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The “dynamical clock”: dating the internal dynamical evolution of star clusters with Blue Straggler Stars

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Abstract We discuss the observational properties of a special class of objects (the so-called “Blue Straggler Stars”, BSSs) in the framework of using this stellar population as probe of the dynamical processes occurring in high-density stellar systems. Indeed, the shape of the BSS radial distribution and their level of central concentration are powerful tracers of the stage of dynamical evolution reached by the host cluster since formation. Hence, they can be used as empirical chronometers able to measure the dynamical age of stellar systems. In addition, the presence of a double BSS sequence in the color-magnitude diagram is likely the signature of the most extreme dynamical process occurring in globular cluster life: the core collapse event. Such a feature can therefore be used to reveal the occurrence of this process and, for the first time, even date it.

Keywords Faint blue stars (blue stragglers) · Hertzsprung-Russell, color-magnitude, and color-color diagrams · Globular clusters in the Milky Way · Stellar dynamics and kinematics

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1 Introduction

Globular Clusters (GCs) are compact aggregates of up to a million stars held together by their mutual gravitational attraction in a nearly spherical configuration. They are sub-galactic structures, with typical masses of $10^4 - 10^6 M_\odot$, ages as old as the Hubble time (~ 13 Gyr), and cores that present the most extreme stellar densities in the Universe, reaching up to a few millions of stars per cubic parsec. GCs are the most populous and oldest systems where stars can be individually observed. At odds with what happens in galaxies, where the orbital motion of stars primarily depends on the average gravitational potential, GCs are “collisional” systems, where two-body interactions cause kinetic-energy exchanges among stars and gravitational perturbations to their orbits, bringing the cluster toward a thermodynamically relaxed state in a timescale (relaxation time) that can be significantly shorter than its age. For this reason they represent unique cosmic laboratories to study the fundamental physical processes characterizing multi-body dynamics. Because of such interactions, heavy stars tend to progressively sink toward the central region of the cluster (dynamical friction), while low-mass stars can escape from the system (evaporation). This yields a progressive contraction of the core, producing an impetuous increase of its density virtually toward infinity: the so-called “core collapse”. The runaway contraction is thought to be halted by the formation and hardening of binary systems, and the post-core collapse phase is characterized by core oscillations, with several episodes of high central density followed by stages during which the cluster rebounds toward a structure with lower density and more extended core. The recurrent gravitational interactions among stars thus modify the structure of the system over the time (the so-called “dynamical evolution”), with a time-scale (the relaxation time) that depends in a very complex way on the initial and the local conditions, thus differing from cluster to cluster and, within the same system, from high- to low-density regions (e.g., ?).

As a consequence of the internal dynamical evolution, clusters born with a given size progressively develop more and more compact cores, the timescale of these changes being hard to determine. Indeed, estimating the formation epoch of a cluster (corresponding to the chronological age of its stars) is relatively simple from the measure of the luminosity of the Main Sequence Turn-Off (MS-TO) level, while measuring its “dynamical age” (corresponding to the level of dynamical evolution it reached since formation) is much more challenging. Following an analogy to human experience, as people with the same biological age can be in very different physical shapes, so stellar aggregates with the same chronological age can have reached quite different levels of internal dynamical evolution. While the age of people is easily readable in the identity card, determining their physical shape is not straightforward (and it depends on the capacity of correctly reading a few characteristics impressed on their body). The same holds for star clusters. Thus, a proper characterization of any GC requires the knowledge, not only of its internal structure and kinematics, but also of its dynamical age.

1.1 Blue Stragglers as gravitational test particles of GC dynamics

The internal dynamical activity of GCs is thought to also generate a variety of stellar exotica, as blue straggler stars (BSSs) and interacting binaries containing

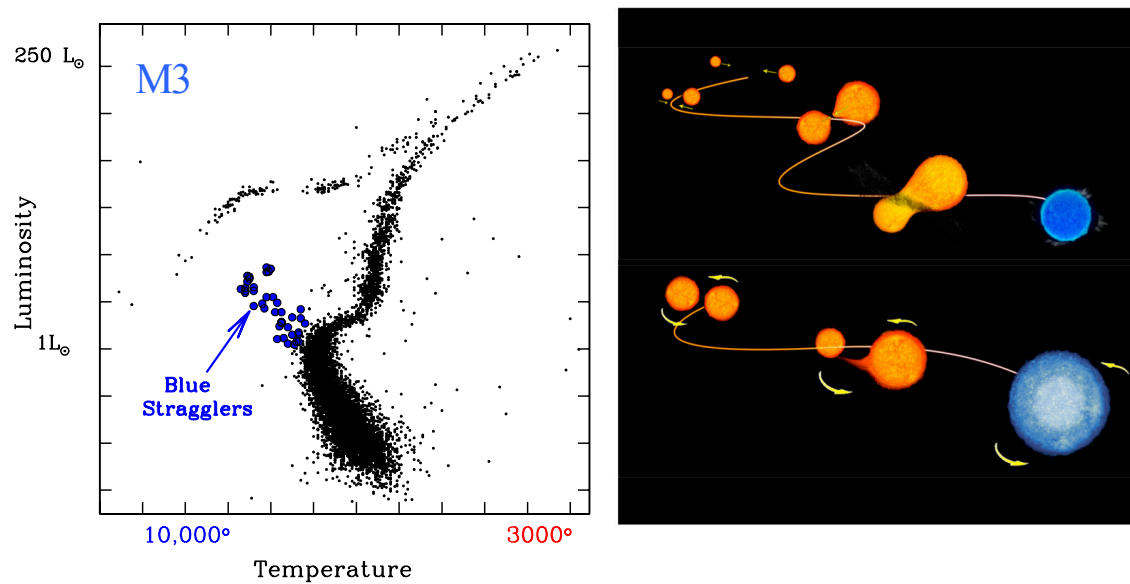


Fig. 1 Left: indicative illustration of the location of BSSs (large blue circles) in a Temperature - Luminosity diagram. Luminosities are expressed in Solar units, temperatures in Kelvin. Right: artistic illustration of the two main BSS formation channels, namely stellar collisions (upper panel), and vampirism phenomena between two companion stars in a binary system (lower panel).

heavily degenerate objects, like black holes and neutron stars (see ??????????). Among these, BSSs are certainly the most abundant and they are the easiest to distinguish from normal stars in a color-magnitude diagram (CMD), since they define a sort of sequence extending brighter and bluer than the cluster MS-TO point, mimicking a sub-population of young stars (see Fig. ??; ??????????).

