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Two newly identified, relatively old star clusters in the Small Magellanic Cloud

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ABSTRACT

We present the results on the age and metallicity estimates of the Small Magellanic Cloud (SMC) clusters L 110, L 112 and L 113 obtained from CCD Washington CT_1 photometry. We confirm L 113 as a relatively old and metal-poor cluster, and report for the first time that L 110 and 112 are also relatively old clusters ($t \sim 6.5$ Gyr). Their derived ages and metallicities reinforce previous suggestions that the farther a cluster is from the centre of the galaxy, the older and more metal-poor it is, with some dispersion. In addition, the bursting star formation model still appears to be the most probable paradigm to describe the SMC's star formation history. We call attention to a second possible burst at ∼6–7 Gyr, besides the known burst at ∼3 Gyr.

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

1 INTRODUCTION

The Milky Way galaxy system includes the Large and Small Magellanic Clouds (LMC and SMC, respectively) along with numerous dwarf spheroidal galaxies. The oldest star clusters in the Milky Way halo, in the Fornax dSph, and in the LMC have the same age, ∼13 Gyr, to within 1 Gyr (e.g. Harris et al. 1997; Johnson et al. 1999). This is not true, however, for the SMC wherein the oldest cluster, NGC 121, is some 2 Gyr younger (Olszewski, Suntzeff & Mateo 1996). If there was a common epoch of cluster formation very early in the Universe (e.g. Fall & Rees 1985), one would expect that the oldest clusters in all galaxies should have common ages. The question arises as to whether there are old clusters in the SMC of which we are not aware, possibly older than NGC 121.

The properties of the oldest known star clusters in the SMC were studied by Mighell, Sarajedini & French (1998a,b). They presented ages and metallicities of seven SMC clusters older than ∼5 Gyr – Lindsay 113, Kron 3, NGC 339, NGC 416, NGC 361, Lindsay 1, and NGC 121 – in order of increasing age. Rich et al. (2000) analyzed data for a subset of these as well as additional clusters and suggested that there had been two significant bursts of cluster formation in the SMC's past – one at 8 ± 2 Gyr ago and the other around 2 ± 0.5 Gyr ago. A very recent study by Sabbi et al. (2007) found an additional cluster at 4.5 ± 0.1 Gyr. However, in general accurate age determination for SMC clusters has been lacking. The number of clusters with well-known ages is still quite small, leaving open such questions as to whether there may be as yet undiscovered old clusters, and how many bursts have ocurred and when. In addition, despite their unique ability to investigate chemical evolution and the star formation history of their parent galaxy (e.g. Da Costa & Hatzidimitriou 1998), SMC clusters have been generally overlooked.

In an effort to remedy these shortcomings, over the last few years our group has been conducting a survey of SMC clusters. One of our goals has been to improve the census of old clusters and, in particular, to search for clusters possibly older than NGC 121. In a previous paper (Piatti et al. 2001), photometry for the SMC clusters Lindsay 32 and 38 was presented and ages of 4.8 and 6.0 Gyr were derived, respectively, adding L 32 and 38 to the list of SMC clusters older than ∼5 Gyr. Here, we report that two additional star clusters – Lindsay 110 and 112 – are found to have ages older than 5 Gyr.

The observations and data reduction are described in the next section while the resultant colour–magnitude diagrams (CMDs) of these clusters along with Lindsay 113 are presented in Section 3. The properties of these diagrams and their implications for the cluster formation history of the SMC are discussed in Section 4. Our conclusions are given in Section 5.

2 OBSERVATIONS AND REDUCTIONS

The observations of L 110, 112 and 113 were obtained with the Danish Faint Object Spectrograph and Camera (DFOSC) on the 1.54-m

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Table 1. Observations log of selected clusters.

Star cluster[a]	α_{2000} (h m s)	δ_{2000} (° ′ ″)	l (°)	b (°)	Date	Filter	Exposure (s)	Air mass	Seeing (arcsec)
L 110, ESO 29-SC48	1 34 26	−72 52 28	298.56	−43.89	1999 Nov 5	C	1800	1.46	1.6
						R	600	1.46	1.4
L 112	1 35 58	−75 27 28	299.23	−41.35	1999 Nov 4	C	1800	2.10	1.8
						R	600	2.16	1.4
L 113, ESO 30-SC4	1 49 28	−73 43 42	297.44	−42.78	1999 Dec 29	C	1800	1.43	1.7
						R	600	1.62	1.6

[a]Cluster identifications are from Lindsay (1958, L) and Lauberts (1982, ESO).

