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CCD photometry of young MC clusters I: NGC 2172*

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Abstract. We present a new CCD photometry for the young LMC cluster NGC 2172, giving B, V, I magnitudes for more than 600 stars within $70''$ from the cluster center, down to -approximately- V= 21 mag. After correction for completeness and field stars contamination, we discuss the cluster HR diagram and the MS luminosity function in the light of current evolutionary theories and in connection with the problem of cluster age.

Key words: stars: evolution – stars: fundamental parameters – stars: luminosity function, mass function – galaxies: Magellanic Clouds – galaxies: star clusters

1. Introduction

This paper is the first of a series devoted to a photometric investigation of young stellar clusters in the Magellanic Clouds. The observing program was originally aimed to the detection of new cluster cepheids, in order to improve observational data for these objects which play such a relevant role in the problem of Magellanic Clouds distances. However, we found that photometric data collected to this purpose allow a parallel investigation of cluster CM diagrams, providing new and improved data for several target clusters.

In this paper we present photometric data for NGC 2172, a young cluster with moderate luminosity (V=11.75 mag, van den Bergh 1981) and moderate concentration ($\log\rho_0 \sim 1.5$–$2.7\ M_\odot\ \mathrm{pc}^{-3}$, Elson et al. 1987) located north-east of the central LMC bar ($\mathrm{RA}_{2000} = 06\,00\,05.6\ \delta_{2000} = -68\,38\,14$). A previous CCD investigation on this cluster has been presented by Elson (1991), who published BV CCD photometry for 95 bright stars within $100''$ from the cluster center. Taking advantage of better seeing conditions, we will discuss new B, V and I data for more than 600 stars in a similar area, reaching $V \approx 21$ mag.

In Sect. 2 and 3 we will present and discuss observational data, whereas Sect. 4 will be devoted to a comparison with evolutionary predictions, in connection with the problem of cluster age. A short discussion will close the paper.

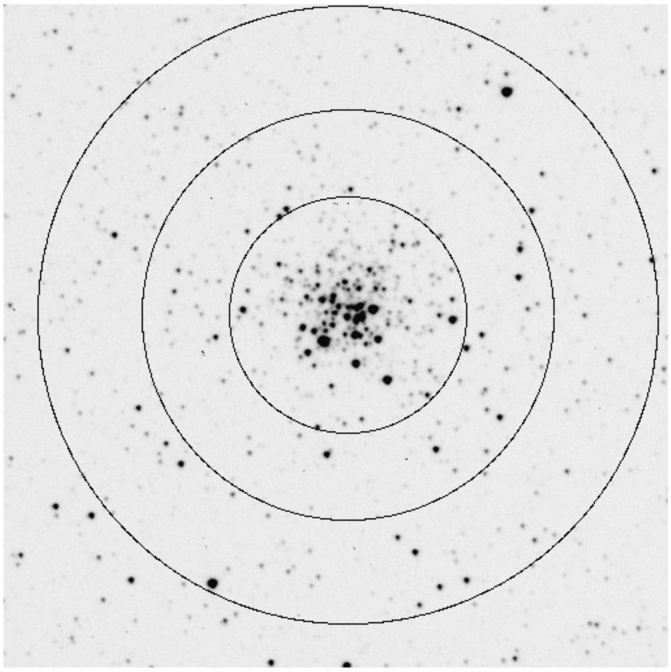

Fig. 1. A V frame of NGC 2172 region. The circles have radii of size $40''$,$70''$ and $105''$ respectively.

2. Observations, data reduction and calibration

Observations were carried out in the BV and i_{gunn} filters during November 1996 with the 0.9 m. "Dutch" telescope at ESO (La Silla, Chile). The telescope was equipped with a TEK 512x512 pixels CCD (ESO # 33); the scale was 0.44 arcsec/pixel, with a total field of about 3.8 arcmin. Fig. 1 shows the investigated area, whereas Table 1 gives the log of the observation; note that the three observing periods follow the need of covering Cepheid luminosity variations. The mean seeing was about 1.4–1.6 arcsec during the first 7 nights, and about 1.1–1.2 during the last four nights.

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[*] Based on observations collected at the European Southern Observatory, La Silla, Chile

Table 1. Log of the observations; exposure times are in seconds

Date Nov. 1996	exp. time B	exp. time V	exp. time I	notes
3		90,90	60	
4	420,420	150,150,150	150,150	calibration
5	540,540	180,180	150,150	
6	540,540	180,180	150,150	
14	480	150	150	calibration
15	150,720	50,270	45,230	
16	480,480	180,180	150,150	
21	420	180	150	calibration
21	420	180	150	field
22	150,660	60,300	45,250	
23	150,660	60,300	45,250	
24	150,660	60,300	45,250	

Data reduction was performed using the ROMAFOT code (Buonanno et al. 1979, 1983), which allows accurate photometry in the crowded central regions of the cluster.