Their history dates back to 1953, when the American astronomer Allan Sandage first discovered this puzzling population of stars that seemed to go against the rules of the stellar evolution theory, in the Galactic GC Messier 3 (M3). He dubbed them “stragglers” because they are located outside the main evolutionary sequences in the CMD and they seem to be trailing in the evolution with respect to the vast majority of stars in the cluster. The presence of these (apparently) young stars in a GC was completely unexpected, since star formation essentially stopped 13 billion years ago in these systems. Indeed, BSSs are not thought to be a young stellar population, and it is widely accepted that they are hydrogen-burning stars more massive than the MS-TO objects (?). However, the details of their formation mechanism are not completely understood yet, and two main mechanisms are commonly advocated to explain their origin (see Fig. ??): (1) direct collisions (COLL), in which the stars might actually merge, mix their nuclear fuel and “re-stoke” the fires of nuclear fusion (?), and (2) mass-transfer (MT) in tight binary systems, where the less massive object acts as a “vampire”, siphoning fresh hydrogen from its more massive companion, possibly up to the complete coalescence of the two stars (?). Both processes are suggested to add fresh fuel (hydrogen) into the stellar core, thus prolonging the star lifetime and making it look more youthful (blueness and brightness being the attributes of stellar youth). Both these processes have an efficiency that depends on the local environment (????????????), and they can act simultaneously within the same cluster (e.g., ???????).

Irrespective of their formation mechanism, BSSs represent a population of heavy objects ($M_{\text{BSS}} = 1.0 - 1.4M_{\odot}$; e.g., ??; see also ?) orbiting in an “ocean” of lighter stars (the average stellar mass in an old GC is $\langle M \rangle = 0.3M_{\odot}$; e.g., ?). For this reason, BSSs can be used as powerful gravitational probes to investigate key physical processes (such as mass segregation and dynamical friction) characterizing the dynamical evolution of star clusters (e.g., ???). *But, how difficult is to collect complete samples of BSSs in GCs?*

1.2 The UV route to search for BSSs in GCs

Because of their high surface temperatures ($T_{\text{eff}} \sim 6500\text{-}9000$ K), BSSs are among the brightest objects at ultraviolet (UV) wavelengths in Galactic GCs (see Fig. ??). Thus, their systematic search strongly benefitted from the advent of UV space facilities. More than 20 years ago we promoted the so-called *UV route to BSS study in GCs* (see ?????). This approach consists first in identifying the stellar sources in images acquired at UV wavelengths, then, in using the positions of those stars to enable the source detection in images acquired in the other filters. Such a technique naturally optimizes the detection of relatively hot stars and allows the collection of complete sample of BSSs even in the central region of high-density clusters. Indeed UV CMDs are the ideal diagrams where to study BSSs, since these stars appear to be clearly distinguished from the other evolutionary sequences and can be safely selected (see Fig. ??). In particular, (1) together with the hottest horizontal branch

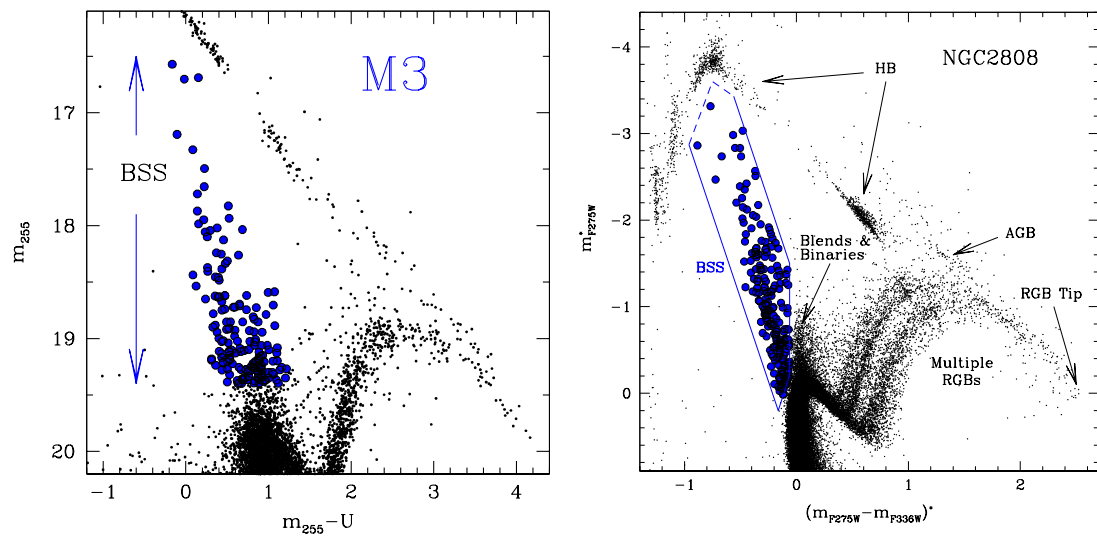
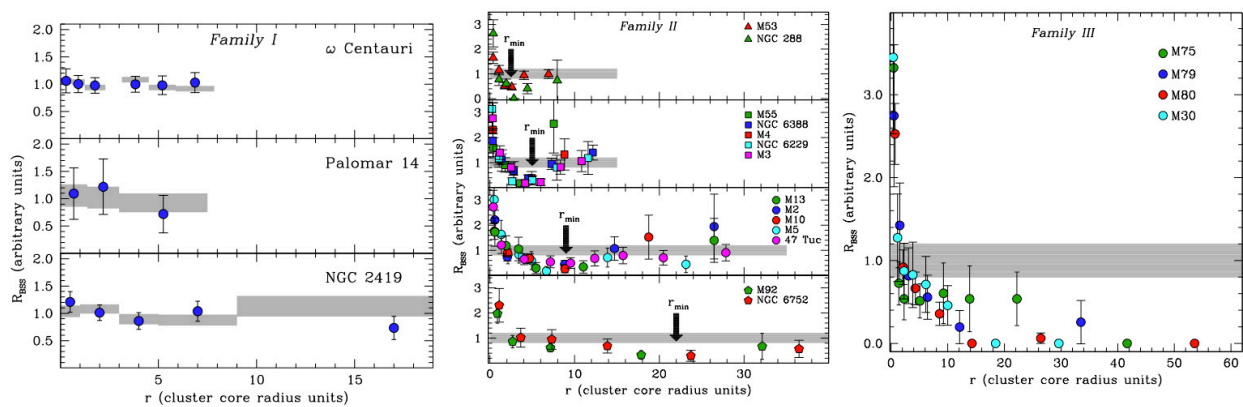


Fig. 2 Ultraviolet CMDs of two massive globular clusters (namely, M3 and NGC 2808). In both cases, BSSs are plotted as large blue circles. In the right panel, the position of the main evolutionary sequences are also marked.



