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Constraining the LMC cluster age gap: Washington photometry of NGC 2155 and SL 896 (LW 480)

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ABSTRACT

We carried out Washington system photometry of the intermediate-age Large Magellanic Cloud (LMC) star clusters NGC 2155 and SL 896 (LW 480). We derive ages and metallicities from the T_1 versus $C - T_1$ colour–magnitude diagrams (CMDs). For the first time an age has been obtained for SL 896, 2.3 ± 0.5 Gyr. For NGC 2155 we derive 3.6 ± 0.7 Gyr. The two clusters basically define the lower age limit of the LMC age gap. In particular, NGC 2155 is confirmed as the oldest intermediate-age LMC cluster so far studied. The derived metallicities are $[Fe/H] = -0.9 \pm 0.2$ and -0.6 ± 0.2 for NGC 2155 and SL 896, respectively. We also studied the CMDs of the surrounding fields, which have a dominant turn-off comparable to that of the clusters themselves, and similar metallicity, showing that one is dealing with an intermediate-age disc where clusters and field stars have the same origin. We inserted the present clusters in the LMC and Small Magellanic Cloud (SMC) age–metallicity relations, using a set of homogeneous determinations with the same method as in our previous studies, now totalling 15 LMC clusters and four SMC clusters, together with some additional values from the literature. The LMC and SMC age–metallicity relations appear to be remarkably complementary, since the SMC was actively star-forming during the LMC quiescent age gap epoch.

Key words: techniques: photometric – galaxies: individual: LMC – Magellanic Clouds – galaxies: star clusters.

1 INTRODUCTION

The cluster formation history of the Magellanic Clouds constitutes one of the most visible records of the formation and evolution patterns of these galaxies. Da Costa (1991) first drew attention to the existence of a substantial gap in the age distribution of Large Magellanic Cloud (LMC) star clusters. Although this galaxy has a number of bona fide old 'globular' clusters similar to those in our Galaxy, and also contains a rich population of young and intermediate-age clusters (IACs), there is only a single cluster known with an age between ~3 and 12 Gyr. A variety of recent studies have dedicated efforts to improve ages and metallicities, and increase the sample of old clusters and IACs in order to delineate this gap more accurately and search for more clusters that might lie within it (e.g. Geisler et al. 1997). Using *Hubble Space Telescope* (*HST*) *BV* colour–magnitude diagrams (CMDs), Sarajedini (1998, hereafter S98) argued that the populous LMC clusters NGC 2121, NGC 2155 and SL 663 have ages of ≈4 Gyr, thus lying slightly within the gap as previously determined, or alternatively indicating a smaller age range for the gap. Recently, Rich, Shara & Zurek (2001) found an age of 3.2 ± 0.5 Gyr for NGC 2121 using their own deeper *HST* observations. The sample of genuine LMC globular clusters (i.e. with ages similar to those of Galactic globulars) with *HST* CMDs is now significant (e.g. Olsen et al. 1998; Johnson et al. 1999). Surprisingly, recent *HST*-based field star studies (e.g. Geha et al. 1998; Olsen 1999; Holtzman et al. 1999) have made it increasingly clear that this age gap apparently does *not* exist in the general LMC field. However, Harris & Zaritsky (2001) have very recently argued from their relatively shallow ground-based data that this gap may indeed also exist in the field star age distribution.

Clearly, the presence and nature of the age gap, both in the clusters as well as in the field, require substantially more work. The improved determination of the LMC overall cluster

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age–metallicity relation (AMR) can give further constraints for a more realistic modelling of the history of star formation and chemical enrichment. Cluster giants with high dispersion spectroscopy can provide fundamental calibrations and detailed elemental ratios, such as those obtained for 10 giants observed recently with VLT/UVES in four clusters widely distributed in age (Hill et al. 2000). Dirsch et al. (2000) have discussed the LMC AMR based on Strömgren photometry in a wide range of ages.

The Washington system is very useful for age and metallicity determinations in IACs and globular clusters. In particular, metallicity sensitivity is considerably larger than in the Johnson system (Geisler & Sarajedini 1999). A significant sample of LMC clusters and fields have now been gathered. In addition, both the mapping of the AMR and its possible spatial dependence have been the subject of several previous studies in this series (Geisler et al. 1997; Bica et al. 1998; Piatti et al. 1999).

The present study deals with Washington photometry of two clusters closely related to the gap phenomenon: NGC 2155 and SL 896. NGC 2155 is one of the three clusters studied by S98 and is therefore critical to delineate the lower age limit of the gap. Note that the derived ages of S98 depend sensitively on his metallicities, which were derived from the slope and colour of the giant branch in the *BV* CMDs. The superior metallicity sensitivity of the Washington system should help pin down this important parameter. SL 896 (LW 480) drew our attention because of its relatively low metallicity, determined from spectroscopy of a single giant: [Fe/H] = −0.89, as compared to NGC 2155, which has [Fe/H] = −0.55 (Olszewski et al. 1991). Although no age is available for SL 896, its low metallicity level suggests that it might also be similar in age to the unique cluster ESO 121-SC03 ([Fe/H] = −0.93, Olszewski et al. 1991), which is the lone cluster lying in the age gap. It is also important to determine ages and metallicities for the two clusters homogeneously, placing them among LMC clusters with previous Washington photometry, trying to further probe and constrain the age gap limits and, in turn, the details of the AMR. In addition, we continued our related studies of the field populations surrounding LMC clusters.

Let us now consider the locations of these two clusters with respect to the nearly circular internal LMC disc, where the young stellar populations are prominent in field CMDs, and the outer elliptical disc, which is mostly populated by intermediate ages (Geisler et al. 1997 and references therein; Bica et al. 1999). NGC 2155 (SL 803, LW 347) at $\alpha = 5^{h}58^{m}33^{s}$, $\delta = -65^{h}28^{m}37^{s}$ ($\ell = 275\overset{\circ}{.}13$, $b = -29\overset{\circ}{.}96$) is projected on the north-east quadrant of the outer disc. It is located at $\approx 5.5°$ from the bar centre, assumed to be at the position of NGC 1928 ($\alpha = 5^{h}20^{m}56^{s}$, $\delta = -69^{h}28^{m}40^{s}$). SL 896 (LW 480) at $\alpha = 6^{h}29^{m}58^{s}$, $\delta = -69^{h}20^{m}01^{s}$ ($\ell = 279\overset{\circ}{.}68$, $b = -27°13$) is one of the easternmost LMC clusters, at the outer disc edge and at $\approx 6°$ from the bar centre.

In Section 2 we present the observations. In Sections 3 and 4 we analyse the cluster CMDs and determine their ages and metallicities, respectively, as well as those of their surrounding fields. In Section 5 we discuss our results and in Section 6 we summarize the main conclusions of this work.

