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A SEARCH FOR OLD STAR CLUSTERS IN THE LARGE MAGELLANIC CLOUD

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ABSTRACT

There are only a handful of known star clusters in the LMC that are genuinely old, i.e., of similar age to the globular star clusters in the Milky Way. We report the first results of a color-magnitude diagram survey of 25 candidate old LMC clusters, which were uncovered by means of integrated *UBV* photometry and Ca II triplet spectroscopy during previous investigations. The photometry was carried out with the Washington system C,T_1 filters on the Cerro Tololo 0.9 m telescope. For almost all of the sample, it was possible to reach the turnoff region, and in many clusters we have several magnitudes of the main sequence. The efficiency and efficacy of the technique are demonstrated by our deep CMD for ESO 121-SC03 (used as a control and calibrator), which clearly shows a magnitude of main sequence for this ≈9 Gyr old object in a total of <1 hour of integration time. Age estimates based on the magnitude difference δT_1 between the giant branch clump and the turnoff, calibrated using standard clusters, revealed that no new old clusters were found. The candidates turned out to be of intermediate age (1–3 Gyr) (we cannot rule out old ages for NGC 1928 and NGC 1939 since the turnoff was not reached for these compact clusters in crowded bar fields). We show that the apparently old ages as inferred from integrated *UBV* colors can be explained by a combination of stochastic effects produced by bright stars and by photometric errors for faint clusters lying in crowded fields. The relatively metal poor ($[\mathrm{Fe/H}]\sim-1.0$) candidates from the Ca II triplet spectroscopy also turned out to be of intermediate age. This, combined with the fact that they lie far out in the disk, yields interesting constraints regarding the formation and evolution of the LMC disk. We also study the age distribution of intermediate age and old clusters considering not only the present δT_1 parameter, but also δV and δR measured in CMDs from the literature. This homogeneous set of accurate relative ages allows us to make an improved study of the history of cluster formation/destruction for ages >1 Gyr. We confirm previous indications that there was apparently no cluster formation in the LMC during the period from 3–8 Gyr ago, and that there was a pronounced epoch of cluster formation beginning 3 Gyr ago that peaked at about 1.5 Gyr ago. Our results suggest that there are few, if any, genuine old clusters in the LMC left to be found. © *1997 American Astronomical Society.* [S0004-6256(97)03711-4]

1. INTRODUCTION

Globular cluster systems are tracers of the oldest stellar populations in galaxies, and the determination of their number and the study of their properties are fundamental to understanding the formation and evolutionary processes in galaxies. The largest globular cluster systems occur in giant ellipticals, often with populations exceeding 10^3 clusters (see Harris 1991 for a review). Battistini *et al.* (1993) estimated a best sample of 341 globular clusters and candidates in M31. Webbink (1985) compiled a list of 154 globulars in our own Galaxy; however, subsequent observations have revealed that several of these are background galaxies, planetary nebula in rich fields or open clusters (e.g., Djorgovski *et al.* 1990; Bica *et al.* 1995), while some new members have been

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added, including Lyngå7 (Ortolani *et al.* 1993), Pyxis (Da Costa 1995; Irwin *et al.* 1995; Sarajedini & Geisler 1996), and IC 1257 (Harris *et al.* 1997).

As reviewed by Suntzeff *et al.* (1992), the Large Magellanic Cloud has eight bonafide old clusters (here taken to mean similar in age to globular clusters in the Galaxy), including NGC 1466, 1786, 1835, 1841, 2210, 2257, Hodge 11, and Reticulum, confirmed by means of deep color-magnitude diagrams (CMDs) and/or the presence of RR Lyrae stars. Five other clusters (NGC1754, 1898, 1916, 2005, and 2019) have long been suspected of being old on the basis of crude CMDs, integrated properties and/or metallicity estimates (e.g., Hodge 1960; Olszewski *et al.* 1991) but require high quality CMDs for a definitive diagnosis, since they are compact and/or embedded in dense fields. Such CMD investigations using *HST* are currently underway.

LMC clusters with ages determined from CMDs show a pronounced gap between a large number of intermediate age clusters (age $\sim 1-3$ Gyr, hereafter IACs) and the classical globular clusters, with ages >12 Gyr (Olszewski *et al.* 1991), with the sole exception of ESO 121-SC03 with an age of ~ 9 Gyr (Mateo *et al.* 1986). As emphasized by Da Costa (1991), this prevents us from using the known clusters to tell us any details about the chemical evolution of the LMC over most of its history, despite our ability to determine accurate ages and metallicities for them (Olszewski *et al.* 1991). Finding even a single additional cluster in this age gap, or more bonafide old GCs, would significantly enhance our knowledge of the chemical evolution of this important galaxy. Other fundamental questions to be addressed by this study are: (i) Is the present known sample of old clusters complete? A comparison of the luminosity function for old globular clusters in the Galaxy and LMC suggests that the LMC may be harboring several faint old clusters previously unrecognized (Suntzeff *et al.* 1992); and (ii) Have less massive old clusters formed and dynamically survived in the LMC, similar to the Palomar globular clusters in the Galaxy? In order to assess these issues we have undertaken a systematic CMD survey of old globular cluster candidates which have been recently discovered.

Several studies have uncovered a number of interesting old cluster candidates. Our primary source of candidates was the catalog of integrated *UBV* photometry for 624 star clusters and associations in the LMC by Bica *et al.* (1996). They derived equivalent SWB types (Searle *et al.* 1980) for these clusters from their location in the $(U-B)$ vs $(B-V)$ diagram. The SWB sequence is related primarily to age (e.g., Elson & Fall 1985; Chiosi *et al.* 1988). In particular, the SWB type VII clusters are known to be comparable to the Galactic GCs in age and abundance. There are 37 clusters in the Bica et al. sample that fall in the SWB type VII domain, 22 of which had no previous CMD available or were not scheduled for observation with the *HST* at the time of our observing run. However, it is known that such integrated data is not foolproof in isolating clusters older than 3 Gyr (Chiosi *et al.* 1988), so that CMDs are required for a definitive diagnosis (Bica *et al.* 1996).

A second source of candidates are 4 clusters (3 of them observed in the present work) from Olszewski *et al.* (1991) which have metallicities $-1.2<[\mathrm{Fe/H}]<-0.8$ but have no further information regarding their age, including SWB type. The age-metallicity relation derived by Olszewski *et al.* for a large number of LMC clusters suggests that any cluster with such a relatively low metallicity is an excellent candidate for type VII membership. For example, the lowest abundance for an IAC is ~ -0.7, while ESO 121-SC03 has a metallicity of -0.9. Thus, these 4 candidates are about as likely as the above sample to provide genuine old clusters.

In Sec. 2 we present the observations and reduction procedure. In Sec. 3 we determine ages based on the magnitude difference between the giant branch clump and the main sequence turnoff. We also discuss the impact of the new clusters on our knowledge of the age distribution of LMC clusters. In Sec. 4 we study stochastic effects of the number of bright stars on the integrated colors, as well as the influence of photometric errors, in particular for less massive clusters. In Sec. 5 we discuss new insights into the chemical enrichment of the LMC afforded by our results. Section 6 presents concluding remarks.

2. OBSERVATIONS AND REDUCTIONS

Twenty three candidate old LMC clusters from Bica *et al.* (1996) and Olszewski *et al.* (1991) were observed with the CTIO 0.9 m telescope in 1996 December with the Tek2k #3 CCD. We also observed ESO121-SC03 as a reference cluster in order to test how deep this instrumental configuration would reach, and as an age calibrator. The scale on the chip is 0.40″ per pixel, and consequently the area covered by a frame (2048^2 pixels) is about $13.6' \times 13.6'$. Two additional Bica *et al.* clusters (NGC 2153 and SL 769) were observed with the CTIO 4 m in February, 1996 with the Tek2k #4 CCD, with similar pixel and areal coverage. For both observing runs, we obtained data in the Washington (Canterna 1976) *C* and Kron-Cousins *R* filters. Geisler (1996) has shown that the latter is a more efficient substitute for the standard Washington T_1 filter, and we used his prescription for a new *C* filter which is both more efficient and also has a much smaller color term than previous *C* filters. We elected to use the Washington system because of its combination of broad bands, and high metallicity sensitivity provided by the *C* filter and the wide color baseline between *C* and T_1. These data, in addition to providing us with age determinations, will also allow us to derive accurate metal abundances based on the standard giant branch technique outlined in Geisler & Sarajedini (1996, 1997), and will be the subject of another paper in this series.

