NOT-SO-SIMPLE STELLAR POPULATIONS IN THE INTERMEDIATE-AGE LARGE MAGELLANIC CLOUD STAR CLUSTERS NGC 1831 AND NGC 1868

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ABSTRACT

Using a combination of high-resolution Hubble Space Telescope/Wide-Field and Planetary Camera-2 observations, we explore the physical properties of the stellar populations in two intermediate-age star clusters, NGC 1831 and NGC 1868, in the Large Magellanic Cloud based on their color–magnitude diagrams. We show that both clusters exhibit extended main-sequence turn-offs. To explain the observations, we consider variations in helium abundance, binarity, age dispersions, and the fast rotation of the clusters’ member stars. The observed narrow main sequence excludes significant variations in helium abundance in both clusters. We first establish the clusters’ main-sequence binary fractions using the bulk of the clusters’ main-sequence stellar populations \( \geq 1 \) mag below their turn-offs. The extent of the turn-off regions in color–magnitude space, corrected for the effects of binarity, implies that age spreads of order 300 Myr may be inferred for both clusters if the stellar distributions in color–magnitude space were entirely due to the presence of multiple populations characterized by an age range. Invoking rapid rotation of the population of cluster members characterized by a single age also allows us to match the observed data in detail. However, when taking into account the extent of the red clump in color–magnitude space, we encounter an apparent conflict for NGC 1831 between the age dispersion derived from that based on the extent of the main-sequence turn-off and that implied by the compact red clump. We therefore conclude that, for this cluster, variations in stellar rotation rate are preferred over an age dispersion. For NGC 1868, both models perform equally well.

Key words: binaries: general – galaxies: star clusters: individual (NGC 1831, NGC 1868) – Hertzsprung–Russell and C–M diagrams – Magellanic Clouds – stars: rotation

Online-only material: color figures

1. INTRODUCTION

The majority of stars in a given star cluster all formed in close proximity to each other at roughly the same time. They are thought to have originated from the same progenitor molecular cloud and, hence, they are characterized by the same chemical composition. This idea is the basis of the common notion that all observed stars in such a cluster should have roughly the same age and metallicity, which is in essence equivalent to saying that the cluster is composed of a single (simple) stellar population (SSP). Although the SSP approximation remains valid for the bulk of the stellar populations in most observed star clusters, the discovery of extended main-sequence (MS) turn-offs (TOs) and multiple stellar populations in many globular clusters (GCs), as well as in massive extragalactic clusters of any age, challenges this simple picture. Based on the SSP assumption, one expects observed clusters to display narrow sequences in their color–magnitude diagrams (CMDs), including as regards to their MS, subgiant branch (SGB), red-giant branch (RGB), a compact horizontal-branch (HB) clump, and a well-defined, narrow MS TO. However, counterexamples have been found that challenge these expectations for almost all of these narrow and tight CMD features. Some clusters—including NGC 419 (Glatt et al. 2008), NGC 1751, NGC 1806 (Milone et al. 2009), NGC 1783 (Mackey et al. 2008), NGC 1846 (Mackey & Broby Nielsen 2007; Milone et al. 2009), and NGC 2209 (Keller et al. 2012)—display extended or dual TOs. Some old GCs also display double or multiple MSs, such as NGC 2808 (Piotto et al. 2007) and NGC 6397 (Milone et al. 2012). Milone et al. (2008) found that the GC NGC 1851 is characterized by two distinct SGBs. Some GCs, such as ω Centauri (Piotto et al. 2005; Sollima et al. 2007), NGC 288 (Piotto et al. 2013), and M22 (Lee et al. 2009), exhibit double or multiple MSs, SGBs, and/or RGBs; Terzan 5 even shows clear, double HB clumps (Ferraro et al. 2009).

Although some of these features are only found in specific example clusters, extended or double MS TOs seem to occur rather commonly. Milone et al. (2009) suggested that this may also be an ordinary feature of intermediate-age star clusters in the Large Magellanic Cloud (LMC). They found that roughly 70% of their sample of intermediate-age clusters display extended or double TOs. Different models have been proposed to account for these observations, including those involving the presence of chemical inhomogeneities, internal age dispersions, rapid stellar rotation, and possible selection effects (for a discussion, see Keller et al. 2011). An initially promising explanation involved the assumption of helium inhomogeneities (for general overviews, see Rood 1973; Rood & Crocker 1989; Fusi Pecci & Bellazzini 1997). However, it seems that this model only works properly for the multiple populations in (old) GCs, e.g., in NGC 2808 (D’Antona et al. 2005; Piotto et al. 2007) or ω Centauri (King et al. 2012). Since the helium-enrichment scenario predicts the presence of a secondary MS at bluer colors than those of the main stellar population, such models can be used to fit the observed color bifurcation of GC MSs very well. However, intermediate-age clusters also exhibit extended TOs, while their MSs remain narrow (see, e.g., Milone et al. 2009). As a consequence, few authors consider
helium-abundance differences in the context of the extended TOs seen in the CMDs of intermediate-age clusters. In this article, we will confirm that assuming differences in the helium abundance indeed cannot explain our observations of the CMDs of two intermediate-age LMC clusters.