2 OBSERVATIONS

The LMC star clusters NGC 2155 and SL 896, as well as their surrounding fields, were observed during two photometric nights with the Cerro Tololo Inter-American Observatory (CTIO) 0.9-m telescope in 1998 November. The Cassegrain Focus Imager (CFIM) and the Tektronix 2K #3 charge-coupled device (CCD) were used in combination with the Washington (Canterna 1976) *C* and Kron–Cousins *R* filters. The recommended prescription for the *C* filter that we used is the one given in Geisler (1996): 3mm BG3 + 2 mm BG40. However, Geisler (private communication) now recommends the following prescription: 3mm BG3 + 4 mm BG40. The latter avoids a small red leak that is present in the previous prescription. Geisler (1996) has shown that the R_{KC} filter is a very efficient substitute for the Washington T_1 filter and that $C - R$ accurately reproduces $C - T_1$ over at least the range $-0.2 \leq C - T_1 \leq 3.3$. We decided to use the Washington system because of its combination of broad bands and high metallicity sensitivity provided by the *C* filter, and the wide colour baseline between *C* and T_1. Additionally, we were determined to maintain consistency with our previous studies in this series. These data, aside from 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 (1999). The detector used (2048 × 2048 pixels) has a pixel size of 24 μm, producing a scale on the chip of $0\overset{''}{.}396$ pixel^{-1} (focal ratio *f*/13.5) and a field of view of $13\overset{'}{.}5 \times 13\overset{'}{.}5$. The CCD was controlled by the CTIO ARCON 3.3 data acquisition system in the standard *quad* amplifier mode operating at a gain setting of 1.5 e^-/ADU with a readout noise of 4.2 e^- rms. Only a single exposure in each filter was obtained per cluster. Exposures ranging between 2100 and 2400 s in *C*, and between 600 and 900 s in R_{KC} were taken for the two selected fields. Their airmasses were always less than 1.35 and the seeing was typically 1 arcsec. The observations were supplemented with nightly exposures of bias, dome and twilight sky flats to calibrate the CCD instrumental signature. On each photometric night, a large number (typically 19–32) of standard stars from Geisler's (1996) list were also observed. Care was taken to cover a wide colour and airmass range for these standards in order to calibrate the programme stars properly. Several other LMC fields, Small Magellanic Cloud (SMC) clusters and surrounding fields were also observed during the run using the same technique, and they are presented in Piatti et al. (1999, 2001), where a detailed description of the data collection, reduction procedures and

Table 1. Observations log.

Date	Cluster field[a]	Filter	Exposure (s)	Airmass	Seeing (arcsec)
1998 Nov. 23	NGC 2155 = SL 803, LW 347, ESO 86-SC45, KMHK 1563	*C*	2400	1.22	1.1
		R	900	1.23	1.1
1998 Nov. 21	SL 896 = LW 480, KMHK 1758	*C*	2400	1.32	1.0
		R	900	1.30	1.0

[a]Cluster identifications are from Shapley & Lindsay (1963, SL), Lyngå & Westerlund (1963, LW), Lauberts (1982, ESO) and Kontizas et al. (1990, KMHK).

photometric errors is given. The frames used for the present analysis are listed in Table 1. The data are available from the first author upon request.

3 ANALYSIS OF THE COLOUR–MAGNITUDE DIAGRAMS

Fig. 1 shows the (T_1, $C - T_1$) CMDs obtained for the entire observed fields. One of the most remarkable features that they illustrate is the coupling effect of decreasing field star density and increasing age with galactocentric distance described in Santos et al. (1999). They also show main sequences (MSs) extended roughly along 2–4 mag in T_1 and mostly populated by stars approximately 3 Gyr old (see discussion below). We do see evidence for older ages in fainter turn-off (TO) stars. The presence of broad sub-giant branches in the CMDs also supports the significant age range between the most numerous main-sequence turn-off (MSTO) stars and the ones at the faintest limit of our photometry. Note that we do not see any evidence for the presence of vertical structure stars in any of these fields (see Piatti et al. 1999).

With the aim of estimating ages and metallicities of the cluster sample, we built cluster CMDs from Fig. 1 using stars distributed near the cluster centres. Positions of cluster centres were determined by fitting Gaussians to the X and Y distributions of stars. Accuracy in the placement of these centres was <1 pixel for both coordinates. Cluster radial profiles were then obtained by counting the number of stars from cluster centres outwards within rings 5 pixels wide. We used the NGAUSSFIT routine of the STSDAS package to fit the radial density distribution of the clusters and obtained full widths at half-maximum (FWHMs) of 183 and 57 pixels for NGC 2155 and SL 896, respectively. On the basis of these values, we built CMDs for different circular extractions, as Figs 2(a) and (b) show.

In the case of NGC 2155 (Fig. 2a), the inner CMD ($r < 100$ pixels) is adversely affected by photometric errors, which cause the cluster sequences to be spread out. In Figs 3(a) and (b) we plot the T_1 magnitude errors versus the T_1 magnitude for the four radial regions as in Fig. 2. There is more scatter in the $r < 100$ pixels region of NGC 2155 than in the $100 < r < 200$ pixels region of Fig. 3(a). Thus, the second radial region of NGC 2155 ($100 < r < 200$) clearly shows the principal cluster sequences. Well-defined main-sequence (MS), sub-giant branch and red giant branch (RGB), along with the red clump, are particularly visible. For this reason we use the $100 < r < 200$ pixels CMD of NGC 2155 instead of the $r < 100$ pixels CMD for investigating the fiducial cluster features. Finally, for SL 896, Fig. 2(b) shows that the innermost CMD ($r < 100$ pixels) is dominated by cluster stars because its morphology is quite different from the other three radial CMDs.

4 AGES AND METALLICITIES

4.1 Star clusters

Cluster metallicities were derived using the standard giant branches (SGBs) traced by Geisler & Sarajedini (1999) in the [M_{T_1}, $(C - T_1)_o$] plane. These SGBs were obtained using a large number of stars per standard cluster with well-known metal abundances in the range $-2.15 <$ [Fe/H] < -0.05. The authors demonstrated that the SGBs have three times the metallicity sensitivity of the V, I technique (Da Costa & Armandroff 1990), which means that Washington metallicities can be determined three times more precisely for a given photometric error. Once we adopted the cluster reddenings and the LMC distance modulus, we superimposed the cluster CMDs on the SGBs and interpolated the cluster metal contents, as Fig. 4 shows. Cluster reddenings were taken from two sources, namely Burstein & Heiles' (1982) H I emission maps and Schlegel, Finkbeiner & Davis's (1998)100-μm dust emission maps (hereafter BH and SFD, respectively). BH maps provided us with foreground $E(B - V)$ values depending on the Galactic coordinates, whereas the full-sky map of SFD allowed us not only to check possible dust variations in the Galaxy, but also to take into account the internal LMC reddening. We adopted the reddening values from BH in the following analysis, the reddening estimates being listed in Table 2. We assumed an apparent distance modulus for the LMC of $(m - M)_V = 18.55 \pm 0.10$, obtained by

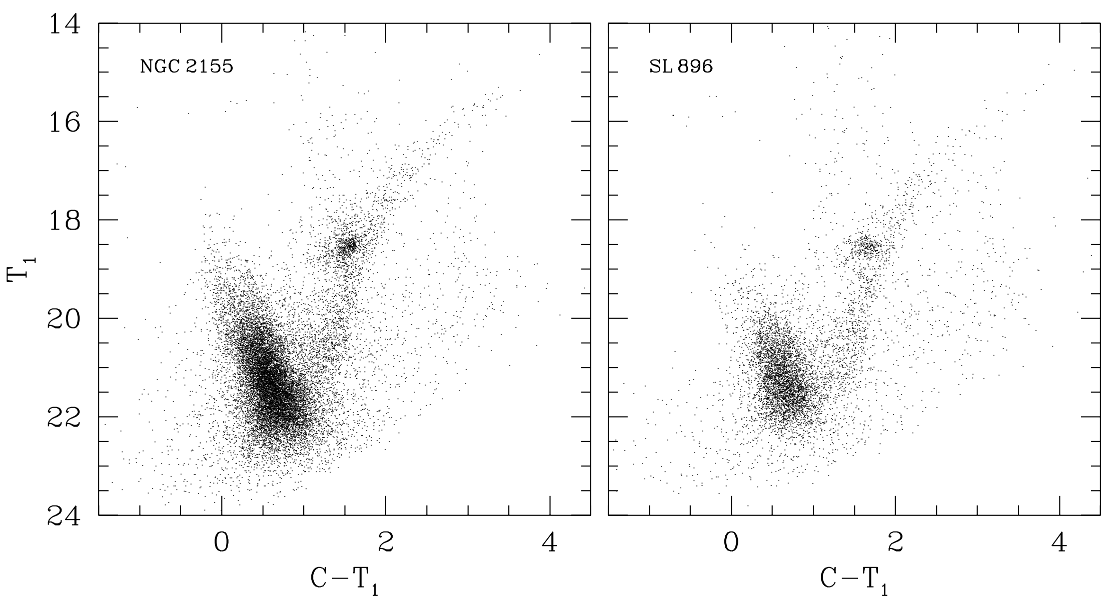

Figure 1. Washington T_1 versus $C - T_1$ CMDs of all stars measured in each of the observed fields.

