Exploring the nature and synchronicity of early cluster formation in the Large Magellanic Cloud – III. Horizontal branch morphology

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ABSTRACT

We leverage new high-quality data from *Hubble Space Telescope* program GO-14164 to explore the variation in horizontal branch morphology among globular clusters in the Large Magellanic Cloud (LMC). Our new observations lead to photometry with a precision commensurate with that available for the Galactic globular cluster population. Our analysis indicates that, once metallicity is accounted for, clusters in the LMC largely share similar horizontal branch morphologies regardless of their location within the system. Furthermore, the LMC clusters possess, on average, slightly redder morphologies than most of the inner halo Galactic population; we find, instead, that their characteristics tend to be more similar to those exhibited by clusters in the outer Galactic halo. Our results are consistent with previous studies, showing a correlation between horizontal branch morphology and age.

Key words: stars: horizontal branch – globular clusters: general – Magellanic Clouds – galaxies: star clusters: general.

1 INTRODUCTION

The variation in horizontal branch (HB) morphology among the Galactic system of globular clusters is known to be strongly – but not entirely – determined by metallicity. Early studies found a clear distinction between the metal-rich GCs, which generally have very red HBs, and the metal-poor GCs, with HBs that are largely populated on the blue side of the RR Lyrae instability strip (Arp, Baum & Sandage 1952; Sandage 1953). However, this trend is not absolute and there are a number of exceptions, particularly in the intermediate-metallicity range of the Milky Way globular clusters. An early example was found by Sandage & Wallerstein (1960) in studying several GCs (e.g. M13, M22) that have bluer than expected HB morphologies despite their intermediate metallicities. Essentially, metallicity is not alone sufficient to explain HB morphology and additional factors are necessary; this is more succinctly referred to as the 'second parameter effect (Sandage & Wallerstein 1960; van den Bergh 1965).

Early suggestions to explain the second parameter effect in HB morphology were cluster-to-cluster variations in age and/or he-

lium abundance (van den Bergh 1965, 1967); these suggestions, among others, continue to be investigated in the present era. In addition to age and helium abundance, newer work also investigates central densities of clusters, extended blue HB tails, and cluster magnitude (e.g. mass), among other parameters (Sarajedini & King 1989; Chaboyer, Sarajedini & Demarque 1992; Sarajedini, Lee & Lee 1995; Chaboyer, Demarque & Sarajedini 1996; Rosenberg et al. 1999; Recio-Blanco et al. 2006; Dotter et al. 2010; see Catelan 2009 for a comprehensive review of proposed second parameters). Some studies have suggested that more than one additional parameter may be necessary (Richer et al. 1996; Milone et al. 2014).

Althoughthe underlying cause of the second parameter effect remains a topic of research, this phenomenon has played a significant role in our interpretation of Galactic formation. Searle & Zinn (1978) found a clear demarcation between inner and outer GCs in the Galaxy, with clusters inside 8 kpc of the Galactic Centre dominated by blue HB morphologies at given metallicity; beyond 8 kpc, clusters with redder HB morphologies become more common (Searle & Zinn 1978; Lee, Demarque & Zinn 1990; Sarajedini 1999; Mackey & van den Bergh 2005; Recio-Blanco et al. 2006; Catelan 2009; Dotter et al. 2010, among others). This observation is often taken as evidence that the inner halo of the Milky Way was formed quickly

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and early, whereas the outer halo continued to develop slowly over time via accretion from dwarf or satellite galaxies.

Under such a Galactic formation model, it is expected that the younger, accreted halo clusters should share broad characteristics (luminosities, ages, abundances, etc.) with the globular clusters in satellite galaxies, such as the Large Magellanic Cloud (LMC; Zinn 1980; Suntzeff et al. 1992; Zinn 1993; Da Costa 2003). Previous work has examined the HB morphology in LMC clusters (Zinn 1993; Johnson et al. 1999; Mackey & Gilmore 2004a,b), largely using the metric $(B - R)/(B + V + R)$, where B is the number of blue HB stars, V is the number of RR Lyrae variables, and R is the number of red HB stars (Lee 1989; Lee, Demarque & Zinn 1994). Early studies found a few LMC globular clusters with particularly blue HB morphology – specifically NGC 2005 (Olsen et al. 1998) and Hodge 11 (Walker 1993) – while also showing that LMC clusters were largely co-located with the young halo clusters in the Milky Way in metallicity–HB morphology space. In addition, the analysis by Mackey & Gilmore (2004a,b) found NGC 1916, NGC 1928, and NGC 1939 to also have very blue HBs.

More recently, the rise of the multiple population problem in globular clusters has shed new light on our understanding of the HB morphology. In the Milky Way, several studies have shown that the chemical differences among stars on the HB can lead to variations in HB morphology (Villanova, Piotto & Gratton 2009; Gratton et al. 2011; Marino et al. 2011; Marino, Milone & Lind 2013; Milone et al. 2014). These studies suggest that the stars at different ends of the sodium–oxygen anti-correlation have different helium abundances, which in turn affects the extension of the HB. Milone et al. (2014) used two different parameters to quantify HB morphology – L1, the difference in colour between the red-giant branch and the red end of the HB, and L2, the overall colour extension of the HB. They showed that L1 correlates largely with intercluster variations in age, whereas L2 correlates most strongly with intracluster variations in helium abundance (which are closely linked to other internal elemental abundance variations).