2.1. Calibration

Calibration has been secured in three different nights by observing selected standards from Landolt (1992) fields. Two stars from Field 92 were observed during each calibration night at different airmasses to evaluate extinction coefficients, whereas other fields (Rubin 149 and four stars in pg231+51) were used to obtain color equations and zero points. Data from the best photometric night (Nov. 14) have been used to calibrate the photometry, even though calibrations from the other two nights would have given quite similar results. The calibrating relations were derived taking into account both the errors on Landolt's magnitudes and the errors in the aperture photometry. Star pg231+51 was excluded in calibrating $(V-I)$ because of the uncertainty in the I magnitude. As a result we found:

$$V - v = 0.020(b - v) + 22.102 - 0.11X \quad \text{rms } 0.009$$
$$(B - V) = 1.055(b - v) - 0.334 - 0.10X \quad \text{rms } 0.007$$
$$(V - I) = 1.050(v - i) + 1.141 - 0.06X \quad \text{rms } 0.006$$

where B, V, I and b, v, i indicate Johnson or instrumental magnitudes, respectively, and X is the airmass. The comparison with magnitudes and colors by Landolt (1992) is given in Fig. 2; the result appears largely satisfactory, but one star.

According to this calibration we obtained BV magnitudes for 640 stars and VI magnitudes for 678 stars within a radius $r < 105''$ from the cluster center. Final magnitudes have been obtained as a mean of about 18 exposures (see Table 1). All the observational data will be available via anonymous ftp at the address: ftp.na.astro.it (pub/NGC2172) or upon request by e-mail; an example of these data is shown in Table 2, where column (1) gives the star identification; (2) and (3) the X and Y coordinates in pixel; (4), (5) and (6) the V, $(B-V)$, $(V-I)$ magnitudes; (7), (8) and (9) the internal errors on V, B and I; (10), (11) and (12) the number of measures in each filter; (13) the distance to the cluster center in arcsec.

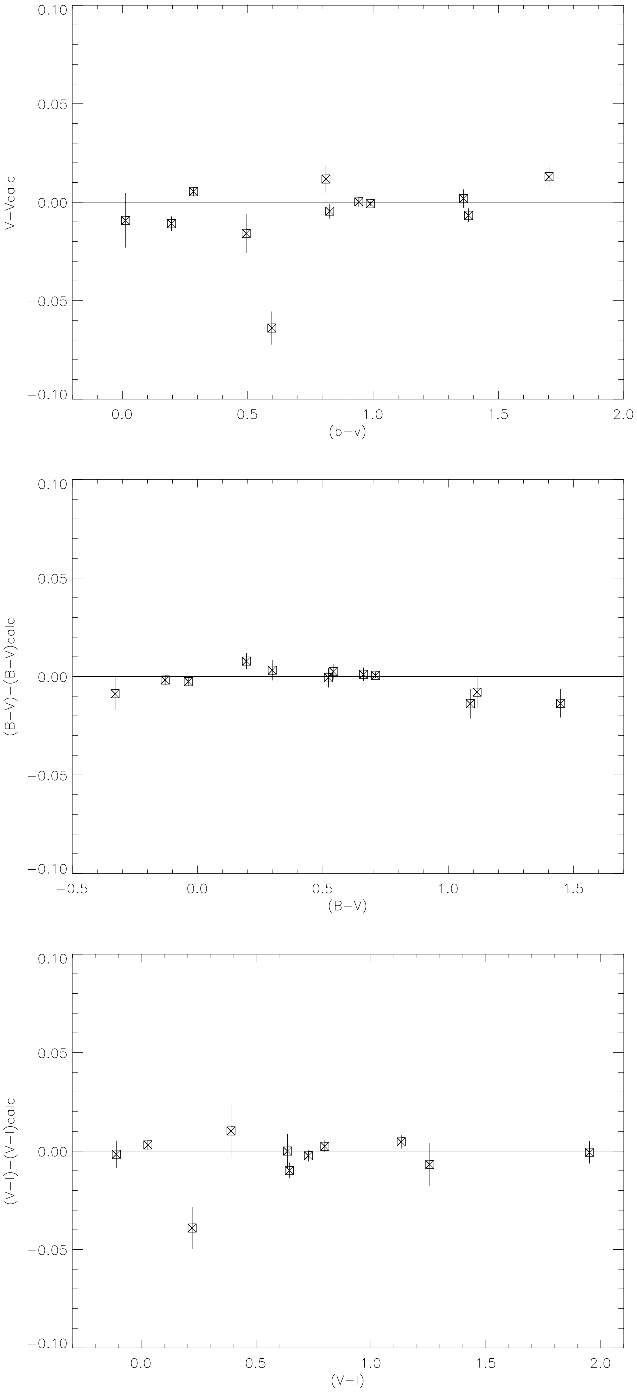

Fig. 2. Difference between Landolt (1992) and calculated magnitudes and colors for the calibration stars

Fig. 3 shows the standard deviations of single measures as a function of magnitude for the three selected photometric bands. One finds that some faint stars located near the cluster center have rather large errors; this appears as a consequence of the variable seeing during the various nights which led to bad pho-

Table 2. Example of photometric data, see text for details.