Danish telescope at the European Southern Observatory (ESO) on La Silla. We observed in the C and T_1 filters of the Washington system (Canterna 1976) in order to maintain consistency with our previous studies. And as before, we substituted an R_{KC} filter for the original T_1 filter given its superior throughput (Geisler 1996). The DFOSC imager has a field-of-view of 13.7 × 13.7 arcmin with a plate scale of 0.42 arcsec pixel^{-1}. Table 1 shows the log of the observations with filters, exposure times, air masses and seeing estimates. All of the data were taken under photometric conditions. Standard stars from the list of Geisler (1996) were observed in order to secure the transformation from the instrumental to the standard system.

The instrumental signatures (e.g. the bias level and pixel-to-pixel sensitivity variations) in the CCD images were removed using standard tasks in IRAF. The stellar photometry was performed using the star-finding and point-spread-function fitting routines in the DAOPHOT/ALLSTAR suite of programs (Stetson 1987). Radially varying aperture corrections were applied to take out the effects of point spread function (psf) variations across the field of view. The resultant instrumental magnitudes were standardized using equations similar to those employed by Piatti et al. (1999). The root-mean-square deviations of the fitted values from the fits to the standards were all less than 0.015 mag. The resultant C and T_1 photometry of stars in the L 110, 112 and 113 fields is given in Tables 2 to 4, respectively, which are available online as supplementary material to the printed article. Typical errors are in average: $\sigma T_1 \leqslant 0.01$ mag for $T_1 = 19$, ≈0.05 mag for $T_1 = 21$ and ≈0.15 mag for $T_1 = 22.5$; $\sigma(C - T_1) \leqslant 0.01$ mag for $T_1 = 19$, ≈0.07 mag for $T_1 = 21$ and ≈0.17 mag for $T_1 = 22.5$.

3 CLUSTER FUNDAMENTAL PARAMETERS

We constructed several colour–magnitude diagrams (CMDs) for each cluster based on different circular extractions in order to properly isolate the cluster stars. Clearly, the CMDs of the innermost regions do not contain only cluster stars but rather minimize the influence of field stars on the cluster's principal sequences. Field CMDs which minimize cluster contamination are constructed from the outermost circular extractions. These areas were chosen to lie well beyond the visible extent of the clusters. Fig. 1 shows the adopted cluster (upper panels) and field star (lower panel) CMDs. The choice of the various radii for each cluster was an iterative, slightly subjective process. We used as a reference the full width at half maximum (FWHM) of a Gaussian fit to the stellar density radial profiles that we have achieved in previous work of this type (see Piatti et al. 2007, and references therein). Also based on previous work, we estimate that the contamination of field stars in the adopted extracted cluster CMDs is smaller than 10 per cent.

Table 2. CCD CT_1 data of stars in the field of L 110. The full table is available online.

Star	X (pixel)	Y (pixel)	T_1 (mag)	$\sigma(T_1)$ (mag)	$C - T_1$ (mag)	$\sigma(C - T_1)$ (mag)
...	...	...	...	...	...	...
180	512.48	106.64	21.111	0.037	0.435	0.045
181	467.97	106.68	20.180	0.020	0.060	0.024
182	1543.95	106.76	16.607	0.006	1.262	0.008
183	1098.32	107.20	21.246	0.032	0.267	0.041
...	...	...	...	...	...	...

Table 3. CCD CT_1 data of stars in the field of L 112. The full table is available online.

Star	X (pixel)	Y (pixel)	T_1 (mag)	$\sigma(T_1)$ (mag)	$C - T_1$ (mag)	$\sigma(C - T_1)$ (mag)
...	...	...	...	...	...	...
250	1417.82	1369.23	19.514	0.012	3.288	0.060
251	739.45	1370.45	21.573	0.050	1.118	0.099
252	1880.00	1371.76	19.806	0.027	2.417	0.050
253	153.46	1372.77	20.311	0.020	1.504	0.035
...	...	...	...	...	...	...

Table 4. CCD CT_1 data of stars in the field of L 113. The full table is available online.

Star	X (pixel)	Y (pixel)	T_1 (mag)	$\sigma(T_1)$ (mag)	$C - T_1$ (mag)	$\sigma(C - T_1)$ (mag)
...	...	...	...	...	...	...
516	1378.61	666.45	19.801	0.015	1.403	0.025
517	1216.68	667.05	20.668	0.027	0.486	0.037
518	705.98	667.05	21.750	0.055	0.663	0.087
519	1024.10	668.08	18.535	0.006	1.539	0.012
...	...	...	...	...	...	...