We obtained generally a single 15 minute T_1 (R) exposure and a 45 minute *C* exposure per cluster. Thus, only an hour of total integration time with an 0.9 m telescope was spent on each cluster. The observed clusters are listed in Table 1, together with their integrated *V* magnitudes (Bica *et al.* 1996) and their metallicities (Olszewski *et al.* 1991), when available. In addition to the clusters in the table, we also observed IC 2134 (SL 437, LW 198) and SL 769 which will be discussed in detail elsewhere, due to apparently composite stellar populations in the CMD. Figure 1 shows the T_1 frame of the SL 555 field, which is typical of the magnitude

TABLE 1. Present CMD sample.

Cluster Name	V	[Fe/H]	δT_1	Age(Gyr)
SL8=LW13	13.80	-	1.3	1.6
SL244	13.04	-	1.3^b	1.6^b
SL262=LW146=ESO119SC40	14.25	−0.34	1.7	2.1
NGC1865=SL307	12.91	-	0.4	0.9
SL359	13.74	-	1.4^b	1.8^b
SL388=LW186	13.85	−0.76	1.9	2.6
NGC1928=SL405=HS243[c]	12.47	-	-	-
NGC1939=SL414[c]	11.78	-	-	-
SL446A[a]	13.45	-	1.8	2.3
SL451=LW206	14.20	-	1.7	2.2
SL505	12.64	-	1.3	1.6
SL509=LW221	13.23	-	1.0	1.4
SL549	13.61	-	0.8	1.3
SL555=LW236	13.06	-	1.3	1.6
SL674=ESO86SC26	13.33	-	1.7	2.1
H7=SL735	12.26	-	1.1	1.4
NGC2153=SL792=LW341	13.05	-	0.8	1.3
SL817	14.18	-	1.9	2.5
SL842=LW399	14.15	−0.36	1.6	1.9
SL862=LW431	13.67	-	1.5	1.8
Candidates from Ca II Spectroscopy				
SL126=ESO85SC21	-	−1.18:	1.9	2.5
OHSC33	-	−1.07	0.8	1.2
OHSC37	-	−0.91	2.0	2.7
Control Cluster				
ESO121SC03=KMHK1591	14.04	−0.93	3.0	8.5

[a] SL 446A is located at $\alpha_{1950}=5^h24^m36^s$, $\delta_{1950}=-67°46'18''$ and it was designated SL 446 in the Hodge & Wright (1967) atlas and in Bica *et al.* (1996). However, the original position of SL 446 (Shapley & Lindsay 1963) fits better another cluster to the east. We thus add "A" to the name of the cluster discussed here.

[b] Cluster located in a crowded field, and consequently, δT_1 and age should be taken as a lower limit.

[c] Compact cluster in very crowded field in the LMC bar: δT_1 and age could not be estimated. It remains as a candidate old cluster.

of the cluster sample and the crowding of the field, although our sample includes large ranges in both of these quantities.

The data were reduced with the stand-alone version of the DAOPHOT II program (Stetson 1987) after standard trimming, bias subtraction and flat-fielding. A quadratically varying PSF yielded aperture corrections which were essentially constant with position. The standard FIND-PHOT-ALLSTAR procedure was performed 3 times on each frame, with typically 30000 objects being measured. Mean aperture corrections were generally determined to only 0.01 mag (rms) in both filters in all but the most crowded frames.

In order to standardize our photometry, standard stars from the lists of Harris & Canterna (1979) and Geisler (1996) were observed at the beginning, middle, and end of each night. A mean of 31 standards was observed per night. Although the air mass range of the standards was rather small, it did encompass the range in which our program clusters was observed. Transformation equations of the form:

$$c=C+a_1+a_2\times(C-T_1)+a_3\times X_c; \qquad (1)$$

$$t_1=T_1+b_1+b_2\times(C-T_1)+b_3\times X_{T_1} \qquad (2)$$

were used, where c and t_1 refer to instrumental magnitudes (corrected to 1s integration using a zero point of 25.0 mag), C, T_1 and $(C-T_1)$ are standard values, and the appropriate air masses are given by X. We first solved for all three transformation coefficients simultaneously (using the PHOTCAL package in IRAF[3]) for each night and found mean color terms of $-0.073\pm0.003(\sigma)$ in c and -0.012 ± 0.002 in t_1 for the 5 nights. Note that the c color term in the revised C, T_1 system (Geisler 1996) is 2-3 times lower than typical values obtained with previous C filters, as designed. We then substituted these mean color terms into the above equations and solved for the remaining two coefficients for each night simultaneously. Typical values were 2.2 and 1.8 for the c and t_1 zero points, and 0.45 and 0.3 for the c and t_1 airmass coefficients. The nightly rms errors from the transformation to the standard system ranged from 0.018 to 0.024 in c and 0.010 to 0.020 in t_1, with means of 0.021 and 0.014, indicating the nights were all of excellent photometric quality.

We then applied these transformation equations to the results of the final ALLSTAR run after first applying the appropriate aperture correction. The photometry for the individual clusters will be presented in subsequent papers.

Our CMD for ESO 121-SC03 is shown in Fig. 2. This object was included in our sample because it is the unique cluster within the age gap between the IACs and classical old globulars in the LMC, as found by Mateo *et al.* (1986), and thus serves as a test of how well our technique works. Clearly, we have reached to about a magnitude below the main sequence turnoff in this ≈9 Gyr cluster and we can therefore be confident that our technique should easily be able to distinguish IACs and older clusters for all but the most crowded fields. Indeed, our CMD is very comparable to that of Mateo *et al.* obtained with the CTIO 4m but with a less sensitive chip. The horizontal branch is very clearly defined as is the turnoff. Note that an equal-area field contains typically only 14 stars, which lie either at very red colors or near the main sequence. A statistical subtraction of these objects from the cluster CMD would not significantly change its appearance or the parameters we derive.

3. AGES

The magnitude difference (δ) between the giant branch clump in intermediate age clusters (the horizontal branch in old clusters) and the main sequence turnoff is well correlated with age (e.g., Phelps *et al.* 1994 and references therein). Phelps *et al.* (1994) and Janes & Phelps (1994) have studied a large sample of intermediate age Galactic open clusters with BV CMDs. They concluded that this magnitude difference (as well as the color difference of these features) provides very accurate relative ages, especially for IACs, since it is independent of reddening and distance modulus. The difference is virtually independent of absolute calibrations, and avoids isochrone fitting which can be very model dependent for IACs.

Most of the available CMDs of LMC clusters are V vs

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[3] IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

