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Probing the physics of dense stellar systems in the
Large Magellanic Cloud

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Abstract

In the context of a new systematic investigation of the structural and dynamical properties of the star clusters in the Large Magellanic Cloud (LMC), this work focuses on: NGC 1835, NGC 1754, and NGC 1916. These systems are among the oldest, most massive, and most compact globular clusters (GCs) in the LMC, and their properties make them ideal laboratories to probe the interplay between stellar dynamics and cluster structure. In particular, the project aims at finally providing an explanation to the well-known *size–age conundrum*. This refers to the peculiar distribution of core radius versus age observed for the star clusters in the LMC: while young systems are all compact, old clusters span a broad range of core radii, from extremely small to very large values, despite having similar chronological ages. The most accepted interpretation of this behavior was proposed by Mackey & Gilmore (2003), who suggested an evolutionary sequence linking young and old clusters: all clusters form compact (as the young systems observed today), but then experience different degrees of core expansion due to the action of a population of stellar-mass binary black-holes (thus explaining why some old GCs are compact, while other have large core radii). More recently, however, Ferraro et al. (2019) proposed an alternative explanation in which the observed distribution of core radii as a function of chronological age for the oldest clusters is shaped by a combination of the clusters’ initial structural conditions and the effects of long-term internal dynamical evolution. In this picture, compact old clusters are expected to have undergone more advanced dynamical evolution than their more extended counterparts. Yet, in the LMC, this scenario has been tested observationally only for a limited subset of systems, mostly those with relatively large cores (Ferraro et al., 2019).

A promising way to tackle this issue is to use an empirical diagnostic that directly traces the internal dynamical evolution of a cluster. The so-called “dynamical clock” method provides exactly such a tool. It is based on the radial distribution of blue straggler stars (BSSs), which are more massive than the average cluster population and therefore progressively sink toward the center as a consequence of two-body relaxation. The degree of mass segregation is quantified by the A^+ parameter, defined as the area enclosed between the cumulative radial distributions of BSSs and that of a reference lighter population. In Galactic globular clusters, A^+ correlates tightly with the number of central relaxation times N_{relax} experienced by the system since

its formation (i.e., the ratio between the chronological age and the central relaxation time of a system). This means that A^+ provides a robust and fully empirical measure of dynamical age, with large values of this parameter corresponding to systems in advanced stages of their internal dynamical evolution. Therefore in the following we distinguish between the chronological age of a cluster, as derived from stellar evolution modeling, and its dynamical age, which reflects the number of two-body relaxation times the system has experienced since its formation.

While the “dynamical clock” method has been extensively applied and calibrated in the Milky Way, its use in the Magellanic Clouds has so far been limited to the clusters with intermediate or large core radii. As a result, the behavior of A^+ in the most compact and dynamically evolved systems remains unexplored. This project aims to fill this gap by focusing on NGC 1835, NGC 1754, and NGC 1916.

To address these goals, we performed a homogeneous analysis of high-resolution *Hubble Space Telescope* (HST) observations for the three clusters. For each system, we used Wide Field Camera 3 images in optical and near-ultraviolet filters to construct deep and precise color–magnitude diagrams (CMDs), resolve the central stellar populations, and build accurate star count density profiles. By fitting these profiles with single-mass, isotropic King models, we derived structural parameters such as core radius, half-mass radius, and tidal radius. In addition, we determined their chronological ages through isochrone fitting based on the morphology of the main sequence turn-off and subgiant branch, and we measure their internal dynamical ages both from the central relaxation time and from the BSS radial distribution where possible.

The results confirm the extreme compactness and ancient ages of all three clusters. For NGC 1835, we derived a chronological age of $t = 12.5 \pm 1$ Gyr and measured a core radius of $r_c = 0.84$ pc. For NGC 1754, the derived age is $t = 12.8 \pm 0.4$ Gyr, with $r_c = 0.84$ pc. NGC 1916 turns out to be the oldest cluster in the sample, with $t = 13.0 \pm 0.5$ Gyr and an exceptionally small core radius of $r_c = 0.46$ pc. These values place the three systems among the most compact and dynamically old in the entire LMC cluster system.

A first analysis of the dynamical age can be carried out through the value of their central relaxation time. The logarithmic central relaxation times derived for the three systems are $\log(t_{rc}/\text{yr}) = 8.16$ for NGC 1835, 7.97 for NGC 1754, and 7.58 for NGC 1916. These very low values confirm that all the three clusters have experienced a large number of relaxation cycles during their lifetimes, consistent with their compact structure and advanced dynamical state. Among them, NGC 1916 shows the shortest central relaxation time, in agreement with its exceptionally small core radius.

The dynamical clock analysis yielded very high values of the A^+ parameter for NGC 1835 and NGC 1754, indicating strong central segregation of BSSs and there-

fore advanced dynamical ages, fully consistent with their compact structure and the large number of central relaxation times they have experienced. The measured values are $A^+ = 0.30$ for NGC 1835 and $A^+ = 0.31$ for NGC 1754. When placed in the $N_{\text{relax}}-A^+$ plane, NGC 1835 and NGC 1754 fall on the same tight correlation defined by Galactic globular clusters and other Magellanic Clouds systems, demonstrating that the dynamical clock is a robust indicator of internal dynamical age that can be used also outside the Milky Way. Similarly, in the r_c-A^+ plane they follow the observed anticorrelation, with smaller core radii corresponding to larger A^+ values.

For NGC 1916, however, the measurement of A^+ was not feasible due to severe field-star contamination in the BSS region, significant incompleteness in the cluster centre, and strong differential reddening. These effects severely affect the reliability of the BSS selection, preventing a meaningful determination of the A^+ parameter for this cluster. For NGC 1916, we must therefore rely on its central relaxation time as a dynamical age indicator.

These findings provide clear observational support to the scenario in which the present-day structural properties of old LMC clusters are the result of their different internal dynamical evolutionary stages. At the same time, they validate the dynamical clock method in a new galactic environment, extending its applicability to the most compact and dynamically evolved clusters in the LMC.

CHAPTER 1

Introduction

1.1 Globular clusters

Globular clusters (GCs) are gravitationally bound systems composed of about $10^5 - 10^6$ stars, distributed in a nearly spherical symmetry around the center of the cluster, where stellar densities can become extremely high. These systems are ubiquitous in large galaxies and provide unique opportunities for studying stellar evolution, since individual stars can be resolved in nearby clusters such as those in the Milky Way (MW), the Small and Large Magellanic Clouds (SMC and LMC), and Andromeda. In the Milky Way, galactic globular clusters (GGCs) are primarily found in the halo and bulge regions. There are about 150 known GGCs (Harris, [1996](#), [2010 edition](#)), all of which are very old systems with estimated ages ranging between 10 and 13 billion years (see, e.g. Gratton et al. [1997](#); Chaboyer et al. [1998](#)). Most of these clusters are metal-poor stellar systems, generally exhibiting metallicities of $[Fe/H] \leq -1$.

To a first approximation, they represent an excellent example of a simple stellar population (SSP, Renzini & Buzzoni [1986](#)), i.e. a stellar population born from a single episode of star formation and therefore characterized by stars of the same age and chemical composition. However, this traditional picture has been challenged by recent observations, which reveal that many globular clusters host multiple stellar populations. These populations show significant star-to-star variations in the abundances of light elements such as sodium (Na), oxygen (O), carbon (C), nitrogen (N) and helium (He) (Kraft, [1994](#); Gratton et al., [2004](#), [2012](#); Milone et al., [2017](#)). Despite these differences, stars within a given cluster are generally chemically homogeneous in terms of iron content (Carretta et al., [2009](#)).

The distinctive characteristics of globular clusters make them exceptionally valuable astrophysical laboratories across a broad spectrum of research topics. They offer a robust framework for testing stellar evolution theory and for tracing the formation and assembly history of their host galaxies. In addition, their compact structure and high stellar densities render them dynamically active systems, ideally suited for studying the impact of various dynamical processes (such as mass segregation, core collapse, and stellar interactions) on stellar evolution.

1.2 Structural Properties

With their high stellar densities and frequent gravitational encounters, globular clusters constitute prime laboratories for examining dynamical processes. The internal dynamical evolution of globular clusters is primarily driven by gravitational interactions between individual stars. Through frequent two-body encounters, stars continuously exchange energy, leading the system toward a state of dynamical relaxation in which the original conditions of the cluster are gradually erased (Binney & Tremaine, 1987; Meylan & Heggie, 1997). In the approximation of a system composed of N stars with an equal mass, the two-body relaxation time can be roughly expressed as (Binney & Tremaine, 1987):

$$t_{2b} = \frac{0.1N}{\ln(N)} t_{cross}, \quad (1.1)$$

where $t_{cross} = R/v$ is the crossing time, hence the time needed for a star with velocity v to cross a system with radius R . A system whose age is much longer than its relaxation time is termed a “non-collisional” system, meaning that the effects of individual stellar encounters are minimal and the system’s evolution is primarily determined by its global gravitational potential. In such a system, dynamical processes act too slowly to erase the system’s initial conditions. In contrast, a system whose age is comparable to or less than its central relaxation time is called a “collisional” system, in which close encounters between stars play a significant role and can drive the evolution of the system’s structure over time. Globular clusters, characterized by $N \sim 10^5$ and $t_{cross} \sim 10^5$ yr, have a relaxation time of $t_{2b} \sim 0.1$ Gyr, much shorter than their typical ages of 10–13 Gyr. This makes them prime examples of collisional systems. On the other hand, galaxies typically contain about $N \sim 10^{11}$ stars and are only a few hundred crossing times old. As a result, interactions between individual stars have little influence on their overall structure and evolution, except in the dense central regions where such encounters can play a more important role.

However, this is only an approximation, since the relaxation time depends in a complex manner on both the system’s internal properties (e.g., stellar density and mass) and external environmental factors (e.g., distance from the dense central regions of the host galaxy). Consequently, the relaxation time can vary not only between different clusters, but also across different regions within a single cluster. To account for this spatial variation, it is therefore useful to define specific relaxation times for distinct parts of the cluster. Following the expression by Djorgovski (1993), we can define the central relaxation time in years as:

$$t_{rc} = 1.491 \times 10^7 \times \frac{k}{\ln(0.4N_*)m_*} \rho_{M,0}^{1/2} r_c^3, \quad (1.2)$$

where the constant $k \sim 0.5592$, $N_* = M_{cl}/m_*$ is the number of stars in the cluster of mass M_{cl} , m_* is the average stellar mass, $\rho_{M,0}$ is the central mass density in units of $M_\odot \text{ pc}^{-3}$, r_c is the core radius in parsecs, and t_{rc} is expressed in years. Similarly, we can define the half-mass relaxation time in years as:

$$t_{rh} = 8.933 \times 10^5 \times \frac{k}{\ln(0.4N_*)m_*} M_{cl}^{1/2} r_h^{3/2}, \quad (1.3)$$

where r_h is the half-mass radius in parsecs, and all other quantities are as previously defined.

As collisional systems, globular clusters experience random exchanges of kinetic energy among their stars, which gradually relax the velocity distribution. Over time, this process drives the system toward a Maxwellian velocity distribution with a high-velocity cutoff corresponding to the escape velocity, reflecting the gradual loss of stars that exceed this limit. The family of King models (King, 1966) provides the best representation of this dynamical behavior. King models can be expressed mathematically as follows:

$$f(E) = \begin{cases} C \left(e^{-E/\sigma^2} - 1 \right) & \text{if } E < 0 \\ 0 & \text{if } E \geq 0 \end{cases}, \quad (1.4)$$

C is a constant related to the density, σ represents the velocity dispersion, and E is the total energy per unit mass. The total energy can be expressed as $E = v^2/2 + \Psi(r)$, where v is the stellar velocity and $\Psi(r)$ is the gravitational potential energy, which by construction is set to zero at the so-called truncation radius r_t . Stars located within r_t are gravitationally bound to the cluster and have negative total energy, whereas stars with positive energy are unbound and lie outside this radius.

King models are single-parameter models that accurately describe the radial behavior of various observable properties of globular clusters, such as the surface brightness profile, the density profile and the velocity dispersion profile. The shape of a King model is uniquely determined by a single parameter, either W_0 , a dimensionless quantity proportional to the central potential, or the concentration parameter c . The latter quantity can be expressed as

$$c = \log(r_t/r_0), \quad (1.5)$$

where r_t is the truncation radius (already mentioned above) and r_0 is a characteristic scale length of the model commonly called King radius and defined as:

$$r_0 = \sqrt{\frac{9\sigma^2}{4\pi G\rho_0}}, \quad (1.6)$$

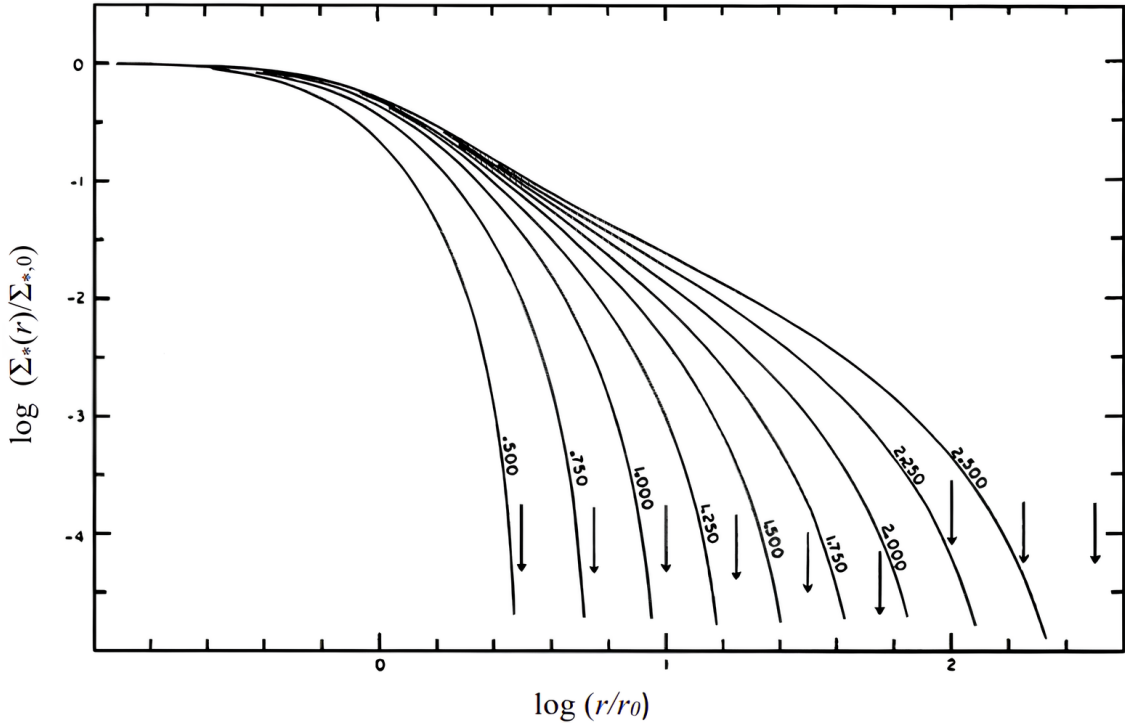


Figure 1.1: Example of different King models. The x-axis shows, in logarithmic units, the distance from the center, r , normalized by the characteristic radius r_0 ; the y-axis shows the surface density, normalized by its central value. The numbers corresponding to each curve are different values of $c = \log(r_t/r_0)$. The arrows indicate the value of $\log(r_t)$. Image taken from King (1966).

where σ is the velocity dispersion, G is the gravitational constant and ρ_0 is the central density.

Among the characteristic quantities of the structure of globular clusters, we can also add the following: the core radius r_c , defined as the radius at which the projected density (or surface brightness) drops to half its central value; the half-mass radius r_h , which encloses half of the cluster's total mass; the half-light radius r_{hl} , containing half of the total luminosity; and the effective radius, corresponding to the projected distance from the center that encompasses half of the total number of stars.

Figure 1.1 displays examples of King models with different values of c , illustrating the typical behavior of these profiles: a flat, central core region followed by a steady decline at larger radii.

1.3 Dynamical evolution

GCs undergo a crucial phase of early evolution during their first few million years, primarily shaped by the effects of stellar evolution. This initial phase is marked by the expulsion of residual primordial gas, left over from star formation, driven by stellar winds from massive stars and Type II supernova explosions. This early

mass loss, particularly in clusters with low initial concentration or strong mass segregation, can induce significant structural expansion and potentially lead to rapid dissolution. Semi-analytical models (e.g., Applegate 1986; Chernoff & Shapiro 1987), Fokker–Planck calculations (Chernoff & Weinberg, 1990), and N-body simulations (e.g., Fukushige & Heggie 1995; Vesperini et al. 2009) consistently show that such systems may evolve into configurations where virial equilibrium is no longer sustainable, resulting in the rapid disruption of the cluster.

For clusters surviving early dissolution, structural evolution is driven by two-body relaxation. Due to frequent interactions between stars, the cluster moves towards a condition of energy equipartition. Lighter stars tend to increase their velocities and drift toward the outskirts of the cluster. In some cases they exceed the escape velocity and are ejected from the system, in a process called “evaporation” (Meylan & Heggie, 1997). In contrast, more massive stars lose kinetic energy and slow down due to the action of dynamical friction, gradually sinking toward the central regions of the cluster. Dynamical friction is an effect arising from the gravitational interaction between a massive object and the background of lighter stars through which it moves. As the massive star travels through the cluster, it perturbs the surrounding stellar distribution, creating an overdense gravitational wake behind it. The pull from this wake acts as a drag force opposite to the direction of motion, causing the object to lose kinetic energy and slowly spiral toward the cluster center.

As the core density increases, gravitational encounters become more frequent, leading to further energy loss from the core. This cycle repeats multiple times, deepening the core contraction and triggering a runaway process known as core collapse (CC). The system’s evolution toward core collapse is accompanied by progressive mass segregation, with massive stars becoming increasingly concentrated in the core. Therefore, the radial distribution of heavy objects (e.g., blue stragglers, neutron stars) can be an excellent indicator of the stage of dynamical evolution. This fundamental concept will be covered in the next section.

In the absence of an internal energy source to counterbalance the energy loss from the core, this process results in a progressively shrinking core and a central density that formally diverges within a finite time. Binary stars, either primordial or dynamically formed through close encounters between single stars, can act as an internal energy source (Heggie & Hut, 2003). During encounters between a binary star and a single star, the binary system transfers part of its binding energy to the incoming single star. This energy exchange leads to the hardening of the binary (i.e., it becomes more tightly bound), while the single star gains kinetic energy and is ejected to a wider orbit. The net outcome is an injection of energy into the cluster core. This energy release supports the cluster against further contraction, effectively reversing the collapse and leading to an expansion of the core region. More accurately, simulations reveal that clusters can undergo multiple phases of contraction

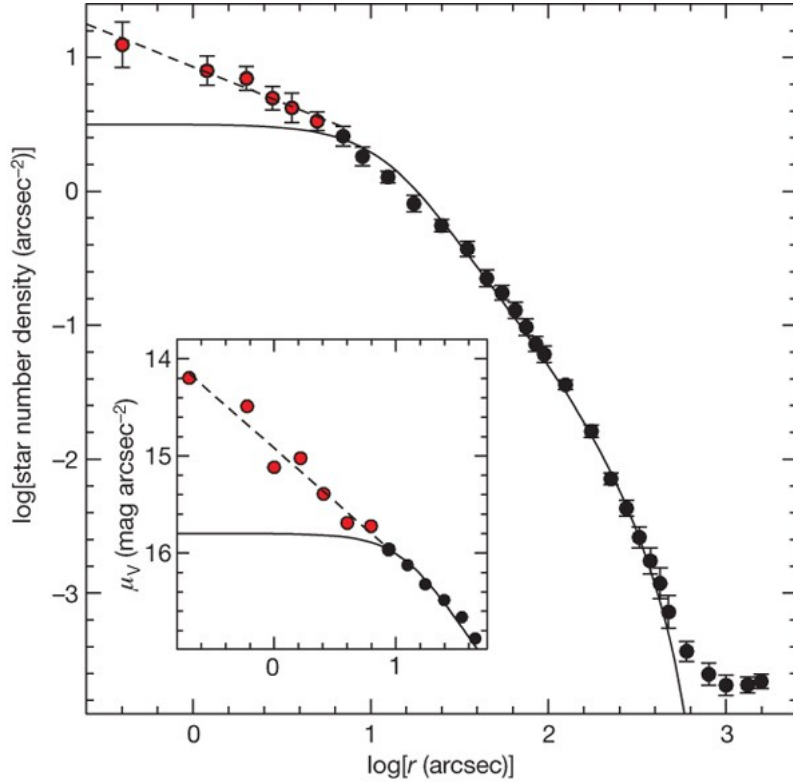


Figure 1.2: Star counts density profile of the GC M30. The best-fit King model, excluding the innermost region, is shown as a solid black line. The central data points (in red), which deviate from the King profile, are well reproduced by a power-law with a slope of $\alpha \sim -0.5$ (dashed line). The inset shows the surface brightness profile with the same behavior. Image taken from Ferraro et al. (2009).

and expansion of the core, a phenomenon known as “gravothermal oscillations” (Sugimoto & Bettwieser, 1983; Bettwieser & Sugimoto, 1984; Makino, 1996).

As a result of core collapse, classical King models, characterized by flat-density cores, fail to reproduce the inner density profiles of post-core collapse (PCC) globular clusters. Instead, these clusters exhibit a central power-law cusp in their surface brightness or density profiles (see Fig.1.2), typically following $\Sigma_*(r) \propto r^\alpha$, with slope values in the range $\alpha \sim -0.7/ -1$ (see e.g. Djorgovski & King 1984, 1986).

Observational studies (e.g. Harris 1996, 2010 edition; Trager et al. 1993) indicate that approximately 15–20% of GGCs show such cuspy profiles and are therefore classified as PCC clusters.

Although a subset of GGCs displays clear observational signatures of core collapse, the internal dynamics of dense stellar systems remains poorly understood since many more clusters should have already undergone core collapse, based on, e.g., their short central relaxation times (Chernoff & Djorgovski, 1989). However, the absence of a cusp does not necessarily imply a pre-core collapse state. During the PCC phase, gravothermal oscillations can cause the cluster’s core to cyclically contract and ex-

pand, making the central cusp shallower or even undetectable at times. Combining dynamical modeling, improved photometric resolution, and consideration of stellar populations is required to accurately assess this evolutionary stage of GCs.

1.4 Blue Straggler Stars

Following the stellar evolution theory for individual (i.e., non-binary) objects, stars spend most of their lifetime on the main sequence, where hydrogen burning occurs in the stellar core. Then, they evolve toward the red giant branch phase, which is characterized by shell hydrogen burning and a significant expansion of the stellar envelope. Following the ignition of helium burning in the core, stars settle onto the horizontal branch (HB). Depending on their initial mass, they finally evolve toward the final stages of their evolution, either exploding as core-collapse supernovae, or progressively cooling as white dwarfs. The initial mass is also the main driver of the evolutionary time-scale, with higher mass stars evolving much faster than low-mass stars. Within this framework, the position of the main-sequence turnoff (MS-TO, marking the moment when core hydrogen burning ends) provides a direct estimate of the cluster chronological age and, taking apart stellar remnants such as black holes, neutron stars, and white dwarfs, the stellar populations observed in old globular clusters are entirely made of low-mass stars (below $\sim 0.8M_{\odot}$).

Blue Straggler Stars (BSSs) represents an exception to this rule. They are a family of peculiar stars in globular clusters, first discovered by Sandage in 1953 (Sandage, 1953) in the color-magnitude diagram (CMD) and then observed in all GCs (e.g., Ferraro et al. 1992, 1997b; Piotto et al. 2004; Simunovic & Puzia 2016). They populate an extension of the cluster’s MS, occupying a region at brighter magnitudes and bluer colors than the MS-TO point (see Fig.1.3), where objects more massive (hence, younger) than the other cluster stars should lie. Constructing complete samples of BSSs in old stellar systems is far from trivial. In the optical domain, the light of globular clusters is largely dominated by bright and cool red giants (with luminosities up to a few $10^2 L_{\odot}$ and temperatures between 3500–5000 K). This makes it extremely difficult to detect fainter, hotter stars such as BSSs, especially in the highly crowded environments of cluster cores, where stellar densities can reach $10^5 - 10^6$ stars per cubic parsec. Even with the high angular resolution of the Hubble Space Telescope (HST), optical searches for BSSs in these regions are strongly affected by crowding and blending. A decisive step forward came from the use of ultraviolet (UV) observations. Because of their high surface temperatures, BSSs are among the brightest stars at UV wavelengths, where red giants become extremely faint. This naturally enhances the contrast between BSS and the bulk of the cluster population, drastically reducing contamination and crowding issues, and producing UV CMDs in which BSS appear as a nearly vertical sequence spanning more than

three magnitudes (see Fig.1.4). When combined with the superb angular resolution of the HST, UV imaging enables the construction of complete and unbiased BSSs samples even in the cores of the most concentrated clusters. This approach is widely referred to as the “UV route”. It was first developed about two decades ago (see Ferraro et al. 1992), and then successfully used in several subsequent works (e.g., Ferraro et al. 1993; Ferraro & Paresce 1994; Ferraro et al. 1995, 1997b, 1999b, 2001, 2003b, 2004; Lanzoni et al. 2007a,c; Dalessandro et al. 2008; Beccari et al. 2008, 2011). The practical application of this methodology during data reduction will be discussed in subsequent chapters.

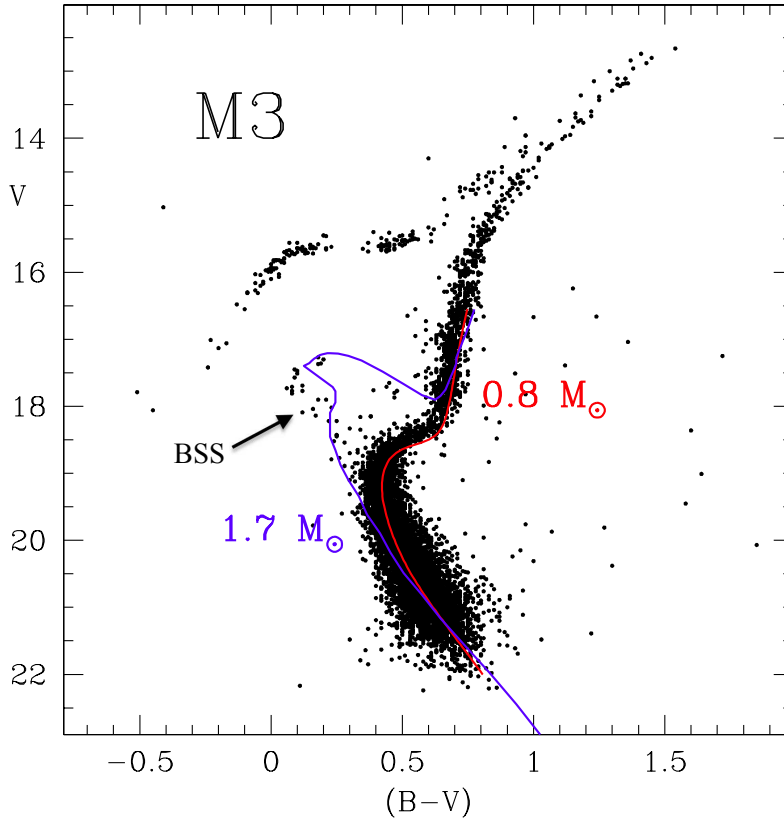


Figure 1.3: CMD of the galactic globular cluster M3. The arrow shows the position of the BSSs. The red line indicates the track corresponding to stars of mass $0.8 M_{\odot}$ and represents well the main evolutionary sequences of the cluster; the blue line indicates stars with mass $1.7 M_{\odot}$ and represents well the region occupied by the BSSs. Image taken from Ferraro et al. (2015).

As suggested by their peculiar position in the CMD, BSSs are more massive than normal cluster stars ($M \sim 0.3 M_{\odot}$). Constraints on their masses, typically in the range of $M \sim 1.2 - 1.7 M_{\odot}$, have been derived through several independent methods. These include direct mass measurements in binary systems, spectroscopic analyses of effective temperature and surface gravity, spectral energy distribution fitting,

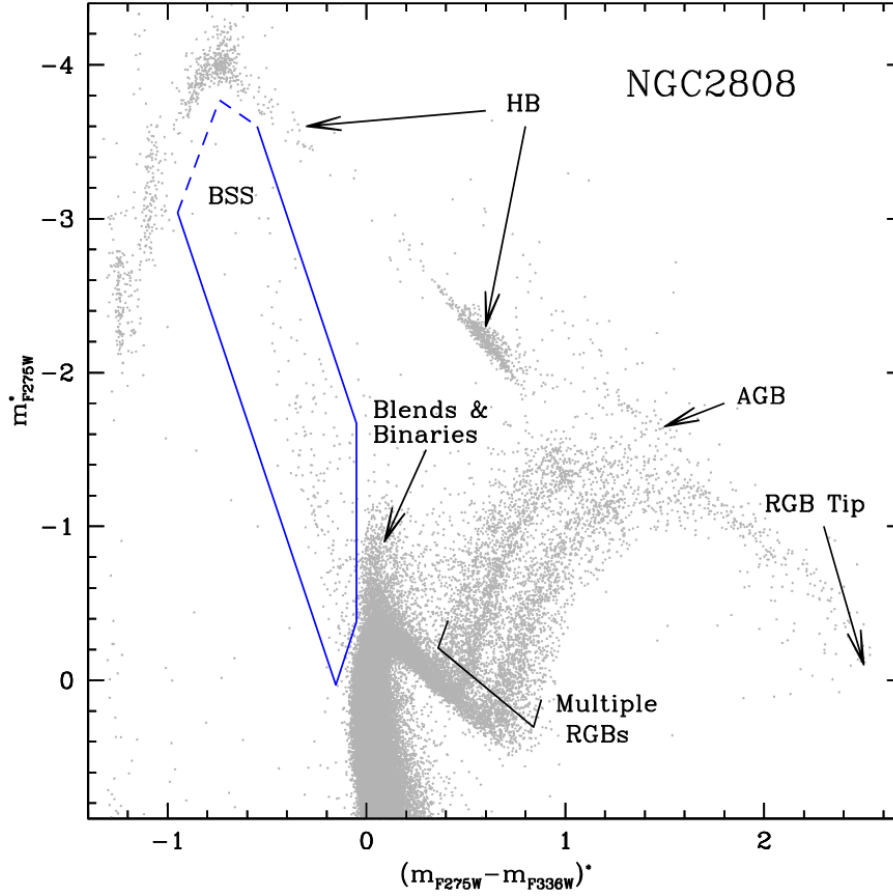


Figure 1.4: CMD of the galactic globular cluster NGC 2808 with the BSSs sequence spanning three magnitude. Image taken from Raso et al. (2017).

and investigations of their pulsational properties (Shara et al. 1997; Fiorentino et al. 2014; Raso et al. 2019).

In the CMD, they mimic the properties of a young population, a phenomenon that should not occur in old globular clusters that have not recently experienced episodes of star formation. Theories explaining their formation should therefore give an explanation for this peculiarity. There are two main known formation scenarios, both involving mass-enhancement mechanisms: i) mass-transfer in binary systems (MT-BSS, McCrea 1964), (ii) direct collisions between two stars (COLL-BSS, Hills & Day 1976). MT-BSSs can originate from a binary system consisting either of a main sequence star and a giant/subgiant star or two main sequence stars. During its evolution, the more massive star (primary) fills its Roche lobe (i.e., the radius that delimits the regions of gravitational influence of the binary system's components) and begins to transfer mass and angular momentum to its companion. The final product is a binary system composed of a MT-BSS and a white dwarf companion, formed from the core of the primary star. Alternatively, if complete coalescence occurs, the result can be a single BSS. The channel efficiency is governed by multiple

factors, including the primordial binary fraction, the evolutionary state of the donor and accretor stars, and the binary system’s dynamical history.

COLL-BSSs, instead, are formed as a result of direct collisions between single stars. This second process strongly depends on the stellar collision rate, influenced by several cluster properties, for example the central stellar density. Both mechanisms yield a more massive star than typical cluster members, enriched with hydrogen either from a binary companion or a stellar collision. This fresh fuel revitalizes the core, naturally placing BSSs in the CMD region typical of young, hydrogen-burning stars.

Distinguishing between BSSs formed through mass transfer and those resulting from stellar collisions remains observationally challenging. While COLL-BSSs are primarily expected to form in high-density environments, such as the central regions of GCs, MT-BSSs are thought to dominate in low-density environments, including open clusters (OCs) and the outer regions of GCs (Sollima et al., 2008; Mathieu et al., 2009). However, this spatial segregation is blurred by the effects of dynamical evolution, as massive stars, as BSSs, undergo mass segregation and tend to migrate toward the cluster core over time (see Sec. 1.3).

From the point of view of chemical composition, the two formation channels are expected to leave distinct signatures on the surface of BSSs. In the case of MT-BSSs, the accreted material originates from the inner layers of an evolved donor star, where partial CNO-burning (nuclear fusion process in stars where hydrogen is converted into helium using carbon, nitrogen, and oxygen as catalysts) has taken place. As a result, MT-BSSs are predicted to exhibit surface anomalies, including carbon and oxygen depletion. For example, evidence from 47 Tucanae and M30 has revealed a subpopulation of BSSs exhibiting carbon and oxygen depletion (Ferraro et al., 2006; Lovisi et al., 2013).

In contrast, rotational velocity does not appear to be a reliable diagnostic for distinguishing between MT- and COL-BSSs. High initial rotation rates are expected in both cases due to angular momentum transfer in MT-BSSs (Packet, 1981; de Mink et al., 2013) and conservation of angular momentum in stellar collisions (Benz & Hills, 1987; Sills et al., 2002). Furthermore, various braking mechanisms such as magnetic braking and disk locking are believed to reduce the rotational velocity over time, potentially erasing the original signatures (Leonard & Livio, 1995; Sills et al., 2005; Leiner et al., 2018; Sun et al., 2024).

Interestingly, a separation of BSSs into two distinct populations was observed in some PCC clusters. It was first detected in the GC M30 (Ferraro et al., 2009, see Fig. 1.5), and subsequently confirmed in other clusters (see e.g. NGC 362 in D’Alessandro et al. 2013b, NGC 1261 in Simunovic et al. 2014, M15 in Beccari et al. 2019, NGC 6256 in Cadelano et al. 2022b).

All these clusters display in the CMD a narrow sequence of blue BSSs and a

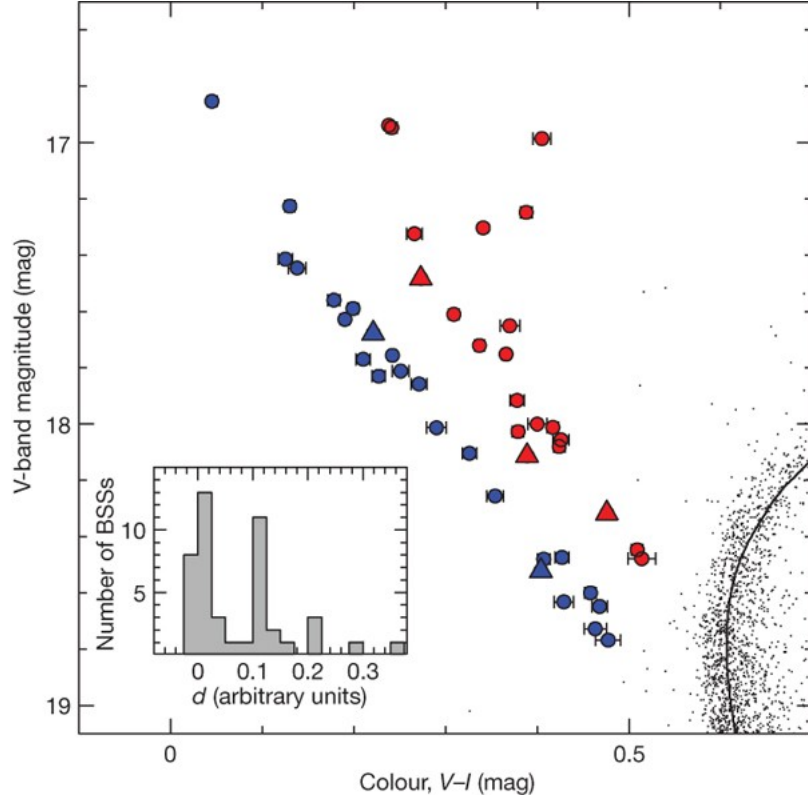


Figure 1.5: The BSS region of the $(V, V-I)$ CMD of M30 is shown, with the selected BSSs marked. Red and blue symbols indicate BSSs belonging to the red and blue sequences, respectively. The inset displays the distribution of the geometrical distances d . Two distinct peaks are clearly visible, highlighting the presence of two separate populations. Image taken from Ferraro et al. (2009).

more scattered red BSS population. The red sequence matches well the location predicted by MT-BSS models (Xin et al., 2015), while the blue one is well reproduced by collisional isochrones of 1-2 Gyr, suggesting a relatively recent formation episode. The presence of such double sequences offers a unique opportunity to disentangle the two main formation channels observationally. However, as both MT-BSSs and COLL-BSSs evolve, their CMD loci should merge over time, erasing the initial separation within a few gigayears. For this reason, Ferraro et al. (2009) suggested that the blue sequence in M30 is composed of COLL-BSS formed recently during the core-collapse phase, which temporarily increased the collision rate, and this hypothesis was later confirmed by dedicated numerical simulations (Portegies Zwart, S., 2019). Notably, the three clusters where a double BSS sequence has been firmly identified (M30, NGC 362, and M15) are all known to have undergone core collapse (Harris, 1996, 2010 edition), reinforcing the link between this structural phase and the recent formation of collisional BSSs.

1.4.1 BSSs as tracer of dynamical evolution

The intense dynamical activity in GCs is thought to boost the formation of stellar exotica, such as the so-called family of BSSs and binaries containing heavily degenerate objects, such as black holes and neutron stars. Consequently, their observable properties can serve as valuable tracers of the internal dynamics within GCs.

Among the various exotica, BSSs are the most numerous and the easiest to detect in the CMD (see the previous section). Since they are more massive than the average cluster star, they are strongly affected by dynamical friction (see Sec.1.3), that causes them to gradually lose kinetic energy and sink toward the cluster center over time. As a consequence, the radial distribution of BSSs serves as a powerful diagnostic of the cluster's dynamical evolution.

The efficiency of dynamical friction is highest in the dense central regions and gradually decreases with increasing radius, depending on both velocity dispersion and local density (Mapelli et al., 2006). Over time, this process shapes the radial distribution of BSSs. In particular, Ferraro et al. (2012) identified three dynamical families of clusters based on their radial distribution shape. They analyzed the radial distribution of BSSs in 21 GGC using the double-normalized ratio, defined as

$$R_{\text{BSS}}(r) = \frac{N_{\text{BSS}}(r)/N_{\text{BSS,tot}}}{L_{\text{samp}}(r)/L_{\text{samp,tot}}} \quad (1.7)$$

where $N_{\text{BSS}}(r)$ indicates the number of stars in the population up to a certain radius r , $N_{\text{BSS,TOT}}$ their total number, $L_{\text{samp}}(r)$ the sampled luminosity up to a certain radius r and L_{TOT} the total luminosity. For all standard cluster populations (such as the horizontal branch or the red giant branch population), which are not affected by mass segregation, this ratio is expected to be equal to 1. In other words, the number of stars in each ring varies proportionally with the sampled luminosity in that same ring (Renzini & Buzzoni, 1986).

The first cluster family is characterized by a radial distribution of BSSs resembling the typical configuration of standard populations, exhibiting a nearly flat distribution. This indicates a young system in which dynamical friction has not yet had time to act. It is the case for example of ω Centauri, Palomar 14 and NGC 2419 (see Fig.1.6). The second family contains clusters that exhibit a bimodal radial distribution with a well-defined peak, a dip at intermediate radii, and a rising branch in the external regions. The radius at which the dip occurs (r_{min}) is particularly significant, as it reflects the maximum distance from the center at which dynamical friction has effectively influenced the BSS population. With increasing dynamical age, dynamical friction progressively affects more distant regions of the cluster, resulting in an increase of r_{min} (see Fig.1.7). The value of r_{min} shows an anticorrelation with the fundamental dynamical timescales of a cluster, such as the central and half-mass relaxation times: clusters with shorter relaxation times tend to have

higher values of r_{min} , indicating more advanced dynamical evolution (see Fig.1.8). This provides additional confirmation of the method’s reliability. The last family includes the most dynamically evolved clusters, whose BSSs radial distributions are characterized by a prominent central peak followed by a monotonic decline. In these systems, dynamical friction has acted throughout the entire cluster. Some examples are M75, M79, M80 and M30 (see Fig.1.9). These results confirm that the degree of radial segregation of BSSs can be effectively used as a sort of “dynamical clock” to trace the evolutionary phase of a stellar system.

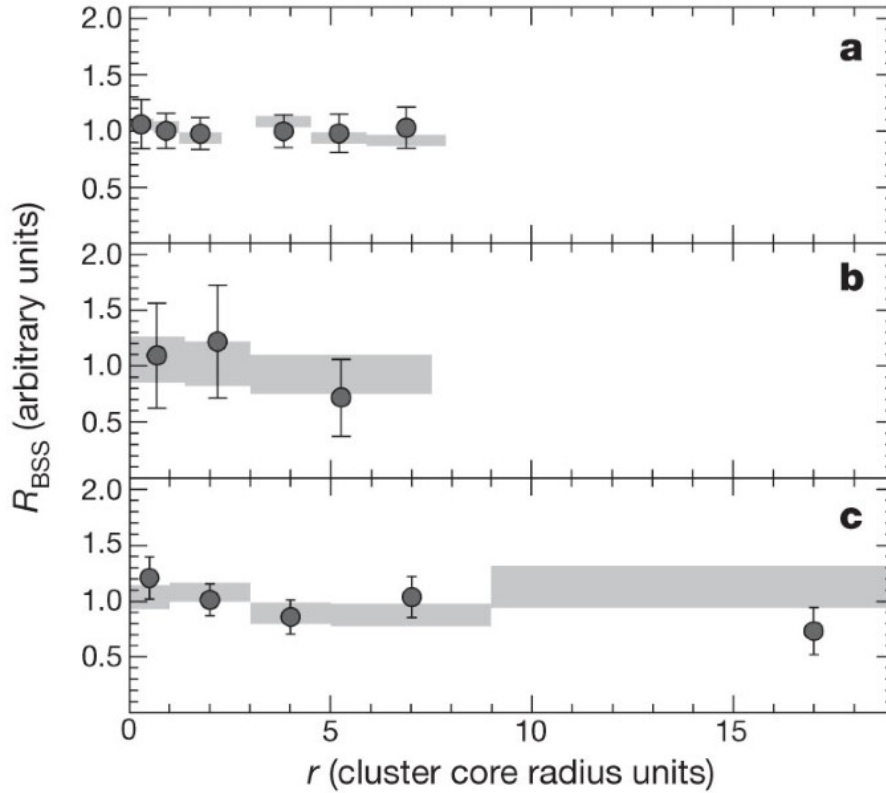


Figure 1.6: The double-normalized ratio of BSSs as a function of radius (in core radius units) for ω Centauri (panel a), Palomar 14 (panel b), NGC 2419 (panel c). Grey regions correspond to the double-normalized ratio measured for a reference population (red giants or horizontal-branch stars). Image taken from Ferraro et al. (2012).

As an outcome of extensive N-body simulations, Alessandrini & Cosmic-Lab Team (2016) identified a new parameter called “ A^+ parameter”, defined as the area enclosed between the cumulative radial distribution of BSSs, ϕ_{BSS} , and that of a reference (and lighter) population, ϕ_{REF} :

$$A^+ = \int_{x_{min}}^x [\phi_{BSS}(x') - \phi_{REF}(x')] dx', \quad (1.8)$$

where $x = \log(r/r_h)$ is the logarithm of the distance from the cluster center normal-

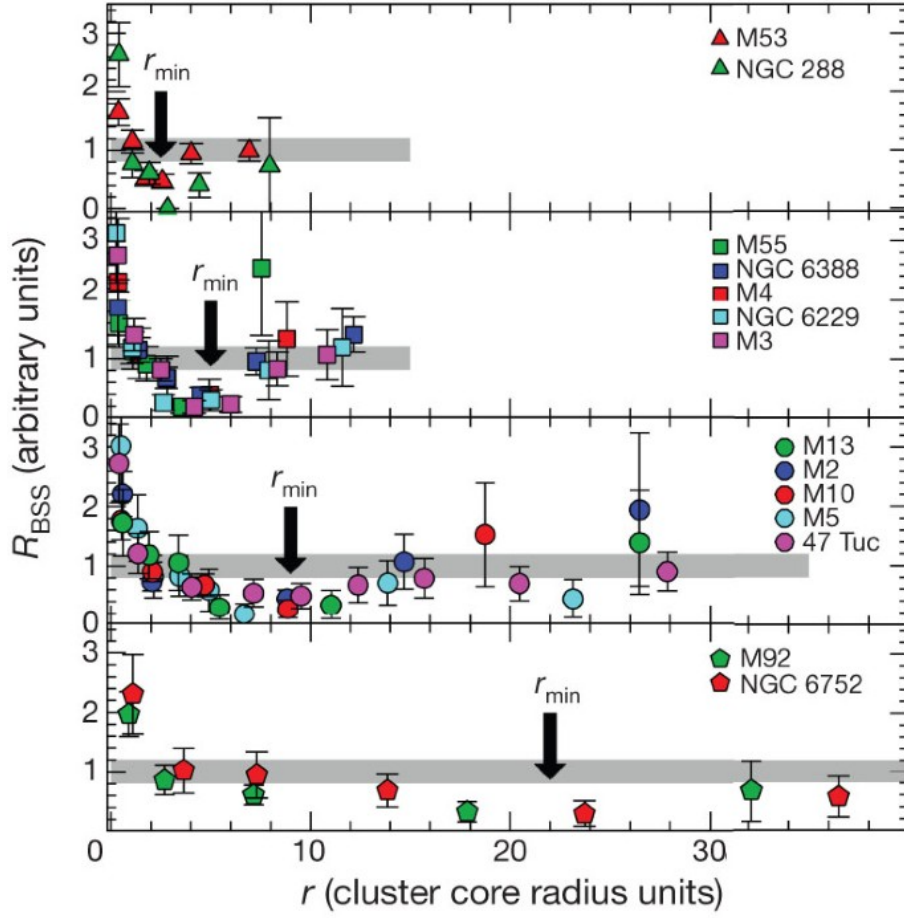


Figure 1.7: The double-normalized ratio of BSSs as a function of radius (in core radius units) for different clusters, grouped according to different values of r_{min} (black arrows). Grey regions correspond to the double-normalized ratio measured for a reference population. Image taken from Ferraro et al. (2012).

ized to the half-mass radius r_h , and x_{min} corresponds to the minimum sampled value of $x = \log(r/r_h)$. In this thesis, the A^+ parameter is evaluated within one half-mass radius, as this region is the most sensitive to the BSS sedimentation process. The resulting value ($A_{r_h}^+$) allows for a meaningful cluster-to-cluster comparison.

