A genuine Large Magellanic Cloud age gap star cluster

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ABSTRACT

We confirm the existence of a second Large Magellanic Cloud (LMC) star cluster, KMHK 1592, with an age that falls in the middle of the so-called LMC star cluster age gap, a long period of time (∼ 4 - 11 Gyr) where no star cluster had been uncovered, except ESO 121-SC 03. The age (8.0 ± 0.5 Gyr) and the metallicity ([Fe/H] = -1.0 ± 0.2 dex) of KMHK 1592 were derived from the fit of theoretical isochrones to the intrinsic star cluster colour-magnitude diagram sequences, which were unveiled using a robust star-by-star membership probability procedure. Because of the relative low brightness of the star cluster, deep GEMINI GMOS images were used. We discuss the pros and cons of three glimpsed scenarios that could explain the presence of both LMC age gap star clusters in the outskirts of the LMC, namely: in-situ star cluster formation, capture from the Small Magellanic Cloud, or accretion of a small dwarf galaxy.

Key words: techniques: photometric – galaxies: individual: LMC – galaxies: star clusters: KMHK 1592

1 INTRODUCTION

The absence of star clusters with ages between ∼ 4 and 11 Gyr in the Large Magellanic Cloud (LMC), the sole exception is ESO 121-SC 03 (Mateo et al. 1986), was noticed by Olszewski et al. (1991). They also found that the age gap correlates with a star cluster metallicity gap, in the sense that star clusters younger than 3 Gyr are much more metal-rich than the ancient LMC globular clusters. Although different observational campaigns have searched for unknown old LMC star clusters, they have confirmed previous indications that star clusters were not formed during the age gap (Da Costa 1991; Geisler et al. 1997).

The upper age limit of the LMC star cluster age gap is given by the youngest ages of the 15 known LMC globular clusters (∼ 12 Gyr Bica et al. 2008). The lower age limit, however, has been changed as more intermediate-age star 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) re-estimated their ages to be 0.8 Gyr younger. 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 & Geisler 2013).

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 (SMC) ∼ 2-3 Gyr ago. Such a star cluster formation history was not that of the SMC, 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 with the Milky Way since then, that explain their abrupt observed chemical enrichment history and increase of the star cluster formation rates (Perren et al. 2017). For the sake of the reader we refer to some recent studies dealing with the LMC formation and interaction with the SMC, namely: Baumgardt et al. (2013); Zivick et al. (2018); Williams et al. (2021); Mazzi et al. (2021); Cullinane et al. (2022), among others.

Piatti et al. (2014b) used a Ks vs Y − Ks colour-magnitude diagram (CMD) to estimate for the first time the age of KMHK 1592, a low surface brightness LMC star cluster located in the LMC outer disc (RA = 90.375°; Dec = -66.987°). Although the CMD does not reach the star cluster Main Sequence turnoff, Piatti et al. (2014b) estimated an age of 6.3 Gyr, which places KMHK 1592 in the middle of the age gap. The star cluster could be even older, for instance, of the age of the LMC globular clusters (∼ 12-13 Gyr).

Because of the discovery of only one LMC age gap star cluster would be worthy by itself, this astonishing new age gap star cluster candidate deserves our attention. Furthermore, Piatti (2021a) analysed 17 previously unidentified star cluster candidates with estimated ages ≥ 4 Gyr (Gatto et al. 2021).
We carried out observations of KMHK 1592 with the Gemini cluster age. Of the data obtained and the discussion of the resulting star data processing, while Section 3 deals with the analysis of the cluster. In Section 2 we describe the observations and selection of deeper photometry. As far as we are aware, KMHK 1592 has not been observed by any of the ongoing LMC surveys (e.g., DES (Flaugher et al. 2015), SMASH (Nidever et al. 2017), STEP (Ripepi et al. 2014), VISCACHA (Maia et al. 2019)). Precisely, the aim of this Letter is to report new observations of KMHK 1592, from ongoing or recent LMC surveys (e.g., DES (Flaugher et al. 2015), SMASH (Nidever et al. 2017), STEP (Ripepi et al. 2014), VISCACHA (Maia et al. 2019)). Precisely, the aim of this Letter is to report new observations of KMHK 1592, from which we confirm it as the second genuine LMC age gap star cluster. In Section 2 we describe the observations and several data processing, while Section 3 deals with the analysis of the data obtained and the discussion of the resulting star cluster age.