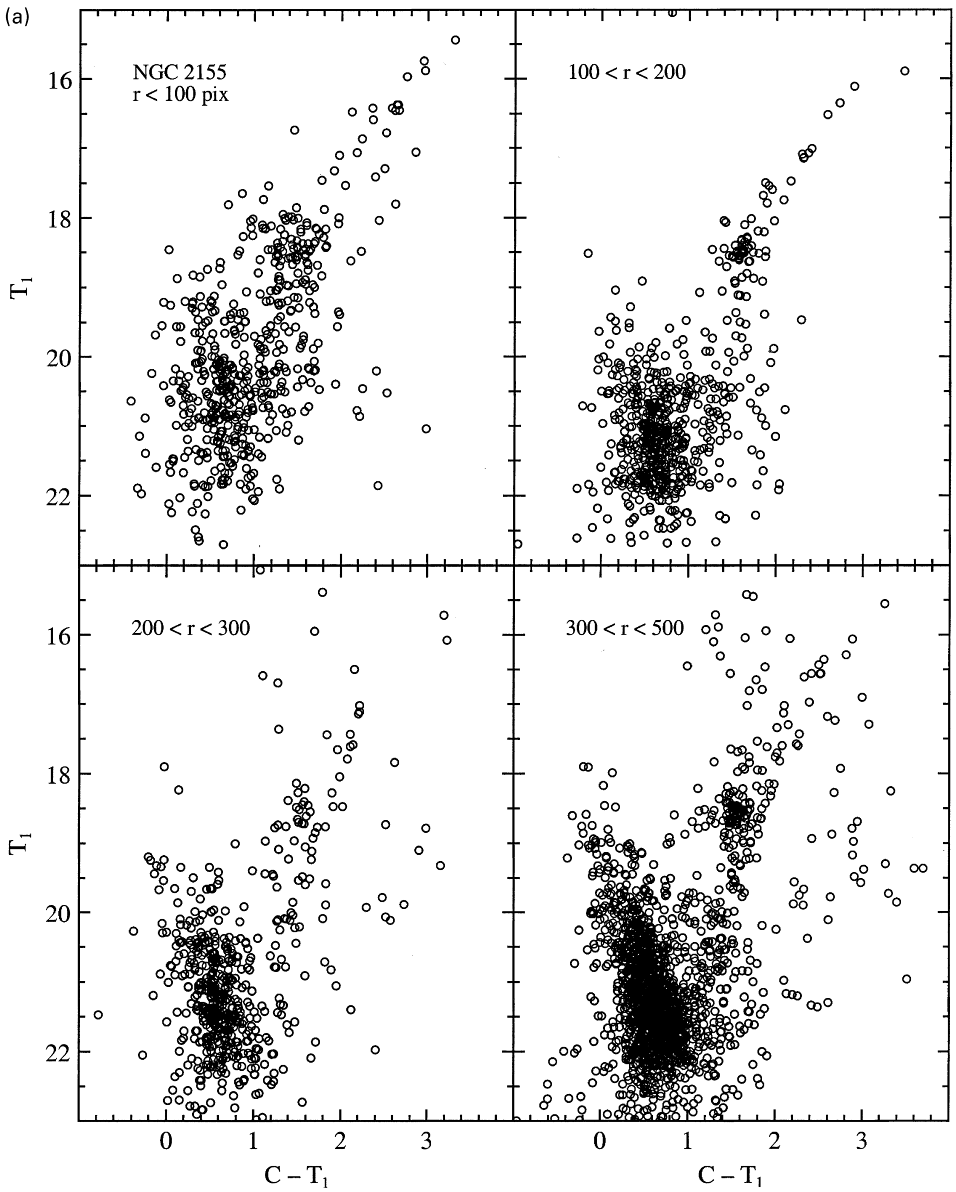

Figure 2. Washington T_1 versus $C - T_1$ CMDs of star clusters. Extraction radius in pixels is given in each panel: (a) NGC 2155 and (b) SL 896.

Cioni et al. (2000) from the apparent bolometric magnitude determinations of the tip of the red giant branch, using data extracted from the DENIS catalogue towards the Magellanic Clouds, and theoretical predictions. Finally, since the SGBs for [Fe/H] < -0.5 were defined using globular clusters with ages >10 Gyr, we applied offsets to our metallicity values of $+0.4$ dex for SL 896 and $+0.2$ for NGC 2155 to correct the noticeable effect of the age differences on broad-band colours. We refer readers to the work of Piatti et al. (2001) for a justification of these offsets. Table 2 lists the corrected metallicities and the corresponding uncertainties, estimated bearing in mind uncertainties in reddening values, apparent distance modulus and calibration dispersions and age correction.

Cluster ages were estimated following two different procedures based on the information provided by CMDs: (1) we used the δT_1 age indicator calibrated by Geisler et al. (1997) for the Washington system, which is equivalent to the δV index defined by Phelps, Janes & Montgomery (1994); and (2) we fitted theoretical isochrones to the CMDs recently computed by Lejeune & Schaerer (2001) for the $[M_{T_1}, (C - T_1)_o]$ plane.

The δT_1 values – the difference in magnitude between the mean magnitude of the giant clump/horizontal branch and the MSTO – were calculated by determining T_1 magnitudes of both red giant clump (RGC) and cluster TO in Fig. 2. We used the brightest part of the TO region, which is well populated for determining their TOs. We assigned to the TO determination an uncertainty twice that of the photometry at the TO level, i.e. $\langle \sigma_{TO} \rangle = 0.10$ mag. Table 3 lists the obtained δT_1 values and the estimated ages according to equation (4) of Geisler et al. (1997).