(HB) stars, BSSs are the brightest objects in UV CMDs, while most of the RGB stars are significantly fainter (at odds with what happens in the optical diagrams), and (2) BSSs draw a narrow and well-defined sequence spanning approximately 3 magnitudes.

By following this approach, we derived complete samples of BSSs in the central cores of several Galactic GCs, including systems of very high central density (see ?????????). The dataset recently acquired within the HST UV Legacy Survey of Galactic Globular Clusters (?) allows the extension of this approach to a significant number of additional clusters (see Section ??). By using this dataset, ? quantitatively demonstrated the clear advantages of the *UV-guided* search for BSSs, with respect to the *optical-guided* approach. In fact, the detailed comparison between the catalogs obtained through the two different methodologies in four GCs (namely, NGC 2808, NGC 6388, NGC 6541 and NGC 7078) has shown that a large sample of stars in the innermost region of these systems are missed in the *optical-guided* case. The number of missed stars depends on the cluster structure, varying from a few hundreds up to thousands in high density clusters. The vast majority (> 70%) of the missed stars is located within the innermost 20"-30" from the cluster centre, thus demonstrating the potential risk of using optical-driven catalogs to study the radial distributions and population ratios of BSSs.

2 Setting the “dynamical clock”

According to their formation mechanisms, BSSs are significantly heavier than the average cluster population. Hence, as the dynamical evolution of the parent cluster advances, these objects progressively tend to migrate to the innermost regions. Of course, this modifies the radial distribution of BSSs, by producing a progressive depletion of these stars in the outer regions and an increase of their density toward the cluster center. Hence, the dynamical age of a star cluster is mirrored by the shape of the radial distribution and by the level of central sedimentation of its BSS population, exactly as the physical shape of people is imprinted on their body through many observable features. Because the progressive flow of BSSs toward the center measures the dynamical age of the parent cluster in a similar way as the progressive sedimentation of sand grains in an hourglass measures the flow of time, we named this method the “dynamical clock”.

2.1 Reading the signature of dynamical evolution from the BSS radial distribution

? analyzed the BSS distribution over the entire radial extension in a sample of 21 Galactic GCs (????????????????) and first demonstrated that its shape can be used to measure the level of dynamical evolution reached by the host system.

To this aim, ? used the “BSS normalized radial distribution” (hereafter BSS-nRD), defined as the ratio (R_{BSS}) between the fraction of BSSs sampled in a radial bin and the fraction of cluster light sampled in the same bin (?). Since the number of stars scales as the sampled luminosity, this ratio is equal to one for any population not affected by dynamical evolution. Hence, this parameter is particularly powerful in quantifying any excess or deficit of stars with respect

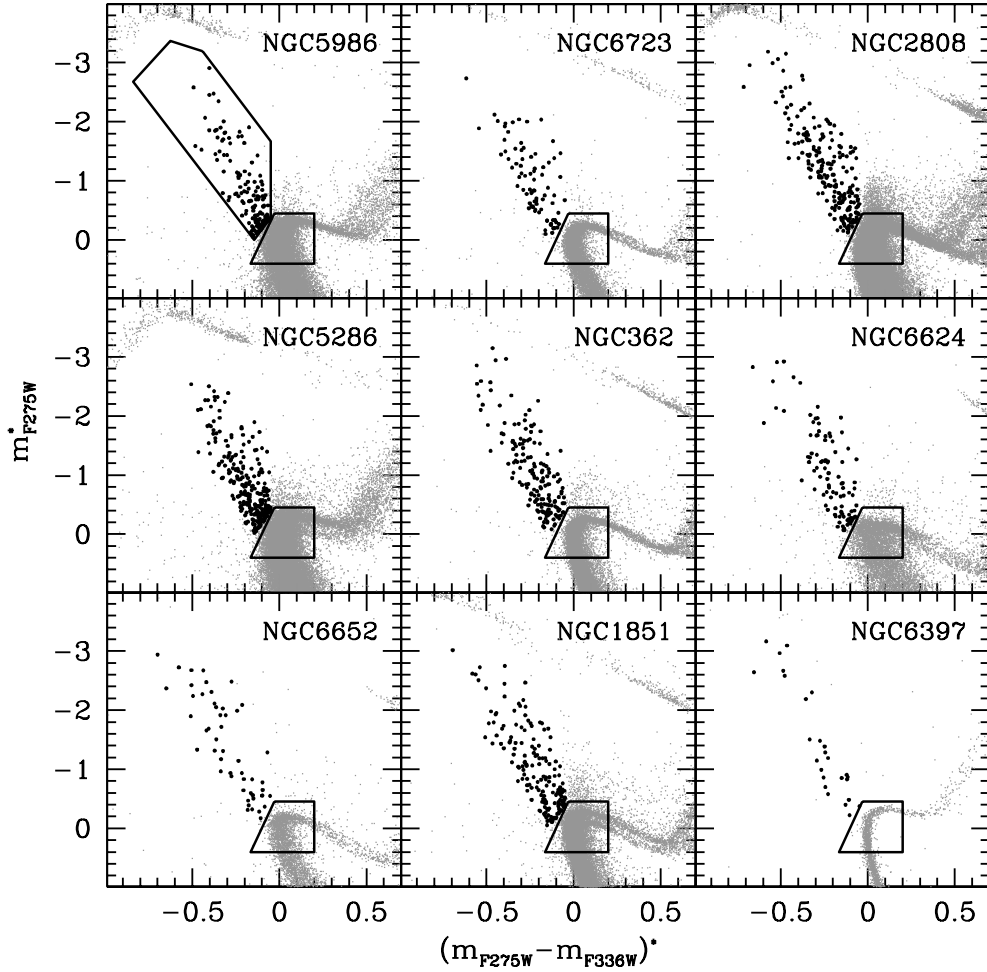


Fig. 4 The sample of BSSs (black dots) identified in the n-CMD for a representative sample of 9 clusters discussed in ?. The BSS selection box is drawn in the first panel, the one adopted for the MS-TO population is marked for all clusters.