An alternative model, which assumes that the cluster stars have been forming continuously, with an age dispersion of roughly 300 Myr, has been more successful in explaining the extended TOs observed for intermediate-age clusters. However, the origin of such an age dispersion as incorporated in this model remains unclear. D’Ercole et al. (2008) and Goudfrooij et al. (2009) suggested that the ejecta of first-generation asymptotic giant branch (AGB) stars might be the main contributors, but this again necessitates helium self-enrichment. Some authors have also suggested that this postulated age dispersion may originate from dynamical interactions, leading to differently aged populations that are each characterized by a specific chemical abundance. For instance, Mackey & Broby Nielsen (2007) proposed that mergers of two star clusters with an age difference of $\geq 200$ Myr might be the origin of the observed multiple populations in their sample clusters. Similarly, Bekki & Mackey (2009) proposed a new scenario involving interactions or mergers of star clusters and star-forming giant molecular clouds. Although it is still unclear why such dynamical processes might have acted in a global manner and affected many intermediate-age LMC clusters, the age-dispersion model has been successful in reproducing most of the observations.

A recently proposed competing scenario invokes fast stellar rotation, the effects of which become particularly pronounced in MS TO stars. This model can also reproduce the observations, while more importantly it avoids challenging the SSP assumption. The main principles of this latter model are that the centrifugal force resulting from rapid rotation causes a star to expand, thus decreasing its effective temperature. The reduced effective gravity also results in a lower luminosity (Bastian & de Mink 2009; Yang et al. 2013). Royer et al. (2007) investigated this issue. They all found that rapid rotation should be less than 100 Myr, in which case the fast-rotation approach is outlined in Section 2. In Section 3, we first rule out the possibility of different helium abundances as the driver of the occurrence of secondary populations and then show to what extent the age-dispersion model reproduces the data, corrected for the effects caused by the presence of a significant fraction of MS binary systems. We show that the age dispersion in NGC 1831 can be further constrained to within 100 Myr by taking into account its compact RC. In Section 4, we discuss the performance of models involving rapid rotation. A discussion and our conclusions are contained in Section 5.

2. DATA REDUCTION

2.1. CMD Determination

The data sets pertaining to NGC 1831 and NGC 1868 were obtained as part of HST program GO-7307 (PI: Gilmore) using the Wide-Field and Planetary Camera-2 (WFPC2). These two clusters were originally selected because they form a pair in terms of their ages, have similar masses (de Grijs et al. 2002a), and are also located at similar distances from the LMC’s center (Westerlund 1990; Bica et al. 1996). The latter property minimizes any differences caused by the LMC’s tidal field. As we will see, their stellar (field) backgrounds are sparse and allow for easy decontamination. Both clusters were observed through the F555W and F814W filters, which roughly correspond to the Johnson–Cousins V and I bands, respectively. We will henceforth refer to these HST filters as V and I. In both filters, three images with total exposure times of, respectively, 2935 s and 3460 s were obtained. Among these three images, two were taken with the clusters’ center regions located on the Planetary...
Camera chip; the total exposure times of these images were 435 s in the V band and 960 s in I (for more details about the data sets, see de Grijs et al. 2002a). The longer-exposure images (characterized by exposure times of 2500 s in both the V and I bands) were centered on locations representative of the clusters’ half-light radii. Images with exposure times of 1200 s in the V band and 800 s in I cover a nearby representative field region for both of our clusters (see also Kerber et al. 2002). These images are used to correct for background contamination (for more details of the relevant procedures used, see de Grijs et al. 2002c; Hu et al. 2010).

We used the HSTphot package (Dolphin 2000) to perform photometry on the images. HSTphot is a specialized photometry package for analyzing HST/WFPC2 images (Dolphin 2005; Hu et al. 2010), which can be used to automatically deliver HST/WFPC2 photometry and the corresponding photometric uncertainties. We specifically chose to use point-spread-function photometry. The photometric catalogs resulting from all three images were combined, separately for both filters. The stars in the combined catalog all have associated photometric uncertainties of less than 0.22 mag. We applied the same photometric procedures to our observations of the nearby field region (for details, see Li et al. 2013). By virtue of the long exposure time of the final, combined data set, the photometric uncertainties in the magnitude range of interest ($V \lesssim 24$ mag; see below) are much smaller than the width of the clusters’ MSs or the extent of their TO regions. At these magnitudes, our photometric completeness levels are $>80\%$ (cf. de Grijs et al. 2002b).

We decontaminated the cluster CMDs based on an approach similar to that applied by Kerber & Santiago (2005a), Hu et al. (2010), and Li et al. (2013). For the CMDs of both the cluster and the nearby field region, we generated a common grid using 50 bins in color (spanning the range from $V - I = -0.8$ to $3.1$ mag for NGC 1831, and from $V - I = -1.3$ to $3.2$ mag for NGC 1868) and 100 bins in magnitude ($15.8 \leq V \leq 27.0$ mag for NGC 1831; $16.0 \leq V \leq 27.3$ mag for NGC 1868). We recently showed that varying the bin size has a trivial effect on the quality of our decontamination procedure (Li et al. 2013). For each grid cell, we counted the number of nearby stars per unit area. Following a correction for the difference in the area covered between the cluster and field regions, we then calculated the number of possible contaminating stars in the same cell of the cluster CMD and randomly deleted this number of stars from the relevant cell. Figure 1 (top panels) shows the raw NGC 1831 CMD, as well as the corresponding CMD of the nearby field region and the decontaminated cluster CMD. The bottom panels show zooms of the CMD region containing the TO and RC. Only few background stars are contained in this region, so the decontamination process is mainly important for the faint section of the MS, which we will use to estimate the clusters’ binary fractions (see Section 3).