N-body simulations demonstrate that this parameter increases systematically over time, reflecting the progressive segregation of BSSs and the dynamical evolution of the cluster. In a dynamically young cluster, when the distribution of BSSs is similar to that of a standard population, the two curves overlap and the value of A^+ is therefore close to zero. As dynamical age increases, the segregation of BSSs grows, and the area between the curves widens. In the left panel of Fig. 1.10 A^+ values are shown for 4 clusters, with increasing dynamical ages from top to bottom.

Lanzoni et al. (2016) found a tight anti-correlation between the A^+ parameter and the central relaxation time, validating its use as a proxy for cluster dynamical

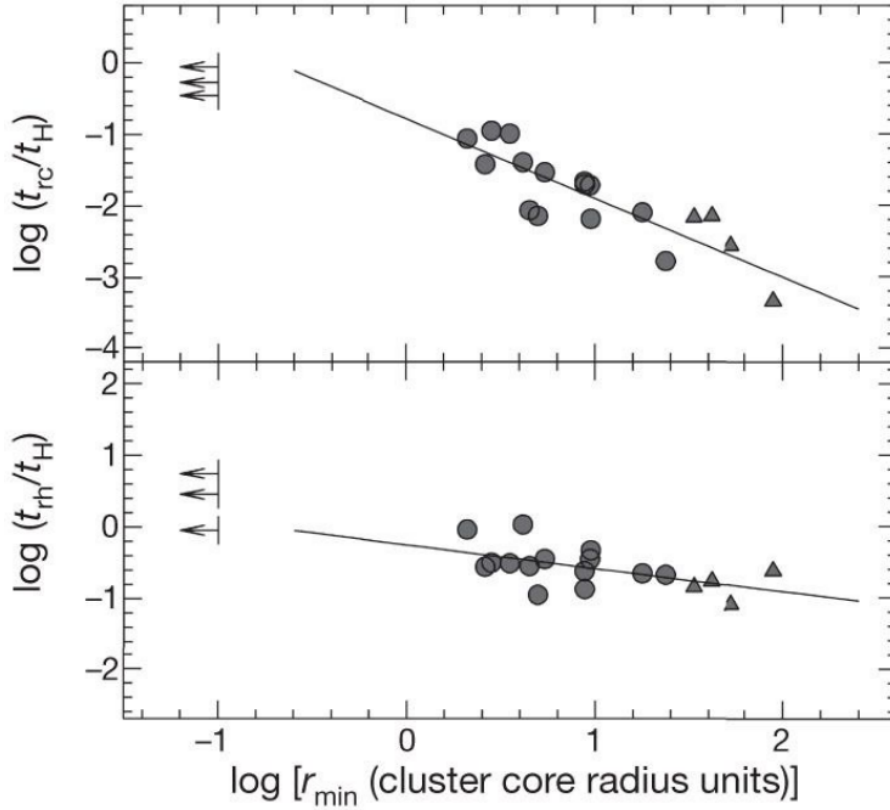


Figure 1.8: Top panel: t_{rc} as a function of $r_{\min}$ normalized for the Hubble time. Bottom panel: t_{rh} as a function of $r_{\min}$ normalized for the Hubble time. Family I clusters are shown as lower limit arrows, because no minimum can be detected. Family II clusters are represented as grey circles, and Family III clusters as grey triangles. Image taken from Ferraro et al. (2012).

age. Another way to illustrate this is through the correlation presented in Ferraro et al. (2018a, 2023) between A^+ and N_{relax} (see Fig.1.11). N_{relax} is defined as the ratio of the cluster's age to its central relaxation time ($N_{relax} = t_{age}/t_{rc}$) and quantifies the number of current central relaxation times that have occurred since cluster formation. The correlation indicates that both the A^+ parameter and the central relaxation time can be used as reliable indicators of the dynamical age of stellar clusters. However, the central relaxation time (see Eq.1.2) is derived from an analytical expression assuming the system is spherically symmetric, isotropic, and non-rotating. On the contrary, recent observational studies have shown that many globular clusters exhibit internal rotation and velocity anisotropy (Fabricius et al., 2014; Watkins et al., 2015; Bellini et al., 2017; Lanzoni et al., 2018a; Ferraro et al., 2018b; Kamann et al., 2018; Leanza et al., 2022, 2023, 2024). Importantly, t_{rc} is not static; it evolves over time as the cluster's structural parameters change (e.g., central density, core radius, and total mass). Therefore, the present-day value of t_{rc} may not accurately reflect the cluster's entire dynamical history. Thus, the main advantages of the A_{rh}^+ parameter with respect to t_{rc} can be summarized as follows: (i) the A_{rh}^+

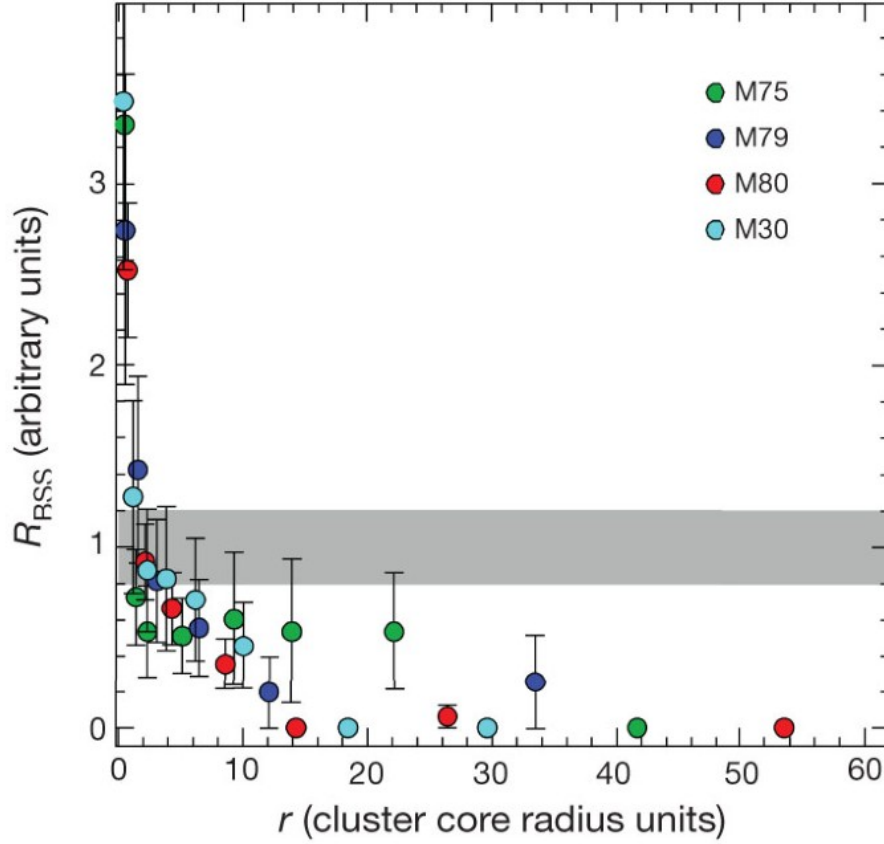


Figure 1.9: The double-normalized ratio of BSSs as a function of radius (in core radius units) for M75, M79, M80, M30. Grey regions correspond to the double-normalized ratio measured for a reference population. Image taken from Ferraro et al. (2012).

parameter is entirely and directly measured from observations; (ii) it is specifically designed to have maximum sensitivity in quantifying the mass segregation of the heaviest and brightest (hence, easily identifiable) stellar population (the BSSs); and (iii) at odds with t_{rc} , its definition does not require oversimplified assumptions (e.g. spherical symmetry, no rotation, or King model structure) or approximations (for instance, the definition of r_c , which is very uncertain, in particular in dynamically evolved stellar systems where the presence of a central cusp makes the definition more complicated and possibly meaningless).

Furthermore, as expected, the A^+ parameter also correlates with the value of r_{min} (Lanzoni et al., 2016). Clusters with larger A^+ values tend to show deeper segregation patterns, and this is reflected in a larger r_{min} value, as mentioned above. A comparison of the left and right panels of Fig. 1.10 shows that as A^+ increases, from top to bottom, the r_{min} value also increases. However, from a practical point of view the A^+ parameter offers several advantages over the method based on the radial distribution of BSSs described above. In fact, the determination of r_{min} is highly sensitive to the choice of binning used to construct the radial profile. More-

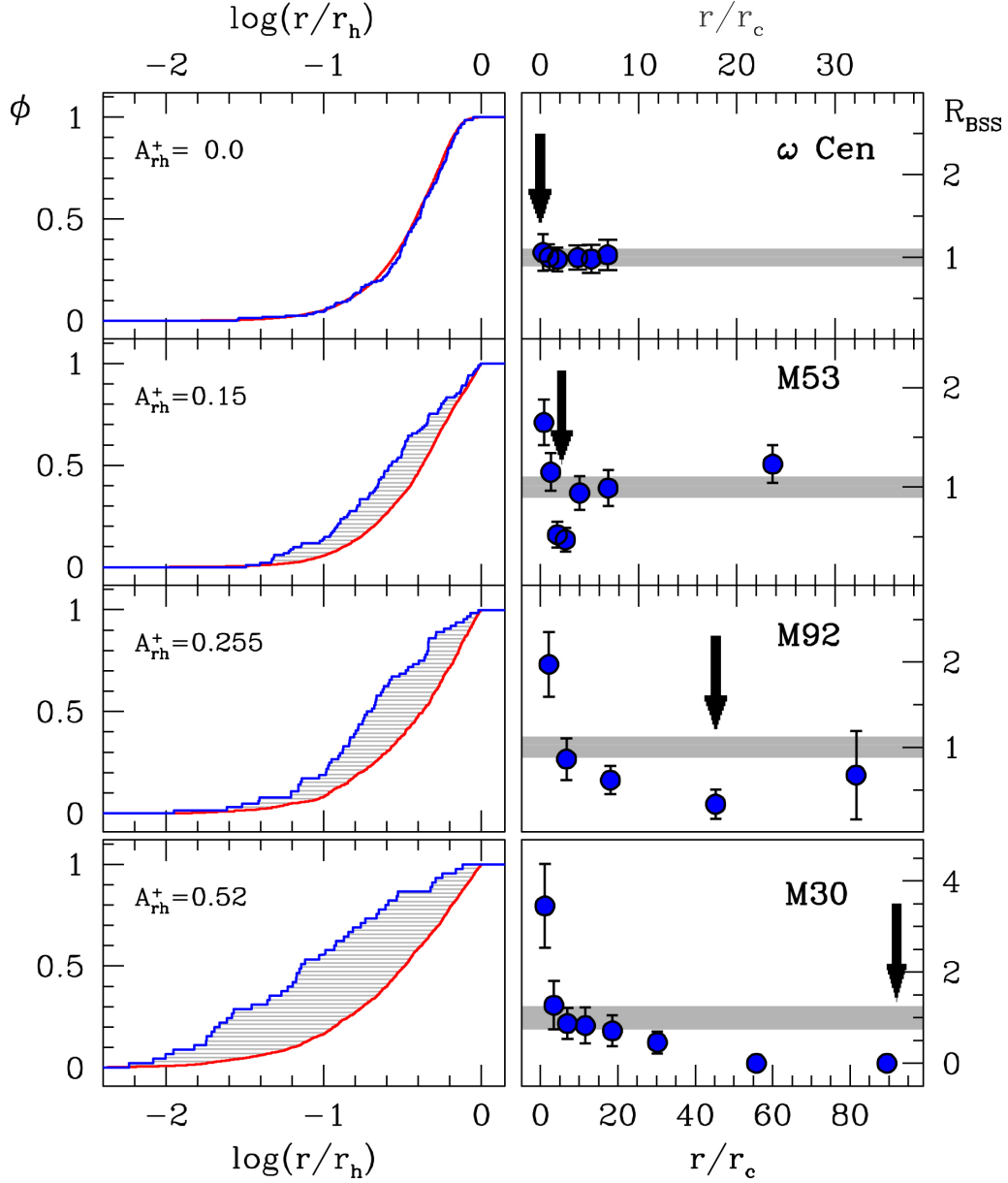


Figure 1.10: Left panels: Cumulative radial distributions of BSSs (blue line) and reference stars (red line) observed within one half-mass radius (r_h) for four globular clusters: ω Centauri, M53, M92, and M30 (from top to bottom). The gray shaded area between the two curves corresponds to the value of A_{rh}^+ indicated in each panel. Right panels: Normalized radial distributions of BSSs for the same clusters shown in the left panels. Black arrows indicate the position of the minimum in the BSS distribution. The gray shaded bands schematically represent the distribution of the reference population. Image taken from Lanzoni et al. (2016).

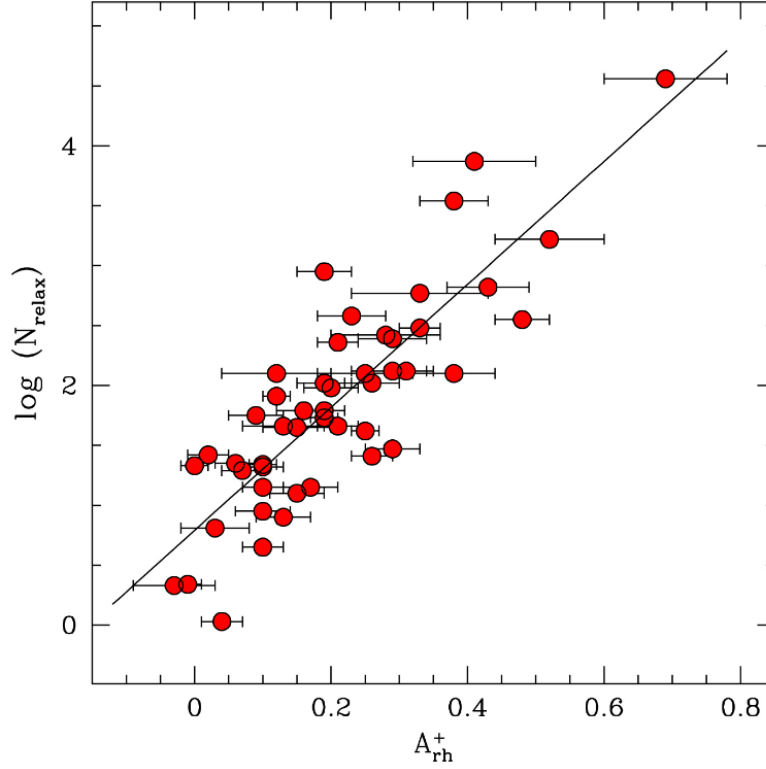


Figure 1.11: Correlation between N_{relax} and A_{rh}^+ for a sample of 48 GGCs. Image taken from Ferraro et al. (2018a).

over, while the determination of r_{min} requires sampling the full cluster radial extent, the measurement of A_{rh}^+ only relies on the central regions ($r < r_h$), which can be adequately probed with HST observations.

1.5 Star clusters in the Large Magellanic Cloud

As mentioned in Sect. 1.1, globular clusters are ubiquitous. In addition to those in the Milky Way, individual stars can also be resolved in GCs belonging to the Magellanic Clouds (MCs). They are two irregular galaxies called the Large Magellanic Cloud and the Small Magellanic Cloud, members of the Local Group*.

The star formation history of the LMC is very complex and unique (see, e.g. Da Costa, 1991). An initial burst of star formation occurred 12-13 Gyrs ago, involving the formation of massive clusters ($M > 10^5 M_\odot$) at any distance from the center of the galaxy (see panel b and c of Fig. 1.12). After a long period of quiescence of about 10 Gyr, called the “age gap”, star formation resumed. This was probably due to a collision between the LMC and the MW, or between the LMC and SMC (Bekki et al.,

*The Local Group is a group of galaxies, including three large spiral galaxies (Milky Way, M31, M33) and small fainter dwarf galaxies such as the Large and Small Magellanic Clouds.

2004; Rich et al., 2001). This has resulted in the formation of less massive structures ($M < 10^5 M_\odot$) located up to 4-5 kpc from the center of the galaxy (see panel b and c of Fig.1.12). Therefore, in both galaxies we find very young clusters (from a few million years to about 3 billion years) and very old clusters (12-13 billion years). The GCs of the MCs also describe a wider range in metallicity ($[Fe/H] \sim -2.2/0.0$ dex) than those of the MW.

1.5.1 The size-age conundrum

The study of LMC clusters, when added to the information already gathered from Milky Way systems, provides significant advantages. It expands our view of globular cluster evolution by including systems formed in a different galactic environment. In fact, the LMC provides a galactic environment that differs from that of the Milky Way in terms of total mass, star formation history and chemical enrichment (as mentioned in the previous section). Such differences can affect the initial structural and chemical properties of globular clusters, thereby regulating their long-term dynamical evolution.

In particular, the coexistence of both young and old clusters allowed to trace dynamical evolution across a broader age range than is possible in the Milky Way alone. These kind of studies (Elson et al., 1989; Elson, 1991; Mackey & Gilmore, 2003) revealed a peculiar trend between the core radius r_c and the chronological (stellar) age of the clusters, the so-called “size–age conundrum”. Specifically, while young clusters all have small core radii ($r_c < 2.5$ pc), the older ones exhibit a broader range of sizes, reaching up to $r_c = 10$ pc, as shown in panel (a) of Fig.1.12. Mackey et al. (2008) attempted to explain the phenomenon by hypothesizing an evolutionary sequence linking young and old clusters. According to this hypothesis, all clusters begin as compact configurations and then undergo varying degrees of core expansion due to some “ad hoc” mechanism. Of the various possibilities, the most accepted was the heating action of a population of stellar-mass binary black holes.

However, the characteristics of the youngest clusters are not compatible with them representing how the oldest appeared at the epoch of their formation. As mentioned above, the younger systems are less massive and located within ~ 5 kpc of the LMC center, while the oldest systems are more massive and located at all distances. This is therefore not compatible with the hypothesis of an evolutionary sequence. Moreover, according to our knowledge of GGCs (as presented in Sect.1.3), dynamical evolution tends to lead systems towards more compact configurations, the opposite of what this scenario advocates.

Recently, Ferraro et al. (2019) suggested that the variability in the core radii observed in older clusters could be naturally explained by differences in their dynamical ages. Specifically, in line with the observed properties of GGCs, the hypothesis suggests that clusters exhibiting larger core radii are dynamically younger,

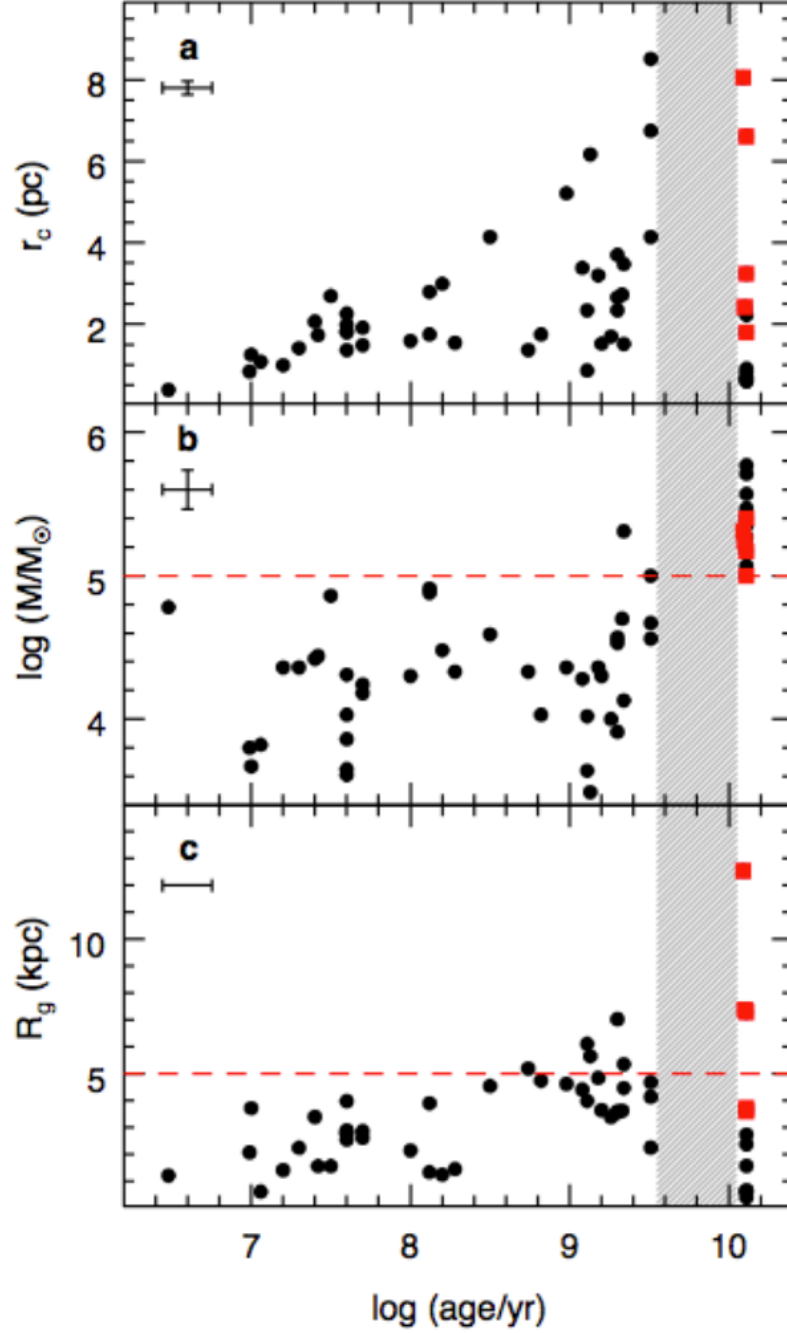


Figure 1.12: From top to bottom panel: distribution of core radius, mass and galactocentric distance as a function of the chronological age of the clusters in the LMC. The five clusters studied in Ferraro et al. (2019) are shown in red. The grey band represents the 10 Gyr period of quiescence in the formation history of the Magellanic Cloud clusters. Image taken from Ferraro et al. (2019).

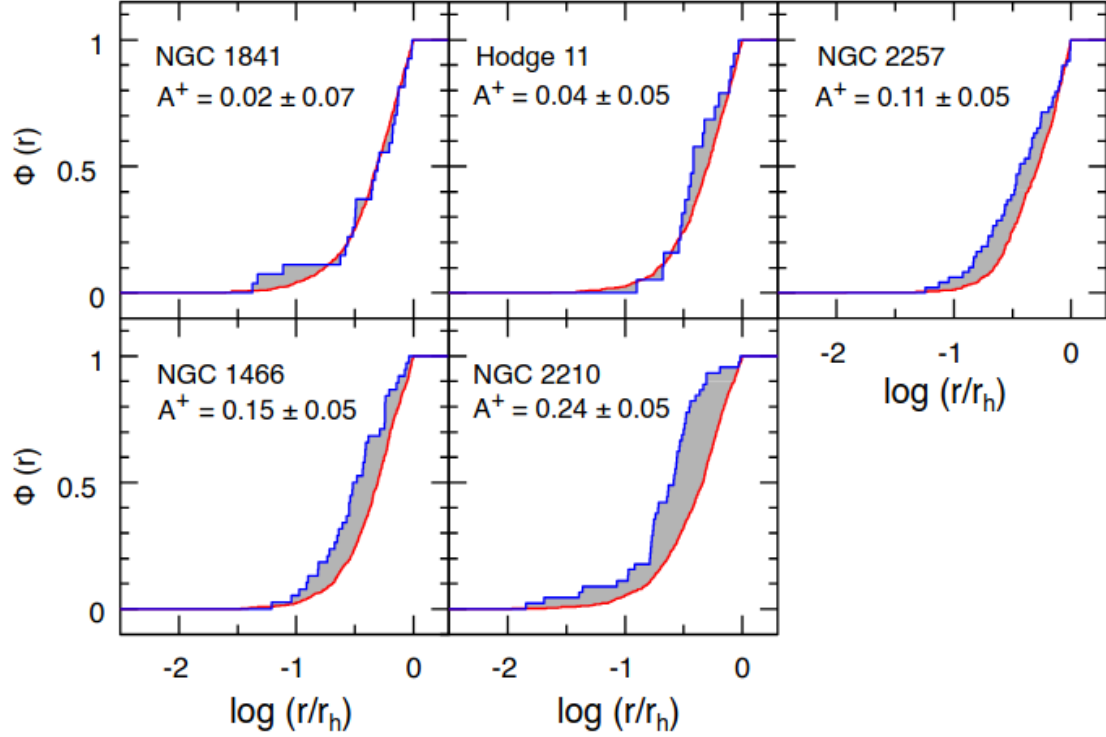


Figure 1.13: Cumulative radial distributions of BSSs (blue) and reference stars (red) in the five LMC GCs studied in Ferraro et al. (2019). The size of the shaded area between the two distributions corresponds to the labelled value of A^+ . Image taken from Ferraro et al. (2019).

whereas those with more compact cores are dynamically more evolved. The study examined five old ($t \sim 12 - 13$ Gyr), massive ($\log(M/M_\odot) \sim 5.2 \pm 0.2$) and metal-poor ($[Fe/H] \sim -1.9 \pm 0.2$) clusters in the LMC, namely NGC 1841, Hodge 11, NGC 2257, NGC 1466, NGC 2210. Using the dynamical clock, their dynamical ages were obtained in terms of the A^+ parameter. In particular they obtained $A_{rh}^+ = 0.02, 0.04, 0.11, 0.15, 0.24$ for NGC 1841, Hodge 11, NGC 2257, NGC 1466, NGC 2210 respectively (see Fig.1.13). As shown in the left panel of Fig.1.14, in the plane $N_{relax}-A^+$ the five LMC clusters (red squares) follow the same correlation described by galactic globular clusters (grey circles). This showed for the first time that the dynamical clock method is valid also beyond the MW.

Furthermore, in the plane core radius- A^+ the five LMC clusters exhibit a clear anticorrelation, following again the well-known behavior of galactic clusters (see right panel of Fig.1.14). As anticipated above, this finding explains that the significant variation in the core radius values observed in the old LMC clusters can be attributed to their natural dynamical evolution. Specifically, these clusters appear to be transitioning to increasingly compact configurations as their dynamical age increases.

However, this scenario does not account for the behavior of the youngest clusters.

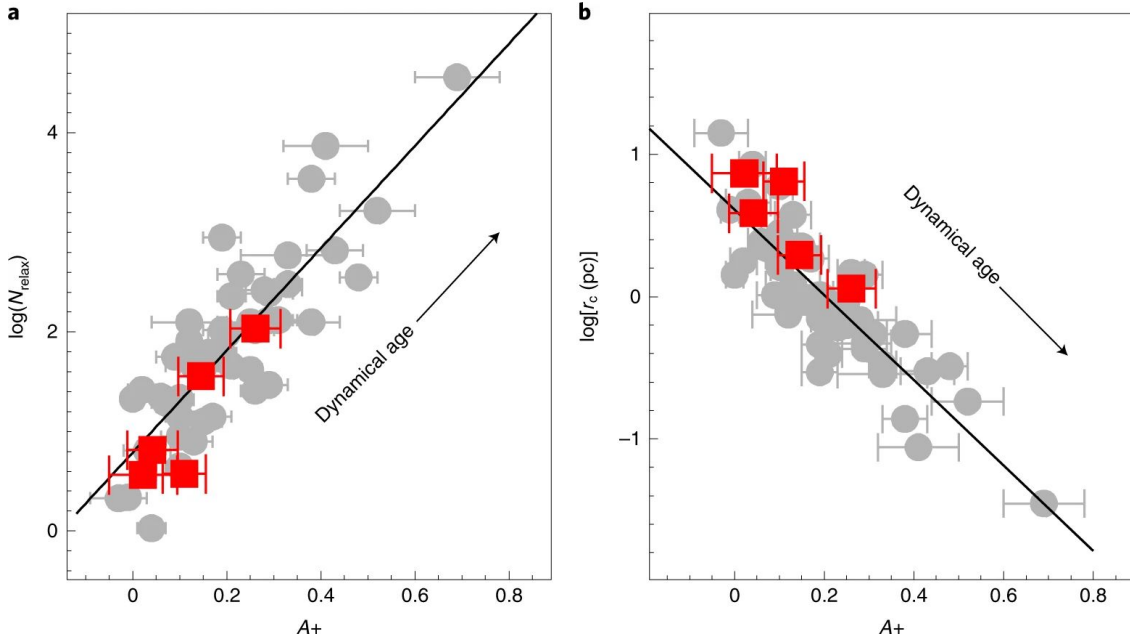


Figure 1.14: Left panel: correlation between N_{relax} and A^+ for a sample of GGCs (in grey) and the five LMC clusters (in red) studied in Ferraro et al. (2019). Right panel: anticorrelation between r_c and A^+ for the same systems. Image taken from Ferraro et al. (2019).

Their compact configuration cannot be explained by a high dynamical age, which they could not have reached in their brief lifetime. Instead, this behavior is more naturally understood in the context of the LMC’s peculiar star formation history. During the last ~ 3 Gyr, the galaxy has formed only low-mass clusters (see panel b of Fig. 1.12). This naturally leads to the predominance of compact young systems, because they are likely the only ones capable of surviving the strong tidal forces of the host galaxy, whereas more extended clusters would have been quickly disrupted.

One crucial component needed to complete this scenario is the analysis of the most compact clusters among the old LMC population. In fact, the portion of the diagram in Fig. 1.14 corresponding to LMC clusters in the most advanced stages of dynamical evolution is still totally unexplored, thus preventing any solid confirmation of the hypothesis presented in Ferraro et al. (2019). To address this, the clusters NGC 1835, NGC 1754, and NGC 1916 (see Fig. 1.15) were observed using the Wide Field Camera 3 (WFC3) on board the *Hubble Space Telescope* (programme GO 16361, PI: Ferraro), employing both near-ultraviolet (F300X) and optical (F606W, F814W) filters. They are all very compact ($r_c < 0.8$ pc) and massive enough ($M > 10^5 M_\odot$) to allow for an in-depth study of their characteristics. This thesis will therefore present a detailed study of the stellar populations, the measurement of the chronological ages, and the determination of the structural parameters of these three clusters. In addition, the internal dynamical ages of NGC 1835 and NGC

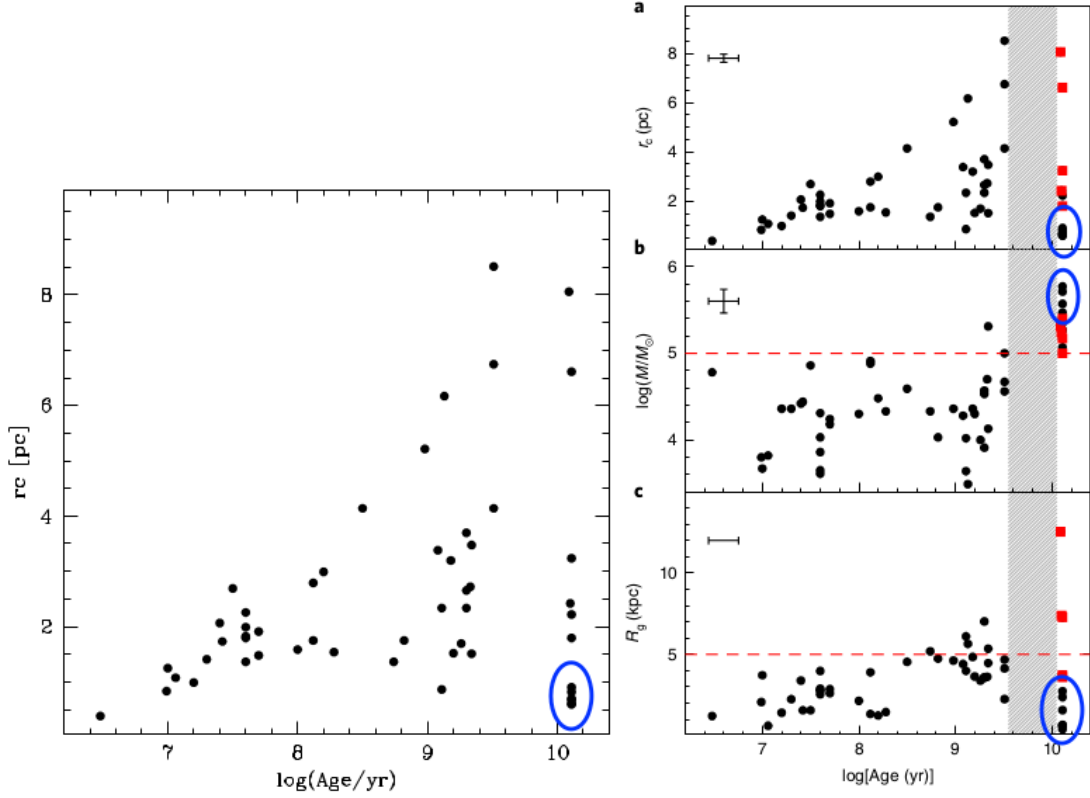


Figure 1.15: Left: Distribution of core radius versus chronological age for the LMC GCs. Right: From top to bottom, core radius, total mass and distance from the LMC center as a function of the chronological age observed for the LMC GCs. The blue ellipse encircles the three globular clusters targeted by the thesis (NGC 1835, NGC 1754, NGC 1916).

1754 will be derived using the dynamical clock method. For NGC 1916, however, the determination of the A^+ parameter is not feasible because of severe field contamination, significant incompleteness in the cluster center, and strong differential reddening; therefore, only its central relaxation time will be used as a dynamical age indicator. Thanks to the high spatial resolution of the WFC3/HST images, these results will represent the most accurate measurements obtained for these clusters to date, and they will provide the critical test needed to validate the proposed interpretation of the LMC size–age distribution in terms of initial conditions and internal dynamical evolution.

CHAPTER 2

The globular cluster NGC 1835

*Mainly based on:
Giusti et al. (2024a), A&A, 687, A310*

Giusti et al. (2024b), A&A, 686, A6

2.1 Introduction

In this chapter we present a high angular-resolution multi-wavelength study of the massive and old globular cluster NGC 1835 in the LMC ($\log M = 5.83M_{\odot}$, $t \sim 16$ Gyr, see Mackey & Gilmore 2003). Thanks to a combination of optical and near-ultraviolet images acquired with the WFC3 on board the HST, we performed a detailed inspection of the stellar population in this system, adopting a “UV-guided search” to optimize the detection of relatively hot stars.

We determined precise values of the distance modulus, reddening, and absolute age of the cluster, finding $(m - M)_0 = 18.58$, $E(B - V) = 0.08$, and $t = 12.5$ Gyr, respectively. Furthermore, we took advantage of the high spatial resolution of the new data to construct the star density profile from resolved star counts, determining the values of the core, half-mass, and tidal radii through comparison with the King model family. The results confirm that NGC 1835 is a very compact cluster with a core radius of only 0.84 pc.

The same data also allowed us to evaluate the dynamical age of the cluster by using the “dynamical clock” (see Chap. 1, Sect. 1.4.1). The estimated value of A_{rh}^+ (0.30 ± 0.04) is very high, providing evidence of a highly dynamically evolved stellar system. NGC 1835 fits nicely into the correlation between A_{rh}^+ and the central relaxation time and in the anti-correlation between A_{rh}^+ and the core radius defined by the Galactic and Magellanic Cloud clusters investigated to date.

The UV-optimized photometry allowed us to also discover a remarkably extended horizontal branch. It spans more than 4.5 mag in both the optical and the near-ultraviolet bands, and its color (temperature) ranges from the region redder than the instability strip up to effective temperatures of 30 000 K. This is the first time that such a feature has been detected in an extragalactic cluster, demonstrating that the

physical conditions responsible for the formation of extended HBs are ubiquitous. A detailed discussion of the peculiar HB morphology of NGC 1835 is provided in Appendix A.

Finally, in the field of view of the acquired images, at a projected angular separation of approximately $2'$ from the cluster, we detected the small stellar system KMK88-10. The observations provided the deepest CMD ever obtained for this cluster, revealing that it hosts a young stellar population with an age of 600-1000 Myr. The cluster surface brightness profile is nicely reproduced by a King model with a core radius $r_c = 4''$ (0.97 pc), a half-mass radius $r_h = 12''$ (2.9 pc), and a concentration parameter $c \sim 1.3$ corresponding to a truncation radius $r_t \sim 81''$ (19.5 pc). We also derived its integrated absolute magnitude ($M_V = -0.71$) and total mass ($M \sim 80 - 160 M_\odot$). The most intriguing feature emerging from this analysis is that KMK88-10 presents a structure elongated in the direction of NGC 1835, with an intracluster overdensity that suggests the presence of a tidal bridge between the two systems. If confirmed, this would be the first evidence of a tidal capture of a small star cluster by a massive globular. The study of the KMK88-10 cluster is discussed extensively in Appendix B.

2.2 Dataset

The photometric study of NGC 1835 was performed using a dataset of deep and high-resolution images obtained with the UVIS channel of the WFC3 on board the HST. A total of 16 images (see left panel of Fig. 2.1) were acquired using the F300X, F606W and F814W filters to cover a broad range of wavelengths. Specifically, six images (2×900 s, 1×917 s, 2×920 s, 1×953 s) were taken in the near-UV F300X filter, six images (2×407 s, 4×408 s) in the F606W, and four exposures (1×630 s, 1×645 s, 2×700 s) in the F814W. In each pointing, the center of NGC 1835 was aligned with the center of the WFC3 UVIS1, while UVIS2 sampled distances out to approximately $120''$.

The WFC3 dataset was complemented with simultaneous parallel observations acquired with the Wide Field Camera of the Advanced Camera for Surveys (ACS/WFC) in the F606W and F814W filters. These cover a $200'' \times 200''$ wide region located at $\sim 5'$ from the cluster, thus properly sampling the LMC field contaminating the cluster population (see right panel of Fig. 2.1). A total of seven images (1×335 s, 3×340 s, and 3×350 s) were acquired in the F606W filter, and six (1×550 s, 5×600 s) in the F814W.

We performed the data reduction using the software DAOPHOT II (Stetson, 1987), following the recipes described in detail in Cadelano et al. (2020c,b); Deras et al. (2023, 2024). We selected about 200 bright, well-distributed, and isolated stars in order to model a spatially varying point spread function (PSF) for each image. The

PSF model thus obtained was then used to perform the PSF fitting of all the sources with a flux peak above 5σ from the background level. We created a reference master list of stars identified in at least half of the images acquired with the UV filter, and we then forced the fit of the PSF model to the location of these sources in all the other images, using DAOPHOT/ALLFRAME (Stetson, 1994). This is the “UV-guided search” already described in Chap. 1, and it was extensively adopted by our group (see Ferraro et al. 1997b, 1999b, 2001, 2003b; Lanzoni et al. 2007a; Dalessandro et al. 2013b, and more recently Raso et al. 2017; Chen et al. 2021, 2022, 2023; Cadelano et al. 2022b) to optimize the detection and obtain complete samples of hot stars (such as extremely blue HB stars, blue straggler stars, and white dwarfs) in stellar populations dominated by cool giants, like old star clusters. In fact, the technique mitigates the crowding effects caused by the presence of giants and main sequence turn-off (MS-TO) stars, making it easier to retrieve blue and hot stars that would be lost in optical and infrared images, thus sensibly increasing the level of completeness of the observed samples.

For each identified star, the magnitudes estimated in different images were combined using DAOMATCH and DAOMASTER. The final catalogues consisted of frame coordinates, instrumental magnitudes, and photometric errors for a total of more than 100,000 sources: approximately 65000 sources in the WFC3 catalogue sampling the entire cluster extension, and 82000 in the ACS catalogue, sampling the LMC field. The magnitudes have been calibrated onto the VEGAMAG photometric system by applying appropriate aperture corrections and the zero points reported on the HST WFC3 and ACS websites. Finally, after the geometric distortion effects were corrected by applying the coefficients from Bellini et al. (2011) for WFC3 and from Meurer et al. (2003) for ACS, the positions were transformed to the absolute coordinate system (α, δ) by cross-correlation with the Gaia DR3 catalogue (Gaia Collaboration et al., 2023) sampling the same regions of the sky.

2.3 The colour-magnitude diagram

Figure 2.2 shows the CMDs obtained from the WFC3 observations in all the filter combinations. The optical CMD of the LMC field sampled by the ACS observations is shown in Figure 2.3. From a visual analysis of these figures it appears clear that the CMD of NGC 1835 is significantly contaminated by field stars, in agreement with what expected for a GC located close to the central bar of the LMC. However, the main evolutionary sequences belonging to NGC 1835 are clearly distinguishable in the CMD. The most severe contamination is produced by the MS of the LMC field, which is essentially superposed to the cluster MS and extends up to magnitudes brighter than the cluster HB (up to $m_{F606W} \sim 18$). The Red Giant Branch (RGB) of the LMC field is clearly distinguishable from that of NGC 1835 when colours

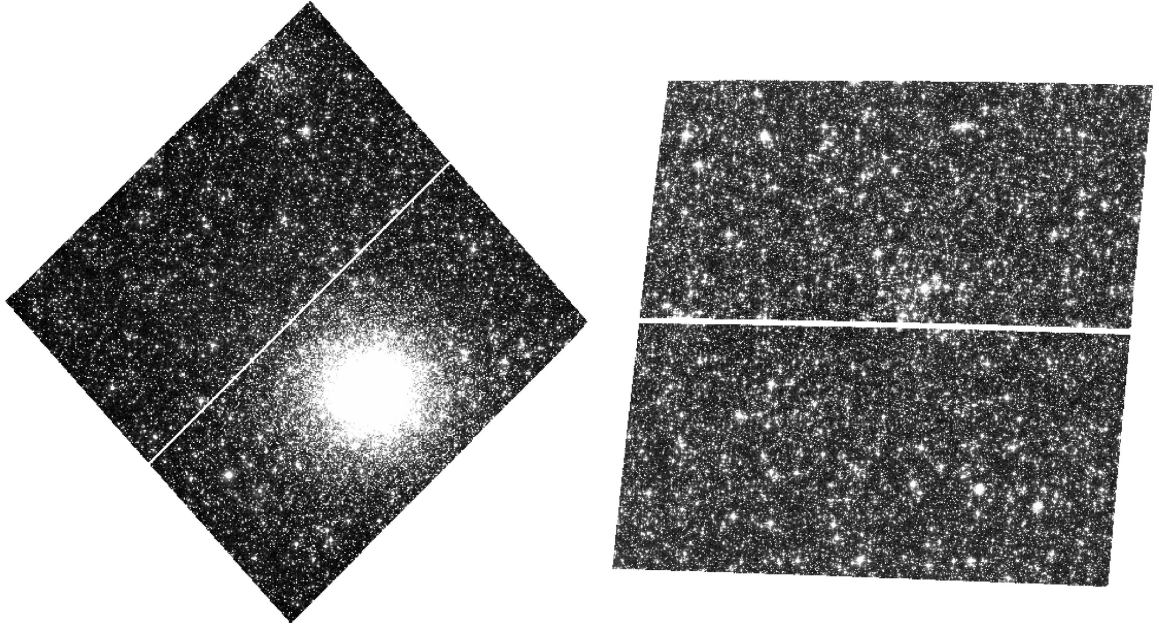


Figure 2.1: Left panel: WFC3/HST image of the cluster NGC 1835 in the F606W filter. Nord is up and est is left. Right panel: ACS/HST image of the reference LMC field region at 5' from the center of the cluster in the F606W filter. Nord is up and est is left.

including the F300X filter are used (left and central panels of Fig. 2.2). In these colour combinations also the field Red Clump is well visible (the rightmost clump of stars at $m_{\text{F606W}} \sim 19$). On the other hand, no significant field contamination is observed in the bluest region of the CMD, at colours bluer than 0. This is the region where the most intriguing and unexpected feature of the CMD (i.e. a remarkably extended blue tail of the HB; see Appendix A) is located.

