Astrophysical properties of newly discovered Magellanic Cloud star clusters

Andrés E. Piatti¹,²⋆

¹ Instituto Interdisciplinario de Ciencias Básicas (ICB), CONICET-UNCUYO, Padre J. Contreras 1300, M5502JMA, Mendoza, Argentina;
² Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Godoy Cruz 2290, C1425FQB, Buenos Aires, Argentina

ABSTRACT

New star cluster candidates projected toward the Large and Small Magellanic Clouds (L/SMC) have been recently discovered from relatively deep imaging surveys. We here conduct a sound analysis of 24 star cluster candidates located in the outer regions of the L/SMC using PSF photometry produced by the Survey of the Magellanic Stellar History. With only one exception, the studied objects resulted to be genuine stellar aggregates. We conclude on their physical reality once their observed color-magnitude diagrams (CMDs) were statistically decontaminated by the presence of field stars, and the resulting cleaned CMDs for stars with assigned membership probabilities higher than 50% were compared with synthetic CMDs generated for thousand combinations of ages, distances, metallicities, star cluster mass and binary fractions. The parameter of the best-matched synthetic CMDs obtained from a likelihood approach were adopted as the star cluster astrophysical properties. The present star cluster sample spans a wide range of distances, from those star clusters located in front of the LMC, to those along the onset of the Magellanic Bridge, up to those behind the SMC. Their ages reveal different formation episodes that took place along the galaxy formation and others as a consequence of the galaxy interactions. From their estimated metallicities and ages, we speculate with the possibility that relatively metal-deficient gaseous flows have existed between these galaxies during nearly the last one Gyr (log(age/yr) ≈ 9.0), that made possible the formation of young star clusters in the galaxy peripheries. Despite the L/SMC interactions, the studied star clusters are similar or more massive than their counterparts in the Milky Way, which suggests that tidal effects are relatively more important in our Galaxy.

Key words. Methods: observational - techniques: photometric - Galaxies: Magellanic Clouds - Galaxies: star clusters: general

1. Introduction

Recent imaging surveys of the Magellanic Clouds have allowed the community to embark in searches of relatively compact, small and poorly populated star clusters (see, Table 1 in Maia et al. 2019). Imaging visual inspections (e.g., Bica et al. 2020) or machine learning techniques (e.g., Cerny et al. 2020) revealed the existence of stellar overdensities proposed as star clusters spread throughout the surveyed areas. Several of these star cluster candidates have not been confirmed as genuine physical systems (Piatti et al. 2014; Piatti 2018b), while others turned out to be star clusters with properties that have defied our previous knowledge about the Magellanic Clouds formation, structure, dynamics and chemical evolution (Piatti et al. 2016; 2018b; Gatto et al. 2020).

By using wide-field high-quality images released in advance from the Survey of the Magellanic Stellar History (SMASH) (Nidever et al. 2017; Piatti 2017) used density kernel estimators with physically meaningful bandwidths to detect the smallest and/or less dense star clusters in the Magellanic Clouds. He found out 24 new star cluster candidates (see his Table 1), most of them located in the outer regions of both Clouds, thus reinforcing previous suggestions that those regions were less explored in the past. He did not estimate their fundamental parameters, which means that the reality of these candidates as stellar aggregates needs to be confirmed. The SMASH DR2 is now publicly available from the portal of the Astro Data Lab[1], which is part of the Community Science and Data Center of NSF’s National Optical Infrared Astronomy Research Laboratory. Therefore, we have now the chance of studying in details these candidates, providing for the first time with their astrophysical properties. SMASH is a community Dark Energy Camera (DECam) survey of the Magellanic Clouds mapping 480 deg² (distributed over ~2400 deg² at ~20% filling factor, which complements the 5000 deg² Dark Energy Survey’s partial coverage of the Magellanic periphery) to ~24th mag griz (and u ~23), with the goal of identifying broadly distributed, low surface brightness stellar populations associated with the stellar halos and tidal debris of the Magellanic Clouds. SMASH will also derive spatially-resolved star formation histories covering all ages out to large radii of the Magellanic Clouds that will further complement our understanding of their formation. DECam is a wide-field optical imager (FOV = 2.2×2.2 deg², scale = 0.263 arcsec/pix) attached at Cerro Tololo Interamerican Observatory Blanco 4m telescope.