2.2. Cluster Centers and Sizes

To select a proper cluster region to examine in detail, derivation of reliable cluster center coordinates is essential. We obtained new and updated cluster center positions by following the same approach as Li et al. (2013). We divided the stellar spatial distributions into 20 bins in both right ascension ($\alpha_{2000}$) and declination ($\delta_{2000}$). In both spatial coordinates, the stellar number densities follow Gaussian-like profiles, which allow us to determine the coordinates corresponding to the two-dimensional maximum density (see also de Grijs et al. 2013). The resulting center coordinates of NGC 1831 and NGC 1868 are, respectively, $\alpha_{2000} = 05^h 06^m 17^s 3 (76.571707^\circ)$, $\delta_{2000} = -64^\circ 55' 09'' 5 (-64.919302^\circ)$, and $\alpha_{2000} = 05^h 14^m 35^s 9 (78.649207^\circ)$, $\delta_{2000} = -63^\circ 57' 12'' 9 (-63.953577^\circ)$. These coordinates are consistent with those determined by Mackey & Gilmore (2003).

Figure 1. Top left: raw NGC 1831 CMD. Top middle: CMD of a representative nearby field region. Top right: decontaminated cluster CMD. Bottom: enlargements of the region containing the TO and RC. (A color version of this figure is available in the online journal.)

3. HELIUM-ABUNDANCE INHOMOGENEITIES AND AGE DISPERSION

We first investigate at which level helium-abundance variations will affect the observed extent of the MS TO. The main features of the observed CMDs explored in this study are the following (see also Figure 3):

\[ \text{At the canonical distance to the LMC, (}M - M_0\text{)} = 18.50 \text{ mag.} \]

1'' corresponds to 0.26 pc.
with that of Javiel et al. (2005), although it is slightly higher than that derived by Liu et al. (2009), $E(B-V) = 0.00$ mag. This latter apparent discrepancy is driven by our choice of fitting the MS ridgeline rather than the bottom of the MS envelope, as done by Liu et al. (2009); see below. The isochrone characterized by these parameters matches the ridgeline of the faint section of the NGC 1831 (NGC 1868) MS, $V \lesssim 21.0$ (21.5) mag, as well as the blue boundary of the extended MS TO and the compact RC; see Figure 3 (blue isochrone). We use the isochrone database of Bertelli et al. (2008, 2009), obtained from the YZVAR interactive Web service, specifically to generate isochrones for different helium abundances. However, this database cannot be used to generate isochrones in the HST/Advanced Camera for Surveys (ACS)–High-Resolution Camera (HRC) photometric system. Following Sirianni et al. (2005) we convert the ACS–HRC isochrones to the HST/WFPC2 system.

However, even if we increase the helium abundance to $Y = 0.40$, the corresponding isochrone still hardly contributes to the generation of an extended TO (in combination with the $Y = 0.26$ isochrone). More importantly, isochrones characterized by $Y = 0.40$ define a clearly bluer MS than the equivalent $Y = 0.26$ isochrones, and a redder RC, but the observed narrow MS and compact RC invalidate any suggestion of a significant spread or significant inhomogeneities in helium abundance.

Next, we explore whether the age-dispersion model—for the same $Y, Z$ chemical abundance—can satisfactorily match our observational data. We use the Bressan et al. (2012) isochrones to match the decontaminated CMDs because these isochrones are up to date and include the HST/WFPC2 filter set (as opposed to the Bertelli et al. 2008, 2009, isochrones used above). First, we focus on the extended MS TO region. For most intermediate-age LMC clusters, the age-dispersion model has been used to show that their extended MS TOs can be described accurately by two isochrones with an age difference of $\sim 300$ Myr. We determine the isochrones that best match the blue (younger) and red (older) outer boundaries of the

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1. A clear, well-defined MS crosses the NGC 1831 CMD from $V \sim 21.0, (V-I) \sim 0.35$ mag (for NGC 1868, the equivalent values are $V \sim 21.5, V-I \sim 0.4$ mag) to the “bottom” of the CMD ($V \sim 27.0$ mag, i.e., close to detection limit).

2. For approximately $V \in [21.0, 24.0]$ mag ($V \in [21.5, 24.0]$ mag for NGC 1868), the CMD exhibits a lower-density, extended envelope to redder colors and (up to 0.752 mag) brighter magnitudes (see below), which is mainly composed of unresolved binary systems (for more details, see Rubenstein & Bailyn 1997; Elson et al. 1998; Hu et al. 2010; de Grijs et al. 2013; Li et al. 2013). The properties of this “binary envelope” allow us to estimate reliable binary fractions for our two sample clusters, which we use as an input parameter in our analysis.

3. For $V \lesssim 21.0$ (21.5) mag, the MS broadens and the distinct boundary between the MS and its binary envelope disappears. The MS turns into an extended MS TO region. The color dispersion of the MS TO region reaches $\gtrsim 0.2$ mag, which cannot be simply owing to photometric uncertainties.