ID (1)	X (2)	Y (3)	V (4)	$(B-V)$ (5)	$(V-I)$ (6)	σ_V (7)	σ_B (8)	σ_I (9)	N_V (10)	N_B (11)	N_I (12)	r (13)
1	115.12	1.20	18.596	0.658	1.004	0.182	0.405	0.160	20	18	14	136.80
2	272.00	2.00	20.711	0.172	0.000	0.190	0.103	0.000	4	3	0	119.38
3	264.85	2.88	15.667	0.706	0.987	0.155	0.426	0.150	21	18	15	118.95
4	295.36	2.96	19.171	0.236	0.736	0.160	0.226	0.439	19	16	15	119.67
5	320.00	3.58	20.247	0.367	0.909	0.173	0.190	0.219	15	13	12	121.11
6	502.69	3.17	20.555	0.498	0.948	0.185	0.281	0.177	14	13	11	158.61
8	91.12	4.71	20.981	0.417	0.915	0.163	0.214	0.177	14	12	11	140.94
9	85.70	5.02	20.615	0.380	0.892	0.181	0.196	0.244	14	12	12	142.15
10	206.88	5.32	16.836	0.673	0.939	0.162	0.402	0.170	21	18	16	120.64

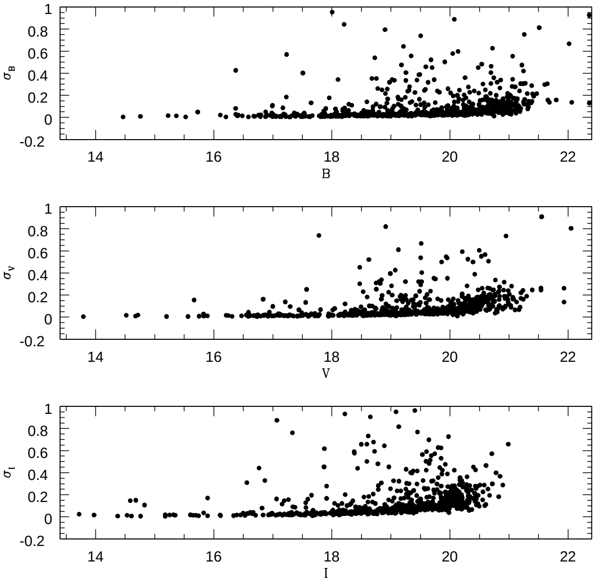

Fig. 3. Standard deviations of single measures of cluster stars in the various filters as a function of the corresponding magnitudes.