2.4 Reddening, distance modulus, and age of NGC 1835

For the determination of the reddening and distance modulus of NGC 1835, we considered two Galactic GCs (namely, M3 and M13) as reference systems. These clusters have been extensively studied in the literature and their properties are well established (see Ferraro et al. 1997a; Johnson et al. 2005; Sneden et al. 2004; Dalessandro et al. 2013b; Cadelano et al. 2019, 2020a). They are two “twin” GCs, with similar age, metallicity, and central density. They respectively have ages of 12.50 ± 0.50 Gyr and 13.00 ± 0.50 Gyr (Dotter et al., 2010), $[\text{Fe}/\text{H}] = -1.50 \pm 0.05$ and $[\text{Fe}/\text{H}] = -1.58 \pm 0.04$ (Carretta et al., 2009), and V -band central surface brightness $\mu_0 = 16.64 \text{ mag arcsec}^{-2}$ and $16.59 \text{ mag arcsec}^{-2}$ (Harris, 1996, 2010 edition). In addition, they have a similar mass of about $\log M/M_\odot \sim 5.8$ (McLaughlin & van der Marel, 2006; Pryor & Meylan, 1993). These values are compatible with those measured in NGC 1835: $[\text{Fe}/\text{H}] = -1.69 \pm 0.01$ (Mucciarelli et al., 2021), $\mu_0 = 16.64$

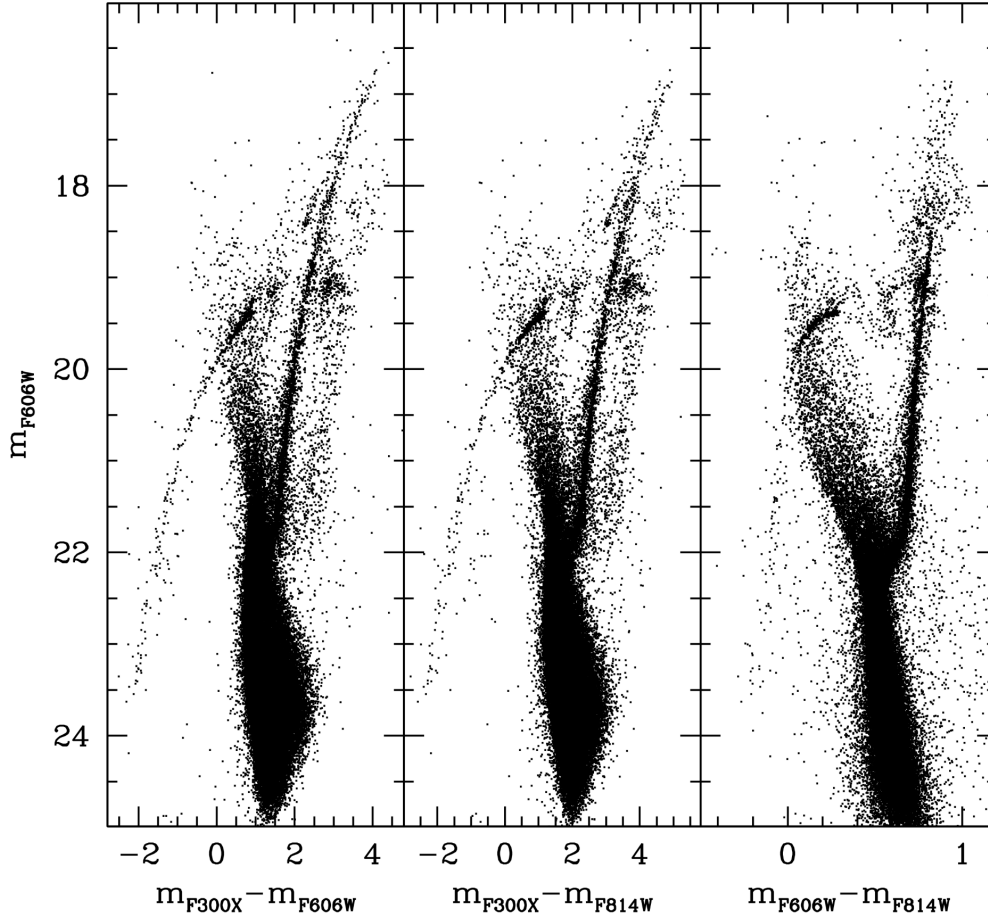


Figure 2.2: CMD of NGC 1835 obtained from the WFC3 dataset in all the filter combinations.

mag arcsec⁻² in the F555W filter (Mackey & Gilmore, 2003) and $\log M/M_{\odot} \sim 5.83$ (Mackey & Gilmore, 2003). As for the age, there is general agreement on the fact that NGC 1835 belongs to the class of old LMC clusters, but the absolute age is still quite uncertain and strongly overestimated: $\log t = 10.2^{+0.07}_{-0.08}$, corresponding to an age $t \sim 16$ Gyr (see Olsen et al. 1998; Olszewski et al. 1991). In addition, the HB of M13 shows a well extended and populated blue tail, reminiscent of that discovered in NGC 1835 (see Appendix A), but very few RR Lyrae (only ten are quoted in the Clement catalogue; Clement et al., 2001*) and just a few stars redder than the instability strip. Conversely, M3 hosts a large population of RR Lyrae (more than 200), similarly to NGC 1835 (see Appendix A), but no evidence of the blue tail. Hence, M3 and M13 are excellent reference clusters for an in-depth study of NGC 1835. Indeed, through the direct comparison of the CMDs we determined the reddening and the distance of NGC 1835, which are then used to estimate the age of the cluster. This piece of information allowed us to also perform a direct comparison between the HBs of the three systems, as well as to determine the

*<https://www.astro.utoronto.ca/~cclement/read.html>

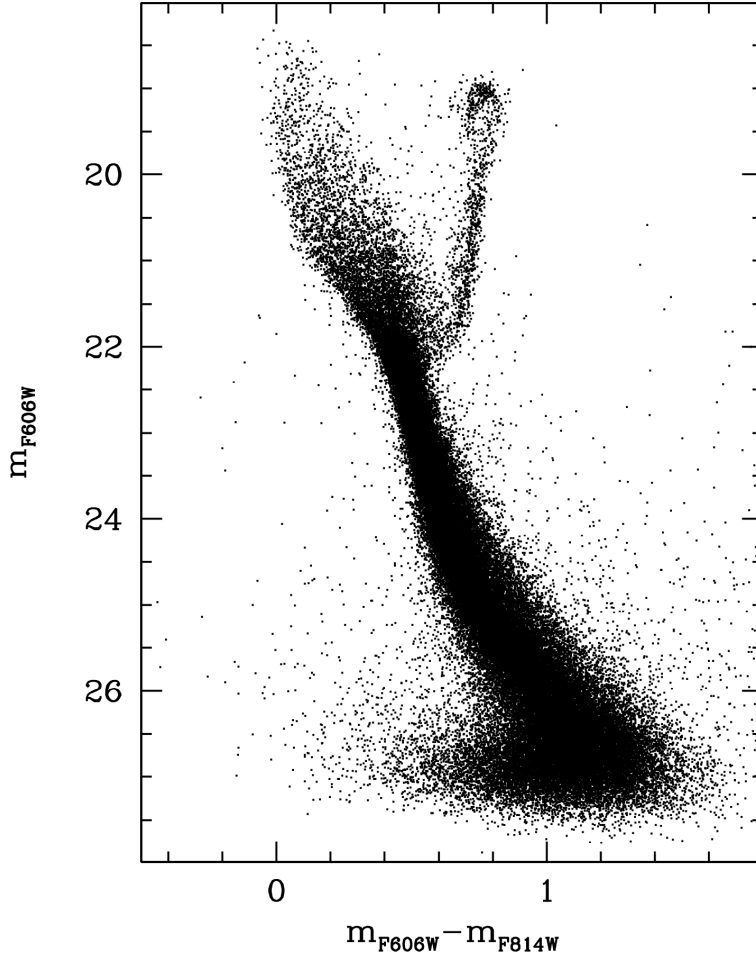


Figure 2.3: CMD of the LMC field obtained from the ACS parallel observations.

effective temperature distribution of the HB stars in NGC 1835 (see Appendix A).

We performed the cluster-to-cluster comparison in the optical (m_{F606W} , $m_{F606W} - m_{F814W}$) CMD. To maximize the accuracy of such a comparison, we first constructed a field-decontaminated CMD of NGC 1835. We decided to perform a statistical decontamination following the prescriptions briefly summarized below. We considered an annular region of the CMD included between $5''$ and $26''$ from the cluster center. The very central region has been excluded because it is typically sampled with larger photometric errors, and the most external one is rejected to keep low the number of contaminating field stars. Then, a region with the same area has been selected in the ACS catalogue of the LMC field and, for each star of this sample, we removed one star from the cluster sample according to its position in the CMD. In particular, we flagged as the most likely interloper (and removed it from the cluster sample) the closest star (in terms of magnitude and colour) to the considered star in the LMC field sample. The procedure was repeated several times considering different LMC field regions, finding qualitatively consistent results in all the cases.

The field-decontaminated CMD of NGC 1835 thus obtained was then compared with those of the two reference clusters, M3 and M13, by using the data collected in the ACS Survey of Galactic Globular Clusters (Anderson et al., 2008). We then aligned these CMDs with that of NGC 1835 by applying appropriate shifts in magnitude and colour, chosen on the basis of χ^2 tests: for M3 we used $\Delta_{\text{mag}} = 3.78$ and $\Delta_{\text{col}} = 0.07$; for M13 we applied $\Delta_{\text{mag}} = 4.37$ and $\Delta_{\text{col}} = 0.06$. The left panel of Figure 2.4 presents the comparison between the decontaminated CMD of NGC 1835 (black dots) and the CMD of M3 (red dots). The right panel shows the same, but for M13. Most of the evolutionary sequences of NGC 1835, such as the MS and the RGB, exhibit striking similarities with those of M3 and M13. Specifically, all the three clusters show a comparable morphology of the MS-TO region and have a similar colour extensions of the sub-giant branch. Moreover, the RGBs of the three clusters display comparable extensions and slopes. These results are consistent with the three clusters having similar ages and metallicities, as discussed above.

Using the extinction coefficients $R_{\text{F606W}} = 2.8192$ and $R_{\text{F814W}} = 1.8552$ (Cardelli et al., 1989; O'Donnell, 1994) and assuming for M3 a distance modulus of $(m - M)_0 = 15.00 \pm 0.04$ (Ferraro et al., 1999a; Dalessandro et al., 2013b) and a colour excess $E(B - V) = 0.01$ (Ferraro et al., 1999a), we found $(m - M)_0 = 18.58$ and $E(B - V) = 0.08$ for NGC 1835. The same results are obtained by adopting M13 as a reference and thus assuming its distance modulus and reddening, $(m - M)_0 = 14.38 \pm 0.05$ and $E(B - V) = 0.02$ (Ferraro et al., 1999a). These findings are fully consistent with previous estimates in the literature: in fact, a reddening value of $E(B - V) = 0.08 \pm 0.02$ and a distance modulus ranging between 18.43 ± 0.12 and 18.65 ± 0.16 are quoted in Olsen et al. (1998).

To determine the absolute age of NGC 1835 we adopted the isochrone fitting technique. This consists in comparing the cluster CMD with a set of isochrones of different ages to identify the one that best reproduces the observed evolutionary sequences. We extracted isochrones from two different databases, BaSTI (Pietrinferni et al., 2021) and PARSEC (Bressan et al., 2012; Chen et al., 2015). BaSTI isochrones have been computed for $[\text{Fe}/\text{H}] = -1.7$, an α -element abundance $[\alpha/\text{Fe}] = +0.4$ (Mucciarelli et al., 2021), and a standard helium abundance $Y = 0.248$. Similarly, we downloaded solar-scaled PARSEC isochrones with a total metallicity $[\text{M}/\text{H}] = -1.4$, which corresponds to $[\alpha/\text{Fe}] = +0.4$ and $[\text{Fe}/\text{H}] = -1.7$. Both datasets were downloaded for a suitable range of ages (between 10 Gyr and 15 Gyr in steps of 0.5 Gyr). They have been superposed to the observed CMD by adopting the distance modulus and the reddening values estimated above. A small colour offset of $\delta(m_{\text{F606W}} - m_{\text{F814W}}) = 0.015$ mag (lower than the typical errors introduced by the photometric calibration) was applied to the isochrone in order to better match the data. Using χ^2 tests, we compared the isochrones and the observed data in the most age-sensitive region of the CMD (namely, the MS-TO and the sub-giant branch, in

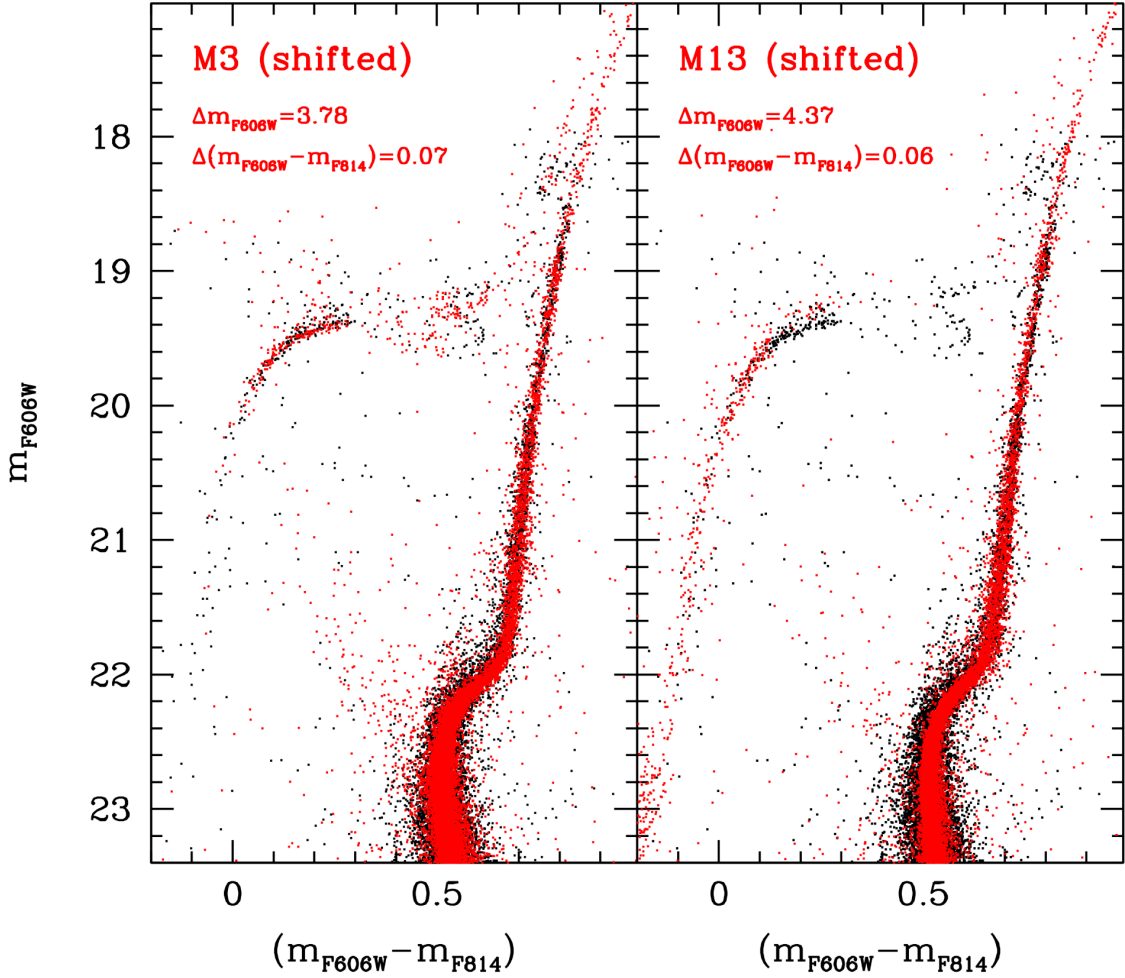


Figure 2.4: Comparison between the decontaminated CMD of NGC 1835 (black dots) and the CMDs of M3 and M13 (red dots in the left and right panels, respectively) shifted to match that of NGC 1835.

a magnitude range $21.8 < m_{\text{F606W}} < 23.0$). For a maximum photometric quality of the data and to avoid severe contamination from the LMC field, we limited the analysis to an annular region between $15''$ and $26''$ from the cluster center.

The results obtained for the two considered models are shown in Figure 2.5. The left panels depict the trend of the χ^2 values for different ages and show that, for both the adopted model, the minimum χ^2 value (i.e. the best-fit solution) is found at an age of 12.5 Gyr, with a conservative uncertainty of ± 1 Gyr. The right panels of Fig. 2.5 show the isochrones corresponding to the best-fit ages (solid red line) along with the uncertainty ranges (dashed lines).

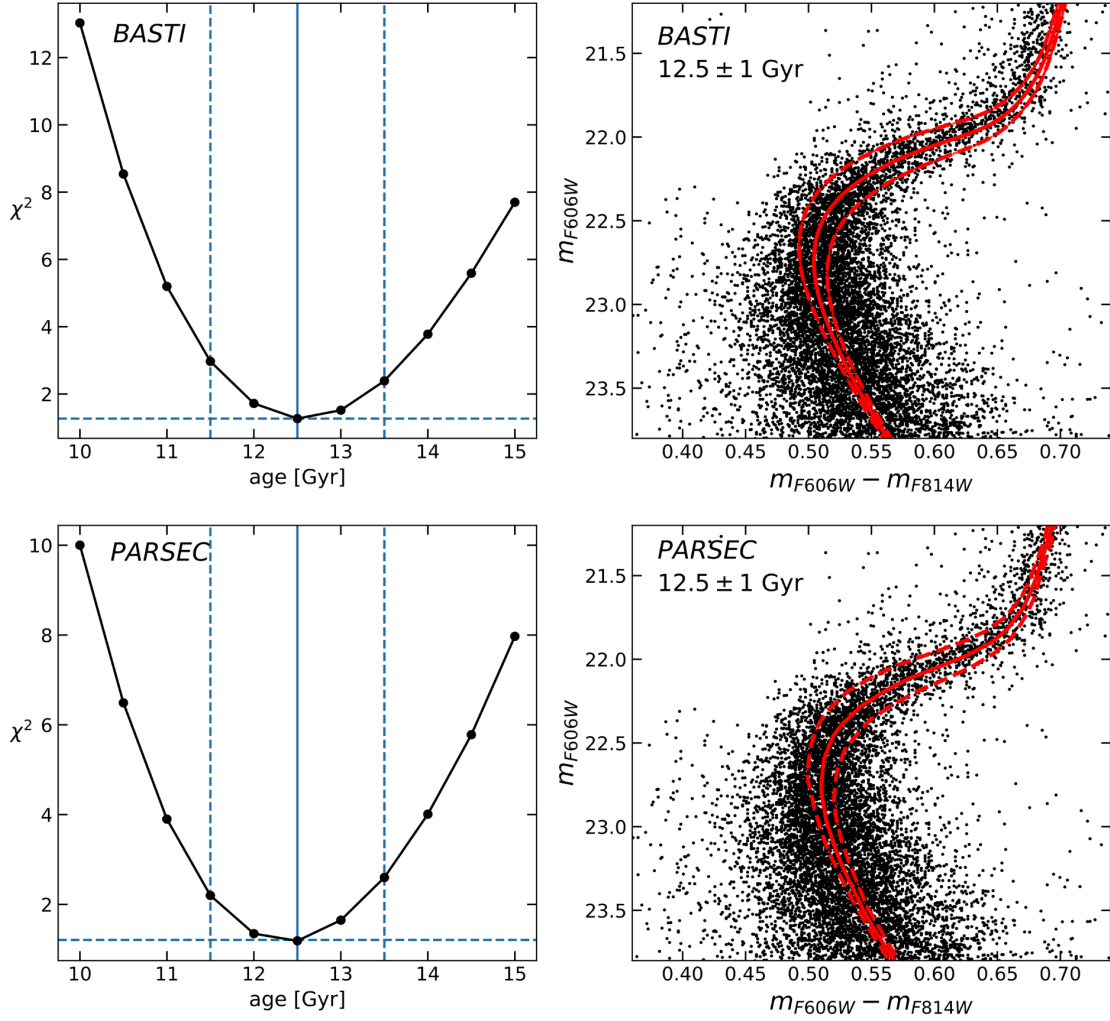


Figure 2.5: Determination of NGC 1835 absolute age. *Left panels:* Trend of the χ^2 values obtained from the isochrone fitting of the MS-TO region of the models (top and bottom panels, respectively) computed for $[\text{Fe}/\text{H}] = -1.7$, $[\alpha/\text{Fe}] = +0.4$, $Y = 0.248$, and ages ranging between 10 Gyr and 15 Gyr. *Right panels:* Decontaminated CMD of NGC 1835 with the BaSTI and PARSEC isochrones superposed (top and bottom panels, respectively), corresponding to the best-fit age (12.5 Gyr, solid lines) and the estimated age interval (± 1 Gyr, dashed lines).

2.5 Gravitational center

As already discussed in many works (e.g. Ferraro et al., 1999b, 2003a; Lanzoni et al., 2007b; Ibata et al., 2009; Miocchi et al., 2013), the precise location of the center of gravity plays a very important role in the accurate determination of the star density and surface brightness profiles. Mackey & Gilmore (2003) determined the center position of NGC 1835 from the location of the cluster’s surface brightness peak, finding: $\alpha = 05^h : 05^m : 06^s.7$, $\delta = -69^\circ : 24' : 15''$. However, this method is prone to significant biases due to the possible presence of even a few bright stars not located at the cluster’s center, because the surface brightness peak would be systematically

shifted towards them. Thanks to our high-resolution dataset, we have been able, instead, to determine the position of the gravitational center (C_{grav}) from resolved star counts using the method outlined in Montegriffo et al. (1995) (see also Lanzoni et al. 2007b, 2019).

This consists of an iterative procedure that starts from a test value of the center (e.g. a literature value) and determines the average of the coordinates of a sample of stars within a fixed distance, r . This procedure produces a new estimate of the center, from which the next iteration starts. The convergence is fixed when the difference between the position of two successive centers is less than $0.01''$. The search radius r must be chosen carefully. It should be larger than the core radius r_c ($4.76''$ for NGC 1835; Mackey & Gilmore 2003), to work in a region where the stellar density is not uniform. On the other hand, excessively large radii lead to decreased sensitivity to the central concentration. The procedure also allows for a magnitude selection of the sample stars. A faint magnitude limit is necessary to obtain sufficient statistics, but a too high value introduces spurious incompleteness effects. In consideration of these compromises, we iterated the process considering different radius values ($r \leq 10'', 15'', 20''$) and different magnitude limits ($m_{\text{F814W}} < 21.5, 22, 22.5$), ensuring in each combination a minimum of 70% completeness (see Sect. 2.7.2) and thousands of stars included within the search radius. We repeated the iterative procedure for the nine possible combinations. The final value of C_{grav} was then obtained from the average of these nine values: $\alpha = 05^h : 05^m : 6^s.71$, $\delta = -69^\circ : 24' : 14''.78$. Their dispersion provided us with an uncertainty $\sigma = 0.25''$. Our new estimate of C_{grav} is consistent within 1σ with that quoted by Mackey & Gilmore (2003).

2.6 Star count density profile

We constructed the projected density profile of NGC 1835 from resolved star counts following the procedure described in Miocchi et al. (2013); Lanzoni et al. (2019); Raso et al. (2020). We used only evolved stars ($m_{\text{F300X}} < 22.5$), in order to work with objects of approximately the same mass and to ensure a completeness of $\sim 80\%$ in the central region. We also excluded the brightest sources ($m_{\text{F300X}} < 18$) to avoid possible biases due to saturation. We divided the WFC3 field of view into 18 radial rings centered on the cluster center (see Sect. 2.5) and we divided each ring into four sub-sectors. For each sub-sector, we counted the number of stars in it and we divided the result by the sector's area. We adopted as the density value in each ring the average of the values in the four corresponding sub-sectors, while the error was calculated as their standard deviation. The resulting projected density profile, $\Sigma_*(r)$, is shown in the left panel of Figure 2.6 (empty circles). The profile shows a central plateau out to $\sim 3''$, followed by a gradually decrease in stellar density as the

distance from the center increases. A centrally flat profile suggests that the cluster is not core-collapsed yet, since a steep power-law cusp in the innermost portion of the density distribution is expected for systems that already experienced this process (see e.g. Meylan & Heggie, 1997). In the outer regions ($r > 40''$), where the LMC field contribution becomes predominant over that of the cluster, a constant density value is observed. From averaging the values of the last 4 bins we derived the LMC mean field density ($\log \Sigma_* \sim -0.9$; see the horizontal dashed line in Fig. 2.6). We subtracted this quantity from the density value measured in each bin and we then obtained the background decontaminated profile, which is shown as filled circles in the left panel of the figure.

2.6.1 Fit of the density profile

To determine the structural parameters of NGC 1835, we determined the best-fit model to the cluster's background decontaminated density profile by comparing it with the family of spherical, isotropic, single-mass King models (King, 1966). The single-mass assumption works with our observed density profile since it was constructed by selecting a sample of stars of approximately the same mass. We followed the procedure outlined in Raso et al. (2020, see also Pallanca et al. 2023; Deras et al. 2023, 2024). It consists in a Monte Carlo Markov chain (MCMC) fitting technique assuming flat priors for the fitting parameters (namely the central density, the concentration parameter c , and the core radius r_c) and a χ^2 likelihood. The resulting best-fit model is represented by the red line in the left panel of Fig. 2.6.

From this procedure we find that NGC 1835 is a cluster characterised by a relatively high concentration parameter ($c = 1.47_{-0.14}^{+0.15}$, corresponding to a dimensionless central potential $W_0 = 6.8 \pm 0.5$), a very compact core radius $r_c = 3.5_{-0.5}^{+0.7}$ arcsec, a half-mass radius $r_h = 13_{-1}^{+3}$ arcsec, and a tidal radius $r_t = 109_{-18}^{+36}$ arcsec. Knowing the LMC distance (49.6 kpc, Pietrzyński et al. 2019) the results can be expressed as $r_c = 0.84$ pc, $r_h = 3.13$ pc, and $r_t = 26.23$ pc (see Table 2.1). Mackey & Gilmore (2003) had previously determined some of the structural parameters of the cluster by fitting the observed surface brightness profile with an EFF model (Elson et al., 1987). In particular, they find $r_c = 4.76''$, the small difference with respect to our result being likely attributable to the different adopted approaches. The residuals of the fit (see the bottom panel of Fig. 2.6) show no significant discrepancy from the trend expected from a King model profile in the central regions, further confirming that NGC 1835 is not a core collapse cluster. This is in disagreement with the work of Mackey & Gilmore (2003), where NGC 1835 was classified as a possible core collapse system since a low significance cusp was detected.

2.6.2 Surface brightness profile

To obtain further confirmation of the cluster's structural parameters, we also analyzed the surface brightness profile. The procedure is analogous to the one adopted for the density profile (see Sect. 2.6). Also in this case, we divided the WFC3 field of view into several concentric rings (21 rings from C_{grav} up to $\sim 120''$) and each ring into four sub-sectors. We adopted as integrated surface brightness of each ring the average of the four values of the corresponding sub-sectors and we assumed the standard deviation as its uncertainty. The resulting surface brightness profile obtained in the m_{F606W} filter is shown in the right panel of Fig. 2.6 (open circles). The average surface brightness of the last 3 points provided us with the mean surface brightness of the LMC background ($\mu_{\text{F606W}} \sim 21.5 \text{ mag arcsec}^{-2}$). We subtracted this value from all the observed points, obtaining the background decontaminated profile (solid circles). The fit to the profile was carried out following the same procedure described above, comparing it with the family of King models. The results have provided a King concentration index $c = 1.57 \pm 0.02$, a central surface brightness $\mu_{\text{F606W},0} = 15.6 \text{ mag arcsec}^{-2}$, a core radius $r_c = 3.45^{+0.06}_{-0.04} \text{ arcsec}$ (0.83 pc), an half-mass radius $r_h = 15^{+0.2}_{-0.3} \text{ arcsec}$ (3.61 pc), and a tidal radius $r_t = 137 \pm 3 \text{ arcsec}$ (32.72 pc). All these quantities are in good agreement within the errors with the results obtained from the fit of the star count density profile. Even in this case, no evidence of central cusp is found.

2.7 Measuring the dynamical age

Under the assumption of a spherically symmetric and isotropic stellar system well reproduced by a King model, we computed the central relaxation time of the cluster following Eq. (10) in Djorgovski (1993, see also Spitzer 1987):

$$t_{rc} = 1.491 \times 10^7 \times \frac{k}{\ln(0.4N_*)m_*} \rho_{M,0}^{1/2} r_c^3, \quad (2.1)$$

For a more detailed discussion of this equation and its terms, see Sect. 1.2.

To measure $N_* = M/m_*$ we adopted the cluster total mass provided in Mackey & Gilmore (2003) ($\log M/M_\odot = 5.83$ that was estimated by using a mass-to-light ratio $M/L_V = 3.56$), rescaled to $M/L_V = 2$, which is the typical value for 10-13 Gyr old clusters (Maraston, 1998). In addition, to keep the work consistent with the assumptions of Ferraro et al. (2019), we measured the central mass density $\rho_{M,0}$ from the equations (4), (5), (6) of Djorgovski (1993), respectively:

$$\rho_{M,0} = \frac{\Sigma_0}{r_c p}, \quad (2.2)$$

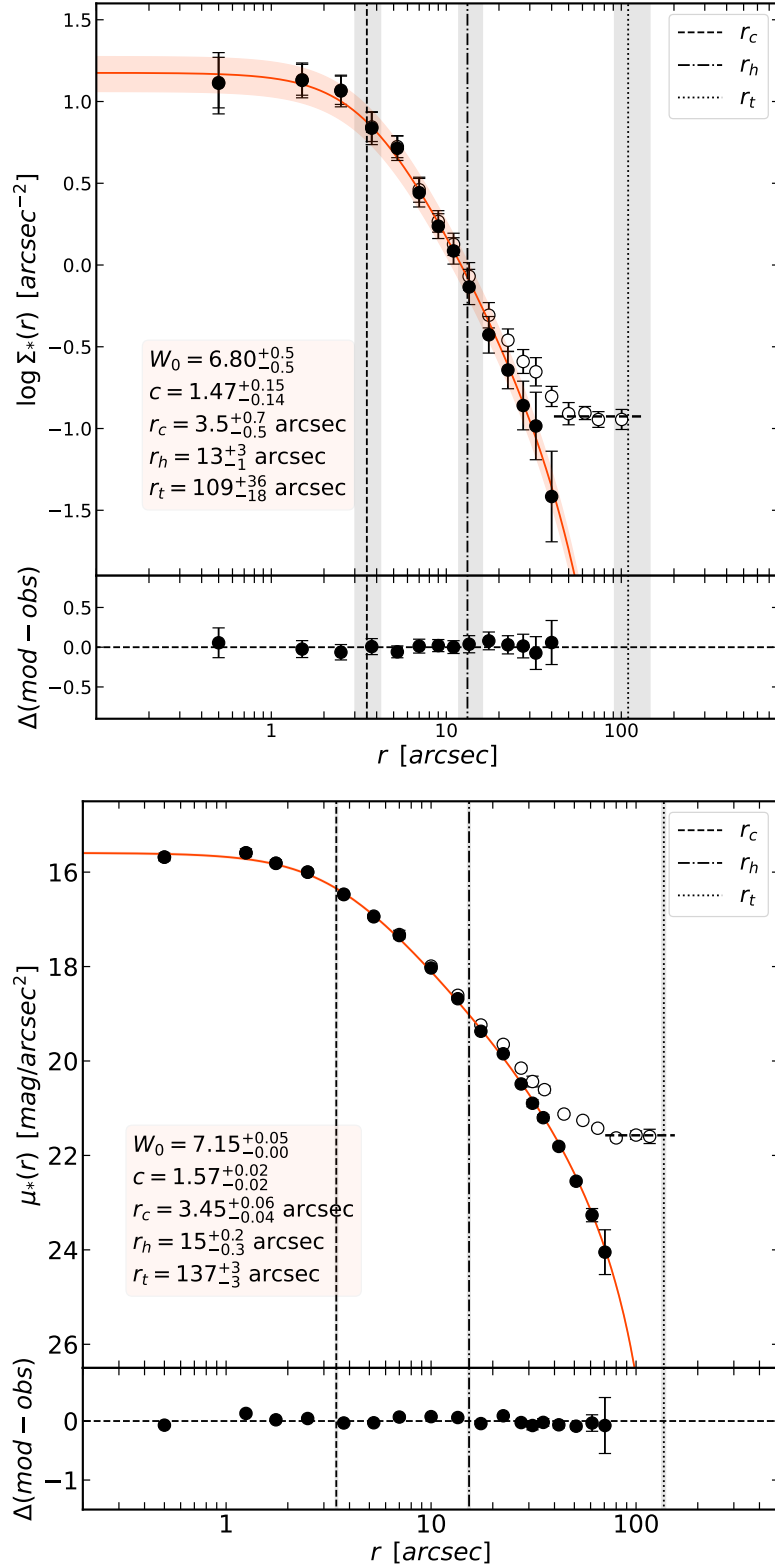


Figure 2.6: Density and brightness profiles of NGC 1835. *Left panel:* Projected density profile of NGC 1835 obtained from star counts in concentric annuli around the cluster center (empty circles). The horizontal dashed line marks the LMC field density that has been subtracted from the observed points to determine the background subtracted profile (filled circles). The solid red line represents the best-fit King model to the cluster density profile, and the red stripe outlines the range of $\pm 1\sigma$ solutions. The vertical lines mark the locations of the core radius (dashed line), half-mass radius (dot-dashed line), and tidal radius (dotted line), with their respective 1σ uncertainties indicated with grey stripes. The values of the main structural parameters determined from the fitting process are also marked (see details in the main text). *Right panel:* Same as in the left panel, but for the surface brightness profile of NGC 1835 in the F606W filter.

$$\log \Sigma_0 = 0.4[26.362 - \mu_{555}(0)], \quad (2.3)$$

$$\log p = -0.603 \times 10^{-c} + 0.302. \quad (2.4)$$

We adopted the concentration parameter c and the core radius r_c determined from the star density profile fit (see Table 2.1), and the central surface brightness $\mu_{555}(0) = 16.37$ quoted in Mackey & Gilmore (2003) for the measure of the central surface brightness Σ_0 . The result for NGC 1835 is $\log(t_{rc}/\text{yr}) = 8.16$.

We used this value to obtain a first indication about the dynamical status of the cluster through the parameter N_{relax} . This is defined as the ratio between the system's chronological age and its current central relaxation time, thus quantifying the number of t_{rc} experienced by the system during its lifetime. A high value of N_{relax} identifies dynamically evolved clusters, whereas a low value corresponds to dynamically young systems. For NGC 1835, using the chronological age measured in Sec. 2.4 (12.5 Gyr) we find $N_{\text{relax}} = 86.9$. This is one of the largest value obtained so far in the LMC (see Ferraro et al. 2023), meaning that NGC 1835 is highly dynamically evolved.

Table 2.1: Main properties of NGC 1835 estimated in this work.

Parameter	Estimated value
Center of gravity	$\alpha_{J2000} = 05^h05^m06^s.7$ $\delta_{J2000} = -69^\circ24'15''$
Age	$t = 12.5 \pm 1$ Gyr
King concentration	$c = 1.47^{+0.15}_{-0.14}$
Central dimensionless potential	$W_0 = 6.8^{+0.5}_{-0.5}$
Core radius	$r_c = 3.5^{+0.7}_{-0.5}$ arcsec (0.84 pc)
Half mass radius	$r_h = 13^{+3}_{-1}$ arcsec (3.13 pc)
Tidal radius	$r_t = 109^{+36}_{-18}$ arcsec (26.23 pc)
Central relaxation time	$\log t_{rc} = 8.158$ (yr)
Age/Central relaxation time	$N_{\text{relax}} = 86.9$

2.7.1 Selection of BSSs and reference population

The first step for estimating the A_{rh}^+ parameter of NGC 1835 is to select its population of BSSs and reference stars. In a cluster's CMD, BSSs are found in the region bluer and brighter than the cluster MS-TO. We followed the selection procedure already described in several works (see Ferraro et al. 1992, 2001, 2003b, 2023).

Due to effective temperatures larger than those of MS and RGB stars, BSSs are best selected in CMDs built with blue and possibly UV filters. We therefore drew

the BSS selection box in the $(m_{\text{F300X}}, m_{\text{F300X}} - m_{\text{F814W}})$ UV plane (see the multi-sided polygon shown in the left panel of Figure 2.7). We constructed the left side of the polygon by adopting as an approximate reference the cluster zero-age main sequence (ZAMS), represented in the figure by a PARSEC (Marigo et al., 2017) isochrone with a very young age (40 Myr, red dotted line). The top and right-hand sides are designed to exclude the bulk of HB and RGB stars. In general, the location of the bottom side of the box is somehow arbitrary, as there is no clear division between the MS-TO and BSSs. Usually, it is assumed that the BSS population begins 4-5 σ magnitudes above the MS-TO, where σ is the photometric error at this magnitude level. However, both to minimise the risk of contamination from MS-TO stars and blends, and to increase the efficiency of the A_{rh}^+ parameter, Ferraro et al. (2018a) selected only the brightest portion of the BSS sequence, where the most massive BSSs are expected to be located. Thus, they considered only BSSs that are approximately $0.2M_{\odot}$ more massive than MS-TO stars. To construct the stellar evolutionary tracks in the F300X, we downloaded PARSEC isochrones[†] (Marigo et al., 2017) in this filter in a very wide age range (500 Myr-21 Gyr) in steps of 10 Myr and with properties compatible with those of NGC 1835: metallicity $[\text{Fe}/\text{H}] = -1.7$ and α -element abundance $[\alpha/\text{Fe}] = +0.4$ (Mucciarelli et al., 2021), and standard helium abundance ($Y = 0.248$). The track corresponding to the $0.8M_{\odot}$ stars (rightmost solid line in Fig. 2.7), as expected, reproduces the MS-TO region well. Hence, we adopted as threshold for the bright BSS sample the position of the $1M_{\odot}$ evolutionary track (leftmost solid line in Fig. 2.7). The final BSS sample is shown by the blue circles in the figure, and it contains 86 objects.

Since the MS-TO region is contaminated from LMC field stars, we chose the RGB stars as reference population. We selected them in the optical CMD (where they appear more evident and brighter than hot populations) and in a magnitude range similar to that covered by the BSS sample in this plane (see the black box in the right panel of Fig. 2.7). This avoids both faint magnitudes, to prevent incompleteness problems, and bright magnitudes, to prevent saturation effects. We obtained a very rich final sample of 596 objects. Given the large statistics of this sample, small differences in the selection lead to negligible differences in the value of A_{rh}^+ (see below).

2.7.2 The A_{rh}^+ parameter

As mentioned in Sect. 1.4.1, the A_{rh}^+ parameter is defined as the area enclosed between the normalised cumulative radial distribution of BSSs and that of a reference population of lighter stars, counted within one half-mass radius from the cluster center. To obtain a meaningful value of A_{rh}^+ , it is therefore crucial to assess the level

[†]<http://stev.oapd.inaf.it/cgi-bin/cmd>

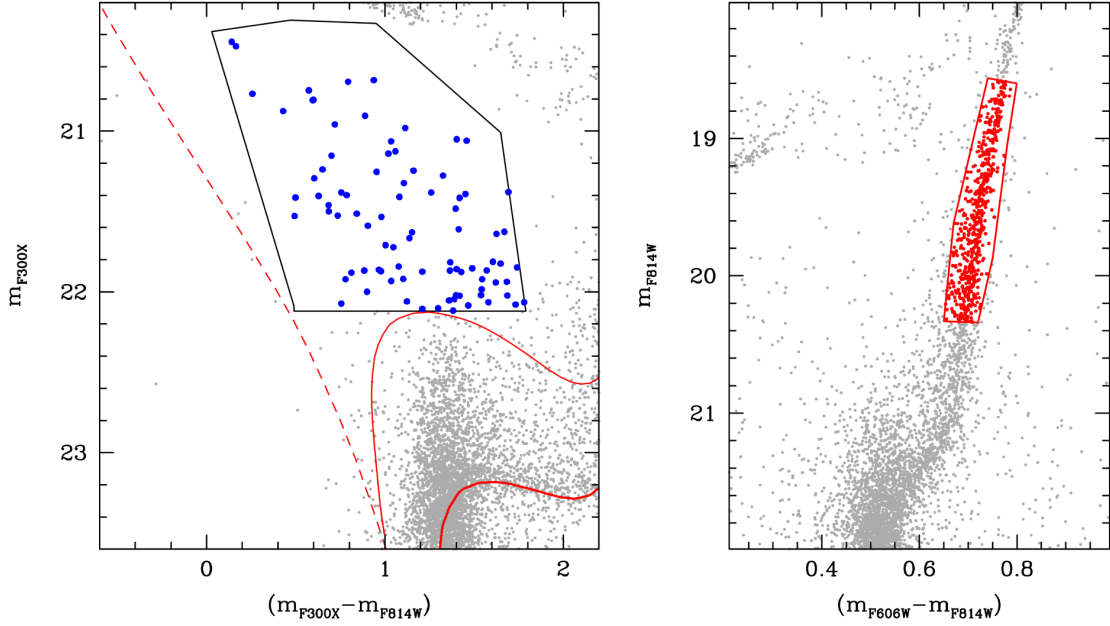


Figure 2.7: BSS and RGB samples selection. *Left panel:* Near-UV CMD of NGC 1835, with the selected BSS sample shown with blue circles. The rightmost solid line is the evolutionary track corresponding to a mass of $0.8M_{\odot}$. The leftmost solid line is the evolutionary track of a $1M_{\odot}$ mass. The dotted line is the PARSEC isochrone corresponding to a very young age (40 Myr), representing the cluster ZAMS. *Right panel:* Optical CMD of NGC 1835, with the selected RGB sample shown with red circles.

of photometric completeness and of field contamination of both population.

To estimate the completeness information, we carried out artificial star experiments using the prescriptions discussed in Dalessandro et al. (2015); Cadelano et al. (2020b). We determined the mean ridge lines of the BSS sequence (down to $m_{F300X} \sim 23$) and of the RGB+MS population (between $m_{F814W} \sim 17.8$ and $m_{F814W} \sim 26$) in the $(m_{F606W}, m_{F300X} - m_{F606W})$ and $(m_{F606W}, m_{F606W} - m_{F814W})$ CMDs, respectively. We then generated a list of artificial stars with an input m_{F606W} magnitude within the considered range, and assigned to each star the corresponding $(m_{F300X} - m_{F606W})$ or $(m_{F606W} - m_{F814W})$ colour according to the respective mean ridge line. These artificial stars have then been added to the acquired images using the DAOPHOT/ADDSTAR software. They have been positioned in a grid of cells with side corresponding to ten times the typical full width at half maximum of the point spread function and, in order to avoid artificial crowding effects, only one star at a time was simulated in each cell. Using the point spread function model already derived, we repeated the data reduction process in the multiple modified images, and we obtained a catalogue of ~ 454000 and ~ 208100 stars for the BSS and the MS+RGB populations, respectively. We simulated the stars only for the WFC3 UVIS1 detector. This choice is dictated by the fact that the A_{rh}^+ parameter is determined from the stars located within one half-mass radius, which is just $13''$

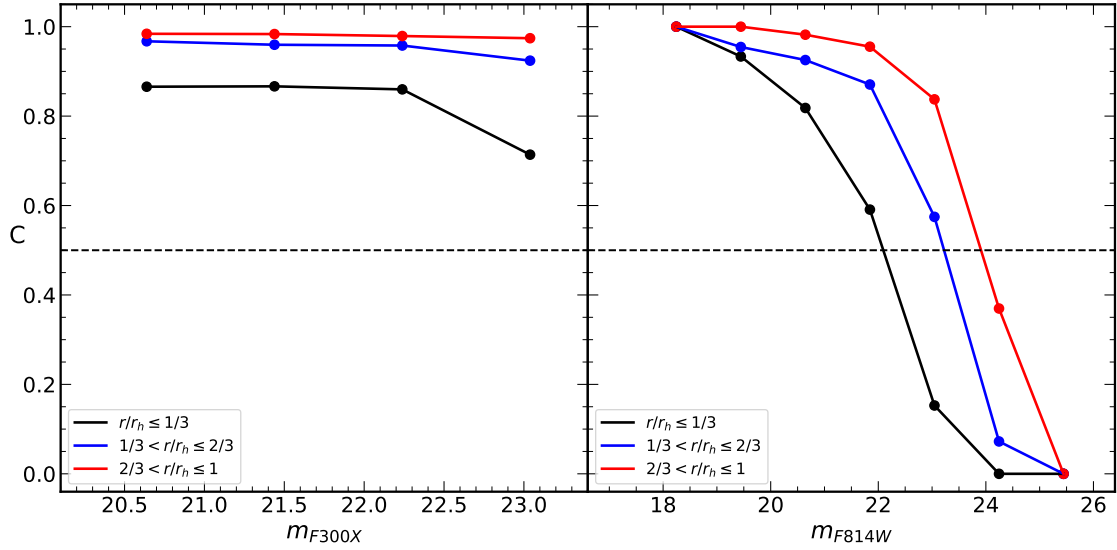


Figure 2.8: Completeness curves of the BSS and MS+RGB populations as a function of the m_{F300X} and the m_{F814W} magnitudes, respectively (left and right panels). The different line colours refer to three different radial distances from the cluster center (see the labels).

for NGC 1835 (see Sect. 2.6). The completeness C is defined as the ratio between the number of stars recovered in output at the end of the artificial star test (N_o), and the number of input stars actually simulated (N_i). The completeness curves for the three radial bins ($r/r_h \leq 1/3$, $1/3 < r/r_h \leq 2/3$, $2/3 < r/r_h \leq 1$) that will be used in the calculation of $A_{r_h}^+$ (see Sect. 2.7) are shown in Figure 2.8. The left panel shows the completeness curves as a function of the m_{F300X} magnitude in the three radial bins for the simulated BSSs, while the right panel shows C versus m_{F814W} for the simulated MS+RGB population. These results guarantee that the selected BSS and RGB populations, which extend down to $m_{F300X} \sim 22$ and $m_{F814W} \sim 20.2$, respectively, are poorly affected by incompleteness, both showing $C > 80\%$. Nevertheless, we corrected the two samples by using the derived completeness curves: to build the cumulative radial distributions, each star has been counted as $1/C$ (instead of 1), with the value of C being derived from the completeness curves based on the star magnitude and cluster-centric distance. Thus, the completeness-corrected total numbers of BSSs and RGB stars amount to 93.9 and 623.6 stars, respectively, with a correction of the observed sample of only a few percent (9% and 5%, respectively).