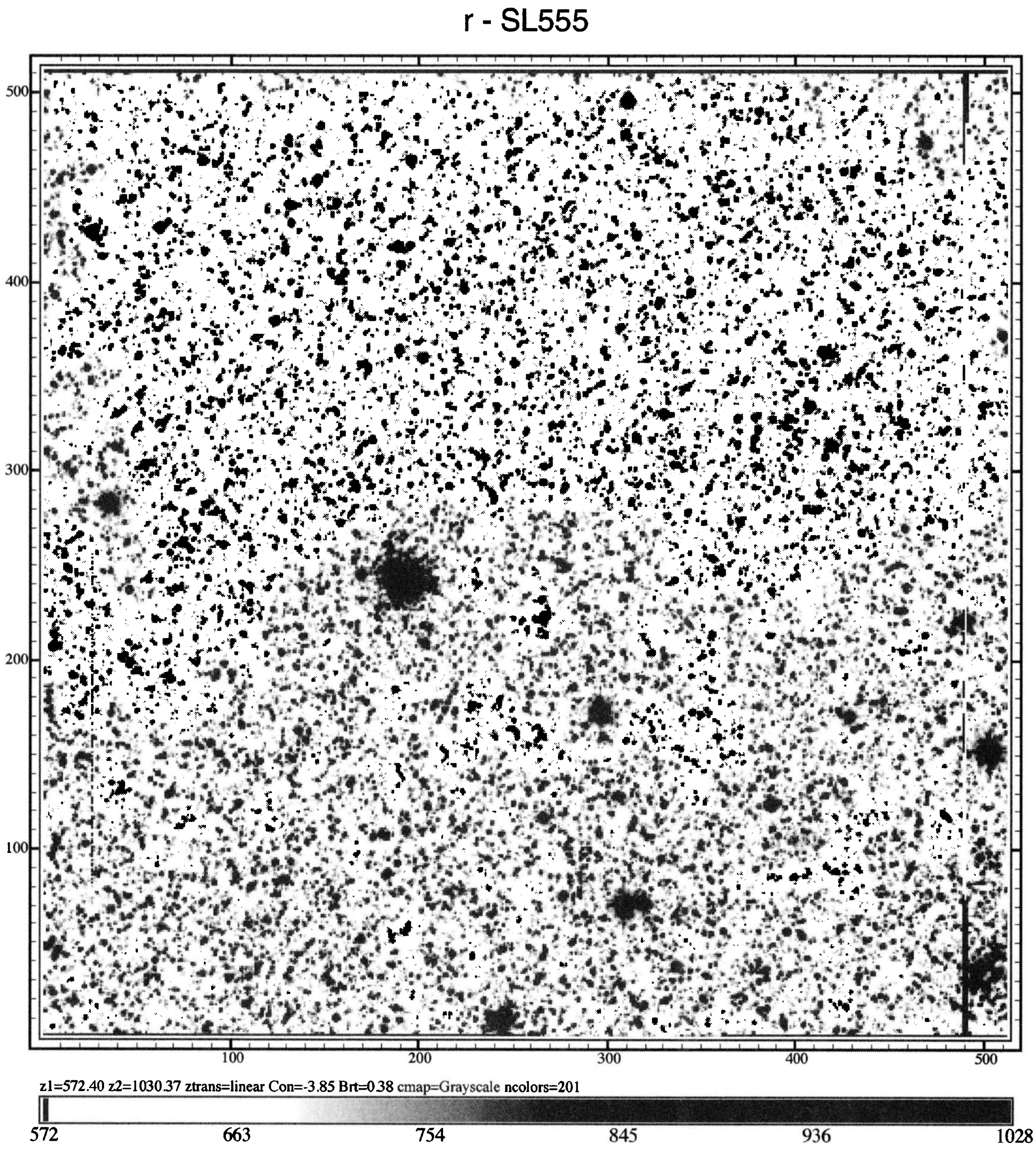

FIG. 1. The $T_1(R)$ frame for the field of SL 555. This is from a 15 minute exposure with the CTIO 0.9 m telescope. The field is 13.6′ on a side. About 33,000 objects were photometered on this frame.

$(B-V)$, with some R vs $(B-R)$ as well. We list in Table 2 all LMC IACs with CMDs reaching the main sequence turnoff, which are not expected to be seriously affected by field contamination. We also include some blue clusters (SWB III) and known old clusters (SWB VII) for comparison purposes. Available integrated V magnitudes and equivalent SWB types are from Bica *et al.* (1996), and metallicities from Olszewski *et al.* (1991). We measured δV and δR for the literature CMDs together with the turnoff magnitudes, and present them in Table 2 as well. Typical errors in these measurements are $\pm 0.15-0.25$ mag. For the present cluster sample, we measured δT_1 values which are presented in Table 1. Note that this should be within ~ 0.02 mag of δR given the similarity of the two filters (Geisler 1996). Typical errors are as above. The clusters NGC 1928 and NGC 1939 are so compact and embedded in such dense bar fields that the photometry is not as deep as for the rest of the sample, and we do not detect the main sequence. Thus, we cannot infer their ages from the present data. Two other clusters, SL 244 and SL 359, are located in dense LMC disk fields, so that the CMDs are very contaminated, and the δT_1 values (and derived ages) should be taken as lower limits (Table 1).

We then tested the similarity of the δV and δR (or δT_1) parameters for the clusters which have observations in both filters. One LMC cluster in the literature, NGC 2213, has been observed in both δR and δT_1: the value $\delta R = 1.3$ (Table 2) is essentially the same, within the uncertainties, as the $\delta T_1 = 1.2$ that we measured in the CMD of Geisler (1987). In addition to the δV vs δR values shown in Fig. 3, we included in the comparison two clusters (SL 842 and ESO 121-SC03) which have δV (Table 2) and δT_1 from the present data (Table 1). Finally, genuine old clusters in the

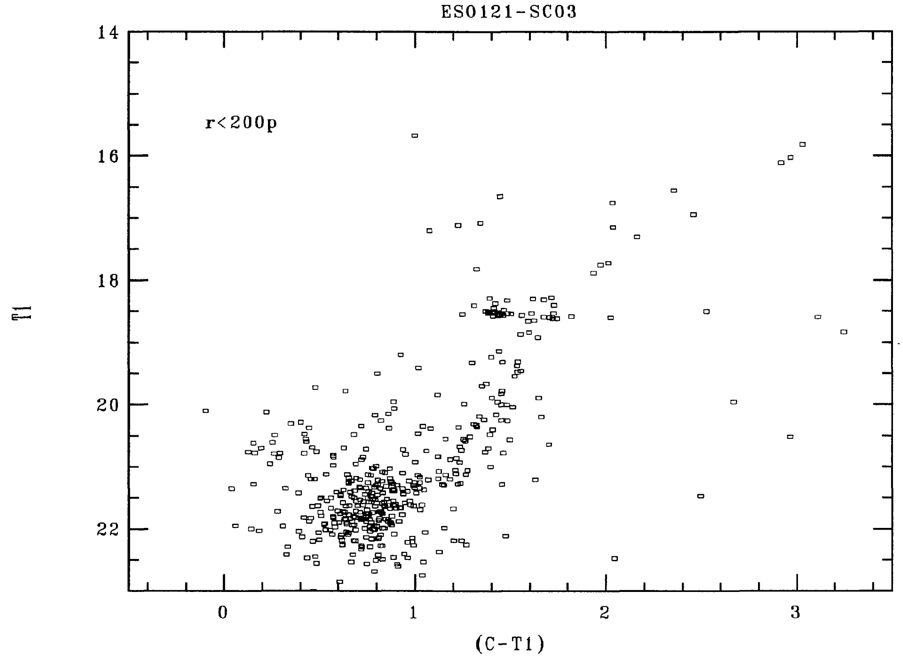

FIG. 2. Washington T_1 vs $(C-T_1)$ CMD for ESO 121-SC03 from a total exposure time of 55 minutes with the CTIO 0.9 m. All objects within 200 pixels of the cluster center are shown. An equal-area adjacent field contains typically only 14 objects. The magnitude difference between HB and turnoff is $\delta T_1=3.0$ (Sec. 3).

LMC have only been observed in *BV* (Table 2); in order to test old clusters in Fig. 3 we compared the average of the latter values ($\langle\delta V\rangle=3.4\pm0.1$) with the average $\langle\delta R\rangle=3.3\pm0.2$ of the Galactic globular cluster Pyxis (from Da Costa 1995; Irwin *et al.* 1995; Sarajedini & Geisler 1996). Some additional points in Fig. 3 were measured from CMDs of Galactic open clusters, for which δV and CMD references are: Tombaugh 2 (1.4, Kubiak *et al.* 1992), M67 (2.2, Montgomery *et al.* 1993), NGC 1245 (0.4, Carraro & Patat 1994), and NGC 6791 (2.9, Montgomery *et al.* 1994). For the same clusters δT_1 and references are given in the discussion of Fig. 5 below. A good correlation is observed in Fig. 3. In fact, a linear least-squares fit gives

$$\delta R=\delta T_1=0.15+0.99\times\delta V \qquad (3)$$

with correlation coefficient of $r=0.993$.

We show in Fig. 4 δV as a function of the V turnoff magnitude, where a good relation is seen. Since the turnoff magnitude is an excellent age indicator, so are also δV, δR, and δT_1. SWB types are also indicated in the figure. For the range $0.3<\delta V<1.2$ the relation is bivalued, and it might be used as an age estimator only when combined with additional information, e.g., integrated color. It is worth noting that the relation presents a minimum for SWB IVA.