In studying the HB morphology of the Galactic cluster population, Dotter et al. (2010) used another alternative approach to quantifying the HB morphology, rather than simply counting stars in and around the instability strip. Following the logic from Sarajedini (1999), their HB morphology measurement compares the median colour of the HB stars to the median colour of the RGB at the level of the HB (Dotter et al. 2010). This metric, referred to as $\Delta(V - I)$, is greater for clusters with bluer HBs and correlates well with other morphological estimates. However, this approach is less dependent on observational restrictions or choice of the instability strip boundaries in addition to possessing greater sensitivity in extreme morphological cases.

We utilize this methodology to conduct a direct comparison between the HB morphologies of globular clusters in the LMC and those in the Milky Way. It allows us to extend the HB analysis from Dotter et al. (2010) to the LMC clusters and provide a baseline measurement of HB morphology. Although another option would have been to adopt the methodology outlined by Milone et al. (2014), unfortunately the dearth of high-resolution spectroscopic studies of LMC clusters, in conjunction with less well-determined photometry than available for Galactic globular clusters (particularly in the UV), leaves us with little clear and consistent independent information about the chemistry of their multiple populations. Moreover, the generally lower quality photometry available for clusters in the LMC, means that measuring the two parameters defined by Milone et al. (2014), in particular the L1 parameter, is much more prone to significant error than measuring the median HB colour.

With deep observations of six LMC globular clusters, and supplemental observations of five additional clusters in the LMC bar region, we can examine which trends, if any, seen in the HB behaviour of Milky Way clusters extend to our neighbouring satellite. Incorporating information on the HB morphologies of clusters in galaxies external to the Milky Way will help shed more light on the use of globular clusters as tracers of galactic formation and evolution.

In Section 2, we discuss the data sets from *Hubble Space Telescope* (*HST*). We examine HB morphology in LMC clusters and compare to Galactic GCs in Section 3. In Section 4, we discuss and conclude.

2 DATA

2.1 Photometry

The data for the six outer LMC clusters come from *HST* Cycle 23 program GO-14164 (PI: Sarajedini). This program obtained deep imaging in the *F606W* and *F814W* filters with the Advanced Camera for Surveys (ACS) Wide Field Channel (WFC) on *HST* for the clusters NGC 1466, NGC 1841, NGC 2210, NGC 2257, Hodge 11, and Reticulum. Paper I in this series (Mackey et al., in preparation) provides a full description of the data acquisition and process of photometric analysis and evaluation. In short, each of the six clusters was in the *F606W* filter for two orbits and *F814W* for three orbits. Two images in each filter were short-exposure images (≈50–70 s per frame), with the rest being longer exposures (∼350–520 s per frame). The DOLPHOT software package (Dolphin 2000) was used to photometer the short- and long-exposure image sets separately. These two catalogues were quality-filtered and merged to generate the final photometric catalogue. The signal-to-noise ratio of stars in the region of the HB is largely ∼1000 and greater, and near the main-sequence turn-off point (MSTOP), the signal-to-noise ratio is ∼300. The photometric depth reliably reaches down to more than 4 magnitudes below the MSTOP. Where necessary in this work, the *F606W* and *F814W* magnitudes have been converted to *V* and *I* magnitudes through the transformations provided by Sirianni et al. (2005).

Photometry for the other five LMC clusters analysed here comes from Olsen et al. (1998). We use their published photometric catalogues for the LMC bar clusters NGC 1754, NGC 1835, NGC 1916, NGC 2005, and NGC 2019.[1] These clusters were observed in the *F555W* and *F814W* filters with the WPFC2 Planetary Camera with both short (40 and 60 s combined, *F555W* and *F814W,* respectively) and long (1500 and 1800 s combined, *F555W* and *F814W,* respectively) exposures. The images were photometered with DOPHOT (Schechter, Mateo & Saha 1993) and the process included cosmic ray rejection and a CTE correction. As the LMC bar clusters are in high-density stellar fields, field star subtraction was modelled in detail through extensive artificial star tests. Using these tests, Olsen et al. (1998) removed field stars from their photometry, and we use these cleaned data sets for our own analysis.

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[1] NGC 1898 was also included in the study by Olsen et al. (1998), but photometry for this cluster is not included in the online repository. The photometry for NGC 1928 and 1939 described by Mackey et al. (2004b) suffers from extremely heavy field contamination as well as differential reddening, such that the HB measurements are largely uninformative.
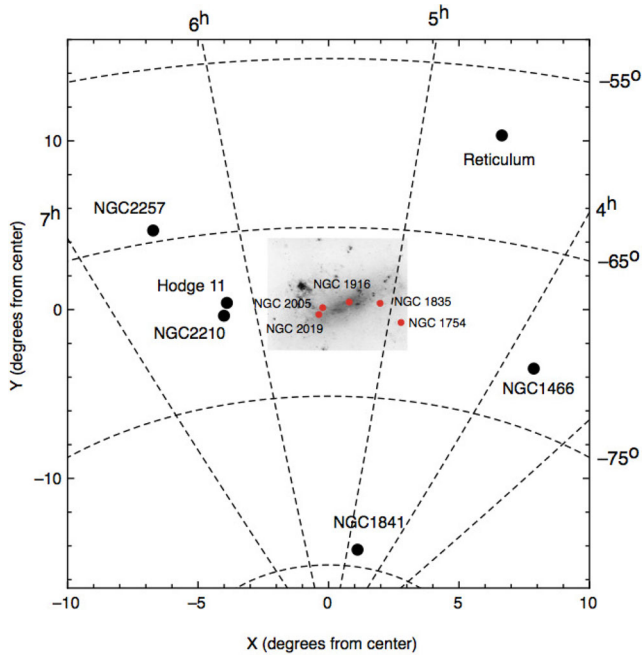
Figure 1. The LMC and surrounding region from a SkyView Digital Sky Survey composite. The six clusters from *HST* Cycle 23 program GO-14164 (PI: Sarajedini) are indicated in black and the five LMC bar clusters from Olsen et al. (1998) are indicated in red.