4. Both NGC 1831 and NGC 1868 show a RC that is extended in magnitude but compact in color: $V, (V-I) \sim [18.2-19.2, \sim 0.9]$ mag for NGC 1831 and $V, (V-I) \sim [18.7-19.7, \sim 0.9]$ mag for NGC 1868.

To quantitatively estimate the effects of helium-abundance variations, we first use an isochrone characterized by the standard helium abundance, $Y = 0.26$, to obtain an adequate, visual fit to the observed CMD. We only take NGC 1831 as an example here, because we will show that assuming a dispersion in helium abundance is inconsistent with the observed, narrow MS; in fact, for NGC 1868 we find the same inconsistency. For NGC 1831, we adopt an age of $\log(t \text{ yr}^{-1}) = 8.80$ here (we will vary the cluster age in the remainder of our analysis), a metallicity of $Z = 0.012$ (where $Z_0 = 0.019$), which is identical to that derived by Kerber & Santiago (2005a), and a total extinction of $E(B-V) = 0.03$ mag. Our adopted age is within the range quoted by Kerber & Santiago (2005b), $8.70 \leq \log(t \text{ yr}^{-1}) \leq 8.95$, while our extinction estimate is consistent

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**Figure 2.** Projected azimuthal stellar number-density profiles for (top) NGC 1831 and (bottom) NGC 1868, corrected for incompleteness and only based on stars with magnitudes brighter than the relevant 50% completeness limits. Black solid lines: field-star levels. Black vertical dashed lines: radii where the cluster densities disappear into the relevant field levels.

**Figure 3.** NGC 1831 CMD, combined with the best-fitting $Y = 0.26$ isochrone (blue) and the corresponding $Y = 0.40$ isochrone (red).

(A color version of this figure is available in the online journal.)

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[4] http://stev.oapd.inaf.it/YZVAR/cgi-bin/form

[5] See their Equation (12), Tables 11 and 21.
NGC 1868.

of the regions covering the extended MS TOs of (left) NGC 1831 and (right) presumably single) MS stars. For NGC 1831, both isochrones cross at \([V, (V - I)] \sim [21.0, 0.35]\) mag \((V, V - I) \sim [21.5, 0.40]\) mag for NGC 1868). The best-fitting age dispersion for NGC 1831 covers the range from \(\log(t \, \text{yr}^{-1}) = 8.74\) to 8.92, i.e., roughly 280 Myr. For NGC 1868, the age range covered runs from \(\log(t \, \text{yr}^{-1}) = 8.93\) to 9.07, again indicating a potential age dispersion of roughly 320 Myr. Thus, the age dispersion implied by our isochrone fits is consistent with the average age dispersion reported previously for intermediate-age LMC clusters \((\sim 300\) Myr).
distribution in the MS TO regions should reflect the stellar populations’ age distributions. For example, double MS TOs may indicate the occurrence of two distinct starburst events, while extended MS TOs would be more appropriately described by a scenario based on continuous star formation. To constrain the clusters’ age distributions, we explored the “pseudocolor” distributions of the stars found near the MS TOs as follows:

1. We defined a region containing a subset of MS TO stars that are not contaminated by subgiant stars. The adopted young and old isochrones define the magnitudes and colors of their respective MS TO points, which we connected using a straight line. Using this line as one boundary to the region of interest, we slide the young MS TO to a locus that is close to the blue boundary defined by the MS TO stars. From this point, we generate a roughly tangential final boundary coincident with the blue envelope of the MS TO stars; see Figures 5 and 6. We explored a number of options to define the most appropriate region for our analysis of the presence of a possible age gradient, ranging from thin, ≲0.5 mag-wide “shells” along the pseudocolor vector similar to those adopted by Goudfrooij et al. (2011) to the full extent of the regions indicated in Figures 5 and 6. The resulting pseudocolor distributions also exhibit broad red wings. Part of this broadening may be owing to the presence of unresolved binaries. In the selected regions in Figures 5 and 6, different isochrones cover different pseudocolors. One can define a range of ages in order to explore the possible presence of an age gradient across the regions. In Figure 7, we show the results for four appropriate distinct ages (see labels), which divide the entire allowed age dispersion into four roughly equal ranges. Note that the isochrones in the selected region are not exactly straight lines, so that these distinct age steps are only indicative of the positions of the theoretical ridgelines represented by the isochrones labeled.

2. For each star in this region, we calculate their minimum “distance” to the region’s left-hand boundary, which is tangent to the blue edge of the extended MS TO region (see the black dashed lines in Figures 5 and 6). This distance represents the pseudocolor for each MS TO star.

3. Finally, we obtained the distribution of the stars in this region along the pseudocolor direction, normalized to the total number of stars in the region.

The resulting pseudocolor distributions are shown in Figure 7. For both clusters, the MS TO stars’ pseudocolor spread can reach 0.6–0.8 mag, which again cannot be simply due to photometric uncertainties (see Figure 8). Both clusters show clear peaks in their pseudocolor distributions, at ~0.30 mag and 0.18 mag for NGC 1831 and NGC 1868, respectively. The pseudocolor distributions also exhibit broad red wings. Part of this broadening may be owing to the presence of unresolved binaries. In the selected regions in Figures 5 and 6, different isochrones cover different pseudocolors. One can define a range of ages in order to explore the possible presence of an age gradient across the regions. In Figure 7, we show the results for four appropriate distinct ages (see labels), which divide the entire allowed age dispersion into four roughly equal ranges. Note that the isochrones in the selected region are not exactly straight lines, so that these distinct age steps are only indicative of the positions of the theoretical ridgelines represented by the isochrones labeled.