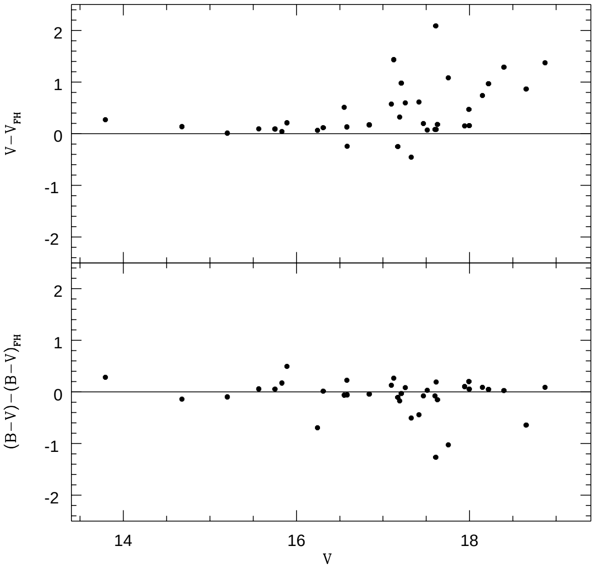

Fig. 4. Comparison between present photometry and FH photographic photometry

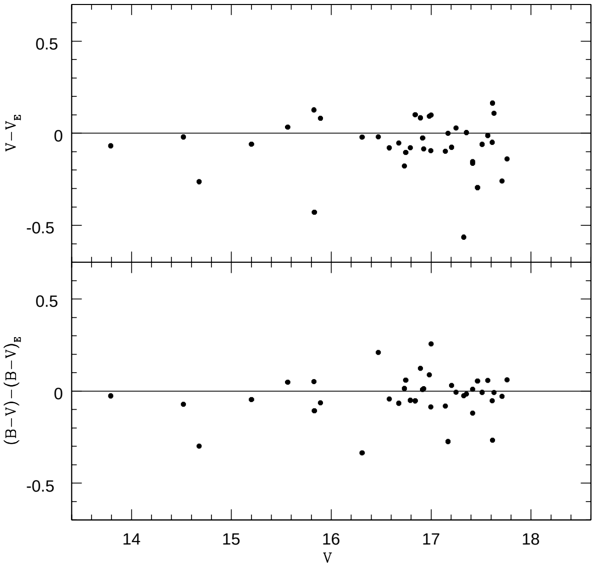

Fig. 5. Comparison between present and Elson (1991) photometry.

tometry for faint stars near bright companions. Additional errors in I filter are due to focus variations during observations.

This sample of stars was finally implemented with data for stars in a field centered about $3'$ East of the cluster center, with calibration and photometry performed according to the above quoted prescriptions.

2.2. Comparison with previous photometry

Fig. 4 shows a comparison between present photometry and the photographic photometry by Flower & Hodge (1975: hereafter FH). One finds a good agreement at least down to V=16.8, with a growing scatter at fainter magnitudes. Fig. 5 shows the comparison between present and Elson (1991) photometry for stars with $V < 18$ mag. There is no evidence of significant zero point offsets between these previous observations in V or $(B-V)$; moreover the scatter is in general rather reduced with only few stars showing an anomalous large scatter, as probably due to the much larger seeing in Elson's observations ($5''$ FWHM), which in the most crowded region can heavily affect the data.

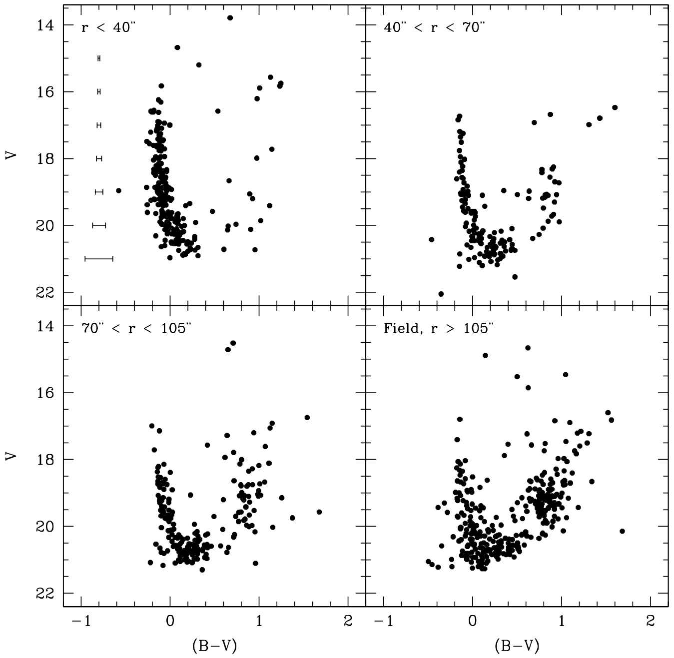

Fig. 6. CMD in $V-(B-V)$ for NGC 2172 and for the field (lower corner on the right)