to the “normal” radial distribution, as indeed observed for exotic populations, like BSSs. Thus, by analyzing the shape of the BSS-nRD, the surveyed sample of chronologically old and coeval GCs has been partitioned in three main families (see Fig. Fig. ??):

- Family I, where the BSS-nRD is flat (i.e., the radial distribution of BSSs within the cluster is fully compatible with that of the sampled light and indistinguishable from that of “normal” stars);
- Family II, where the BSS-nRD is bimodal, with a high peak in the cluster center, a dip at an intermediate radius (r_{\min}), and a rising branch in the

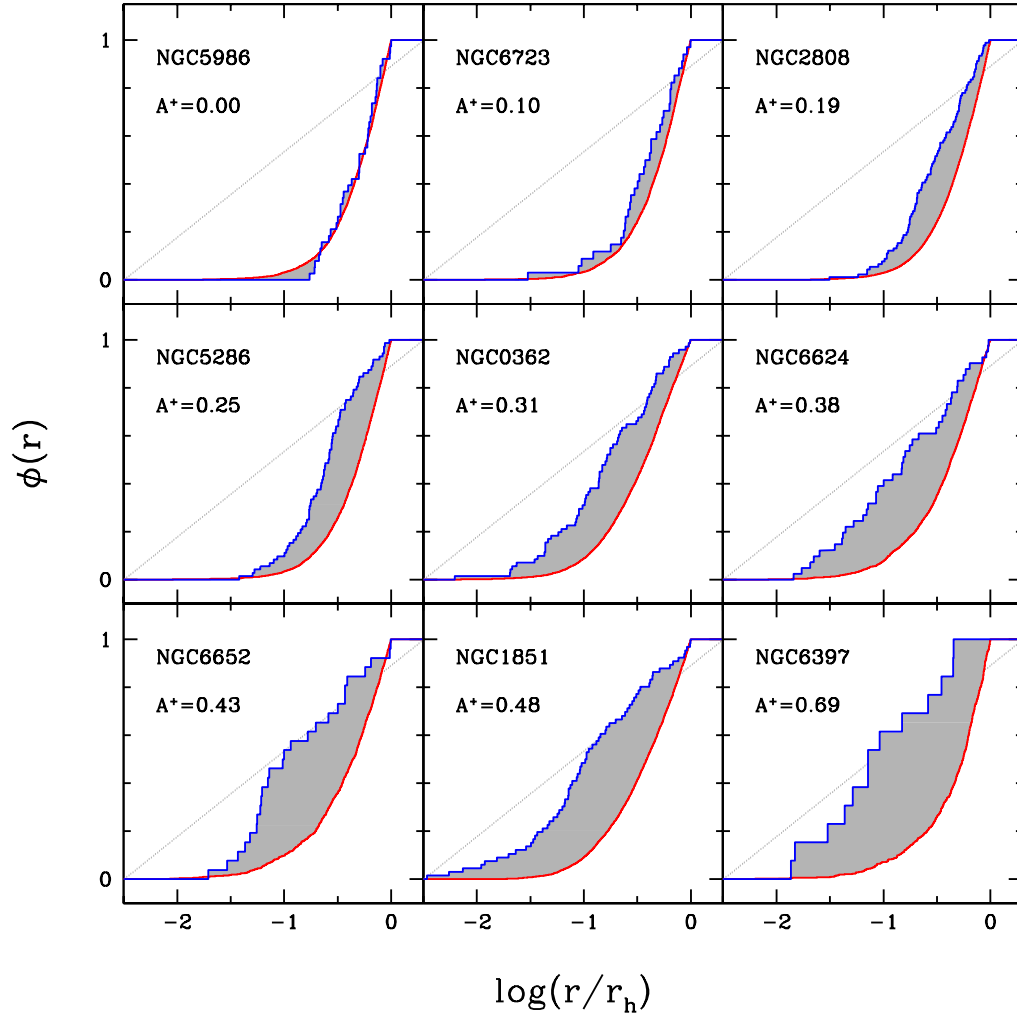


Fig. 5 Cumulative radial distributions of BSSs (blue line) and REF stars (red line) in the nine GCs shown in Figure ???. The horizontal axis provides the logarithm of the cluster-centric distance, in units of the half-mass radius r_h . The size of the area between the two curves (shaded in grey) corresponds to the labelled value of A^+ . Clusters are ranked in terms of increasing value of A^+ .

external regions (this behavior indicates an excess of BSSs in the center and a depletion at intermediate radii, with respect to normal cluster stars);

- Family III, where the BSS-nRD shows only a central peak, followed by a monotonically decreasing trend (this indicates a huge excess of BSSs in the center and a severe lack of them anywhere else in the cluster).

This variety of shapes (also detected in extra-Galactic GCs; see ?) has been interpreted as the manifestation of the effect of dynamical friction, which drives the

objects more massive than the average toward the cluster centre (e.g. ???), with an efficiency that mainly depends on the local star density (i.e., it decreases at increasing radial distance; see ?). Hence, a flat BSS-nRD indicates that dynamical friction has not affected the BSS population yet (not even in the innermost regions), and therefore Family I globular clusters are “dynamically young” (left panels in Fig. ??). In more evolved GCs (Family II), dynamical friction has progressively removed BSSs at increasingly larger distances from the center, thus generating a minimum in the BSS-nRD at increasingly larger values of r_{\min} (from top to bottom, in the central panels of Fig. ??). In Family III systems, dynamical friction already affected also the most remote BSSs, accumulating all of these stars toward the cluster center and thus producing a monotonic BSS-nRD with a central prominent peak; these are “dynamically old” GCs (right panel in Fig. ??).