Beyond the usefulness of enlarging the sample of well-studied Magellanic Cloud star clusters, the fact that Piatti (2017)’s new candidates are located in the outer regions of both Clouds is of particular interest. The outer regions of the Large and Small Magellanic Clouds (L/SMC) have been primary scenarios of the interaction between both galaxies, namely: star clusters were stripped off (Carpintero et al. 2013); new stars clus-

---

[1] https://datalab.noao.edu/smash/smash.php

---

Received / Accepted
We retrieved R.A and Dec. coordinates, PSF parameters of stellar sources distributed within circles with radii of 6′ (the star cluster candidates are smaller than ~0.3′) from the Astro Data Lab. In order to assure the selection of point sources, we applied the following filters: $0.2 < \text{SHARPNESS} < 1.0$ and $\chi < 0.5$, so cosmic rays, bad pixels, galaxies, and unrecognized double stars were excluded. SHARPNESS and $\chi$ are image quality diagnostic parameters used by DAOPHOT.

We carefully monitor the contamination of field stars in the star cluster CMDs by using 6 different star field CMDs built from stars distributed in circular areas of equal size as the cluster area distributed around it (see, Fig. [1]). This is because the star field varies in stellar density as well as in the distribution of brightness and color of its stars from one place to the other. The chosen regions are meant to include any possible star field population and reddening variation around the star clusters. Because the star cluster candidates are relatively small and would seem to contain a relative small number of stars (see, Fig. 3 in Piatti [2017]), we decided to clean cluster areas with radii slightly larger than the readily visible clusters’ dimensions. Thus, we minimize the presence of potential residuals from the cleaning procedure when building the cleaned star cluster CMDs.

Field star contamination plays an important role when analyzing Magellanic Cloud star cluster CMDs. Because of the galactocentric distances of both galaxies, star cluster and field star sequences in the CMDs can be superimposed. This means that it is not straightforward to consider a star a cluster member from its lone position in the CMD. Such an ambiguity can be solved, sometimes, with additional information of proper motions, radial velocities, and/or chemical abundances of individual stars. Unfortunately, in the case of our star cluster candidates, Gaia DR2 proper motions [Gaia Collaboration et al. 2016 2018] are unavailable for several stars concentrated in very small regions or they are unreliable because of their apparent low brightness. For this reason, we exploit the photometry of reference field stars to decontaminate the star cluster CMDs.

In general terms, the reference star field is placed adjacent to the star cluster field, but not too far from it, so that it can be a suitable representative of the star field projected along the line-of-sight (LOS) of the star cluster. Frequently, the assumption of homogeneity in the stellar density and in the distribution of luminosities and effective temperatures of field stars across the star cluster field and around it is adopted. This means that field stars located along the LOS of the star cluster can be mimic in number and astrophysical properties by those located along a direction slightly shifted from that toward the star cluster. However, even though the star cluster is not projected onto a crowded star field or is not affected by differential reddening, it is highly possible to find differences throughout the star cluster surrounding 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 6 different devised reference star field areas described above.

We follow three main steps while decontaminating the star cluster CMDs. On the one hand, we properly represent each reference star field by considering simultaneously its stellar density and the observed distribution of its stars in luminosity and effective temperature (number of stars per CMD mag and color units). Then, we statistically subtract the reference star field from the star cluster CMD and, finally, we assign membership probabilities from the consideration of the six different resulting cleaned star cluster CMDs (one cleaned CMD per reference star field CMD). Stars with relatively high membership probabilities that are located along a single theoretical isochrone (corresponding to an age, distance and metallicity) are considered cluster members. The method was devised by Piatti & Bica [2012] and successfully used elsewhere to decontaminate CMDs of star clusters projected on to crowded fields in the Milky Way and the Magellanic Clouds (see, e.g. Piatti et al. 2016 Piatti 2018a Piatti et al. 2020 and references therein).

We subtract from the star cluster CMD a number of stars equal to that in the reference star field. If we subtracted less or more stars, we could conclude on the presence of a more populous object or the absence of a real aggregate, respectively. The distribution of magnitudes and colors of the subtracted stars needs in addition to resemble that of the reference star field. 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 boundaries around the magnitude and color of each field star. 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. We started here with boxes of $(\Delta g, \Delta(g-i)) = (2.0 \text{mag},1.0 \text{mag})$ centered on the magnitude and color values of each reference field star. We based our analysis on redder CMDs, so we first corrected by interstellar extinction the $g$ and $i$ magnitudes using the $E(B-M)$ values provided by SMASH and the $A_{\lambda}/E(B-M)$ ratios, for $\lambda = g, i$, given by Abbott et al. [2018]. The photometric errors are also taken into account while searching for a star to be subtracted from the star cluster CMD. With that purpose, we iterate up to 1000 times the comparison between the magnitude and color of the reference field star and those of the stars in the star cluster CMD. If a star in the star cluster CMD falls inside the box defined for the reference field star, we subtract that star. The iterations are carried out by allowing the magnitude and color of the star in the star cluster CMD takes smaller or larger values than the mean ones according to their respective errors. Figure 2 illustrates the results of the decontamination of field stars using the six different reference star fields depicted in Fig. 1. The spatial distribution of these stars is shown in Fig. 3.