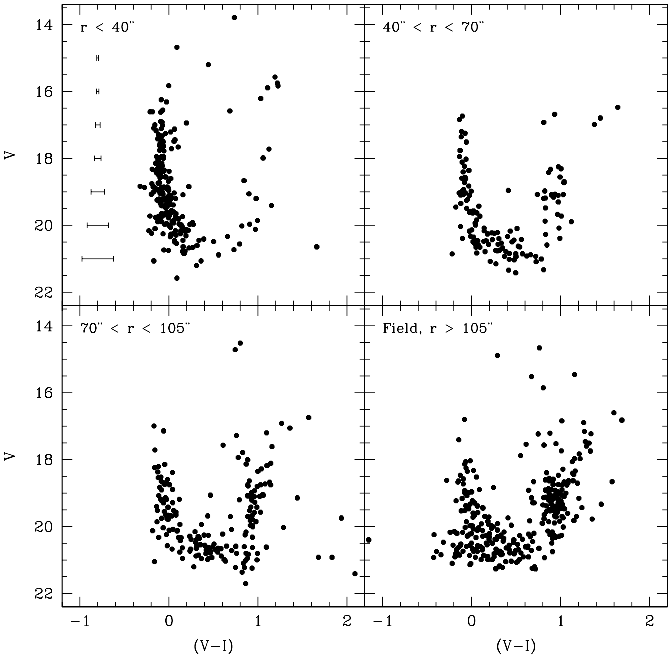

Fig. 7. As in Fig. 6 but for the $V-(V-I)$

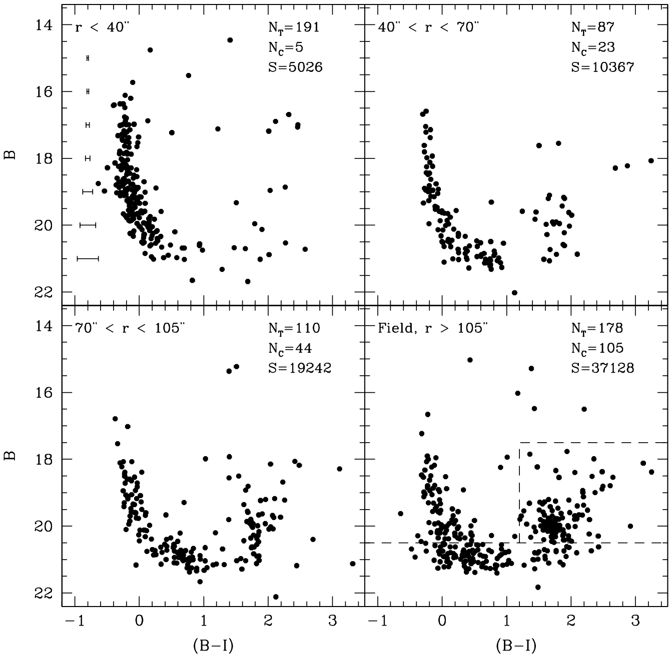

Fig. 8. As in Fig. 6 but for the $B-(B-I)$; in each panel N_T reports the total number of stars above $B=20.5$ (horizontal line in the lower right panel); N_C reports the number of field clump stars (box in the the lower right panel); S is the area in squared arcsec.

3. The CM diagram

Inspection of observational data for the luminous stars does not reveal variability, therefore the cluster does not contain any Cepheid variables. As for non-variable stars, Fig. 6,7,8 show the CM diagrams in the $V-(B-V)$, $V-(V-I)$ and $B-(B-I)$ planes, respectively, for selected areas around the cluster center (see Fig. 1). The CMD for stars in the field frame is reported in the lower right panel of these figures, whereas in the upper left panel we give an evaluation of the uncertainty in the evaluated colors.

In the innermost region, i.e. within $r \leq 40''$ from the cluster center, one finds that the diagram is dominated by a well defined cluster Main Sequence (MS) ranging from $V \sim 16$–16.5 mag down to the limiting magnitudes. Moreover, to the right of the MS one finds the expected occurrence of some He burning field giants plus nine stars brighter than $V \sim 17$ mag, possibly to be interpreted as off Main Sequence stars. However, the very bright star at $V = 13.792 \pm 0.004$, $(B-V) = 0.674 \pm 0.05$, $(V-I) = 0.735 \pm 0.008$ (n. 17 in FH), early reported as a possible candidate for "Superluminous Giants" in LMC by FH and Flower et al. (1980), has been found by both Sowell (1986) and Baird & Flower (1986) to be a foreground object, with radial velocity 20–30 $\mathrm{km\,s^{-1}}$ against $\sim 270\,\mathrm{km\,s^{-1}}$ for LMC. Thus eight luminous stars remain as possible cluster members.

As expected, when going toward more external regions one finds that the populations of MS and bright stars are both decreasing, whereas the evidence for the clump of field He burning giants increases, according to the increased area covered by observation. Fig. 9 shows the $V,(B-V)$ diagram for all the measured stars, together with an estimate of the center of the clump as observed in the region around the near cluster NGC 2004 (Bencivenni et al. 1991). One finds that in NGC 2172 area the clump appears a bit fainter and redder, an occurrence that could suggest a moderate larger reddening in NGC 2172.

Before proceeding to a comparison with theoretical predictions, one needs to account for the effects of both crowding and field contamination. As for completeness, a crude inspection of data reveals that the very central region within $10''$ from the