2.2 Reading the signature of the dynamical evolution from the BSS segregation level

In ? we proposed a new parameter (A^+) to measure the level of BSS central sedimentation. A^+ is defined as the area enclosed between the cumulative radial distribution of BSSs and that of a reference (REF), lighter, population (as the HB, RGB, or MS-TO stars), measured within a given distance from the cluster center (the half-mass radius). N-body simulations demonstrate that this parameter systematically increases as a function of time, following the dynamical evolution of the cluster and, more specifically, tracking the process of BSS segregation (see Figure 5 in ?). At initial times, when all stars are spatially mixed regardless of their mass, BSSs and the REF population share the same cumulative radial distributions and $A^+ = 0$. As the action of dynamical friction proceeds, BSSs migrate toward the centre of the system and the two curves start to separate, thus providing a progressively increasing value of A^+ . ? measured the new parameter within one half-mass radius (A_{rh}^+) for the same set of GCs discussed in ?, finding a tight correlation with r_{\min} (see their Figure 2). This demonstrates that both parameters measure the effect of dynamical friction: as clusters get dynamically older, dynamical friction progressively removes BSSs at increasingly larger distances from the center (thus generating a minimum at increasingly larger values of r_{\min}) and accumulates them toward the cluster center (thus increasing A^+). In addition, ? found a strong correlation between A^+ and the central relaxation time of the cluster (t_{rc}) (similar to that found by ? using the parameter r_{\min}), thus fully confirming that A^+ can be efficiently used to measure the level of dynamical evolution reached by star clusters (see also the simulations by ?).

This approach was recently extended (?) to 27 additional systems observed within the HST UV Legacy Survey of Galactic Globular Clusters (?, see also ?). Combined with the clusters studied in ?, this provided us with a total sample of 48 GCs, corresponding to almost 33% of the entire Milky Way population. To perform a fully homogeneous selection of BSSs in clusters with different values of distance, reddening and metallicity, ? made use of “normalized” CMDs (see also ?), where the magnitudes and colors of all the measured stars in a given cluster are arbitrarily shifted to locate the cluster MS-TO at (0,0) coordinates (see, e.g., Fig. ??, where the “normalized” magnitudes and colors are indicated with m_{F275W}^* and $(m_{F275W} - m_{F336W})^*$, respectively). The advantage of using n-CMDs is that,

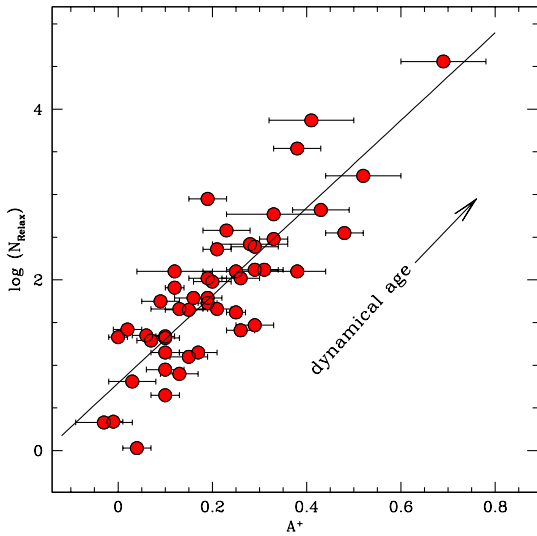


Fig. 6 The strong correlation between A^+ and $\log(N_{\text{relax}})$ for the sample of 48 GCs discussed in ?. The parameter N_{relax} quantifies the number of current central relaxation times occurred since cluster formation. The tight relation between these two parameters demonstrates that the segregation level of BSSs measured by A^+ can be used to evaluate the level of dynamical evolution experienced by the parent cluster. The best fit relation (eq. 1) is also shown as a solid line. The arrow indicates increasing dynamical ages.

independently of the cluster properties, BSSs are expected to populate the same region of the diagram. Hence, the same selection box can be used in all GCs for a homogeneous selection of the BSS population. For the sake of illustration, Fig. ?? shows a sample of nine n-CMDs analyzed in ?, with the BSS selection box marked in the top-left panel.

To compute the A^+ parameter, the radial distribution of BSSs must be compared with that of a REF population of normal cluster stars tracing the overall density profile of the system. As REF population, ? adopted MS stars in the MS-TO region, since this portion of the CMD includes several hundred objects and therefore is negligibly affected by statistical fluctuations. Fig. ?? illustrates the cumulative radial distributions obtained for the sub-sample of nine clusters shown in Fig. ??, covering the entire range of values measured for A^+ in the full sample of 48 GCs (NGC 5986 the lowest value, and NGC 6397 having the largest one).

To investigate the connection between the BSS segregation level and the dynamical status of the parent cluster, we studied the relation between the measured values of A^+ and the number of current central relaxation times (t_{rc}) that have occurred since the epoch of cluster formation (t_{GC}): $N_{\text{relax}} = t_{GC}/t_{rc}$. Because all Galactic GCs have approximately the same age, for all the program clusters we assumed $t_{GC} = 12$ Gyr (see the compilation of ?). A strong correlation was found (Fig. ??):