We then estimated ages of the cluster sample by fitting theoretical isochrones to their CMDs. Lejeune & Schaerer (2001) calculated isochrones in different photometric systems, among which was the Washington photometric system, using an updated version of the empirically and semi-empirically calibrated *BaSeL* library of synthetic spectra (Lejeune, Cuisinier & Buser 1997, 1998; Westera, Lejeune & Buser 1999). As far as we are aware,

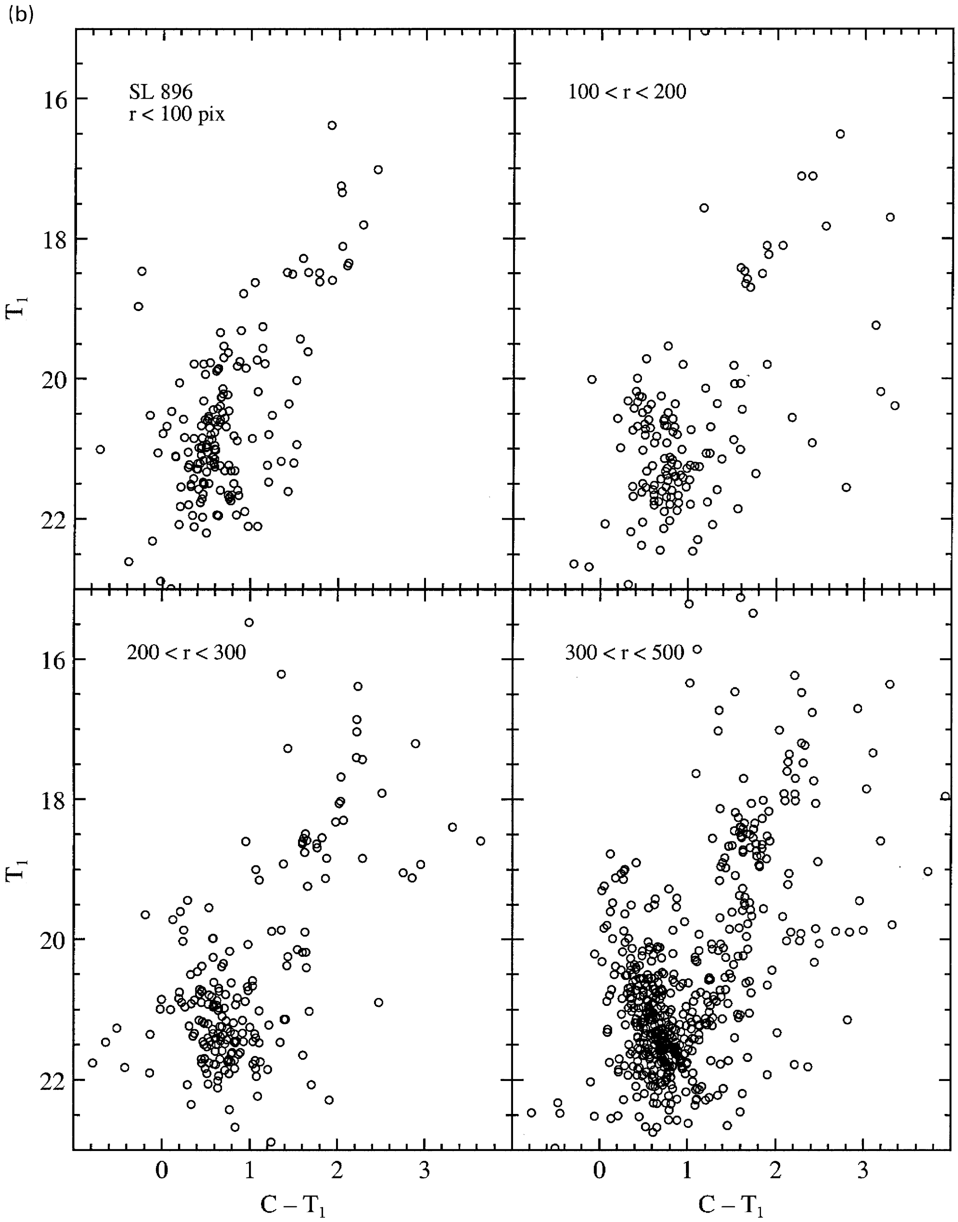

Figure 2 – *continued*

these are the first available isochrones in the Washington system. Thus, we could determine cluster ages by fitting the isochrone that most resembles the cluster CMD, without previously transforming isochrones from the *UBVRI* to the CMT_1T_2 systems. We selected a set of isochrones computed with overshooting and corresponding to $Z = 0.004$, which was the metallicity value included in the isochrone grid closest to our derived cluster metal abundances. Fig. 5 shows the result of the fits for each cluster, while Table 3 lists the derived ages. The comparison between ages determined from δT_1 magnitude differences and isochrone fits shows a very good agreement, with a mean difference of only 0.3 Gyr and a sigma of 0.3. This gives us confidence that our ages are reliable. We adopted the former ages in order to maintain consistency with our previous results (e.g. Bica et al. 1998).

4.2 Surrounding fields

We performed the same data analysis as described above to determine representative ages and mean metallicities of the cluster-surrounding fields. The surrounding field of a cluster was delimited as the region extending from a circle centred on the cluster and with a radius three times that of the cluster out to the boundary of the CCD field. Here, we define the radius of a cluster as the distance from its centre at which the number of stars per arcmin^2 above the background level is greater than $4 \times \sigma_{\rm back}$, where $\sigma_{\rm back}$ represents the standard deviation of the star density in the surrounding field. The limiting circle statistically constrains the contamination of cluster stars in the field CMDs to be less than 5 per cent. LMC fields thus resulted in sky regions of ~ 158 and 184 arcmin^2 around NGC 2155 and SL 896, respectively. We did not take into account the contamination of foreground Galactic field stars, since such stars do not define any feature that could blur the LMC field MSs and RGCs (see Geisler et al. 1997; Piatti et al. 2001).

Mean field metallicities were obtained by matching the SGBs of Geisler & Sarajedini (1999). We corrected the derived abundances due to the age effect on the C, T_1 colours by applying offsets of