We finally assign a membership probability to each star that remain unsubtracted after the decontamination of the star cluster CMD. Because unsubtracted stars vary from one cleaned CMD to the other, we define the membership probability $P (%) = \ldots$
Fig. 1. Schematic chart centered on Field 16-02. The size of the symbols is proportional to the g brightness. The radius of the superimposed circles equals the adopted cluster’s radius (see Table 1). Six labeled reference star fields distributed around the star cluster circle are also drawn.

Fig. 2. Color-magnitude diagram of Field 16-02. Black points represent all the measured stars located within the cluster radius. 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 Fig. 1).

At first glance, the cleaned star cluster CMDs reveal objects seemingly spanning young to moderately old ages. Because the age estimate depends on the star cluster metallicity and distance, we employ routines of the Automated Stellar Cluster Analysis code (ASteCA, Perren et al. 2015) to derive all of them simultaneously. ASteCA is a suite of tools designed to analyze data sets of star clusters in order to determine their basic parameters. We thus obtain a synthetic CMD that best matches the star cluster CMD. The metallicity, age, distance, star cluster present mass and binary fraction associated to that generated synthetic CMD are adopted as the best-fitted star cluster parameters.

We start by using the theoretical isochrones computed by Bressan et al. (2012) for the SMASH photometric system. We downloaded theoretical isochrones for different metallicities values, from $Z = 0.000152$ ([Fe/H]=-2.0 dex) up to 0.030152 ([Fe/H]=0.30 dex) in steps of $\Delta Z=0.001$. This metallicity range cover almost all the metallicity regime of the Magellanic Clouds (Piatti & Geisler 2013). This is an important consideration, because the studied star clusters lie in the outer regions of the L/SMC, where metal-poor old and metal-rich young objects formed at the galaxy formation and galaxy interaction, respectively. As for ages, we downloaded isochrones from log(age/yr)=6.0 (1 Myr) up to 10.1 (12.5 Gyr) in steps of $\Delta \log(\text{age/yr})=0.05$. In total, we gathered nearly 2500 different theoretical isochrones.

The input data sets consist in intrinsic magnitudes $g_0$ and dereddened colors $(g-i)_0$ for all the stars with membership probabilities $P \geq 50 \%$, i.e., all colored points in Figures 1 and 2, with their respective uncertainties. For generating the synthetic CMDs, we adopted the initial mass function of Kroupa (2002), a minimum mass ratio for the generation of binaries of 0.5, and a range of true distance moduli from 18.0 mag (40 kpc) up to 19.5 mag (80 kpc). We explore the parameter space of the synthetic CMDs through the minimization of the likelihood function defined by Tremblay et al. (2013) using a parallel tempering Bayesian MCMC algorithm. Errors in the obtained parameters are estimated from the standard bootstrap method described in Efron (1982). We refer the reader to the work of Perren et al. (2015) for details concerning the implementation of these algorithms. Table 1 lists the resulting parameters for the entire star cluster sample. We illustrate the performance of the parameter matching procedure by superimposing the isochrone corre-

### 2.2. Estimating star cluster fundamental parameters

At first glance, the cleaned star cluster CMDs reveal objects seemingly spanning young to moderately old ages. Because the age estimate depends on the star cluster metallicity and distance, we employ routines of the Automated Stellar Cluster Analysis
Fig. 4. Spatial distribution (left panel) and corresponding intrinsic CMD (right panel) of stars measured by SMASH in the field of Field 16-02. Symbols for stars with membership probabilities $P \geq 50\%$ are painted according to the color bar. The best fitted theoretical isochrone is also superimposed in the cluster CMD.