To correct for LMC field contamination, we took advantage of the parallel ACS observations. Indeed, the CMD plotted in the rightmost panel of Fig. 2.9 shows that both the BSS and the RGB regions suffer from a non-negligible contamination from field stars, as expected in the case of a GC located near the central bar of the LMC. The decontamination via proper motions is not possible. In fact, just another HST dataset centered on NGC 1835 is available in the archive, but it has been acquired with the Wide Field and Planetary Camera 2 (WFPC2) in 1995 (Olsen

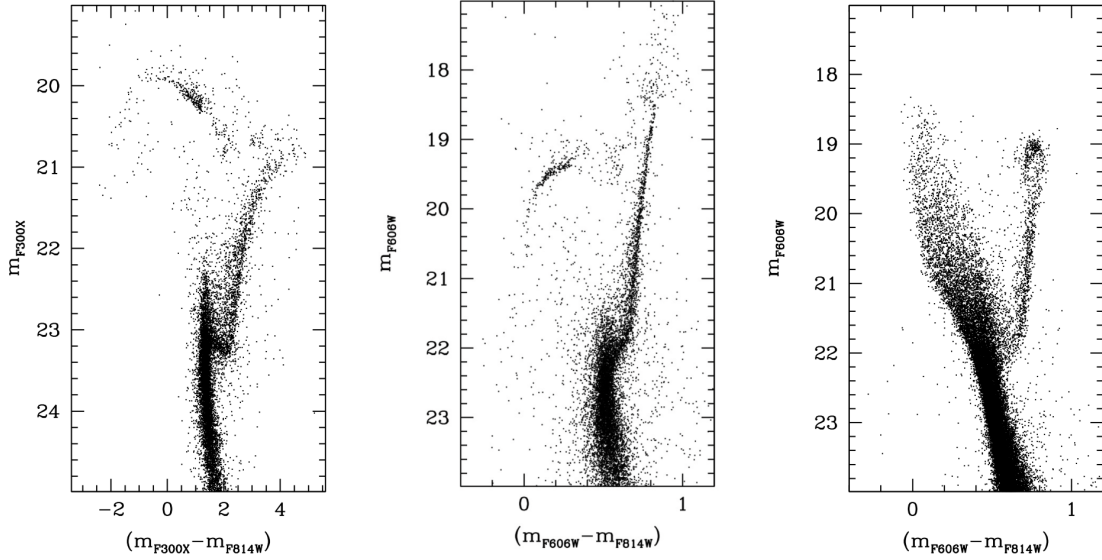


Figure 2.9: CMDs of the cluster region and the field region in different filter combinations. *Left panel:* Near-UV CMD of NGC 1835 for the stars sampled within $r < 13''$ from the center. *Central panel:* Optical CMD of NGC 1835 for the same stars as in the left panel. *Right panel:* Optical CMD of the LMC field region sampled by the ACS parallel observations.

et al., 1998), while higher quality observations and a longer time baseline would be necessary, given the distance of the LMC and the similar motion of the GC and the host galaxy. For this reason, we decided to perform a statistical decontamination exploiting the parallel ACS pointing (e.g. Dalessandro et al., 2019). First of all, since for this dataset only the F606W and F814W filters are available, we transported the BSS selection box (previously defined in the near-UV CMD; see Fig. 2.7) in the optical $(m_{F814W}, m_{F606W} - m_{F814W})$ plane. This is shown in panel (a) of Figure 2.10, where the blue circles are the BSSs selected in the near UV, and the box has been drawn to enclose them. Panel (b) shows the same box superposed to the ACS sample. The selection box of RGB stars was already defined in the optical plane, and it is shown superposed to the cluster WFC3 and the field ACS CMDs in panels (c) and (d) of Fig. 2.10, respectively. We counted the number of field stars falling in the two boxes and we divided the values by the area sampled by the ACS/WFC observations, obtaining the number density of field stars populating the CMD regions covered by the two boxes: $\rho_{\text{field,BSS}} = 0.0562 \pm 0.0012 \text{ arcsec}^{-2}$, $\rho_{\text{field,RGB}} = 0.0092 \pm 0.0005 \text{ arcsec}^{-2}$. Thus, we expect that within one half-mass radius ($r_h = 13''$), a total of 30 LMC stars contaminate the BSS sample, and 5 contaminate the RGB sample. However, the different radial distribution of field stars with respect to that of cluster stars must be taken into account for a proper field decontamination procedure. In fact, while the distribution of the LMC field is essentially uniform over the cluster size scale, the radial distributions of cluster BSSs and RGB stars follow the King profile (see Fig. 2.6), with a sensibly increasing star density towards the center

Table 2.2: Completeness-corrected samples of BSSs and RGB stars (top and bottom row, respectively), and the number of estimated field contaminants (values enclosed in the brackets). N_{TOT} is the total number of stars, while the last three columns provide the numbers of stars estimated in the three adopted radial bins.

	N_{TOT}	$N(r/r_h < 1/3)$	$N(1/3 < r/r_h < 2/3)$	$N(2/3 < r/r_h < 1)$
BSS	93.9 (30)	48.6(3)	25(10)	20.3(17)
RGB	623.6 (5)	165.6(1)	280.2(1)	177.8(3)

of the system. Thus, we divided the field of view included within r_h in the same three concentric radial annuli adopted above: $r/r_h \leq 1/3$, $1/3 < r/r_h \leq 2/3$, and $2/3 < r/r_h \leq 1$. Then, by multiplying the estimated star density by the area of each radial bin (A_{bin}), we determined the number of contaminating field stars expected in the bin: $N_{\text{field,pop}}(r) = \rho_{\text{field,pop}} \times A_{\text{bin}}$ (with pop=BSS, RGB). The resulting values are listed in Table 2.2.

To build the cumulative radial distributions, we randomly subtracted these numbers of stars from the completeness-corrected samples of BSSs and RGB stars, and we obtained the value of $A_{r_h}^+$ as the area of the region bounded by the two cumulative functions. We repeated the measurement of $A_{r_h}^+$ 100 times, each time randomly removing from the samples a number of stars equal to $N_{\text{field,pop}}(r)$ in each bin. We then adopted as final estimate of the parameter the average of the 100 values of $A_{r_h}^+$ computed in this way, finding $\langle A_{r_h}^+ \rangle = 0.30$.

Once the photometric incompleteness and field contamination are taken into account, the main uncertainty affecting the result is due to the limited statistics of the BSS sample. We therefore evaluated it by using a jackknife bootstrapping technique (see Lupton 1993). Given a sample of N BSSs, it consists in repeating the calculation of $A_{r_h}^+$ for N times, each time removing one different star. The final uncertainty is therefore calculated as $\sigma_{A_{r_h}^+} = \sigma_{\text{distr}} \times \sqrt{(N-1)}$, where σ_{distr} is the standard deviation of the N estimates of the $A_{r_h}^+$. We found $\sigma_{A^+} = \pm 0.04$. One of the random realizations of the cumulative radial distributions of BSSs (blue curve) and RGB stars (in red) is shown in Figure 2.11, where the grey-shaded area represents the $A_{r_h}^+$ parameter.

2.8 Discussion and conclusions

The result obtained for NGC 1835 can now be compared with the outcomes of previous works. Similar studies have been conducted for a total of 52 Galactic GCs (48 systems in Ferraro et al. 2018a, NGC 6256 in Cadelano et al. 2022b, and three other clusters in Ferraro et al. 2023), plus a total of seven clusters in the

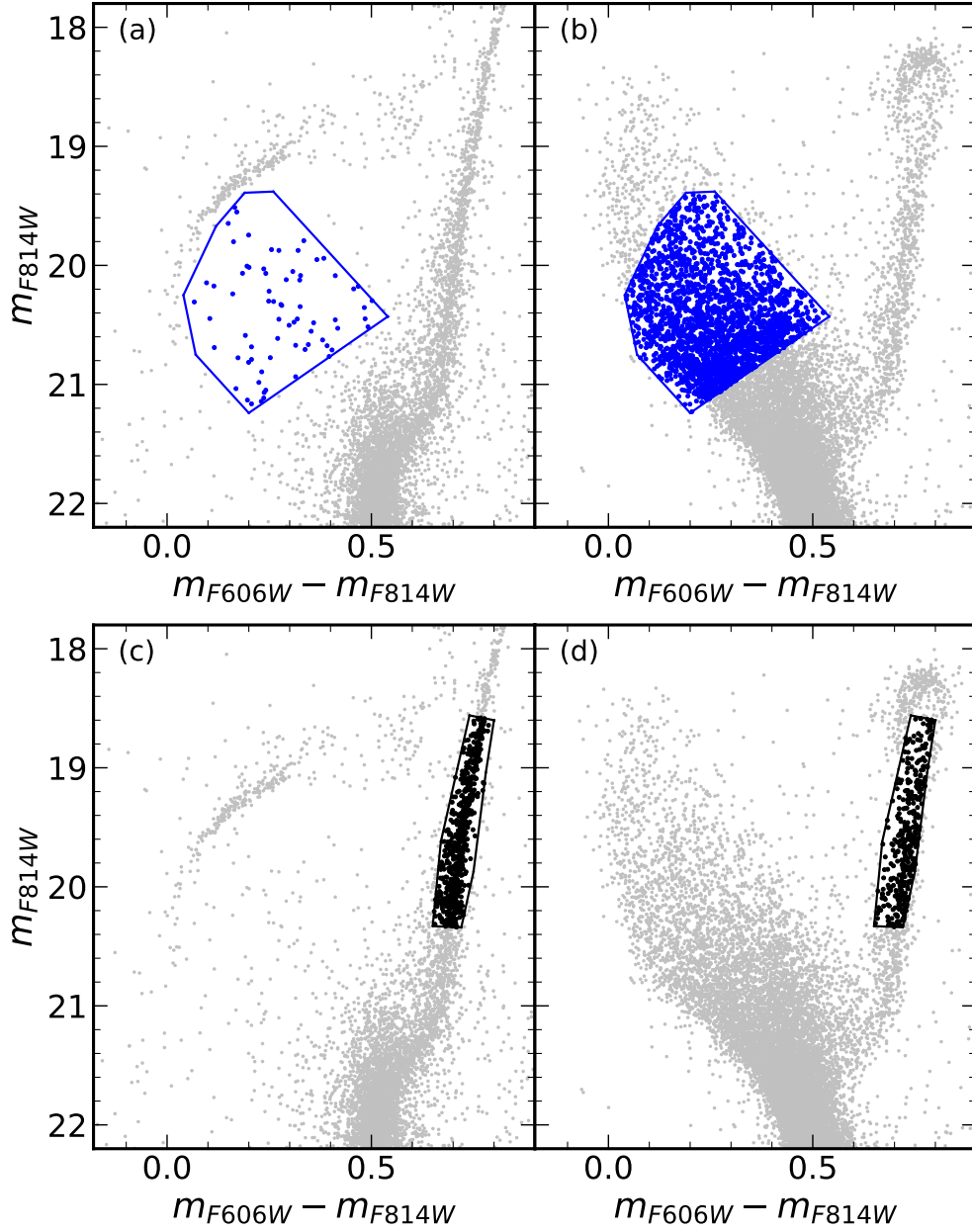


Figure 2.10: Decontamination process for the BSS and RGB samples. *Panel (a):* Optical CMD for the stars sampled by the WFC3 observations within one half-mass radius from the cluster center (grey dots). The blue circles mark the position of the BSSs selected using the near-UV box drawn in Fig. 2.7, and the blue contour enclosing these objects is the adopted BSS selection box in the optical CMD. *Panel (b):* Optical CMD of the stars sampled by the ACS parallel observations (grey dots). The blue contour is the optical selection box defined in panel (a), and the blue circles mark all the stars included within it. *Panel (c):* Optical CMD for the WFC3 stars sampled within one half-mass radius from the cluster center (grey dots). The RGB selection is marked in black. *Panel (d):* Optical CMD of the ACS stars sampled (grey dots), with the same selection box marked in panel (c). The black circles highlight the stars included within it.

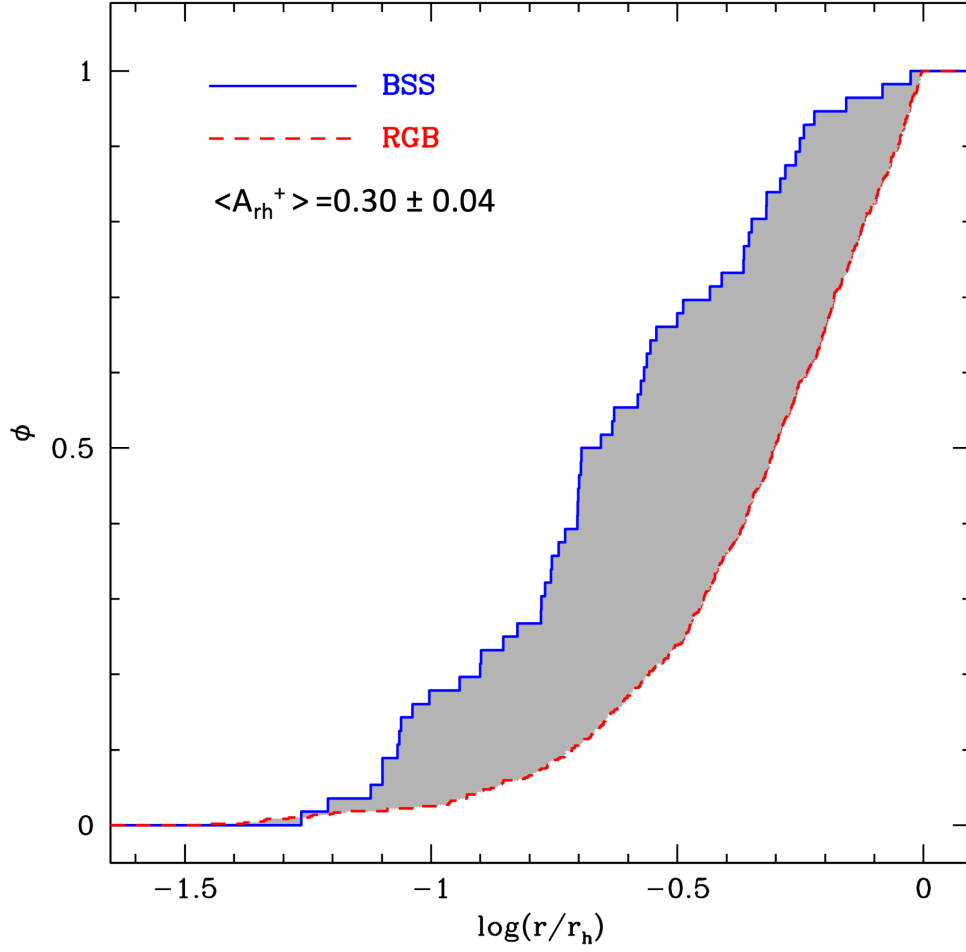


Figure 2.11: Normalized cumulative radial distributions of BSSs (solid blue line) and RGB stars (dashed red line) in one of the random realizations used to estimate the A_{rh}^+ parameter in NGC 1835. The area enclosed between the two curves corresponds to the value of A_{rh}^+ (see the label).

Magellanic Clouds (five old systems in the LMC and two young ones in the SMC; see Ferraro et al. 2019 and Dresbach et al. 2022, respectively). The left panel of Figure 2.12 shows the trend between N_{relax} and the value of A_{rh}^+ for all the clusters consistently investigated in previous studies and for NGC 1835 (shown in red). As discussed in Sect. 1.4.1, both the Milky Way clusters (in grey) and the Magellanic Cloud clusters (in yellow) exhibit a clear correlation, indicating that the dynamical clock parameter can also provide a measure of a cluster’s dynamical ages outside the MW. Notably, the new result for NGC 1835 lies precisely along the previously established correlation, thereby providing compelling evidence that this dynamical relation extends beyond the Milky Way and reinforcing the robustness of the dynamical clock parameter.

In addition, the value of A_{rh}^+ seems to be a very promising discriminator between non-core-collapsed and core-collapsed clusters. In fact, Ferraro et al. (2023) show that

seven Galactic GCs with measured A_{rh}^+ and classified as post-core-collapsed clusters based on evidence of a central cusp in their density profile all exhibit $A_{rh}^+ > 0.29$. In this respect, NGC 1835 (for which we estimate $A_{rh}^+ = 0.30 \pm 0.04$) is likely on the verge of core collapse.

The right panel of Fig. 2.12 shows the relationship between A_{rh}^+ and the core radius for the same systems. As already discussed in Sect. 1.5, it shows that clusters with a larger core radius correspond to dynamically younger systems, characterized by a low degrees of spatial segregation of their most massive visible stars (corresponding to lower A_{rh}^+ values), while those with a smaller core radius are in more advanced dynamical stages with a stronger degree of mass segregation. NGC 1835 falls nicely along this anti-correlation, showing the highest value of A_{rh}^+ in the LMC (hence, the most advanced dynamical age), consistent with its very small core radius. So, while Mackey et al. (2008) proposed resolving the size–age conundrum by taking into account the action of binary black holes that progressively drive the core expansion of the systems, the range of cluster core radii may simply be a consequence of differences in the clusters’ dynamical ages.

In conclusion, this study of the structure of NGC 1835 and the degree of segregation of its BSS builds on previous investigations by (i) adding information about a dynamically old cluster characterized by a significant BSS spatial segregation and (ii) bridging the gap between the dynamical characterization of clusters in the MW and the Magellanic Clouds.

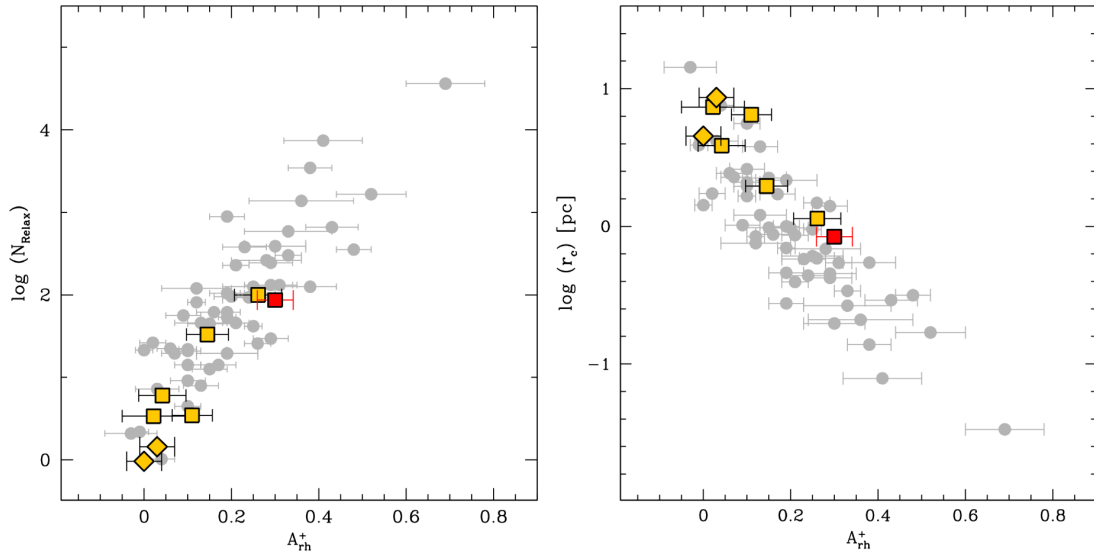


Figure 2.12: Final results for NGC 1835 in comparison with other clusters. *Left panel:* Relation between N_{relax} and A_{rh}^+ for the star clusters homogeneously investigated so far through the dynamical clock approach: the 52 Galactic GCs discussed in Ferraro et al. (2023) are shown as grey circles, the five LMC clusters discussed in Ferraro et al. (2019) are plotted as yellow squares, the two young star clusters in the SMC discussed in Dresbach et al. (2022) are marked as yellow diamonds, and the determination of NGC 1835 obtained in this work is plotted as a filled red square. *Right panel:* Relation between r_c and A_{rh}^+ for the same star clusters plotted in the left panel (same symbols).

CHAPTER 3

The globular cluster NGC 1754

*Mainly based on:
Giusti et al. (2025), A&A, 699, 143*

3.1 Introduction

This chapter presents a high-angular-resolution, multi-wavelength investigation of the massive, ancient globular cluster NGC 1754 in the LMC ($\log M = 5.39M_{\odot}$, $t \sim 15$ Gyr). In particular, we examined its chronological age, structural parameters, and dynamical state.

We used the high-resolution images taken with the WFC3/HST instrument in the F300X, F606W, F814W. The high quality of the images made it possible to construct the star density profile from resolved star counts, and to fit the observed profile with an appropriate King model to obtain the structural parameters (e.g., core, half-mass, and tidal radii). Our findings confirm that NGC 1754 is a very compact globular cluster with a core radius of only 0.84 pc. The analysis of the same dataset allowed us to confirm a very old age ($t = 12.8 \pm 0.4$ Gyr) for this system, providing further support for the idea that the process of globular cluster formation started at the same cosmic time in both the LMC and the Milky Way, independently of the characteristics of the host environment.

We also used the “dynamical clock” method to estimate the dynamical age of the system. This procedure yielded a value of $A_{rh}^+ = 0.31 \pm 0.07$, which is the highest measured so far for LMC clusters. This value indicates an advanced dynamical age for the cluster, which is possibly on the verge of core collapse. The results presented here for NGC 1754 confirm that the natural dynamical evolution of globular clusters plays a role in shaping the age–core radius distributions observed in the LMC.

3.2 Dataset

For the photometric analysis of the cluster, we used a set of 16 high-resolution images taken by the WFC3/HST, with the UVIS1 channel centered on the cluster (see left panel of Fig. 3.1). Specifically, six images (3×927 s, 1×939 s, 1×940 s, 1×953 s) were acquired in the near-UV F300X filter, six (5×414 s, 1×415 s) in the F606W, and four (2×657 s, 2×700 s) in the F814W. The use of the UV filter is crucial in this investigation since it offers optimal sensitivity to the detection of hot stars, as BSSs and stars on the hot HB (see Ferraro et al. 1997a, 2001).

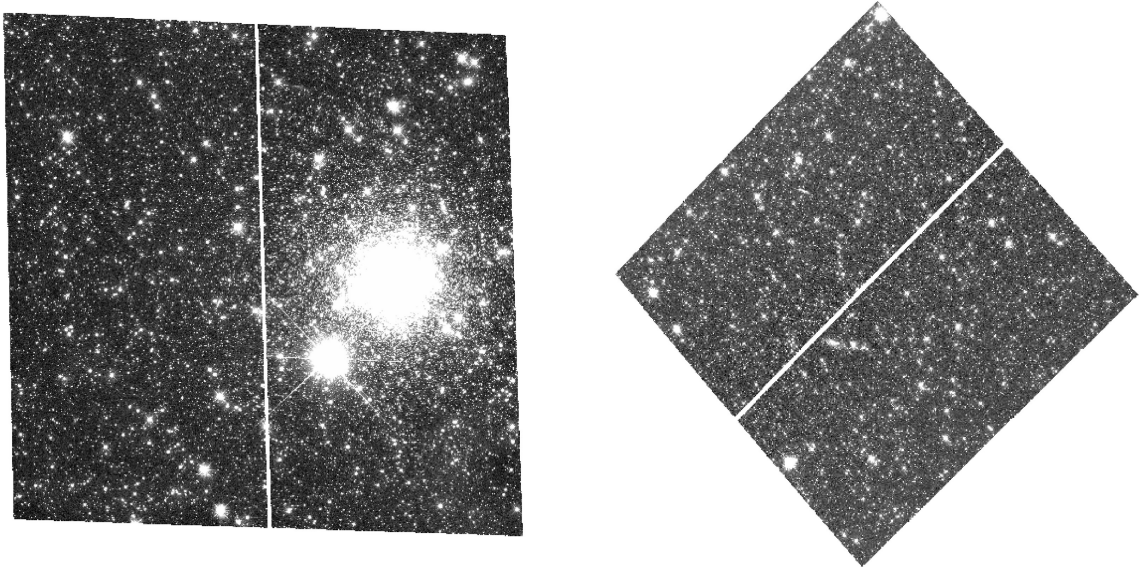


Figure 3.1: Left panel: WFC3/HST image of the cluster NGC 1754 in the F606W filter. Nord is up and est is left. Right panel: ACS/HST image of the reference LMC field region at $5'$ from the center of the cluster in the F606W filter. Nord is up and est is left.

The information from this dataset was complemented with a second one consisting of 13 images taken by the ACS/HST in optical filters (F606W and F814W) and sampling a field region located at $\sim 5'$ from the center of NGC 1754 (see right panel of Fig. 3.1). The data reduction of both datasets was performed using the DAOPHOT II software (Stetson, 1987) with a procedure similar to that used in Chap. 2 (see also Cadelano et al. 2017; Onorato et al. 2023; Chen et al. 2021, 2023). We obtained the PSF model corresponding to each image in each filter by using approximately 200 bright, isolated, unsaturated stars as a reference. We performed a search for the sources at a level of approximately 5σ from the background and fitted the PSF model to each of these sources. We then created a master-list including all the sources detected in at least half of the images of each chip, and we used the command ALLFRAME to force the fit of these stars to their corresponding

positions in all the other images. This approach allowed us to retrieve previously missed hot stars (such as BSSs and white dwarfs), while at the same time recovering the faintest part of the MS. For each identified star, the magnitudes estimated in different images were combined using DAOMATCH and DAOMASTER. In the end, we obtained a catalog with instrumental magnitudes and instrumental positions for ~ 53400 sources in the WFC3 dataset, and ~ 25300 stars in the ACS dataset. We then applied the standard calibration process to these sources, converting the magnitudes to the VEGAMAG reference system by applying the appropriate aperture corrections and the zero points found on the HST website. Finally, after correcting for geometric distortions using the coefficients of Bellini et al. (2011) for WFC3 and of Meurer et al. (2003) for ACS, the catalogs were astrometrized by cross-correlation with a Gaia Data Release 3 catalog (Gaia Collaboration et al., 2023) of the same area, so that the coordinates have been transferred to the absolute coordinate system (α, δ) .

In Figs. 3.2 and 3.3 we present, respectively, the CMD of the cluster obtained from the reduction of the WFC3 dataset in all filter combinations, and the CMD of the field region from the ACS dataset. As expected, the cluster CMD exhibits some field contamination. Specifically, in the optical CMDs the MS and the RGB of the field nearly overlap with those of the cluster. In contrast, in the CMDs using the F300X filter, the RGBs of the field and the cluster are well separated. Despite field contamination, the cluster sequences remain clearly visible, with a MS ranging down to magnitude $m_{F814W} \sim 26$ and the turnoff located at $m_{F814W} \sim 21.5$. The HB is distinguishable in the magnitude range $18.5 \leq m_{F814W} \leq 21$, crossing the extended blue plume of the field. In particular, along the HB in the $m_{F814W}, m_{F606W} - m_{F814W}$ CMD it is possible to appreciate a group of stars at redder colors ($0.6 \leq (m_{F606W} - m_{F814W}) \leq 0.8$) and another one at bluer colors ($0 \leq (m_{F606W} - m_{F814W}) \leq 0.4$), separated by the instability strip region.

3.3 Gravitational center

We reevaluated the position of the gravitational center of the cluster through the iterative procedure first described in Montegriffo et al. (1995, see also Lanzoni et al. 2007b, 2019). The high spatial resolution of the images allowed the determination of the center by averaging the positions (right ascension and declination) of the stars located within a fixed distance d from a first-guess value, and selected brighter than a certain magnitude limit. As already mentioned in Sect. 2.5, this approach helps minimize biases that can arise when identifying the gravitational center with the location of the brightness peak, especially in the presence of very bright stars. Specifically, the procedure starts with a first-guess estimate of the center (in our case, the literature value provided by Mackey & Gilmore 2003, $\alpha = 04^h : 54^m :$

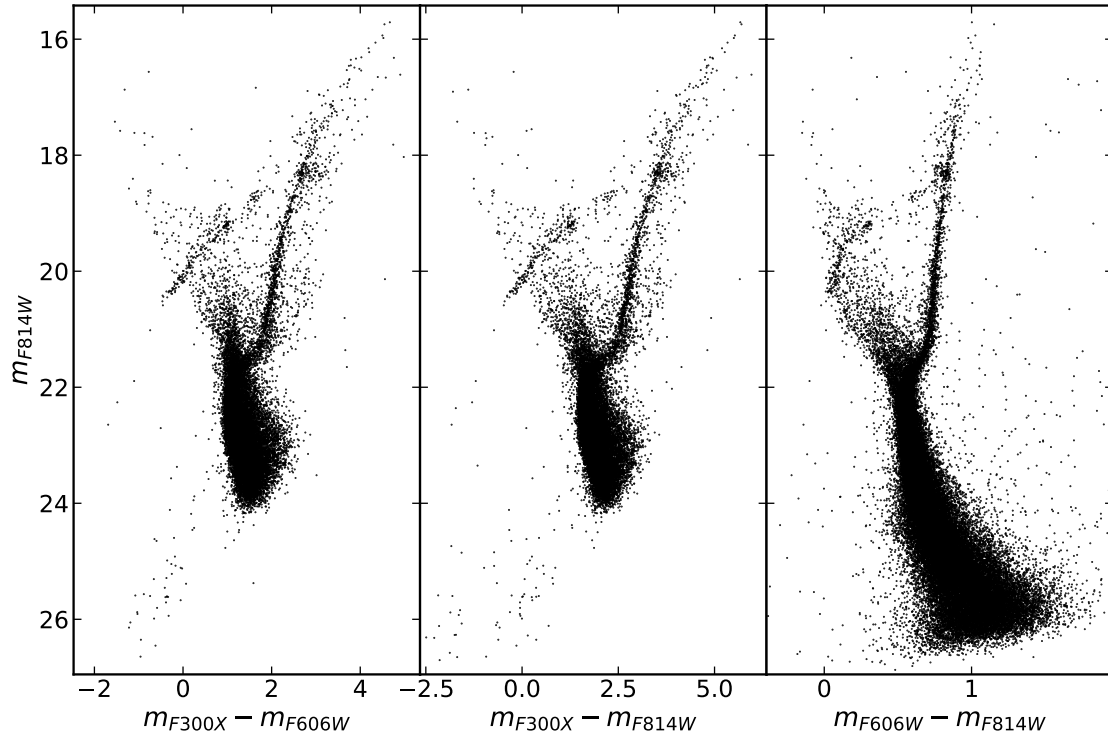


Figure 3.2: CMD of NGC 1754 obtained from the data reduction of the WFC3 dataset in all the filter combinations.

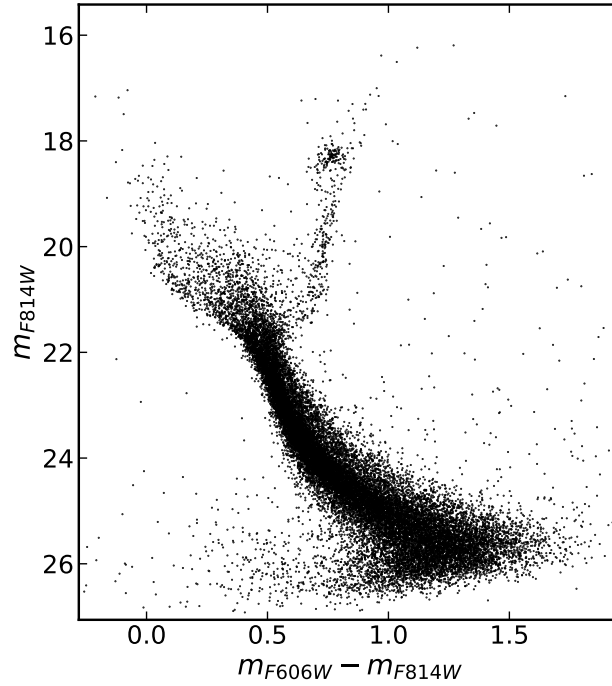


Figure 3.3: CMD of the field region obtained from the data reduction of the ACS dataset.

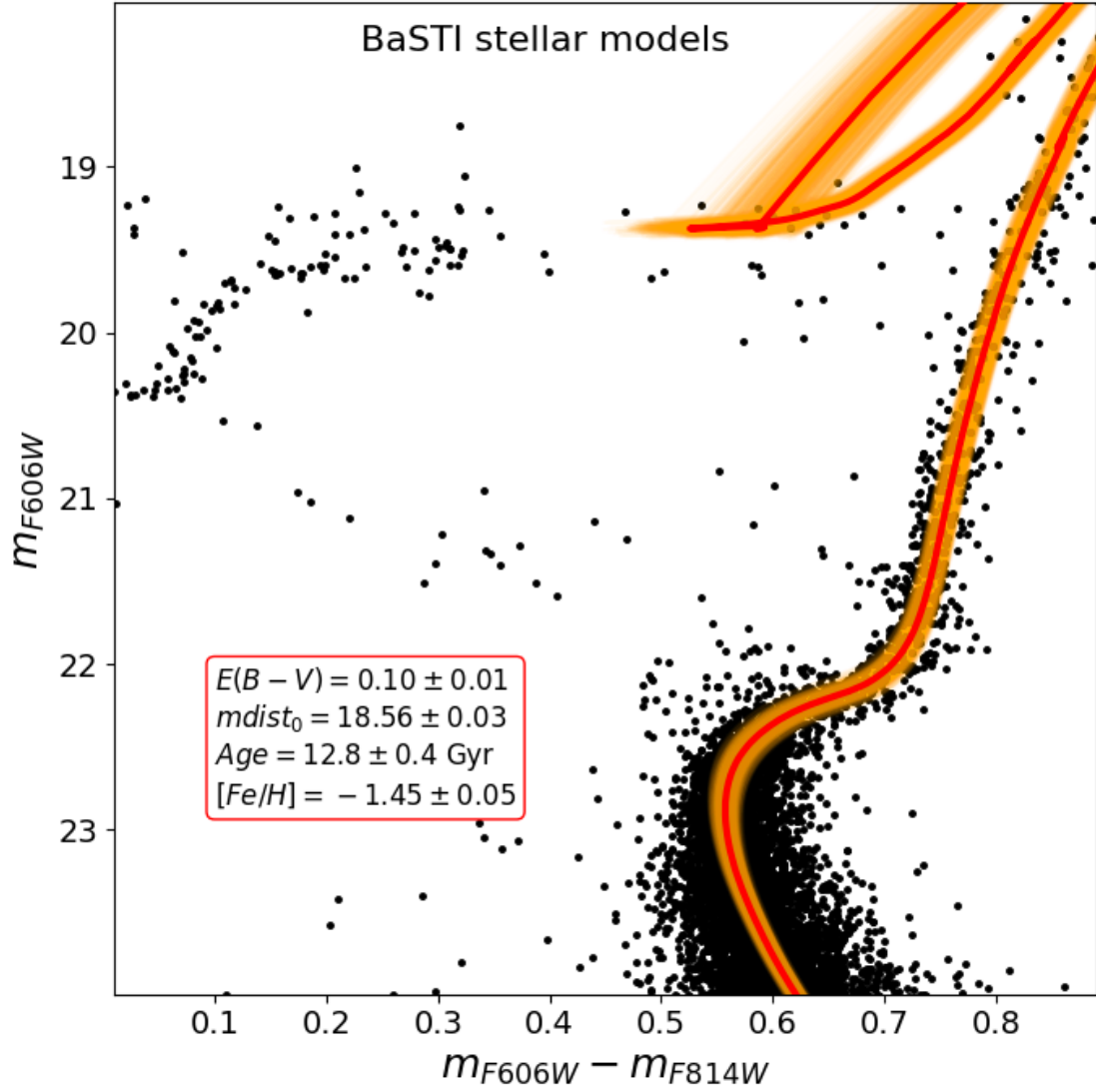


Figure 3.4: Field-decontaminated CMD of NGC 1754 in the radial annulus between 5'' and 30'' (black dots), with the best-fit BASTI isochrone superposed as a red line. The orange-shaded envelope represents the 1σ uncertainty region of the best-fit isochrone. The best-fit values for the reddening $E(B-V)$, distance modulus $(m-M)_0$, age (t), and metallicity ($[\text{Fe}/\text{H}]$) are also labeled.

$18^{\text{s}}.9$, $\delta = -70^{\circ} : 26' : 31''$). The selection distance, d , must exceed the cluster's core radius ($r_c = 3.61''$, Mackey & Gilmore 2003) to avoid operating in a region of nearly constant density, which would hinder convergence. At the same time, it must remain sufficiently small to avoid losing sensitivity to the central area. Similarly, the magnitude limits are chosen as a compromise: they must be faint enough to ensure high statistical significance, while avoiding incompleteness issues. The averaged positions of the selected sample of stars yield a new center, which serves as the starting point for the next iteration. Convergence is achieved when the positions of two consecutive centers differ by less than $0.01''$. We repeated the procedure for three values of maximum distance from the center ($d < 8, 12, 16''$) and three magnitude limits ($m_{\text{F814W}} \leq 21.5, 22.0, 22.5$), thus providing nine samples of stars, each with a minimum of a few hundred objects and a completeness level above 60% (see Sect. 3.6). As expected, each of the nine center calculations resulted in small differences, influenced by perturbations in the star distribution and reflecting the natural variations within the cluster's core region. For this reason, we chose as value of the gravitational center of NGC 1754 the average of the nine determinations, namely $\alpha = 04^{\text{h}} : 54^{\text{m}} : 18.6549^{\text{s}}$, $\delta = -70^{\circ} : 26' : 31.0329''$, and their standard deviation $\sigma = 0.2$ as the error. The center thus found is only $d \sim 1.2''$ from the center of the literature.

3.4 Chronological age, reddening, and distance modulus

We determined the chronological age of the cluster using a Bayesian method similar to the one adopted in previous studies (see, e.g., Cadelano et al., 2020c; Deras et al., 2023, 2024). The procedure consists of an isochrone fitting technique that compares the observed CMD of the cluster with a set of isochrones, exploring reasonable grids of values for the relevant parameters and allowing the simultaneous estimate of the chronological age, reddening, distance modulus and metallicity. We restricted our analysis to the CMD in a radial annulus between $5''$ and $30''$, to avoid the central region where photometric errors are larger due to severe crowding and the outer region where field stars begin to have strong importance. We further reduced field star contamination by applying the statistical decontamination process described also in Sect. 2.4 (see e.g., Dalessandro et al. 2019). This procedure consists of comparing the cluster CMD (in this case the radial one between $5''$ and $30''$) with a field CMD (from the ACS dataset) in a region of equivalent area, and removing from the former the likely field interlopers. First of all, for each object present in the field CMD, we identified the closest star in the cluster CMD, with the reciprocal distance measured as the square root of the magnitude and color differences summed in quadrature. Then, we classified as possible field intruders and removed from the cluster CMD all the selected stars with reciprocal distance smaller than 0.30 magnitudes. At the

end of the cleaning process the key evolutionary sequences (RGB, sub-giant branch and the MS turnoff region) of the cluster population are clear and well defined in the CMD (see the black dots in Fig. 3.4).

We focused the comparison between the CMD and the isochrones in the regions around the MS turnoff, sub-giant branch, and the lower portion of the RGB ($21.3 < m_{\text{F606W}} < 23$), as these are more sensitive to age and metallicity variations. We used BASTI isochrones (see Hidalgo et al. 2018; Pietrinferni et al. 2021) downloaded with standard helium abundance ($Y = 0.25$) and $[\alpha/\text{Fe}] = +0.4$, for a wide range of ages (from 9.0 to 14.0 Gyr, with a step of 100 Myr) and metallicities (from $[\text{Fe}/\text{H}] = -1.8$ to $[\text{Fe}/\text{H}] = -0.95$, in steps of 0.05). The comparison between the field-decontaminated CMD and the isochrones has been performed through a MCMC sampling technique and we used the *emcee* code to sample the posterior probability distribution in the n-dimensional parameter space defined by age, distance modulus, reddening and metallicity (Foreman-Mackey et al., 2013, 2019). For the metallicity we assumed a Gaussian prior distribution with peak and dispersion values $[\text{Fe}/\text{H}] = -1.45 \pm 0.05$ (Mucciarelli et al., 2021). Gaussian priors were also adopted for the reddening and the distance modulus, using the values determined by aligning the CMDs of M3 and M13 with that of NGC 1754 for the Gaussian mean and dispersion. As also said in Chap. 2.4, M3 and M13 are twin clusters in our galaxy with a metallicity similar to NGC 1754 and well-defined parameters: $(m - M)_0 = 15.00 \pm 0.04$ and $E(B - V) = 0.01$ for M3, $(m - M)_0 = 14.32 \pm 0.05$ and $E(B - V) = 0.02$ for M13 (see, e.g., Dalessandro et al., 2013a). From the color and magnitude shifts needed to superpose their CMDs to that of NGC 1754, we found for the latter a color excess $E(B - V) = 0.13 \pm 0.02$ and a distance modulus $(m - M)_0 = 18.58 \pm 0.05$, which have been used as Gaussian priors in the MCMC procedure. When converting absolute magnitudes of the isochrones to the observed frame, we used the extinction coefficients $R_{\text{F606W}} = 2.8192$ and $R_{\text{F814W}} = 1.8552$ (Cardelli et al., 1989; O'Donnell, 1994).

Figure 3.4 shows the best-fit isochrone (solid red line) with its 1σ uncertainty (orange shaded envelope) superposed to the field-decontaminated CMD of NGC 1754 (black dots). The best-fit values obtained with this procedure are an age $t = 12.8 \pm 0.4$ Gyr, a reddening $E(B - V) = 0.10 \pm 0.01$, a distance modulus $(m - M)_0 = 18.56 \pm 0.03$, and a metallicity $[\text{Fe}/\text{H}] = -1.45 \pm 0.05$. The uncertainties are determined using the MCMC procedure, by calculating the 16th and 84th percentiles of each parameter's probability distribution. The reddening and distance modulus obtained in this work are compatible, within the errors, with the literature values quoted in Olsen et al. (1998), namely $E(B - V) = 0.09 \pm 0.02$ and $(m - M)_0$ ranging between 18.60 ± 0.16 and 18.70 ± 0.16 . In addition, the metallicity value is fully consistent with that measured from spectroscopy by Mucciarelli et al. (2021).

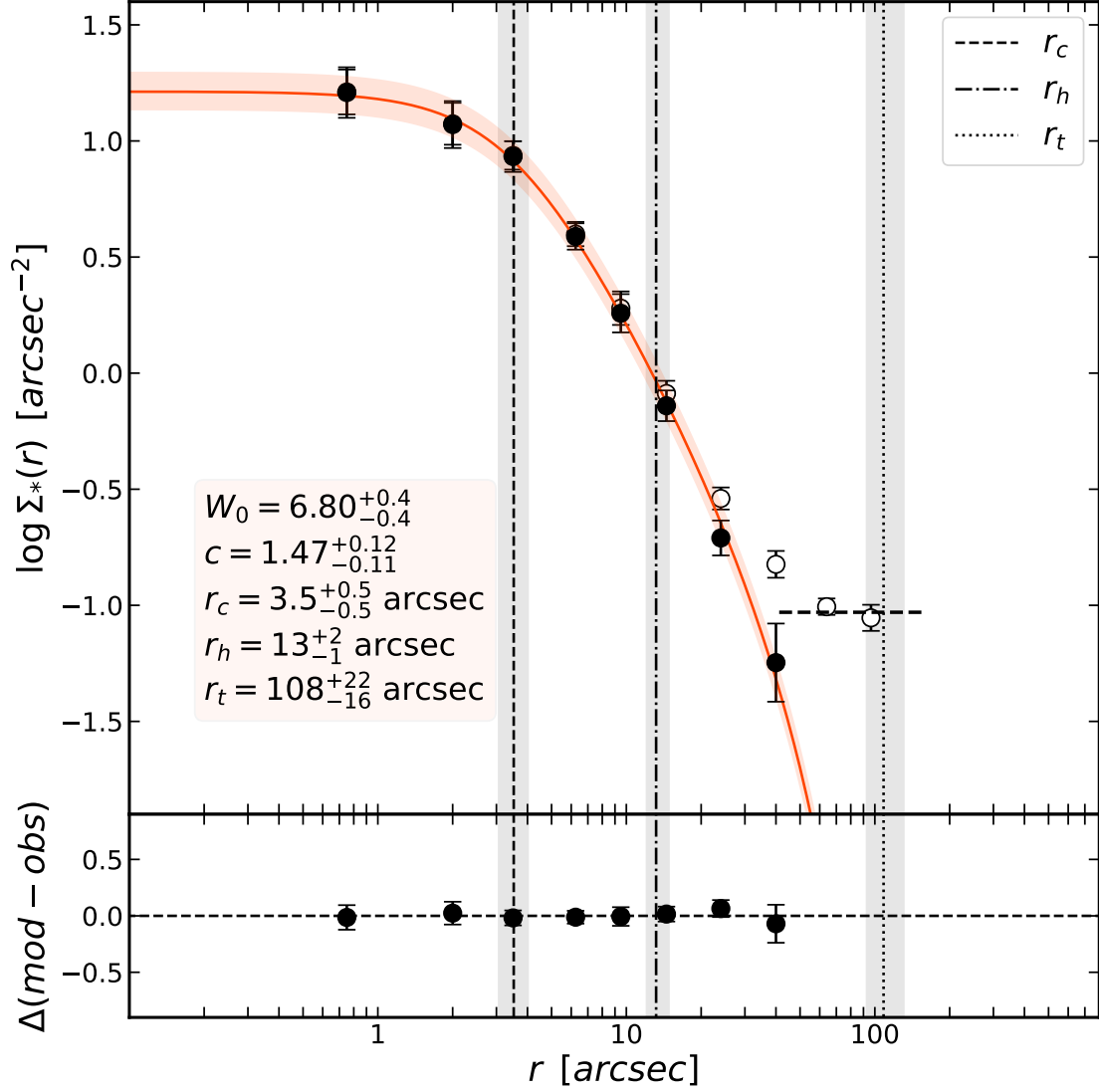


Figure 3.5: Projected density profile of NGC 1754 derived from resolved star counts (empty circles). The horizontal dashed line represents the mean LMC field density, which was subtracted to obtain the background-subtracted profile (filled circles). The solid red line illustrates the best-fit King model, while the red shading indicates the $\pm 1\sigma$ range of solutions. Vertical lines denote the core radius (dashed line), half-mass radius (dot-dashed line), and tidal radius (dotted line), with their respective 1σ uncertainties indicated by the gray shading.

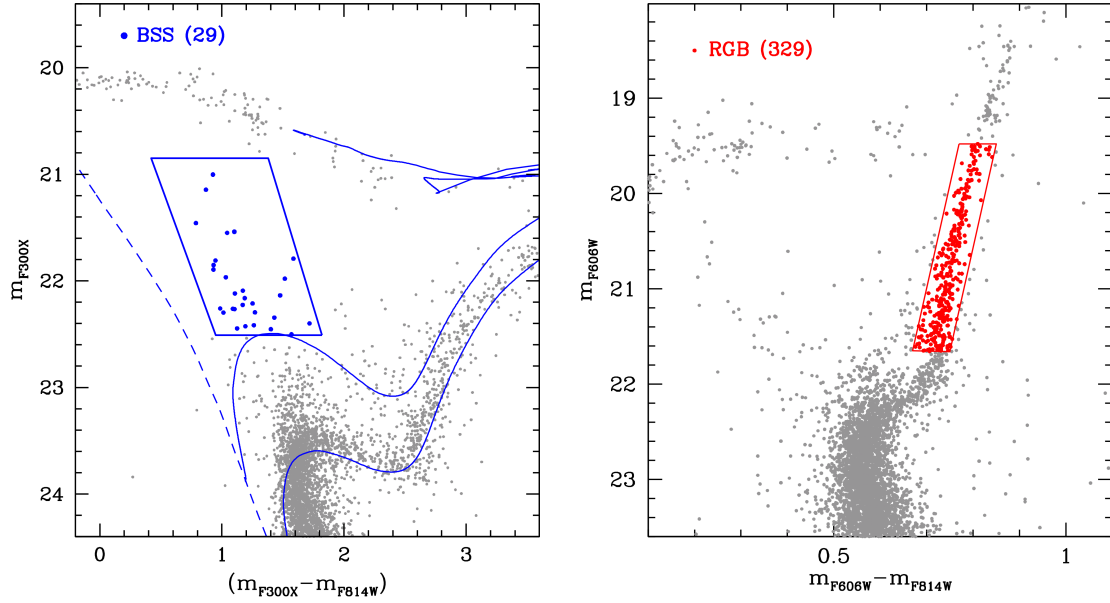


Figure 3.6: Selections of the BSS and RGB samples. Left: Near-UV CMD of NGC 1754 within the half-mass radius ($r < r_h = 13''$; gray dots), with the selected BSS sample shown with blue circles and the BSS selection box marked in blue. The rightmost solid line is the evolutionary track for a star of $0.78M_{\odot}$ (which is the MS turnoff mass for an age $t = 12.8$ Gyr). The leftmost solid line is the evolutionary track of a $0.98M_{\odot}$ star. The dashed line is the BASTI isochrone corresponding to a very young age (30 Myr), representing the cluster ZAMS. Right: Optical CMD of NGC 1754 for $r < r_h = 13''$ (gray dots), with the selected RGB sample shown as red circles and the RGB selection box also marked in red.

