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New insights on the bursting formation of star clusters in the Large Magellanic Cloud

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ABSTRACT

We present the results on the age estimates of 36 Large Magellanic Cloud (LMC) clusters obtained for the first time from CCD Washington CT_1T_2 photometry. By using the (T_1, $C - T_1$) and (T_1, $T_1 - T_2$) diagrams, we estimated ages for the cluster sample using the δT_1 index. We confirm that the studied cluster sample belong to the ∼2 Gyr bursting formation epoch of the LMC. Furthermore, when rebuiling the cluster age distribution – taken into account the estimated age errors – we found that the number of clusters with ages between 1 and 3 Gyr now doubles that of the known bursting cluster population, which suggests that the tidal interaction between both Magellanic Clouds and, perhaps, also the Milky Way, was more stronger than expected.

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

1 INTRODUCTION

It is known that signs of star cluster formation from bursting episodes have been found in the Large Magellanic Cloud (LMC). For instance, Piatti et al. (2002, 2003) showed that the bursting model by Pagel & Tautvaišienė (1998) for the LMC fits the star cluster age–metallicity relation (AMR) better than the closed-box enrichment model computed by Geha et al. (1998) using the star formation history of Holtzman et al. (1997). Evidence of gravitational triggered episodes of cluster formation due to the most recent close interaction between both Magellanic Clouds (MCs) was also found in their cluster age distributions (Chiosi et al. 2006; Piatti et al. 2011a,b). These results show star cluster excesses within a relatively narrow age range at $t \sim 2$ Gyr (Piatti et al. 2007, 2009, for example).

On the other hand, Piatti et al. (2011a) compared their LMC cluster age distribution with the star formation rates (SFRs) analytically derived by de Grijs & Anders (2006) and Harris & Zaritsky (2009), respectively. The former showed that the cluster formation rate (CFR) in the LMC has been roughly constant outside the well-known age gap between ∼3 and 13 Gyr, when the CFR was a factor of ∼5 lower. The least-squares power-law fit for the most likely age ranges where disruption may dominate evolutionary fading derived by them shows a satisfactory agreement with the Piatti et al.'s (2011a) LMC cluster age distribution, except for the largest ages, where Piatti et al. found an excess of clusters. This is because de Grijs & Anders (2006) used cluster subsamples. In turn, Harris & Zaritsky (2009) presented the first-ever global, spatially resolved reconstruction of the star formation history (SFH) of the LMC, based on the application of their StarFISH analysis software to the multi-band photometry of twenty million of stars from the Magellanic Clouds Photometric Survey. The general outlines of their results are consistent with previously published SFHs as well as with Piatti et al.'s (2011a) results.

In this Letter we identify 28 LMC clusters with ages close to ∼2, the age at the peak of the bursting formation episode occurred in the LMC. If confirmed by more detailed studies, this result would make much of an impact. Since the cluster sample represents more than the double of the known bursting cluster population, it would pose new challenges about our knowledge about the cluster formation and disruption rates, about the infant mortality phenomenon in this galaxy, among others. The data handling from which we found these bursting clusters is described in Section 2. Section 3 deals with the resultant cluster colour–magnitude diagrams (CMDs) and the cluster ages; whereas Section 4 summarizes our results.

2 DATA HANDLING

Despite their utility and unique advantages, LMC clusters have been surprisingly underexploited. From the 2268 clusters catalogued by Bonatto & Bica (2010), the number of those with well-determined ages is minimal. Thus, the information necessary to fully utilize LMC clusters as tracers of LMC formation and chemical evolution history is sorely lacking. On the other hand, in our previous series of studies about LMC clusters we have used the CT_1 Washington photometric system (Canterna 1976; Geisler 1996) whose ability to estimate ages and metallicities of star clusters have long been proved. For those reasons, and in order to keep consistent with our previous studies as well, we performed a search within the National Optical Astronomy Observatory (NOAO) Science Data

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Table 1. Unstudied and control clusters in the LMC.