3.1 Ages From δT_1

For the clusters in our sample, we first derive an age calibration based on clusters which have δT_1 values available, as well as accurate ages. There are 6 such clusters: NGC 2213 ($\delta T_1=1.2$ mag, age=1.5 Gyr, Geisler 1987) and ESO 121-SC03 (3.0 mag—this paper, 9 Gyr—Mateo *et al.* 1986) in the LMC, and the Galactic open clusters NGC 1245 (0.5 mag, 1 Gyr—Wee & Lee 1996), Tombaugh 2 (1.5 mag, 2 Gyr—Wee *et al.* 1996), M67 (2.4 mag—Geisler & Sarajedini 1997, 4 Gyr—Dinescu *et al.* 1995) and NGC 6791 (3.2 mag—Geisler & Sarajedini 1997, 10 Gyr—Tripicco *et al.* 1995). Figure 5 plots these points together with a least-squares fit which was obtained by means of the IRAF routine FITPARAM. The resulting equation is

$$\mathrm{age(Gyr)}=0.23+2.31\times\delta T_1-1.80\times\delta T_1^2+0.645\times\delta T_1^3 \qquad (4)$$

with an uncertainty of ~0.4 Gyr over the age range of IACs. We note that a relation of the form: age $\propto 10^{(a\delta T_1+b\delta T_1^2)}$, as used by Janes and Phelps, did not fit the data as well as this relation. We then applied Eq. (4) to our program sample and the results are given in column 5 of Table 1.

Our intriguing result is that all the old cluster candidates where we could determine δT_1 turned out to be IACs, with ages between $\sim1-3$ Gyr. Figures 6 and 7 show two of our CMDs, including one cluster (H7, 1.4 Gyr) in the middle of the age range of our sample and a cluster amongst the oldest in our sample (SL 388, 2.6 Gyr). The increasing difference between the clump and the turnoff is obvious, but even in SL 388 this difference is still ~1 mag less than that in ESO 121-SC03. In Sec. 4 we discuss several likely explanations for why the candidates from the *UBV* integrated photometry turned out not to be old clusters. As for the three candidates from the Olszewski *et al.* (1991) sample, selected because of their relatively low metallicities ([Fe/H]≈-1.0), they too turned out to be IACs. These will be discussed further in Sec. 5.

Two of the integrated *UBV* candidates for old clusters have not been observed in the present study. SL 354 (LW

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TABLE 2. CMDs from the literature

Cluster Name	V	SWB	[Fe/H]	V_{TO}	R_{TO}	δV	δR	CMD ref.	Age(Gyr) lit.	Age(Gyr) this paper
NGC1866=SL319=LW163	9.73	III	-	17.20	-	1.1	-	1	0.1	-
NGC1953=SL459	11.74	III	-	-	17.42	-	0.9	3	0.25	-
NGC2010=SL531	11.72	III	-	17.10	-	0.9	-	4	0.12	-
NGC2031=SL577	10.83	III	-	-	16.92	-	1.4	40	0.14	-
NGC2134=SL760	11.05	III	-	17.72	-	0.5	-	2	0.19	-
NGC1756=SL94	12.24	IVA	-	17.80	-	0.3	-	5	-	-
NGC1831=SL227=LW133	11.18	IVA	+0.01	18.60	-	0.1	-	5	-	-
				18.92	-	0.5	-	6	0.40	-
NGC1868=SL330=LW169	11.57	IVA	−0.50	19.40	-	0.3	-	5	-	-
				19.33	-	0.3	-	7	0.70	-
NGC2107=SL679	11.51	IVA	-	18.25	-	0.7	-	5	-	-
NGC1777=SL121=LW96	12.80	IVB	−0.35	20.10	19.70	0.6	0.7	10	0.90	1.2,1.2
NGC2209=SL849=LW408	13.15	IVB	-	19.80	-	0.3	-	5	-	1.0
				19.58	-	0.3	-	8	1.2	0.9
NGC2249=SL893=LW479	11.94	IVB	-	19.14	-	0.4	-	2	0.55	1.0
				19.66	-	0.5	-	9	0.6	1.2
NGC1651=SL7=LW12	12.28	V	−0.37:	-	20.25	-	1.6	19	2.0	2.0
SL28=LW47	13.53	V	−0.37:	20.50	-	1.1	-	14	2.0	1.5
SL61=LW79	13.99	V	−0.50	20.74	-	1.3	-	18	1.8	1.8
NGC1783=SL148	10.93	V	-	-	19.65	-	0.9	20	0.9	1.3
NGC1795=SL165	12.42	V	−0.23	-	19.74	-	1.3	12	0.9	1.7
H14=SL506=LW220	13.42	V	−0.66	-	20.54	-	1.4	12	2.5	1.8
H4=SL556=LW237	13.33	V	−0.15	20.90	20.70	1.9	2.1	11	2.0	2.8,3.2
NGC2162=SL814=LW351	12.70	V	−0.23	19.62	-	0.7	-	17	0.7	1.3
				19.80	-	0.7	-	5	-	1.3
NGC2190=SL819=LW357	12.94	V	−0.12	19.79	-	0.4	-	17	0.7	1.1
				19.90	-	0.5	-	5	-	1.2
NGC2193=SL839=LW387	13.42	V	-	-	20.30	-	1.8	16	2.2	2.3
NGC2213=SL857=LW419	12.38	V	−0.01	-	19.85	-	1.3	15	1.3	1.6
NGC2231=SL884=LW466	13.20	V	−0.67	20.19	-	1.0	-	13	1.3	1.5
SL455=LW207	14.12	VI	−0.77	20.31	-	1.3	-	14	2.0	1.7
NGC1978=SL501	10.70	VI	−0.42	20.93	20.53	1.4	1.7	23	2.2	1.9,2.1
				20.47	-	1.5	-	24	2.0	2.0
NGC2121=SL725=LW303	12.37	VI	−0.61	20.07	-	1.5	-	22	0.4	2.0
NGC2173=SL807=LW348	11.88	VI	−0.24	20.32	20.25	1.6	1.7	39,5	1.8	2.2,2.1
NGC2203=SL836=LW380	11.29	VI	−0.52	20.52	-	1.4	-	21	1.0	1.8
NGC2241=SL888=LW471	13.25	VI	-	20.42	-	1.4	-	9	3.5	1.9
ESO121SC03	14.04	VII	−0.93	21.60	-	3.0	-	25	9.0	9.2
NGC1466=SL1=LW1	11.59	VII	−2.17	22.49	-	3.3	-	32	-	12.7
RETICULUM=Sersic40/3 =ESO118SC31	14.25	VII[a]	-	22.39	-	3.6	-	28	17.0	16.7
NGC1786=SL149	10.88	VII	−1.87	22.35	-	3.5	-	27	15.0	15.2
NGC1841=ESO4SC15	11.43	VII	-	22.50	-	3.3	-	27	15.0	12.5
				22.31	-	3.2	-	29	-	11.9
NGC2210=SL858=LW423	10.94	VII	−1.97	22.51	-	3.5	-	27	15.0	15.8
H11=SL868=LW437	11.93	VII	−2.06	22.52	-	3.5	-	26	15.0	15.2
NGC2257=SL895=LW481	12.62	VII	-	22.20	-	3.2	-	38	13.0	11.9
				22.19	-	3.2	-	30	15.0	12.1
				22.29	-	3.5	-	31	14.0	15.8
SL354=LW177	13.65	VII[b]	−0.08	20.49	-	1.5	-	14	2.2	2.0
SL842=LW399	14.15	VII[b]	−0.36	20.69	-	1.5	-	14	3.0	2.0
LW75=SL59w	-	-	-	19.52	-	0.6	-	33	0.8	1.2
LW76=SL59e	-	-	-	19.57	-	0.6	-	33	0.8	1.2
SL869=LW441	-	-	-	19.91	-	0.9	-	34	1.5	1.4
SL34=LW55	-	-	-	19.92	-	1.0	-	33	1.0	1.5
H88-1=NC1	-	-	-	20.34	-	1.0	-	35	1.6	1.5
SL832=LW376	-	-	-	20.14	-	1.0	-	36	0.8	1.5
SL4=LW4	-	-	-	20.64	-	1.2	-	30	2.0	1.7
	-	-	-	20.16	-	1.1	-	35	1.4	1.5
LW195=ESO119SC61	-	-	−0.33	20.52	-	1.5	-	14	2.0	2.1
E2=ESO120SC8	-	-	−0.70	20.76	-	1.6	-	37	2.0	2.2

[a] Candidates from the integrated photometry for old clusters, which CMDs revealed to be intermediate age ones.