We are primarily interested in determining the age and metal abundance of each cluster in our sample. In order to maintain consistency, we have utilized the same techniques to measure these quantities as in our previous papers on SMC clusters (Piatti et al. 2001, 2005a). First, we adopt a distance modulus of $(m - M)_o = 18.77 \pm 0.06$ mag (Crowl et al. 2001) along with the equations $E(C - T_1) = 1.97E(B - V)$ and $M_{T_1} = T_1 - 2.62E(B - V) - 18.77$ from Geisler & Sarajedini (1999). The reddening values are taken both from the Burstein & Heiles (1982, hereafter BH) and Schlegel, Finkbeiner & Davis (1998, SFD) extinction maps. As reddening estimates differ by only a few hundredths, we adopt the average value from both colour excesses (see Table 5).

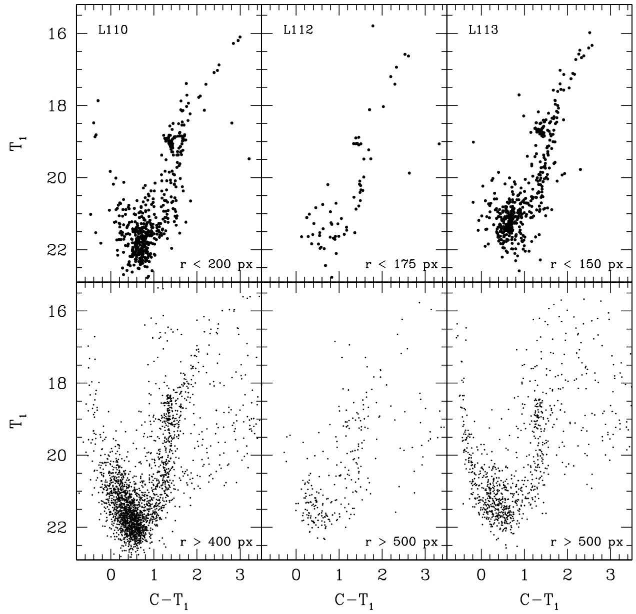

Figure 1. Washington T_1 versus $C - T_1$ CMDs for measured stars in the three cluster fields. Extraction radii in pixels are given in each panel.

The ages are calculated by determining the difference in T_1 magnitude between the red clump (RC) and the main sequence turnoff (MSTO) from the cluster CMDs and then using equation (4) of Geisler et al. (1997) to obtain the ages. Note that this age measurement technique does not require absolute photometry. The derived δT_1 differences are listed in Table 5; their uncertainties $\sigma(\delta T_1)$ are estimated by considering the photometric errors at the RC and MSTO T_1 magnitudes (see columns 3 and 4 of Table 5) and/or the intrinsic dispersion in the CMDs. Note that, due to the smaller number of stars in the L 112 CMD, the δT_1 value for this cluster should be used with caution. Then, from equation (4) of Geisler et al. (1997) we obtain for L 110, 112 and 113 ages of 5.1 ± 0.9, 5.4 ± 0.9 and 4.0 ± 0.7 Gyr, respectively. The errors in the derived ages come from the propagation of $\sigma(\delta T_1)$ through equation (4) of Geisler et al.

All our previous SMC cluster age estimates (Piatti et al. 2001, 2005a,b, 2007) are in an age scale where Lindsay 1 is 9 ± 1 Gyr old (Olszewski et al. 1996). In this system, L 113 is 5.3 ± 1.3 Gyr (Mighell et al. 1998a), so we have added 1.3 Gyr to the ages derived above. The final adopted age uncertainties are slightly larger than those previously calculated, as we have taken into account the error in the age of L 113 as estimated by Mighell et al. (1998a). Table 5 lists the final cluster ages. In any case, L 110 and 112 are clearly older than L 113 and are thus newly discovered relatively old clusters in the SMC.

The metallicities have been estimated by comparing the cluster red giant branches (RGBs) with the standard fiducial globular cluster RGBs from Geisler & Sarajedini (1999). The scattering of the data in the $[M_{T_1}, (C - T_1)_o]$ plane, with the different iso-abundance lines superimposed, was used to assign the random errors to the metallicities. This derived metallicity is then corrected for age effects via the prescription given in Geisler et al. (2003). We note that metallicities determined in this way have been found to be in good agreement with those derived from comparison to appropriate theoretical isochrones (e.g. Geisler et al. 2003; Piatti et al. 2003a,b). The resulting metal abundances are listed in Table 5, where we took into account errors associated with the age correction. Finally, we checked the derived ages by fitting theoretical isochrones of Girardi et al. (2002) to the cluster CMDs. We used isochrones for $Z = 0.001$ and 0.004, since there is none available for $Z = 0.002$, and confirmed the derived cluster ages of Table 5.