3. Analysis and discussion

The advantage of playing with thousands of synthetic CMDs allows a larger number of free parameters to be fitted. This is the case of the true distance modulus. In dealing with theoretical isochrones fitted to star cluster CMDs, a mean distance modulus is frequently adopted, because the combination of the Magellanic Cloud distances with their respective LOS disk depths implies a variation of the distance modulus -bearing in mind that any star cluster could be placed in front of or behind the L/SMC- of $\Delta(m-M)_0 \sim 0.2$ mag. The latter comes from considering for the LMC: $(m-M)_0 = 18.49 \pm 0.09$ mag (de Grijs et al. 2014) and $<\text{LOS}> = 3.44 \pm 1.16$ kpc (Subramanian & Subramaniam 2009), and for the SMC: $(m-M)_0 = 18.98 \pm 0.03$ mag (Graczyk et al. 2020) and $<\text{LOS}> = 6.0 \pm 1.7$ kpc (Crowl et al. 2001). This difference is much smaller than the difference in absolute magnitude between two closely spaced isochrones with $\Delta \log \text{(age/yr)} = 0.1$ (a typical age error), so that adoption of a unique value for the distance modulus does not dominate the final error budget incurred in matching isochrones to the star cluster CMDs. However, the Magellanic Clouds are more extended than previously estimated, showing tidally-induced warps, substructures and tidal distortions in the peripheries, etc (Mackey et al. 2016, 2017; Choi et al. 2018; Mackey et al. 2017). Therefore, the use of the true distance modulus as a free parameter in the likelihood approach helps us to place the studied star clusters more accurately.

The resulting spatial distribution of the studied star clusters is depicted in Figure 5. For comparison purposes, we included as reference the positions of star clusters cataloged by Bica et al. (2008). They clearly delineate the bars, arms, outer disks, bridge, etc. As can be seen, the present star cluster sample consists of objects spread out across the outer regions of the L/SMC and the Magellanic Bridge. The LMC star clusters span a narrower range of distances than those in the SMC, suggesting that the SMC is more elongated than the LMC along the LOS. This spatial pattern traced by star clusters is also seen from other galaxy components which show that the Magellanic Bridge, with its onset in the SMC (Pietti et al. 2015), connects both Clouds (Wagner-Kaiser & Sarajedini 2017), and that the SMC is elongated along the LOS (Jacyszyn-Dobrzenecka et al. 2017; Nidever et al. 2019; Massana et al. 2020). We point out that the novel picture of SMC star clusters spanning a range of $\sim 15$ kpc in...
distance along the LOS would not have been disentangled if a mean distance modulus had been adopted while analyzing the star cluster CMDs.

The age estimates of these star clusters (see Figure 6) are also worthy of discussion. In general terms they confirm the outside-in formation scenario (Carrera et al. 2008; Meschin et al. 2014), in which more metal-poor star clusters formed first and the youngest ones were born from the gas that collapsed to the innermost regions. Old star clusters formed at the core of the galaxy had more chances to be disrupted. Hence, a spatial age distribution similar to an age gradient is observed. There is some exceptions to this simple view, that arise as a consequence of the galaxy interactions. Relatively young star clusters with a metallicity content of those formed in the LMC bar or inner disk were found in the outer LMC disk, where older and more metal-poor ones are expected to survive (Piatti 2016). Piatti et al. (2018b) showed that such objects could have been born in the innermost LMC regions and then scattered to the outer LMC disk. Ram pressure interaction between the LMC and the Milky Way and between both Magellanic Clouds could also triggered star formation in the periphery of the Clouds (Sitko et al. 2016; Piatti et al. 2018a), while some old globular clusters could be associated to the accreted satellite populations of the LMC (Martin et al. 2016; Cerny et al. 2020).

Within our studied star cluster sample, Field 4-01 is located in the so-called West halo of the SMC (Dias et al. 2014), a region placed on the opposite side of the bridge that was predicted by Diaz & Bekki (2012) models and most likely has a tidal origin linked to the dynamical history of the Magellanic Clouds. Most of the known star clusters grouped in this area are in general of intermediate-age or older (Dias et al. 2016), so that Field 4-01 can be now added to this group (log(age /yr)=9.45). Below the onset of the Magellanic bridge and somehow superimposed to it (to the southeast from the SMC center), there is also a region of moderately old star clusters (Piatti et al. 2007b; Piatti 2011c). We estimated an age of 5.5 Gyr (log(age /yr)= 9.74) for Field 12-

---

**Table 1.** Fundamental parameters of Magellanic Clouds clusters: radius of the cleaned star cluster area (r); true distance modulus ((m – M)₀); age; metallicity ([Fe/H]); star cluster mass; and binary fraction (q).