$$\log N_{\text{relax}} = 5.1 \times A^+ + 0.79, \quad (1)$$

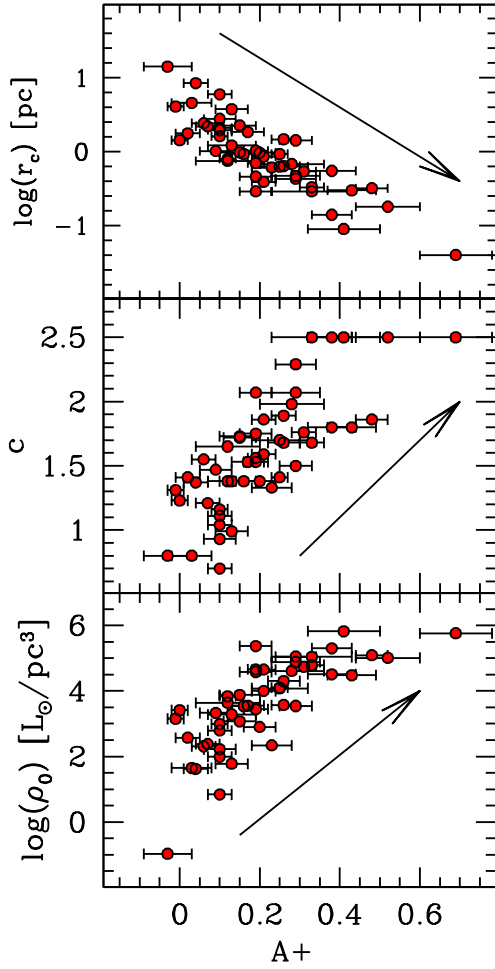


Fig. 7 Relation between A^+ and three physical parameters that are expected to change with the long-term dynamical evolution of GCs: the core radius r_c (*top panel*), the concentration parameter c (*middle panel*), and the central luminosity density ρ_0 (*bottom panel*). The values of r_c , c and ρ_0 are taken from ?. The arrows indicate increasing dynamical ages.

clearly demonstrating that A^+ is a powerful indicator of GC internal dynamical evolution. This is indeed a key relation: it allows the empirical determination of the dynamical age of a star cluster from just the measure of the central sedimentation level of its BSS population. By using this relation it is possible to learn how much dynamically-old is a GC, and if it is more or less evolved than other systems with comparable or different structural/dynamical properties.

Measuring the A^+ parameter offers the opportunity to empirically describe the effect of the dynamical aging of star clusters on their structural parameters. Fig. ?? shows the behavior of the core radius (r_c), the concentration parameter c (defined as the logarithm of the ratio between the tidal and the core radii), and the

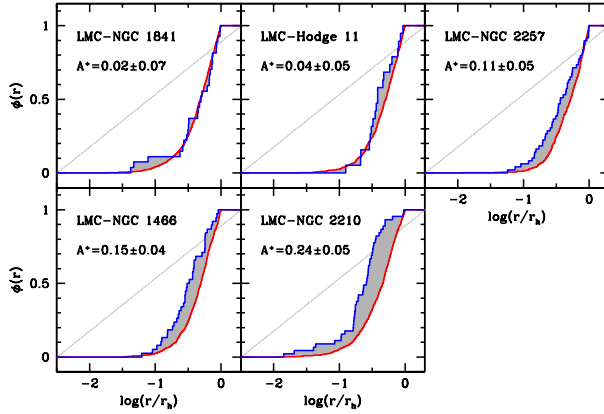


Fig. 8 Cumulative radial distributions of BSSs (blue line) and REF stars (red line) for the five GCs in the LMC discussed by ?. The size of the area between the two curves (shaded in grey) corresponds to the labelled value of A^+ . Clusters are ranked in terms of increasing value of A^+ .

central luminosity density (ρ_0 ; all are taken from ?, 2010 edition), as a function of A^+ . Quite well-defined trends are apparent in the figure, with r_c decreasing, and c and ρ_0 increasing with A^+ (i.e., with increasing dynamical age), confirming that star clusters tend to develop small and dense cores as a consequence of their long-term internal dynamical evolution, in nice agreement with what expected from the theoretical framework.

3 The “dynamical clock” beyond the Galaxy: an alternative reading of the core size-age enigma in the Large Magellanic Cloud clusters

The next obvious step in this line of investigation was to apply the same method to star clusters in other galaxies, and the Large Magellanic Cloud (LMC) is indeed the closest, and hence the most natural, target. Moreover the LMC is also the most intriguing one. In fact, there is a 30 year old dilemma related to the LMC clusters: the so-called “core size-age conundrum” (?). It can be summarized in just one question: *why all the young star clusters in the LMC are compact, while the old ones show both small and large core radii?* One of the most commonly accepted solution to this dilemma was that all clusters in the LMC formed compact, then they suffered more or less significant expansions of their core driven by populations of binary black holes (?). However, studies of GC dynamical ageing in the Milky Way show that compact cores tend to be developed as time passes (top panel in Fig. ??), which is just the opposite of what suggested to occur in the LMC. Hence, deeper investigations appeared to be necessary to solve the r_c -age dilemma in this external galaxy. ? applied the “dynamical clock” to measure the dynamical evolutionary stage of 7 intermediate-age (between 700 Myr and 7 Gyr) clusters in the LMC, finding a low-level of dynamical evolution. On the other hand, the dynamical ageing effects are expected to be most evident in old star clusters, with chronological ages comparable to those of the Milky Way systems (12-13 Gyr).

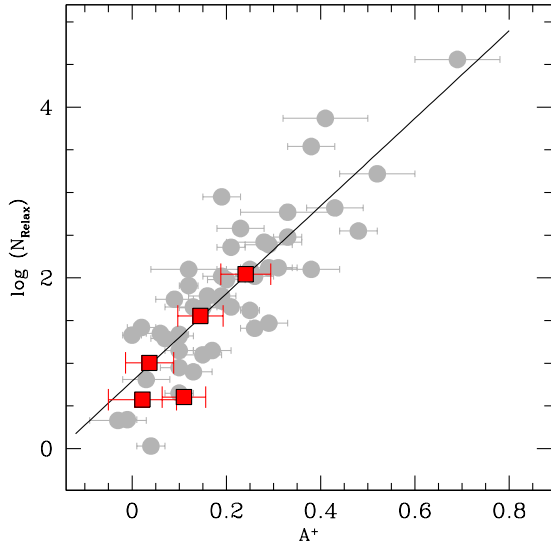


Fig. 9 The application of the “dynamical clock” to extra-Galactic clusters: $N_{\text{relax}} - A^+$ relation for the five LMC clusters discussed in ? (large red squares). For the sake of comparison, the sample of 48 Galactic GCs previously investigated (??) is shown with grey circles. The LMC GCs ranked for increasing value of the dynamical age (A^+) are NGC 1841, Hodge 11, NGC 2257, NGC 1466, and NGC 2210. The arrow indicates increasing dynamical age.

Hence, ? selected five 13 Gyr-old GCs in the LMC, showing different core sizes (ranging from 1 to 7 parsec), and measured their stage of internal dynamical evolution via the BSS sedimentation level.

