Revisiting Newly Large Magellanic Cloud Age-gap Star Clusters

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Abstract

Recently, a noticeable number of new star clusters was identified in the outskirts of the Large Magellanic Cloud (LMC) populating the so-called star-cluster age gap, a space of time (~4–12 Gyr) where the only known star cluster is up-to-date ESO 121-SC03. We used Survey of the Magellanic Stellar History DR2 data sets, as well as those employed to identify these star-cluster candidates, to produce relatively deep color–magnitude diagrams (CMDs) of 17 out of 20 discovered age-gap star clusters with the aim of investigating them in detail. Our analysis relies on a thorough CMD cleaning procedure of the field-star contamination, which presents variations in its stellar density and astrophysical properties, such as luminosity and effective temperature, around the star-cluster fields. We built star-cluster CMDs from stars with membership probabilities assigned from the cleaning procedure. These CMDs and their respective spatial distribution maps favor the existence of LMC star field density fluctuations rather than age-gap star clusters, although a definitive assessment on them will be possible from further deeper photometry.

Unified Astronomy Thesaurus concepts: Astronomical methods (1043); Large Magellanic Cloud (903); Star clusters (1567)

1. Introduction

The absence of star clusters with ages between ~3 and 10 Gyr in the Large Magellanic Cloud (LMC)—the sole exception is ESO 121-SC03 (Mateo et al. 1986)—was noticed by Olszewski et al. (1991). They also found that the age gap correlates with a cluster-metallicity gap, in the sense that star clusters younger than 3 Gyr are much more metal-rich than the ancient LMC globular clusters. The LMC age gap spans most of the galaxy lifetime, thus, making it difficult to reconstruct its chemical enrichment from cluster ages and metallicities. Although different observational campaigns have searched for unknown old star clusters, they have confirmed previous indications that star clusters were not formed during the age gap (e.g., Da Costa et al. 1991; Geisler et al. 1997).

The upper age limit of the LMC age gap is given by the youngest of the 15 LMC globular clusters (~12 Gyr; Piatti & Mackey 2018; Piatti et al. 2018b). The lower age limit, however, has been changed as more intermediate-age stars clusters were studied in detail. For instance, Sarajedini (1998) found that NGC 2121, 2155, and SL 663 are ~4 Gyr old star clusters, while Rich et al. (2001) reestimated their ages to be 0.8 Gyr younger (see, also, Piatti et al. 2002). Age estimates of poorly studied or unstudied star clusters were derived during the last decade, and the oldest ones turned out to be ~2.5–3.0 Gyr old (see, e.g., Piatti et al. 2009; Piatti 2011a; Piatti & Geisler 2013). From the above results, we use here a conservative definition of age-gap star clusters as those with ages between 4 and 12 Gyr.

The LMC star cluster age distribution was modeled by Bekki et al. (2004), who proposed that the LMC was formed at a distance from the Milky Way that did not allow its tidal forces to trigger star-cluster formation efficiently. The star-cluster formation resumed in the LMC at its first encounter with the Small Magellanic Cloud ~2–3 Gyr ago. Such a star-cluster formation history was not that of the Small Magellanic Cloud, which would have been formed as a lower mass galaxy closer to the Milky Way, and thus more continuously influenced by its gravitational field. Nevertheless, both Magellanic Clouds have had a series of close interactions between them and their first passage around the Milky Way that explain their abrupt observed chemical enrichment history and increase of the star cluster formation rates (Piatti 2011a, 2011b; Piatti & Geisler 2013; Kallivayalil et al. 2013; Lucchini et al. 2020).