Crowding was found to strongly affect completeness and introduce additional photometric uncertainty. The published photometric catalogues present photometry that the authors have transformed to the *V* and *I* filters in the Johnson–Cousins system using (Holtzman et al. 1995, ; equation 9). Further details on the process may be found in Olsen et al. (1998). Despite the removal of field stars, photometry for the bar clusters remains substantially noisier than for the outer clusters; however, the median colour measurements we make to analyse HB morphology are largely robust to outliers, as discussed further in Section 3.

For reference, the locations of the six outer LMC clusters (Paper I) and the five bar clusters (Olsen et al. 1998) are shown in Fig. 1. Data and photometry for the Galactic globular clusters comes from the ACS Globular Cluster Treasury program (GO Cycle 14 Proposal 10775; Sarajedini et al. 2007) and Dotter et al. (2010).

3 HORIZONTAL BRANCH MORPHOLOGY

3.1 Measurement

The quantification of HB morphology takes a variety of forms, from the HB type (Dickens 1972) to the widely used HB ratio [$(B-R)/(B+V+R)$; Lee 1989; Lee et al. 1994], and the L1 and L2 parameters defined by Milone et al. (2014). We elect to employ the measurement of $\Delta(V-I)$, the difference in the median colour of the HB stars, and the RGB stars at the level of the HB, generally following the method of Dotter et al. (2010). This method has a few advantages over measurement of the HB ratio (though as demonstrated by Dotter et al. 2010, they remain correlated). Specifically, at the extreme ends of very red and very blue HBs, the $\Delta(V-I)$ metric is more sensitive, allowing for greater differentiation between clusters. Further, the choice of the instability strip boundaries may bias the final HB ratio, but it does not influence the $\Delta(V-I)$ value. The measurement
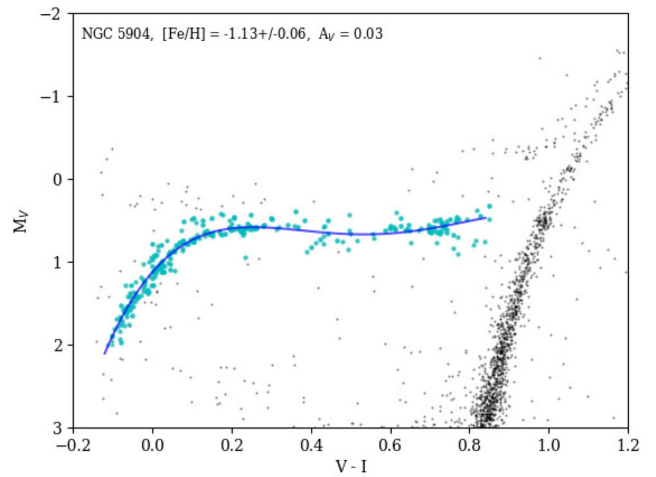

Figure 2. ACS Treasury Program photometry of NGC 5904 in black (Sarajedini et al. 2007). HB stars included in the fiducial fit are shown in cyan, with the HB fiducial demarcated by the solid blue line. NGC 5904 is used in Dotter et al. (2010), and herein as a reference cluster.

of $\Delta(V-I)$ is also less affected by small number statistics or observational limitations that could otherwise bias the derivation of an HB ratio. However, we do note that $\Delta(V-I)$ is not as sensitive to the effects of internal helium variations on the morphology of the HB as, say, the L2 parameter introduced by Milone et al. (2014). Although this means that we do not have significant leverage on the effect of helium on the HB in this analysis, using $\Delta(V-I)$ we are able to provide a robust baseline comparison to the Dotter et al. (2010) study.

In order to adequately measure the $\Delta(V-I)$ metric for the LMC clusters, two measurements must be made – the median colour of the RGB at the level of the HB and the median colour of the HB. For the former, the magnitude of the HB must be determined, and for the latter, it is necessary to pick the HB stars out from the CMD. To determine these values, we use the Galactic cluster NGC 5904 as a reference, as in Dotter et al. (2010), with photometry from the ACS Globular Cluster Treasury Program (Sarajedini et al. 2007). NGC 5904 was chosen for its broad HB, allowing it to be compared to diverse cluster HB morphologies. Although the chemistry of a cluster is expected to cause variations in the morphology of the HB, the overall *shape* of the HB is largely consistent for different cluster morphologies (Brown et al. 2016; Denissenkov et al. 2017).

First, an HB fiducial for NGC 5904 is derived from the photometry. The initial fiducial estimate is made by eye at several points along the HB across the visible colour range of the HB, then fit with a radial basis function spline. To improve on the fiducial, we include stars within 2σ of the initial fiducial estimate and determine a moving average with bins of 0.02 in colour with a window of 0.05. A new spline is fit to these points to determine the HB fiducial. Fig. 2 shows the fiducial on the de-reddened, distance corrected CMD of NGC 5904.