| Star cluster | R.A. (deg) | Dec. (deg) | r (arcmin) | (m – M)₀ (mag) | log(age /yr) | [Fe/H] (dex) | Mass (M☉) | q |
|--------------|------------|-----------|------------|---------------|--------------|-------------|-----------|---|
| Field 4-01   | 8.254      | -72.989   | 0.30       | 18.73±0.22    | 9.47±0.16    | -0.97±0.31  | 806±626   | 0.44±0.27 |
| Field 10-01  | 16.895     | -72.164   | 0.30       | 18.76±0.24    | 7.54±0.49    | -0.92±0.05  | 338±297   | 0.39±0.25 |
| Field 10-02  | 18.089     | -72.292   | 0.30       | 18.92±0.29    | 8.27±0.21    | -0.53±0.27  | 177±38    | 0.51±0.28 |
| Field 10-03  | 16.194     | -72.716   | 0.30       | 18.87±0.36    | 8.11±0.18    | -0.43±0.26  | 358±147   | 0.51±0.25 |
| Field 11-01  | 15.982     | -72.933   | 0.30       | 19.04±0.37    | 7.87±0.18    | -0.52±0.34  | 926±586   | 0.53±0.28 |
| Field 11-02  | 15.325     | -73.465   | 0.30       | 18.56±0.34    | 8.15±0.13    | -0.44±0.25  | 628±250   | 0.53±0.24 |
| Field 11-03  | 16.048     | -74.299   | 0.20       | 19.10±0.26    | 8.96±0.62    | -0.71±0.45  | 534±341   | 0.52±0.29 |
| Field 12-01  | 18.427     | -74.753   | 0.30       | 18.42±0.24    | 9.74±0.15    | -0.98±0.44  | 155±44    | 0.54±0.29 |
| Field 15-01  | 20.753     | -73.218   | 0.25       | 18.72±0.21    | 8.05±0.45    | -0.80±0.43  | 208±85    | 0.37±0.25 |
| Field 16-01  | 22.471     | -74.846   | 0.50       | 19.01±0.15    | 9.09±0.07    | -0.53±0.13  | 390±58    | 0.53±0.25 |
| Field 16-02  | 22.461     | -74.682   | 0.50       | 18.87±0.31    | 9.19±0.13    | -0.83±0.30  | 1085±198  | 0.68±0.19 |
| Field 30-01  | 72.066     | -69.672   | 0.30       | 18.58±0.26    | 7.88±0.39    | -0.44±0.27  | 238±102   | 0.51±0.28 |
| Field 40-01  | 80.275     | -71.913   | 0.30       | 18.64±0.41    | 7.34±0.41    | -0.78±0.18  | 601±377   | 0.58±0.30 |
| Field 40-02  | 81.364     | -72.639   | 0.40       | 18.42±0.25    | 8.76±0.25    | -0.78±0.37  | 186±60    | 0.60±0.28 |
| Field 40-03  | 78.142     | -72.626   | 0.40       | 18.52±0.28    | 8.89±0.27    | -0.49±0.28  | 116±16    | 0.58±0.28 |
| Field 40-04  | 79.484     | -73.557   | 0.30       | 18.62±0.40    | 9.01±0.23    | -0.26±0.17  | 213±84    | 0.54±0.29 |
| Field 40-05  | 80.489     | -73.513   | 0.50       | 18.40±0.32    | 9.86±0.16    | -0.73±0.17  | 215±100   | 0.63±0.26 |
| Field 40-06  | 78.088     | -73.270   | 0.30       | 18.83±0.41    | 8.66±0.17    | -0.37±0.23  | 254±118   | 0.50±0.29 |
| Field 40-07  | 81.081     | -73.091   | 0.30       | 18.69±0.33    | 8.55±0.72    | -0.26±0.15  | 342±376   | 0.56±0.28 |
| Field 44-01  | 82.674     | -75.668   | 0.30       | 18.50±0.37    | 9.34±0.25    | -0.38±0.24  | 389±340   | 0.53±0.29 |
| Field 44-02  | 81.523     | -75.416   | 0.25       | 18.42±0.29    | 9.35±0.21    | -0.54±0.22  | 217±196   | 0.53±0.28 |
| Field 51-01  | 87.308     | -70.673    | 0.30       | 18.57±0.26    | 8.78±0.38    | -0.78±0.47  | 262±122   | 0.55±0.29 |
| Field 55-01  | 96.733     | -70.300    | 0.20       | 18.56±0.34    | 8.70±0.29    | -0.48±0.18  | 154±46   | 0.52±0.28 |

* Star cluster identifications are from [Piatti 2017, Table 1].
01 that matches very well the ages of this group of star clusters. Other two star clusters, Field 16-01 and 16-02, also located in this region, are a bit younger though (log(age / yr) ∼ 9.2). We note that Field 12-01 is located at the LMC distance, so that it could be a halo SMC star cluster affected by the LMC gravitational field (Carpintero et al. 2013). By using the elliptical framework devised by Piatti et al. (2007a) to reflect more meaningfully the flattening of the galaxy, the remaining studied SMC star clusters are located to the east of the SMC center at semi-major axes of ∼ 3◦ and beyond. They resulted to be young objects (age ≤ 200 Myr), with only one exception, Field 11-03 (log(age / yr) ∼ 9.0). While the older one is in agreement with the average age of star clusters in that region (log(age / yr) ∼ 9.0) (Dias et al. 2016), the younger one would seem more tightly related to the onset of the Magellanic bridge (Piatti et al. 2015). As for the spatial distribution of ages of LMC star clusters, that of Field 55-01 (the easternmost star cluster in the studied sample) would seem to be that of a likely runaway object (Piatti et al. 2018b), while the other star clusters agree with the presence of an age gradient; those farther from the LMC center being older.