At the distance to the LMC, most binary systems in compact clusters are unresolved in observations with current instruments. The magnitudes of these unresolved binary systems will thus be composed of the coadded fluxes of the individual components:

$$m_b = -2.5\log(10^{-0.4m_1} + 10^{-0.4m_2}),$$

where $m_1$ and $m_2$ are the component magnitudes. Binaries that are composed of two identical components will exhibit the same color but be brighter by 0.752 mag than the individual stars themselves. Unresolved binaries composed of individual member stars that are not identical will exhibit shifts in both color and magnitude. The resulting color will be redder than that of the primary star but bluer than that of the secondary component.

In this article, the approach we used to determine the clusters’ binary fractions is similar to that employed by Milone et al. (2011). In Figure 9, we take NGC 1868 as an example. For unresolved binaries characterized by different mass ratios—$q = m_2/m_1$—the resulting photometry will be biased to brighter...
magnitudes and redder colors as \( q \) increases from 0 to 1, thus resulting in a statistical broadening of the MS toward the brighter and redder side (see also Hu et al. 2010; Milone et al. 2011; de Grijs et al. 2013; Li et al. 2013). For the brightest section of the MS, the possible presence of an age dispersion will blur any features due to binarity, so the bright magnitude range cannot be used to determine the clusters’ binary fractions. The faintest section of the observed MS is not an ideal range to explore the quantitative contributions of binaries either because the prevailing large(r) photometric uncertainties cause contamination due to a mixture of single stars and binaries.

Thus, we can only use MS stars of intermediate magnitudes to determine the binary fractions. For NGC 1868, we only select primary stars between \( V = 21.6 \) mag and 22.2 mag for further analysis of their binary populations. For NGC 1831, the equivalent magnitudes range from \( V = 21.4 \) mag to 21.9 mag. HSTPHOT also yields the photometric uncertainties for all stars. We use an exponential function of the form \( \sigma(m) = \exp(a \times m + b) + c \) to fit the photometric uncertainties as a function of stellar magnitude, following Hu et al. (2010) and Li et al. (2013). The best fit is shown in Figure 8. Using the equation thus obtained, we adopt as the blue boundary of the MS range for further analysis the locus of the best-fitting isochrone, adjusted by the prevailing \(-3\sigma\) photometric uncertainties of the stellar distribution in the relevant magnitude range (see Figure 9). We show “binary isochrones” for different mass ratios, from \( q = 0 \) to unity (corresponding to the single-star isochrone shifted by \(-0.752\) mag). The locus of the \( q = 1 \) binary isochrone +3\( \sigma \) uncertainty is the red boundary of the region of interest for this analysis (see Figure 9). Both boundaries, as well as the black solid lines connecting the different values of \( q \), define the region we used to count binaries and single stars.

Because of the prevailing photometric uncertainties in de Grijs et al. (2013) and Li et al. (2013), we adopted \( q = 0.55 \) as the critical locus to distinguish between single stars and binaries. In this article, we increase this threshold to \( q = 0.6 \) (see the dark green line in Figure 9) because the MS magnitude range of interest is fainter than that used by both de Grijs et al. (2013) and Li et al. (2013). Finally, adopting the constraints given by the black solid lines, we adopted stars located within the region from \(-3\sigma\) of the best-fitting isochrone to the \( q = 0.6 \) binary isochrone as single stars (shown as the blue dots in Figure 9), while stars that lie beyond the \( q = 0.6 \) binary isochrone but with colors bluer than the \( q = 1.0 \) isochrone +3\( \sigma \) were assumed to be binaries (the red dots in Figure 9). The binary fraction resulting from this procedure, \( f_b = N_b/(N_b + N_s) \), is 29.2\% for NGC 1831 and 33.5\% for NGC 1868. These values are similar to those of Sollima et al. (2010), who analyzed five Galactic open clusters using a similar approach as adopted in this paper, and found cluster core binary fractions between 11.9\% and 34.1\%. These fractions are, however, significantly higher than those of Milone et al. (2012), who derived the (core) binary fractions of 59 Galactic GCs. Their maximum core binary fraction only reaches 17\%. This is because they mainly investigated old GCs so that primordial binaries would likely have been disrupted. Indeed, in Li et al. (2013, their Figure 8) we found binary fractions (for a similar magnitude range) of \(-35\%\) and \(30\%\) for the young massive clusters NGC 1805 and NGC 1818, respectively.

Note that these binary fractions only apply to \( q \geq 0.6 \) binaries. Occasional blending of stars along the line of sight will
introduce a small bias. We assume a flat mass-ratio distribution and use a Monte Carlo method to correct for this blending bias (for more details, see Hu et al. 2010; de Grijs et al. 2013; Li et al. 2013). This leads to a final estimate of the total binary fraction, for all mass ratios, of 67.2% for NGC 1831 and 76.9% for NGC 1868.

