An empirical clock to measure the dynamical age of stellar systems.

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Abstract. Blue Straggler Stars (BSS) are among the brightest and more massive stars in globular clusters (GCs). For this reason they represent an ideal tool to probe the dynamical evolution of these stellar systems. Here I show, following the results by Ferraro et al. (2012), that the BSS radial distribution can be used as a powerful indicator of the cluster dynamical age. In fact on the basis of their BSS radial distribution shape, GCs can be efficiently grouped in different families corresponding to the different dynamical stages reached by the stellar systems. This allows to define a first empirical clock, the dynamical clock, able to measure the dynamical age of a stellar system from pure observational quantities.

1. Introduction

Among the large variety of exotic objects which populate the dense environments of globular clusters (GCs), for sure Blue Straggler Stars (BSS) represent the most numerous and ubiquitous population. BSS were observed for the first time by Sandage (1953) in the outer regions of M3. Since then, they have been detected in any properly observed stellar system, from open clusters (see for example Mathieu & Geller 2009) to dwarf galaxies (Mapelli et al. 2009).

In the color magnitude diagram (CMD) of an old stellar population, BSS define a sparsely populated sequence more luminous and bluer than the turn-off (TO) mass of a normal hydrogen-burning main sequence (MS) star. Therefore they appear younger and more massive than normal cluster stars. Indeed observations have shown that they have a mass $m = 1.2 - 1.7 M_\odot$ (Shara et al. 1997; Gilliland et al. 1998; De Marco et al. 2004), which is about twice that of TO stars ($m \sim 0.8 M_\odot$), thus they are thought to be the result of some mechanism responsible for increasing the masses of single stars.

Two main formation scenarios have been proposed over the years: the mass transfer scenario (MT-BSS; McCrea 1964; Zinn & Searle 1976) according to which BSS are the result of mass accretion between two stars in a binary system, and the collisional scenario (COL-BSS; Hills & Day 1976) in which BSS are the end products of stellar mergers induced by collisions between single stars or binary systems. These mechanisms are believed to work simultaneously within the same cluster (see the case of M30 - Ferraro et al. 2009 - and NGC362 - Dalessandro et al. 2013a), with efficiencies that may be function of the environment (Ferraro et al. 1995; Davies et al. 2004).

Independently of the formation mechanism and because of their mass, BSS are heavily affected by dynamical friction and thus they are natural test particles to probe the internal dynamics of stellar aggregates. In particular their radial distribution has been found
2. The general approach

In order to obtain a reliable BSS radial distribution it is important to build a complete sample of BSS and of at least one reference population (typically Red Giant Branch - RGB - or Horizontal Branch - HB - stars) for the entire cluster extension (see for example Ferraro et al. 1993; 1997). With this aim, our group have observed, over the past fifteen years, about 25 GCs adopting a multi-band and multi-telescope approach (see Dalessandro et al. 2008 and references therein). In particular, we combined (Figure 1) high-resolution optical and ultra-violet (UV) Hubble Space Telescope (HST) data to properly sample the innermost and most crowded regions, and wide-field optical (from ground-based facilities like ESO, CFHT, SUBARU and LBT; see Beccari et al. 2013 for example) and UV (from the space mission GALEX; Schiavon et al. 2012, Dalessandro et al. 2012) data to observe the external regions and sample the entire extension of the clusters. Typical examples of the adopted procedures are described by Dalessandro et al. (2009; 2013b) for the cases of M2 and M10.

It is important to stress that the use of UV filters is of crucial importance for systematic studies of BSS. In fact, the optical CMD of old stellar populations is dominated by the cool stellar component, as a consequence the construction of complete samples of hot stars (like BSS or extreme HB stars) is difficult in this plane. Moreover in the optical plane, BSS may be contaminated by blends of Sub Giant Branch (SGB) and RGB stars. On the contrary at UV wavelengths, BSS are among the brightest sources (see Figure 1), while RGB are faint. In particular, as shown in Figure 1, BSS describe an almost narrow sequence spanning 2-3 mag in the UV CMD, and so they are more...
3. The BSS radial distribution

Once complete samples are built, it is possible to study the BSS radial distribution by dividing the surveyed clusters in a number of concentric annuli and counting in each of them the number of BSS and reference populations (RGB and HB) stars. In this way it is possible to use the double normalized ratio $R_{POP}$ defined by Ferraro et al. (1993). The radial distribution of HB and RGB stars follows that of the cluster sampled light and $R_{HB/RGB} = 1$ as expected by stellar evolution theory (Renzini & Buzzoni 1986) for post-MS stars. On the contrary the BSS radial distribution shows different and more complex behaviors.

F12 have analyzed the entire database of BSS collected by our group. This database is made of clusters with almost the same age ($t \sim 12 - 13$ Gyr) and very different structural properties. Although significant variations in the radial distribution of BSS between clusters are already known, F12 found that, when the radial distance is expressed in units of the core radius ($r_c$), the BSS radial distribution is surprisingly easily detectable. In addition, blends are less severe because of the relative faintness of RGB and SGB. Indeed CMDs involving UV bands, like the HST F255W filter, are ideal tools for selecting BSS even in the cores of the densest GCs.