Star Cluster[a]	α_{2000} (h m s)	δ_{2000} (° ′ ″)	Date	Exposure *C R I* (s)	Airmass *C R I*	Seeing *C R I* (arcsec)
BSDL 527	05 04 34	−68 12 30	2008 Dec 20	500 120 120	1.581 1.557 1.569	1.2 1.1 0.9
H 3	05 33 20	−68 09 08	2008 Dec 18	1200 180 180	1.497 1.474 1.485	1.4 0.9 0.9
H88-52	04 58 10	−68 03 37	2008 Dec 20	500 120 120	1.549 1.526 1.537	1.2 1.1 0.9
H88-67	04 58 54	−67 50 49	2008 Dec 20	500 120 120	1.549 1.526 1.537	1.2 1.1 0.9
H88-334	05 46 52	−69 11 23	2008 Dec 19	1200 180 180	1.368 1.355 1.362	1.0 0.8 0.7
HS 8	04 30 40	−66 57 25	2008 Dec 20	500 120 120	1.326 1.315 1.320	1.1 0.9 0.8
HS 114	05 06 02	−68 01 35	2008 Dec 20	500 120 120	1.581 1.557 1.569	1.2 1.1 0.9
HS 121	05 07 46	−67 51 41	2008 Dec 20	500 120 120	1.581 1.557 1.569	1.2 1.1 0.9
HS 264	05 23 12	−70 46 40	2008 Dec 18	1200 180 180	1.475 1.457 1.466	1.3 1.0 1.0
HS 329	05 29 46	−71 00 02	2008 Dec 18	1200 180 180	1.475 1.457 1.466	1.3 1.0 1.0
KMHK 58	04 43 14	−73 48 43	2008 Dec 19	1200 180 180	1.421 1.414 1.417	1.0 0.9 0.7
KMHK 112	04 49 07	−67 20 30	2008 Dec 20	500 120 120	1.512 1.490 1.501	1.3 1.0 0.9
KMHK 586	05 08 51	−67 58 49	2008 Dec 20	500 120 120	1.581 1.557 1.569	1.2 1.1 0.9
KMHK 1023	05 31 46	−68 14 08	2008 Dec 18	1200 180 180	1.497 1.474 1.485	1.4 0.9 0.9
KMHK 1668	06 08 53	−72 23 02	2008 Dec 19	1200 180 180	1.437 1.424 1.430	1.0 0.8 0.8
LW 263	05 39 08	−74 51 12	2008 Dec 19	1200 180 180	1.447 1.439 1.443	1.0 0.8 0.7
LW 393	06 06 31	−72 13 35	2008 Dec 19	1200 180 180	1.437 1.424 1.430	1.0 0.8 0.8
LW 397	06 07 29	−72 29 39	2008 Dec 19	1200 180 180	1.437 1.424 1.430	1.0 0.8 0.8
SL 5	04 35 38	−73 43 54	2008 Dec 19	1200 180 180	1.421 1.414 1.417	1.0 0.9 0.7
SL 13	04 39 42	−74 01 02	2008 Dec 19	1200 180 180	1.421 1.414 1.417	1.0 0.9 0.7
SL 35	04 46 40	−67 41 07	2008 Dec 20	500 120 120	1.512 1.490 1.501	1.3 1.0 0.9
SL 96	04 55 01	−67 42 51	2008 Dec 20	500 120 120	1.549 1.526 1.537	1.2 1.1 0.9
SL 132	04 57 26	−67 41 07	2008 Dec 20	500 120 120	1.549 1.526 1.537	1.2 1.1 0.9
SL 151	04 58 51	−69 57 28	2008 Dec 18	1500 300 300	1.302 1.299 1.300	1.3 1.2 1.0
SL 162	04 59 53	−67 55 25	2008 Dec 20	500 120 120	1.549 1.526 1.537	1.2 1.1 0.9
SL 290	05 10 36	−70 29 15	2008 Dec 18	1500 300 300	1.302 1.299 1.300	1.3 1.2 1.0
SL 707	05 46 12	−69 04 57	2008 Dec 19	1200 180 180	1.368 1.355 1.362	1.0 0.8 0.7
SL 869	06 14 41	−69 48 07	2008 Dec 18	1200 180 180	1.318 1.311 1.314	1.1 0.9 0.9
			Control clusters			
IC 2146	05 37 46	−74 46 58	2008 Dec 19	1200 180 180	1.447 1.439 1.443	1.0 0.8 0.7
NGC 1644	04 37 39	−66 11 58	2008 Dec 20	500 120 120	1.389 1.373 1.381	1.2 0.9 0.9
NGC 1751	04 54 12	−69 48 25	2008 Dec 18	1500 300 300	1.302 1.299 1.300	1.3 1.2 1.0
NGC 1795	04 59 46	−69 48 04	2008 Dec 18	1500 300 300	1.302 1.299 1.300	1.3 1.2 1.0
NGC 1846	05 07 35	−67 27 39	2008 Dec 18	1200 180 180	1.279 1.273 1.276	1.3 1.2 1.0
NGC 1852	05 09 23	−67 46 42	2008 Dec 18	1200 180 180	1.279 1.273 1.276	1.3 1.2 1.0
NGC 1917	05 19 02	−69 00 04	2008 Dec 18	1200 180 180	1.403 1.385 1.394	1.3 1.0 0.9
NGC 2108	05 43 56	−69 10 50	2008 Dec 19	1200 180 180	1.368 1.355 1.362	1.0 0.8 0.7