In the following simulation, we simply assume binary fractions of 70% for NGC 1831 and 75% for NGC 1868. Even though the estimated binary fractions are strictly only valid for the magnitude range from $V = 21.4$ (21.6) mag to $V = 21.9$ (22.2) mag for NGC 1831 (NGC 1868), we make the assumption that these values represent the global binary fractions, i.e., the binary fractions characterizing the clusters as a whole (see below). Adoption of the observational level of photometric noise will cause faint binaries with low $q (q \leq 0.6)$ to almost all mix with and become indistinguishable from single stars. For the TO region, the observed age dispersion blurs the expected broadening owing to the presence of binaries. We checked that the simulated luminosity function is similar to its observed counterpart, which hence implies that our adoption of the measured binary fractions as representative of the clusters as a whole is appropriate.

We next performed simulations of clusters characterized by different age dispersions and binary fractions. For both NGC 1831 and NGC 1868, we simulated a series of clusters with different ages but characterized by the same binary fractions. Our simulated clusters have similar numbers of member stars, binary fractions, and extended TOs as the observed clusters. We subsequently employed the same approach as illustrated in Figures 5 and 6 to find the pseudocolor distribution of the simulated MS TO stars. By adjusting the stellar age distributions of the simulated clusters, we determined the distributions that most closely reproduce the observed pseudocolor distributions. Figures 10 and 11 show the best-fitting simulated cluster CMDs.
for NGC 1831 and NGC 1868, respectively. The relevant adopted input parameters are summarized in Table 1.

The resulting pseudocolor distributions for the simulated clusters equivalent to NGC 1831 and NGC 1868, as well as a comparison with the observations (Figure 7), are shown in Figure 12. The corresponding best-fitting age distributions for our two clusters are displayed in Figure 13. For NGC 1831, the best-fitting age distribution peaks at \( \log(t/\text{yr}) = 8.80 \), with gradual decreases toward either side. The age distribution pertaining to NGC 1868 does not exhibit a clear peak but instead shows a gradual decrease from \( \log(t/\text{yr}) = 9.07 \) to 8.93. We quantify the similarities of the observed and simulated pseudocolor distributions using a Kolmogorov–Smirnov (K–S) test.\(^6\) Our K–S evaluation shows that the simulated pseudocolor distributions are indeed drawn from the same underlying distributions \( (H = 0) \), for both clusters. For both NGC 1831 and NGC 1868, the K–S test returns \( P = 74\% \). Figure 12 shows that the simulated pseudocolor distribution pertaining to the NGC 1831 simulation (top panel) almost perfectly fits that of the observed sample. For NGC 1868, a small offset is seen on the red side. Nevertheless, across the full range, the K–S test implies that the distributions are indiscernible for both clusters.

The compactness of the RC offers another tight constraint in the context of the age-dispersion model. Any age dispersion would also affect the size of the observed RC. Therefore, we further explored the quality of our isochrone fits to the RC region. In Figure 14, we display the corresponding, zoomed-in regions centered on the RC. For NGC 1831 (left-hand panel), we found that a dispersed star-formation history would lead to a relatively large spread in the RC in the magnitude direction. However, the compact size (in CMD space) of the observed RC further constrains the cluster’s maximum age dispersion to fall within the range \( 8.74 \leq \log(t/\text{yr}) \leq 8.81 \). Clearly, the oldest isochrones we have adopted based on the NGC 1831 MS spread, \( \log(t/\text{yr}) = 8.92 \), cannot fit the compact, observed RC. However, based only on our analysis of the extent of the MS TO region, Figure 13 indicates that a significant fraction of the cluster’s stellar population may have ages \( \log(t/\text{yr}) \geq 8.81 \). This apparent conflict renders applicability of the age-dispersion model for NGC 1831 uncertain. The right-hand panel of Figure 14, which shows the equivalent analysis for the NGC 1868 RC, implies that the age-dispersion model provides a more consistent picture for NGC 1868.

In summary, if we adopt the age-dispersion model, it is not difficult to reproduce the observed MS TOs in detail. We only need to carefully adjust the clusters’ internal age distribution. However, the observed size of the RC in CMD space imposes an additional constraint on the most appropriate age range so that the relevant age (age range) of our sample clusters is not a completely free parameter.

4. FAST STELLAR ROTATION

The main effect of rapid stellar rotation in the context of our CMD-based analysis can be summarized as follows:

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\(^6\) The K–S test returns two values, \( H \) and \( P \). \( H \) can only attain the two concrete values 0 and 1, which depend on the null hypothesis that the two underlying samples are independent. If \( H \) is returned as 0, the null hypothesis is rejected, which means that the two samples are drawn from the same distribution. \( P \) represents the \( p \) value, which indicates the probability that the two samples are drawn from the same underlying population.
1. The centrifugal force associated with rapid rotation only partially balances a star’s self-gravity, which thus causes the star to expand. The expansion reduces the star’s temperature, which in turn renders its observed color redder than that of its nonrotating counterparts.

2. The reduced gravity also decreases the star’s core pressure, which reduces the amount of nuclear energy released (Faulkner et al. 1968), and thus the observed rapidly rotating star becomes relatively fainter than the equivalent nonrotating stars.

3. Rotation affects the sizes of stellar convective cores. Increased convective core sizes will prolong the stellar MS lifetime (Maeder & Meynet 2000; Yang et al. 2013).