Recently, Gatto et al. (2020) performed a search for unidentified star clusters in LMC outermost regions and detected 20 star-cluster candidates with estimated ages ≥4 Gyr. They used the YMCA (Yes, Magellanic Clouds Again) and STEP (The Small Magellanic Cloud in Time: Evolution of a Prototype interacting late-type dwarf galaxy; Ripepi et al. 2014) surveys carried out with the Very Large Telescope Survey Telescope (VST) at the European Southern Observatory (ESO). Because the discovery of only one LMC age-gap star cluster would be noteworthy in itself, this astonishingly large number of new age-gap star cluster candidates caught our attention. Gatto et al. (2020) mentioned that these candidates come from surveying previously unexplored regions in the LMC periphery and from their deep photometry. While the outermost LMC regions have started to be targeted relatively recently with the aim of looking for new star clusters (see Table I in Maia et al. 2019), the depth of the photometric campaigns could even improve (see, e.g., Sarajedini 1998; Rich et al. 2001). In this work, we make use of the same data sets employed by Gatto et al. (2020) and the publicly available Survey of the Magellanic Stellar History (SMASH) DR2 data sets (Nidever et al. 2021) to further confirm the ages of the new star-cluster candidates, so to reinforce their discoveries. In Section 2, we present the data used in this work, while in Section 3 we describe the analysis carried out in order to unveil the fiducial star-cluster features in the color–magnitude diagram (CMD). Finally, in Section 4 we discuss the present results and summarize the main conclusions.
The retrieved data sets consist of sources with 0.2 from the star clusters 'SHARPNESS' adopted as the cluster to the color bar. The radius of the superimposed circles is three times that proportional to the brightness, while their color excesses are coded according to the color bar. The size of the symbols is three times that of the star cluster, we selected six adjacent represented by a circle centered on the star cluster with a radius three times that of the star cluster, we selected six adjacent distributed around the cluster region, as depicted in Figure 1.

\[ \Delta \text{A}(\text{R.A.}) \times \cos(\text{Decl.}) \]  
\[ \Lambda(\text{B-V}) \]

\[ \Delta(\text{B-V}) \]

Figure 1. Schematic chart centered on STEP-0029. The size of the symbols is proportional to the g brightness, while their color excesses are coded according to the color bar. The radius of the superimposed circles is three times that adopted as the cluster’s radius (Gatto et al. 2020). Six labeled reference star fields distributed around the star cluster circle are also drawn.

2. The Data

We use the portal of the Astro Data Lab, which is part of the Community Science and Data Center of National Science Foundation’s (NSF’s) National Optical-Infrared Astronomy Research Laboratory, to retrieve R.A. and decl. coordinates, point-spread function g, i magnitudes, and their respective errors, interstellar reddening \( E(B-V) \) and \( \chi \), and SHARPNESS parameters of stellar sources located inside a radius of 6' from the star clusters' centers listed by Gatto et al. (2020). The retrieved data sets consist of sources with 0.2 \( \leq \) SHARPNESS \( \leq 1.0 \) and \( \chi^2 < 0.5 \), so bad pixels, cosmic rays, galaxies, and unrecognized double stars were excluded. Gatto et al. (2020) discovered 85 star-cluster candidates. In this work we analyze 17 out of 20 objects with estimated ages \( \geq 4 \) Gyr (log(age/yr) \( \geq 9.6 \)). STEP-0004, YMCA-0031, and YMCA-0033 are age-gap star-cluster candidates, but they fall outside the areal coverage of SMASH DR2. Figure 1 illustrates a typical star-cluster field, where the variation of the interstellar reddening is shown with color-coded symbols.

The radii of the studied star-cluster candidates are relatively small, from 0'2 up to 0'55, with an average of 0'35 (see Table B1 in Gatto et al. 2020). Because we downloaded information for circular areas much larger than the star-cluster fields, we thoroughly monitored the contamination of field stars in the star clusters’ CMDs. Indeed, for each star cluster field, represented by a circle centered on the star cluster with a radius three times that of the star cluster, we selected six adjacent reference star-field regions of equal star-cluster field area distributed around the cluster region, as depicted in Figure 1.