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1With the only exception of Palomar 14 (which has $t = 10.5$ Gyr)
Figure 3. As in Figure 2, but for intermediate dynamical-age (Family II) GCs.

similar within distinct subsamples. Similarities are so evident that all the clusters can be grouped in at least three different families. The BSS radial distributions ($R_{BS}$ compared to $R_{HB}/RGB$) of the three groups of clusters defined by F12 are shown in Figures 2, 3 and 4. As can be seen from these plots, most of the clusters show a bimodal BSS radial distribution: highly peaked in the center, with a clear-cut dip at intermediate radii and with an upturn in the external regions (Figure 3). However some exceptions to this general behavior exist. In fact, in some clusters, BSS have the same radial distribution of the reference populations (Figure 2), while in others BSS show a monotonic decreasing distribution (Figure 4).

4. The dynamical clock

Simple analytic models (Mapelli et al. 2004, 2006) have shown that the BSS radial distribution is primarily modeled by the long-term effect of dynamical friction acting on the cluster binary population and its by-products. In fact, whereas BSS generated by stellar collisions are expected to be the main contributors to the central peak of the distribution (Davies et al. 2004), the portion beyond the cluster core, where the minimum is observed (Figure 3) is due to BSS generated by mass-transfer or merger in primordial binary systems (Geller & Mathieu 2011). MT-BSS are the by-product of the evolution of a $\sim 1.2M_\odot$ primordial binary that has been orbiting the cluster and suffering the effects of dynamical friction acting at larger and larger distances from the cluster center. Therefore binary systems are expected to drift toward the cluster core and their radial distribution is expected to develop a central peak in the cluster center and a dip that progressively propagates outwards. As the dynamical evolution of the host systems proceeds, the portion of the cluster where dynamical friction has been effective increases and the position of the minimum in the radial distribution ($r_{min}$) increases.
Interestingly, there is a good agreement between the location of $r_{\text{min}}$ and the theoretical expected value (Binney & Tremaine 1987) of the radius at which the dynamical friction is expected to segregate the BSS (Figure 3).

Following this interpretation, the groups of clusters shown in Figures 2, 3 and 4 correspond to families with different dynamical ages. In particular, clusters with a flat radial distribution (Family I, Figure 2) are dynamically young, so that the effect of dynamical friction is still not present. In more evolved clusters (Family II; Figure 3), dynamical friction starts to be effective and segregates heavy stars orbiting at distances relatively close to the center. As a consequence a peak in the center and a minimum at small radii appear in the BSS distribution. Meanwhile, the most remote BSS have not yet been affected by the action of dynamical friction, thus generating the external rising branch and the bimodal distribution. With time, dynamical friction extends its action at progressively larger distances from the cluster center, as a consequence the dip in the BSS radial distribution moves outwards (note the different positions of $r_{\text{min}}$ in the four panels of Figure 3). Indeed in highly dynamically evolved clusters (Family III; Figure 4) also the most external BSS are expected to have already sunk toward the cluster center and the rising branch to have already disappeared.

The classification in three groups of GCs based on their dynamical age is of course a first approximation. Indeed $r_{\text{min}}$ is expected to move continuously. On this basis, F12 defined the first empirical clock, the dynamical clock, able to measure the dynamical age of a stellar system from pure observational quantities. $r_{\text{min}}$ is the clock hand of the dynamical clock. In fact as dynamical friction moves $r_{\text{min}}$ within the cluster, the location of $r_{\text{min}}$ allows the observer to measure the dynamical age of the system.

As expected for a meaningful dynamical clock, $r_{\text{min}}$ nicely anti-correlates with the central relaxation time ($t_{\text{rc}}$): clusters with relaxation times of the order of the age of the Universe ($t_H = 13.7$ Gyr) show no signs of BSS segregation, hence the radial distri-
Figure 5. Central relaxation time ($t_{rc}$), normalized to the age of the Universe $t_H$, as a function of $r_{min}$, expressed in units of the core radius $r_c$. Family II systems are plotted as filled circles. Family I clusters are plotted as lower-limit arrows at $r_{min} = 0.1$. Triangles correspond to the dynamically old (Family III) GCs. A clear anti-correlation is found: GCs with relaxation times of the order of $t_H$ show no signs of BSS segregation, while for decreasing relaxation times the radial position of the minimum increases progressively.

Distribution of BSS is flat and $r_{min}$ is not definable. For decreasing relaxation times values, $r_{min}$ increases progressively. $t_{rc}$ is indicative of the relaxation time at a specific radial distance from the cluster center. On the contrary the dynamical clock defined by F12 is much more sensitive to the global dynamical evolutionary stage reached by the cluster. In fact the BSS radial distribution is able to simultaneously probe the dynamical evolution degree at all distances from the cluster center, providing a much finer ranking of dynamical ages.

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