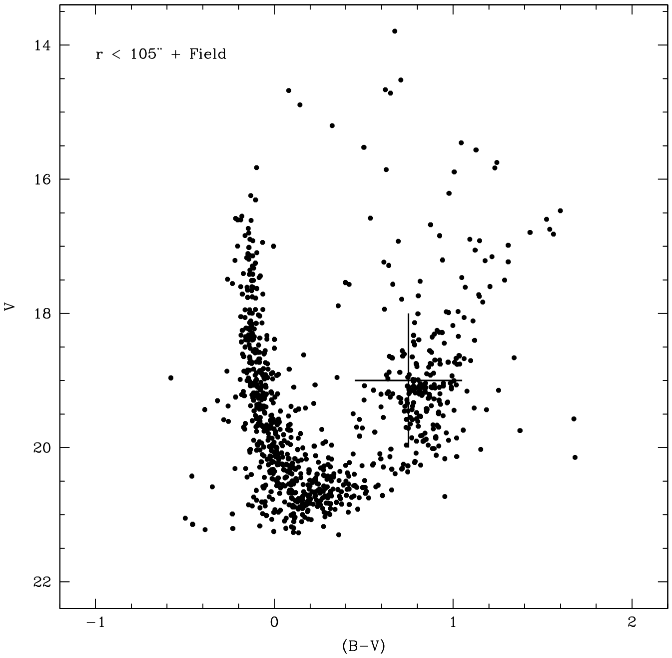

Fig. 9. The $V, (B-V)$ diagram for all the measured stars in the region of NGC 2172. The cross gives the location of the center of the clump of field stars in the region around NGC 2004 (see text). .

cluster center is too heavily affected by crowding, so that it will not considered in the following discussion. In order to test the completeness of the remaining sample, we followed the usual procedure (command ADDSTAR in ROMAFOT), by randomly disseminating artificial stars (taken from the cluster list) of different magnitudes into the original frame. More in detail, we considered the two annuli $10 < r < 40$ and $40 < r < 70$ arcsec; in each of these two annuli we added 100 stars for each chosen magnitude; note that in order to avoid to introduce additional crowding, the artificial stars were disseminated ten by ten. The result of such a test is reported in Fig. 10. One finds that photometry in the outer annulus is fairly complete down to the faintest magnitudes, whereas images in the inner annulus are strongly affected by crowding.

To account for the contribution of field stars one can start from the evidence that beyond 70 arcsec from the cluster center the surface density of stars agree, within the expected statistical fluctuation, with the value found for field stars in the more external frame. Thus we retained the sample of stars within 70 arcsec from the center as a suitable sample for cluster stars to be corrected according to the density of stars in the external frame for selected bin of magnitudes. Note that according to such a procedure, one also finds that some out of the seven bright stars should be field stars. One must conclude that NGC 2172 provides little convincing evidence for the evolution off the MS. This lack of evidence makes the following discussion about the cluster age much more difficult.

Fig. 11 (upper panel) shows the original MS LF together with the LF after correction for crowding and field contamination. Fig. 11 (lower panel) gives the adopted LF with the relative errors which were calculated on the basis of the formula given by Bolte (1989) plus a term taking into account the statistical subtraction of field stars. Data on the LF are also reported in Table 3 (see caption).

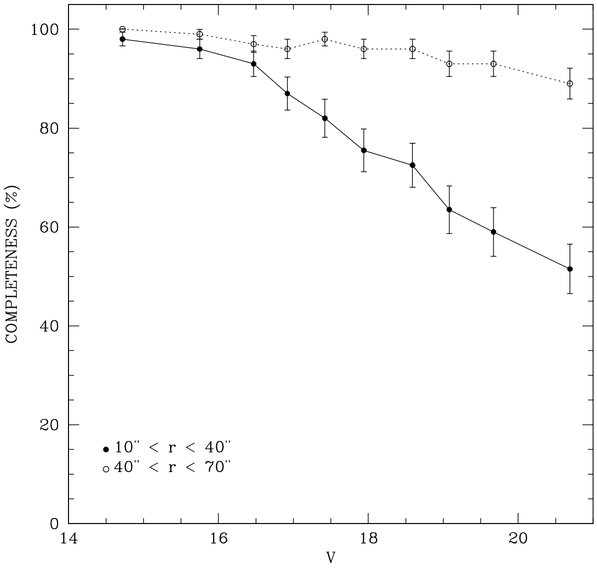

Fig. 10. Completeness results form artificial star dissemination experiments in the two labeled annuli around the cluster center. The errorbars were calculated as shown by Bolte (1989).