Bastian & de Mink (2009) first suggested that extended TOs could be explained by rapid stellar rotation, while Yang et al. (2013) suggested that the broadening of the TOs depends on a cluster’s intrinsic age. However, neither of these authors directly compared their results with observations. Li et al. (2012) compared simulated CMDs that included rapidly rotating stars with the observed CMDs of NGC 1846 and NGC 1987 (Mackey et al. 2008; Milone et al. 2009). They claimed that fast rotation is necessary to reproduce the observations. However, their comparison was only based on the perceived similarities of their model CMDs to observational counterparts (they do not directly compare their model CMDs with observed CMDs; they merely refer the reader to published observational CMDs). In this article, we directly and quantitatively compare simulated CMDs to our observational data.

In our simulations, we first assume a single age for the observed stars. We opted to select the “youngest age” that we used in the age-dispersion model because fast rotation results in redder and fainter stars. Following Bastian & de Mink (2009), stars less massive than 1.2 $M_\odot$ are assumed to lack significant rotation because of magnetic braking (Schatzman 1962; Mestel & Spruit 1987). Stars that have evolved off the MS do not rotate rapidly either, even if they originally rotated rapidly, because the expansion associated with the SGB and RGB evolutionary phases slows down their rotation velocity because of conservation of angular momentum. Since fast rotation only affects MS stars that are more massive than 1.2 $M_\odot$, this effect will not broaden either the faint section of the MS or the compact RC.

In the age-dispersion model, the age distribution determines the observed pseudocolor distribution. For the fast-rotation model, the distribution of the stellar rotation velocities is the operational parameter. However, this distribution cannot be taken at will, although the exact distribution of rotation velocities is as yet unknown for cluster stars.

Royer et al. (2007) analyzed the rotation velocities of 1100 late-B to late-F-type stars. They found that the rotation velocities of FO–F2-type stars typically peaks at both $\omega \sim 0.1$ and 0.5 (their Figure 10), where $\omega = \Omega/\Omega_c$ is the fraction of the critical break-up rotation rate. They find that the peak at $\omega = 0.1$ is sharper than the peak at $\omega = 0.5$. The latter peak also exhibits a broadening toward higher rotation rates. Bastian & de Mink (2009) artificially assumed a Gaussian distribution of rotation velocities with a peak at $\omega = 0.4$. They excluded stars with $\omega \geq 0.7$ because above this value the assumptions in the (one-dimensional) stellar evolution code start to break down. In this article, we adopt the $\omega$ distribution of Royer et al. (2007). We do not impose any threshold on $\omega$, except that we limit $\omega$ to be less than unity (otherwise stars will become unstable and are disrupted by the centrifugal force), but we note that the fraction of stars with $\omega \geq 0.7$ is only 2.5% (74 out of 3500 stars). We assume that the rotation velocities peak at both $\omega = 0.1$ and 0.5, and that these peaks host 20% and 80% in number of the stellar sample, respectively. The standard deviations corresponding to both peaks are 0.05 and 0.15, respectively. Figure 15 shows the probability distribution adopted for $\omega$. Our adopted $\omega$ distribution is similar to that of F-type stars (Royer et al. 2007).

Stellar rotation velocities are mass dependent. We assume that the rotation velocities increase linearly for stars with masses from 1.2 $M_\odot$ to 1.65 $M_\odot$ (Bastian & de Mink 2009). Stars more massive than 1.65 $M_\odot$ are assumed to be fast rotators, with $\omega$ distributed according to Figure 15. Stars with masses between 1.2 $M_\odot$ and 1.65 $M_\odot$ follow the same $\omega$ distribution, adjusted by a factor between 0 (for a stellar mass of 1.2 $M_\odot$) and 1 (for 1.65 $M_\odot$). Stars less massive than 1.2 $M_\odot$ are assumed to be nonrotating.
Figure 15. $\omega$ (fraction of the critical break-up rate) distribution of rotating stars, with double Gaussian peaks at 0.10 and 0.50, and standard deviations of 0.05 and 0.15, respectively.

Figure 16. Steps to generate our simulated NGC 1831 CMD. From left to right: (a) Step 1, we generate stars that exactly match the parameters given by the adopted isochrone. (b) Step 2, for stars more massive than $1.2 M_\odot$, we randomly assign rotation velocities, based on the $\omega$ distribution of Figure 15. (c) Step 3, we assign “binary status” to 70% of the artificial stars and adjust their photometry based on the adopted binary properties. (d) Step 4, we adopt the appropriate photometric uncertainties according to Equation (1).

Following Bastian & de Mink (2009), the stellar temperatures and luminosities modified by rotation are given by

$$T_{\text{eff}}(\omega)/T_{\text{eff}}(0) = 1 - a\omega^2,$$

and

$$L_{\text{eff}}(\omega)/L_{\text{eff}}(0) = 1 - b\omega^2,$$

where $a$ and $b$ cover the ranges 0.17–0.19 and 0.03–0.07, respectively, during MS evolution. Since it is not fully understood how rotation affects stars at the masses of interest, these predicted range are uncertain. Therefore, we adopt the average values, $a = 0.18$ and $b = 0.05$, respectively, and emphasize caution in their use at face value. First, we generate a population of stars that exactly match the isochrone. For stars more massive than $1.2 M_\odot$, we randomly adopt a rotation velocity drawn from the assumed $\omega$ distribution (Figure 15). We subsequently calculate the resulting stellar temperature and luminosity, based on our adopted theoretical isochrone set, and convert these values to a color and magnitude based on the theoretical isochrone set. We also select some of the stars thus generated as the primary components of unresolved binary systems. By adopting a flat mass-ratio distribution, we correct their magnitudes and colors according to Equation (1). Finally, we adopt the appropriate photometric uncertainties to mimic the observed CMD. Figure 16 illustrates our procedure for NGC 1831.