[b] Genuine old cluster but located in the SWB V zone.

Note. 1. Brocato *et al.* 1989; 2. Vallenari *et al.* 1994; 3. Mould *et al.* 1993; 4. Mateo 1988a; 5. Corsi *et al.* 1994; 6. Hodge 1984; 7. Flower *et al.* 1980; 8. Dottori *et al.* 1987; 9. Jones 1987; 10. Mateo & Hodge 1985; 11. Mateo & Hodge 1986; 12. Jensen *et al.* 1988; 13. Walker 1979; 14. Olszewski 1988; 15. Da Costa *et al.* 1985; 16. Da Costa *et al.* 1987; 17. Schommer *et al.* 1984; 18. Mateo & Hodge 1987; 19. Mould *et al.* 1986; 20. Mould *et al.* 1989; 21. Harris *et al.* 1983; 22. Flower *et al.* 1983; 23. Bomans *et al.* 1995; 24. Olszewski 1984; 25. Mateo *et al.* 1986; 26. Mighell *et al.* 1996; 27. Brocato *et al.* 1996; 28. Gratton & Ortolani 1987a; 29. Walker 1990; 30. Hesser *et al.* 1984; 31. Stryker 1983; 32. Walker 1992b; 33. Westerlund *et al.* 1995; 34. Walker 1993; 35. Hodge & Flower 1987; 36. Hardy *et al.* 1980; 37. Gratton & Ortolani 1987b; 38. Testa *et al.* 1995; 39. Mould *et al.* 1986; 40. Mould *et al.* 1993

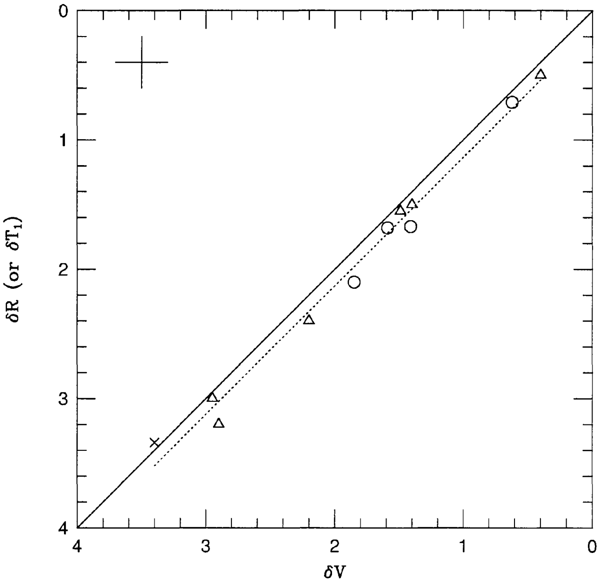

FIG. 3. Comparison of the magnitude difference (δ) between clump/HB and turnoff in different filters: circles are R vs V, triangles are T_1 vs V, X is R (Pyxis) vs V (LMC old clusters). Typical error bars are shown. As reference, we show the line of equal values for the axes (solid line). We show also a linear fit (dashed line).

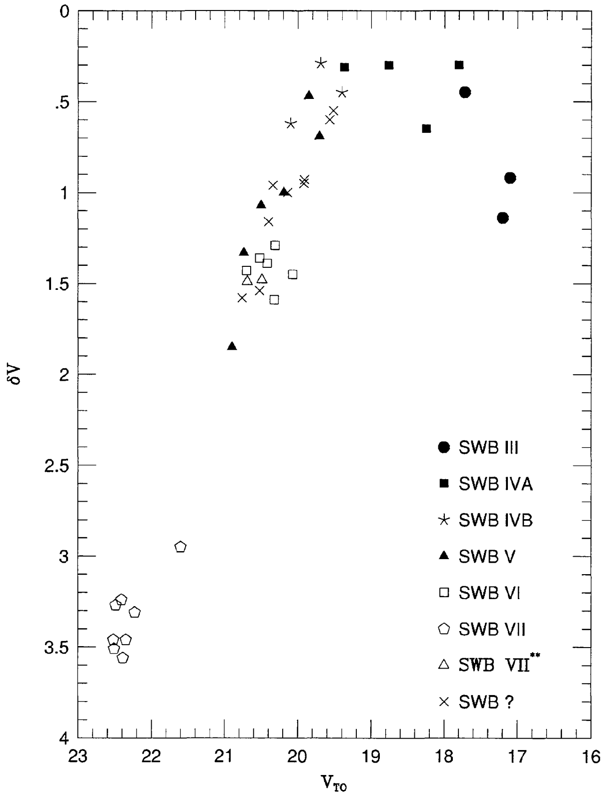

FIG. 4. δV vs turnoff V magnitude. Different SWB types are indicated, when available. Triangles represent SWB VII clusters from Bica *et al.* (1996) which we find to be IACs.

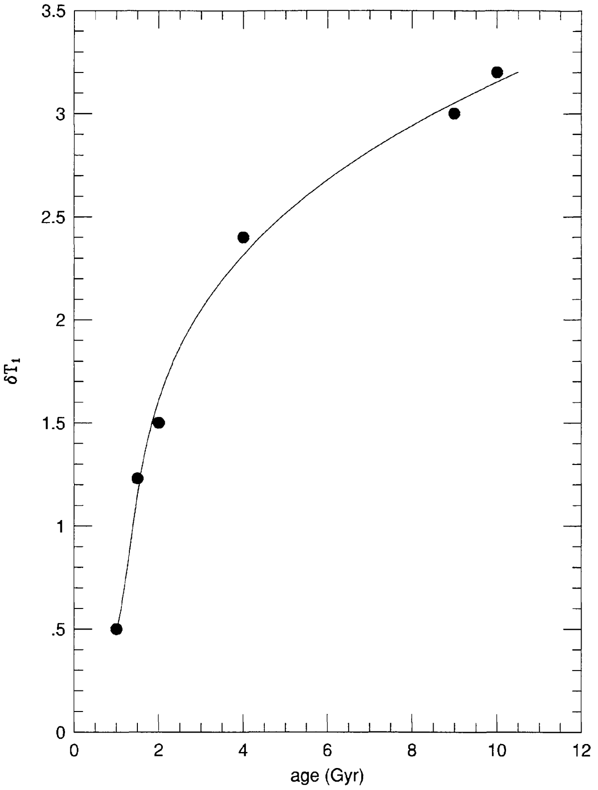

FIG. 5. Age calibration of the δT_1 index, i.e., the mag. difference in T_1 between the clump/HB and the turnoff, derived from LMC and Galactic clusters with good main sequence photometry and accurate ages. The curve is a 3rd order fit.

177) has a preliminary *BV* CMD (Olszewski 1988) indicating intermediate age (Table 2). NGC 1997 (SL 520, LW 226) does not have a published CMD but the high metallicity from the Ca II spectroscopy (Olszewski *et al.* 1991) also points to an intermediate age.

3.2 Ages For the Combined Sample

Using Eq. (3) it is possible to transform δV into equivalent δT_1 values, and by means of the age calibration for δT_1 [Eq. (4)], to estimate homogeneous relative ages for the literature sample of CMDs in Table 2. For the sample of CMDs involving the R band, δR values are used directly in Eq. (4), due to the equivalence with δT_1. The resulting ages are provided in column 11 of Table 2. For comparison purposes we also give in Table 2 (column 10) the age values derived in the original CMD source papers. The overall agreement is good. However, since in the CMD sources different sets of isochrones and different fitting criteria were used, the magnitude difference (δ) between clump/HB and turnoff method is more homogeneous, and consequently the relative ages in the present study are expected to be more precise.