The application of the dynamical clock in the LMC clusters is much more tricky than in our galaxy, because field stars (not belonging to the clusters) intervening along the line of sight can strongly contaminate the region of the CMD where BSSs are selected. The situation appeared particularly critical for two clusters (Hodge 11 and NGC 2210). However the use of appropriate parallel HST observations in the cluster neighborhoods, allowed us to statistically decontaminate the BSS samples. Indeed, the LMC field stars turned out to be slightly brighter and redder than the bulk of genuine BSSs, thus affecting only the reddest portion of the population. Hence, the statistical decontamination was quite effective and the results were surprisingly stable: over 5000 repeated random subtractions, the values of A^+ showed a very peaked distribution with a small dispersion, thus certifying the reliability of the measure.

The estimate of the BSS sedimentation level in all five selected clusters confirms that these systems are at different stages of internal dynamical evolution (see Fig. ??). Indeed, A^+ shows a nice correlation with the number of relaxation times they suffered since formation, and the impressive match with the trend defined by the Galactic population (grey circles) demonstrates that the “dynamical clock” can be efficiently used in any stellar environment and is weakly affected by the tidal field of the host galaxy.

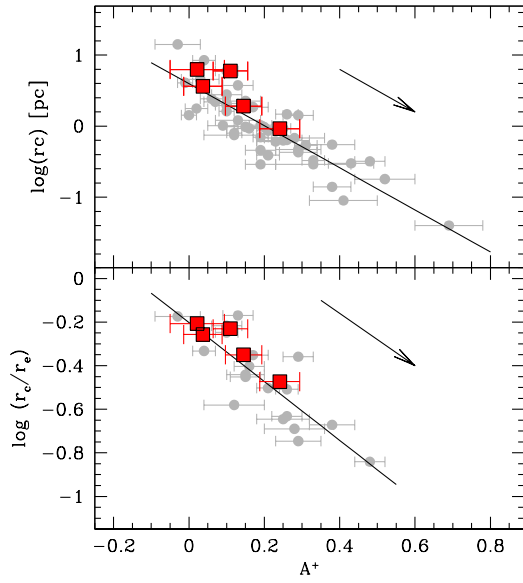


Fig. 10 *Top panel:* the $r_c - A^+$ relation for the five LMC clusters discussed in ? (large red squares), compared to that obtained for Galactic GCs (grey circles). The arrow indicates increasing dynamical age. *Bottom panel:* the relation between A^+ and the ratio between the core radius and the effective radius (r_e) for the five investigated LMC clusters (red squares), compared to that obtained for 19 GCs in the Milky Way (grey circles; r_e is from ?).

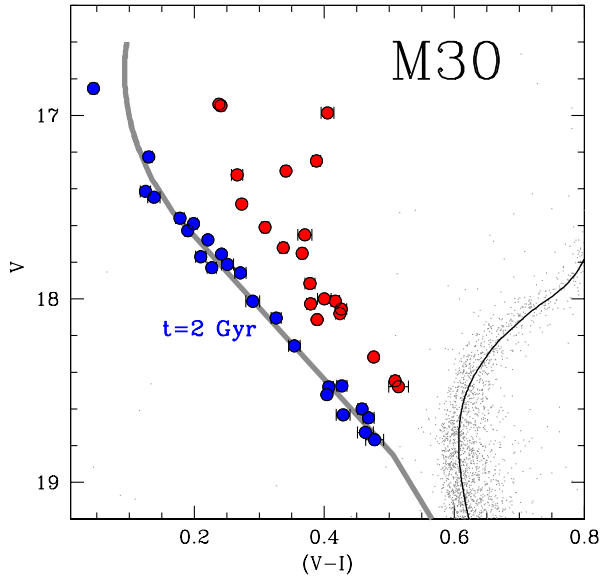


Fig. 11 The double BSS sequence in M30 (from ?). The thick grey line is the 2 Gyr collisional isochrone from ?. The black line is the 12 Gyr-old isochrone, best reproducing the cluster MS-TO (from ?).

The five surveyed LMC GCs also follow the tight correlation between dynamical age and core radius found by ? for the Galactic systems (top panel of Fig. ??), confirming that the long-term dynamical evolution tends to generate compact objects. This result has been recently confirmed by ? who re-computed all relevant structural parameters of these five LMC clusters from newly determined star density profiles. In particular, they re-determined the core radius and the effective radius (r_e), which is defined as the radius of the circle that, in projection, includes half the total counted stars. The ratio between r_c and r_e has been found to correlate with the dynamical age in a sample of 19 Galactic GCs, with systems characterized by large values of r_c/r_e being dynamically younger than those showing small values of this ratio (see ?), as expected from dynamical evolution driven by two-body relaxation. The bottom panel of Figure ?? shows that the 5 LMC GCs nicely fit the trend defined by the Galactic population, and reveal that no dynamically-old system with large value of r_c/r_e exists. In turn, this indicates that the observed properties of these systems are just consistent with their natural dynamical ageing, with no need of anomalous energy sources responsible for significant core expansion (as, e.g., a population of binary black holes; ?).

These results confirm that the internal dynamical evolution tends to produce clusters with more and more compact cores, and demonstrate that the spread in core size observed for the old LMC GCs is the natural consequence of these processes. On the other hand, the analysis discussed in ? also demonstrates that only low-mass systems have been recently (in the last ~ 3 Gyr) formed in the LMC, and essentially all of them were generated in the innermost regions of the galaxy. Hence, they surely cannot resemble the progenitors of the currently old clusters, which are much more massive (by up to factors of 100) and orbit at any distance from the centre of the LMC. Among the young generation of (low-mass) clusters, only the most compact systems survived and are observable: hence we do not see young clusters with large core-size just because, if formed, they have been already disrupted by gravitational interactions within the LMC potential well. These results suggest a new reading of the long-standing r_c -age distribution of LMC GCs, which does not require the action of a population of black holes (as suggested by ?), and is just the natural manifestation of the long-term internal dynamical evolution (?). Thus, from one side, this deepens our understanding of the processes that govern the internal dynamical evolution of dense stellar systems in different environments, allowing a direct connection between the old GCs in the LMC and those in our Galaxy. From the other side, these findings offer an alternative (and less exotic) reading of the long-standing LMC conundrum, with a strong impact on our understanding of star cluster formation and their evolution over cosmic time. Moreover, as it often happens in science, while answering an old dilemma, this discovery poses a new, probably deeper, question that needs to be addressed: *why did only relative low-mass clusters form in the last 3 Gyr in the LMC?*