This process is repeated to derive HB fiducials for the LMC clusters. The HB fiducial for NGC 5904 is shifted via least squares to match the HB fiducials of the LMC clusters; the difference in magnitude between the two fiducials provides the HB level for each cluster relative to NGC 5904. Using RGB stars within ± 0.5 magnitudes of this level, the RGB median colour is determined. The median HB colour is determined from the stars used to derive the final HB fiducial. Subtracting these two values gives us $\Delta(V-I)$ for each cluster. One benefit of this approach is that
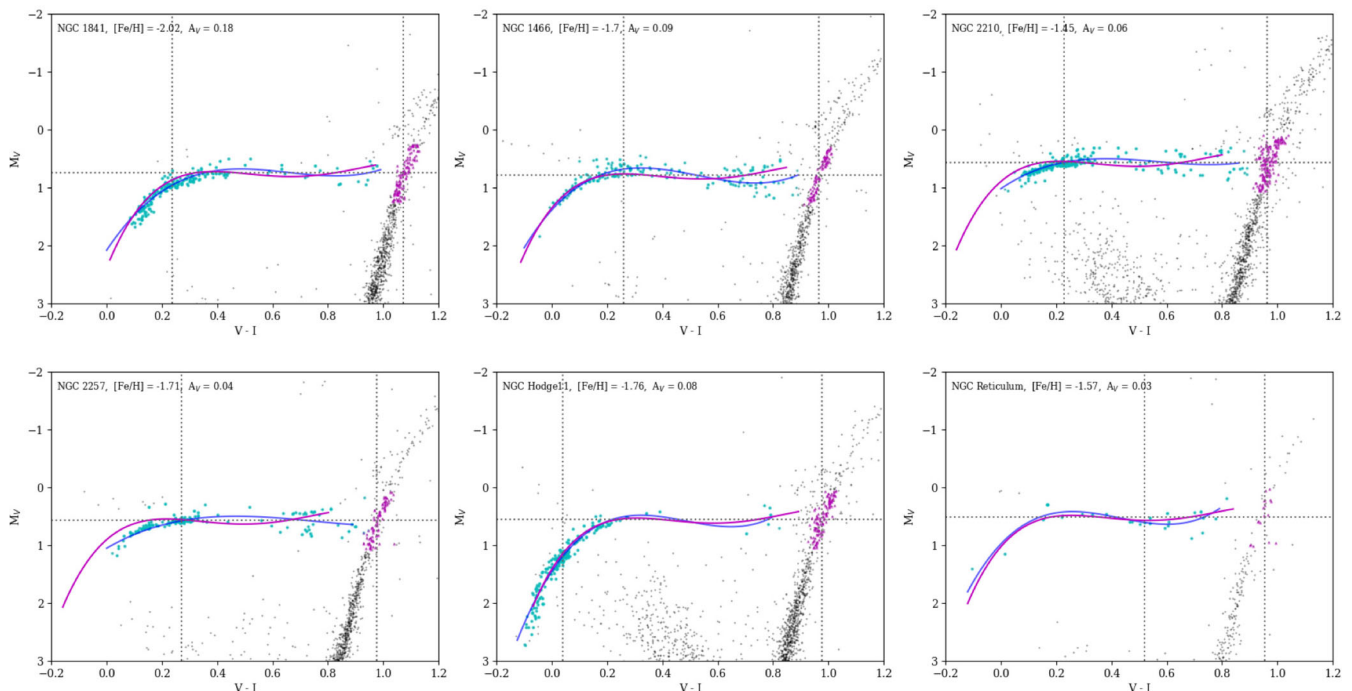
Figure 3. The $\Delta(V-I)$ determination of the six outer LMC clusters from *HST* Cycle 23 program GO-14164. The NGC 5904 HB fiducial is indicated by the solid magenta line and the HB fiducial for the cluster in each panel is shown as the solid blue line. HB stars included in the median colour determination are shown as cyan circles in each panel; the RGB stars are indicated by magenta triangles. The horizontal line indicates the HB level of the cluster, and the two vertical lines mark the median colours of the HB and RGB.
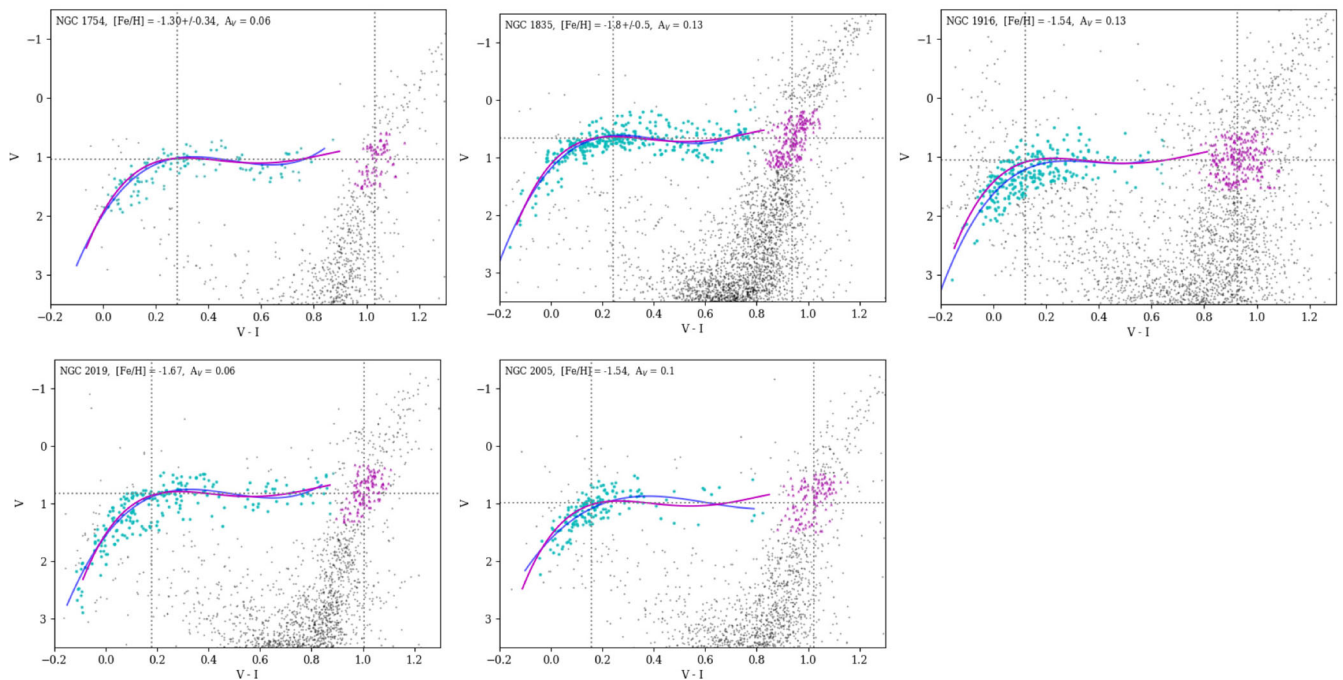