4 ANALYSIS AND DISCUSSION

As far as we are aware, L 113 is the only cluster of the sample with previous estimates of its age and metallicity. Mould, Da Costa & Crawford (1984) obtained an age of 5 Gyr using CCD *BR* photometry adopting $(m - M)_o = 18.8$ and [Fe/H] = −1.4 ± 0.2 dex. Later, Seidel, Da Costa & Demarque (1987) reanalysed the photometry of Mould et al. (1984) and derived an age of 5 ± 1 Gyr using $(m - M)_o = 18.8$ and 4 ± 1 Gyr with $(m - M)_o = 19.3$, both adopting a metal abundance of [Fe/H] = −1.4 ± 0.1. Da Costa & Hatzidimitriou (1998) used Ca II spectroscopy of cluster giants to measure the metal abundance of L 113. They find [Fe/H] = −1.44 ± 0.16, which leads to an age of $t = 6 \pm 1$ Gyr. The metallicity derived by Da Costa & Hatzidimitriou is on the Zinn & West (1984) scale, as is the Standard Giant Branch calibration of Geisler & Sarajedini (1999) used to estimate the present cluster metallicities. More recently, Mighell et al. (1998a), using *Hubble Space Telescope* Wide Field Planetary Camera 2 (*HST* WFPC2) observations, estimated the cluster age and metallicity at 5.3 ± 1.3 Gyr and [Fe/H] = −1.24 ± 0.11 dex. All previous age and metallicity estimates are in good agreement with our values. Thus, we confirm L 113 as a relatively old, metal-poor SMC cluster and solidify its use as a control cluster in the estimation of the ages and metallicities of L 110 and 112, which are previously unstudied.

Our results show that L 110 and 112 are relatively old SMC clusters ($t \sim 6.5$ Gyr) with metallicities ∼0.3 dex more metal-rich than the previously known old SMC clusters with similar ages (see Table 3 and Da Costa & Hatzidimitriou 1998). Furthermore, at present there are only nine known clusters in the SMC with ages older than ≈5 Gyr, including L 113; the remaining clusters are younger than 3 Gyr. Therefore, adding two new clusters to the list of the oldest clusters in the SMC is important to improving our knowledge of the chemical evolution of this satellite galaxy. In addition, the fact that their metallicities may be higher than the other SMC clusters at the same age can shed new light on possible scenarios of galaxy formation and evolution.

Table 5. Fundamental parameters of SMC clusters.

Name	$\langle E(B-V)\rangle$ (mag)	T_1(MSTO) (mag)	T_1(RC) (mag)	δT_1 (mag)	Age[a] (Gyr)	[Fe/H][b]	R (°)
L 110	0.030 ± 0.005	21.60 ± 0.10	19.05 ± 0.05	2.55 ± 0.15	6.4 ± 1.1	−1.15 ± 0.25	3.07
L 112	0.060 ± 0.010	21.60 ± 0.10	19.00 ± 0.05	2.60 ± 0.15	6.7 ± 1.1	−1.10 ± 0.25	3.94
L 113	0.030 ± 0.010	21.10 ± 0.10	18.75 ± 0.05	2.35 ± 0.15	5.3 ± 1.0	−1.40 ± 0.25	4.17

[a]Age estimates assume that Lindsay 1 is 9 Gyr old. [b]Metallicities were corrected according to Fig. 6 of Geisler et al. (2003). See Section 3 for details.

