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Probing the dynamical state of globular clusters: BSS, binaries and MF

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Abstract. Globular Clusters (GCs) are the only astrophysical systems that, within the time-scale of the age of the Universe, undergo nearly all the physical processes known in stellar dynamics, such as: gravothermal instability, violent relaxation and core collapse, energy equipartition, 2-body and higher order collisions, binary formation and heating, erosion by the tidal interaction with external fields. In this framework, Blue Straggle Stars (BSSs) have been proposed to be ideal particles to efficiently prove the effect of 2-body encounters in dense stellar systems and to infer the dynamical age of GCs. I report here the first results of a long term project whose final goal is to validate the use of the minimum of the BSS radial distribution to prove the dynamical state of GCs. To this end, I discuss two independent indicators, namely, the radial trend of the mass function slope and the radial trend of the fraction of main sequence binaries.

Key words. Stars: luminosity function, mass function – binaries: general – globular clusters: general

1. Introduction

Globular Clusters (GCs) are gravitationally bound aggregates of million of stars whose age, distance and chemical abundance are typically well known. For these simple reasons GCs are the ideal benchmark to study both stellar and dynamical evolution, separately and also in terms of if and how the physical processes driving these two evolutionary channels influence each other.

While the main engine of stellar evolution are stellar thermonuclear reactions, the long-term dynamical evolution of GCs is driven by two-body relaxation with time-scales that are typically shorter (1-2 Gyr; Meylan & Heggie 1997) than their age. Therefore GCs may have already experienced basically all the phases of dynamical evolution.

Because of two-body relaxation, heavier objects segregate toward the center of the cluster (mass segregation), while low mass stars move towards the external regions. The effect of this physical process is that the radial distribution of stars of different masses in the cluster changes while the cluster is dynamically ageing. Hence, one possible observational approach to trace the dynamical state of star clusters is to look at the radial variations of the luminosity function (LF) and/or the mass function (MF) of main sequence (MS) stars (see e.g. Da Costa 1982; Marconi et al. 2001; Albrow et al. 2002; Koch et al. 2004; De Marchi et al. 2007). Shortly, the slope α of the

MS-MF is expected to become steeper with increasing distance from the cluster's center.

While the study of the radial variation of the MF slope certainly gives direct clues on the level of mass segregation in a GC, it requires exquisite photometric data able to reveal the low mass end of the MS even in the central regions of the clusters. Such regions are typically affected by severe stellar crowding challenging the resolution capabilities (and hence the photometric completeness) of even space-based observations.

An alternative approach to infer the level of mass segregation in GCs is offered by the study of the radial distribution of Blue Straggler Stars (BSSs). In the colour-magnitude diagram (CMD) of a GC, BSSs are located along the MS, in a position brighter and bluer than the Turn Off (TO). These stellar exotica are the outcome of the interaction between MS stars through stellar collisions or mergers of primordial binaries (e.g. Davies et al. 2004; Ferraro et al. 2009). As shown in Ferraro et al. (2012), since BSSs are more massive ($0.9 - 1.6 M_{\odot}$) than the average stars in a GC (where the MS-TO mass is $\sim 0.8 M_{\odot}$), their radial distribution can be used to study the effect of two-body relaxation. As the hosting cluster is dynamically evolving, BSSs tend to concentrate towards the center, showing a central increase in their radial distribution computed with respect to normal stars. Ferraro et al. (2012) were able to classify GCs is 3 families. *Family I* clusters are dynamically young, not showing significant signs of mass segregation and having a flat BSS radial distribution (e.g. ω Centauri, NGC 2419, Palomar 14; Ferraro et al. 2006; Dalessandro et al. 2008; Beccari et al. 2011). *Family II* and *Family III* GCs are classified as dynamically intermediate and old, respectively, the former showing bimodal BSS radial distributions (see, e.g., the cases of M3, Ferraro et al. 1997, 47 Tucanae, Ferraro et al. 2004 and M55, Lanzoni et al. 2007a), the latter dysplaying monotonically decreasing BSS radial distributions (as in the cases of M79, Lanzoni et al. 2007b, and M75 Contreras Ramos et al. 2012). Hence BSSs can be efficiently used as test particles to infer the dynamical state and age of a cluster, .i.e. the shape of their radial distribution can be used as a "dynamical clock". Even if the physical processes responsible for the formation of BSSs are not fully understood yet, the obvious advantage of using BSSs as dynamical clocks is that these stars are present at some extent in all GCs and they are easily detectable even in the clusters' center, being brighter than the MS-TO.

Recently we have started a long term project aimed at using different and independent dynamical indicators in GCs (namely, the radial trend of the MF slope and the radial distributions of BSSs and binaries) to probe the solidity and coherency of these observational approaches. In the next sections I will summarise the first results of this work, focusing of the case of the GC NGC 5466, which serves in this context as a example of the adopted strategy.