4 Exploring the post-core collapse (PCC) phase

The BSS observational features might also provide crucial information about the most spectacular dynamical event in cluster lifetime: core collapse (CC). This was first realized by ? with the discovery of two well-separated and almost parallel

sequences of BSSs in the post-core collapse (PCC) cluster M30 (Fig. ??). This was the very first time that such a feature was detected in any stellar system, opening the possibility to disentangle between the two BSS formation processes. In fact, the comparison with evolutionary models of BSSs formed by direct collisions of two MS stars (?) showed that the blue-BSS sequence is well reproduced by a collisional isochrone with an age of ~ 2 Gyr. Instead, the red-BSS population is far too red to be reproduced by collisional isochrones of any age, and it turned out to be located in the portion of the CMD where MT binary models are expected to lie (??; see also recent models by ? showing that MT-BSSs might also “contaminate” the blue-BSS sequence). The impressive agreement between the blue-BSS sequence and the collisional isochrone suggests that the vast majority of these stars have a collisional origin. Due to standard stellar evolution, they are destined to move toward the red in the CMD, in typical timescales of a few Gyrs that are shorter for brighter (more massive) stars. Hence, the extension in magnitude of the blue sequence and the existence of a clear-cut gap between the two chains suggest that these BSSs are nearly coeval and have been generated by a *recent* and *short-lived* event. This latter characteristic is typical of CC (?), during which the stellar collision rate is also known to significantly increase. On the basis of these considerations, ? concluded that *most BSSs along the blue sequence formed simultaneously during the CC event, approximately 2 Gyr ago*. This scenario has been fully confirmed by ?, who presented detailed stellar merger simulations for M30, concluding that the BSS distribution along the blue sequence is well consistent with a burst of formation started ~ 3.2 Gyr ago, a duration of approximately 0.93 Gyr and a peak of formation rate of 30 BSSs/Gyr. Such an impressive formation rate was possibly triggered by the cluster CC. Instead, the BSSs along the red sequence formed with a much more modest and constant rate of ~ 2.8 BSSs/Gyr over the last 10 Gyr.

Interestingly, the double BSS feature has been later detected in two additional clusters: NGC 362 (?) and NGC 1261 (?). The case of NGC 2173, an intermediate-age cluster in the LMC, is instead still debated, since the feature can possibly be due to the contamination of the BSS population from LMC field stars (see ????).

M15: another surprise – By applying an advanced photometric de-blending technique to a set of high-resolution images, ? discovered an even more peculiar double BSS sequence in the innermost regions of the PCC cluster M15 (see Fig. ??). Also in this case the red BSS sequence cannot be reproduced by collisional isochrones of any age, but this time the blue BSS sequence showed a quite complex structure. In fact two distinct branches are visible: the first branch appears to be extremely narrow and it extends up to 2.5 mag brighter than the cluster MS-TO point, while the second branch extends up to 1.5 mag from the MS-TO. The comparison with formation models of collisional BSSs (?) indicates that both these populations formed through this channel, at two different epochs: approximately 5.5 and 2 Gyr ago, respectively. The two branches could therefore be the observational signatures of two major collisional episodes suffered by M15, likely connected to the most advanced stages of dynamical evolution of its core: the first one (possibly tracing the beginning of CC) occurred approximately 5.5 Gyr ago, while the most recent one (possibly associated with a core oscillation in the PCC evolution) dates back to 2 Gyr ago. This scenario is consistent with the results of Monte Carlo simulations (Fig. ??), showing that the deep initial CC (clearly distinguishable at $t/t_{CC} = 1$) leads to the largest increase of the collision rate

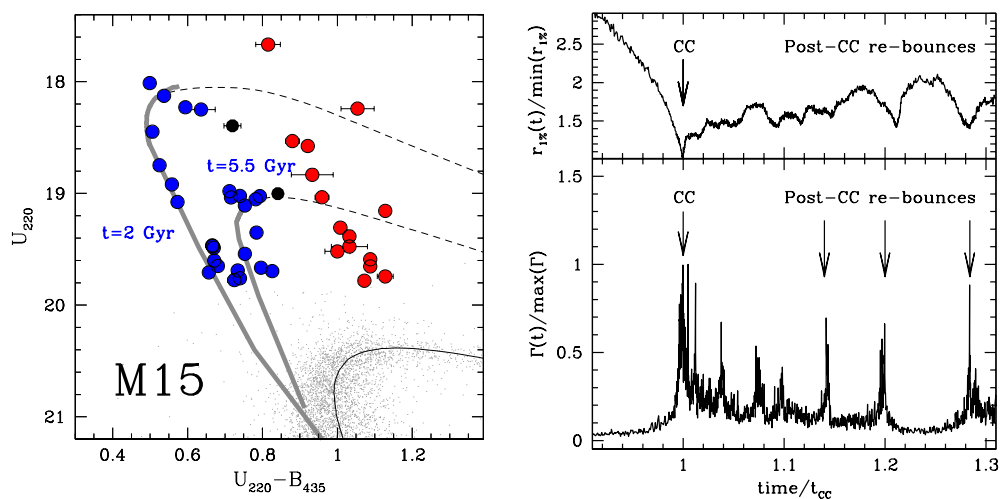


Fig. 12 *Left Panel:* The double BSS sequence in M15 (from ?). Two branches are apparent along the blue sequence: they are reproduced by a 2 Gyr-old and a 5.5 Gyr-old collisional isochrone, respectively. *Right Panel:* The evolution in time of the 1% Lagrangian radius (top panel) and of the collisional parameter (bottom panel) in dynamical simulations. The epochs of core collapse and the main post-core collapse re-bounces are indicated with arrows.

(Γ), and it is followed by several distinct re-collapse episodes leading to secondary peaks of the Γ parameter.

These results further provide strong evidence in support to the tight connection between the BSS properties and the internal dynamical evolution of collisional stellar systems, also opening new perspectives in the study of the most extreme phenomena, as the CC event and post-CC evolution.

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Conflict of interest

The authors declare that they have no conflict of interest.

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