We based our analysis on dereddened CMDs, so we first corrected by interstellar extinction the g and i magnitudes using the \( E(B-V) \) values provided by SMASH and the \( A_\lambda/E(B-V) \) ratios, for \( \lambda = g, i \), given by Abbott et al. (2018). The retrieved SMASH \( E(B-V) \) value for each star (see the color bar in Figure 1) corresponds to the median \( E(B-V) \) around it obtained by using the reddening map of Schlegel et al. (1998; see also Choi et al. 2018; Nidever et al. 2021).

As for the data sets used by Gatto et al. (2020), they were kindly provided by V. Ripepi. We note that the g, i bands of the STEP/YMCA surveys are not the same used by SMASH (see Figure 1 in Ripepi et al. 2014). Therefore, g – i color ranges are not straightforwardly comparable, nor are their CMDs. Both STEP/YMCA and SMASH data sets are then independent sources. Nidever et al. (2017) presented in their Table 4 the SMASH average photometric transformation equations. By adding in quadrature zero-point, extinction, and color term errors, we computed an accuracy \( \leq 0.02 \) mag in gi. They showed that these calibration errors imply a SMASH photometry precision of \( \sim 0.5\% - 0.7\% \) in gi. Such a precision implies in turn an uncertainty of \( \sim 0.11 - 0.14 \) mag in gi, for a star at the main-sequence turnoff of a \( \sim 4 \) Gyr old LMC star cluster (\( g_0 \gtrsim 22.0 \) mag). Gatto et al. (2020) obtained an average photometry accuracy of 0.02–0.03 mag in g and i, respectively, which is comparable to that of SMASH. We note that the zero-point and color terms errors obtained by Ripepi et al. (2014, see their Table 8), on which the photometry of Gatto et al. (2020) relies, are of the same order as those of SMASH.

3. Data Analysis

The contamination of field stars plays an important role when dealing with star-cluster CMDs, because it is not straightforward to consider a star as a cluster member only on the basis of its position in that CMD. Sometimes, additional information like proper motions, radial velocities, and/or chemical abundances of individual stars can help with disentangling between field and star-cluster members. Unfortunately, in the case of our star-cluster sample, Gaia DR2 proper motions (Gaia Collaboration et al. 2016, 2018) are unreliable at the main-sequence turnoff level (\( g_0 \gtrsim 22.0 \) mag). When such a piece of information is not available, photometry of reference star fields are usually employed. These reference star fields are thought to be placed far from the star-cluster field, but not too far from it as to become unsuitable as a representative of the star field projected along the line of sight (LOS) of the star cluster. Frequently, it is assumed that the stellar density and the distribution of luminosities and effective temperatures of stars in these reference star fields are similar to those of field stars located along the LOS of the star cluster. However, even though the star cluster is not projected onto a crowded star field nor is not affected by differential reddening, it is highly possible to find differences between the astrophysical properties of the reference star fields and the star-cluster field. Bearing in mind the above considerations, we decided to clean the star-field contamination in the star-cluster CMDs by using, at a time, the six different devised reference star-field areas introduced in Section 2.

The decontamination of a star-cluster CMD comprises of three main steps, namely: (i) to properly deal with each of the six reference star fields by considering the observed distribution of their stars in luminosity and effective temperature; (ii) to reliably subtract the reference star fields from the star-cluster CMD (one reference field at a time) and; (iii) to assign membership probabilities to stars that remained unsubtracted in the resulting cleaned star-cluster CMDs. Stars with relatively high membership probabilities can likely be cluster members, if they are placed along the expected star-cluster CMD sequences. However, in general, they represent overdensities along the LOS of the composite stellar-field population. We refer the readers to Piatti & Bica (2012), who devised the above
procedure, which was satisfactorily applied in cleaning CMDs of star clusters projected toward crowded star fields (e.g., Piatti 2017a, 2017b, 2017c, and references therein) and affected by differential reddening (e.g., Piatti 2018a; Piatti et al. 2018a, and references therein).

