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Blue straggler stars in globular clusters: observational results

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Abstract. In this paper we briefly summarize the main observational results obtained within the Cosmic-Lab project about Blue Straggler Stars (BSSs) in globular clusters. We focus on two main aspects: the first one is the use of BSSs as tracers of the dynamical state and evolution of stellar systems; the second one is related to the definition of a tool to measure stellar masses and study evolved BSSs in globular clusters.

Key words. globular clusters: general – blue stragglers – Stars: kinematics and dynamics

1. Introduction

Among the large variety of exotic objects (like X-ray binaries, millisecond pulsars, etc.) that populate the dense environment of globular clusters (GCs), blue straggler stars (BSSs) surely represent the most numerous and ubiquitous population (see, e.g., Ferraro et al. 1997, 1999, 2003; Piotto et al. 2004; Lanzoni et al. 2007a,b; Dalessandro et al. 2009, 2013; Sanna et al. 2014. BSSs were observed for the first time in the outer regions of the GC M3 (Sandage 1953). Since then, they have been detected in any properly observed stellar system, ranging from GCs, to open clusters and dwarf galaxies. BSSs are brighter and bluer than the main-sequence turnoff (MSTO), thus mimicking a population significantly younger than normal cluster stars. Indeed, observations demonstrated that they have masses larger than MSTO stars ($m = 1.2 - 1.7 M_{\odot}$; Shara, Saffer, & Livio 1997; Fiorentino et al. 2014). In stellar systems with no evidence of recent star formation, their origin cannot be explained in the framework of normal, single-star evolution. Two main formation channels are currently favored: (1) mass-transfer (MT) in binary systems (McCrea 1964) possibly up to complete coalescence of the two stars, and (2) stellar collisions (Hills & Day 1976). Both these processes can potentially bring new hydrogen into the core and therefore "rejuvenate" a star to its MS stage (Lombardi et al. 2002).

2. Setting the dynamical clock

Independently of their formation mechanism, BSSs are surely the brightest among the most massive stars within their host cluster. For this reason they are ideal tools to probe the dynamical evolution of stellar systems. In fact, BSSs are affected by dynamical friction (DF), which makes heavy objects drift toward the core from larger and larger distances from the cluster center as the time goes on.

Ferraro et al. (2012) compared the BSS radial distribution in a sample of Galactic GCs with very different structural properties (hence possibly at different stages of their dynamical evolution), but with nearly the same chronological age (12-13 Gyr). Once the radial distance from the centre of the cluster is expressed in units of the core radius (thus to allow a meaningful comparison among clusters), GCs can be efficiently grouped on the basis of the shape of their BSS radial distribution. Ferraro et al. (2012) used this argument to define the so-called *dynamical clock*, an empirical tool able to measure the dynamical age of a stellar system. Indeed in this framework, GCs with a flat BSS radial distribution (compared to normal cluster populations like horizontal branch – HB – or red giant branch stars) are dynamically young, as DF has not played a major role yet even in the innermost regions. In more evolved clusters, DF starts to be effective and to segregate BSSs that are orbiting at distances still relatively close to the centre: as a consequence a peak in the centre and a minimum at small radii ($r_{\rm min}$) appear in the distribution, while the most remote BSSs are yet affected by the action of DF, thus generating the rising branch of the observed bimodal distributions. Since the action of DF progressively extends to larger and larger distances from the centre, $r_{\rm min}$ progressively moves outward. In highly evolved systems DF already affected even the most remote BSSs which starts to gradually drift toward the center. As a consequence, the external rising branch of the radial distribution disappears. All GCs with a single-peak BSS distribution can therefore be classified as dynamically old.

The position of $r_{\rm min}$ is found to vary with continuity and it represents the time-hand of the *dynamical clock*: as the engine of a chronometer advances the clock hand to measure the time flow, in a similar way, the progressive sedimentation of BSSs towards the cluster center moves $r_{\rm min}$ outward thus marking its dynamical age. This is indeed confirmed by the tight correlation found between the clock-hand ($r_{\rm min}$) and the central relaxation time (t_{rc} – Fig. 1), which is commonly used to measure the cluster dynamical evolution time-scales.

