [Fe/H] by $\sim 0.1-0.2$ between the two subpopulations would be sufficient.

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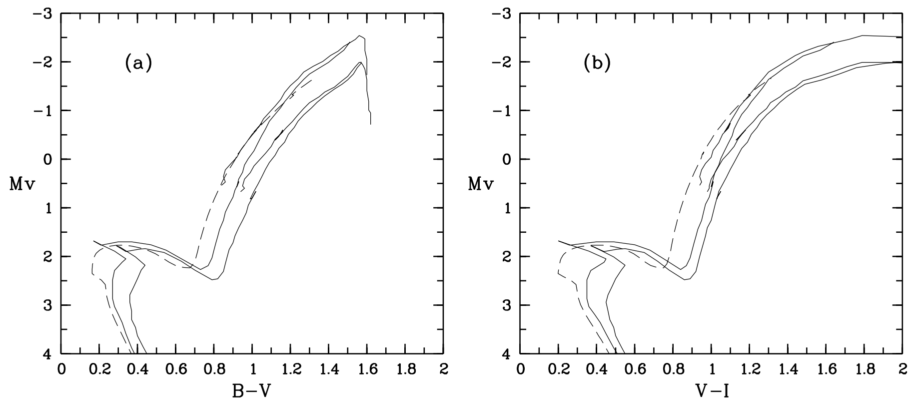

Fig. 7. Comparison of isochrones in the (M_v, $B-V$) plane [panel **a)**] and in the (M_v, $V-I$) plane [panel **b)**]. The pair of isochrones of the set by Bertelli et al. (1994) with an age of 2 Gyr, $Y = 0.24$, $z = 0.004$ ([Fe/H] $= -0.7$) and with an age of 2 Gyr, $Y = 0.25$, $z = 0.008$ ([Fe/H] $= -0.4$) is shown by the solid line. A Yale isochrone from the set by Demarque et al. (1996) with an age of 2 Gyr, $Y = 0.23$, $z = 0.008$ ([Fe/H] $= -0.7$) is shown by the dashed line to demonstrate the difference between the two sets

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