We used a star-cluster field (a circle centered on the cluster with a radius three times that of the cluster (see Table B1 in Gatto et al. 2020) to subtract a number of stars equal to that in a reference star field. We repeated the star subtraction for the six devised reference star fields (see Figure 1), separately, one at a time. Note that if we subtracted fewer or more stars than those in the reference star field, we could conclude on the existence of an unreal stellar excess or on a less populous aggregate, respectively. Moreover, spurious overdensities could even result if the cleaning procedure chose the stars to subtract following a particular arbitrary spatial pattern (e.g., from north to south). If there were any intrinsic spatial gradient of field stars in the cluster area, the cleaning procedure would eliminate it. The procedure finds field stars in the star-cluster CMD (with similar magnitudes and colors as those in the reference starfield CMD) where they actually are located, i.e., it subtracts more field stars where they are more numerous.

The distribution of magnitudes and colors of the subtracted stars from the star-cluster field needs, in addition, to resemble that of the reference star field. The method consists of defining boxes centered on the magnitude and color of each star of the reference star-field CMD, then to superimpose them on the star-cluster CMD, and finally to choose one star per box to subtract. With the aim of avoiding stochastic effects caused by very few field stars distributed in less populated CMD regions, appropriate ranges of magnitudes and colors around the CMD positions of field stars are advisable to be used. Thus, it is highly probable to find a star in the star-cluster CMD with a magnitude and a color within those box boundaries. In the case that more than one star is located inside that delimited CMD region, the closest one to the center of that (magnitude, color) box is subtracted. In the present work, we used boxes of $(g_0, (g - i)_0) = (2.0 \text{ mag}, 1.0 \text{ mag})$ centered on the $(g_0, (g - i)_0)$ values of each reference field star.

In practice, for each reference field star, we first randomly selected the position of a subregion inside the star-cluster field for where to subtract a star. These subregions were devised as annular segments of $90^\circ$ wide and of constant area. Their external radii are chosen randomly, while the internal ones are calculated so that the areas of the annular sectors are constant. Here we adopted an area for the subregions equal to $\pi r_{\text{cls}}$, where $r_{\text{cls}}$ is the star cluster radius. We then looked for a star with $(g_0, (g - i)_0)$ values within a box defined as described above. If no star is found in that annular sector, we randomly selected another one and repeated the search, allowing the procedure to iterate up to 1000 times. If no star in the star-cluster field with a magnitude and a color similar to $(g_0, (g - i)_0)$ is found after 1000 iterations, we do not subtract any star for those $(g_0, (g - i)_0)$ values. The same procedure was applied for all the stars in the reference star field. The photometric errors of the stars in the star-cluster field were taken into account while searching for a star to be subtracted from the star-cluster CMD. With that purpose, we repeated the search up to 1000 times within each defined box, allowing the stars in the star-cluster CMD to vary their magnitudes and colors within an interval of $\pm 1 \sigma$, where $\sigma$ represents the errors in their magnitude and color, respectively.

Figure 2. CMD of STEP-0029. Black points represent all the measured stars the in SMASH DR2 data sets located within a circle with a radius equal to three times the cluster radius. Large magenta points represent the stars that remained unsubtracted after the CMD cleaning procedure. The reference star field used to decontaminate the star-cluster CMD is indicated at the top-left margin (see also Figure 1).

Figure 3. Chart of the stars in the field of STEP-0029. The size of the symbols is proportional to the $g$ magnitude of the star. Open black circles represent all the measured stars in the SMASH DR2 data sets located within a circle with a radius equal to three times the cluster radius. Filled magenta circles represent the stars that remained unsubtracted after the CMD cleaning procedure. The reference star field used to decontaminate the star-cluster CMD is indicated at the top-left margin (see also Figure 1). The large centered circle represents that of the star-cluster radius.