3.5 Star count density profile and structural parameters

Once we determined the cluster gravitational center, we constructed the density profile of the system from resolved star counts (e.g., Miocchi et al., 2013; Lanzoni et al., 2019; Raso et al., 2020). For this operation, we used only stars with $m_{F814W} < 22$, i.e., only those that are brighter than the MS turnoff, and therefore they all have approximately the same mass (the only exceptions are BSSs, which however are so few in number that their contribution to the sample used for the determination of the density profile is negligible). We divided the WFC3 field of view into concentric rings ranging from sub-arcsecond scales up to about $120''$, with each ring further subdivided into three or four sectors. For every radial bin, we counted the number of stars in each sector and we calculated the star density as the average of the resulting values divided by the sampled area, and the error as their standard deviation. The observed star count density profile obtained by this procedure is marked by the empty circles in Fig. 3.5. This profile features a flat inner portion with a density of approximately $\log \Sigma_* \sim 1.2$ up to $\sim 1''$, a subsequent radial decrease and a final plateau. We averaged the plateau points (the last two points of the profile) to obtain the value of the field star density ($\log \Sigma_* \sim -1.05$), and then we subtracted this value from each bin to obtain the field-decontaminated cluster profile (see the

solid circles in Fig. 3.5).

Using stars of approximately the same mass allowed us to compare the decontaminated profile with the family of spherical, isotropic, single-mass King models (King, 1966). This comparison was performed using the MCMC method with flat priors for the fitting parameters (central density, concentration parameter c , and core radius r_c). The likelihood was based on a χ^2 statistic. The final best-fit model is represented by the red line in Fig. 3.5. The residuals in the bottom panel of the figure confirm that a (flat-core) King model accurately reproduces the profile in the central region, effectively ruling out the possibility that the cluster has already undergone CC.

The structural parameters obtained by the profile fit procedure are: concentration parameter $c = 1.47$, core radius $r_c = 3.5''$, half-mass radius $r_h = 13''$, and tidal radius $r_t = 108''$. Assuming a distance of 49.6 kpc for the LMC (Pietrzyński et al., 2019), we obtain $r_c = 0.84$ pc, $r_h = 3.13$ pc, and $r_t = 25.98$ pc (see Table 3.1). This confirms the cluster’s compact nature, as anticipated by previous studies. Notably, our estimate of the core radius aligns well, within the uncertainties, with the literature value of $r_c = 3.61 \pm 0.49''$ (Mackey & Gilmore, 2003), which was obtained using a different method that involved fitting the brightness profile with an Elson-Fall-Freeman model (Elson et al., 1989).

3.6 Measuring the dynamical age

Given the cluster’s old age and compact structure, a very high dynamical age is anticipated, according to the theory explained in Ferraro et al. (2019) (see Sect. 1.5). We calculated the central relaxation time for NGC 1754 following the formulation of Djorgovski (1993) (see Sect. 1.2 and Sect. 2.7 for a detailed explanation):

$$t_{rc} = 1.491 \times 10^7 \times \frac{k}{\ln(0.4N_*)m_*} \rho_{M,0}^{1/2} r_c^3, \quad (3.1)$$

In particular, we adopted the cluster mass from Mackey & Gilmore (2003), originally estimated using a mass-to-light ratio of $M/L_V = 3.36$, and rescaled it to $M/L_V = 2$ to align with the assumptions of Ferraro et al. (2019). In addition we measured $\rho_{M,0}$ from Eqs. (4), (5), and (6) of Djorgovski (1993) (see Sect. 2.7), adopting the concentration parameter c and the core radius r_c determined from the fit to the star density profile (see Sect. 3.5), and the central surface brightness $\mu_{555}(0) = 17.48$ quoted in Mackey & Gilmore (2003). The result obtained for NGC 1754 is $\log(t_{rc}/\text{yr}) = 7.969$ (see Table 3.1). This value is 2 orders of magnitude smaller than the measured chronological age, thus indicating that the cluster core has been significantly affected by two-body relaxation and pointing to an advanced dynamical age for the cluster. Ferraro et al. (2018a) used the parameter N_{relax} (defined as the

ratio of the chronological age of a cluster to its central relaxation time) to quantify this information. Of course higher values indicate clusters that are more dynamically evolved. In the case of NGC 1754, given a chronological age of $t = 12.8$ Gyr, N_{relax} corresponds to a relatively large value of 137 (see Table 3.1).

However, as already mentioned in Sect. 1.4.1, t_{rc} provides just a qualitative indication of the level of dynamical evolution reached by the cluster, since it is evaluated from the present-day structural parameters of the system (which, instead, are known to vary with the dynamical history) and it is estimated through a simplified analytical expression derived under assumptions (such as spherical symmetry, orbital isotropy, and nonrotating internal kinematics) that are challenged by recent kinematic investigations (see, e.g., Fabricius et al. 2014; Watkins et al. 2015; Bellini et al. 2017; Ferraro et al. 2018b; Kamann et al. 2018; Lanzoni et al. 2018a,b; Leanza et al. 2022).

Hence, to verify this result and more accurately quantify the dynamical age of NGC 1754, we applied the dynamical clock method (Ferraro et al., 2018b, 2020, 2023). As described in Sect. 1.4.1, this method evaluates the system's dynamical state by analyzing the degree of central segregation of BSSs compared to a lighter-mass reference population.

Table 3.1: Main properties of NGC 1754.

Parameter	Estimated value
Center of gravity	$\alpha_{J2000} = 04^h 54^m 18^s.66$ $\delta_{J2000} = -70^\circ 26' 31.03''$
Age	$t = 12.8^{+0.4}_{-0.4}$ Gyr
King concentration	$c = 1.47^{+0.12}_{-0.11}$
Central dimensionless potential	$W_0 = 6.8^{+0.4}_{-0.4}$
Core radius	$r_c = 3.5^{+0.5}_{-0.5}$ arcsec (0.84 pc)
Half mass radius	$r_h = 13^{+2}_{-1}$ arcsec (3.13 pc)
Tidal radius	$r_t = 108^{+22}_{-16}$ arcsec (25.98 pc)
Central relaxation time	$\log(t_{rc}/\text{yr}) = 7.969$
Age/Central relaxation time	$N_{relax} = 137$

The first step is to select a sample of bright BSSs within the cluster's half-mass radius (according to Alessandrini & Cosmic-Lab Team 2016; Lanzoni et al. 2016 definition). Because BSSs are hot stars, the selection is expected to be most effective in an ultraviolet CMD (Ferraro et al., 2003b; Raso et al., 2017), here constructed with the F300X filter. Figure 3.6 shows the $(m_{F300X}, m_{F300X} - m_{F814W})$ CMD within

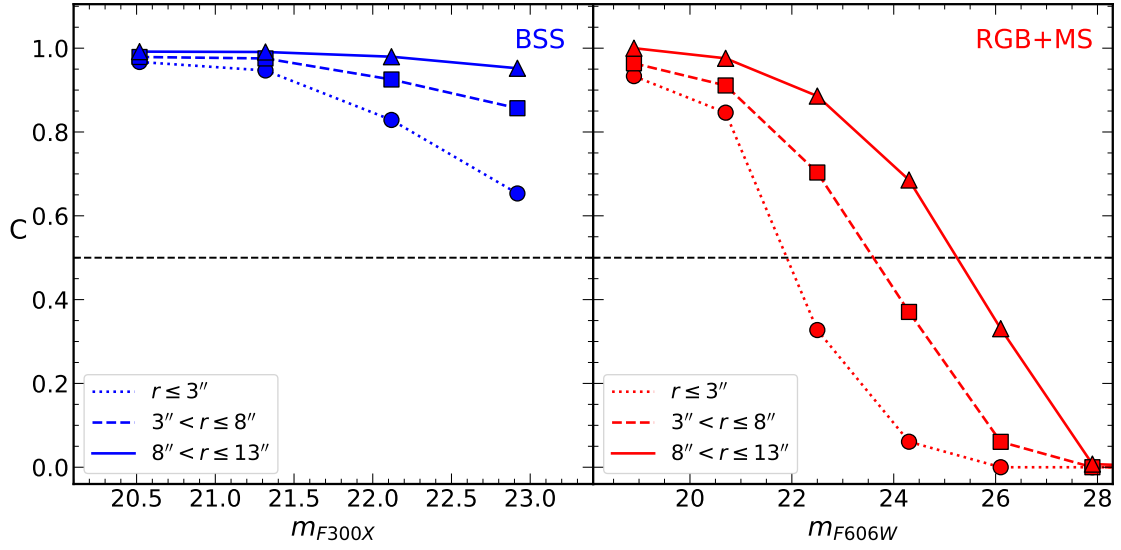


Figure 3.7: Completeness curves of the BSS and RGB+MS populations as a function of the m_{F300X} and the m_{F606W} magnitudes (left and right panels, respectively). The dotted, dashed, and solid lines correspond respectively to the innermost ($r < 3''$), intermediate ($3'' < r < 8''$), and outermost ($r > 8''$) radial bins considered in the analysis.

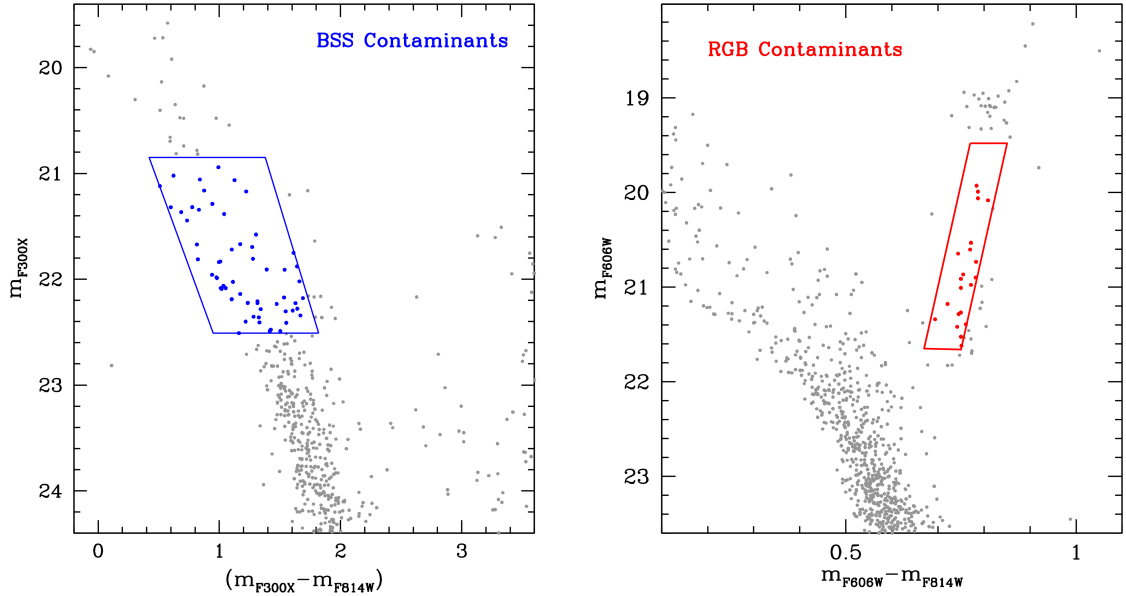


Figure 3.8: Estimating the LMC field contamination. The BSS and RGB selection boxes shown in Fig. 3.6 are over-plotted, respectively, on the UV (left panel) and optical (right panel) CMDs observed beyond the cluster tidal radius ($r > 108''$).

Table 3.2: Completeness-corrected samples of BSSs (top row) and RGB stars (bottom row). N_{TOT} represents the total number of stars, while the last three columns show the estimated numbers of stars in the three radial bins. Numbers in brackets indicate the estimated field contaminants.

	N_{TOT}	$N (r \leq 3'')$	$N (3'' < r \leq 8'')$	$N (8'' \leq r \leq 13'')$
BSS	33 (8)	15 (0)	11 (2)	7 (6)
RGB	378 (3)	80 (0)	199 (1)	99 (2)

$r_h = 13''$ (see Sect. 3.5) and the box chosen for the BSS selection. The box was defined as follows (see Ferraro et al., 2018a, 2019, 2023), using BASTI isochrones and tracks (Pietrinferni et al., 2021) computed for $[\text{Fe}/\text{H}] = -1.45$, $[\alpha/\text{Fe}] = +0.4$, $Y = 0.25$, and shifted in the observed CMD by assuming the distance modulus and the color excess determined in Sect. 3.4. The left side was constructed following approximately the slope of the ZAMS (shown as a dashed line in Fig. 3.6). The upper and right-hand sides were constructed trying to exclude stellar populations belonging to different evolutionary phases, such as HB stars and possible blends with RGB stars. The location of the bottom side is instead set with the aim of selecting the most massive BSSs in the sample, thus maximizing the sensitivity of the A_{rh}^+ parameter, since the most massive stars are those experiencing the strongest effect from dynamical friction. In agreement with the selections adopted in previous papers (Ferraro et al., 2018b, 2019), here we included in the sample BSSs with masses exceeding the MS turnoff mass by at least $0.2 M_{\odot}$. Since the MS turnoff mass of the adopted BASTI isochrone at the cluster age ($t = 12.8$ Gyr; see Sect. 3.4) is $0.78 M_{\odot}$, the lower boundary of the BSS selection box is marked by the evolutionary track of a $0.98 M_{\odot}$ star. The final selection resulted in a sample of 29 BSSs. The right panel of Fig. 3.6 shows the selection of the reference (RGB) sample in the optical ($m_{\text{F606W}}, m_{\text{F606W}} - m_{\text{F814W}}$) CMD, consisting of 329 RGB stars. Small changes in the shape of the boxes lead to negligible changes in the result.

Once the two samples were chosen, we had to take into account their level of photometric completeness. To do this, we performed artificial star experiments using the prescriptions discussed in Dalessandro et al. (2015, see also Cadelano et al. 2020b). As a first step, for both the cluster’s principal sequences (MS and RGB) and the BSS sequence, we constructed two mean ridge lines, in the ($m_{\text{F606W}}, m_{\text{F606W}} - m_{\text{F814W}}$) CMD and in the ($m_{\text{F606W}}, m_{\text{F300X}} - m_{\text{F606W}}$) CMD. We generated a set of artificial stars with an input m_{F606W} magnitude derived from a luminosity function designed to mimic the observed one for both the BSS and MS+RGB samples. Each artificial star was assigned a ($m_{\text{F606W}} - m_{\text{F814W}}$) and ($m_{\text{F300X}} - m_{\text{F606W}}$) color value, determined based on the corresponding mean ridge line. We then added these stars to the WFC3 images using DAOPHOT/ADDSTAR, dividing the field of view into cells

with sides equal to ten times the full-width at half-maximum of the PSF and adding one star in each cell, so as to avoid crowding effects. On these modified images we then performed the same data reduction procedure described in Sect. 3.2, using the PSF models already found. We performed this procedure only in the WFC3 UVIS1 chip, since the analyzed BSS and RGB samples have been selected just within the half-mass radius ($13''$). At the end of the procedure, we obtained a catalog of more than one million simulated sources for both the BSS and the MS+RGB samples, containing for each artificial star the information given in input (i.e., the magnitudes in the three filters and the coordinates) and the corresponding output information obtained after the data reduction. Using these catalogs we constructed completeness curves, with the completeness parameter, C , defined as the ratio between the number of output and the number of input stars ($C = N_{\text{output}}/N_{\text{input}}$). Figure 3.7 shows the completeness curves relative to three different radial bins within $13''$ from the center, obtained for BSSs (as a function of the m_{F300X} magnitude; left panel) and for the MS+RGB sample (in the m_{F606W} filter; right panel). Using these curves, we assigned a completeness value to each of the 29 BSSs and each of the 329 RGB stars according to their magnitude and radial distance from the cluster center.

The next key step is the evaluation of the level of field contamination in the considered BSS and RGB samples. To this end, we took advantage of the fact that the WFC3 field of view is larger than the estimated cluster tidal radius ($r_t = 108''$), which implies that the stellar population in the most external regions (at $r > r_t$) can reasonably be assumed to be representative of the LMC field. This region covers an area of approximately 4000 arcsec^2 , thus allowing a reasonable evaluation of the density of the LMC field population in the proximity of NGC 1754. This approach, compared to the use of the ACS dataset, allowed us to work directly in the $m_{\text{F300X}}, m_{\text{F300X}} - m_{\text{F814W}}$ plane where the BSS have been selected, whereas in the ACS dataset the F300X filter is not present. Thus, the selection boxes have been drawn in the field CMD (see Fig. 3.8) and the number of stars falling in each of them (corresponding to potential contaminants to the BSS and RGB populations) has been counted. The ratio between these number counts and the sampled area gives the value of the expected field contamination density in each population, which turns to be 0.015 and 0.005 contaminant star per square arcsecond for the BSS and the RGB population, respectively. Considering that the portion of cluster within the half-mass radius ($r_h = 13''$) subtends approximately 531 sq.arcsec on the sky, we estimate a total of 8 and 2.7 (in the following we assumed 3) contaminants in the BSS and RGB samples, respectively. However, for a more precise field decontamination we evaluated the number of field interlopers in three distinct radial bins, the same used to estimate the completeness curves (Fig. 3.7). To this end, we multiplied the field densities in the BSS and RGB boxes by the area of each annulus, finding the values listed in brackets in Table 3.2.

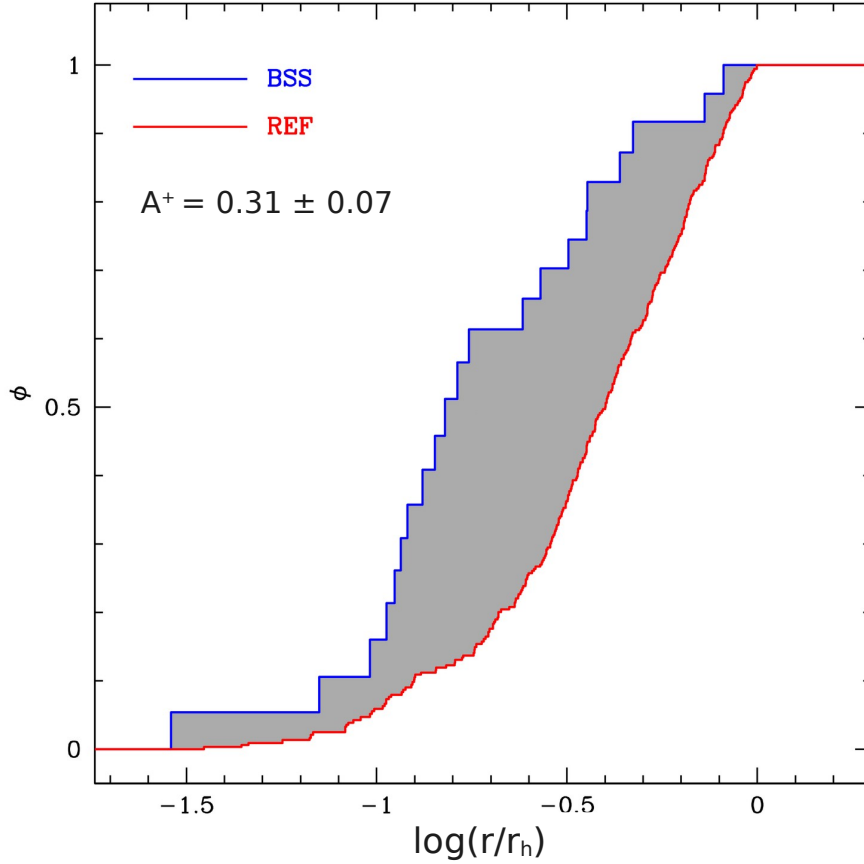


Figure 3.9: Normalized cumulative radial distributions of BSSs (blue line) and RGB stars (red line) from one of the random realizations used to estimate the A_{rh}^+ parameter. The A_{rh}^+ value represents the area enclosed between the two curves.

To measure the A_{rh}^+ parameter, we constructed the cumulative radial distributions of both the BSS and RGB samples after proper correction for incompleteness effects by weighting each star by the inverse of its assigned completeness parameter C . Additionally, to account for field contamination we repeated the calculation of A_{rh}^+ 1000 times, each time randomly removing the estimated number of contaminating field stars. In each individual iteration, the value of A_{rh}^+ was measured as the area enclosed between the cumulative radial distribution of the BSS sample and that of the RGB sample. Figure 3.9 presents a random realization of the cumulative radial distributions of BSSs (blue curve) and RGB stars (in red), with the gray-shaded area indicating the A_{rh}^+ parameter. The final A_{rh}^+ value was obtained as the mean of the 1000 individual measurements, resulting in $\langle A_{rh}^+ \rangle = 0.31$, which indicates an old dynamical age for NGC 1754. While the formal 1σ uncertainty on this value is only 0.01, to obtain a more realistic estimate also accounting for the relatively small number of stars, the error associated with this final value was measured using a jackknife bootstrapping technique. Specifically, for a sample of N BSSs, the measurement of the area enclosed within the two cumulative distributions was repeated

N times, each time randomly removing one star from the sample. The error is then defined as $\sigma_{A_{rh}^+} = \sigma_{\text{distr}} \times \sqrt{(N-1)}$, where σ_{distr} is the standard deviation of the N estimates of A_{rh}^+ . In our case $\sigma_{A_{rh}^+} = 0.07$.

3.7 Discussion and conclusions

The analysis presented in this chapter confirms a very old chronological age for NGC 1754 ($t = 12.8 \pm 0.4$ Gyr), which is fully comparable with that measured both in the other old LMC clusters (see e.g., Wagner-Kaiser et al., 2017) and in the oldest MW GCs (see, e.g., Fig. 2 in Ferraro et al. 2019). This result provides further support to the idea that the beginning of the GC formation process was contemporaneous in the MW and the LMC. This is a relevant point since the relative distance between the two galaxies was much larger at the epoch of GC formation than today (as suggested by their orbit reconstruction; see Kallivayalil et al. 2013), and the MW and LMC offered independent and very different cluster formation environments (in terms of total mass, metallicity, etc). Hence, this evidence points toward a GC formation process starting at the same cosmic time independently of the characteristics of the hosting galaxy.

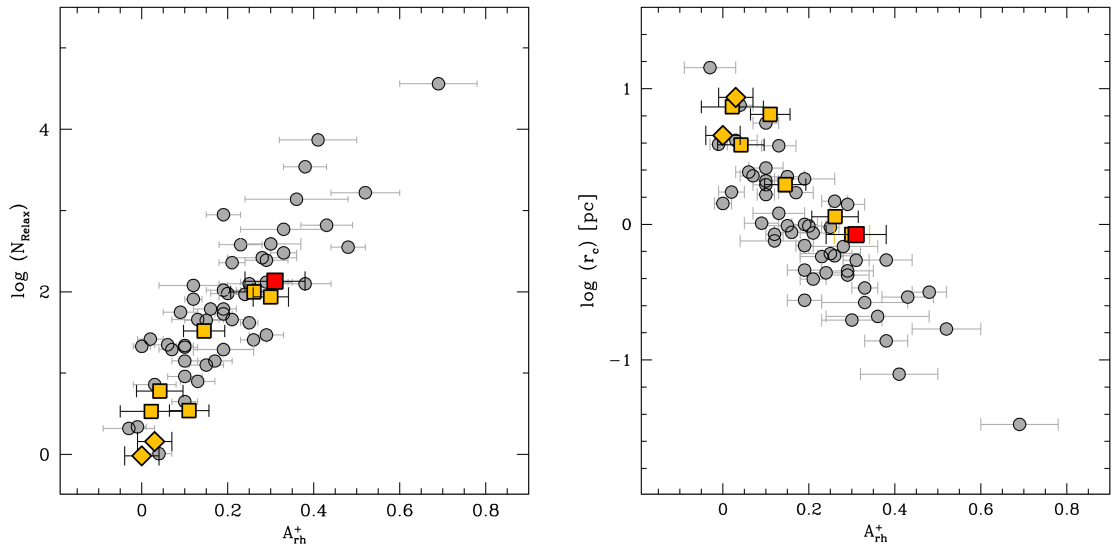


Figure 3.10: Relation between N_{relax} and A_{rh}^+ (left) and between r_c and A_{rh}^+ (right) for star clusters analyzed using the dynamical clock method. NGC 1754 is represented by a large red square, and the 52 Galactic GCs discussed in Ferraro et al. (2023) by gray circles. The five old LMC clusters from Ferraro et al. (2019) and NGC 1835 discussed in Chap.2 are plotted as yellow squares, and the two young Small Magellanic Cloud clusters from Dresbach et al. (2022) as yellow diamonds.

Concerning the dynamical characterization of the cluster, we estimate that it is already in an advanced dynamical stage, and we can now compare the results obtained for NGC 1754 with those published in the literature for other clusters, as

done in Chap.2 for NGC 1835. A first conclusion can be drawn by examining the plane that relates the measured values of A_{rh}^+ to those obtained for the parameter N_{relax} . This is shown in the left panel of Fig. 3.10.

We can see that NGC 1754 (red square) nicely nests into the correlation between A_{rh}^+ and N_{relax} , further extending the distribution of the LMC clusters. Intriguingly, the values of A_{rh}^+ measured for NGC 1754 ($A_{rh}^+ = 0.31$) and NGC 1835 ($A_{rh}^+ = 0.30$; see Chap.2) are very close to the value that seems to flag the core collapse event. In fact, as discussed in Ferraro et al. (2023), $A_{rh}^+ = 0.30$ can be considered a sort of reference value for core collapse, meaning that the proximity of A_{rh}^+ to this value is a likely indication of the imminence or the occurrence of the event.

In the right panel of Fig. 3.10, we compare the values of A_{rh}^+ and the core radius for the aforementioned clusters. In this case, an anticorrelation is observed, with NGC 1754 (large red square) aligning well within this trend. The result is fully compatible with what is expected from the natural dynamical evolution of star clusters, namely that the cluster structure becomes more compact (i.e., r_c decreases) as the dynamical age increases.

CHAPTER 4

The globular cluster NGC 1916

*Mainly based on:
Giusti et al. (2025) in preparation*

4.1 Introduction

In this chapter, we will present the first comprehensive study of the LMC GC NGC 1916 based on new high-resolution observations obtained with the WFC3/HST. NGC 1916 is one of the oldest ($\log t = 10.20$, Mackey & Gilmore 2003) and most massive ($\log M = 5.79M_{\odot}$, Mackey & Gilmore 2003) star clusters in the Large Magellanic Cloud, with a metallicity of $[\text{Fe}/\text{H}] \simeq -1.75$ (Mucciarelli et al., 2021). Its location in the innermost regions of the LMC, very close to the galactic bar, makes it a particularly challenging target. On the one hand, its high mass and ancient age place it among the most important benchmarks for understanding the early phases of cluster formation in the LMC. However, severe contamination from the dense surrounding stellar field, combined with strong differential reddening, has historically hampered its detailed characterization (e.g., Olsen et al., 1998; Mackey & Gilmore, 2003). As a result, fundamental quantities such as age, reddening, and core radius have remained uncertain. Despite these difficulties, NGC 1916 represents a key system. Its extreme compactness makes it an ideal laboratory for testing the link between core radius and dynamical state, and for assessing whether the correlations identified in other old LMC clusters (e.g., Ferraro et al. 2019) extend to the most compact and dynamically evolved systems.

The depth and resolution of the acquired WFC3 data allowed us to construct a deep and well-populated CMD, reaching several magnitudes below the main-sequence turn-off. In addition, the quality of the images allowed a precise determination of the cluster center and the construction of a reliable density profile, from which we derive updated structural parameters using King model fits.

For NGC 1916, however, the determination of A^+ was not feasible because of severe field-star contamination, significant incompleteness in the cluster center, and strong differential reddening, which affect a reliable identification of the BSS population. Hence, to infer the dynamical stage of the system, we rely on the central

relaxation time ($\log t_{rc}/\text{yr} = 7.580$), which is very short and fully consistent with its exceptionally small core radius.

4.2 Dataset

The cluster NGC 1916 was observed in 2022 using the WFC3 instrument on the HST, with different filters ranging from the near ultraviolet to the optical. Specifically, we analyzed 16 images: six in the F300X filter (2x900 sec, 1x917 sec, 2x920 sec, 1x953 sec), six in the F606W filter (2x407 sec, 4x408 sec), and four in the F814W filter (1x630sec, 1x645 sec, 2x700 sec). At almost the same time as the cluster observation, a region of the sky approximately $5'$ from the cluster was observed using the ACS instrument on the HST, in order to independently sample a field population representative of the area (see Fig.4.1).

The photometric analysis of both datasets was carried out using the DAOPHOT and ALLFRAME packages (Stetson, 1987, 1994), following the standard methodology already presented in Chaps.2 and 3 (see also Cadelano et al. 2017, 2020c,b, 2022b; Onorato et al. 2023; Chen et al. 2021, 2023; Deras et al. 2023, 2024). The first step is to identify about 150-200 bright, unsaturated stars that are well-distributed throughout the field of view of each image. These stars are used as reference stars in the procedure for constructing the PSF of the image. The resulting PSF models were subsequently applied using ALLSTAR to all star-like sources detected at a significance level of 5σ above the background. At this stage, each image provided a catalog of detected stars with instrumental coordinates, magnitudes, and associated photometric uncertainties. These individual catalogs were then used to construct a combined master star list incorporating all the stars detected in at least half of the images of each chip. The stars in this input list were subsequently fitted into all the images to their corresponding positions, using ALLFRAME. This method enabled the recovery of hot stars, such as BSSs and white dwarfs, which were not detected in the initial source extraction, and to reach the faintest part of the main sequence. Finally the magnitudes estimated for each identified star in different images were combined and homogenized using DAOMATCH and DAOMASTER.

The next step consisted of transforming the instrumental coordinates to the absolute reference frame (α and δ). Once geometric distortions were corrected using the coefficients from Bellini et al. (2011) for WFC3 and Meurer et al. (2003) for ACS, the astrometric calibration of the catalog was performed by matching the stars in common with the Gaia DR3 catalog (Gaia Collaboration et al., 2023), using the cross-correlation tool CataXcorr (Montegriffo et al., 1995) to derive the transformation from instrumental to equatorial coordinates. In the final step, we calibrated the measured magnitudes by converting them into the VEGAMAG system, using the zero points provided in the official HST database. In total, the final catalogs

includes calibrated magnitudes and positions for roughly 184000 objects detected with the WFC3, and around 171000 stars from the ACS observations.

The catalogs obtained from this analysis allowed us to construct the first deep CMD of NGC 1916. In Fig. 4.2 we present the CMDs obtained with all the filter combinations. Focusing on the optical diagram $m_{F606W}, m_{F606W} - m_{F814W}$ as an example (see the right panel of Fig. 4.2), the main sequence extends more than 4 magnitudes below the main-sequence turnoff. The turnoff itself is located at approximately $m_{F606W} \sim 22$, from which a well-developed red giant branch rises up to $m_{F606W} \sim 16$. For comparison, Olsen et al. (1998) had previously constructed a CMD in the V and I filters from WFPC2 data, but their optical CMD (V, V-I) extended less than 2 magnitudes below the main-sequence turnoff. The CMD also reveals an almost exclusively-blue horizontal branch, as expected in a metal-poor cluster ($[\text{Fe}/\text{H}] = -1.75 \pm 0.03$; see Mucciarelli et al. 2021). Its morphology is better traced in the CMDs based on the F300X filter, where hot stars are more easily detected. In the $m_{F606W}, m_{F300X} - m_{F606W}$, it is located at about $19 < m_{F606W} < 22.5$ and $-1.5 < m_{F300X} - m_{F606W} < 1.5$. However, its identification is complicated by the presence of the young population from the LMC field overlapping in the same region.

Fig. 4.3 shows the CMD obtained from the ACS dataset, illustrating a representative field region. The MS extends from magnitude $m_{F606W} \sim 26$ to ~ 18 , and an extended and well-defined RGB departs from the turn-off ($m_{F606W} \sim 22$). The red clump of the field region is visible at a magnitude $m_{F606W} \sim 19$ and a color $m_{F606W} - m_{F814W} \sim 0.8$.

4.2.1 Photometric completeness

The assessment of photometric completeness was carried out through extensive artificial star experiments, following standard procedures for crowded stellar fields used in Dalessandro et al. (2015, see also Cadelano et al. 2020b). As a first step, we constructed the mean ridge lines of the cluster’s main evolutionary sequences (MS and RGB), both in the $(m_{F606W}, m_{F606W} - m_{F814W})$ and in the $(m_{F606W}, m_{F300X} - m_{F606W})$ CMDs. We then generated a large sample of artificial stars with input m_{F606W} magnitudes extracted from luminosity functions designed to reproduce the observed ones for the MS and RGB populations. For each star, the corresponding $(m_{F606W} - m_{F814W})$ and $(m_{F300X} - m_{F606W})$ colors were assigned according to the appropriate mean ridge line, thus preserving the observed distribution of the sequences. The artificial stars were injected into the WFC3 images using the DAOPHOT/ADDSTAR routine. To avoid artificially increasing the crowding conditions, the field of view was divided into cells with sizes equal to ten times the PSF FWHM, and only one star was placed within each cell. The same reduction and photometric procedures described in Sect. 4.2 were then applied to these modified images, using the PSF

models already derived from the original data. This procedure was repeated until a final catalog of more than 10^6 simulated stars was obtained. For each artificial source the catalog contains both the input parameters (magnitudes in the three filters and positions) and the corresponding output values obtained after the photometric reduction.

Completeness curves were then constructed by defining the completeness parameter as $C = N_{\text{output}}/N_{\text{input}}$, with N_{input} and N_{output} being, respectively, the number of simulated stars and that of stars recovered by the photometric reduction. In Fig. 4.4 we show, as an example, three completeness curves derived in three different radial bins.

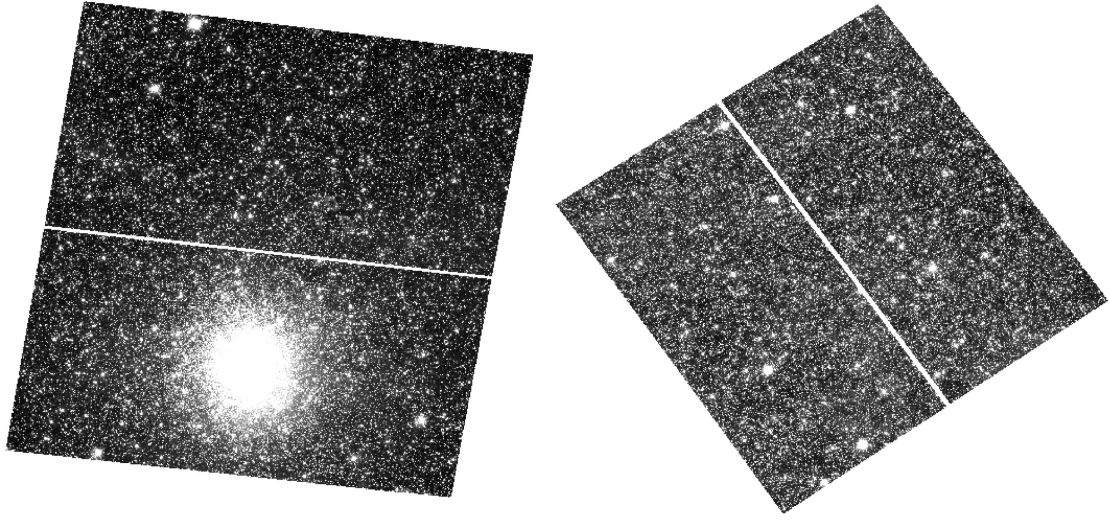


Figure 4.1: Left panel: WFC3/HST image of the cluster NGC 1916 in the F606W filter. Nord is up and est is left. Right panel: ACS/HST image of the reference LMC field region at $5'$ from the center of the cluster in the F606W filter. Nord is up and est is to the left.

4.3 Differential reddening

As stated in previous studies (see e.g., Olsen et al. 1998; Mackey & Gilmore 2004), the cluster NGC 1916 is particularly challenging to study due to severe field star contamination and significant differential reddening.

The so-called interstellar reddening refers to the dimming of starlight as it passes through interstellar dust and gas, which absorb and scatter the light, particularly at shorter (bluer) wavelengths. The entity of the reddening is often quantified by the colour excess $E(B - V)$, defined as the difference between the observed color $(B - V)$ and its intrinsic value $(B - V)_0$. A region is affected by differential reddening

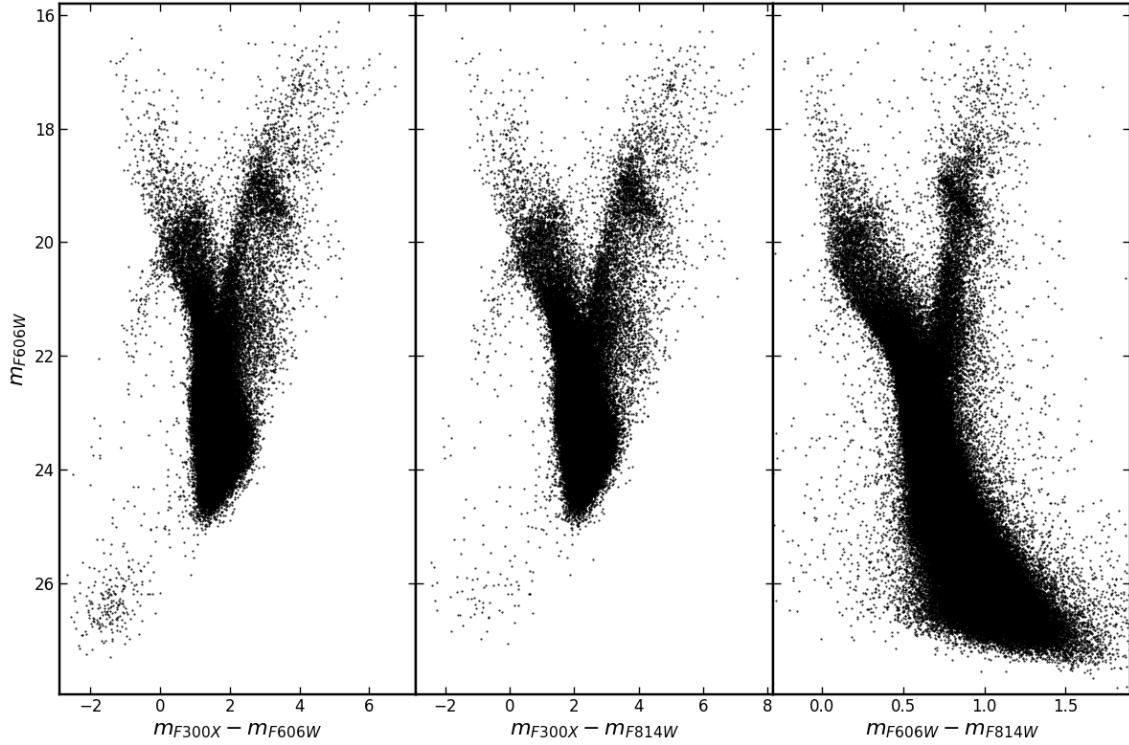


Figure 4.2: CMD of NGC 1916 constructed from the dataset of the WFC3/HST in all the filter combinations (F300X, F606W, F814W).

when the amount of reddening varies across the field, and each star has a different color excess. Observationally, this translates into a broadening of the evolutionary sequences along the reddening vector, as can already be seen in the CMDs of Fig. 4.2. This issue prevented Olsen et al. (1998) from reaching definitive conclusions about the properties of this cluster.

To correct this effect, we adopted the so-called star-by-star approach, that consists in estimating the reddening of each star based on the spatially closest objects (see e.g., Palla et al. 2019). First, we constructed a mean ridge line (MRL) of the cluster’s main evolutionary sequences (main sequence and red giant branch) using only high-quality stars within $d < 50''$ from the cluster center. This ensured that the derived sequence was representative of the cluster population. For each target star in the catalog, we then selected a local sample of N^* nearby bona fide cluster members to build a “local CMD”. These stars were chosen for their high photometric quality, based on sharpness and χ^2 parameters, and their high probability of being cluster members. Proper-motion decontamination could not be applied, as the only additional HST dataset available for NGC 1916 is the WFPC2 data from 1995 (Olsen et al., 1998). Given the distance of the LMC and the similar motion of the cluster and its host galaxy, proper motions would require higher-quality data and a significantly longer time baseline. Nevertheless, most field contaminants, particularly the young LMC stars lying above the cluster turn-off, were easily identified and removed by

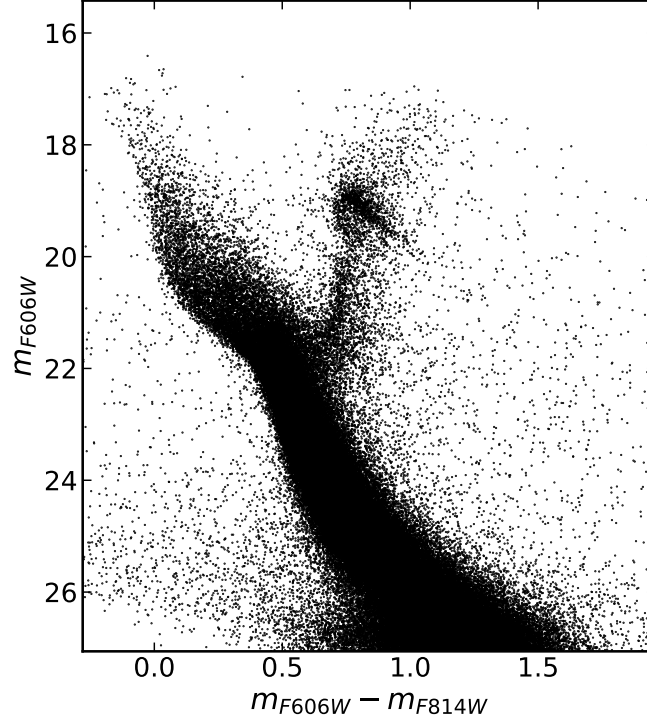


Figure 4.3: CMD of the reference LMC field region at $5'$ from the center of the cluster, observed with the ACS/HST.

visually comparing the cluster and the field CMDs (see Fig.4.2 and Fig.4.3), and defining exclusion boxes in the regions dominated by field stars.

The differential reddening affecting each target star was then estimated by shifting the MRL along the reddening vector in discrete steps of $\delta E(B-V)$. We adopted the absorption coefficients from O'Donnell (1994) computed with $R_V = 3.4$, which is typical of the LMC (Gordon et al., 2003). For each $\delta E(B-V)$ step, we evaluated the residual color ΔVI , defined as the difference between the observed $m_{F606W} - m_{F814W}$ color of each of the N^* stars ($VI_{\text{obs},i}$) and the corresponding color of the shifted MRL at the same magnitude level ($VI_{\text{MRL},i}$):

$$\Delta VI = \sum_{i=1}^{N^*} (|VI_{\text{obs},i} - VI_{\text{MRL},i}| + w_i \times |VI_{\text{obs},i} - VI_{\text{MRL},i}|). \quad (4.1)$$

The weight w_i accounts for both the photometric uncertainty in the color (σ_i) and the spatial distance of the i -th source from the target star (d_i), such that higher

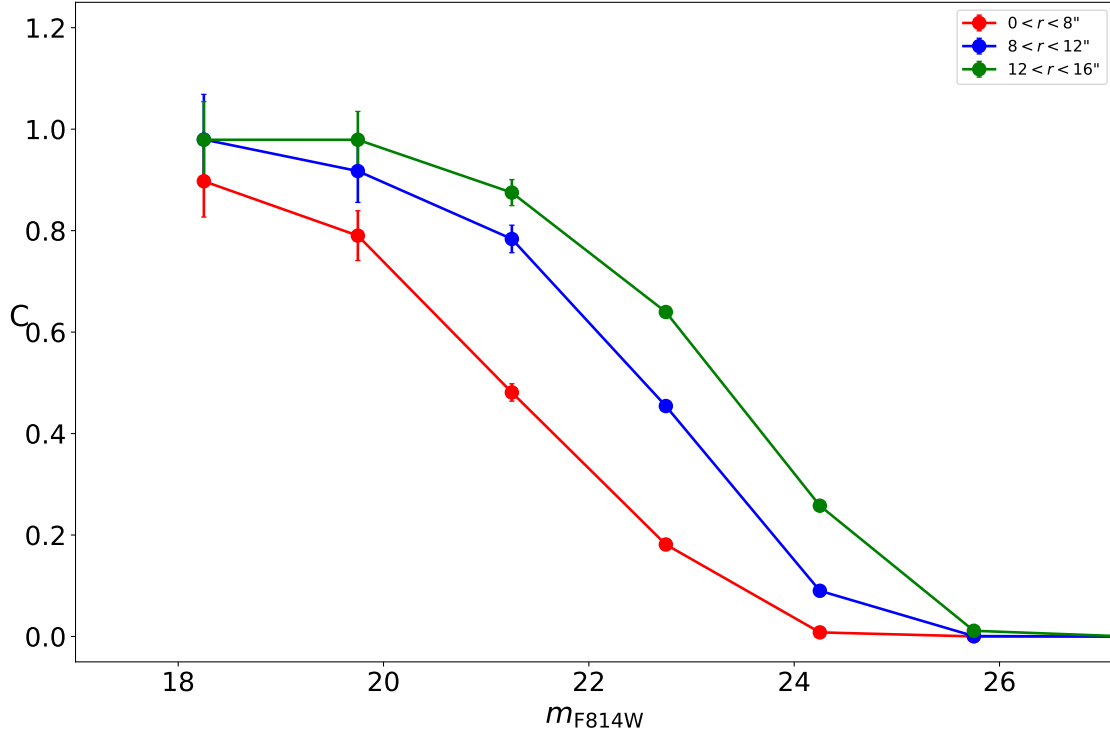


Figure 4.4: Completeness curves of the RGB+MS populations as a function of the m_{F814W} magnitude. The red, blue and green curves correspond to three different radial bins (see labels).

weight is assigned to closer and more accurately measured stars:

$$w_i = \frac{1}{d_i \cdot \sigma_i} \left[\sum_{j=1}^{N^*} \left(\frac{1}{d_j \cdot \sigma_j} \right) \right]^{-1}. \quad (4.2)$$

To further minimize field contamination, a 3σ rejection was applied to exclude stars with color residuals significantly larger than those of the bulk population. For each star, the adopted differential reddening $\delta E(B - V)$ corresponds to the value that minimizes the residual color ΔVI .