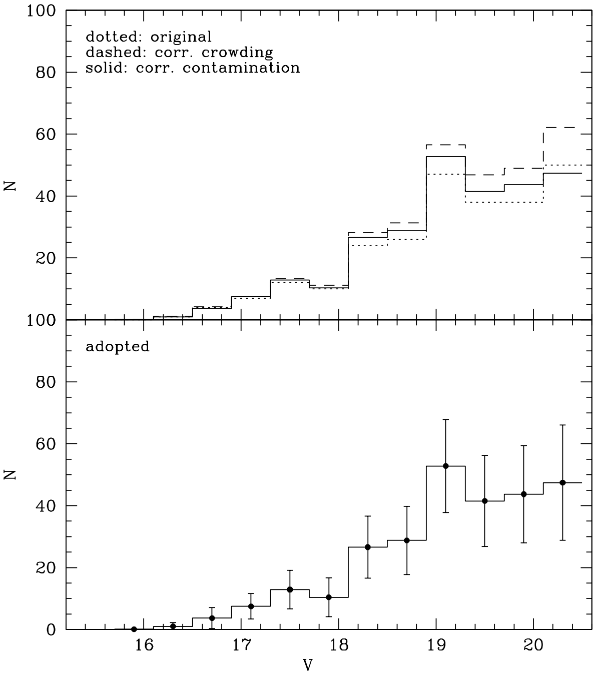

Fig. 11. Luminosity function for MS stars in NGC 2172. Upper panel: original LF (dotted) plus LF corrected for crowding (dashed) and for the contamination from Field stars (solid). Lower panel: adopted LF with errorbars (see text)

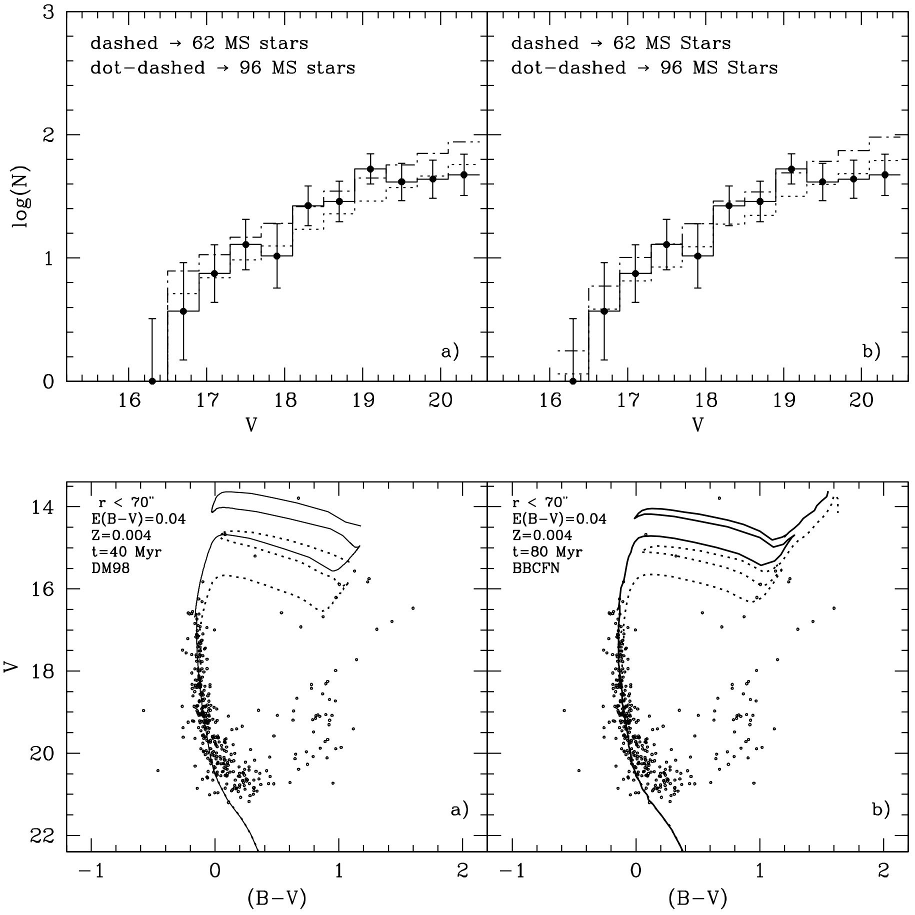

Fig. 12. Upper panel: Comparison between the observational (solid line with error bars) and theoretical LFs as derived from simulations based on the isochrone by: a) DM98 for $\tau = 40\,\mathrm{Myr}$; b) by BBCFN for $\tau = 80\,\mathrm{Myr}$. Different lines refer to the different number of cluster MS stars used to normalize the simulations. As labeled, theoretical LF.s have been alternatively normalized to the observed number of MS stars in the range $17.5 < V < 18.7$ plus or minus the expected standard deviation. **Lower panel:** isochrone fitting for NGC 2172; solid lines show the isochrones: a) by DM98 for $\tau = 40\,\mathrm{Myr}$; b) by BBCFN for $\tau = 80\,\mathrm{Myr}$; dotted lines show the same isochrones but for **a** $\tau = 70\,\mathrm{Myr}$; **b** $\tau = 125\,\mathrm{Myr}$.

Table 3. Luminosity Function for NGC 2172. $N_{\rm or}$ and $N_{\rm corr}$ mean original and adopted (corrected) counts respectively; last column report the estimated error on the adopted counts.