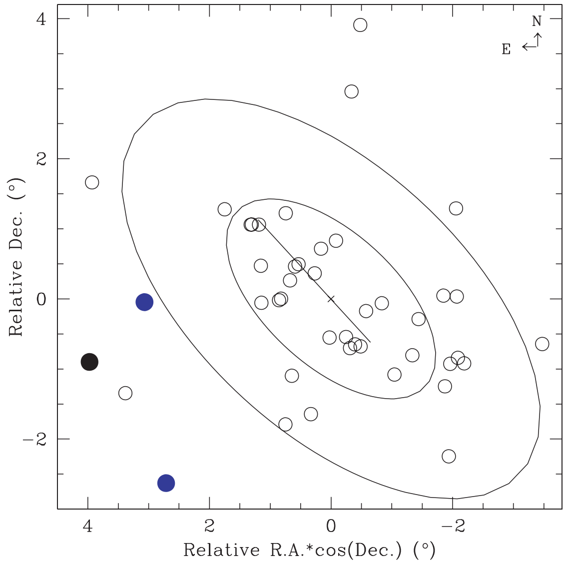

Figure 2. The position of the L 110 and 112 fields (blue filled circles) and the L 113 field (black filled circle) in relation to the SMC main body (straight line) and optical centre (cross). 41 clusters included in Piatti et al.(2007) are also shown as open circles.

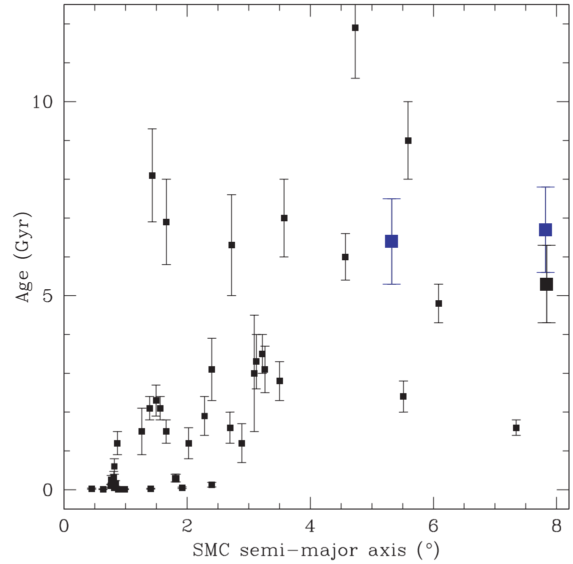

Figure 3. Cluster ages versus semi-major axes of ellipses with $b/a = 1/2$, centred at the SMC optical centre, aligned along the SMC main body, that pass through the cluster positions. Smaller filled boxes represent the 41 included clusters in Piatti et al. (2007). L 110 and 112 are depicted in bigger blue filled boxes, whereas L 113 is represented by the bigger black filled box.

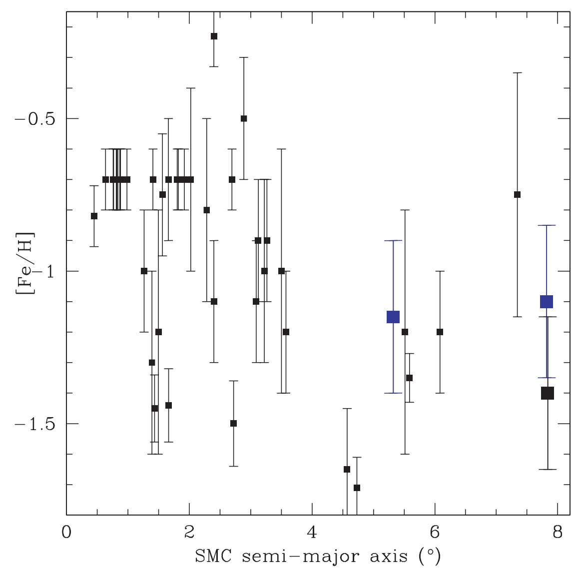

Figure 4. Cluster metallicity versus semi-major axes of ellipses with $b/a = 1/2$, centred at the SMC optical centre, aligned along the SMC main body, that pass through the cluster positions. Symbols are as in Fig. 3.

Including our present sample, we have now studied the chemical enrichment of the SMC using ages and metallicities of 44 star clusters, placed on to a homogeneous scale (Piatti et al. 2002, 2005a,b, 2007). To facilitate the study of the clusters' ages and metallicities as they relate to their spatial distribution, we adopt an elliptical framework with its major axis aligned with the main body and a *b*/*a* ratio of 1/2. Fig. 2 shows the positions of the 44 clusters relative to the SMC optical centre – assumed to be at: RA $00^h52^m45^s$, Dec. $-72°49'43''$ (J2000) (Crowl et al. 2001) – drawn with open circles. The 41 clusters from our previous work are plotted as open circles, L 110 and 112 are each shown with a blue filled circle, and L 113 is depicted with a black filled circle. The semi-major axes of the ellipses drawn in the figure have radii of 2° and 4°, respectively. For completeness purposes, we include in the last column of Table 5 the calculated projected galactocentric cluster distances *R*.