The chemical enrichment of the Magellanic Clouds has long been studied from theoretical and observational approaches. Some of the most recurrent age-metallicity relationships used in this field are the models computed by Pagel & Tautvaisiene (1998, PT98), which predict intensive star formation and chemical enrichment during the initial formation epoch which brought the metallicity up about -0.7 dex and -1.3 dex, for the LMC and SMC, respectively. This turbulent period was subsequently followed by a relatively quiescence period to finally be disturbed by rapid burst of chemical enrichment about 3 Gyr ago (log(age / yr) ∼ 9.5), which brought the global metallicities up to their current values. Because of the coincidence of the ages of L/SMC star clusters formed at that time, it has been argued that the bursting formation events were caused by the interaction between both Clouds (Piatti 2011b, Piatti et al. 2012, Bekki & Tsujimoto 2012, BT12) also presented a bursting model for the LMC with some different ingredients. Closed-box model of chemical evolution presented by Ghez et al. (1998, G98) and da Costa & Hatzidimitriou (1998, closed-box) predicted gradual increase of star formation and metal abundances over time. The major merger scenario for the SMC was proposed by Tsujimoto & Bekki (2009, TB09). The model predicts that major merger occurred ∼ 7.5 Gyr ago and was calculated for three cases: no merger - (TB09-01), one-to-one merger (TB09-02), and one-to-four merger (TB09-03). From an observational point of view, Harris & Zaritsky (2009, HZ09) and Harris & Zaritsky (2004, HZ04) built age-metallicity relationships for the LMC and SMC, respectively based on UBVRI photometry from Magellanic Clouds Photometric Survey, while Piatti & Geisler (2013, PG13) constructed the age-metallicity relationships for L/SMC star clusters using Washington photometry.

Figure 7 shows the above listed age-metallicity relationships for the Magellanic Clouds with the present studied star clusters superimposed. They span a quite wide range of ages, from very young star clusters (log(age / yr) ∼ 6.5) up to intermediate-age ones (log(age / yr) ∼ 9.5). In the LMC, none of the discovered star clusters turned out to be older than ∼ 2.5 Gyr (log(age / yr) ∼ 9.4), which is in agreement with the general consensus of the existence of a star cluster age gap in the LMC, from ∼ 4 Gyr (log(age / yr) ∼ 9.6) up to the oldest globular clusters’ ages (Olszewski et al. 1991, Rich et al. 2001, Piatti et al. 2009, Piatti & Geisler 2013). The metallicities of the L/SMC star clusters are within the theoretically predicted and observed boundaries. Perhaps, the most noticeable feature is the existence of young star clusters (age ≤ 100 Myr) with relatively low metal content in both Magellanic Clouds ([Fe/H] ∼ -0.7 dex), similar to ∼ 1 Gyr old (log(age / yr) ∼ 9.0) metal-poor star clusters. This might imply that a relatively metal deficient gaseous flow could have existed between both Clouds during the last Gyrs, also responsible of the Magellanic Stream and Leading Arm, that triggered star cluster formation (Ruiz-Lara et al. 2020, Tsuge et al. 2020). On the other hand, chemical enhancement has reached slightly different metallicity levels. The iron-to-hydrogen ratios increased on average up to -0.30±0.15 dex nad -0.50±0.20 dex, in the LMC and SMC, respectively. The present results illustrate that the Magellanic Clouds are more complex galactic systems than previously known. The consideration of initial galaxy formation and later interactions between them and with the Milky Way guide us towards a better understanding of their present age and metallicity distributions of star clusters throughout the entire Magellanic system.

4. Concluding remarks

We conducted analyses to obtain fundamental parameters estimates of 24 Magellanic Cloud star cluster candidates recently discovered by Piatti (2017) using the SMASH DR2 database. We find that all candidates resulted to be genuine physical systems, with the sole exception of one candidate called Field 30-02. We arrive to such a conclusion once the observed star cluster CMDs were carefully decontaminated from field stars, and the cleaned CMDs were compared to synthetic CMDs generated for thousand combinations of ages, distances, metallicities, star cluster mass and binary fractions. The parameter of the best-matched synthetic CMDs obtained from a likelihood approach were adopted as the star cluster astrophysical properties. In doing the comparison between observed and synthetic CMDs, we used only stars that passed the cleaning procedure and were assigned membership probabilities higher than 50%. The use of a parallel tempering Bayesian MCMC algorithm to explore the multi-parameter space allowed us to avoid typical constraints of adopting mean Magellanic Cloud distances and metallicities in studies of star clusters. Those assumptions provided with a limited picture of the Magellanic Clouds, where extended halos and tidally distorted peripheries are not distinguished.