Figure 4. Same as Fig. 3 but for the five LMC bar clusters from Olsen et al. (1998).

the median colour is quite robust to low levels of missing stars or wrongly included field stars. These cases will not cause a huge shift in the measured median colours except for those clusters with very few members (e.g. Reticulum).

The results of this approach are shown in Fig. 3 for the outer LMC clusters and Fig. 4 for the LMC bar clusters, where the CMDs are de-reddened and a distance modulus of 18.5 is assumed. In these figures, the HB fiducials of each cluster are compared to NGC 5904; the HB stars and RGB stars are indicated by cyan circles and magenta triangles, respectively. The determinations of the RGB and HB median colours are also marked in each panel as vertical lines.

We present the basic properties of the LMC outer clusters from Paper I in Table 1 and of the LMC bar clusters of the Olsen et al. (1998) sample in Table 2. The derived $\Delta(V-I)$ values are

Table 1. Fundamental properties of the LMC outer clusters from Paper I.

Cluster	[Fe/H]$_{CG97}$[1]	$E(B-V)$[2]	Age (Gyr)[3]	$\Delta(V-I)$	M_V[4]	ρ_0[5]
NGC 1466	−1.7	0.09	$13.38^{+1.67}_{-2.28}$	0.706 ± 0.020	11.59	2.78
NGC 1841	−2.02	0.18	$13.77^{+1.05}_{-2.41}$	0.836 ± 0.014	11.43	1.29
NGC 2210	−1.45	0.06	$11.63^{+1.80}_{-1.12}$	0.734 ± 0.015	10.94	3.34
NGC 2257	−1.71	0.04	$12.74^{+1.87}_{-2.18}$	0.704 ± 0.021	12.62	1.73
Hodge11	−1.76	0.08	$13.92^{+1.48}_{-2.01}$	0.939 ± 0.011	11.93	2.59
Reticulum	−1.57	0.03	$13.09^{+2.21}_{-1.98}$	0.434 ± 0.047	14.25	N/A

Notes. [1] Metallicities from Walker (1992b); Grocholski et al. (2006); Mucciarelli, Origlia & Ferraro (2010); Mateluna et al. (2012), converted to CG97 metallicity scale where necessary (as in Wagner-Kaiser et al. 2017).
[2] $E(B-V)$ values from Walker (1992, 1993), assuming $R_V = 3.1$.
[3] Ages from Wagner-Kaiser et al. (2017).
[4] Magnitudes from Mackey & Gilmore (2003) (none for Reticulum).
[5] Densities from Mackey & Gilmore (2003).

Table 2. Fundamental properties of the LMC bar clusters in the Olsen et al. (1998) sample.

Cluster	[Fe/H]$_{CG97}$[1]	$E(B-V)$[2]	Age (Gyr)[3]	$\Delta(V-I)$	M_V[4]	ρ_0[5]
NGC 1754	−1.30	0.06	12.96 ± 2.2	0.750 ± 0.021	11.57	3.98
NGC 1835	−1.79	0.13	13.37 ± 2.8	0.696 ± 0.012	10.17	4.32
NGC 1916	−1.54	0.13	12.56 ± 5.5	0.807 ± 0.013	10.38	4.63
NGC 2005	−1.54	0.10	13.77 ± 4.9	0.865 ± 0.014	11.57	4.17
NGC 2019	−1.67	0.06	16.2 ± 3.1	0.825 ± 0.018	10.86	4.33

Notes. [1] Metallicities from Olszewski et al. (1991), converted to CG97 metallicity scale.
[2] $E(B-V)$ values from Walker (1992a); Olszewski et al. (1991); Olsen et al. (1998); Johnson, Ivans & Stetson (2006); Pessev et al. (2008), assuming $R_V = 3.1$.
[3] Ages from Carretta et al. (2010), combined from Olsen et al. (1998) and Beasley, Hoyle & Sharples (2002), and put on absolute scale assuming a reference of 13.5 Gyr (Marín-Franch et al. 2009).
[4] Magnitudes from Mackey & Gilmore (2003).
[5] Densities from Mackey & Gilmore (2003).