[a] Cluster identifications are from Bica et al. (1999, BSDL); Hodge (1960, H); Hodge (1988, H88); Hodge & Sexton (1966, HS); Kontizas et al. (1990, KMHK); Lyngå & Westerlund (1963, LW), and Shapley & Lindsay (1963, SL).

Management (SDM) Archives[1] looking for Washington photometric data towards the LMC. As result, we found images corresponding to 21 different fields spread throughout the LMC obtained at the Cerro-Tololo Inter-American Observatory (CTIO) 4-m Blanco telescope with the Mosaic II camera attached (36 × 36 arcmin^2 field on to a 8K × 8K CCD detector array). For the purposes of this Letter, we assume that the area covered by these 21 Mosaic II fields represent an unbiased subsample of the LMC as a whole. They encompass 214 catalogued star clusters (Bonatto & Bica 2010). When examining their CMDs and colour–colour diagrams, we found 36 intermediate-age clusters (IACs), 29 clusters with some sign of evolution, 62 very young clusters and 87 asterisms. Since we are here focusing on to the aforementioned bursting cluster formation event, Table 1 only lists the unstudied clusters found in the search with ages around ∼1–3 Gyr, as well as well-known IACs used as control for age estimates. Note that the *R* filter has a significantly higher throughput as compared with the standard Washington T_1 filter so that *R* magnitudes can be accurately transformed to yield T_1 magnitudes (Geisler 1996). As far as we are aware, none of the clusters listed in Table 1 does have CT_1T_2 photometry published, previously.

We followed the procedures documented by the NOAO Deep Wide Field Survey team (Jannuzi, Claver & Valdes 2003) to reduce the data by utilizing the MSCRED package in IRAF.[2] We performed overscan, trimming and cross-talk corrections, bias subtraction, obtained an updated world coordinate system (WCS) data base, flattened all data images, etc., once the calibration frames (zeros, sky- and dome-flats, etc) were properly combined. Images of standard fields from the list of Geisler (1996) were also found in the NOAO SDM Archives, so that nearly 90 independent measures of standard stars were derived per filter for each night in order to obtain the coefficients of the transformation equations. We solved the transformation equations with the fitparams task in IRAF and found mean colour terms of -0.090 ± 0.003 in C, -0.020 ± 0.001 in T_1

[1] http://www.noao.edu/sdm/archives.php.

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

and 0.060 ± 0.004 in T_2, while typical airmass coefficients resulted in 0.31, 0.09 and 0.06 for C, T_1 and T_2, respectively. The nightly rms errors from the transformation to the standard system were 0.021, 0.023 and 0.017 mag for C, T_1 and T_2, respectively, indicating these nights were of excellent photometric quality.