Indeed, the present star cluster sample spans a wide range of distances, from those star clusters located behind the SMC,
going through those placed in between both Clouds along the Magellanic bridge, to those in from of the LMC. Such spatial distribution is by itself a witness of interaction between both Clouds. Their estimated ages also tell us about a mixture of formation episodes. Some clusters were born according to the outside-in formation scenario, while older star clusters are more commonly seen in outer galaxy regions (Gallart et al. 2008; Carrera et al. 2011). However, because of the interaction between both Magellanic Clouds and that of the Clouds with the Milky Way, gas flows could have existed, initially feeding the outer regions where young star cluster formed out of them. We find evidence of such formation phenomenon from the identification of star clusters with different ages populating the same galaxy region and star clusters that are found projected toward regions with associated stellar ages and metallicities different from those of the star clusters. The estimated ages and metallicities confirm the general accepted evolution of the chemical enrichment in the Magellanic Clouds. We find from the estimated star cluster metallicities another indicator of the existence of gaseous flows between these galaxies. There exist in both Clouds very young clusters (∼ 30 Myr), located in their outer regions, with metal abundances as metal deficient as the most metal-poor star clusters with ages ≤ 1 Gyr (log(age/yr) ≈ 9.0). The most metal-rich young star clusters have slightly different [Fe/H] values, those of the LMC being more metal-rich.

Comparing the present-day masses of the studied star clusters with those of Milky Way open clusters with similar ages located in the solar neighborhood (distance to the Sun < 1.8 kpc, Joshi et al. [2016]), we find that the studied Magellanic Cloud clusters are in general similar or more massive than open clusters. Their binary frequencies is on average q=0.55, independent of the star cluster mass.

Acknowledgements. I thank the referee for the thorough reading of the manuscript and timely suggestions to improve it. This research uses services or data provided by the Astro Data Lab at NSF’s National Optical-Infrared Astronomy Research Laboratory, NSF’s OIR Lab is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under a cooperative agreement with the National Science Foundation.