Figure 2 illustrates the different results of the decontamination of field stars when the six different reference star fields (see Figure 1) are used, separately. As can be seen, the different resulting cleaned star-cluster CMDs (magenta points) show distinct groups of stars, depending on the reference star field used, which suggests that differences in the astrophysical properties of the composite star field population do exist. If all the reference star fields showed a uniform distribution of stars in magnitude and color, all the resulting cleaned CMDs should look similar. The spatial distribution of the stars that remained unsubtracted is shown in Figure 3. From Figures 2 and 3, it is readily visible that the stars that have survived the cleaning procedure are not spatially distributed inside the cluster radius (black circle), nor do they unquestionably follow the expected
sequences in the star-cluster CMD either. This means that those stars could rather represent fluctuations in the stellar density along the LOS of the composite stellar-field population.

We finally assigned a membership probability to each star that remained unsubtracted after the decontamination of the star-cluster CMD. Because the stars in the cleaned CMDs vary with respect to the reference star field employed (see the distribution of magenta points in Figures 2 and 3), we defined the probability \( P(\%) = 100 \times N/6 \), where \( N \) represent the number of times a star was not subtracted during the six different CMD cleaning executions. With this information on hand, we built Figure 4, which shows the spatial distribution and the CMD of all the measured stars located in the field of STEP-0029. Stars with different \( P \) values were plotted with different colors. We applied the above cleaning procedure to the remaining 16 star-cluster candidates discovered by Gatto et al. (2020) with ages \( \geq 4 \) Gyr, for which SMASH DR2 photometry is available. The resulting SMASH cleaned star-cluster CMDs and spatial distribution of the measured stars are shown in Figures 5–7 of the Appendix, while those from STEP/YMCA data sets are depicted in Figures 8–10 of the Appendix.

4. Discussion and Conclusions

By examining the spatial distributions of stars with assigned \( P \) values (color-coded symbols in Figures 4–10), none of the analyzed fields show groups of stars with \( P > 50\% \) concentrated inside the star-cluster radius. This means that the spatial overdensities discovered by Gatto et al. (2020) do not highlight themselves in terms of stellar brightness and color distributions from those of the surrounding field neither in the STEP/YMCA nor the SMASH data sets, when the field-star decontamination procedure described in Section 3 is applied. They could instead reveal small stellar-density fluctuations in the studied LMC regions. Isolated stars spread throughout the cleaned areas spanning a wide range of \( P \) values are seen in all the studied fields. We also detect some local concentrations of stars distinct from the surrounding field in the SMASH data, for example, toward the southern outskirts of STEP-0012, YMCA-0021, and YMCA-0023. Their positions in the cleaned CMDs, however, do not provide hints for any star-cluster sequence.

Because of the LMC distance (49.9 kpc; de Grijs et al. 2014), stars projected along a particular LOS could produce CMDs with features similar to those seen in star-cluster CMDs. For example, from the SMASH cleaned CMD of YMC-0002 (Figure 6), we could conclude on the existence of a star cluster with a few red clump and main-sequence turnoff stars, whereas the spatial distribution of stars with \( P > 70\% \) does not support such a possibility. The SMASH cleaned CMD of YMC-0007 shows a populous red clump of stars with \( P \sim 50\% \) that belong to the field, as judged by their spatial distribution. In summary, Figures 4–10 most likely reveal the composite stellar population of the studied LMC regions and their local fluctuations.