included in the final column with their standard error. The inherent uncertainty in the determination of $\Delta(V - I)$ is larger for the Olsen et al. (1998) photometry due to greater star-to-star scatter. It is therefore possible that the results for the bar clusters could be biased relative to those measured for the outer LMC clusters of Mackey et al. (2017). This bias is difficult to quantify without any overlap in the cluster samples; however, the results for the bar clusters are broadly in line with those from previous studies using other methods of measuring HB morphology. It is also worth noting that Olsen et al. (1998) statistically subtracted the contaminating field populations from their cluster CMDs. This effect could also, in principle, lead to a mild systematic offset between measurements for the bar clusters and those in the outer LMC. However, we expect the effect to be minimal on the overall results, as the median measurements of colour are robust to outliers.

Using the quantification of HB morphology with $\Delta(V-I)$, we can compare to the values determined for the Galactic globular clusters from Dotter et al. (2010). However, differences in chemical abundances among clusters in each galaxy could make a direct comparison of HB morphology incomplete. Few studies have examined individual chemical abundances of individual stars in LMC clusters via high-resolution spectroscopy (Hill et al. 2000; Johnson et al. 2006; Mucciarelli et al. 2009, 2010; Mateluna et al. 2012). Although some elements in the LMC cluster stars have been found to be distinct from GGC clusters (e.g. [Cu/Fe], [Y/Fe]), thus far, the α-abundances in the LMC globular clusters appear to fall in a range of values comparable to GGCs (Johnson et al. 2006; Mucciarelli et al. 2010), suggesting a direct comparison of $\Delta(V-I)$ between the two galaxies is valid.
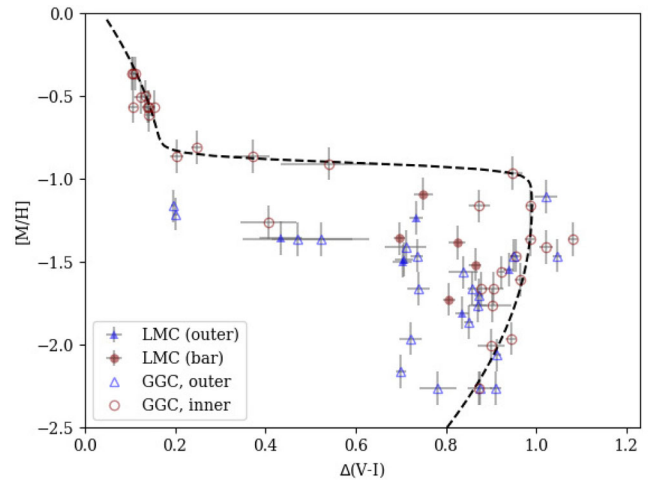

Figure 5. A comparison of the LMC clusters (solid markers) to the Galactic clusters (open markers). The inner clusters are shown as red circles for each galaxy and the outer clusters indicated as blue triangles. The HB morphology fitting functions from Dotter et al. (2010) are shown as the dashed line.

In Fig. 5, the metal abundance [M/H] is calculated as in Salaris, Chieffi & Straniero (1993): [M/H] = [Fe/H]+$\log_{10}(0.638 \times 10$[$\alpha$/Fe] $+ 0.362)$. We assume [α/Fe] = 0.3 on average for the LMC clusters, as suggested by Mucciarelli et al. (2009) for several of the clusters in our sample. We note that this assumption only affects the estimation of [M/H] as in Figs 5 and 6, and has little effect on our overall results. For [α/Fe] values between
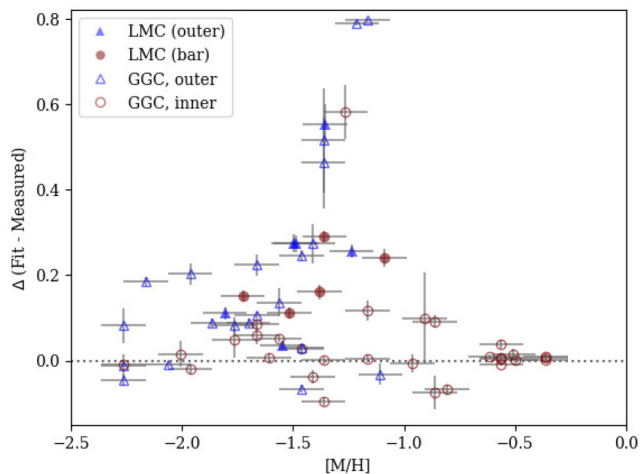
Figure 6. The residual between the equations from Dotter et al. (2010) to describe HB morphology and measured $\Delta(V - I)$ values as a function of metallicity. The markers are the same as in Fig. 5.

0 and 0.4, the values of [M/H] change minimally, by less than 0.2. For the GGCs, $[\alpha/\text{Fe}]$ are taken from Dotter et al. (2010) analysis for a direct comparison of their results to our own, though we note that Carretta et al. (2010) and Nataf et al. (2013) have additional $[\alpha/\text{Fe}]$ estimates for the GGCs.