We show in Fig. 8 the age histograms for the IACs and old clusters (including ESO 121-SC03) from both Tables 1 and 2 using the presently derived ages. Notice that the age

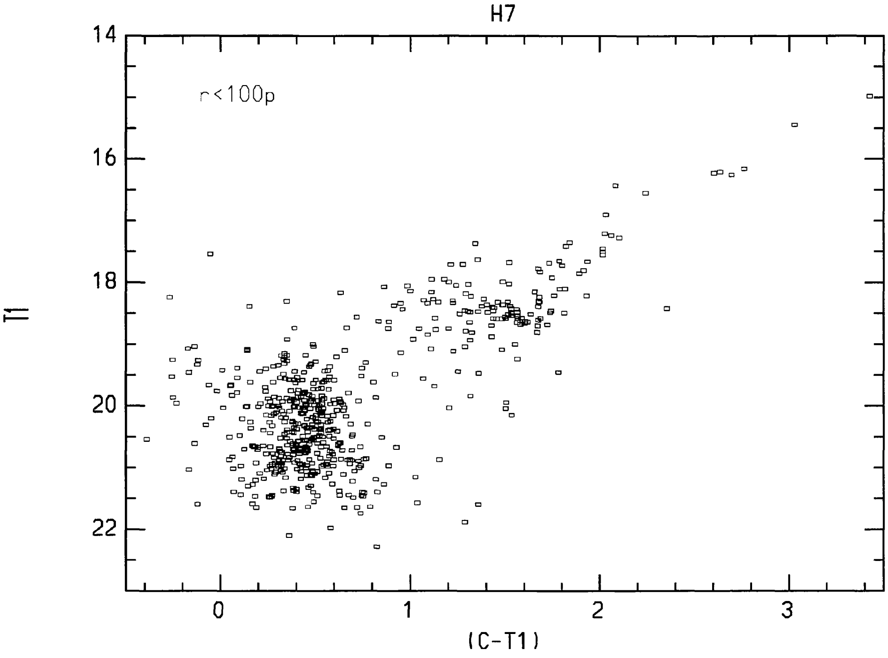

FIG. 6. CMD for H7, a cluster in the middle of the age range of our sample. Note that $\delta T_1 = 1.1$. All objects within 100 pixels of the cluster center have been included. An equal-area adjacent field typically has only about 1/3 as many stars, concentrated to the main sequence.

scale is linear and the bins are 0.2 and 1 Gyr for IACs and old clusters, respectively. This figure synthesizes all age information that can be derived from CMDs available in the literature for LMC clusters attaining the main sequence turnoff, in conjunction with the present sample. We are possibly witnessing the structure of the 1–3 Gyr cluster forming epoch, assuming that cluster disruption effects (Wielen 1988) are negligible. In such a case, the IAC distribution in Fig. 8 would suggest that a burst of star formation occurred, with onset at ≈3 Gyr and a peak at ≈1.6 Gyr. We cannot apply the present age calibration for ages <1 Gyr and consequently incompleteness may affect the distribution at ≈1 Gyr. Alternatively, assuming a constant star formation rate of 10 clusters per 200 Myr (peak of the distribution), the IAC distribution between 1.5 and 3 Gyr would imply a cluster disruption rate of 77% per Gyr.

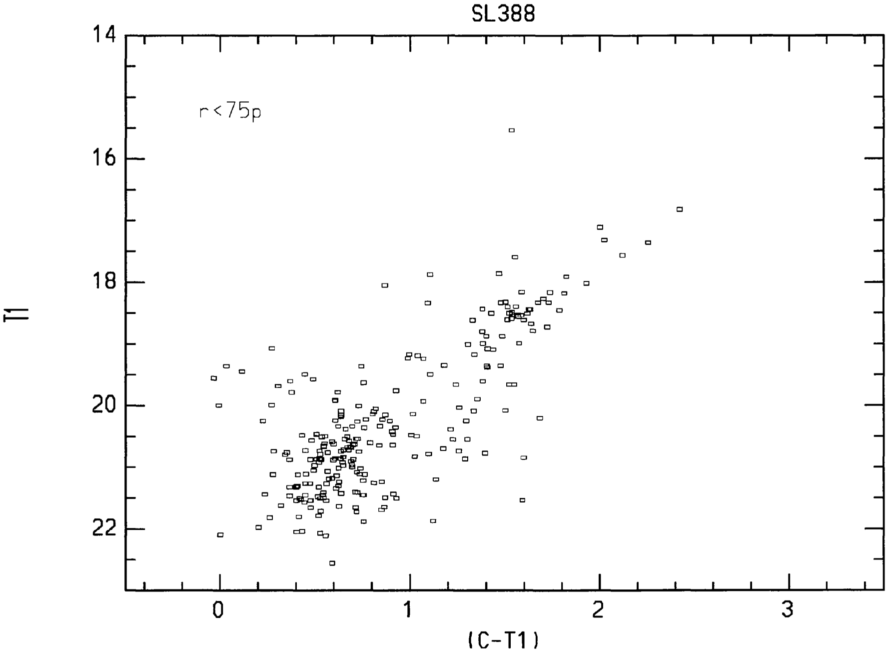

FIG. 7. CMD for SL 388, a cluster among the oldest IACs in our sample. Note that $\delta T_1 = 1.9$. All objects within 75 pixels of the cluster center have been included. An equal-area adjacent field typically has only about 1/10 as many stars, concentrated to the main sequence.

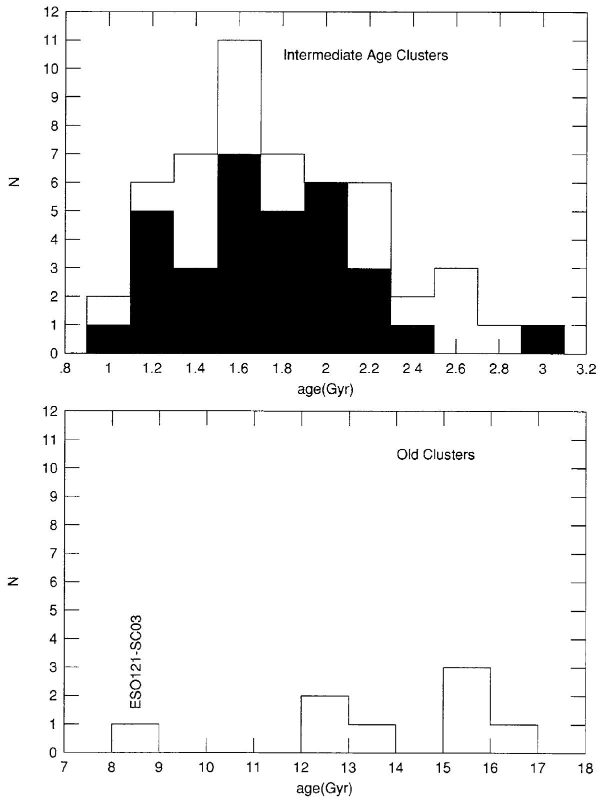

FIG. 8. Age histograms for the IACs (upper panel) and old clusters (lower panel) from Tables 1 and 2. Filled bins in the upper panel refer to clusters with previous CMDs in the literature, while the results from our photometry are shown as the open bins.

Our results confirm previous findings (e.g., Da Costa 1991) that the LMC apparently did not form clusters between 3–8 Gyrs ago, a period covering more than 1/3 of its lifetime, and that it only formed a single (surviving) cluster between 3 Gyr and the epoch of formation of the classical globular clusters. We have also found additional evidence that the onset of IAC formation occurred at 3 Gyr. These results are also in very good agreement with studies of the star formation history of the LMC field, which find an intense star formation event occurred ~2–3 Gyr ago, with little star formation before that time (Butcher 1977; Gallagher *et al.* 1996; Elson *et al.* 1997). This argues against the possibility that the lack of older clusters is due to disruption.

The sample of old clusters is too small for a discussion of the distribution. However, it is worth noting that the δ method detects significant age differences between ESO 121-SC03 and the older clusters. Also note that we have extrapolated our calibration to derive ages for these clusters so their ages are more uncertain.