Piatti (2018b) arrived to a similar conclusion on the newly identified star clusters by Bitsakis et al. (2017), who found that the population of LMC star clusters located at deprojected distances <4° was nearly double the known size of the system. Piatti (2018b) based his findings on the remarkably large number of objects with assigned ages older than 2.5 Gyr, which contrasts with the existence of the LMC star-cluster age gap; the fact that the assumption of a cluster formation rate similar to that of the LMC star field does not help to reconcile the large amount of star clusters either; and nearly 50% of them come from star cluster search methods known to produce more than 90% of false detections. Bitsakis et al. (2017) identified only ~35% of the previously known cataloged LMC star clusters. The LMC star-cluster frequency, i.e., number of star clusters per time unit, is a distribution function that basically does not change if low-mass star clusters are not considered. The known LMC star cluster population is statistically complete down to \( 5 \times 10^3 M_\odot \) and their star-cluster frequency does not show clusters in the age gap, and this is a feature seen all throughout the LMC body (Piatti 2014). The LMC fields analyzed here are located beyond 4° from the LMC center, the number of new detections is not so high, and the recovery fraction of known cataloged LMC star clusters is much higher (see Figure 7 in Gatto et al. 2020). Nevertheless, it is hardly possible that age-gap star clusters have been formed only in the outskirts of the LMC. Indeed, the 15 ancient LMC globular clusters are distributed in the halo and in the disk of the galaxy (Piatti et al. 2019).

The different outcomes obtained by Gatto et al. (2020) and in the present work reflect the different performances of the techniques employed for cleaning the CMDs of field-star contamination. When comparing the present constructed CMDs (Figures 4–10) and those of Gatto et al. (2020, see their figure B1) we note that: (i) those built from SMASH and STEP/YMCA data contain a similar number of stars and reach, in general, similar limiting magnitudes per unit area. (ii) By comparing the observed and cleaned CMDs built by Gatto et al. (2020), it would seem that the number of field stars subtracted was relatively small. Likewise, the number of stars considered as star-cluster members the CMDs of Gatto et al. (2020) would also seem to be small as to conclude on clear features of a relatively old star cluster. In the present work, we subtracted a larger number of field stars per unit area using the SMASH and STEP/YMCA data sets and no definitive signature of star clusters is observed in the cleaned CMDs. Therefore, we speculate with the possibility that the results of Gatto et al. (2020) and ours are based on a low number statistics. (iii) As can be seen, the star distribution along the theoretical
isochrones in CMDs built from SMASH and STEP/YMCA data are comparable. Here we stress the issue that for most of the studied objects, these stars would not seem to belong to a physical aggregate, but to the composite LMC field. Indeed, the observed main-sequence turnoffs are mostly populated by field stars. (iv) The metallicities of the isochrones used by Gatto et al. (2020; Z = 0.004, 0.006 and 0.008) are much more metal-rich than the known metallicity of the only confirmed LMC age-gap cluster ESO 121-SC03 (Z ≈ 0.0015; Piatti & Geisler 2013).

Both independent studies point to the need for further deeper observations of these star-cluster candidates with the aim of providing a definite assessment on their physical realities. Our analysis shows that STEP/YMCA and SMASH surveys do not have the ability to disentangle the existence of LMC age-gap star clusters. The existence of LMC age-gap star clusters has been largely treated in the astronomical community, and the general consensus after different focused campaigns for such star clusters and astrophysical results of the star formation history in the LMC has been that ESO 121-SC03 is the only known age-gap star cluster.

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Appendix

Cleaned Star-cluster CMDs

Figures 5–7 show the SMASH cleaned star cluster CMDs and the respective spatial distribution of the star candidates.

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**Figure 5.** Same as Figure 4 for STEP-0001, STEP-0005, STEP-0012, STEP-0024, STEP-0035, and YMCA-0001 from top to bottom, and from left to right.

**Figure 6.** Same as Figure 4 for YMCA-0002, YMCA-0004, YMCA-0006, YMCA-0007, YMCA-0008, and YMCA-0012 from top to bottom, and from left to right.

**Figure 7.** Same as Figure 4 for YMCA-0013, YMCA-0017, YMCA-0021, and YMCA-0023 from top to bottom, and from left to right.
with ages $\geq 4$ Gyr discovered by Gatto et al. (2020). Symbols are as in Figure 4. Figures 8–10 are those produced from STEP/YMCA data sets.

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