In Figures 17 and 18, we show the simulated clusters’ CMDs, as well as their observed counterparts. Following our approach as applied to the age-dispersion model, we again explore the pseudocolor distributions for both simulated CMDs (cf. Figures 7 and 6). Figure 19 displays the comparison. Again, we run K–S tests on our results to quantify the degree of similarity. The null hypothesis is rejected, which implies that the fast-rotation model indeed succeeds in reproducing the observations adequately. Again, the K–S test yields a probability of 74% that the simulated distributions of both NGC 1831 and NGC 1868 have the same underlying distribution as the observations. This implies that the fast-rotation model is able to appropriately reproduce the observational data to the same extent as the age-dispersion model. This is encouraging because contrary to the age-dispersion model—where we needed to adjust the age distributions to reproduce the observations—there is no need to adopt a special $\omega$ distribution.
5. DISCUSSION AND CONCLUSIONS

We have systematically analyzed the extended TOs associated with the intermediate-age LMC clusters NGC 1831 and NGC 1868. We rule out differences in helium abundances as the cause of the extended MS TOs because of the observed narrow MS and compact RC features. Based on the observational data, we apply a carefully considered set of criteria to select possible MS TO stars for further investigation of their pseudocolor distributions. Using the age-dispersion and fast-rotation models, we generate artificial star clusters to explore which of these models best match the observations.

If we only consider the stars in the extended MS TO region, both models perform equally well. For NGC 1831, the adopted age ranges from \( \log(t \, \text{yr}^{-1}) = 8.74 \) to 8.92, corresponding to an age dispersion of \( \sim 280 \) Myr. We found that if we adopt a dominant age of (i.e., a peak in the age distribution at) \( \log(t \, \text{yr}^{-1}) = 8.80 \), with gradually decreasing wings on either side of the peak, we obtain the highest degree of similarity of the model versus observed pseudocolor distributions. For NGC 1868, it is harder to find a best-fitting model, although we still manage to find an appropriate representation: the age-dispersion model indicates an age range from \( \log(t \, \text{yr}^{-1}) = 8.93 \) to 9.07 (\( \sim 320 \) Myr). The corresponding best-fitting age distribution decreases smoothly from \( \log(t \, \text{yr}^{-1}) = 8.98 \) to 9.07. Both clusters exhibit a similar age difference, which is also consistent with the age ranges inferred for most intermediate-age clusters in the LMC. The origin of any age dispersion within such intermediate-age clusters is still unclear, however.

On the other hand, if we take the compactness (in CMD space) of the clusters’ RCs into consideration, we can set further constraints on the likely maximum age ranges appropriate for either cluster. For NGC 1868, the age-dispersion model is still consistent with the results of a model including rapid rotation, but if the fast-rotation model for NGC 1831 is correct, the corresponding age dispersion would be much smaller—\( \log(t \, \text{yr}^{-1}) = 8.74 \) to 8.81—than that inferred from the age-dispersion model.

In the context of the fast-rotation model, the \( \omega \) distributions used in previous studies have thus far remained unconstrained (Bastian & de Mink 2009; Li et al. 2012; Yang et al. 2013), in essence because the \( \omega \) distribution appropriate for cluster stars is unknown. Here we adopt the \( \omega \) distribution derived by...
If the validity of the age-dispersion model is confirmed, this may indicate that some dramatic events have occurred on a global scale across the LMC. Intermediate-age clusters that are located in close proximity of each other should have experienced similar star-formation histories. Both NGC 1831 and NGC 1868 are located on the same side of LMC, close together in the same (fourth) quadrant, with a projected distance of less than 1.25 kpc. However, the age ranges inferred for NGC 1831 and NGC 1868 do not overlap, and even their age distributions appear to differ significantly. In this article, we found that the fast-rotation model satisfactorily reproduces the observations. However, it is unclear whether the ω distribution adopted from Royer et al. (2007) is realistic for cluster stars. This provides an incentive for future work in this area. We also note that even though most observed intermediate-age LMC clusters display extended TOs, a small fraction display multiple distinct, well-defined TOs, e.g., NGC 1846 (Mackey & Broby Nielsen 2007; Milone et al. 2009), NGC 1806, and NGC 1751 (Milone et al. 2009). Clusters exhibiting such distinct MS TOs most likely include stars of different (distinct) ages, since the smoothly varying fast-rotation model cannot account for such features.

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7 Of the 16 intermediate-age LMC clusters analyzed by Milone et al. (2009), 70% ± 25% (∼11 clusters) exhibit CMD features that are inconsistent with those of simple stellar populations. Of these, three clusters show multiple distinct TOs, while the remaining eight display CMDs that are similar in nature to those of NGC 1831 and NGC 1868 discussed here. Note that our two sample clusters were not included in the study of Milone et al. (2009).