V	$N_{\rm or}$	$N_{\rm corr}$	σ
16.3	1	1	1.2
16.7	4	3.7	3.4
17.1	7	7.5	4.1
17.5	12	12.9	6.2
17.9	10	10.4	6.3
18.3	24	26.6	10.0
18.7	26	28.8	11.0
19.1	47	52.8	15.0
19.5	38	41.5	14.7
19.9	38	43.7	15.7
20.3	50	47.4	18.6

4. Comparison with evolutionary theories

Observational data can be now compared with theoretical predictions concerning cluster isochrones for suitable assumption about the cluster distance modulus and metallicity.

As is well known, the distance of LMC is object of hot debate (see, e.g., Cole 1998). According to the HST Cepheid Key Project assumptions, we will adopt the classical value of $(m-M)_{LMC} = 18.50$ mag as a sort of "average" between the various determinations, bearing in mind that a variation of a few tenths of magnitude will scarcely affect the evolutionary scenario described below.

We need to make a reasonable assumption for the cluster metallicity due to the lack of direct evaluations. We note that if we assume that the cluster has the mean metallicity of LMC ($Z = 0.008$), then theory does not predict the occurrence of blue He burning stars (see, e.g., Castellani et al., 1992). However, if one believes that the two bluest giants are in fact cluster members, then a lower metallicity is clearly required. Accordingly, we will assume $Z = 0.004$, noting that, e.g., Jasniewicz & Thévenin (1994) found $Z = 0.005$ for the LMC cluster NGC 2004 and that Luck et al. (1998), has recently found LMC Cepheids with metallicity as low as $Z = 0.004$.

We then used the standard isochrone fitting procedure, considering two sets of isochrones: i) canonical isochrones by Degl'Innocenti & Marconi (1998, private communication), based on the FRANEC code (Chieffi & Straniero 1989) and ii) isochrones with mild overshooting by the Padua group (Bertelli et al. 1994). Canonical isochrones were transformed into the observational plane by adopting the bolometric corrections and the color-temperature relations by Castelli et al. (1997a,b), whereas for the isochrones from the Padua group we used the data as provided by the authors.

Several authors have previously made age estimates for NGC 2172. Hodge (1983) used FH photographic photometry to derive an age $\tau \sim 60$ Myr. Elson & Fall (1985) give $\tau \sim 80$ Myr from integrated colors whereas Elson (1991) fitted her CMD to Becker (1981) isochrones to derive $\tau \sim 40$ Myr. More recently Bica et al. (1996) classified the cluster as SWB III, estimating an age in the range 70–200 Myr. To investigate this point, we normalized theoretical predictions concerning the MS Luminosity Function to the observed number of cluster MS stars in the magnitude interval $17.5 < V < 18.7$. Following Elson (1991), we adopted for the cluster a Salpeter mass function. However, as discussed, e.g., by Bencivenni et al. (1991), one has to remember that such an assumption does not affect the top luminosity of the LF. As shown in the upper panels of Fig. 12, a) and b) for the case i) and ii) respectively, using the MS termination as an age calibrator one finds for the cluster an age of 40 Myr for canonical evolution or 80 Myr in the case of mild overshooting, with a difference in age which is a well known consequence of the adopted evolutionary scenarios. The corresponding fit of the CM diagram is given in the lower panels of Fig. 12. In both cases the fitting requires $E(B-V) = 0.04$ mag, which appear a rather reasonable value.

Taking into account a reasonable uncertainty in the evolutionary loop and/or in the evaluation of bolometric correction and colors, one finds that only 4 giants above $V = 16$ can be attributed to the given isochrone, against 9 or 5 expected in the canonical or mild overshooting case. Even if statistics is poor, one may conclude that, in the case of NGC 2172, the hypothesis of mild overshooting provides a better fit to the observations.

5. Final remarks

According to the previous section, one finds that the best fit between theory and observation gives a cluster age in the range of 40 to 80 Myr, depending on the efficiency of core overshooting. However, the poor evidence for stars in later evolutionary phases leaves room for speculation. If one insists that the cool giants around $V \sim 17$ are cluster members, then the age estimate must be approximately doubled. This is shown in the lower panels of previous Fig. 12, where dotted lines in a) and b) show isochrones of 70 and 125 Myr respectively. In this case one would expect 14 (canonical) or 9 (mild overshooting) giants against 7 observed. However, in this case, the top MS luminosity is predicted at $V \sim 17$, and one should conclude that NGC 2172 is affected by the occurrence of anomalous bright stars above this predicted limit.

As a final point, note that one may evaluate the integrated cluster color by simply adding the fluxes from all the observed stars, obtaining $(B-V)$= 0.15 for the sample within $10''$ and 0.17 for stars within $70''$ from the cluster center, in excellent agreement with observation of integrated light, which gives for the region $r < 72''$ $(B-V) = 0.18$ mag (van den Bergh 1981).

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