The LMC clusters are plotted as filled markers in Fig. 5, with the red circles indicating the bar clusters from Olsen et al. (1998) and the blue triangles representing the outer clusters from Paper I. The Galactic clusters are included with the same colour and shape convention as open markers, split into inner and outer halo clusters at $R_{\text{GC}} = 8$ kpc. The dashed line in Fig. 5 is from Dotter et al. (2010), specifically their table 2 and equations (2) through 4. This function was designed to represent the behaviour of the inner halo clusters, whose HB morphology can be almost entirely characterized by their metallicities.

3.2 Analysis

In general, the LMC clusters – both the bar clusters and the outer clusters – largely occupy the same region in the metallicity–HB morphology space, having slightly redder HB morphologies than the older, inner Galactic GCs of comparable metallicity. There are no LMC clusters that have as blue HBs as the bluest Galactic clusters; it is possible this is due to differences in the helium abundances of the LMC and Galactic clusters. The primary outlier of the LMC clusters is Reticulum, whose HB is significantly redder than the other LMC clusters. However, it is worth noting that Reticulum has the most sparse HB of the clusters we analyse here, and the largest $\Delta(V - I)$ error bar.

The bar clusters fall within 3 kpc of the LMC centre, whereas the outer clusters are beyond $\gtrsim 4$ kpc. However, there does not appear to be a clear differentiation in HB morphology between the LMC clusters located in the bar of the galaxy and those in the outer regions. The higher level of sensitivity at the blue end of the HB morphology spectrum with $\Delta(V - I)$ allows us to see that as a population, the LMC clusters are more consistent with the outer halo Galactic population of clusters. Although the inner halo clusters are scattered around the fitted line from Dotter et al. (2010), the LMC clusters do not follow suit. That the entire sample of LMC clusters are broadly consistent with the outer halo Galactic GCs lends further evidence to a Galactic formation scenario wherein the

outer halo is built up from the accumulation of satellite galaxies similar to the LMC. However, it is also possible that this result is due to the restricted metallicity range of globular clusters in the LMC, in which there are no metal-rich clusters comparable to the Galactic population.

To examine the remaining deviation in HB morphology not explained by metallicity, we examine the residuals in $\Delta(V - I)$ from Fig. 5. This residual is calculated as the difference between the HB morphology predicted by the dashed line in Fig. 5 and the observed $\Delta(V - I)$. In Fig. 6, this difference is plotted as a function of metal abundance. We see that all the LMC clusters deviate from the expected $\Delta(V - I)$ of the trend line, which is based only on metallicity (the first parameter). On average, the inner clusters deviate by 0.19 ± 0.07 (standard deviation) ± 0.01 (standard error) mag and the outer clusters deviate by 0.25 ± 0.16 (standard deviation) ± 0.03 (standard error) mag. Removing the influential point of Reticulum, the average deviation for the outer clusters is 0.19 ± 0.10 (standard deviation) ± 0.02 (standard error) mag, essentially equivalent to the inner clusters.

These results suggest broad similarity in HB morphology between the LMC clusters regardless of their physical location in the LMC. This is in stark contrast to the Milky Way, where the inner and outer halo clusters have markedly different HB morphologies.

As to what else may contribute to HB morphology beyond metallicity – the possible second parameter(s) – we further explore the deviation of clusters from the HB morphology expected from metallicity alone. We plot the residuals in $\Delta(V - I)$ with age, cluster central density, and integrated magnitude in Fig. 7, with Milky Way values from Dotter et al. (2010). LMC cluster ages are from Wagner-Kaiser et al. (2017) for the outer clusters, and Beasley et al. (2002) and Olsen et al. (1998) for the inner bar clusters (as presented in Carretta et al. 2010). Densities are taken from Mackey & Gilmore (2003) and integrated magnitudes are taken from Geisler et al. (1997). Table 3 provides the correlations for these relations and that of [M/H] (as in Fig. 6) for the LMC and Galactic globular clusters combined.

With age, the leftmost panel of Fig. 7, our results are consistent with that of Dotter et al. (2010). The outer clusters show a statistically significant trend between age and the residual of $\Delta(V - I)$ with a Spearman ρ of -0.50 (p-value $= 0.008$). This is qualitatively similar to the results for the outer clusters from Dotter et al. (2010), with a Spearman ρ of -0.81. Our results are also in agreement with the findings of Milone et al. (2014), who also demonstrate a statistically significant relationship between HB morphology and age (albeit using a different method of quantifying the structure of the HB).

For the LMC bar clusters, however, we do not observe any statistically significant relationship between age and the $\Delta(V - I)$ residual, again consistent with the results from Dotter et al. (2010). Although there is no additional constraining information beyond what is already known from the Galactic population, the LMC clusters are consistent with the Galactic trends. We do note that the oldest cluster, NGC 2019, is a significant outlier at 16 Gyr; however, the quoted uncertainties in Olsen et al. (1998) and Beasley et al. (2002) are on the order of several Gyr.