After this first step and the corresponding preliminary differential reddening correction, we iteratively repeated the entire procedure, this time constructing the MRL on a CMD already corrected for differential reddening. With this improved CMD, the selection of bona fide stars was further refined by excluding not only young field contaminants but also RGB stars. This was possible thanks to CMDs constructed with the F300X-based color combinations, in which field and cluster RGB stars appear well separated (see the left and central panels of Fig. 4.2).

The differential reddening map of the FoV of WFC3/HST is shown in Fig. 4.5. The map appears patchy on spatial scales of only a few arcseconds. The majority of the differential reddening values fall within the range of $-0.2 < \Delta E(B - V) <$

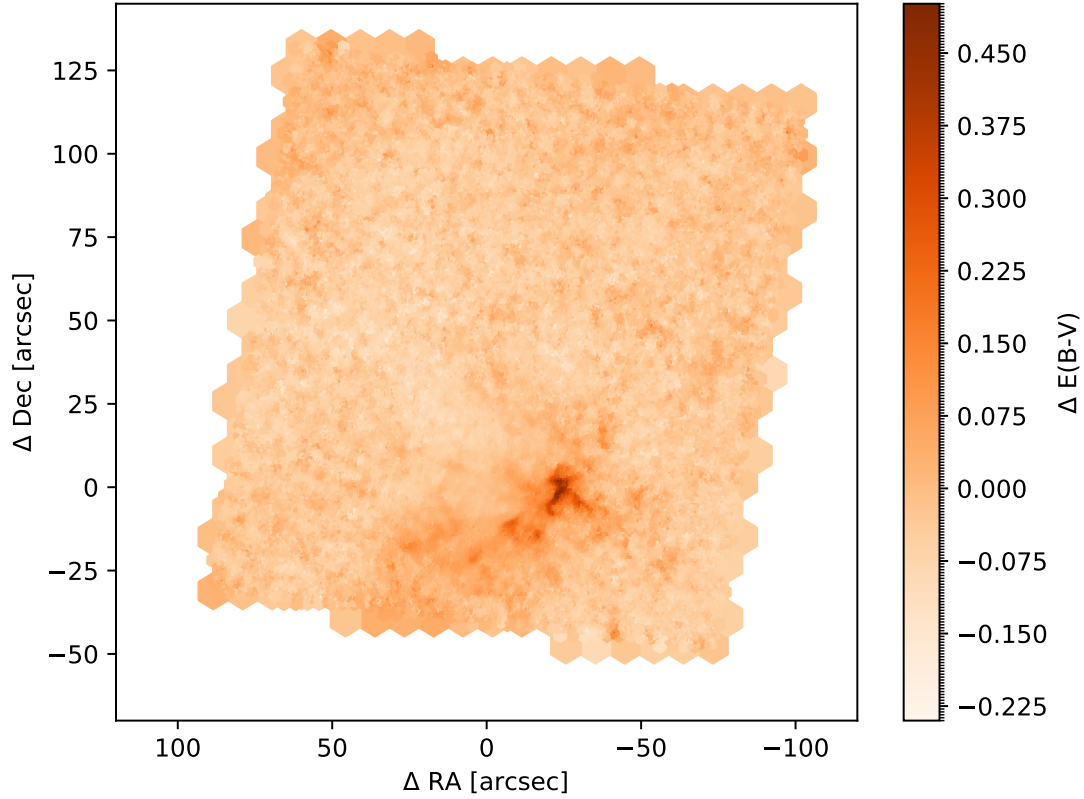


Figure 4.5: Map of the FoV of the WFC3 dataset color-coded for differential reddening. The center of the cluster is in (0,0), north is up, and east is to the left.

0.2. In the south-western region near the center of the cluster, there is an area with high reddening, reaching values of up to $\Delta E(B - V) \sim 0.4$. The optical ($m_{F606W}, m_{F606W} - m_{F814W}$) and hybrid ($m_{F606W}, m_{F300X} - m_{F606W}$) CMDs obtained before and after correction for differential reddening are compared in Fig. 4.6. They are heavily contaminated by field stars so, to better show the results of the differential reddening correction, in Fig. 4.7 we show the same CMDs for just the innermost stellar population, located within $20''$ from the center. The effectiveness of the correction is now evident, as the evolutionary sequences appear significantly narrower in the direction of the reddening vector. In the following analyses, the magnitudes are always corrected for differential reddening.

4.4 Center, star count density profile, and structural parameters

Determining the center of gravity of such a massive and compact cluster is a crucial and delicate task. Thanks to the WFC3/HST data, we identified the coordinates of the cluster center from the geometric mean of the positions of resolved stars.

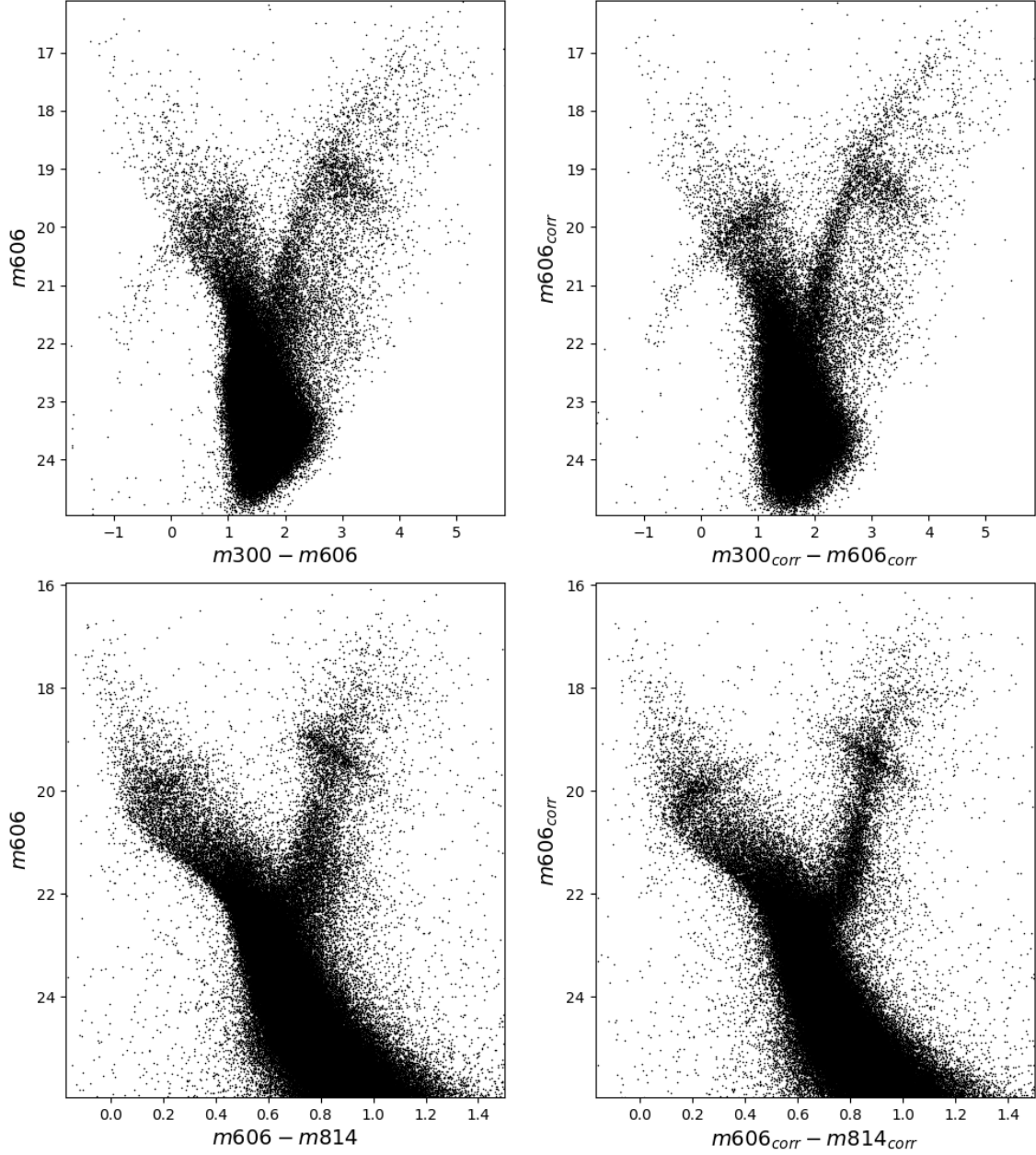


Figure 4.6: Hybrid (upper panels) and optical (bottom panels) CMDs of NGC 1916 before (left panels) and after (right panels) the correction for differential reddening.

This approach avoids the well-known biases of surface-brightness methods, where even a few bright stars can significantly shift the estimated center. In this work, we based our analysis on the iterative method used also in Chaps. 2, 3 (see also Montegriffo et al. 1995; Lanzoni et al. 2007b, 2019). We started the procedure from the location of the literature center (Mackey & Gilmore 2003; $\alpha = 05^h : 18^m : 37^s.5$, $\delta = -69^\circ : 24' : 25''$). At each step, a new center was determined by computing the geometric mean of a selected sample of stars. The selection is

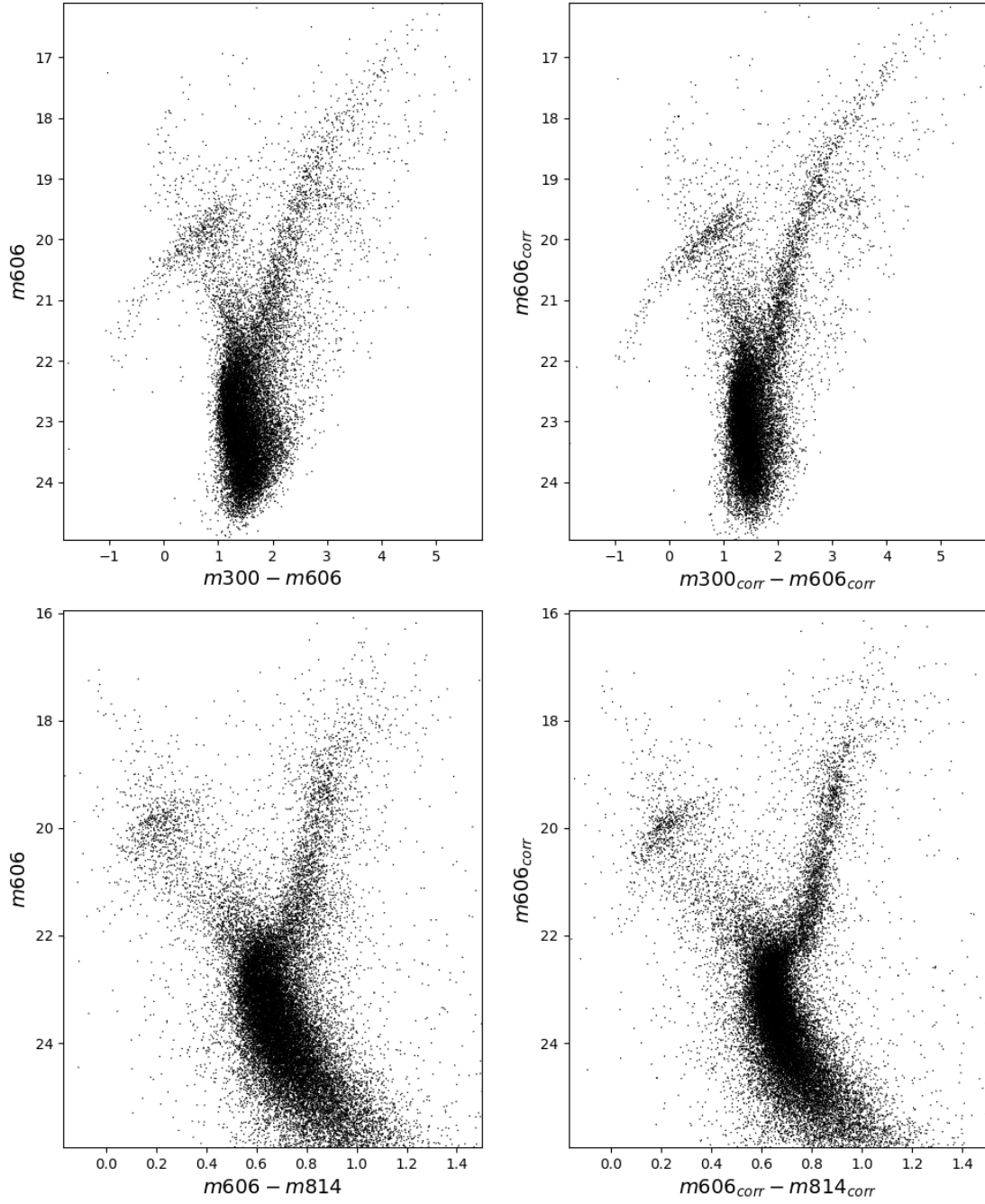


Figure 4.7: The same as in Fig. 4.6, but only for the stars observed within $20''$ from the cluster center.

updated at every iteration according to both the distance from the current center and a magnitude limit, both chosen in order to ensure a sufficiently large number of sources while preserving an adequate level of completeness (see Sec.4.2.1). For NGC 1916 we adopted three radial limits ($d < 8'', 12'', 16''$) and three magnitude thresholds ($m_{F814W} < 20.0, 20.5, 21.0$), thus generating nine independent samples. Each of these

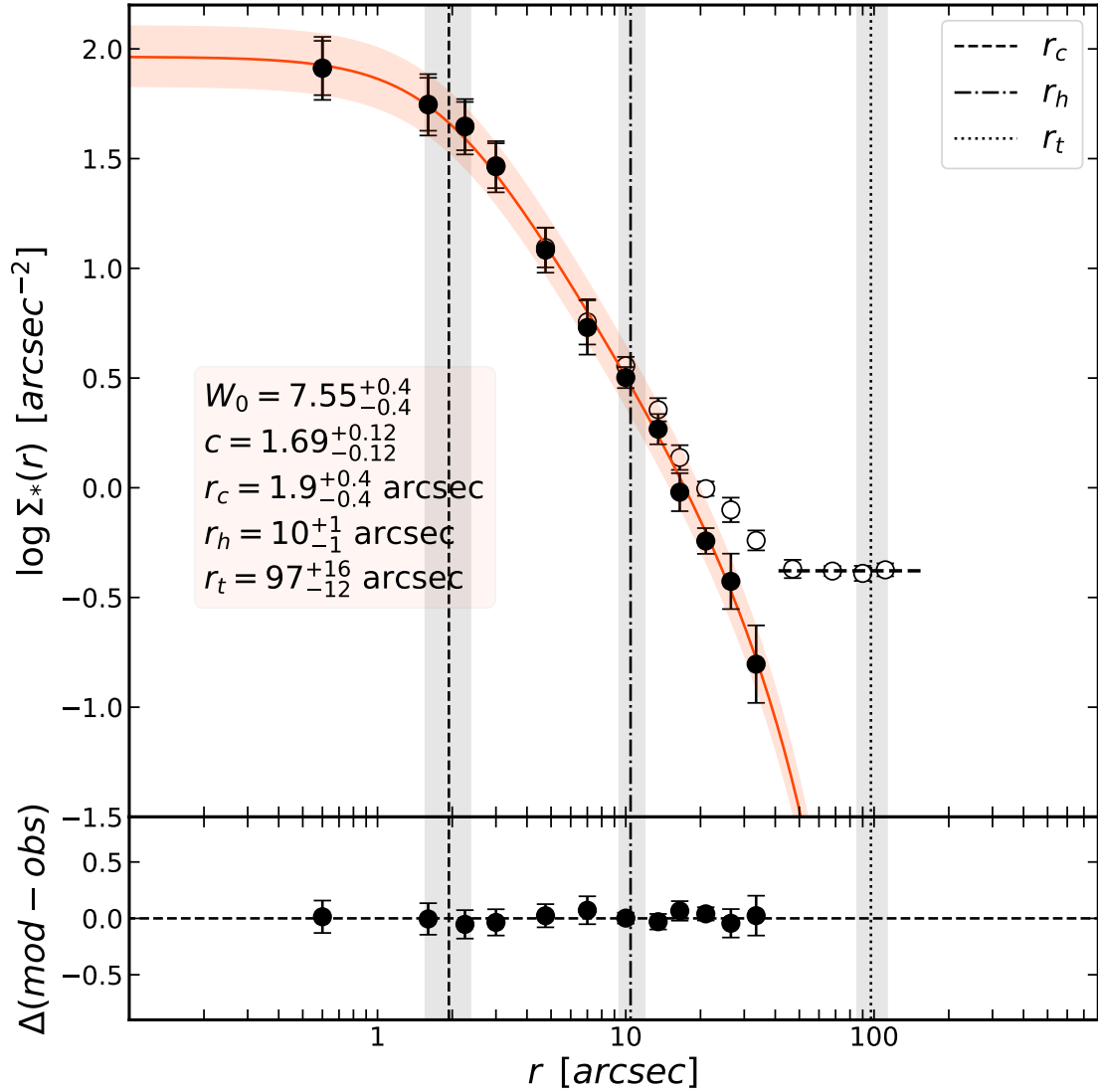


Figure 4.8: Projected density profile obtained from star counts. The empty circles represent the observed hybrid profile, with the innermost five points from the $m_{\text{F606W}} = 20$ selection and the outer points from the $m_{\text{F606W}} = 22$ selection. The horizontal dashed line marks the LMC field density that has been subtracted to determine the field-decontaminated profile (filled circles). The solid red line represents the best-fit King model, and the red stripe outlines the range of $\pm 1\sigma$ solutions. The vertical lines mark the locations of the core radius (dashed line), half-mass radius (dot-dashed line), and tidal radius (dotted line), with their respective 1σ uncertainties indicated by grey stripes. The values of the main structural parameters derived from the fitting are also labelled.

samples contains thousands of stars and guarantees a completeness level of at least 50%. The final cluster center was obtained as the average of the nine determinations, while the standard deviation provided the uncertainty: $\alpha = 05^h : 18^m : 37^s.5$, $\delta = -69^\circ : 24' : 26''$, with an error of $\sigma = 0.12''$. The distance from the literature center is only $0.7''$.

Then, we constructed the star-count density profile of the cluster. Because of the

high central concentration and the severe blending that prevents good completeness in the innermost regions, we constructed two profiles with different magnitude limits ($m_{\text{F606W}} = 20$ and $m_{\text{F606W}} = 22$). For both profiles we divided the WFC3 field of view into 16 concentric rings covering the entire observed region (out to $\sim 120''$). Each ring was split into three or four sub-sectors, and the stellar density within each sub-sector was obtained by counting the stars (brighter than the magnitude limit adopted) and by normalizing by the area. The density of each annulus was then defined as the median of the sub-sector densities, with the standard deviation providing the corresponding uncertainty. The resulting profiles show the typical shape expected for a globular cluster: a central plateau extending out to $\sim 1''$, followed by a decline and then by a second plateau at large radii, defined by the outermost four points in Fig. 4.8. For both profiles the mean of the last four points was adopted as the average surface density of the LMC field and subtracted from all the measured values, thus yielding two decontaminated (cluster only) distributions. We then constructed an hybrid profile, using the brighter magnitude limit in the inner regions (out to $\sim 10''$), and the deeper selection ($m_{\text{F606W}} = 22$) in the outer regions, where incompleteness is less severe. To do this, the inner profile built with the $m_{\text{F606W}} = 20$ selection was shifted to match the $m_{\text{F606W}} = 22$ profile in the overlapping region, and the two distributions were then combined to obtain the final profile. In Fig. 4.8, the white circles show the observed hybrid profile (with the innermost five points from the $m_{\text{F606W}} = 20$ selection and the outer points from the $m_{\text{F606W}} = 22$ selection), while the black circles mark the corresponding field-decontaminated profile.

We then searched for the best fit to the cluster density profile by comparing it with the family of spherical, isotropic, single-mass King models (King, 1966). The method employs the MCMC fitting procedure already described in the previous chapters, assuming uniform (flat) priors for the parameters (specifically the central density, concentration parameter c , and core radius r_c) and utilizes a χ^2 likelihood function. The best-fit model obtained from this approach is shown as a red line in Fig. 4.8. The best-fit values of the cluster structural parameters are a King concentration $c = 1.69$ (corresponding to a dimensionless central potential $W_0 = 7.55$), a very compact core radius $r_c = 1.9''$, a half-mass radius $r_h = 10''$, and a tidal radius $r_t = 97''$. Assuming an LMC distance of 49.6 kpc (Pietrzyński et al., 2019), the results can be expressed as $r_c = 0.46$ pc, $r_h = 2.41$ pc, and $r_t = 23.34$ pc. The structural parameters of the cluster were previously estimated by Mackey & Gilmore (2003), who modeled the observed surface brightness profile using an EFF model (Elson et al., 1987). They derived a core radius of $r_c = 3.35''$. The difference from our measurement is likely due to the different methodologies and images employed.

4.5 Reddening, distance modulus, and chronological age

We derived an initial estimate of the distance modulus and reddening for NGC 1916 by comparing its CMD with that of the Galactic globular cluster M80. The latter is a well-characterized cluster with a metallicity similar to that of NGC 1916 ($[\text{Fe}/\text{H}]_{\text{M80}} = -1.76$; Mucciarelli et al. 2021). According to Harris (1996, 2010 edition), M80 has a distance modulus of $(m - M)_0 = 15.00$ and a reddening of $E(B - V) = 0.18$. We shifted the optical m_{F606W} , $m_{\text{F606W}} - m_{\text{F814W}}$ CMD of NGC 1916, already corrected for differential reddening, until its main evolutionary sequences (MS, subgiant branch, RGB, and HB) aligned with those of M80.

As mentioned above, the evolutionary sequences of NGC 1916 are significantly impacted by the presence of field stars from the LMC. In particular, the younger population hides the morphology of the turn-off and the HB. To obtain a more accurate result, we therefore proceeded with a statistical decontamination of the cluster. We took advantage of the availability of the ACS dataset, which targeted a region of the LMC at about $5'$ from the center of NGC 1916. The statistical decontamination procedure is the one already described in Chaps. 2 and 3. First, we selected a representative “cluster region”, defined between two radial distances from the cluster center to avoid both the innermost area (where photometric uncertainties and crowding are more severe) and the outermost regions (where field contamination is dominant). In this case, we chose a radial annulus between $15''$ and $30''$. A comparison “field region” of equal area was then extracted from the ACS dataset. For each star in the field CMD, the closest star in the cluster CMD was identified in terms of color and magnitude, and subsequently removed from the cluster sample. This matching process was repeated using different field regions to assess the robustness of the result. The final decontaminated CMD, represented as black dots in Fig. 4.9, preserves the intrinsic morphology of the cluster’s evolutionary sequences, minimizing the contamination from the LMC field.

The CMD of M80 was then matched to the decontaminated CMD of NGC 1916 and the resulting shifts ($\Delta x = -0.011$ and $\Delta y = 3.308$) yielded a reddening and distance modulus of $E(B - V) = 0.17$ and $(m - M)_0 = 18.41$, respectively, for the LMC cluster.

We then applied the MCMC procedure, designed to simultaneously fit age, distance modulus, reddening, and metallicity (Foreman-Mackey et al., 2013, 2019). We generated an extensive grid of BASTI isochrones with $[\alpha/\text{Fe}] = +0.4$, $Y = 0.25$, ages varying from 9 to 14 Gyr (in 0.1 Gyr steps), and metallicities spanning the $[\text{Fe}/\text{H}]$ interval between -1.8 and -0.95 (0.05 dex steps). We then compared the observed CMD with this grid of isochrones, focusing on the age-sensitive regions such as the main sequence turn-off, subgiant branch, and lower red giant branch ($21 < m_{\text{F606W}} < 24$). We applied Gaussian priors to the metallicity value based on spectroscopic measurements by Mucciarelli et al. (2021) ($[\text{Fe}/\text{H}] = -1.75 \pm 0.03$), while the priors for the

reddening and distance modulus were set from the M80 CMD matching procedure described above: $E(B - V) = 0.17 \pm 0.02$ and $(m - M)_0 = 18.41 \pm 0.05$. The conversion between absolute and observed magnitudes for the isochrones was performed using the same coefficients employed in the differential reddening procedure described in Sect. 4.3. The best-fit isochrone is shown in Fig. 4.9, superposed to the decontaminated CMD, and the final parameter estimates correspond to the median values of the posterior distributions, with uncertainties defined by the 16th and 84th percentiles. The results are an age of $t = 13.0 \pm 0.01$ Gyr, $E(B - V) = 0.17 \pm 0.01$, $(m - M)_0 = 18.41 \pm 0.01$ and $[\text{Fe}/\text{H}] = -1.75 \pm 0.03$. The metallicity thus found is fully consistent with that presented in Mucciarelli et al. (2021), and the reddening and distance modulus values are the same as those obtained using the matching procedure with M80.

Finding literature information for the reddening of this cluster is very challenging, as the high field contamination and significant differential reddening have often led to it being overlooked in previous studies, as stated for example in Olsen et al. (1998). The reddening value often cited in literature (see e.g. Pessev et al. 2008) for NGC 1916 is $A_v = 0.42$ (corresponding to $E(B - V) = 0.13$), derived using the online tools provided by the Magellanic Clouds Photometric Survey (MCPS, Zaritsky et al. 1997). As for age, Mackey & Gilmore (2003) cite a greatly overestimated value of $\log(t) = 10.20$ yr, corresponding to more than 15 Gyr.

4.6 Measuring the dynamical age

Before discussing the dynamical state of NGC 1916, it is important to note that the dynamical clock method could not be applied to this cluster. The CMD of NGC 1916 is strongly affected by the presence of the young stellar population of the LMC, which overlaps with the cluster BSS sequence, making it extremely difficult to distinguish bona fide cluster BSSs from field contaminants. In addition, the cluster central regions suffers from severe incompleteness even up to very bright magnitudes. Fig. 4.10 shows the CMDs (left panels) and completeness curves (right panels) for NGC 1916 within two radial ranges, corresponding to the cluster core ($r \leq r_c = 1.9''$) and the half-mass radius ($r \leq r_h = 10''$). The completeness for the BSS region was calculated through artificial star experiments using the same procedure described in Sect. 4.2.1. The CMD within the core region is sparsely populated because of the severe crowding and strong photometric incompleteness, which significantly affects even relatively bright stars. The completeness curves confirm that, in the innermost region, the completeness drops below 50% already at $m_{F300X} \simeq 21$. These effects clearly prevent a reliable identification and selection of BSSs, and therefore the A^+ parameter cannot be measured for this system. For this reason, the level of dynamical evolution of NGC 1916 is assessed solely through its central relaxation

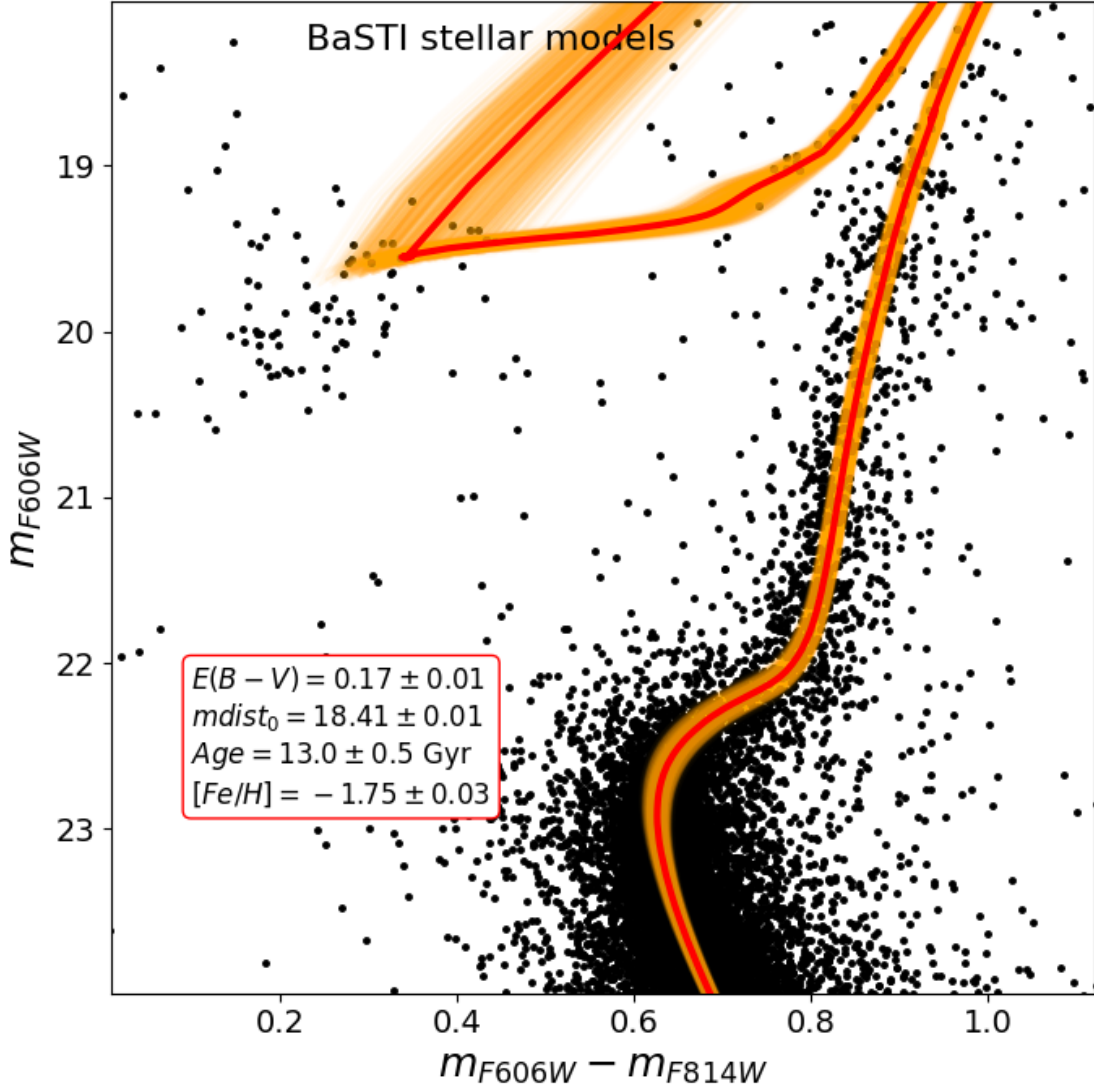


Figure 4.9: Field-decontaminated CMD of NGC 1916 in the radial annulus between $15''$ and $30''$ (black dots). The best-fit BASTI isochrone is represented as a red line and the 1σ uncertainty region as an orange-shaded envelope.

time.

In fact, as explained before, one of the options for expressing the level of dynamical evolution of a cluster is its central relaxation time (see Sect. 1.2 for a more detailed explanation of the formula):

$$t_{rc} = 1.491 \times 10^7 \times \frac{k}{\ln(0.4N_*)m_*} \rho_{M,0}^{1/2} r_c^3. \quad (4.3)$$

For NGC 1916, we adopted the total cluster mass from Mackey & Gilmore (2003), originally derived assuming a mass-to-light ratio of $M/L_V = 3.37$, and rescaled it to $M/L_V = 2$ to maintain consistency with the assumptions of Ferraro et al. (2019).

The central mass density $\rho_{M,0}$ was computed following Eqs.(4), (5), and (6) of Djorgovski (1993) (see Sect.2.7), using the concentration parameter $c = 1.69$ and the core radius $r_c = 1.9''$ obtained from our fit to the star density profile (see Sect.4.4), combined with the central surface brightness $\mu_{555,0} = 15.93$ mag arcsec $^{-2}$ reported by Mackey & Gilmore (2003). Finally, assuming a mean stellar mass $m_* = 0.3 M_\odot$, we obtained a core relaxation time of $\log(t_{rc}/\text{yr}) = 7.580$. Given a chronological age of $t = 13$ Gyrs, the corresponding number of central relaxation times experienced by the cluster is $N_{\text{relax}} = t/t_{rc} \simeq 342$ ($\log N_{\text{relax}} \simeq 2.5$), indicating that NGC 1916 is in a very advanced stage of dynamical evolution.

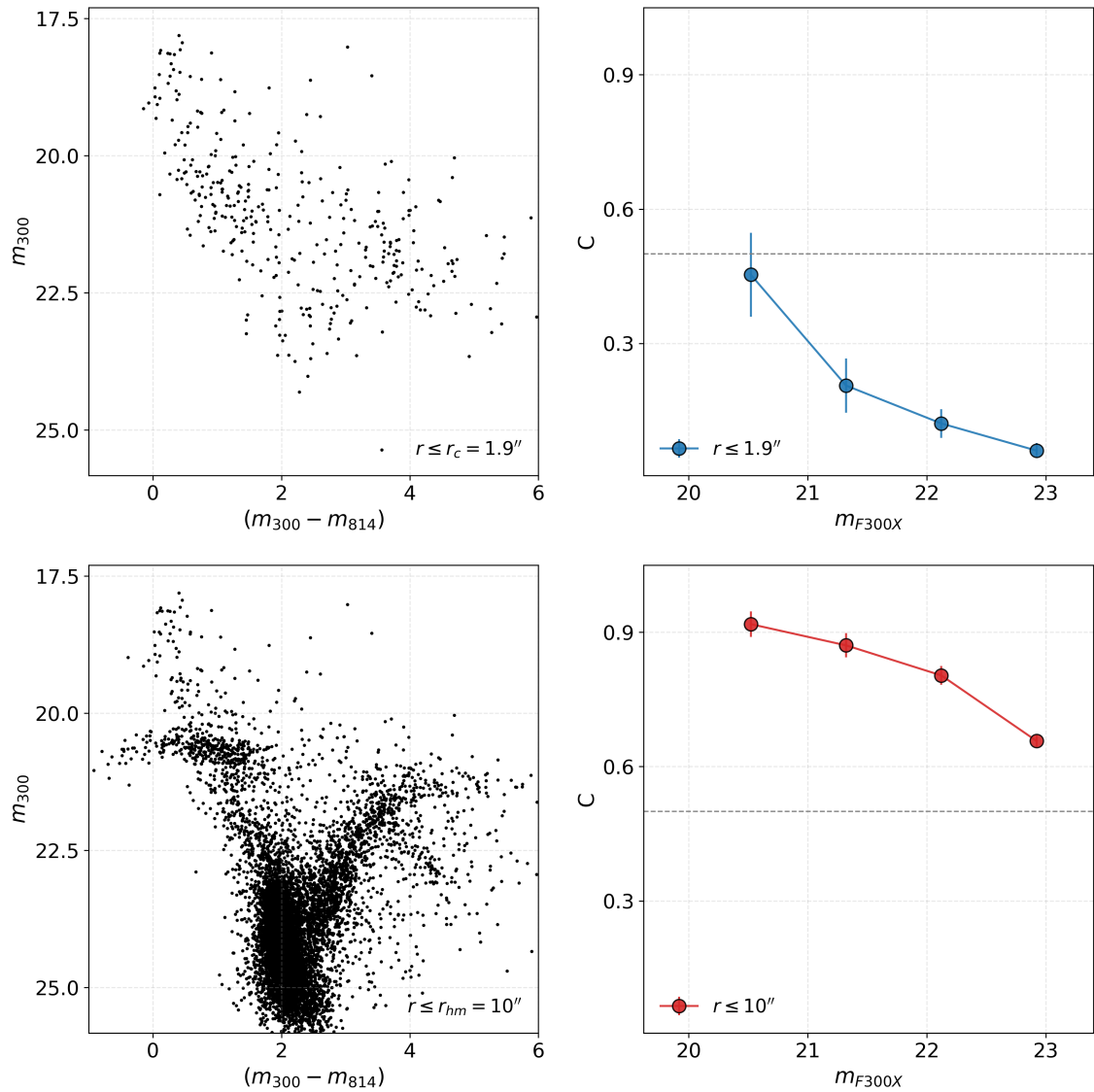


Figure 4.10: CMDs (left panels) and completeness curves (right panels) for NGC 1916 within two radial ranges: the core radius $r \leq r_c = 1.9''$ (top) and the half-mass radius $r \leq r_h = 10''$ (bottom). The completeness (C) has been derived from artificial star tests. The dashed horizontal line marks $C = 0.5$.

4.7 Discussion and conclusions

In this chapter we have presented a comprehensive analysis of the stellar populations, chronological age, structural parameters, and dynamical properties of NGC 1916. This cluster is one of the oldest, most massive, and most compact globular clusters in the Large Magellanic Cloud. Although it has been the subject of several previous studies, the presence of significant field contamination and strong differential reddening affecting its CMD have long hampered precise determinations of its physical properties.

Here, we carried out a new, homogeneous analysis of NGC 1916 based on high-resolution HST observations, with the goal of deriving updated and reliable estimates of its structural parameters, chronological age, and dynamical state. First, we corrected the photometry for differential reddening across the entire field of view, which significantly improved the definition of the CMD sequences. We then derived the structural parameters by fitting the decontaminated stellar density profile with single-mass, isotropic King models, obtaining a core radius of $r_c = 0.46$ pc, hence the smallest value among the three clusters investigated in this work. Finally, we determined the cluster's chronological age using a Bayesian MCMC isochrone-fitting procedure, which allowed us to robustly explore the parameter space for the chronological age, reddening, distance modulus and metallicity. The resulting best-fit parameters are: $t = 13$ Gyr, $E(B - V) = 0.17$, $(m - M)_0 = 18.41$, and $[\text{Fe}/\text{H}] = -1.75$.

Unlike the other two clusters analyzed in this thesis (NGC 1835 and NGC 1754), it was not possible to apply the dynamical clock method to NGC 1916. The region of the CMD where BSSs are expected is heavily contaminated by the young stellar population of the LMC, and the central regions of the cluster suffer from severe incompleteness. These issues prevent a reliable identification and selection of BSSs, making it impossible to reliably determine the A^+ parameter. To assess the dynamical state of NGC 1916, we therefore relied on the central relaxation time as an alternative tracer. The derived value, $\log(t_{rc}/\text{yr}) = 7.580$, corresponds to approximately $N_{\text{relax}} \simeq 342$ relaxation times over the cluster lifetime, indicating that NGC 1916 is in a very advanced stage of dynamical evolution. As shown in Fig. 4.11, the cluster lies along the general correlation between core radius and central relaxation time defined by Galactic (Harris, 1996, 2010 edition) and LMC globular clusters (Ferraro et al., 2019). Its position, characterized by the shortest relaxation time among the LMC clusters, is in agreement with its very small core radius value. Despite the impossibility of applying the dynamical clock method, the combination of its extremely short relaxation time and compact structure places NGC 1916 firmly among the most dynamically evolved clusters in the LMC. Its structural and dynamical properties are in excellent agreement with the scenario proposed by Ferraro et al. (2019), in which the present-day core radius distribution of old LMC clusters

reflects different levels of internal dynamical evolution.

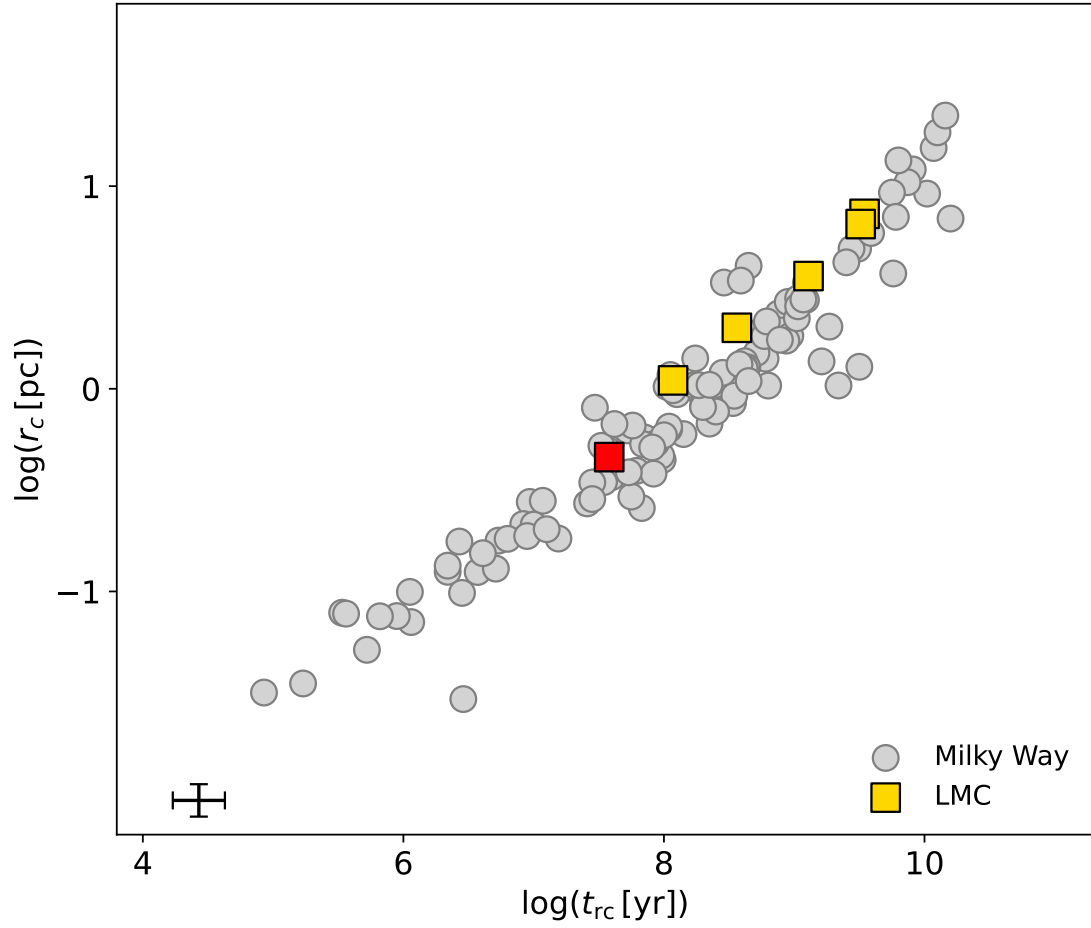


Figure 4.11: Core radius as a function of the central relaxation time for Galactic (gray circles, from Harris 1996, 2010 edition) and LMC (yellow squares, from Ferraro et al. 2019) GCs. The positions of NGC 1916 (red square) is highlighted. The plotted values are expressed in logarithmic scale, with r_c in parsecs and t_{rc} in years.

CHAPTER 5

General conclusions and future perspectives

In this thesis, we have presented a detailed study of three old and massive globular clusters in the Large Magellanic Cloud (NGC 1835, NGC 1754, and NGC 1916) with the aim of characterizing their stellar populations, structural properties, and dynamical states (see Chapters 2, 3, and 4, respectively; see also Appendix A for a discussion of the peculiar HB morphology of NGC 1835). These clusters are of particular importance because they are among the oldest stellar systems in the LMC, they are all located in its innermost regions, and they exhibit extremely compact structures. In addition, NGC 1835 shows signatures of a tidal bridge with a nearby young star cluster name KMK88-10 (see Appendix B). Their analysis therefore provides new and valuable insights into both the formation history of the LMC and the universality of globular cluster evolution across galactic environments different from the Milky Way.

From the perspective of the stellar populations, the three clusters show remarkably similar characteristics. They are metal-poor systems, with metallicities $[\text{Fe}/\text{H}] \approx -1.45$ for NGC 1754, $[\text{Fe}/\text{H}] \approx -1.69$ for NGC 1835 and $[\text{Fe}/\text{H}] \approx -1.75$ for NGC 1916, fully consistent with the population of ancient clusters in the LMC. We obtained their CMDs from a data reduction procedure of WFC3/HST images described in Sect.2.2, Sect.3.2 and Sect.4.2. The CMDs (see Fig.5.1) reveal well-populated red giant branches, and horizontal branches extending toward the blue, although with morphological differences that likely reflect the interplay between the effects of metallicity and other second-parameters, such as helium abundance. In particular, NGC 1835 shows a well-populated HB extending to both the red and the blue, indicating a broad range of stellar temperatures. NGC 1754 exhibits a comparatively redder and less extended HB, consistent with its higher metallicity. In contrast, NGC 1916 presents an almost exclusively blue HB, lacking a significant red component. This morphology is typical of more metal-poor and/or helium-enhanced populations.

By employing both a χ^2 minimization technique and the MCMC sampling to compare theoretical isochrones with the observed diagrams (see Sect.2.4, Sect.3.4 and Sect.4.5), we derived robust chronological age estimates of 12.5 ± 1 Gyr for NGC

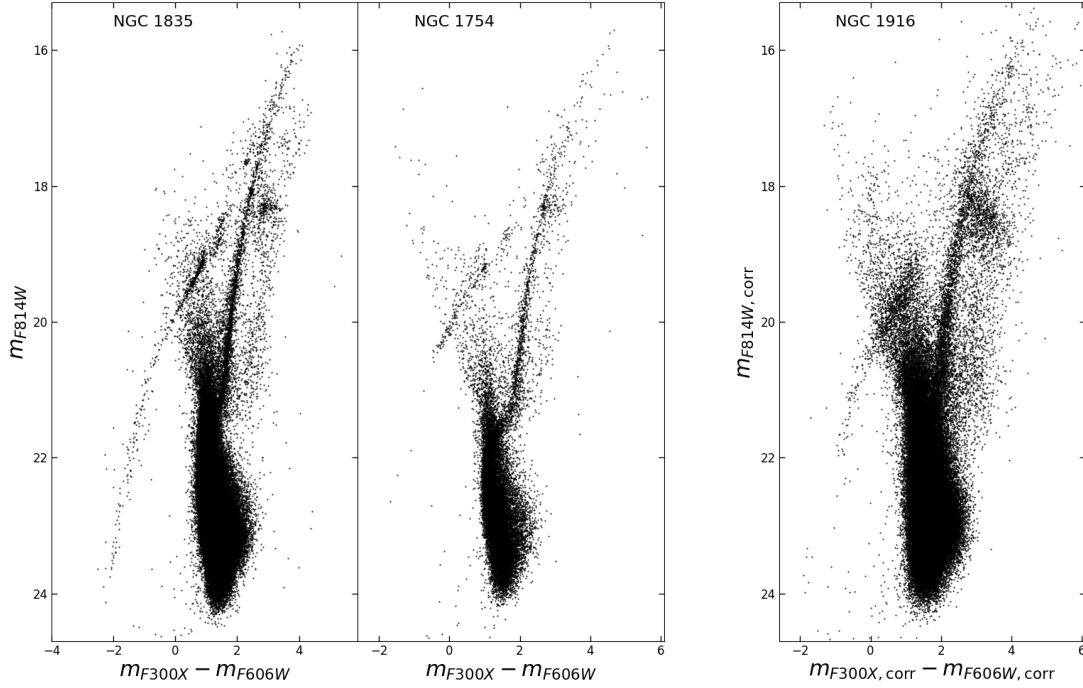


Figure 5.1: Left panel: CMD of NGC 1835. Central panel: CMD of NGC 1754. Right panel: CMD of NGC 1916 corrected for differential reddening.