References
Abbot, T. M. C., Abdalla, F. B., Alam, S., et al., 2018, ApJS, 239, 18
Bekki, K. & Tsujimoto, T. 2012, ApJ, 761, 180
Bica, E., Bonatto, C., Dutra, C. M., & Santos, J. F. C. 2008, MNRAS, 389, 678
Bica, E., Westera, P., Kerber, L. d. O., et al., 2020, AJ, 159, 82
Bressan, A., Marigo, P., Girardi, L., et al., 2012, MNRAS, 427, 127
Carpintero, D. D., Gómez, F. A., & Piatti, A. E. 2013, MNRAS, 435 [arXiv:1307.6231]
Carrera, R., Gallart, C., Aparicio, A., et al. 2008, AJ, 136, 1039
Carrera, R., Gallart, C., Aparicio, A., & Hardy, E. 2011, AJ, 142, 61
Cerryo, W., Pace, A. B., Drlica-Wagner, A., et al. 2020, arXiv e-prints, arXiv:2009.08550
Choi, Y., Nidever, D. L., Olsen, K., et al. 2018, ApJ, 866, 90
Crowl, H. H., Sarajedini, A., Piatti, A. E., et al. 2001, AJ, 122, 220
Da Costa, G. S. & Hatzidimitriou, D. 1998, AJ, 115, 1934
de Grijs, R., Wicker, J. E., & Bono, G. 2014, AJ, 147, 122
Dias, B., Kerber, L., Barbary, B., Bica, E., & Ortolani, S. 2016, A&A, 591, A11
Dias, B., Kerber, L. O., Barbary, B., et al. 2014, A&A, 561, A106
Diaz S. J. & Bekki, K. 2012, ApJ, 750, 36
Elfron, B. 1982, The Jackknife, the Bootstrap and other resampling plans
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2018, A&A, 616, A1
Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., et al. 2016, A&A, 595, A1
Gallart, C., Stetson, P. B., Meschin, I. P., Pont, F., & Hardy, E. 2008, ApJ, 682, 139
Gatto, M., Ripepi, V., Bellazzini, M., et al. 2020, MNRAS, 494, 4114
Geha, M. C., Holtzman, J. A., Mould, J. R., et al. 1998, AJ, 115, 1934
Graczyk, D., Pietrzyński, G., Thompson, I. B., et al. 2020, arXiv e-prints, arXiv:2010.08754
Harris, J., & Zaritsky, D. 2004, AJ, 127, 1531
Harris, J. & Zaritsky, D. 2009, AJ, 138, 1243
Jacyszyn-Dobrzniecka, A. M., Skowron, D. M., Mróz, P., et al. 2017, Acta Astron., 67, 1
Joshi, Y. C., Dambis, A. K., Pandey, A. K., & Joshi, S. 2016, A&A, 593, A116
Kroupa, P. 2002, Science, 295, 82
Mackey, A. D., Koposov, S. E., Da Costa, G. S., et al. 2017, MNRAS, 472, 2975
Mackey, A. D., Koposov, S. E., Erik, D., et al. 2016, MNRAS, 459, 239
Maga, F. F. S., Dias, B., Santos, J. F. C., et al. 2019, MNRAS, 484, 5702
Martin, N. F., Jungbluth, V., Nidever, D. L., et al. 2016, ApJ, 830, L10
Massana, P., Noel, E. D., Nidever, D. L., et al. 2020, MNRAS, 498, 1034
Meschin, I., Gallart, C., Aparicio, A., et al. 2014, MNRAS, 438, 1067
Nidever, D. L., Olsen, K., Choi, Y. et al. 2019, ApJ, 874, 118
Nidever, D. L., Olsen, K., Walker, A. R., et al. 2017, AJ, 154, 199
Olszewski, E. W., Schommer, R. A., Suntzeff, N. B., & Harris, H. C. 1991, AJ, 101, 515
Pagel, B. E. J. & Tautvaisiene, G. 1998, MNRAS, 299, 535
Perren, G. I., Vázquez, R. A., & Piatti, A. E. 2015, A&A, 576, A6
Piatti, A. E. 2011a, MNRAS, 416, L39
Piatti, A. E. 2011b, MNRAS, 418, L40
Piatti, A. E. 2011c, MNRAS, 418, L69
Piatti, A. E. 2012, MNRAS, 422, 1109
Piatti, A. E. 2016, MNRAS(arXiv:1603.06881)
Piatti, A. E. 2017, ApJ, 834, L14
Piatti, A. E. 2018a, MNRAS, 477, 2164
Piatti, A. E. 2018b, MNRAS, 478, 784
Piatti, A. E., Alfaro, E. J., & Cantat-Gaudin, T. 2019, MNRAS, 484, L19
Piatti, A. E. & Bica, E. 2012, MNRAS, 425, 3085
Piatti, A. E., Carballo-Bello, J. A., Mora, M. D., et al. 2020, A&A, 643, A15
Piatti, A. E., Cole, A. A., & Emptage, B. 2018a, MNRAS, 473, 105
Piatti, A. E., de Grijs, R., Rubele, S., et al. 2015, MNRAS, 450, 552
Piatti, A. E. & Geisler, D. 2013, AJ, 145, 17
Piatti, A. E., Geisler, D., Sarajedini, A., & Gallart, C. 2009, A&A, 501, 585
Piatti, A. E., Guandalini, R., Ivanov, V. D., et al. 2014, A&A, 570, A74
Piatti, A. E., Ivanov, V. D., Rubele, S., et al. 2016, MNRAS, 460, 383
Piatti, A. E., Salinas, R., & Grebel, E. K. 2018b, MNRAS[arXiv:1810.04695]
Piatti, A. E., Sarajedini, A., Geisler, D., Clark, D., & Seguel, J. 2007a, MNRAS, 377, 300
Piatti, A. E., Sarajedini, A., Geisler, D., Gallart, C., & Wischnjewsky, M. 2007b, MNRAS, 381, L84
Rich, R. M., Shara, M. M., & Zurek, D. 2001, AJ, 122, 842
Ruz-Lara, T., Gallart, C., Monelli, M., et al. 2020, A&A, 639, L3
Sitek, M., Szymański, M. K., Skowron, D. M., et al. 2016, Acta Astron., 66, 255
Subramanian, S. & Subramaniam, A. 2009, A&A, 496, 599
Tremmel, M., Frago, T., Lehmer, B. D., et al. 2013, ApJ, 766, 19
Tsuge, K., Sano, H., Sano, K., et al. 2020, arXiv e-prints, [arXiv:2010.08816]
Tsujimoto, T. & Bekki, K. 2009, ApJ, 700, L69
Wagner-Kaiser, R. & Sarajedini, A. 2017, MNRAS, 466, 4138

Article number, page 8 of 8