The star finding and point spread function (PSF) fitting routines in the DAOPHOT/ALLSTAR suite of programs (Stetson, Davis & Crabtree 1990) were used with the aim of performing the stellar photometry. For each frame, we selected ~960 stars to fit a quadratically varying PSF, once the neighbours were eliminated using a preliminary PSF derived from the brightest, least contaminated ~240 stars. Both groups of PSF stars were interactively selected. We then used the ALLSTAR program to apply the resulting PSF to the identified stellar objects and to create a subtracted image which was used to find and to measure magnitudes of additional fainter stars. This procedure was repeated three times for each frame. Finally, we standardized the resulting instrumental magnitudes and combined all the independent measurements using the stand-alone DAOMATCH and DAOMASTER programs, kindly provided by Peter Stetson. The final information gathered for each cluster consists of a running number per star, of the x and y coordinates, of the measured T_1 magnitudes and $C - T_1$ and $T_1 - T_2$ colours, and of the observational errors $\sigma(T_1)$, $\sigma(C - T_1)$ and $\sigma(T_1 - T_2)$.

3 DATA ANALYSIS

Fig. 1 depicts with filled circles annular extracted (T_1, $C - T_1$) CMDs for stars distributed around the cluster centres. These raw cluster CMDs, although not statistically cleaned from field star contamination, allow us to recognize more or less clearly the cluster red clumps (RCs) and the main sequence turnoffs (MSTOs). These features are also visible in the counterpart (T_1, $T_1 - T_2$) CMDs. For comparison purposes, we have overplotted with green circles the respective extracted field CMDs, where the adopted field regions are equal cluster ring areas around cluster centres and with internal radii four times those of the clusters. Then, bearing in mind the photometric T_1 magnitude errors at the RC and MSTO (Piatti 2011, see his fig. 1) and the intrinsic cluster dispersion in the (T_1, $C - T_1$) and (T_1, $T_1 - T_2$) CMDs, we measured T_1(MSTO) and T_1(RC), calculated its difference (δT_1, Phelps et al. 1994; Geisler et al. 1997) and obtained the cluster age following the precepts and calibration obtained by Geisler et al. (Geisler et al. 1997, equation 4). Note