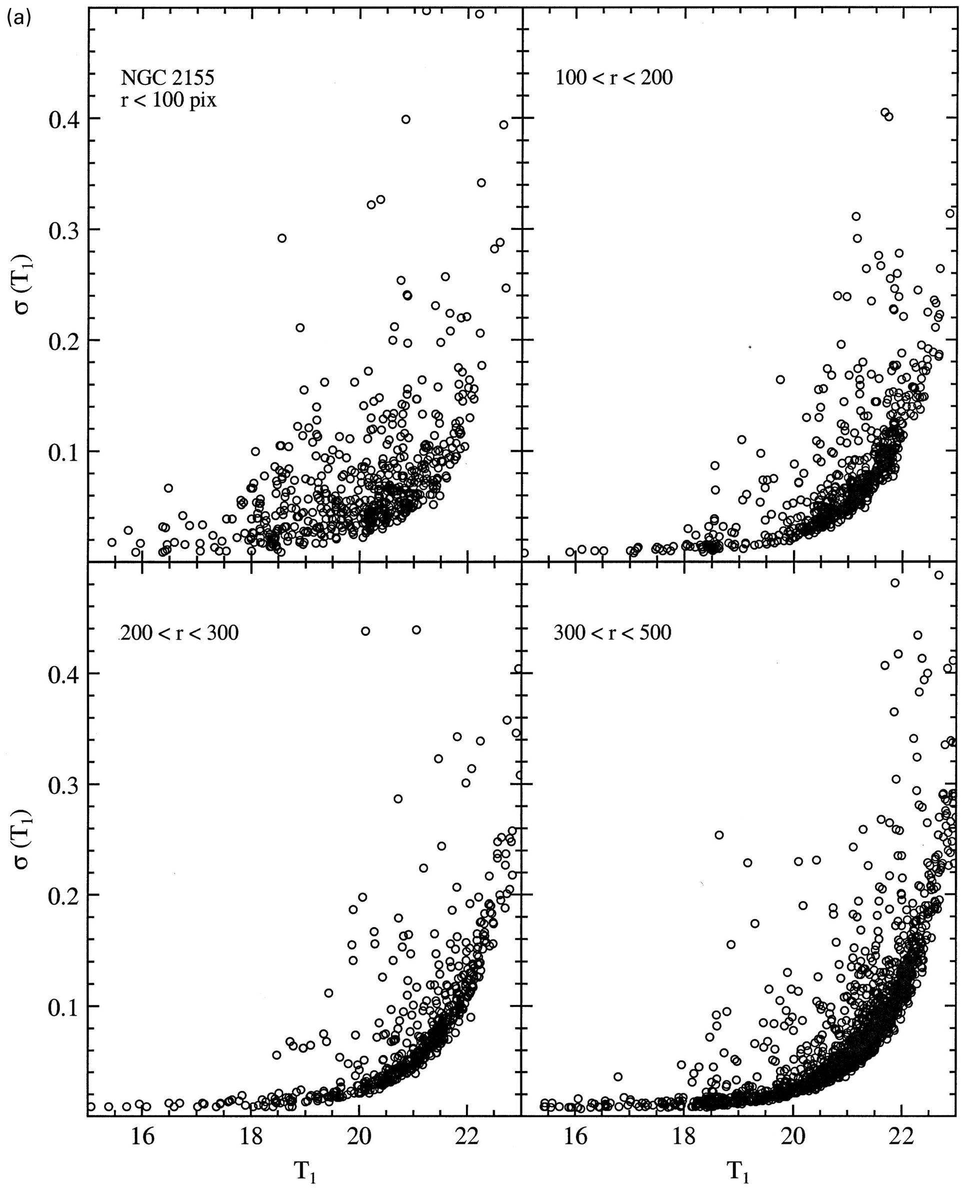

Figure 3. Plot of $\sigma(T_1)$ versus T_1 for the same circular extractions of Fig. 2: (a) NGC 2155 and (b) SL 896.

+0.4 for NGC 2155, and of +0.2 for SL 896 fields, according to the prescriptions given in Piatti et al. (2001). Corrected [Fe/H] values are listed in Table 2.

We measured δT_1 values for the most numerous stellar population in each field, defined as the stellar population associated with the MSTO containing the largest number of stars. We assume that the MS of the observed field is the result of the superposition of MSs with different TOs (ages) and constant luminosity functions. To determine the most populated TO, we first split the T_1 magnitude range of the MS into bins of 0.1 mag, and counted the number of MS stars in each magnitude interval. We traced the lower envelope of the MS with two lines:

$$T_1 = 18 \times (C - T_1 - \alpha_1) + 20.0$$

and

$$T_1 = 4.4 \times (C - T_1 - \alpha_2) + 20.0,$$

where α_1 and α_2 are constants equal to 0.0 for NGC 2155 and 0.1 for SL 896, and shifted the lines towards redder colours by $\Delta(C - T_1) = 0.5$ mag in order to take into account the width of the MS. Star counts were performed within these limits. The difference between the number of stars of two adjacent bins supplies the intrinsic number of stars belonging to the faintest bin, and therefore the biggest difference is directly related to the most populated TO. Table 3 lists the calculated δT_1 values with their uncertainties and the derived LMC field ages. Finally, using the adopted apparent LMC distance modulus and foreground reddenings from BH, we estimated field ages by fitting isochrones of Lejeune & Schaerer (2001) to the field CMDs. The derived metallicities were used as reference for choosing the appropriate set of isochrones, i.e. $Z = 0.004$ for both fields. The last column of Table 3 lists the adopted ages from the fit. As can be seen, both field age determinations show very good agreement within the errors.

5 DISCUSSION

Recently, S98 obtained $(V, B - V)$ CMDs for NGC 2155 using

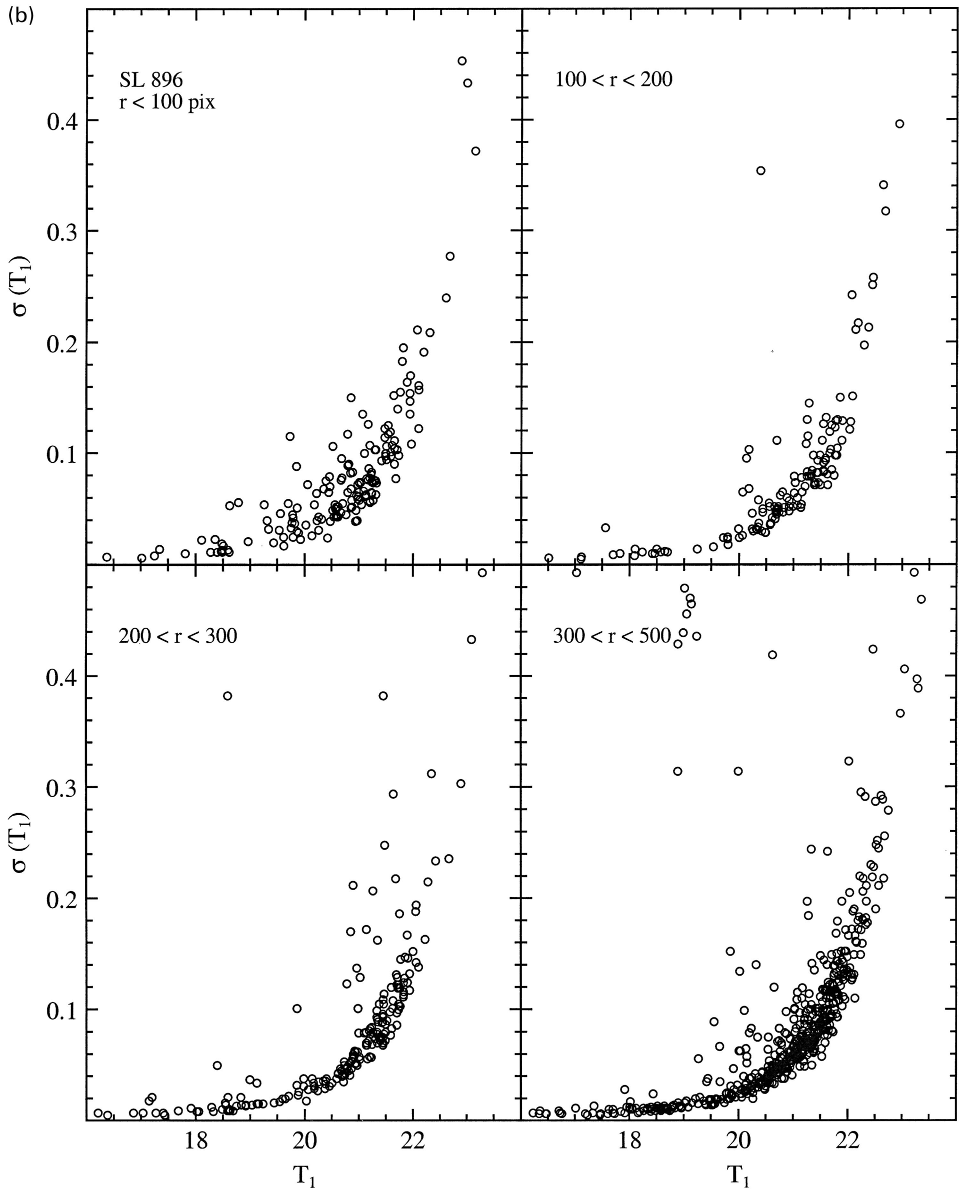

Figure 3 – *continued*

HST WFPC2 archival data from which he derived its age and metallicity. He found an age for NGC 2155 of 4 Gyr and a [Fe/H] value of -1.08. Previous determinations of the cluster parameters placed its age between 2.5 and 3.5 Gyr (Elson & Fall 1988; Olszewski et al. 1991), and its metallicities at ~ -0.6 (Olszewski et al. 1991), making both S98's ages and metallicities extreme for LMC IACs. Note that S98's age determinations are dependent on his metallicities and that higher metallicity values would lower his ages. On the basis of his age determinations, S98 claimed that the inclusion of NGC 2121, NGC 2155 and SL 663 (the first three clusters with an age of 4 Gyr found in the LMC) in the LMC age–metallicity relationship reduces the discrepancy between the age distribution of LMC clusters and the field stars and helped fill in the lower range of the cluster age gap. It is important to note that S98 adopted a mean age of 4 Gyr, averaging the values of 4.5 and 3.5 Gyr, directly obtained from the fit of isochrones with $Z = 0.001$ and 0.004, respectively. He averaged these ages because he determined a mean cluster metallicity equal to $[Fe/H] = -1$, just at the middle of the metal abundance range covered by the set of isochrones. S98's metallicities are in turn ~ 0.2 dex more metal-poor than the [Fe/H] value that we determined. The method we used to derive metallicities is three times more precise than the *V*, *I* technique, and therefore also more precise than any similar technique involving the *B*, *V* passbands. Our preference for the abundance value we derive is also supported by the fact that S98's metallicities are also ~ 0.4 dex more metal-poor than those provided by Olszewski et al.'s (1991) generally accepted metallicity scale.