4. STOCHASTIC EFFECTS ON INTEGRATED COLORS

The brightest LMC clusters ($10<V<12.5$) were used by Searle *et al.* (1980) to define the SWB zones in a color-color diagram based on the Gunn system. Bica *et al.* (1992) have transposed this (mostly age) sequence to the integrated $(U-B)$ vs $(B-V)$ diagram, creating borderlines which encompassed the known SWB clusters. Bica *et al.* (1996) determined equivalent SWB types for a large sample, including clusters fainter than $V=14$. Since the number of stars in different evolutionary stages in the CMDs are subject to stochastic effects, fluctuations in integrated colors are expected, and should become increasingly important for fainter clusters as the number of bright stars decreases and the relative importance of statistical fluctuations increases.

Stochastic effects on optical colors have been previously studied by King (1966), Barbaro & Bertelli (1977), Chiosi *et al.* (1988), Girardi & Bica (1993), and Girardi *et al.* (1995). In Girardi & Bica (1993) special attention was devoted to red supergiants, which produce large color dispersions for SWB I clusters. More recently Santos & Frogel (1997) have studied such effects in optical and infrared integrated colors, and found that significant color dispersions in *JHK* arise at different ages due to AGB and red supergiant stars even for massive clusters.

In the present study we carried out experiments on integrated *UBV* color fluctuations due to Poissonian noise in the number of bright stars in different parts of the CMD of individual clusters. We tested stars in the cluster turnoff, clump and giant branch (GB) tip, and field (LMC disk) bright main sequence (MS) stars. The experiments indicated that GB tip and bright field MS stars are the relevant ones to explain the suspected integrated color shifts. We adopted typical stellar magnitudes and colors as observed in *BV* CMDs of the SWB VI clusters like NGC 1978 (Bomans *et al.* 1995): $V=16.8$, $(B-V)=1.70$ for a GB tip star, and $V=16.8$, $(B-V)=-0.10$ for an MS star. Since CMDs involving the U color are not available for such LMC clusters, we adopted solar neighborhood $(U-B)$ values from Gunn & Stryker (1983) and reddened them according to the LMC foreground reddening $E(B-V)=0.06$ (Mould & Aaronson, 1980), resulting in $(U-B)=2.00$ for a GB tip star (M1/M2 III), and $(U-B)=-0.45$ (B5 V) for a field MS star.

The results are shown in Fig. 9. Clusters like SL 842 and SL 8 are outlying and faint, with $V\approx 14.0$. Their fields are not significantly disturbed by bright MS stars, but their integrated colors can be shifted from their observed positions as type VII clusters to the type VI domain by simply adding 4-5 upper GB stars to their relatively underpopulated CMDs. H 7, a brighter cluster ($V=12.2$), lies in a more central field, where the contribution of LMC disk stars is significant. The arrows in Fig. 9 show the effects of subtracting 3 GB and adding 3 MS stars. A combination of such stars and/or Galactic foreground stars of suitable magnitude and colors might explain the observed cluster locus. Finally, we show the effect of subtracting two field MS stars from the massive cluster NGC 1978. The shift is only moderate despite the large color differences between the cluster and these blue stars. The effects of adding 4 upper GB stars is only to redden both colors by 0.01 mag.

Thus, it appears reasonable from these experiments that faint, apparently old clusters lying in the lower right region of the type VII domain could actually be SWB type VI IACs with a relatively small number of giants, or similarly that an apparent VII in the upper left domain is actually a type IV IAC with a relatively large number of bright giants.

Fluctuations also appear to occur in the opposite sense, as

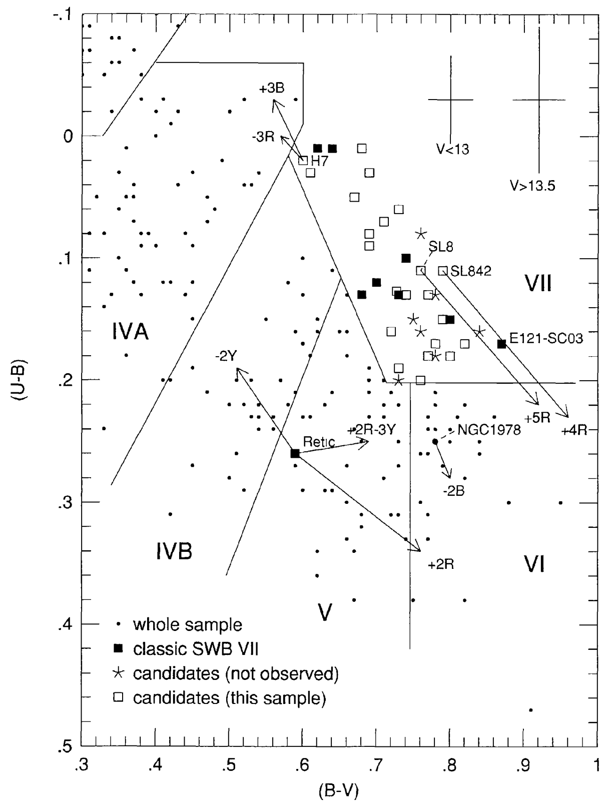

FIG. 9. Enlargement of Fig. 2(a) from Bica *et al.* (1996), showing the integrated $(U-B)$ vs $(B-V)$ diagram for LMC clusters (dots), except: (i) fiducial old clusters (filled squares), (ii) candidate old clusters not studied in the present sample (asterisks), (iii) candidates from the present sample (open squares). Arrows leading from some of these clusters show the effects of possible fluctuations produced by small changes in the number of bright stars. R represents the addition (or subtraction) of upper giant branch stars; B field main sequence stars; Y yellow bright stars (probably Galactic field stars). The error bars show total photometric errors for our program clusters. Both of these effects together can account for the presence of IACs in the type VII domain.

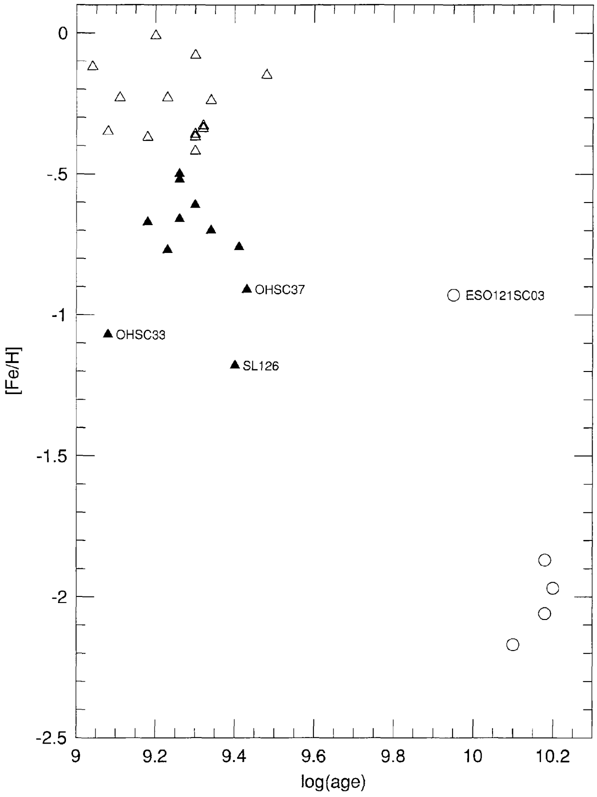

FIG. 10. Chemical evolution of the LMC for IACs (triangles) and old clusters (circles). The more metal poor IACs are indicated by filled triangles, and the candidates from Olszewski *et al.* are labelled.

discussed by Bica *et al.* (1996): the giant branch of the old, faint cluster Reticulum is so sparsely populated that it is located in the SWB V region, despite having an age indistinguishable from that of M3 (Walker 1992a). Since Reticulum is a metal poor globular cluster (Gratton & Ortolani 1987a; Walker 1992a), the bright giant used for the experiment must be accordingly metal poor. We used $V=17.5$, $(B-V)=1.02$, $(U-B)=0.57$ (Gratton & Ortolani 1987a; Eggen 1972). Thus in Fig. 9 the R arrow associated with Reticulum corresponds to a different star from that used for the IACs. Reticulum is far out in the LMC where the LMC disk main sequence is absent. Some bright yellow stars (probably Galactic field) are however present in that CMD. We also include in our experiments (Y in Fig. 9) this type of star, adopting $V=16.7$, $(B-V)=0.65$, and $(U-B)=0.27$. The $(U-B)$ value is from a Galactic G5 V star from Gunn & Stryker (1983), reddened to the LMC extinction. The experiments in Fig. 9 show that, in combination with photometric errors, Reticulum's integrated colors might move to the SWB VII zone.