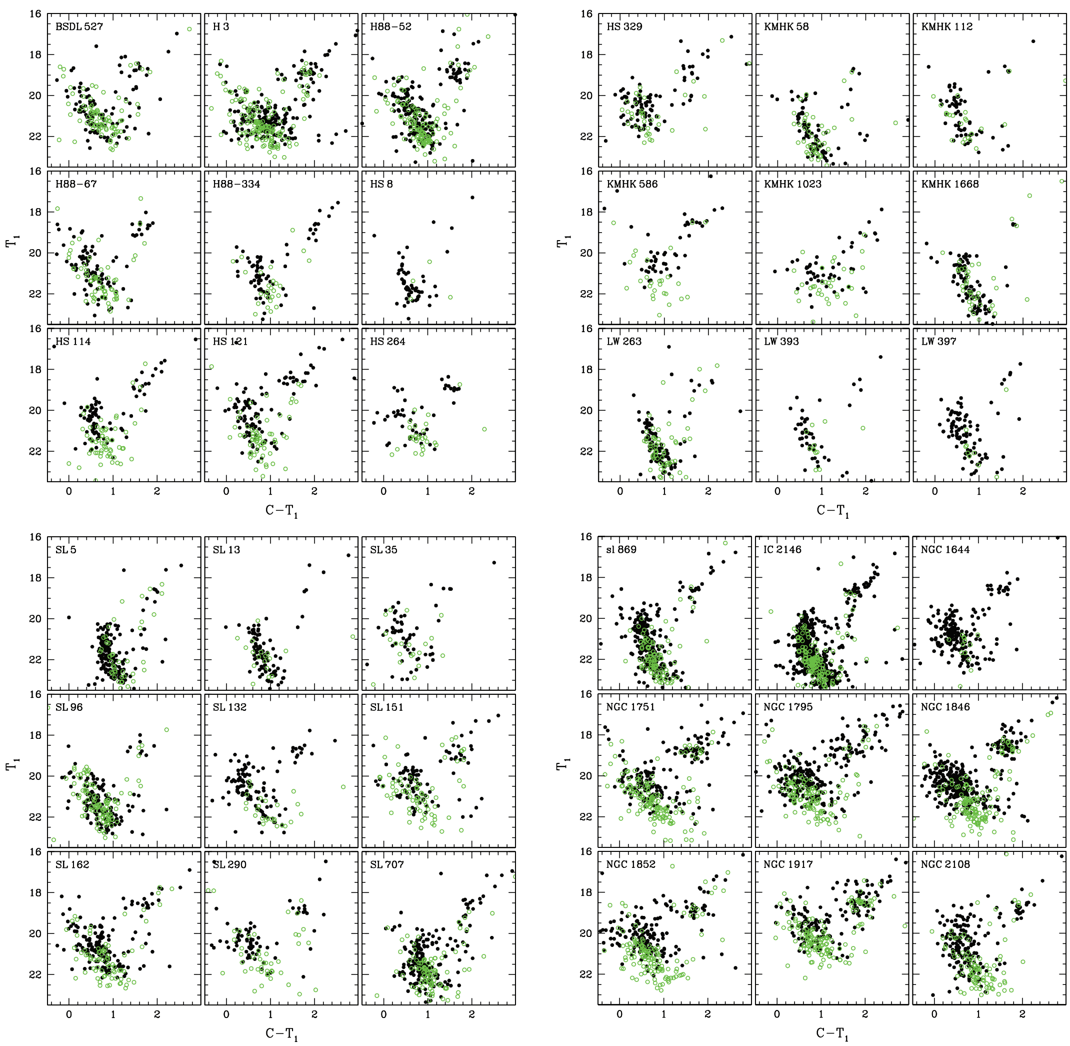

Figure 1. Annular extracted cluster ($C - T_1$, T_1) CMDs (filled circles) and the corresponding surrounding field CMDs for equal cluster areas (green circles) overplotted.

Table 2. Fundamental parameters of LMC clusters.