Given our higher metallicity value, S98's data would now favour a younger age of ~ 3.5 Gyr, which is in excellent agreement with our derived age of 3.6 Gyr. Finally, in the case of SL 896, we only find a single previous abundance estimate ($[Fe/H] = -0.89$), based on the calcium triplet measurement of one star (Olszewski et al. 1991), in reasonable agreement with our cluster metallicity. The present age and metallicity determinations allow us to draw the conclusion that these two clusters are not LMC age gap clusters,

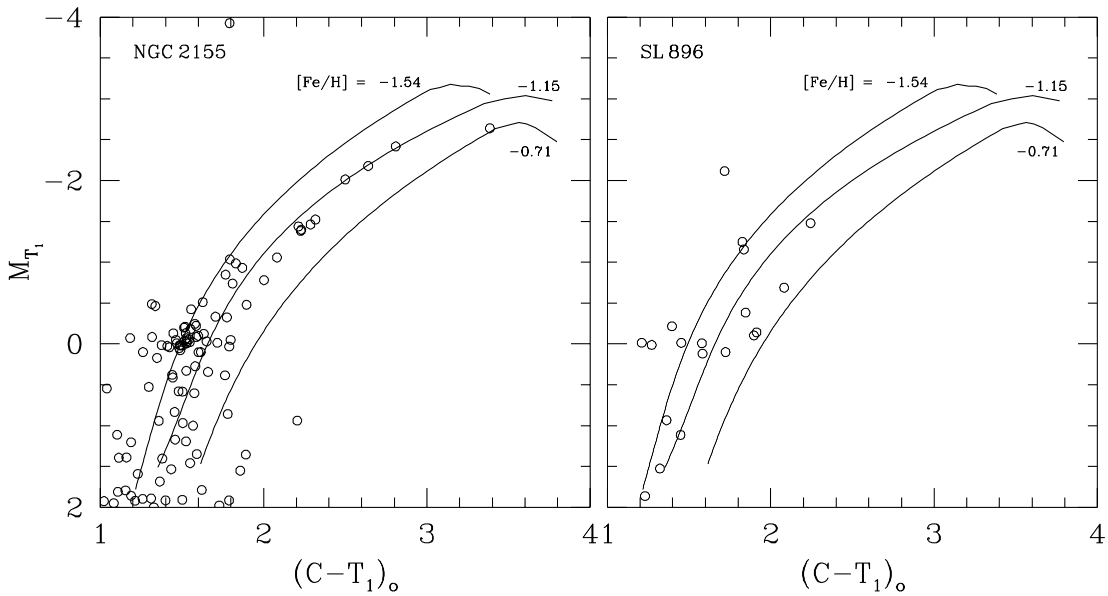

Figure 4. Metallicity derivation for the cluster sample. The clusters have been placed in the absolute T_1 magnitude versus dereddened $(C - T_1)$ colour plane assuming an apparent distance modulus of 18.55 and the Burstein & Heiles (1982) reddening values. Standard giant branches from Geisler & Sarajedini (1999) are marked with their metallicity values. Note that an age-dependent correction to the indicated metallicities is required for these IACs.

Table 2. Reddenings and metallicities of LMC clusters and surrounding fields.

Name	$E(B-V)_{BH}$	$E(B-V)_{SFD}$	$[Fe/H]_{cluster}$[a]	$[Fe/H]_{field}$[a]
NGC 2155	0.04	0.05	−0.9 ± 0.2:	−0.7 ± 0.2
SL 896	0.10	0.07	−0.6 ± 0.2:	−0.9 ± 0.2

[a]Metallicities were corrected by +0.2 and +0.4 for ages between 3 and 4 Gyr and between 2 and 3 Gyr, respectively (see Section 4 for details).

but rather the oldest known LMC intermediate-age clusters (IACs) studied in detail; i.e. they define the lower limit of the cluster age gap.

A simple inspection of Tables 2 and 3 reveals that field properties, which strictly represent the most populated LMC field star component, are within the age and metallicity ranges typical of IACs. The difference in absolute values between cluster and field ages turns out to be $\Delta t = 0.8 \pm 0.2$ Gyr, whereas absolute metallicity difference yields $\Delta[Fe/H] = 0.05 \pm 0.25$ dex, the clusters being slightly younger and more metal-rich than their respective fields. Thus, our results are consistent with the conclusions drawn by Bica et al. (1998) in the sense that clusters and surrounding fields in the outer disc have nearly similar properties.

We added the two observed clusters to a list of selected IACs and old clusters with the aim of investigating the chemical evolution of the LMC. A selection was performed in order to generate a cluster sample representative of the LMC chemical enrichment, avoiding uncertain fundamental parameter determinations and zero-point offsets between different age and/or metallicity scales. For the IACs we included those clusters observed by Bica et al. (1998), as well as ESO 121-SC03, which have ages and metallicities on the same scales as the present cluster sample. We also included NGC 2121 (Rich et al. 2001), since the age determined by the authors for NGC 2155 ($t = 3.2$ Gyr) is in very good agreement with the present derived value, while for old clusters we chose the most precise values recently published in the literature (Brocato et al. 1996; Olsen et al. 1998; Johnson et al. 1999; Carretta et al. 2000; Hill et al. 2000). Our list is given in Table 4.

Fig. 6 shows the resulting age–metallicity relationship (AMR), in which filled circles represent IACs and old clusters taken from the literature. The locations of NGC 2155 and SL 896 in the AMR are represented by the filled triangle and square, respectively, with the corresponding error bars. Their respective surrounding fields are represented by open symbols. We note that the clusters of Bica et al. and NGC 2121 span the entire IAC age and metallicity ranges known. Our two clusters define the lower limit of the age gap, NGC 2155 being the oldest IAC.

The distribution of clusters in the LMC AMR suggests that two main cluster formation epochs have taken place in this galaxy: one at the beginning of the LMC's life and another starting around 3 Gyr ago, as is well known. The first epoch formed metal-poor clusters with metallicities spread over a wide range ($-2.2 \lesssim [Fe/H] \lesssim -1.4$), whereas the second epoch produced clusters with metallicities covering a range of $\Delta[Fe/H] \sim 0.5$ dex, from $[Fe/H] \sim -1.0$ to -0.5 dex. Da Costa (1991) and Olszewski et al. (1991) were the first to note that the cluster age gap also

Table 3. Ages of LMC clusters and surrounding fields.