1835, 12.8 ± 0.4 Gyr for NGC 1754, and 13 ± 0.5 Gyr for NGC 1916 (see the tripanel in Fig. 5.2). These results firmly establish all three systems among the oldest clusters

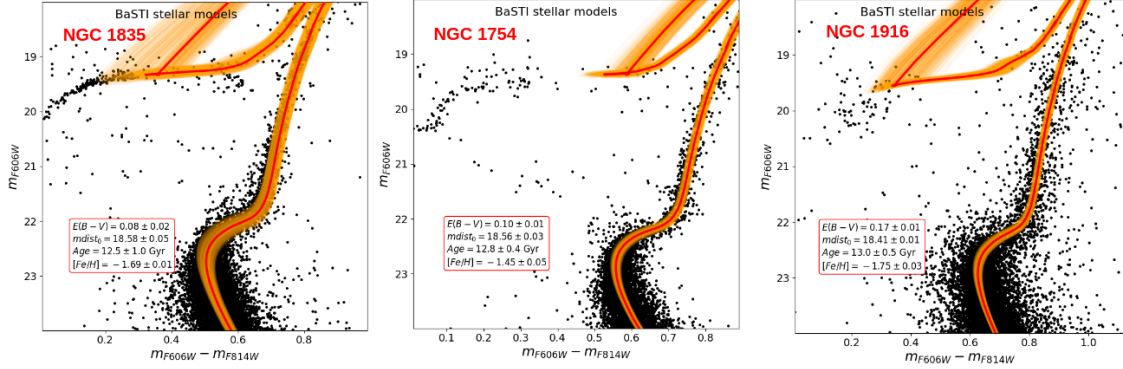


Figure 5.2: Field-decontaminated CMDs of NGC 1835, NGC 1754 and NGC 1916, with the best-fit isochrones superposed as red lines. The values of the reddening, distance modulus, best-fit age and metallicity are labelled in each panel.

in the LMC and strongly reinforce the idea that globular cluster formation in the LMC and in the Milky Way occurred nearly simultaneously, at the earliest epochs of galaxy formation. This point is particularly relevant because the relative separation between the two galaxies was substantially larger during the epoch of GC formation than it is at present (as indicated by orbital reconstructions; see Kallivayalil et al. 2013). At that time, the MW and the LMC constituted independent environments

for cluster formation, characterized by markedly different global properties such as total mass and star formation conditions. Hence, this result suggests that the onset of cluster formation was driven primarily by universal cosmological conditions (such as the availability of primordial gas and the rapid early assembly of dark matter halos), rather than by the local environment of the host galaxy.

Turning to the structural properties, we constructed radial density and surface brightness profiles for the three systems and fitted them with King models (see Sect. 2.6, Sect. 3.5 and Sect. 4.4). In Fig. 5.3 we show the best-fit King models for the three clusters. All three systems were found to have very small core radii (0.84

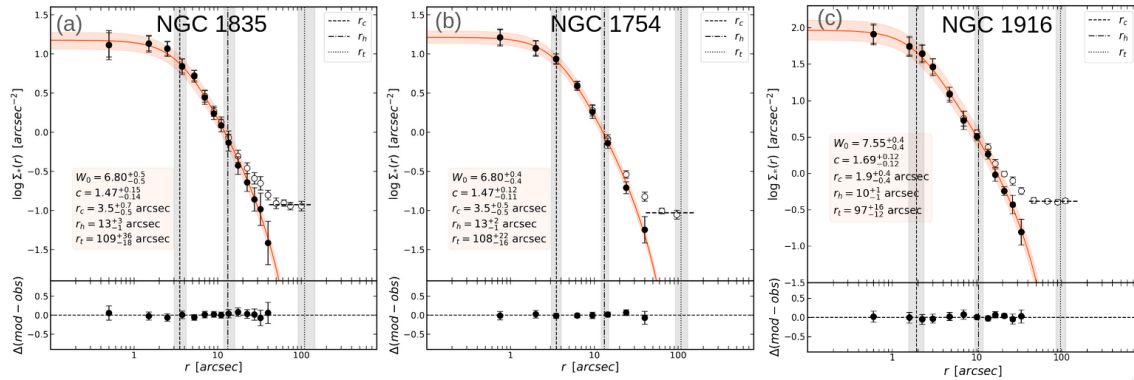


Figure 5.3: Star count density profiles of NGC 1835, NGC 1754, NGC 1916. For each cluster, the empty circles are the observed profiles, the black circles are the field-decontaminated profiles, and the red line is the best fit King model. The structural parameters are labelled in each figure.

pc for NGC 1835 and NGC 1754, and 0.46 pc for NGC 1916), confirming their extreme compactness. This result is particularly significant in the context of the so-called *size-age conundrum* in the LMC, which refers to the fact that while all young clusters appear to be compact, old clusters span a wide range of core radii, from very small to very large values, in spite of their comparable chronological ages (see Sect. 1.5.1). Previous studies (see e.g., Mackey et al. 2008) explained this by proposing an evolutionary sequence that links young and old clusters. According to this hypothesis, all star clusters form compact and then experience varying degrees of core expansion due to the heating effect of a population of stellar-mass binary black holes. However, young and old clusters exhibit very different masses (older clusters are more massive than younger ones) and different distances from the LMC center (with young clusters being observed in the innermost 5 kpc only, while older systems orbiting at all galactocentric distances; see Fig. 1.12). This rules out the existence of a direct evolutionary sequence linking the two groups of clusters. Even more importantly, our understanding of multi-body dynamics and studies of Galactic globular clusters suggest the opposite behavior: clusters tend to evolve toward more compact configurations as their dynamical evolution progresses. Recently, Ferraro et al. (2019) established the existence of a correlation between the core radius

and the degree of dynamical evolution for LMC clusters. They focused primarily on clusters with larger cores and therefore excluded the most compact systems. The analysis of NGC 1835, NGC 1754, and NGC 1916 is particularly valuable because these clusters occupy the extreme regime of old age and high compactness, making them ideal benchmarks to compare both with the more extended LMC clusters and with the Galactic globular clusters.

To quantify the dynamical evolution of the surveyed clusters, we applied the dynamical clock method, which relies on the radial distribution of blue straggler stars relative to a reference population (see also Sect. 1.4.1). Because BSSs are more massive than any other thermonuclearly active star in a cluster, they are more strongly affected by dynamical friction, making them excellent dynamical probes. The degree of central segregation of the BSS population is measured through the A^+ parameter, defined as the area between the cumulative radial distribution of BSSs and that of a lighter population measured within a half-mass radius. This parameter increases as mass segregation proceeds.

For NGC 1835 and NGC 1754, we successfully measured A_{rh}^+ (see Sect. 2.7 and Sect. 3.6). A first conclusion can be drawn by examining the plane that relates the measured values of A_{rh}^+ to those obtained for the parameter N_{relax} (see Sect. 1.5.1), which is defined as the ratio between the chronological age of a cluster and its central relaxation time. This is shown in the left panel of Fig. 5.4, where the distribution of the MW and LMC clusters defines two perfectly superposed, almost diagonal sequences. The observed trend clearly indicates that the two parameters are measuring the same physical phenomenon, the dynamical aging of star clusters. In this diagram, NGC 1835 and NGC 1754 follow the same correlation already defined by Galactic globular clusters and other Magellanic Cloud systems, confirming the reliability of A^+ as an indicator of internal dynamical age across different galactic environments.

Similarly, in the right panel of Fig. 5.4, we compare the values of A_{rh}^+ and the core radius for Milky Way and MC clusters. Also in this case NGC 1835 and NGC 1754 follow the expected anticorrelation, with smaller core radii corresponding to larger A^+ values. These results extend the scenario proposed by Ferraro et al. (2019) and demonstrate that the dynamical evolution of compact clusters in the LMC mirrors that observed in the Milky Way.

For NGC 1916, however, it was not possible to apply the dynamical clock method. The CMD of this cluster is heavily affected by contamination from the young stellar population of the LMC, whose sequence overlaps with the region where BSSs are expected to lie. This severely hinders the ability to separate genuine cluster BSSs from field stars. Furthermore, the strong differential reddening and the severe incompleteness in the crowded central regions make any reliable identification of the BSS population unfeasible. For this reason, we relied on the central relaxation time as

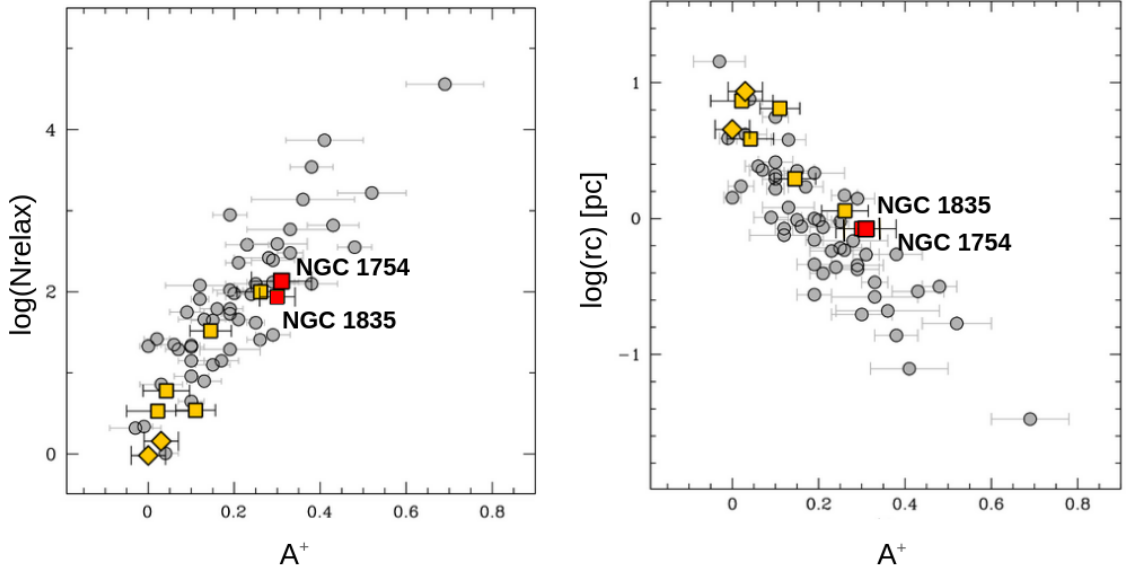


Figure 5.4: Left panel: relation between N_{relax} and A^+ for Galactic (in gray), LMC (yellow squares), and SMC (yellow diamonds) GCs. The two GCs studied in this thesis for which A^+ has been determined (namely, NGC 1835 and NGC 1754) are shown as large red squares. Right panel: relation between core radius and A^+ for the same clusters.

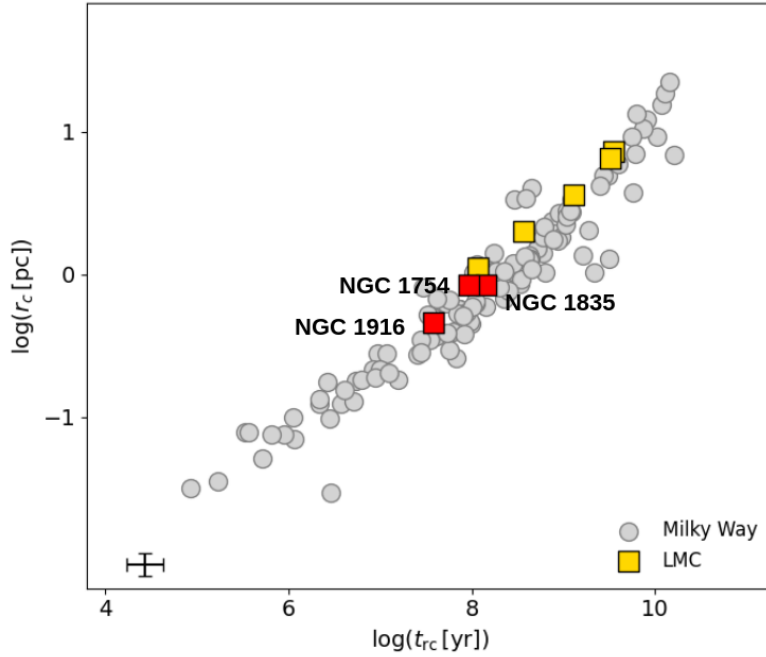


Figure 5.5: Relation between core radius and central relaxation time for Galactic (in gray) and LMC (yellow squares) GCs, and for NGC 1835, NGC 1754 and NGC 1916 (in red).

the only dynamical indicator. The derived value for NGC 1916, $\log(t_{rc}/\text{yr}) = 7.580$, corresponds to approximately $N_{\text{relax}} \simeq 342$ relaxation times over the cluster lifetime, indicating that NGC 1916 is the most dynamically evolved system among the three

studied. This is fully consistent with its extremely small core radius ($r_c = 0.46$ pc), which is the smallest in the sample. For comparison, NGC 1835 and NGC 1754 have $\log(t_{rc}/\text{yr}) = 8.158$ and 7.969 , corresponding to $N_{relax} \simeq 87$ and $N_{relax} \simeq 137$, respectively. This quantitative comparison clearly shows that NGC 1916 has undergone significantly more relaxation cycles than the other two, in line with its compact structure, and further supports its classification as the most dynamically evolved cluster in the sample. In Fig. 5.5 we show the correlation between core radius and central relaxation time for the Galactic globular clusters (grey points), the LMC clusters from Ferraro et al. (2019) (yellow squares), and NGC 1835, NGC 1754 and NGC 1916 (red squares). The three systems nicely fits in the correlation shown by the other clusters already studied.*

Although the three clusters experienced different degrees of dynamical evolution, they all show the same qualitative behavior observed in the Milky Way: dynamical aging is accompanied by a progressive reduction of the core radius and an increase in the segregation of massive stars. As mentioned in the Introduction, although this trend is qualitatively expected for all dynamically active stellar systems, the close match between the results observed in the MW and in the Magellanic Clouds is important and not entirely expected. In fact, star cluster internal dynamical evolution is driven by a complex combination of effects associated with a variety of processes (e.g., two-body relaxation, interactions with the Galactic tidal field along the cluster orbit, initial structural and kinematic properties of the cluster and its stellar content). Hence, the striking similarity between the dynamical aging of MW and Magellanic Cloud GCs, which were born and evolved in very different environments, is not obvious and suggests that the properties of the local environment, such as the parent galaxy tidal field, play, at most, a secondary role with respect to the internal properties.

For what concerns the size-age conundrum, the results obtained confirm the validity of the scenario proposed in Ferraro et al. (2019), namely that the difference in the values of the core radius observed for the old LMC clusters is due to their different dynamical ages, with less compact clusters being less dynamically evolved than the more compact ones.

Finally, the peculiar star formation history in the LMC provides an explanation for the behavior of the young, less massive systems. In particular, all of these younger clusters are observed to be compact. However, their compactness cannot be interpreted as the result of an advanced dynamical evolution, given their relatively young chronological ages, and the collected observational results suggest the following scenario. The earliest star formation episode in the LMC, around 12-13

*The correlation in Fig. 5.5 clearly shows a smaller scatter with respect to those plotted in Fig. 5.4. However, this is explained by the fact that t_{rc} is calculated through r_c (it directly depends on r_c raised to the third power: see equation 1.2).

Gyr ago, produced the most massive clusters ($M > 10^5 M_\odot$), which have survived until today and now appear as systems of different sizes depending on the stage of internal dynamical evolution they reached at present. After a long quiescent period, a second burst of star formation occurred in the LMC about 2-3 Gyr ago, generating a population of significantly less massive clusters ($M < 10^5 M_\odot$) in the central regions of the galaxy. The strong tidal forces in this environment likely prevented the survival of extended, low-density clusters, favoring instead the persistence of compact configurations. This scenario naturally explains the absence of young clusters with large core radii and further emphasizes the link between star formation history and the structural evolution of the LMC cluster system.

In summary, this thesis demonstrates that NGC 1835, NGC 1754, and NGC 1916 represent key laboratories for studying the earliest phases of globular cluster formation and the long-term dynamical evolution of compact stellar systems. Their properties provide compelling evidence for the universality of globular cluster evolution: regardless of whether they formed in the Milky Way or in the LMC, old clusters show comparable structural and dynamical properties. This work therefore strengthens the view that globular clusters are fundamental building blocks of galaxies and that their evolution is primarily governed by internal dynamics. Naturally, to gain a more complete understanding of the problem, it would be particularly valuable to extend this investigation to clusters of intermediate age ($\log t \approx 8-9$), which may already exhibit subtle signatures of dynamical evolution. Preliminary attempts to quantify the dynamical ages of a few such clusters in the LMC have indicated only modest levels of internal evolution (see for example Li et al. 2019). However, a systematic and detailed analysis of the oldest objects within this age range (those with ages exceeding 2–3 Gyr, such as NGC 2121, NGC 2155, and SL 663) is still missing. A focused study of these systems could provide crucial insights into the progressive evolution of cluster structures, offering a bridge between the relatively unevolved young populations and the dynamically mature old globular clusters. Such an analysis would also help constrain the timescales and efficiency of dynamical processes, such as mass segregation and core contraction, in shaping the structural diversity observed among stellar clusters in the LMC, providing deeper insight into the co-evolution of star clusters and their host galaxies across cosmic time.

APPENDIX A

The horizontal branch of NGC 1835

*Mainly based on:
Giusti et al. (2024b), A&A, 686, A6*

A.1 Introduction

In this chapter we present the detailed investigation of the HB morphology of NGC 1835 that we performed thanks to the “UV-guided search” photometric procedure discussed in Chapter 2, which optimizes the detection of hot stars. This allowed us to discover a remarkably extended HB in this cluster. It spans more than 4.5 mag in both the optical and the near-ultraviolet bands, and its color (temperature) ranges from the region redder than the instability strip up to effective temperatures of 30 000 K. This is the first time that such a feature has been detected in an extragalactic cluster, demonstrating that the physical conditions responsible for the formation of extended HBs are ubiquitous.

A.2 The Horizontal Branch problem

The Horizontal Branch is a phase of low-mass stellar evolution, most evident in old systems such as GCs, that follows the RGB phase after central hydrogen is exhausted and helium ignites. In these stars, helium ignition occurs under electron degeneracy, producing a helium flash that sets an almost universal core mass. Because HB stars begin core He burning with nearly the same core mass, what differs from star to star is the hydrogen-rich envelope left on the zero-age HB (ZAHB). The envelope mass governs the surface temperature: thick envelopes yield larger radii and cooler, redder stars (i.e., giving rise to the morphology known as the *red clump*), whereas thin envelopes produce hotter, bluer HB stars.

Because the envelope mass, and thus the surface temperature, depends on several factors, the overall distribution of HB stars varies from system to system. Among these factors, metallicity has long been recognized as the primary one shaping HB morphology. At fixed age, higher metallicity implies a higher main-sequence turnoff mass and therefore a larger total mass in the ZAHB. Since the core mass is nearly

fixed by the helium flash, a larger total mass means a thicker envelope and hence a cooler (redder) ZAHB position. Increased metallicity also raises opacity and atmospheric line blanketing, which pushes observed colors further to the red. These effects explain the broad tendency for metal-poor clusters to host bluer HBs and metal-rich clusters redder ones.

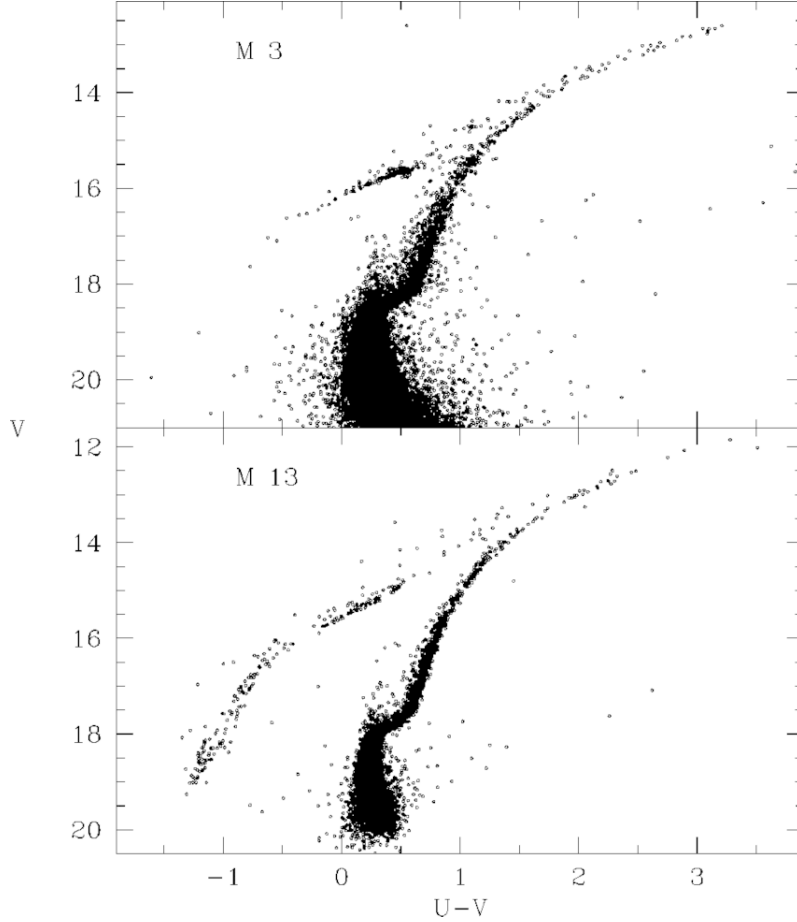


Figure A.1: CMDs of the GGCs M13 and M3. The figure clearly shows the different morphologies of the two HBs. Image taken from Ferraro et al. (2009).

However, metallicity alone cannot account for the full diversity of horizontal branch (HB) morphologies, as clusters with similar metallicity can display very different HB distributions. For example, at high metallicity ($[\text{Fe}/\text{H}] \sim -0.4$), NGC 5927 exhibits a predominantly red HB, while NGC 6388 shows an extended HB with a significant blue component. At intermediate metallicity ($[\text{Fe}/\text{H}] \sim -1.5$), M3 and M13 display markedly different HBs, with M3 hosting a well-populated HB spanning both red and blue regions, and M13 characterized by a predominantly blue and extended HB (Ferraro et al. 1997a; see Fig. A.1). Finally, at low metallicity ($[\text{Fe}/\text{H}] \sim -2.3$), M15 shows a very extended blue HB, whereas M92 has a comparatively less extended HB morphology. This mismatch is called “second-parameter problem” (Freeman & Norris, 1981; Catelan, 2009). The identity of this second pa-

parameter has been the subject of extensive research and debate. Several candidates have been proposed, including age, helium abundance and mass loss on the RGB. In particular, an increase in age, helium abundance, or mass loss leads to bluer HB stars because it results in stars with lower envelope masses, which raises their surface temperatures during helium burning.

A precise understanding of the HB morphology is crucial, since it strongly influences the integrated light of stellar populations, affecting both their observed colours and spectral line indices (Schiavon et al., 2004).

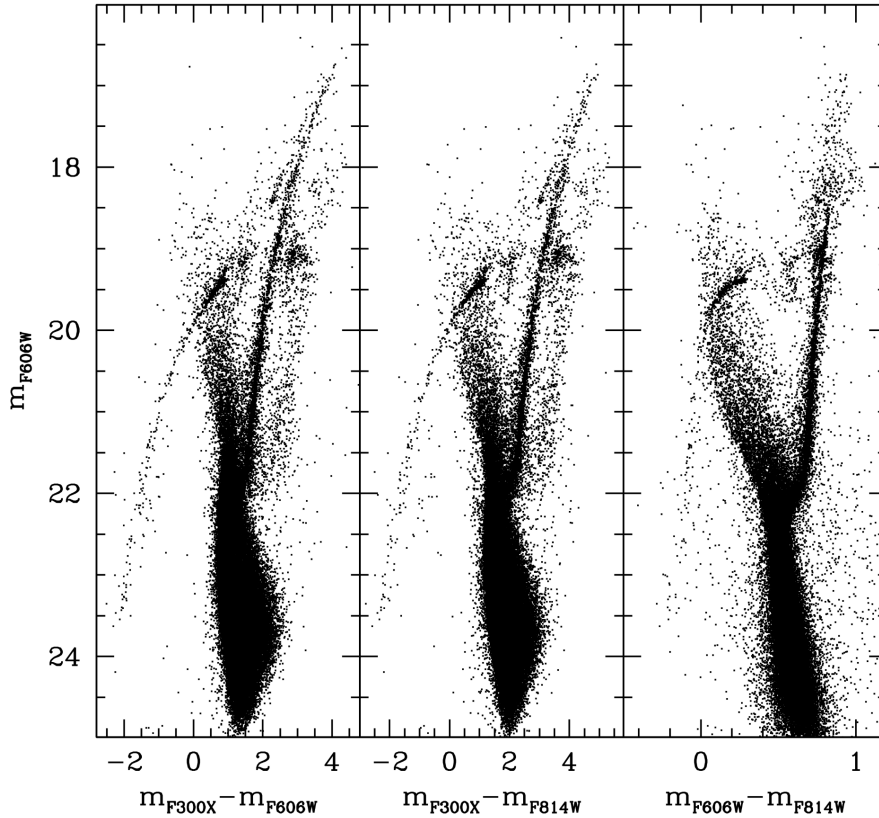


Figure A.2: CMD of NGC 1835 obtained from the WFC3 dataset in all the filter combinations (the same as Fig. 2.2).

A.3 The Horizontal Branch of NGC 1835

The observations and data analysis used to investigate the HB morphology of NGC 1835 are discussed in Chap. 2.2, and Figure A.2 (same as Fig. 2.2) shows the CMDs obtained in all the available filter combinations. The HB extension of NGC 1835 is fully appreciable in the CMDs involving the F300X filter, which has “guided” the detection of hot stars (see Sect. 2.2). However, the peculiarity of this HB is not only its magnitude extension, but also its color distribution: in fact, the HB

appears to be well populated both in its red ($0.5 < m_{\text{F300X}} - m_{\text{F606W}} < 0.8$) and blue ($-2.1 < m_{\text{F300X}} - m_{\text{F606W}} < 0.4$) portions, and also shows a large population of stars in the instability strip.

A.3.1 RR Lyrae

The identification of RR Lyrae variable stars is a crucial step for the proper analysis of the HB morphology. For their identification we exploited a photometric “variability index”, defined as the ratio between the standard deviation of the star luminosities measured at different epochs (which provides an estimate of the amplitude of the light curve) and the internal photometric error (which provides an estimate of the quality of the star’s photometry; Kjeldsen & Frandsen 1992). For stars having magnitude values from different exposures that consistently fall within the photometric error, the variability index tends to approach unity. Conversely, an increase in the index value corresponds to an increasing probability of stellar variability. In the case of NGC 1835, we find that the variability indexes computed in the near-UV tend to be larger than those obtained in the optical bands, thus suggesting that the F300X filter is best suited for this kind of study. We therefore assumed as variable stars all the sources with a variability index higher than 2 in this filter.

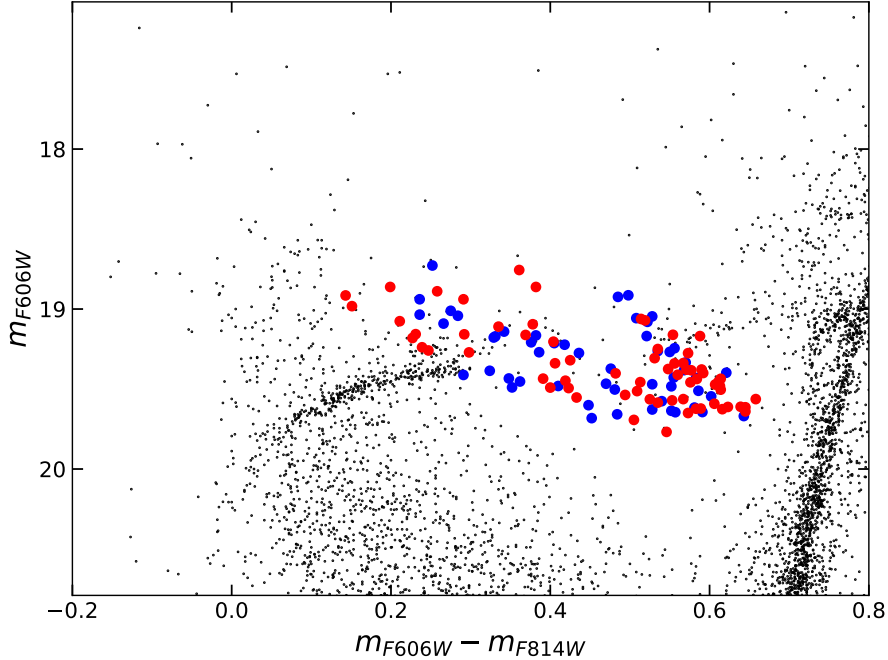


Figure A.3: CMD of NGC 1835, zoomed into the HB region. The 67 confirmed OGLE variables and 52 new candidate RR Lyrae are highlighted as red and blue circles, respectively. Only non-variable stars observed at $r < 60''$ from the center are shown for reference, as black dots.

The number of variable stars recovered with this approach is 95. However, since

our dataset was not originally intended for variability studies, we complemented this information with the Optical Gravitational Lensing Experiment (OGLE) IV catalogue*, which provides information on variable stars and transient objects in the Magellanic Clouds and Galactic bulge. This catalogue presents an updated list of variables found in the direction of the cluster NGC 1835, for a total of 125 objects, mainly RR Lyrae (Soszyński et al., 2016). After proper cross-correlation, we found a total of 67 variable stars in the region of the instability strip in common between our catalogue and the OGLE one. Interestingly enough, 43 of them were also identified via the variability index, while the remaining 24 OGLE variables were possibly caught in low luminosity variation phases by our observations. In addition, the DAOPHOT variability index indicates that in the field of view sampled by our observations there are 52 more candidate RR Lyrae that are not included in the OGLE catalogue. Thus, NGC 1835 hosts a very large population of RR Lyrae variables, counting 119 objects in the field of view sampled by our observations: 67 are confirmed OGLE variables, and 52 are possible new candidates identified by the variability index (see Fig. A.3).

A.3.2 Field decontamination and extension of the HB

As shown in Fig. A.2, the main LMC field contamination along the HB is in the red portion of the branch, in the colour range $0 < m_{F300X} - m_{F606W} < 1.2$, with a minor contribution in the adjacent colour bin $1.2 < m_{F300X} - m_{F606W} < 2$ (“extremely red” portion). With the available datasets (only HST Wide Field and Planetary Camera 2, WFPC2, images of the cluster are present in the HST archive), the decontamination through proper motions is not feasible. In fact, given the large distance of the LMC (Harris & Zaritsky, 2009; Pietrzyński et al., 2019), a first epoch dataset with an astrometric quality better than that provided by the archive WFPC2 observations is required, possibly combined with a significantly longer time baseline between the two epochs. Thus, we performed a statistical decontamination of these portions of the HB taking advantage of the parallel ACS observations (see Fig. A.4; Ferraro et al., 2019; Dalessandro et al., 2019). Schematically, after removing all the confirmed and candidate variables, we selected the HB stars in the $(m_{F606W}, m_{F300X} - m_{F606W})$ CMD. Then, we used the position of these stars in the $(m_{F606W}, m_{F606W} - m_{F814W})$ CMD to draw the optical selection boxes of the red and extremely red HB portions. We counted the number of stars belonging to ACS catalogue that fall within the two selection boxes and, dividing by the area sampled by the parallel observations, we finally obtained the density of LMC field stars contaminating the red and the extremely red portions of the HB. This procedure yielded a field density contamination of 17.28 and 3.44 stars per square arcminute, which corresponds to a total of 120 and 25 field stars potentially contaminating the red and the extremely

*<https://ogledb.astrouw.edu.pl/ogle/CVS/>

red HB portions, respectively. The statistical decontamination was then performed taking into account the distance from the cluster center and the geometric distance of each stars from the mean ridge line of the HB, since the membership probability typically decreases if these distances increase. Hence, the cluster (WFC3) sample has been divided into concentric annuli, and the expected number of contaminating stars was determined in each radial annulus from the estimated field density and the bin area. Finally, the estimated number of field stars has been removed from the WFC3 sample starting from the objects located at larger geometric distances from the HB mean ridge line.

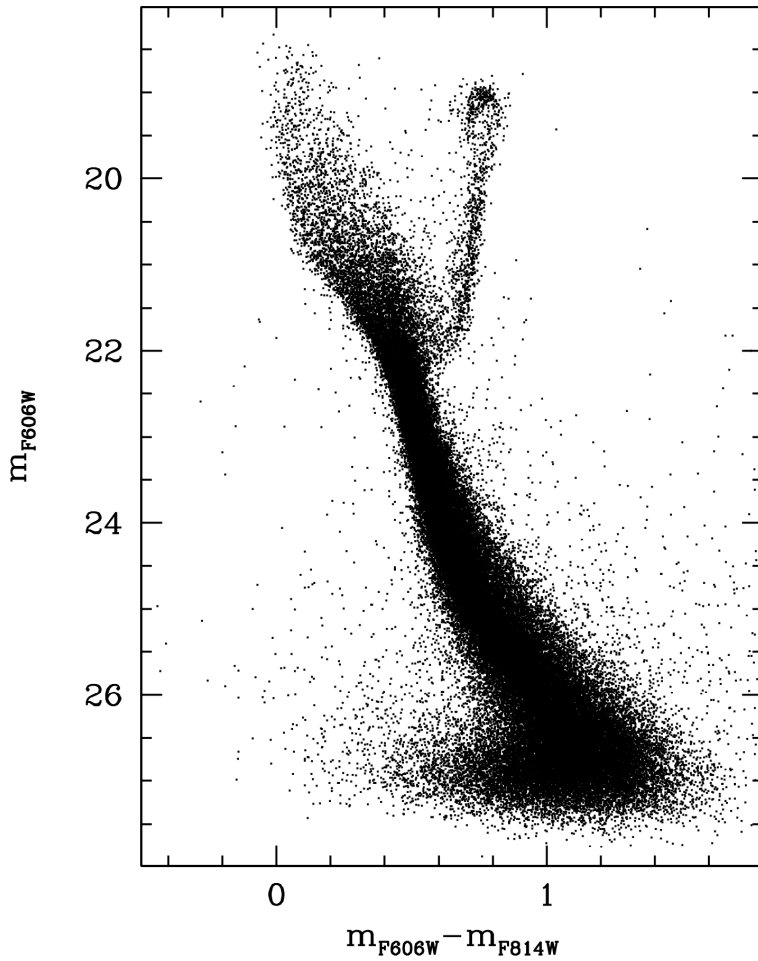


Figure A.4: CMD of the LMC field obtained from the ACS parallel observations.

The HB of NGC 1835 obtained after statistical decontamination counts 602 non-variable stars and is plotted in Figure A.5. For the sake of clarity, we also explicitly mark the large extension in colour (~ 4 mag) and in magnitude (~ 4.6) of the branch. Indeed, even neglecting the faintest stars detected at $m_{F606W} \sim 24.2$, the extension in magnitude and colour is remarkable: this is the first time that such an extended HB has been detected in an extragalactic cluster.

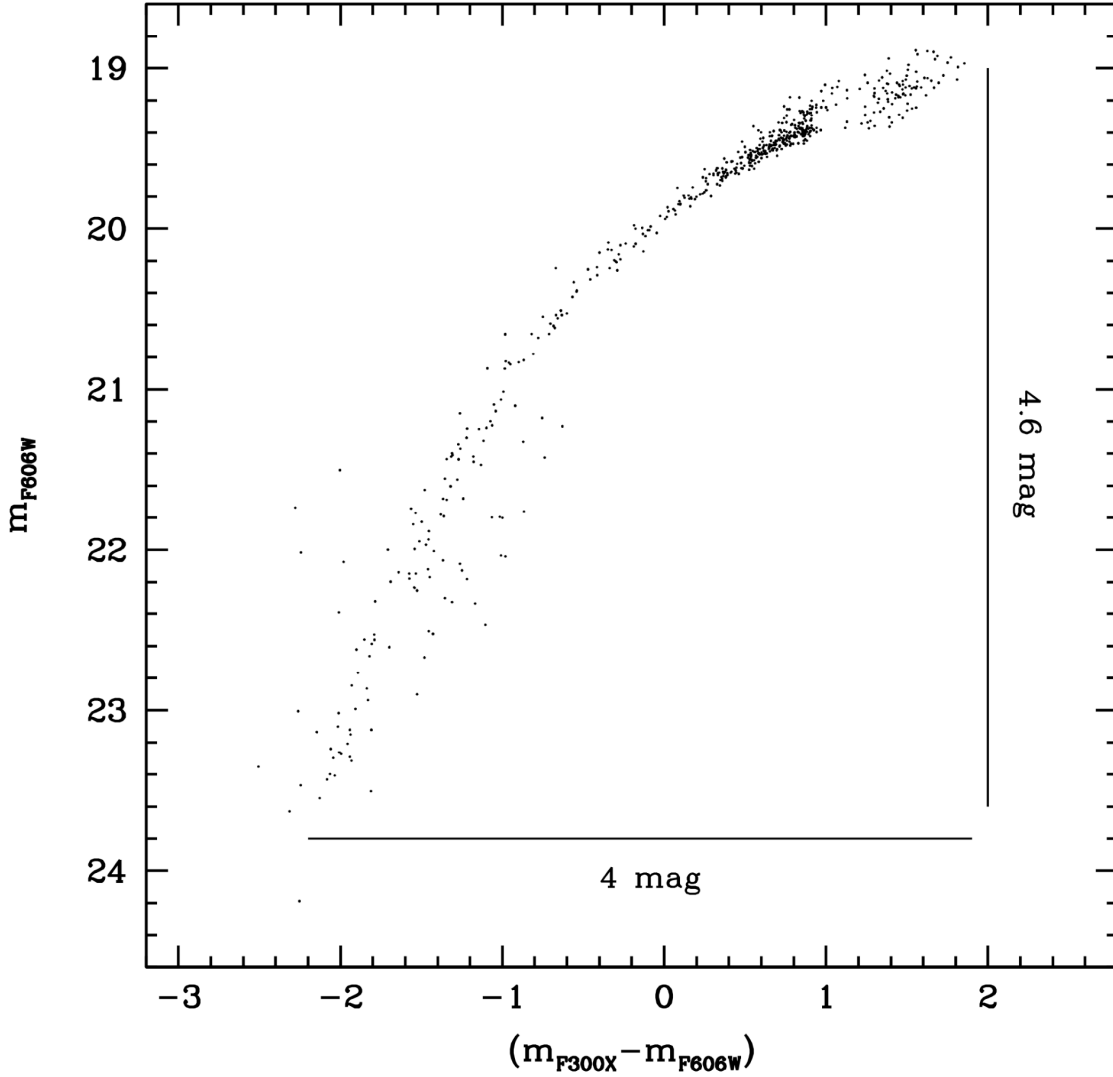


Figure A.5: HB of NGC 1835 after the statistical decontamination of the reddest portions. Only non-variable stars are plotted. The extension in colour (~ 4 mag) and in magnitude (~ 4.6 mag) is also marked.

A.3.3 The surprising HB morphology of NGC 1835

As mentioned above, the HB of M13 shows a well extended and populated blue tail, very few RR Lyrae, and the portion redder than the instability strip that is poorly populated. Conversely, in M3 the star distribution is peaked around the instability strip, with a large population of RR Lyrae, and the red and the blue side of the strip are both well populated, but with no evidence of a blue tail. These characteristics make the two Galactic GCs particularly useful for the description of the HB morphology in NGC 1835.

As shown in Fig. A.5, the colours using the F300X filter tend to stretch the high-temperature tail of the branch, while compressing the low-temperature portion.

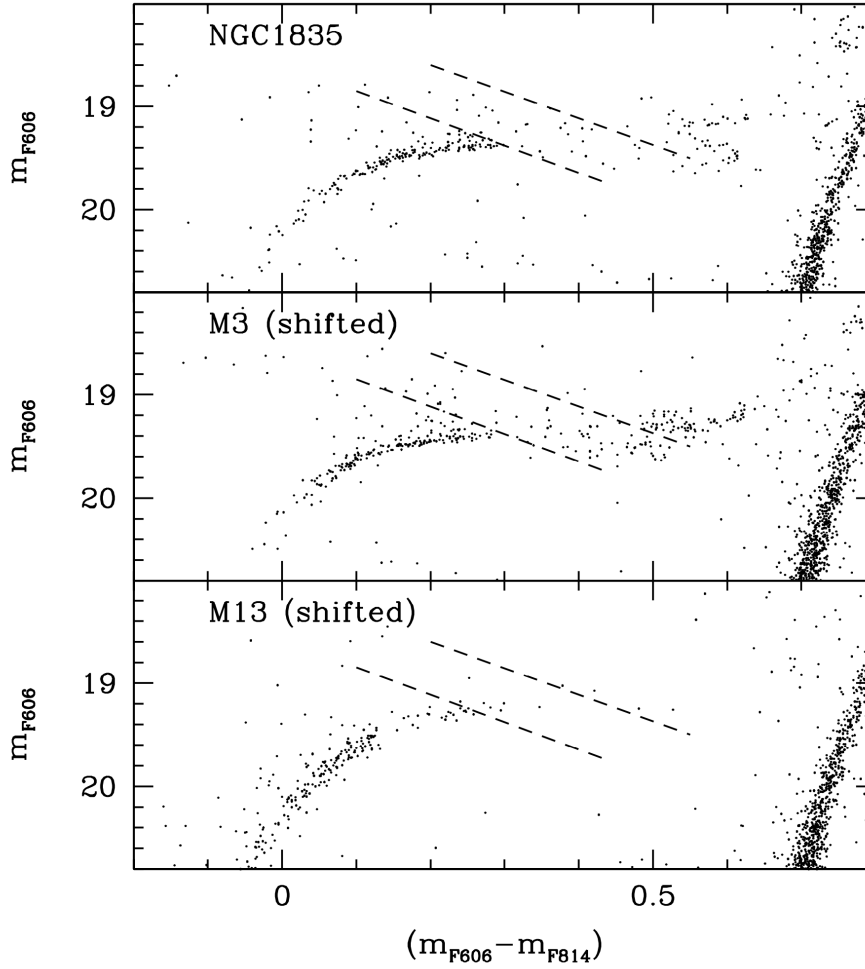


Figure A.6: Low-temperature portion of the HB of NGC 1835 (top panel) compared with those of M3 (central panel) and M13 (bottom panel). The CMD of M3 and M13 have been shifted to the same distance and reddening of NGC 1835. In all panels, the two dashed lines delimitate the region where most of the RR Lyrae observed at random phases are expected to be located.

Thus, better insights into the star distribution in the red (cold) side of the HB are obtainable in the purely optical colour ($m_{F606W} - m_{F814W}$), which also allows a clear identification of the location of the instability strip. Figure A.6 shows the comparison in the optical CMD among the low-temperature portion of the HB observed in NGC 1835 (top panel), in M3 (central panel) and in M13 (bottom panel). The CMDs of M3 and M13 have been shifted to the distance and reddening of NGC 1835 estimated above. The similarity between M3 and NGC1835 in the morphology of this portion of the HB is impressive, and it is further supported by the existence of large populations of RR Lyrae detected in both systems. On the other hand, it is evident that the HB in M13 extends mainly on the blue side of the instability strip, consistently with the low number of confirmed variables in this cluster.

For the sake of comparison, Figure A.7 shows instead the comparison between

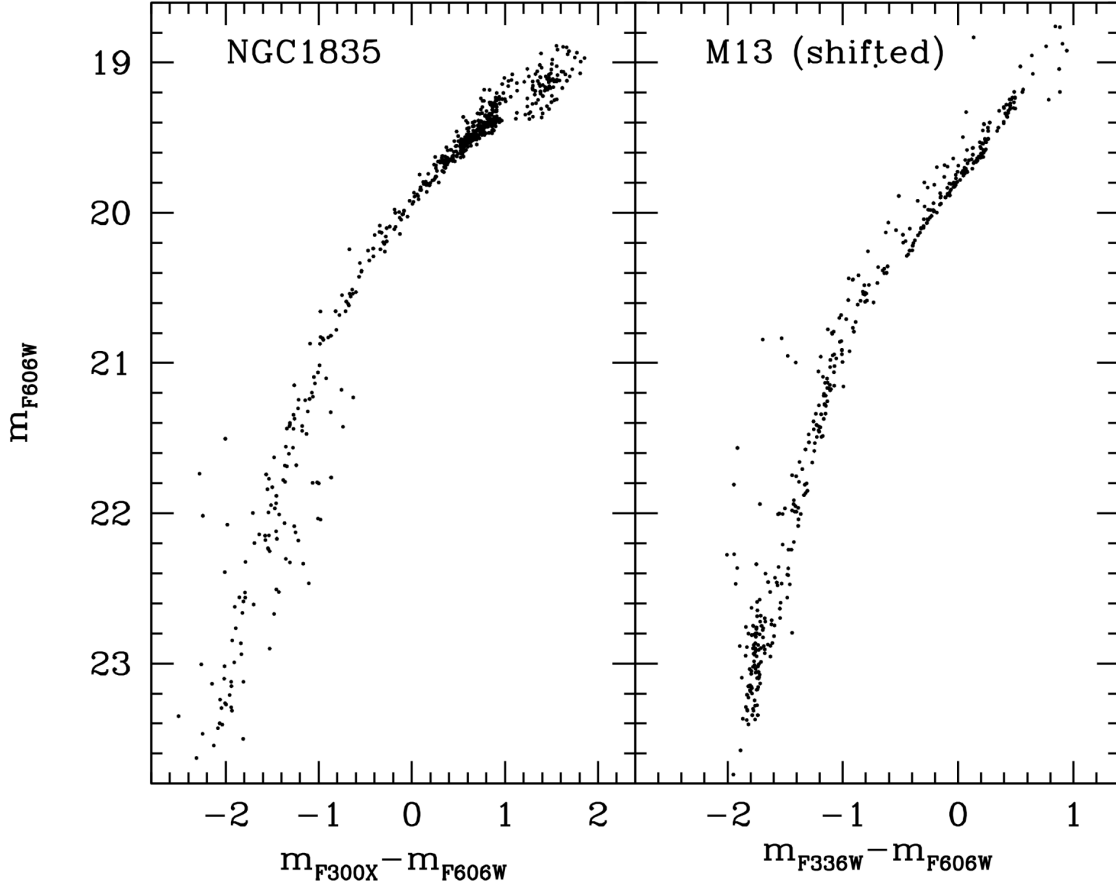


Figure A.7: HB of NGC 1835 (left panel) compared to that of M13 (right panel). Variable stars are not shown.

the HB of NGC 1835 (left panel) and that of M13 (right panel) in the optical/near-UV hybrid CMD. As usual the CMD of M13 has been shifted to the distance of NGC 1835 estimated above. Only non-variable stars are plotted here. Although the filters used in this comparison are not exactly the same, the overall magnitude extension of the branch is strikingly similar. Notably, the colour extension in NGC 1835 looks wider than in M13, with several stars reaching redder colours at the right-end side of the instability strip, where almost no objects are observed in M13 (see also Fig. A.6). This comparison therefore shows that the HB observed in NGC 1835 looks like a combination of the HBs of M3 and M13, with a well-populated red portion characterized by a relevant number of RR Lyrae (like in M3, and at odds with M13) and an extended blue tail (at odds with M3, but as in M13).