Name	T_1(MSTO) (mag)	T_1(RC) (mag)	δT_1 (mag)	Age (Gyr)	Age (ref.)[a] (Gyr)
BSDL 527	19.70 ± 0.10	18.70 ± 0.05	1.00 ± 0.15	1.40 ± 0.10	
H 3	20.80 ± 0.10	18.90 ± 0.05	1.90 ± 0.15	2.50 ± 0.40	
H88-52	19.80 ± 0.10	18.80 ± 0.05	1.00 ± 0.15	1.40 ± 0.10	
H88-67	20.00 ± 0.10	18.60 ± 0.05	1.40 ± 0.15	1.70 ± 0.15	
H88-334	20.40 ± 0.10	18.80 ± 0.05	1.60 ± 0.15	2.00 ± 0.20	
HS 8	20.00 ± 0.10	18.70 ± 0.05	1.30 ± 0.15	1.60 ± 0.15	
HS 114	19.70 ± 0.10	18.80 ± 0.05	0.90 ± 0.15	1.30 ± 0.10	
HS 121	19.70 ± 0.10	18.60 ± 0.05	1.10 ± 0.15	1.50 ± 0.10	
HS 264	20.20 ± 0.10	18.90 ± 0.05	1.30 ± 0.15	1.60 ± 0.15	0.40 (1)
HS 329	20.20 ± 0.10	18.70 ± 0.05	1.50 ± 0.15	1.80 ± 0.20	
KMHK 58	20.00 ± 0.10	18.70 ± 0.05	1.30 ± 0.15	1.60 ± 0.15	
KMHK 112	19.50 ± 0.10	18.70 ± 0.05	0.80 ± 0.15	1.25 ± 0.10	0.60 (1)
KMHK 586	20.10 ± 0.10	18.60 ± 0.05	1.50 ± 0.15	1.80 ± 0.20	
KMHK 1023	20.50 ± 0.10	19.10 ± 0.05	1.40 ± 0.15	1.70 ± 0.15	
MKHK 1668	20.10 ± 0.10	18.70 ± 0.05	1.40 ± 0.15	1.70 ± 0.15	
LW 263	20.20 ± 0.10	18.70 ± 0.05	1.50 ± 0.15	1.80 ± 0.20	
LW 393	20.20 ± 0.10	18.70 ± 0.05	1.50 ± 0.15	1.80 ± 0.20	
LW 397	20.20 ± 0.10	18.70 ± 0.05	1.50 ± 0.15	1.80 ± 0.20	
SL 5	20.50 ± 0.10	18.60 ± 0.05	1.90 ± 0.15	2.50 ± 0.40	
SL 13	20.50 ± 0.10	18.60 ± 0.05	1.90 ± 0.15	2.50 ± 0.40	
SL 35	19.80 ± 0.10	18.70 ± 0.05	1.10 ± 0.15	1.50 ± 0.10	0.60 (1)
SL 96	20.00 ± 0.10	18.70 ± 0.05	1.30 ± 0.15	1.60 ± 0.15	
SL 132	20.00 ± 0.10	18.70 ± 0.05	1.30 ± 0.15	1.60 ± 0.15	0.40 (1)
SL 151	19.80 ± 0.10	18.70 ± 0.05	1.10 ± 0.15	1.50 ± 0.10	
SL 162	19.60 ± 0.10	18.50 ± 0.05	1.10 ± 0.15	1.50 ± 0.10	0.40 (1)
SL 290	19.70 ± 0.10	19.00 ± 0.05	0.70 ± 0.15	1.20 ± 0.10	0.20 (1)
SL 707	20.50 ± 0.10	18.70 ± 0.05	1.80 ± 0.15	2.30 ± 0.30	
SL 869	21.00 ± 0.10	18.60 ± 0.05	1.40 ± 0.15	1.70 ± 0.15	
			Control clusters		
IC 2146	20.00 ± 0.20	18.70 ± 0.10	1.30 ± 0.30	1.60 ± 0.30	1.55 (2)
NGC 1644	19.60 ± 0.20	18.50 ± 0.10	1.10 ± 0.30	1.50 ± 0.20	1.55 (2)
NGC 1751	19.60 ± 0.20	18.70 ± 0.10	0.90 ± 0.30	1.30 ± 0.20	1.30–1.50 (2,3)
NGC 1795	20.00 ± 0.20	18.70 ± 0.10	1.30 ± 0.30	1.60 ± 0.30	1.30 (2)
NGC 1846	19.60 ± 0.20	18.60 ± 0.10	1.00 ± 0.30	1.40 ± 0.20	1.35–1.60 (2,3)
NGC 1852	19.60 ± 0.20	18.60 ± 0.10	1.00 ± 0.30	1.40 ± 0.20	1.20–1.45 (2)
NGC 1917	19.50 ± 0.20	18.60 ± 0.10	0.90 ± 0.30	1.30 ± 0.20	1.20–1.35 (2)
NGC 2108	19.40 ± 0.20	18.60 ± 0.10	0.80 ± 0.30	1.25 ± 0.20	0.95–1.10 (2,3)

[a] (1) Glatt et al. (2010); (2) Milone et al. (2009); (3) Goudfrooij et al. (2011a).

that this age measurement technique does not require absolute photometry. The measured T_1(MSTO) and T_1(RC) magnitudes, their uncertainties (we adopted values $\gtrsim \sigma T_1$, see fig. 1 of Piatti 2011) and the derived δT_1 differences are listed in Table 2.

The computed cluster ages are listed in column 5 of Table 2, and their errors come from the propagation of $\sigma(\delta T_1)$ through equation (4) of Geisler et al. Fortunately, all the control clusters have ages in excellent agreement with those previously published, even though most of them have clear signs of multiple MSTOs (Milone et al. 2009; Goudfrooij et al. 2011a). On the other hand, Glatt, Grebel & Koch (2010) have recently studied some clusters in common, assuming that they are young clusters. As they mentioned, this could be due to their limited photometric depth and/or biased field star contamination cleaning. Table 2 shows that the selected clusters have ages distributed around ∼2 Gyr, the age at the peak of the bursting formation episode occurred in the LMC.