2. The data-set

We have collected a number of deep, wide-field images of the GC NGC 5466, by using the $23' \times 23'$ field of view Large Binocular Camera (LBC; Giallongo et al. 2008) mounted at the Large Binocular Telescope (LBT). The LBC data-set was complemented with a set of archival deep and high-resolution images acquired with the Advanced Camera for Survey (ACS) on board the Hubble Space Telescope (GO-10775; PI: Sarajedini). As shown in Beccari et al. (2013, 2015), the combination of the catalogues obtained from these data-sets allowed us to sample MS stars with masses ranging between the TO mass ($\sim 0.8 M_{\odot}$) and $\sim 0.3 M_{\odot}$, from the cluster's center out to the tidal radius ($r_t = 1580''$). A very similar approach was used by Dalessandro et al. (2015) to study the radial distribution of the MF slope and that of BSSs and binary fraction in NGC 6101, while for the study of the dynamical state of M10 we only used archival HST data Beccari et al. (2010).

We stress here that, in order to study the dynamical state (and age) of a given cluster using the radial distributions of BSSs, MF slope and/or binary fraction, it is critical to be able to sample the stellar populations form the cluster center to the external regions. This fact offers

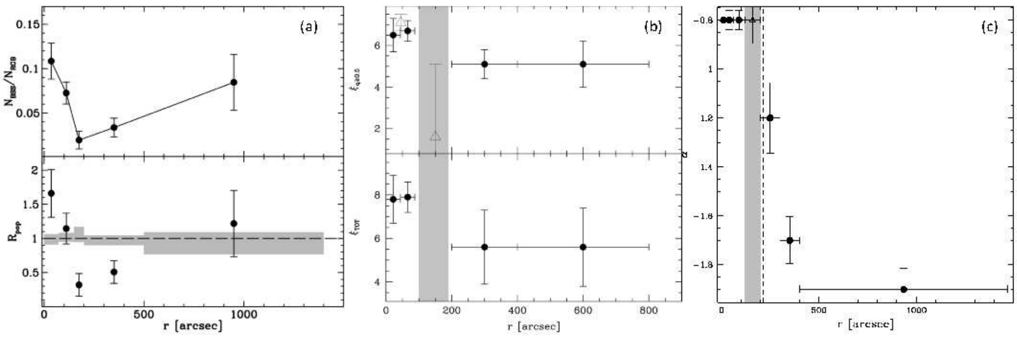

Fig. 1. (a): radial distribution of the BSS population (with respect to that of giant stars; (b): radial distribution of the fraction of binaries; (c): radial distribution of slope of the MF. All distributions are computed from the cluster's center, to the external radii.

the unique opportunity to infer how efficiently two-body relaxation worked in a given cluster and allows to perform comparative studies of populations' ratios among different clusters.

3. Results and conclusions

In Figure 1 we show the radial distribution of the fraction of BSSs (panel a), the fraction of binaries (panel b) and the slope α of the MF (panel c) in NGC 5466. The vertical grey areas shown in panels (b) and (c) mark the region sampled with the LBC data-set where a low photometric completeness[1] affects the statistical significance of the results.

The ratio between the number of BSSs and that of Red Giants Branch (RGB) stars (adopted as a reference population) suggests that BSSs are more centrally concentrated respect to "normal" stars in the cluster. This is an observational proof that dynamical friction has already been effective in segregating BSSs towards the cluster centre. In the contest of the "dynamical clock" proposed by Ferraro et al. (2012) and briefly described in the introduction, NGC 5466 can be classified as an "early Family II" GC. The position of the minimum ($r_{\rm min} \sim 200''$) of the BSS radial distribution marks the distance at which dynamical friction has already been effective in segregating BSSs towards the cluster centre.

A similar result is also obtained from the study of the radial distribution of the fraction of binaries. The values of the minimum and total binary fraction ($\xi_{q\geq0.5}$ and $\xi_{\rm TOT}$) change from 6.5% and 8% in the center, to 5% and 5.6% in the external regions, respectively. In the upper panel of figure 1b we show the value of $\xi_{q\geq0.5} = (1.6 \pm 3.5)\%$ estimated by Milone et al. (2012) in the area not covered by our data ($2.35'$ to $2.45'$). Very interestingly, the value computed by Milone et al. (2012) defines a minimum in the radial distribution of the binary fraction, thus implying that also the radial distribution of binaries seems to be bimodal in NGC 5466.

Finally, Figure 1c shows that α slowly decreases from -0.6 in the cluster center to -1.9 in the external regions.[2] In short, the difference between the slope of the MF from the center out to $5 \times r_c$ ($r_c = 72''$ being the cluster core radius) is $\Delta\alpha_{5r_c} = 0.6$. For comparison, we find that $\Delta\alpha_{5r_c} = 1.6$ in the GC M10, meaning that the variation of the MF slope is more than a factor of 2 shallower in NGC 5466 than in a dynamically old GC as M10 is. Such a comparison indicates that two-body relaxation processes worked more efficiently in shaping the mass distribution of MS stars in M10, with re-

[1] Please see Beccari et al. (2013) for an exhaustive explanation of the characterisation of the photometric completeness.

[2] In our notation, the Salpeter IMF would have a slope $\alpha = -2.35$, and a positive index implies that the number of stars decreases with decreasing mass.

spect to what happened in NGC 5466 (Beccari et al. 2015).

In conclusion, the study performed in NGC 5466 shows that all the three different and independent dynamical indicators adopted so far (namely, the radial distributions of BSSs, of binaries, and of the MF slope) agree upon showing that NGC 5466 is a GC that just started to evolve dynamically.

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