In the present work we have investigated the influence of a few bright stars on the integrated light of IACs. Specifically, we are not computing a standard deviation from the mean integrated color but we are simply adding or subtracting the flux produced by selected star types from the cluster observed integrated color. Consequently, in comparison with the statistical analysis in Girardi *et al.* (1995), who studied cluster color dispersions, we are studying the color effects produced by stars in the tail of the Gaussian distribution, which lead to larger color fluctuations. The variable observed number of bright giants in clusters of similar age and mass shows the importance of the present approach. We also took into account bright field stars, especially those differing significantly in color with respect to the cluster mean color.

In addition to stochastic fluctuations, photometric errors also likely contribute to the presence of IACs in the type VII area. We show in Fig. 9 total photometric error bars for bright and faint clusters from Bica *et al.* (1996). Observational errors will be particularly large for fainter clusters in more crowded regions.

5. DISCUSSION

In the most recent discussion of the chemical evolution of LMC clusters, Olszewski *et al.* (1991) used metallicities from the Ca II triplet and ages from the literature obtained from CMDs. Although their metallicities were on a uniform scale, the ages were from a variety of studies and are not

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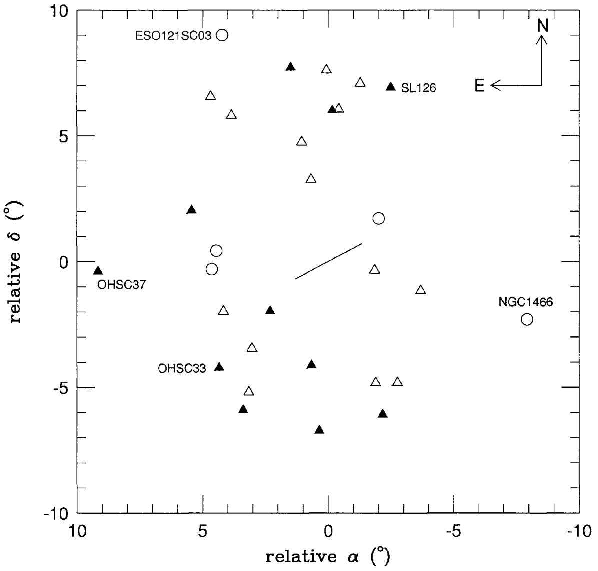

FIG. 11. Spatial distribution of clusters which have both metallicity values (Olszewski *et al.* 1991) and ages from CMDs as determined in this paper. As a reference, the LMC bar is schematically indicated.

homogeneous. In the present paper, although no new genuine old clusters were detected, we have increased the number of IACs with CMDs and accurate ages by ≈50%, and also derived homogeneous relative ages for all LMC clusters with reliable CMDs. We can thus address the question of the chemical evolution of LMC clusters using an improved dataset.

We show in Fig. 10 the resulting chemical evolution of the LMC for the IACs and old clusters. The spatial distribution of these clusters is shown in Fig. 11. The three new clusters (OHSC 33, SL 126, and OHSC 37) from the Ca II spectroscopy with metallicities [Fe/H]~-1.0 (Table 1) have ages in the range 1–3 Gyr. They fall below (i.e. at lower metallicities than) the bulk of IACs in the cluster age-metallicity relation, suggesting that their parent gas clouds have not shared the same enrichment as that for the IACs located in the upper-left region of Fig. 10. Note that the metallicity of the old cluster ESO 121-SC03 is also ~-1.0, which confirms that the LMC has not undergone important star formation processes during the period from 3–9 Gyr ago, and consequently also not experienced significant chemical enrichment.

The IAC sample with $-1.2<$[Fe/H]<0.0 is separated into two metallicity groups in Fig. 10. Their spatial distribution in Fig. 11 is well-mixed, suggesting no significant metallicity gradient for the disk, as also found by Olszewski *et al.* (1991). Nevertheless, it is necessary to know the dynamics of the clusters in order to investigate whether there exists any similarity between the present abundance distribution in the disk and the so-called paleodistributions, namely, the distribution in metallicity of the gas out of which the clusters were generated. Note that the LMC IACs' metallicity range is twice as large as that of Galactic open clusters. The former were mostly born during an ~2 Gyr period, while the formation of the Galactic open cluster system took at least 6-8 Gyr (see Fig. 3 of Piatti *et al.* 1995). This fact suggests that the LMC has suffered more violent star formation processes than those that occurred during the formation of the Galactic disk. Some IACs have been born in regions whose chemical enrichment ocurred on a shorter time scale than those for other parts of the LMC disk. On the other hand, the fact that there exist IACs with different metal contents within the same spatial region (see Fig. 11) suggests that parts of the LMC were not chemically well-mixed, or that the progenitor gas clouds of differing metallicity that originated in different regions have subsequently been brought together by large random motions.

6. CONCLUDING REMARKS

We have obtained CMDs from Washington C,T_1 photometry for 25 candidate old clusters in the LMC and determined ages from the T_1 magnitude difference (δ) between the giant branch clump and the main sequence turnoff for 23 of these. The calibration of age vs (δT_1) was obtained using LMC and Galactic clusters with well-determined parameters. Our technique is capable of detecting the main sequence of a 10 Gyr old cluster in an uncrowded field in 1 hour of observing with a 0.9 m telescope, as demonstrated by the present photometry of the "standard" cluster ESO 121-SC03.

The candidates turned out to be of intermediate age (1–3 Gyr), although we cannot rule out old age for NGC 1928 and NGC 1939, which are compact and are located in crowded bar fields. The reason why integrated photometry can confuse intermediate age clusters with genuine old ones can be understood by stochastic effects produced by bright cluster giants and bright field main sequence stars for clusters fainter than $V\approx13.5$, and by photometric errors for faint clusters in crowded fields.

The present study constitutes a significant increase in the sample of intermediate age clusters in the LMC with CMDs. The determination of relative ages allows one to obtain accurate information on the LMC history of cluster formation/disruption for ages >1 Gyr. Our results confirm that the LMC apparently did not form clusters between 3–8 Gyr ago, and that it only formed a single (surviving) cluster between 3 Gyr and the epoch of formation of the classical globular clusters. We have also found additional evidence that the onset of IAC formation ocurred at 3 Gyr.

The relatively metal poor ([Fe/H]≈-1.0) candidates from the Ca II triplet spectroscopy also turned out to be of intermediate age. They occupy a locus below that of the bulk of the intermediate age clusters in the LMC age-metallicity relation of Olszewski *et al.* (1991). These clusters (SL 126, OHSC 33, OHSC 37) are outlyers in the LMC disk, suggesting that part of the parent gas clouds in these regions have not shared the same chemical enrichment as that in the inner regions, or that the outer gas clouds were not chemically well-mixed. This result points to new interesting scenarios to be explored for formation and evolution models of the LMC. We will readdress the issue of metallicities in our program clusters in a future paper.

In addition to the eight LMC clusters already established as old by means of deep CMDs and the presence of RR Lyraes, NGC 1939, and NGC 1928 are still candidates together with NGC 1754, NGC 1898, NGC 1916, NGC 2005, and NGC 2019. High spatial resolution photometry, e.g., with *Hubble Space Telescope*, is necessary for a definitive diagnosis of these clusters and indeed such studies are underway. Our investigation of the possible missing faint old clusters has yielded no new members. It is however possible that such clusters do exist but have not yet been identified. For example, Wielen (1988), using the results of Mateo (1988b), argues that a typical dissolution time is ~ 2 Gyr for a cluster in the outer LMC with an initial mass of 500 $M_\odot$ and a core radius of 1 pc. Thus, among the large number of faint unstudied clusters, several clusters older than ~ 3 Gyr may exist. Our technique of obtaining the CMD directly is quite efficient for searching for such clusters, requiring only an hour of time on an 0.9 m telescope per cluster, and no followup observations are required, at least for clusters not severely affected by crowding.

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