Finally, we rebuilt the LMC cluster age distribution for clusters older than 0.5 Gyr by following the precepts outlined by Piatti et al. (2011a), which take into account the variation of the age bin sizes in terms of the estimated age errors, and by now adding the clusters of Table 2. The result is shown in Fig. 2 (solid line), wherein we included with a dotted line that previously obtained by Piatti et al. (2011a). Fig. 2 shows that the number of clusters with ages between 1 and 3 Gyr doubles that of the known bursting cluster population. Thus, if such clusters could arise as a consequence of the

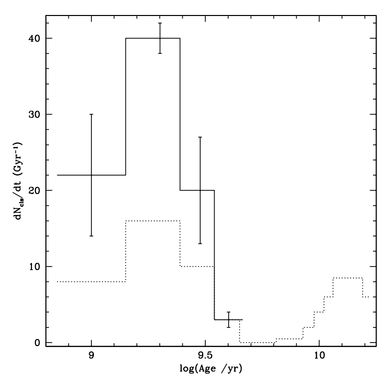

Figure 2. The intrinsic age distribution of LMC clusters older than 0.5 Gyr (solid line) and that obtained by Piatti et al. (2011a, dotted line), overplotted.

interaction between both MCs, the present result would appear to suggest that the tidal encounter was more violent/intense than expected. Indeed, as far as we are aware, the general outlines of the Harris & Zaritsky's (2009) SFH is consistent with previously published SFHs as well as with Piatti et al.'s (2011a) results. On the other hand, the present results would not appear to be affected by cluster disruption effects, in the sense that the cluster disruption could be blurred by the noticeable bursting cluster formation episode. For example, Glatt et al. (2011) recently obtained relaxation times for intermediate-age Small Magellanic Cloud (SMC) clusters between ∼1.4 and 9.2 Gyr. Furthermore, we calculated the cluster masses following the precepts outlined by Mackey & Gilmore (2003) and obtained masses ($\log(M/M_{\odot})$) in the range 4.20 ± 0.20 up to 4.35 ± 0.30. The cluster luminosities were estimated by adding the individual star luminosities, obtained by using the respective *C* magnitudes and the corresponding theoretical isochrone of Girardi et al. (2002), according to the cluster age. The light-to-mass ratios were obtained from fig. 13 of Mackey & Gilmore. Finally, by using the expression quoted by Santiago (2009), we obtained relaxation times from 2.55 up to 3.16 Gyr. On the other hand, Goudfrooij et al. (2011b) obtained masses for three of our control clusters ranging from 4.41 up to 5.17 in $\log(M/M_{\odot})$. It's worth considering whether such stronger interaction have left any observable effects in the SMC and, perhaps, also in the Milky Way (MW). Recently, Diaz & Bekki (2011) presented orbital models for the MW–LMC–SMC galaxies consistent with *Hubble Space Telescope*'s proper motions (Kallivayalil et al. 2006a; Kallivayalil, van der Marel & Alcock 2006b), and found that the three galaxies experienced a close encounter at ∼1.5–2.0 Gyr ago. Similarly, from an observational point of view, Piatti et al. (2011b) and Piatti (2010) also found evidences of cluster bursting formation events at ∼1.5–2.0 Gyr in the SMC and MW, respectively.

4 SUMMARY

In this study we present, for the first time, CCD Washington CT_1T_2 photometry of stars in the field of 36 LMC clusters. The analysis of the photometric data leads to the following main conclusions.

(i) CMD cluster features – mainly cluster RCs and MSTOs – turn out to be identifiable when performing annular extractions around their respective centres, although they have not been cleaned from field star contamination.

(ii) By using the (T_1, $C - T_1$) and (T_1, $T_1 - T_2$) diagrams, we estimated ages for the cluster sample using the δT_1 index. Although multiple MSTO features are seen in eight control clusters, their estimated ages result in excellent agreement with those previously published, thus confirming our present age scale.

(iii) We confirm that the studied cluster sample belong to the ∼2 Gyr bursting formation epoch of the LMC. Furthermore, when rebuilding the cluster age distribution, taken into account the estimated age errors, we found that the number of clusters with ages between 1 and 3 Gyr now doubles that of the known bursting cluster population, which suggests that the tidal interaction between the MCs and, perhaps, also the MW, was more stronger than expected.

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