Name	δT_1 (mag) cluster	δT_1 (mag) field	δT_1 age (Gyr) cluster	δT_1 age (Gyr) field	Isochrone age (Gyr) cluster	Isochrone age (Gyr) field
NGC 2155	2.25 ± 0.20:	2.05 ± 0.15	3.6 ± 0.7	3.0 ± 0.4	2.8 ± 0.5	2.7 ± 0.4
SL 896	1.80 ± 0.30:	2.15 ± 0.15	2.3 ± 0.5:	3.3 ± 0.5	2.2 ± 0.2:	3.2 ± 0.4

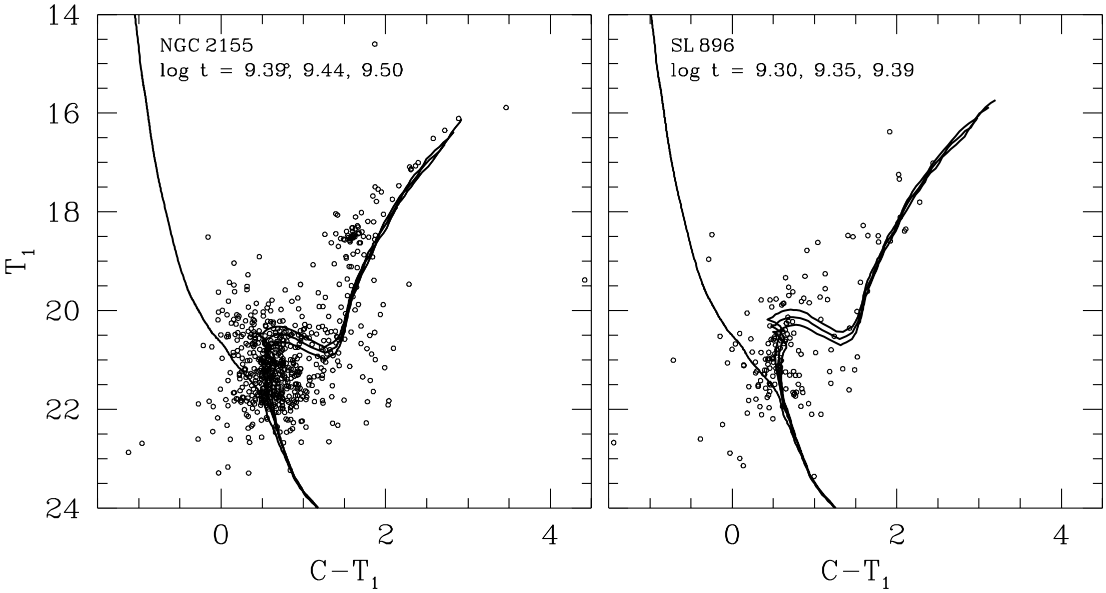

Figure 5. Washington T_1 versus $C - T_1$ CMDs for star clusters. Isochrones from Lejeune & Schaerer (2001), computed taking into account overshooting and $Z = 0.004$, are overplotted. The zero age main sequence is also shown for the sake of completeness.

corresponds to a metallicity gap. As far as we know, there is no observed cluster with metallicity between ~ -1.4 and -1.0. Thus, the LMC somehow continued to enrich chemically during the long hiatus (covering about half of its lifetime) when it apparently managed to form a single surviving star cluster. As noted for example by Olszewski, Suntzeff & Mateo (1996), the age/abundance gap presents an apparent paradox: How could the LMC enrich in metals by a factor of at least 3 during a period in which it formed no stars? The answer may well lie in the decoupling of the cluster and field star formation rates, as discussed for example by Cole, Smecker-Hane & Gallagher (2000), who have shown that an equivalent abundance gap does not appear to be present in the field star metallicity distribution. Recent *HST* -based field star studies (e.g. Geha et al. 1998; Olsen 1999; Holtzman et al. 1999) indicate that this age gap apparently does *not* exist in the general LMC field, with substantial evidence that up to 50 per cent of the field stars have ages >4 Gyr.

Both cluster formation episodes occurred during a relatively short time-span of 2–3 Gyr. In particular, comparing the time spent in the formation of IACs with that of the formation of the Galactic open cluster system ($\Delta t \approx 6-8$ Gyr) with metallicities in a similar range, it seems that the involved nucleosynthesis mechanisms have proceeded in two very distinct modes in each galaxy. The two cluster formation events are clearly separated by the LMC cluster age gap, ESO 121-SC03 being the only observed cluster in that age range. Instead, our cluster sample, NGC 2121 and SL 663 belong to the old age tail of the IAC distribution, as suggested also by S98.

We compared our AMR with those derived from theoretical models computed by different authors, namely Geha et al. (1998, hereafter G98), Da Costa & Hatzidimitriou (1998, hereafter DH98) and Pagel & Tautvaišienė (1998, hereafter PT98). The theoretical AMRs are shown in Fig. 6. G98 calculated closed-box enrichment models on the basis of the star formation history (SFH) derived by Holtzman et al. (1997) and Vallenari et al. (1996a,b). We chose the model following the SFH of Holtzman et al. because this is the one that most closely resembles the observed AMR (dotted line). DH98 also computed theoretical models (short dashed line) presenting a simple closed system with continuous star formation under the assumption of chemical homogeneity for their SMC cluster sample, whereas PT98 used bursting star formation rates to fit the AMRs of both Magellanic Clouds (MCs). Their theoretical AMRs for the LMC and SMC are depicted with long dashed and solid lines, respectively. Although all models predict a steady chemical enrichment from the time of the galaxy's formation until the present, the bursting model computed for the SMC appears to trace the LMC AMR more tightly.

With the aim of looking into whether the chemical evolution of the LMC is connected with the metallicity enrichment of the SMC, we gathered the AMRs for clusters of both galaxies into a single plot. To do this, we used 16 SMC star clusters with ages and metallicities on the same scales as the cluster sample of Fig. 6 (for a discussion of the SMC cluster sample, see the paper of Piatti et al. 2001). The values are given in Table 4 and the resulting combined MCs cluster AMR is shown in Fig. 7. Filled symbols are the same as in Fig. 6, while open circles represent SMC star clusters. One of the most remarkable features of Fig. 7 is that the age range between 12 and 15 Gyr is only populated by LMC clusters, whereas SMC clusters are found during the LMC age gap, with the sole exception of ESO 121-SC03. During the last $\lesssim 4$ Gyr, clusters have formed profusely in both galaxies. Furthermore, assuming that the LMC gap is real, i.e. that there existed a quiescent period of cluster formation in the LMC, and that the first SMC clusters were formed ~ 12 Gyr ago (NGC 121), a possible scenario suggests itself: First, the SMC was formed from the detachment of some part of the LMC containing gas and/or star clusters, possibly from the interaction between the LMC and our Galaxy. Secondly, an interaction between both MCs generated a bursting cluster formation, which peaked at ~ 1.5 Gyr ago.

There are some existing findings that might shed light on the validity of our claim that the LMC and SMC were once a single galaxy. On the one hand, in support of our hypothesis, abundances of the α elements and s-process elements in the two galaxies closely track one another from intermediate metal abundances all the way up to present-day values (Pagel & Tautvaišienė 1998). In contrast, the numerical simulations of Gardiner, Sawa & Fujimoto (1994; see also Sawa, Fujimoto & Kumai 1999), which use the

Table 4. Literature ages and metallicities for additional LMC and SMC clusters.