2 DATA COLLECTION AND PROCESSING
We carried out observations of KMHK 1592 with the Gemini South telescope and the GMOS-S instrument (3×1 mosaic of 2K×4K EEV CCDs) through $g$ and $i$ filters on the night of November 25, 2021, under program GS-2021B-FT-108. We obtained 3×150 sec images per filter in excellent seeing (0.62″ to 0.93″ FWHM) and photometric conditions, at a mean airmass of 1.25. In order to transform the instrumental magnitudes into the standard system, we obtained 3×30 sec exposures in $g$ and $i$, respectively, of NGC 2155, an LMC intermediate-age star cluster located $\sim$1.5° from KMHK 1592 with standard $g,i$ photometry obtained by Piatti et al. (2014a). The observations were performed just after finishing those for KMHK 1592. The data reduction followed the procedures documented in the Gemini Observatory webpage1 and utilized the GEMINI/GMOS package in Gemini IRAF. We performed overscan, trimming, bias subtraction, flattened all data images, etc., once the calibration frames (bias and flats) were properly combined.

We derived the stellar photometry of KMHK 1592 and NGC 2155 using the star-finding and point-spread-function (PSF) fitting routines in the DAOPHOT/ALLSTAR suite of programs (Stetson et al. 1990). For each frame, we obtained a quadratically varying PSF by fitting $\sim$ 100 stars, once we eliminated the neighbours using a preliminary PSF derived from the brightest, least contaminated $\sim$ 40 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 measure magnitudes of additional fainter stars. This procedure was repeated three times for each frame. We combined all the independent $g,i$ instrumental magnitudes using the stand-alone DAOMATCH and DAOMASTER programs2. As a result, we produced three data sets per star cluster containing the $x$ and $y$ coordinates for each star, and the instrumental $g$ and $i$ magnitudes ($\tilde{g},\tilde{i}$) with their respective errors. We cross-matched the instrumental and standard photometries of NGC 2155 and found 2671 stars in common, from which we obtained the following transformation equations:

$$g = (0.998 \pm 0.004) \times \tilde{g} + 6.535 \pm 0.007, \text{rms} = 0.031$$

$$i = (1.025 \pm 0.003) \times \tilde{i} + 6.522 \pm 0.005, \text{rms} = 0.028$$

for $15.0 < g \text{ (mag)} < 25.0$, where right and left terms refer to instrumental and standard magnitudes, respectively, indicating excellent photometric quality. We finally transformed instrumental magnitudes of KMHK 1592 into standards ones from eqs. (1) and (2), and derived robust photometric uncertainties from the average of the three independent photometric data sets.

A key tool to unveil the actual age of KMHK 1592 is the cluster CMD cleaned of field star contamination. We applied a decontamination procedure based on that devised by Piatti & Bica (2012), which properly reproduces the composite observed field star population, and assigns membership probability to each star. In order to clean the cluster CMD, we need to compare it with that of a reference star field, and then to properly eliminate from the former a number of stars equal to that found in the latter, bearing in mind that the magnitudes and colours of the eliminated stars in the cluster CMD must reproduce the respective magnitude and colour distributions in the reference star field. For that purpose, we traced an annulus in the GMOS field of view (see Fig. 1) with an inner radius $\gtrsim 2$ times the KMHK 1592’s radius (0.8′, Piatti et al. 2014b), and an area equal to the inner circle ($r=1.8′$). The outer annulus was used as the reference star field, while the inner circle served as the cluster circle to be cleaned.

The methodology to select stars to subtract from the

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1 http://www.gemini.edu
2 Program kindly provided by P.B. Stetson
cluster CMD consists in defining boxes centred on the magnitude and colour of each star of the reference star field; then to superimpose them on the star cluster CMD, and finally to choose one star per box to subtract. In order to guarantee that a star is within the box boundary, we considered boxes with size of \((\Delta g, \Delta(g - i)) = (0.50 \, \text{mag}, 0.25 \, \text{mag})\). In the case that more than one star is located inside a box, the closest one to its centre is subtracted. During the choice of the subtracted stars we took into account their magnitude and colour errors by allowing them to have a thousand different values of magnitude and colour within an interval of \(\pm 1 \sigma\), where \(\sigma\) represents the errors in their magnitude and colour, respectively. We also imposed the condition that the spatial positions of the subtracted stars were chosen randomly. In practice, for each reference field star we randomly selected a position in the cluster circle and searched for a star to subtract within a box of 0.2′ a side. We iterated this loop up to 1000 times, if no star was found in the selected spatial box. The outcome of the cleaning procedure is a cluster CMD that likely contains only cluster members.