In order to examine how cluster ages and metallicities vary in terms of the distance from the SMC centre, we computed for each cluster the value of the semi-major axis (a) that an ellipse would have if it were centred at the SMC centre, had a *b*/*a* ratio of 1/2, and one point of its trajectory coincided with the cluster position. In this scenario, clusters located on the same ellipse would have the same value for their semi-major axes. We plot the calculated semi-major axes versus cluster ages and metallicities in Figs 3 and 4, respectively, wherein the clusters in the present study and those from the literature are represented by smaller and bigger filled (L 110, 112 = blue, L 113 = black) boxes, respectively. The position of L 110, 112 and 113 in these figures confirms that there is a clear trend (more noticeable in Fig. 3), in the sense that the further a cluster is from the centre of the galaxy, the older and more metal-poor it is, with some dispersion. This supports the results of Noel et al. (2007), who examined the star formation history of the galaxy from CMDs of 12 star fields located between ∼1° and ∼4° in different parts of the SMC. Particularly, they found that intermediate-age and old star populations are distributed throughout the surveyed regions, while those younger are preferably distributed towards the central regions. Consequently, the abundance gradient seems to reflect the combination of an older and more metal-poor population of clusters distributed throughout the SMC and a younger and metal-richer one mainly formed in the inner disc.

We show in Fig. 5 the age–metallicity relationship constructed from the enlarged sample of 44 star clusters. We have also overplotted two star formation models for comparison purposes. The solid line represents the bursting star formation history of Pagel & Tautvaišienė (1998), whereas the dashed line depicts a simple closed system with continuous star formation under the assumption of chemical homogeneity (Da Costa & Hatzidimitriou 1998). The appearance of Fig. 5 still supports the bursting star formation model as the most probable paradigm to describe the SMC. However, the metallicity dispersion in the 6–7 Gyr age range – L 110 and 112

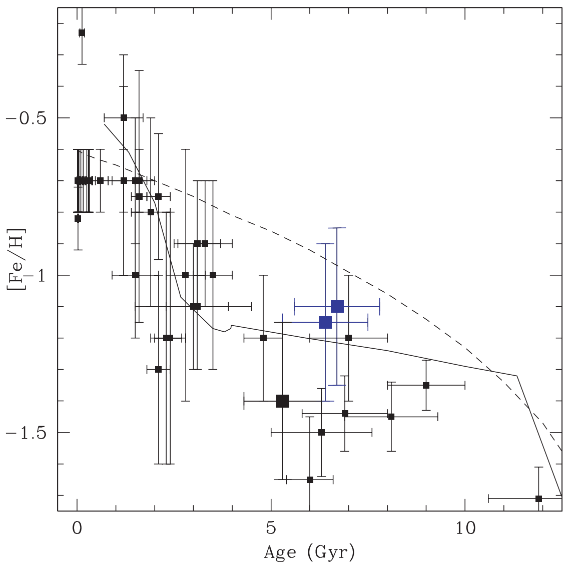

Figure 5. Age–metallicity relationship for star clusters in the SMC. Symbols are as in Fig. 3.

are the most metal-rich clusters – suggests another possible burst, first shown by Rich et al. (2000), in addition to the clear burst of cluster formation at ∼3 Gyr. Much further and more detailed work is needed to clarify and quantify these suggested trends.

5 SUMMARY

In this study we present CCD photometry in the Washington system C and T_1 passbands of stars in the field of the SMC clusters L 110, 112 and 113. The analysis of the photometric data leads to the following main conclusions.

(i) L 110 and 112 turn out to be relatively old clusters (t ∼ 6.5 Gyr), which are now added to the list of the other nine known oldest clusters in this galaxy. L 113 is also confirmed in this group of clusters.

(ii) The ages and metallicities of L 110, 112 and 113 reinforce previous suggestions with respect to the chemical evolution of the SMC, that the further a cluster is from the centre of the galaxy, the older and more metal-poor it is, with some dispersion. This trend is more noticeable for the clusters' ages than for their metallicities.

(iii) In addition, the bursting star formation model continues to be the most probable paradigm to describe the SMC. In this context, we call the attention to a possible burst at ∼6–7 Gyr, in addition to the well-known burst at ∼3 Gyr.

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SUPPLEMENTARY MATERIAL

The following supplementary material is available for this article:

Table 2. CCD CT_1 data of stars in the field of L 110.
Table 3. CCD CT_1 data of stars in the field of L 112.
Table 4. CCD CT_1 data of stars in the field of L 113.

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