As last piece of information, we determined the temperature distribution of the HB stars in NGC 1835. In doing this, we first translated the decontaminated HB into the absolute plane, adopting the distance modulus and the reddening determined in Section 2.4. We then projected the non-variable stars perpendicularly onto the mean ridge line of the branch (see the inset in Figure A.8), thus obtaining their projected

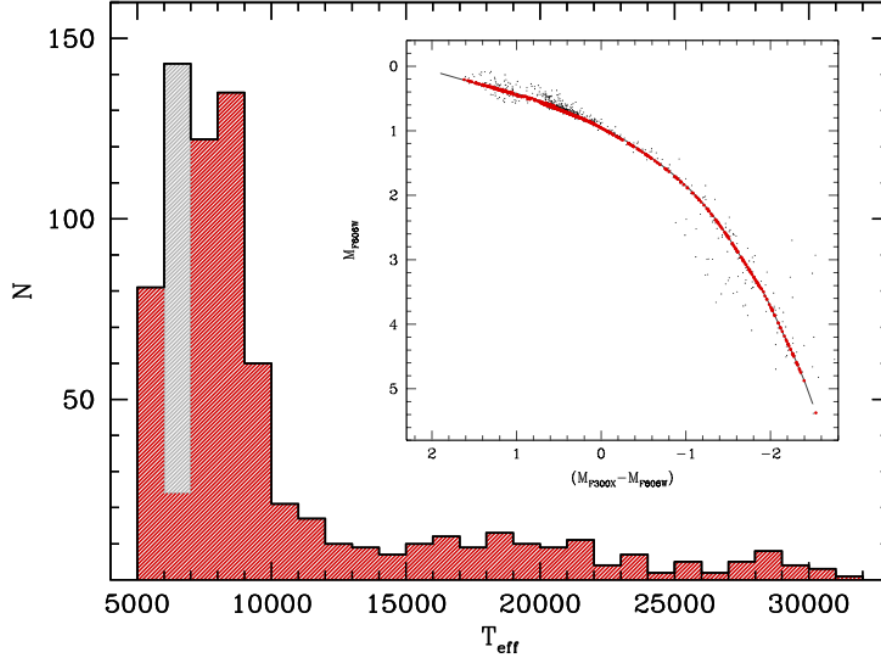


Figure A.8: Effective temperature distribution of the HB stars in NGC 1835. The histogram shaded in grey refers to the sample of 119 confirmed and candidate variable stars distributed within the range of temperatures covered by the instability strip ($6000 < T_{\text{eff}} < 7000$). The inset shows the locations of non-variable HB stars in the absolute CMD (black dots) and the corresponding positions projected onto the HB mean ridge line (red dots along the solid black line). The colour axis is inverted (with bluer colours to the right) to be consistent with the x-axis of the histogram (increasing temperature to the right).

intrinsic colour and absolute magnitude. Then, to transform the $(M_{\text{F300X}} - M_{\text{F606W}})$ colour into effective temperature (T_{eff}), we adopted the colour-temperature relation for zero-age HB models of appropriate metallicity ($[\text{Fe}/\text{H}] = -1.7$) extracted from the BASTI dataset (Pietrinferni et al., 2021). To complete the overall picture, we arbitrarily attributed T_{eff} values to all the confirmed and candidates RR Lyrae in the temperature range covered by the instability strip ($6000 < T_{\text{eff}} < 7000$). The resulting T_{eff} distribution (see Fig. A.8) shows a main peak in the red portion of the HB (possibly in the instability strip), and a long tail extending to temperatures as large as 30,000 K. The tail is not uniformly populated (in agreement with what observed in all other similar cases; see e.g. the discussion in Ferraro et al. 1998), but it seems to show a secondary peak (by far less populated than the main one) in the region between 15,000 and 20,000 K.

While a spread of stellar ages is excluded in NGC 1835 by the apparent narrowness of its MS-TO, the combined action of mass loss and helium spread can in principle account for its complex HB morphology. Indeed, Dalessandro et al. (2013b) discuss the HB morphology of M 3 and M 13, concluding that it can be interpreted in terms of different helium contents. Unfortunately, however, the photometric band combination used here is not optimized for detecting light-element multiple popu-

lations and, in fact, we observe no evidence of splitting or broadening along the evolutionary sequences in the CMD. The physical reason behind the observed HB extension in NGC 1835 therefore remains an open question.

APPENDIX B

KMK88-10

*Mainly based on:
Giusti et al. (2023), ApJ, 953, 2, 125*

B.1 The young star-cluster KMK88-10

As mentioned in the introduction, the LMC is the closest (irregular) galaxy to the MW. Due to its proximity (~ 50 kpc, Harris & Zaritsky 2009; Pietrzyński et al. 2019), it is possible to resolve individual stars, also within its stellar clusters. These are both rich star clusters, with properties similar to those of the MW globular clusters, and lower-mass systems resembling the Galactic open clusters. At odds of their Galactic counterparts, globular clusters in the LMC exhibit a wide range of ages (from a few million, to several billion years), thus providing an unique laboratory to study the major changes in the observational properties of stellar populations as a function of the age (see, e.g., Ferraro et al. 1995, 2004; Mucciarelli et al. 2006). Moreover, they provide deep insights into the LMC star formation history (Baumgardt et al., 2013) and chemical enrichment (e.g. Pietrzyński & Udalski, 2000; Glatt et al., 2010). While these systems have been targeted for several studies through the years (Olsen et al. 1998; Brocato et al. 1996; Mackey & Gilmore 2003; Mucciarelli et al. 2008, 2010; Ferraro et al. 2019; Lanzoni et al. 2019; Cadelano et al. 2022a), an extensive and comprehensive study of LMC low-mass clusters is still lacking. This is because they are composed of a limited number of stars embedded in the LMC field population, which severely hinders their detection and makes them easily misidentifiable with asterisms (Bica et al., 2008; Choudhury et al., 2015; Nayak et al., 2016). Nevertheless, such systems are crucial for understanding the formation and evolution of the LMC (Piatti, 2012; Palma et al., 2013; Piatti et al., 2014; Choudhury et al., 2015; Palma et al., 2016).

Interestingly, “star cluster pairs” with small projected relative distances are frequently observed in the LMC (Priyatikanto et al., 2019a,b). Bhatia & Hatzidimitriou (1988); Bhatia et al. (1991); Subramaniam et al. (1995); Dieball et al. (2002) used statistical arguments to prove that the large number of observed cluster pairs cannot be fully explained by random projection effects. This indicates that at least some

of them are likely gravitationally bound, and observational confirmations of this hypothesis have been found in a few cases (e.g. Mucciarelli et al., 2012; De Silva et al., 2015; Dalessandro et al., 2018). Interacting binary clusters could be the result of the primordial fragmentation of a common molecular cloud, or the outcome of a close encounter between two clusters during their motion in the galaxy, and a subsequent tidal capture (see, e.g. Dieball et al., 2002; Mucciarelli et al., 2012; Dalessandro et al., 2018). While in the former case binary clusters are expected to share some common property (such as the age and chemical composition), in the latter case the two members can have very different ages, masses and chemical abundances.

Cluster pairs generated by encounter processes can bring a wealth of information about the evolutionary history of the host galaxy, and also explain the properties of individual systems with peculiar characteristics, such as unusual rotation patterns (Lee et al., 1999; Baumgardt et al., 2003; Brüns & Kroupa, 2011), or spreads in chemical abundances (e.g. Amaro-Seoane et al., 2013; Gavagnin et al., 2016; Hong et al., 2017). For this reason they have been extensively studied in the past, mainly through N -body simulations (Rao et al., 1987; de Oliveira et al., 1998, 2000; Portegies Zwart & Rusli, 2007; de la Fuente Marcos & de la Fuente Marcos, 2010; Priyatikanto et al., 2016; Darma et al., 2021). The fate of these systems seems to be twofold: those having a small initial separation will likely experience a merger in a relative short timescale, while the ones with larger initial separation will probably be moved apart by the tidal forces of the host galaxy (Darma et al., 2021). Tidal captures are expected to occur more often in dwarf galaxies such as the LMC, rather than in the MW, due to a smaller relative velocity of star clusters (van den Bergh, 1996). In spite of this, the encounter rate per cluster in the LMC is predicted to be quite low ($dN/dt \sim 10^{-9}$ yr; Vallenari et al. 1998), making the possibility of an encounter highly unlikely for very young clusters.

In this work, we provide the first tentative evidence of an ongoing tidal capture of the small star cluster KMK88-10 by the massive globular cluster NGC 1835 in the LMC. In fact, a small and loosely populated star cluster was clearly visible near the border of the images of the massive globular cluster NGC 1835 (see Fig. B.1). This is KMK88-10 (also named H88 120 and OGLE-CL LMC 74, see Narloch et al. 2022). It was first identified by Pietrzynski & Udalski (2000) and later studied by Bica et al. (2008); Nayak et al. (2016); Narloch et al. (2022), who estimated a very low-mass ($\sim 300M_{\odot}$) and young age ($t \sim 500$ Myr). However, its characteristics have never been investigated in depth with adequate high-resolution and deep observations. Thanks to the acquired data-set, here we provide a detailed characterization of this stellar system and probe the possibility that it is experiencing a physical interaction with NGC 1835. In agreement with the previous considerations about the encounter rate per cluster in the LMC, very few cases of this kind are known observationally, and no evidence of ongoing tidal captures between systems with very different ages and

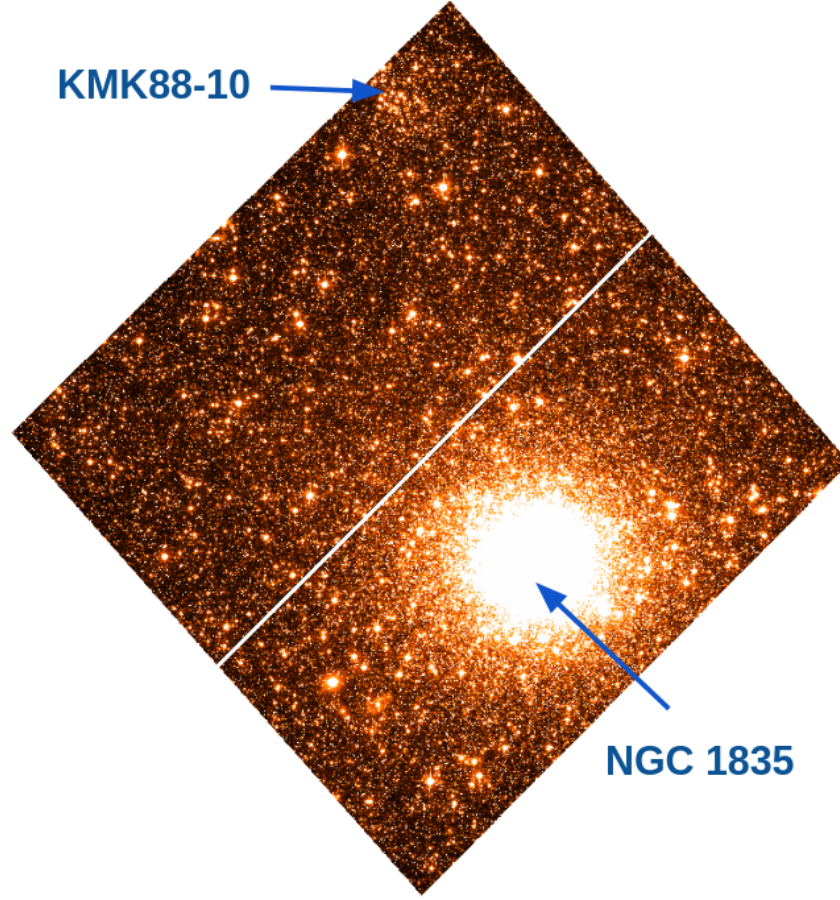


Figure B.1: HST/WFC3 image in the F814W filter showing the positions of KMK88-10 and NGC 1835. The field of view is $160'' \times 160''$. North is up, and east is left.

extremely high mass-ratio ($M_1/M_2 \geq 10^3$) has been collected so far. Only theoretical simulation studies are available (de la Fuente Marcos et al., 2014), predicting that such interactions should lead to the tidal destruction and/or the accretion of the lower-mass system (secondary) by the higher mass one (primary). A stellar over-density in the region connecting the two clusters (de Oliveira et al., 1998; Leon et al., 1999), and a dynamical heating of the stars in the outer regions of the primary are also expected (Rao et al., 1987; de la Fuente Marcos et al., 2014).

B.2 Decontamination of the color-magnitude diagram

As anticipated in Chap.2, the main target of the acquired HST observations was NGC 1835. Hence one of the two chips of the WFC3 camera was roughly centered on the cluster center (see Figure B.1). During the analysis we detected an over-density of stars located at the northern edge of the field of view resembling a small stellar cluster. By cross-correlating its position with the SIMBAD catalog (Wenger et al., 2000), we identified this over-density as the star cluster KMK88-10. Figure

B.1 shows one of the secured images in the F814W band, with the positions of both KMK88-10 and NGC 1835 highlighted. Interestingly, the two stellar systems are separated by a projected distance of about $130''$, which is only slightly larger than the tidal radius of NGC 1835 of $\sim 109''$ (see Sect. 2.6.1).

The data reduction procedure of the WFC3/HST images is already described in Sect. 2.2. The optical CMD of a circular region with a radius of $15''$ centered on KMK88-10 is shown in Figure B.2(a). The radius was chosen as best compromise between including most of the cluster stars and, at the same time, minimizing the number of field interlopers. Down to magnitude $m_{\text{F606W}} = 24$, this area includes 701 stars. The CMD shows a very extended main sequence, ranging from $m_{\text{F606W}} \sim 18.4$ to $m_{\text{F606W}} \sim 25.5$. An extended and well-defined red giant branch occupies the region at magnitude $18.2 < m_{\text{F606W}} < 22$ and color $0.5 < m_{\text{F606W}} - m_{\text{F814W}} < 0.9$. For comparison, in Figure B.2(b) we show the CMD of a LMC field region of the same size, selected beyond the tidal radius of NGC 1835. From an immediate visual comparison between the cluster and the field CMDs, it appears evident that the extended RGB visible in panel (a) can be almost entirely attributed to the old field population, while the small clump of stars at $m_{\text{F606W}} = 18.5$ seems to be present only in KMK88-10. Also the brightest portion of the main sequence ($m_{\text{F606W}} < 20$) appears to be as a component not present in the field. The selected reference field area contains 409 stars down to magnitude $m_{\text{F606W}} = 24$. Thus, we can roughly estimate that the overall contribution of LMC field stars in the direction of KMK88-10 down to $m_{\text{F606W}} = 24$ is as large as $\sim 58\%$. This clearly indicates that a proper decontamination of the CMD of KMK88-10 from the field contribution is mandatory to perform a detailed characterization of the cluster properties.

A decontamination through proper motions would be very challenging at the large distances of the LMC (see e.g. Cadelano et al., 2022b), and in this case it is not feasible at all because of the lack of second-epoch of observations. We therefore applied a statistical decontamination technique, following an approach similar to that proposed in Milone et al. (2018) (see also Dalessandro et al., 2019). For each star observed in the reference field, we removed one star from the cluster sample selected on the basis of its relative position in the CMD. More specifically, for each i^{th} star in the reference field, we calculated its CMD distance (d_i)* from all the stars belonging to the cluster sample. Then, we selected as most likely interloper stars in the cluster sample the objects having the lowest values of d_i . Thus, by construction, the procedure returns 409 field interlopers and 292 likely cluster member stars. The entire process was repeated several times by using different reference fields of equal size. All the decontaminated CMDs thus obtained are qualitatively in

*The CMD distance between a star belonging to the cluster sample and the i^{th} star of the reference field is defined as $d_i = \sqrt{(COL_c - COL_f)^2 + (MAG_c - MAG_f)^2}$, where COL_c and COL_f are the $(m_{\text{F606W}} - m_{\text{F814W}})$ colors of the stars in the cluster and field samples, respectively, while MAG_c and MAG_f are the corresponding values of their F606W magnitude.

agreement, confirming that the adopted procedure provides reliable results. An example of decontaminated CMD obtained with this approach is shown in Figure B.2(c),(d),(e) for all the filter combinations. As apparent, an extended MS survived the selection, indicating the existence of a young population with a MS turn-off point at $m_{F606W} \approx 19$. Also a small clump of objects at the position of the red clump of this young population remained in the cluster sample: see the stars located at an average magnitude $m_{F606W} \sim 18.5$ and color $(m_{F606W} - m_{F814W}) \sim 0.7$. As expected, most of the stars along the RGB have been removed. The only exception are four red objects with colors $0.8 < (m_{F606W} - m_{F814W}) < 0.95$ and magnitudes $18 < m_{F606W} < 19.5$, which most likely are residual field stars that survived the decontamination process due to the low statistics along the bright portion of the LMC RGB.

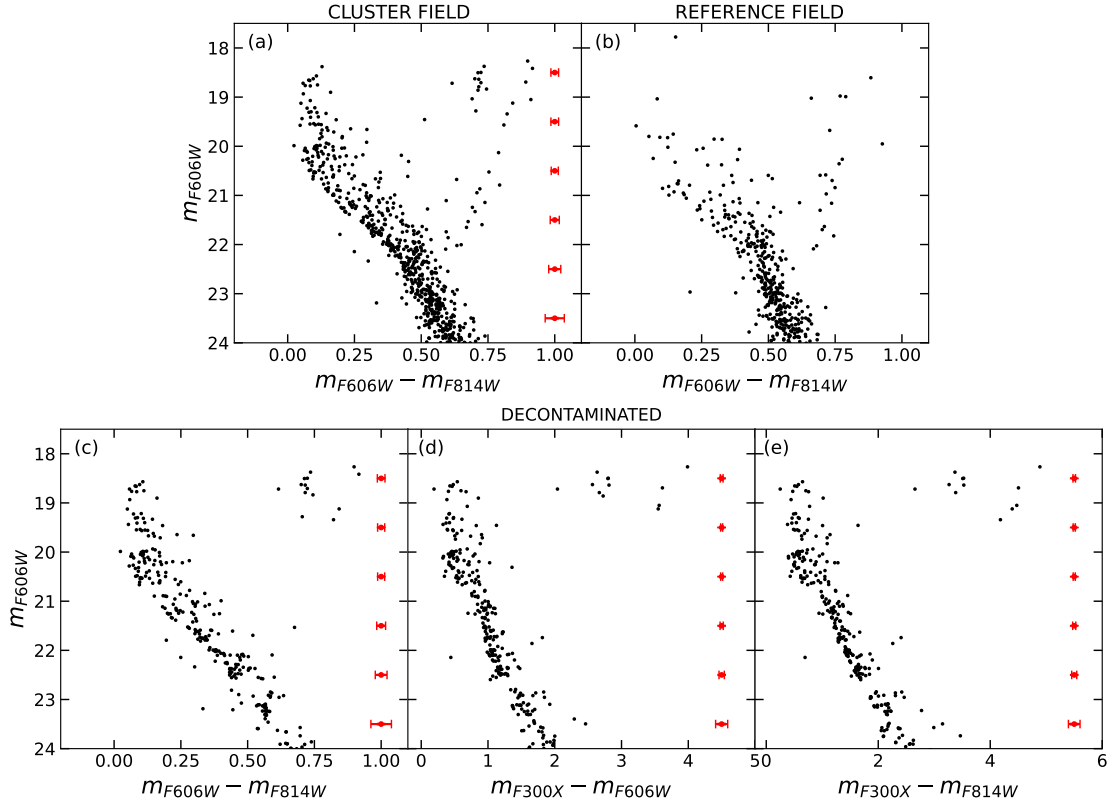


Figure B.2: Panel (a): optical CMD of a circular area with a radius of $15''$ centered on KMK88-10. Panel (b): optical CMD of a field region with an equal size area used for decontamination purposes. Panels: (c), (d), (e): decontaminated CMDs of KMK88-10 in all the filter combinations. The typical photometric errors for different magnitude bins are shown in red.

B.3 The cluster age

To estimate the cluster age, we compared the decontaminated CMD with a set of isochrones from the PARSEC database (Marigo et al., 2017). We extracted isochrones at different ages (between 600 and 1000 Myr) assuming a metallicity $[\text{Fe}/\text{H}] = -0.4$ dex, which is typical for the young LMC stellar population (Mucciarelli et al., 2008) and compatible with that derived by Narloch et al. (2022), who quote a value ranging between -0.52 dex and -0.44 dex. We also adopted a color excess of $E(B - V) = 0.08$, found for the region of NGC 1835 (see Sect. 2.4) and the LMC distance modulus $(m - M)_0 = 18.48$, corresponding to a distance of 49.6 kpc (Pietrzyński et al., 2019). In Figure B.3 we show the decontaminated optical and hybrid ($m_{\text{F814W}}, m_{\text{F300X}} - m_{\text{F814W}}$) CMDs. As can be seen, the MS turn-off region appears broadened in color, as commonly observed in young star clusters and likely due to the effects of stellar rotation (Mackey & Broby Nielsen, 2007; Kamann et al., 2020; Martocchia et al., 2023) and the presence of MS binaries. This hampers a solid determination of the cluster age, as rotating stars can be brighter or fainter than non-rotating stars depending on their angular velocities and inclination angles with respect to the observer. However, the comparison with isochrones for non-rotating stars, shows that the stellar population of this cluster is quite young, with an age between 600 Myr and 1 Gyr. In fact, isochrones in this age range nicely reproduce both the MS turn-off region, also accounting for its broadening in color, and the position of the red clump of stars. These results are qualitatively in agreement with those independently obtained by Narloch et al. (2022), who quote $t \sim 537 \pm 23$ Myr.

B.4 Surface brightness profile and structural parameters

The very low number of stars in this cluster hampers a characterization of its density profile via number counts (Lanzoni et al., 2007b, 2010, 2019; Ibata et al., 2009; Miocchi et al., 2013; Cadelano et al., 2017). Therefore, to constrain its structural properties, we analyzed the surface brightness profile. As a first step, we divided the field of view into concentric radial rings centered on the cluster gravitational center quoted in Nayak et al. (2016); Bica et al. (2008): $\alpha : 05^h : 05^m : 05^s$, $\delta : -69^\circ : 24' : 12''$. Each ring was then divided in 4 sectors and the integrated surface brightness of each sector was determined. The average of the values measured among the considered sectors was then adopted as integrated surface brightness of each ring, while the standard deviation has been assumed as its uncertainty. In this procedure, the portions of the images included within the tidal radius of NGC 1835 were excluded. To properly estimate the background level, we extended the measurement of the surface brightness to the parallel images obtained with the ACS, in a region far distant from both the clusters. The resulting surface brightness profile

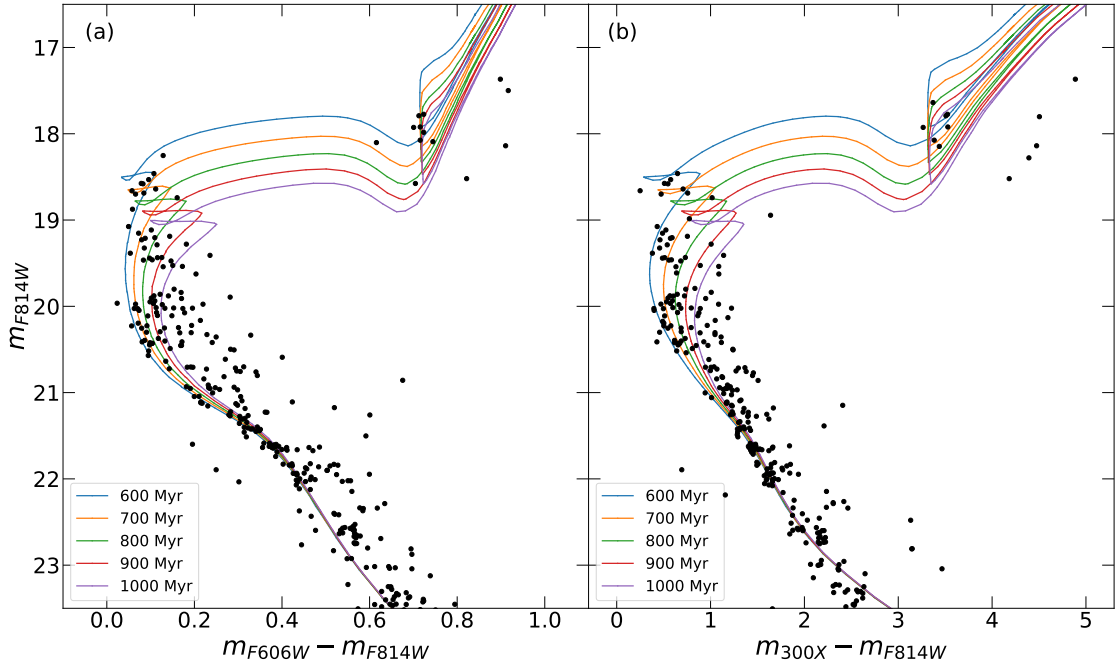


Figure B.3: *Panel (a):* decontaminated optical CMD of KMK88-10 (black dots) with a set of Parsec isochrones (Marigo et al., 2017) computed for different ages superposed as colored lines (see the legend). The adopted metallicity is $[\text{Fe}/\text{H}] = -0.4$ dex. A distance modulus $(m - M)_0 = 18.48$ and a color excess $E(B - V) = 0.08$ have been assumed to plot the isochrones in the observed CMD. *Panel (b):* same as in Panel (a), but in the hybrid m_{F814W} vs. $(m_{\text{F300X}} - m_{\text{F814W}})$ CMD.

obtained in the m_{F606W} filter is shown in Figure B.4 (open circles). The profile shows an almost constant value in the most central regions ($r < 4''$), then it smoothly declines toward a plateau at distances $r > 20''$, where the contamination due to field stars becomes dominant. The average surface brightness of the last 3 points provided an estimate of the mean background surface brightness ($\mu_{\text{F606W}} \sim 21.5$ mag arcsec $^{-2}$) and this value was subtracted to all the observed points to obtain the decontaminated profile of KMK88-10 (solid circles).

The decontaminated profile has the typical shape of the King models (King, 1966). Hence, to determine the structural parameters of KMK88-10, we fitted the obtained profile with the family of spherical, isotropic, single-mass King models. The comparison was performed through a Monte Carlo Markov Chain fitting technique following the prescriptions by Raso et al. (2020); Cadelano et al. (2022b); Deras et al. (2023). We assumed χ^2 likelihood and flat priors for all the fitting parameters. The resulting best-fit model is shown in Figure B.4. It turns out that the cluster is characterized by a King concentration index of about $c = 1.3$, a central surface brightness $\mu_{\text{F606W},0} = 19.8$ mag arcsec $^{-2}$, a core radius $r_c = 4.0''$, a half-mass radius $r_h = 12''$, and a tidal radius $r_t = 81''$. By integrating the best-fit surface brightness profile, we obtained an integrated magnitude $m_{\text{F606W,int}} = 17.9$. This value, assuming the distance modulus and the color excess quoted above, corresponds to

an absolute magnitude $M_{F606W, \text{int}} = -0.75$ that, following the prescriptions by Harris (2018), corresponds to an absolute Johnson V -band magnitude $M_V = -0.71$. Finally, assuming a mass-to-light ratio $(M/L_V) \sim 0.5 - 1$, as appropriate for such a young stellar population (Maraston, 1998), the total mass is $M \sim 80M_\odot - 160M_\odot$, compatible with that of a low-mass open cluster (e.g. Piskunov et al., 2008). This value is 2-4 times smaller than that derived by Popescu et al. (2012), likely because of the different data-sets, background decontamination procedure, and mass estimate technique adopted there.

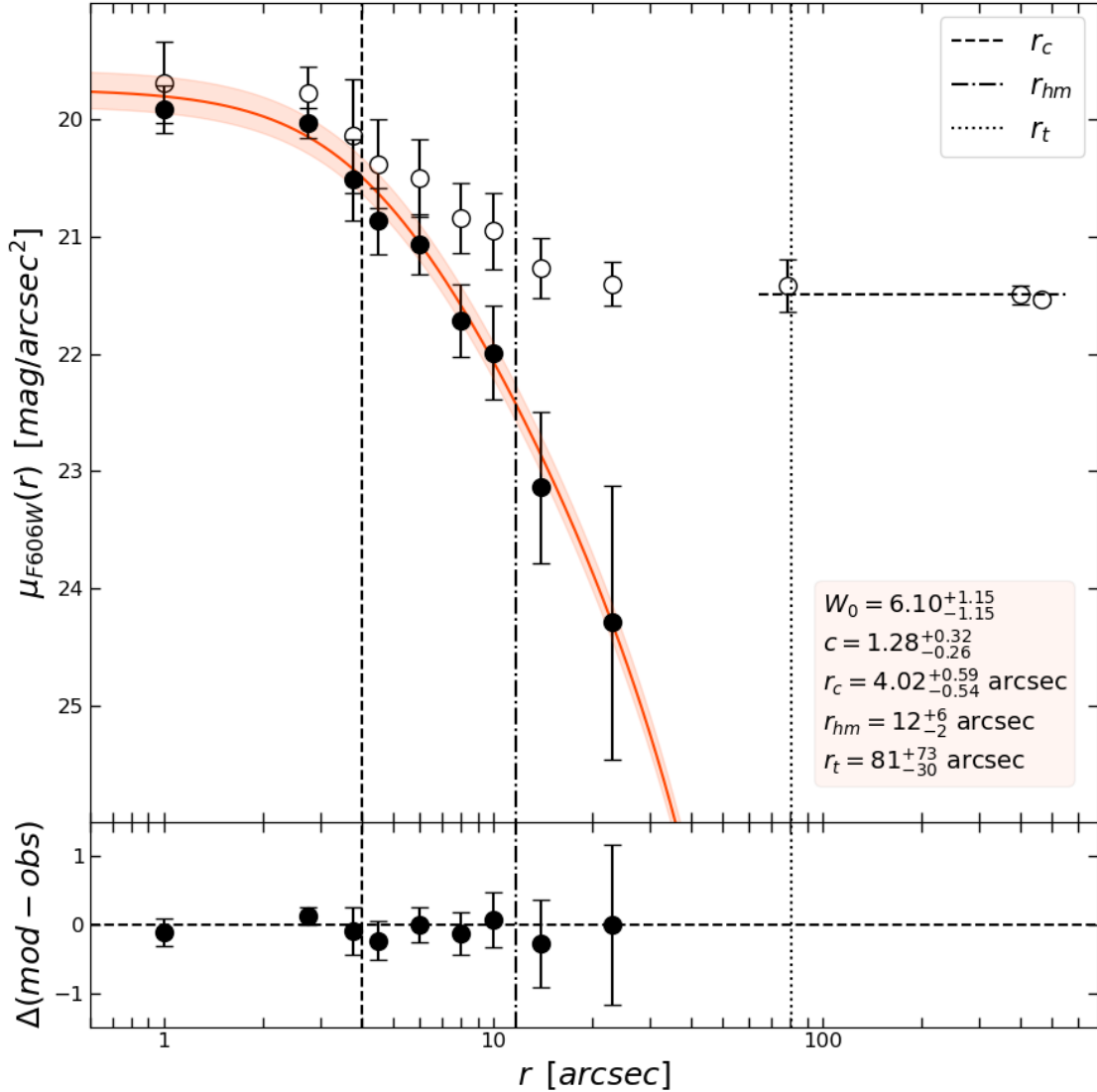


Figure B.4: Surface brightness profile of KMK88-10 in the F606W filter. The open circles represent the observed measures, while the filled circles correspond to the cluster profile after subtraction of the LMC field contribution (horizontal dashed line). The red solid line shows the best-fit King model, with the corresponding structural parameter values labelled in the figure legend. The vertical lines mark the locations of the core radius (dashed line), half-mass radius (dot-dashed line), tidal radius (dotted line).

B.5 A tidal bridge between KMK88-10 and NGC 1835?

Interestingly, the projected distance between the gravitational centers of KMK88-10 and NGC 1835 ($d = 130''$, corresponding to ~ 31 pc) is smaller than the sum of the tidal radii of the two clusters ($r_t \sim 80'' \sim 19$ pc for KMK88-10, $r_t \sim 109'' \sim 26$ pc for NGC 1835). Moreover, we find that the two systems share similar bulk proper motions. These have been estimated from the Gaia Data Release 3 catalog (Gaia Collaboration et al., 2023) for the stars that survived the decontamination procedure in KMK88-10, and for those located between $15''$ and $40''$ from the center in NGC 1835 (this selection is aimed to minimize the number of contaminating field objects and, at the same time, to exclude low quality proper motion measurements in the inner region of such a dense cluster). We obtained a final sample of 34 stars in KMK88-10 and 246 stars in NGC 1835, from which we calculated the average proper motion in right ascension (μ_α) and in declination (μ_δ) of the two clusters, finding: $(\mu_\alpha, \mu_\delta)_{\text{KMK88-10}} = (2.12 \pm 0.25, 0.02 \pm 0.27)$ mas yr $^{-1}$ for the former, and $(\mu_\alpha, \mu_\delta)_{\text{NGC1835}} = (1.93 \pm 0.27, -0.08 \pm 0.30)$ mas yr $^{-1}$ for the latter. Although the statistic is poor, the evidence of a comparable bulk proper motion, together with a small projected distance on the sky, opens to the possibility that the two clusters are gravitationally bound.

To further investigate this hypothesis, we compared the observed separation with the Jacobi radius (r_J) and the Roche-Lobe radius (r_{RL}) of NGC 1835. The former has been calculated as Bertin & Varri (2008, see also Dalessandro et al. 2018):

$$r_J = \left(\frac{GM}{\xi \Omega^2} \right)^{1/3}, \quad (\text{B.1})$$

where G is the gravitational constant, M is the total mass of the cluster, and Ω is its orbital frequency in the host galaxy. Under the assumption that the LMC potential is properly described by a spherical Plummer model with characteristic radius $b = 2.6$ kpc (see, e.g., Bekki & Chiba, 2005), the dimensionless parameter ξ can be calculated as:

$$\xi(R_0) = \frac{3R_0^2}{b^2 + R_0^2}, \quad (\text{B.2})$$

where R_0 is the radius of the circular orbit (i.e., the galactocentric distance of the cluster). Assuming a total mass $M = 6 \times 10^5 M_\odot$ (Mackey & Gilmore, 2003; McLaughlin & van der Marel, 2005), a galactocentric radius $R_0 = 1.56$ kpc (McLaughlin & van der Marel, 2005) and an orbital frequency $\Omega = 0.03$ km s $^{-1}$ pc $^{-1}$ (Dalessandro et al., 2018), we find that the Jacobi radius of NGC 1835 is $r_J \sim 155$ pc, which suggests that KMK88-10 is totally contained (at least in projection) within its gravitational sphere of influence. Finally, the Roche-Lobe radius of NGC 1835, calculated following Eggleton (1983) and assuming a mass ratio of ~ 1000 , turns

out to be ~ 0.8 times the separation between the two systems ($r_{\text{RL}} \sim 25$ pc), thus indicating that KMK88-10 extends within it.

Although both r_J and r_{RL} have been compared with a projected (rather than 3D) distance, it is definitively worth investigating the intriguing possibility that the proximity of these two systems is not merely due to a chance coincidence, but to a physical connection. The lack of tidal tails in the observed surface brightness profile of KMK88-10 is not conclusive in this sense, because the largely dominant field contribution in the external region of the system could easily hide this feature. Thus, to test this hypothesis we created a 2D density map where the severe contamination from field objects is minimized. To this end, we first drew selection boxes enclosing the MS and post-MS stars of KMK88-10 in its decontaminated CMD (bottom panel of Figure B.2), and three additional selection boxes corresponding to the MS, RGB and horizontal branch sequences of NGC 1835. Then, we selected the stars located across the whole field of view and falling within one of these boxes in the observed CMD. To drastically reduce the contamination from bright field stars, the sample was further refined including only stars with $m_{\text{F606W}} < 20.2$. The 2D density map of this sample was created by gridding the field of view in $1'' \times 1''$ cells, and applying a Gaussian kernel to obtain a smoothed distribution. The result is shown in Figure B.5, with different colors and lines corresponding to different values of significance (σ) above the background level. The latter is computed as the mean value of the smoothed density distribution in a region far from both clusters, toward the east corner of the sampled field of view (see Fig. B.1), while σ corresponds to its standard deviation. The map clearly shows the presence of two overdensities in north and south-west directions, centered on KMK88-10 and NGC 1835, respectively. Interestingly, the KMK88-10 density distribution appears to be non spherical and elongated toward the direction of NGC 1835. Indeed, the isodensity countours have significant ellipticity, with the major axis directed toward the center of NGC 1835. Furthermore, a small overdensity of stars is present in the region connecting the two clusters, creating a sort of bridge between the two systems. Despite the small number of stars and some residual contamination from field objects, this feature suggests a possible physical connection between the two clusters.

In principle, however, the observed intracluster overdensity could also be due to the mere superposition of the two individual density profiles. To investigate this possibility we reused the brightness profile already constructed for NGC 1835 (see Sect. 2.6), and we measured the surface brightness distribution in two rectangular regions covering the “bridge area” between the two systems. Since the field level found for NGC 1835 is equal to that observed for KMK88-10 (see the horizontal dashed line in Fig. B.4), this has been used to decontaminate all the observed surface brightness values from the LMC contribution. The results, as a function of the distance from the center of NGC 1835, are shown as grey circles in Fig. B.6. The

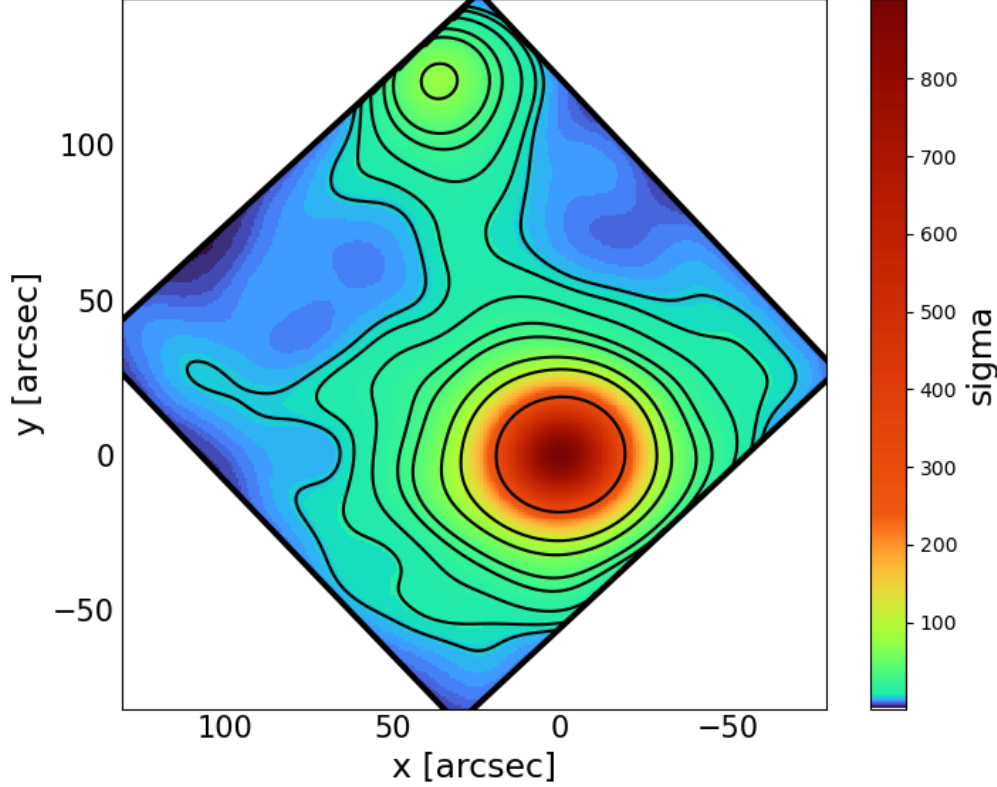


Figure B.5: Surface density map of the field sampled by the discussed HST/WFC3 observations, with the same size and orientation of Fig. B.1. Different colors correspond to different values of significance (σ) above the background level (see the side color-bar). The isodensity contour levels (black lines) range from $\sim 4\sigma$ to $\sim 300\sigma$, with irregular steps. The highest density peak corresponds to the location of NGC 1835, while the northern overdensity is KMK88-10. The presence of a bridge between the two systems is also apparent.

red line is the best-fit King model to the surface brightness profile of KMK88-10 (the same as in Fig. B.4), while the blue line is the same but for NGC 1835 (see Sec.2.6.2). The black line is the sum of the two profiles. As apparent, only a very small overdensity of $\mu_{F606W} \sim 25$ is expected at $r \sim 90''$ from the superposition of the surface brightness profiles of the two clusters, while the value measured along the bridge at the same distance is ~ 2 magnitudes brighter. This indicates that the observed intracluster bridge could be indeed the result of an ongoing interaction between the two systems, where the small cluster KMK88-10 is being tidally captured by the massive globular cluster NGC 1835. Unfortunately, KMK88-10 is adjacent to the northern edge of the sampled field of view, thus preventing any detection of the trailing tail expected in the case of a tidal distortion effect. On the other hand, we verified that the bridge is not visible in the density map obtained from stars belonging to NGC 1835 alone (i.e., selected along the MS and RGB of the globular cluster,

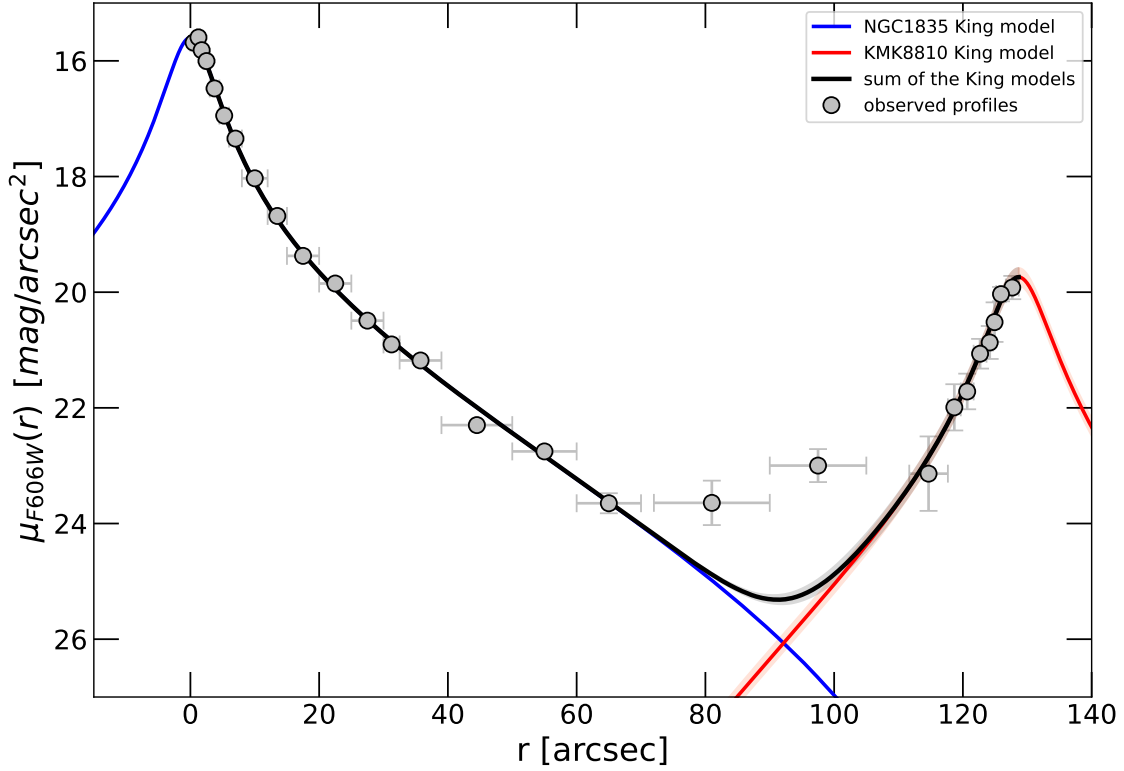


Figure B.6: Decontaminated surface brightness profile (grey circles) of NGC 1835, KMK88-10, and the bridge region between them, as a function of the distance from the center of the globular cluster. The blue and red lines are the best-fit King models to the profiles of NGC 1835 and KMK88-10, respectively. The black line is the sum of the two King models.

at magnitudes $m_{F606W} > 20$, where the contribution from KMK88-10 stars is totally negligible). This indicates that the bridge is primarily composed of KMK88-10 stars that are gravitationally pulled in by NGC 1835.

As discussed above, such events are supposed to be quite rare and have significant impact on the evolution and the observed characteristics of massive star clusters. Indeed, cluster mergers could explain the properties of massive and dynamically complex systems (e.g. Baumgardt et al., 2003; Brüns & Kroupa, 2011) and could provide an explanation to the presence of the light-element complexities in LMC intermediate-age clusters (Hong et al., 2017) and multiple iron distribution in some old clusters (Gavagnin et al., 2016). The final fate of this interaction should lead to the tidal destruction of KMK88-10 in a time scale that depends on its orbit, possibly leaving an observable kinematical signature due to the dynamical heating of the stars in the outer regions of NGC 1835. This could be observable through a rise in the stellar velocity dispersion in the cluster outskirts. Hence, spectroscopic observations aimed at measuring the stellar velocity dispersion profile of NGC 1835 might shed light on this, and help confirming the tidal capture scenario.

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