We executed 1000 times the decontamination procedure described above, so that we obtained 1000 different cleaned CMDs. From them, we defined a membership probability \(P\) (%) as the ratio \(N/10\), where \(N\) (between 0 and 1000) is the number of times a star was found among the 1000 different cleaned CMDs.

### 3 ANALYSIS AND DISCUSSION

Fig. 2 shows the observed CMD of KMHK 1592, where stars located within the cluster radius are coloured according to their membership probability. As can be seen, a red giant branch, a red clump, a populous subgiant branch and a Main Sequence turnoff are clearly highlighted as the most probable star cluster sequences. It is readily visible that the cluster red clump nearly superimposes that of the composite star field population, which implies that KMHK 1592 belongs to the LMC and is nearly at the mean LMC distance (49.9 kpc de Grijs et al. 2014). Likewise, Piatti et al. (2014b) estimated a low cluster reddening of \(E(B - V) = 0.042 \pm 0.010 \, \text{mag}\) from the Magellanic Cloud extinction values based on red clump stars photometry provided by the OGLE collaboration (Udalski 2003) as described in Haschke et al. (2011). Both parameters do not affect the cluster age estimate, which is mainly driven by the difference between the magnitude at the red clump and that of the Main Sequence turnoff.

The position of the red giant branch is metallicity-dependent, in the sense that the more metal-rich an old star cluster the redder the red giant branch. Such a behaviour can be blurred by the age-metallicity degeneracy that mainly affects star clusters younger than \(\sim 6 \, \text{Gyr}\) (Ordoñez & Sarajedini 2015; Piatti 2020).

We fitted theoretical isochrones computed by Bressan et al. (2012, PARSEC\(^3\)) and Pietrinferni et al. (2004, BaSTI\(^4\)). We used PARSEC isochrones spanning metallicities ([Fe/H]) from -1.5 dex up to -0.5 dex (Y=0.25), in steps of 0.2 dex and log(age) from 9.7 up to 9.95 in steps of 0.25.

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3 http://stev.oapd.inaf.it/cgi-bin/cmd  
4 http://basti-iac.oa-abruzzo.inaf.it/index.html
BaSTI isochrones are available only for $\alpha$/Fe = 0.0 dex (Y=0.25). We fitted these isochrone sets to stars with $P > 50\%$ allowing shifts of $\Delta E(B-V) = \pm 0.01$ mag in order to mitigate zero point offsets between different isochrone sets, alongside the selective to visual absorption ratios $A_{\lambda}/A_V$ given by Cardelli et al. (1989) and $A_V/E(B-V) = 3.1$. As for the age and metallicity uncertainties, we verified that isochrones differing in $\Delta$(age) = 0.5 Gyr, or $\Delta$[Fe/H] = 0.2 dex, result clearly distinguishable when superimposed on the cluster CMD. The isochrones which best resemble the cluster CMD features are shown in Fig. 3, where we also indicated their associated parameter values. From Fig. 3, we conclude that KMHK 1592, located at a mean heliocentric distance of 49.9 kpc and affected by a low interstellar reddening ($E(B-V)$=0.042), is a genuine LMC age gap star cluster, with an age ($\sim 8.0\pm0.5$ Gyr) and a metal content ([Fe/H]=−1.0±0.2 dex) similar to those of ESO 121-SC 03.