In examining the central densities of the clusters, a similar pattern emerges. The relation with central density for clusters with [M/H] < -1.5 is fairly convincing, and the LMC clusters are again consistent with the trend seen in the Galactic clusters. The correlation is statistically significant with a Spearman correlation of -0.41.
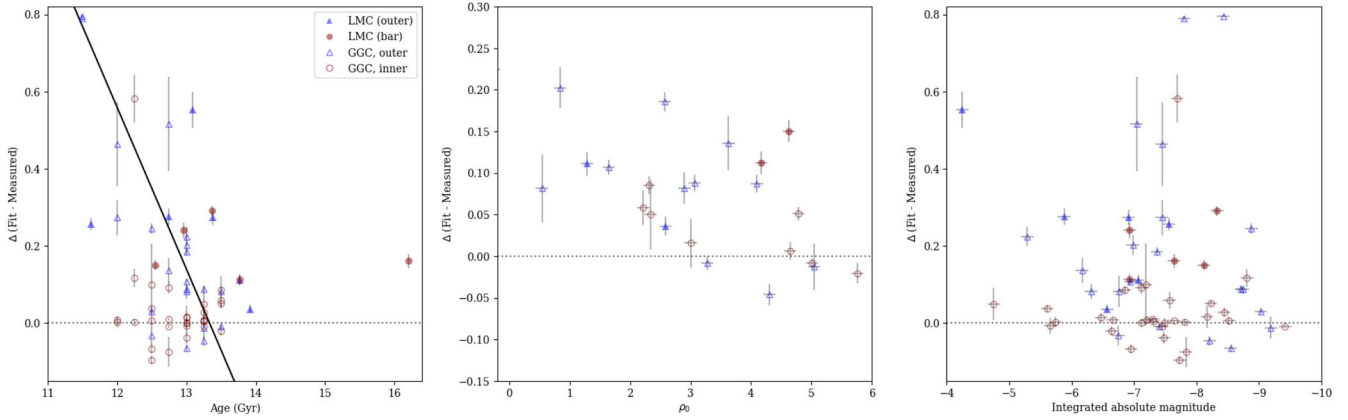
Figure 7. Left-hand panel: the residual between the fitted and measured $\Delta(V - I)$ values as a function of cluster age. The symbols are the same as in Fig. 5. The bar cluster NGC 2019, at an estimated 16 Gyr, is the extreme outlier. The solid line is the fit from Dotter et al. (2010). Middle panel: $\Delta(V - I)$ residual compared to cluster central densities (Mackey & Gilmore 2003). As in Dotter et al. (2010), we plot only the metal-poor clusters with $[M/H] < -1.5$. Right-hand panel: residuals compared to cluster integrated magnitudes (Geisler et al. 1997; Mackey & Gilmore 2003).

Table 3. Spearman correlation results for Figs 6 and 7.

Variable	ρ	p value
[M/H]	−0.08	0.51
Age (inner)	0.15	0.38
Age (outer)	−0.50	<0.01
Density	−0.41	0.02
M_V	0.09	0.46

For the absolute integrated magnitude, the LMC clusters present similar scatter as seen in the Milky Way clusters, though the data show no clear trend. The relationship has a Spearman correlation coefficient of 0.10, consistent with the results of Dotter et al. (2010), who find a Spearman correlation coefficient of 0.11. However, Milone et al. 2014 have showed that their L2 parameter, which measures the overall colour extension of the HB, correlates with the absolute magnitude of the clusters. This finding implies that the absolute integrated cluster magnitude correlates with helium variations, with larger helium variations in more luminous (massive) clusters. Although we do not see such a correlation, this does not mean there is no such correlation, as our choice of HB parameter is not sensitive to helium variations, as previously discussed.

Hodge 11 exhibits a bluer HB than the other LMC clusters we examine. If this extension is driven by helium, we expect that future observations of Hodge 11 should demonstrate that the cluster has the largest internal helium variation amongst the clusters considered here. However, we note that Hodge 11 does not appear to be the brightest (or most massive) cluster of this cluster sample, which does not seem consistent with what would be expected. At present, there is little or no quantitative assessments of these parameters for the LMC clusters. Our understanding of these clusters would benefit from further work exploring these possibilities.

NGC 2210 is another intriguing cluster in the LMC sample. This cluster is thought to be about 1.5 Gyr younger than the other LMC clusters (Wagner-Kaiser et al. 2017). However, its median HB colour does not reflect this, even though $\Delta(V - I)$ is age-sensitive. Although NGC 2210 has a bluer HB than predicted, it does not have an unusually strong blue HB extension. If blue HB extensions are driven by helium enhancements, then helium may not be the cause of the HB variation in NGC 2210. It may be that the higher

central density (compared to the other outer LMC clusters) could be the cause of the bluer than expected HB. The same may be true for Reticulum, which has the reddest median HB colour of the clusters we examine, yet does not have a markedly different age or metallicity from the other LMC clusters.

4 CONCLUSIONS

In this paper, we have examined the HB morphology of globular clusters in the LMC and compared their characteristics to the Milky Way globular clusters. Our findings include the following:

(i) The inner (bar) and outer clusters in the LMC are generally comparable in their HB morphology characteristics as described by the $\Delta(V - I)$ measure. Despite their galactocentric differences, they occupy the same region in metallicity–HB morphology space.

(ii) As observed for the outer halo population of GCs, the LMC clusters deviate from HB morphologies that can be explained by metallicity alone. This is a clear indication that these clusters exhibit the classical second parameter effect, which is consistent with the idea that the outer halo Galactic population was accreted from dwarf satellites as originally advocated by Searle & Zinn (1978).

(iii) Despite the fact that the HB morphologies of the LMC clusters are clearly affected by at least one parameter in addition to metallicity, we do not find any convincing evidence to uniquely identify this parameter or parameters. The LMC clusters generally agree with the trends seen in Galactic GCs between median HB colour and age, central density, and integrated absolute magnitude. Reticulum, NGC 2210, and Hodge 11 constitute good examples of clusters for which age cannot be the sole second parameter. Internal helium variations could be important for Hodge 11, which has a strongly extended HB; however, this does not appear to be the case for Reticulum or NGC 2210.

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