Name	Age (Gyr)	[Fe/H]	Source[a]
LMC intermediate-age clusters			
SL 8, LW 13	1.8	−0.50	1
SL 126, ESO 85-SC21	2.2	−0.45	1
SL 262, LW 146	2.1	−0.55	1
SL 388, LW 186	2.2	−0.65	1
SL 451, LW 206	2.2	−0.70	1
SL 509, LW 221	1.2	−0.85	1
NGC 2121	3.2	−0.60	10
SL 769	1.8	−0.50	1
SL 817	1.5	−0.50	1
ESO 121-SC03	8.5	−1.05	1
SL 842, LW 399	2.2	−0.60	1
SL 862, LW 431	1.8	−0.85	1
OHSC 33	1.4	−1.00	1
OHSC 37	2.1	−0.65	1
LMC old clusters			
NGC 1466	14.8	−1.87	2, 3
NGC 1754	15.5	−1.42	4
NGC 1786	12.3	−2.10	3, 5
NGC 1835	16.2	−1.62	4
NGC 1841	12.3	−2.20	3, 5
NGC 1898	13.5	−1.37	4
NGC 2210	12.3	−1.75	3, 5, 6
Hodge 11	14.8	−2.05	2, 3
NGC 2257	14.8	−1.85	2, 3
SMC clusters			
Lindsay 113	5.3	−1.24	7
Kron 3	6.0	−1.16	7
NGC 121	11.9	−1.71	7
NGC 152	1.9	−0.80	8
NGC 330	0.025	−0.82	8
NGC 339	6.3	−1.50	7
NGC 361	8.1	−1.45	7
NGC 411	1.8	−0.84	8
NGC 416	6.9	−1.44	7
NGC 419	1.2	−0.70	8
NGC 458	0.3	−0.23	8
Lindsay 1	9.0	−1.35	7
Lindsay 32, ESO 51-SC2	4.8	−1.20	9
Lindsay 38, ESO 13-SC3	6.0	−1.65	9
Kron 28, Lindsay 43	2.1	−1.20	9
Kron 44, Lindsay 68	3.1	−1.10	9

[a](1) Bica et al. (1998); (2) Johnson et al. (1999); (3) Carretta et al. (2000); (4) Olsen et al. (1998); (5) Brocato et al. (1996); (6) Hill et al. (2000); (7) Mighell, Sarajedini & French (1998); (8) Da Costa & Hatzidimitriou (1998); (9) Piatti et al. (2001); (10)Rich et al. (2001).

observed proper motions of the Magellanic Clouds to trace their past orbits, suggest that the LMC and SMC have been a fairly stable *binary* system for the entire age of the Milky Way. While there is no question that the MCs have experienced interactions with each other and with the Milky Way (e.g. Crowl et al. 2001), it is unclear just how long these multi-body interactions have been occurring. The possibility that the LMC and SMC could have been one galaxy at some point in the past is an intriguing conclusion and one that deserves further investigation.

6 CONCLUSIONS

We presented new Washington photometry for two clusters (NGC 2155 and SL 896) and surrounding fields located in the Large Magellanic Cloud. On the basis of their colour–magnitude diagrams, we have determined age and metallicity for both clusters and respective surrounding fields. The two clusters turned out to be, besides NGC 2121, the oldest known LMC IACs (⟨age⟩ ∼ 3.0 Gyr, ⟨[Fe/H]⟩ ∼ −0.7 dex) studied in detail. The whole sample of known IACs with ages and metallicities determined on a

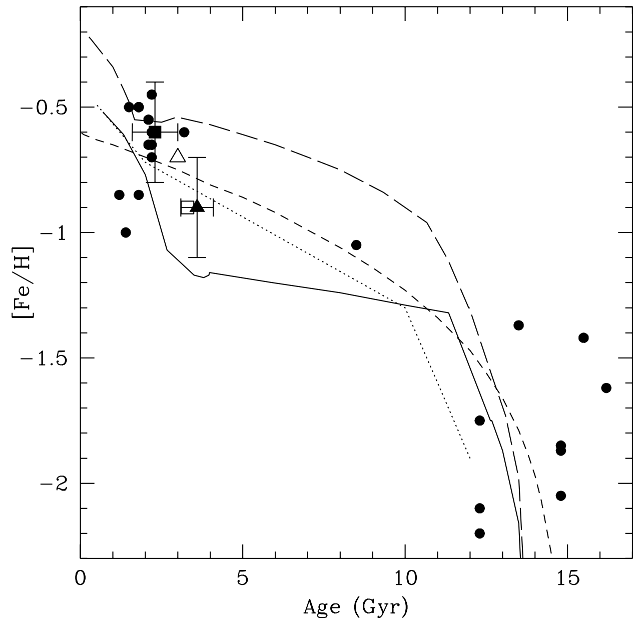

Figure 6. Age–metallicity relationship for selected star clusters in the LMC. Filled circles represent data previously published (see Section 5 for details), while filled triangle and square correspond to NGC 2155 and SL 896, respectively. Error bars are also included. Open symbols represent their respective surrounding fields. The data are compared with the closed-box models (dotted and short dashed lines) computed by Geha et al. (1998) and Da Costa & Hatzidimitriou (1998), respectively, and the bursting models (long dashed and solid lines) of Pagel & Tautvaišienė (1998).

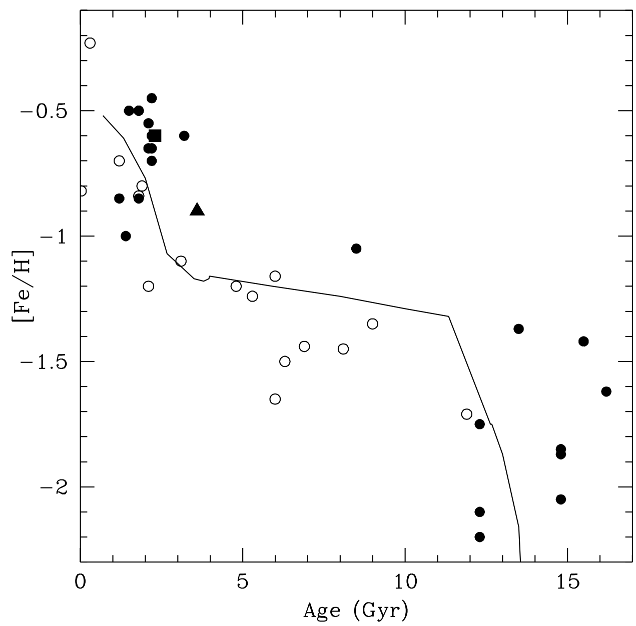

Figure 7. Combined age–metallicity relation for selected LMC and SMC star clusters. Filled symbols are the same as in Fig. 6, while open circles represent SMC clusters (see Section 5 for details).

uniform scale has now increased to 15. Surrounding fields were found to have practically similar properties.

We confirm that the LMC has undergone two main cluster formation events: the first of them at the beginning of its life and the second one starting ~3 Gyr ago. IACs appear to have been formed during the latter cluster formation epoch, along a relatively short time-span of 2–3 Gyr, preceded by a quiescent cluster formation period, which covers about half of the LMC lifetime. Our two clusters define the lower limit of this apparent cluster formation gap (the age gap), NGC 2155 being the oldest IAC. By comparing the LMC cluster AMR with those generated theoretically, we found that, although all models predict a steady chemical enrichment from the time of the galaxy's formation until the present, the bursting model computed for the SMC by PT98 appears to trace the LMC AMR more tightly.

Finally, the LMC and SMC age–metallicity relations appear to be remarkably complementary, basically consistent with the possibility of the SMC being a detached LMC part at $t \approx 10$ Gyr, which subsequently evolved quite independently. The SMC was actively star-forming during the LMC quiescent age gap epoch. Both Magellanic Clouds show a significant cluster formation epoch, which started ~3 Gyr.

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