This second LMC age gap cluster spurs us to speculate on its origin, as well as that of ESO 121-SC 03. Fig. 4 shows the location of both star clusters with respect to the LMC and LMC cluster populations. We glimpse three possible scenarios, namely: in-situ formation, stripping off the SMC, or accretion of a dwarf galaxy. Although the origin of each of these two star clusters could have in principle been different, their very similar ages and metallicities favour by chance a common origin. As for the in-situ formation, the LMC star formation history tells us that the galaxy has experienced a continuous formation of stars out of the available gas chemically enriched over time. Indeed, Piatti & Geisler (2013) showed that old and metal-poor field stars have been preferentially formed in the outer disc, while younger and more metal-rich stars have mostly been formed in the inner disc, confirming an outside-in formation. Particularly, they provided evidence for the formation of stars between 5 and 12 Gyr, during the star cluster age gap, although chemical enrichment during this period was minimal. The star formation history maps built by Mazzi et al. (2021) also reveal as a main feature of the LMC disc a wider and smoother distribution of stellar populations older than $\sim 4$ Gyr, which formed at a rate nearly half that of the period of most intense star formation, which occurred roughly between 4 and 0.5 Gyr ago, at a rate of $\sim 0.3M_\odot/yr$ (see, also Harris & Zaritsky 2009). Star clusters and field stars in the LMC and the SMC have similar age-metallicity relationships (Piatti & Geisler 2013; Narloch et al. 2021; Piatti 2021b), so that we would also expect star clusters formed during the age gap, accompanying the field star formation. However, the existence of only two star clusters of 8-9 Gyr old calls our attention. For this reason, we think that an ex-situ origin could explain their appearance in the LMC, unless an enough large population of 6-10 Gyr old clusters is discovered in the LMC. Note that the ex-situ origin scenario does not provide any hint to explain the apparent cease of cluster formation during that period.

The tidal interaction between both Magellanic Clouds can also be a source for star clusters formed in the SMC were then stripped off by the LMC. Indeed, Carpintero et al. (2013) modelled the dynamical interaction between both galaxies and their corresponding stellar cluster populations, and found that for eccentricities of the orbit of the SMC around the LMC $\geq 0.4$, nearly 15 per cent of the SMC star clusters are captured by the LMC, while another 20-50 per cent is scattered into the intergalactic environment. The star clusters lost by the SMC are the less tightly bound ones. These star clusters populate the outer galaxy regions, which have long been commonly thought to harbour old star clusters. According to the numerical simulations performed by Carpintero et al. (2013) star clusters that originally belonged to the SMC are more likely to be found in the outskirts of the LMC. The comparison of the star cluster age-metallicity relationships of the LMC and SMC shed light to reconstruct the interaction history between both Magellanic Clouds. Piatti (2011a) showed that a bursting cluster formation episode took place in the LMC $\sim 2-3$ Gyr ago, which has also been detected in the SMC Piatti (2011b). Furthermore, field star formation in both galaxies have also experienced the chemical enrichment observed in the star cluster age-metallicity relationships. This means that field star and star cluster formation were synchronized in the LMC/SMC and that both galaxies interacted at that time. The SMC exhibits another enhancement of star clusters and field stars at $\sim 6-8$ Gyr with a noticeable metallicity spread (Piatti 2012). Tsujimoto & Bekki (2009) suggested that such an older bursting formation episode was caused by the merger with a small gas-rich dwarf. Therefore, ESO 121-SC 03 and KMHK 1592 could form in the SMC (their ages and metallicities agree well with the older enhanced formation event) and later captured by the LMC (Carpintero et al. 2013).

More recently, several studies dealt with the LMC formation and interaction with the SMC, although they do not focus on the cluster formation history. To this respect, for completeness purposes, we refer the reader to Wan et al. (2020); Ruiz-Lara et al. (2020); Mazzi et al. (2021); Williams et al. (2021); Roman-Duval et al. (2021); Grady et al. (2021);
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Shipp et al. (2021); Cullinane et al. (2022); and references therein, among others.

Mucciarelli et al. (2021) reported that the LMC experienced a merger event in the past with a galaxy with a low star formation efficiency and with a stellar mass similar to those of dwarf spheroidal galaxies. Such an LMC satellite completely dissolved into the LMC, and it was recognized by the peculiar chemical composition of NGC 2005, one of the fifteen known LMC ancient globular clusters. NGC 2005 would be the only surviving witness, unless ESO 121-SC 03 and KMHK 1592 also had belonged to it. With the aim of confirming this possibility a chemical tagging of both star clusters is needed, in order to compare their abundances of different chemical elements with those of LMC field stars for a similar overall metallicity. A detailed chemistry of both star clusters will definitively address whether the LMC, the SMC or another dwarf is their progenitor.

4 DATA AVAILABILITY

Data used in this work are available upon request to the author.

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