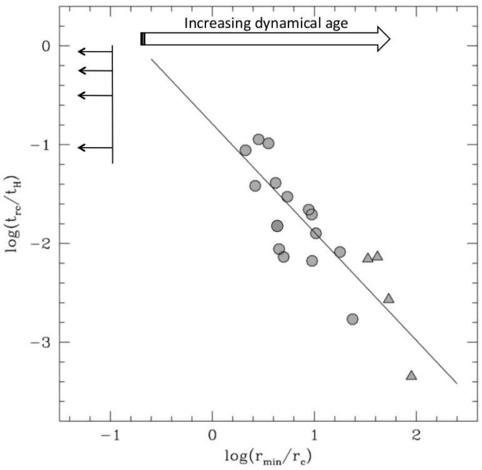

Fig. 1. Core relaxation time (normalized to the Hubble time t_H) as a function of the time hand of the proposed *dynamical clock* ($r_{\rm min}$, in units of the core radius). Dynamically young systems show no minimum and are plotted as lower-limit arrows at $r_{\rm min} = 0.1 r_c$. For dynamically old clusters, the distance of the farthest radial bin where no BSSs are observed, is adopted as value of $r_{\rm min}$.

The correlation found with t_{rc} provides an indication of the relaxation timescales at specific radial distances from the cluster center. The *dynamical clock* here defined provides instead a measure of the global dynamical evolution of these systems, because the BSS radial distribution simultaneously probes all distances from the cluster center.

3. BSS double sequences

A further application of the use of BSSs as tracers of the dynamical state and evolution of GCs, comes from the discovery of double BSS sequences, almost parallel and clearly separated in the CMDs of the post core-collapse candidate GCs M30 (Ferraro et al. 2009) and NGC 362 (Dalessandro et al. 2013 – see also Simunovic et al. 2014).

Fig. 2 shows that the blue-BSS sequence is nicely reproduced by collisional isochrones (Sills et al. 2009), while the red-BSS population is far too red to be consistent with collisional isochrones of any age. Red-BSSs lie in a sparse area adjacent to the lower luminosity boundary of binary stars currently experiencing MT, in a region that we can call *MT-BSS domain* (Fig. 2). Indeed, binary evolution models (Xin et al. 2015) demonstrate that this region of the CMD is populated by synthetic MT-BSSs, thus providing strong support to the MT origin for these stars. In addition the CMD distribution of synthetic MT-BSSs never attains the observed location of the blue-BSSs, thus reinforcing the hypothesis that the latter formed through a different channel (likely collisions).

The fact that we observe two distinct sequences and in particular a well-defined blue one, implies that the event that triggered the formation of the double sequence is recent and short-lived. If this event is connected with the dynamical evolution of the system, in the cases of M30 and NGC 362, it could likely be the collapse of the core (or its initial phase). Indeed, during the collapse, the central density rapidly increases, also enhancing the probability of gravitational encounters (Meylan & Heggie 1997). Blue-BSSs could be formed by direct collisions boosted by the high densities reached in the core, while the red BSS population could have been incremented by binary systems brought to the MT regime by hardening processes induced by gravitational encounters (Hurley et al. 2008). As a consequence, the identification of double-BSS sequences in GCs, can provide useful constraints about the event of core-collapse.

4. The search for evolved BSSs in GCs

BSSs are expected to experience a post-MS evolution analogous to that of any "normal" star with a mass $m \sim 1.2 - 1.6M_{\odot}$ (Sills et al. 2009). However, only a few direct identifications of evolved (post-MS) BSSs have been obtained so far and indirect evidence comes from number counts and radial distributions of stars in the HB-asymptotic giant branch (AGB) region of GCs, where BSS are expected to be located during their core He burning phase (see, e.g., Ferraro et al. 1997, 1999; Beccari et al. 2006; Dalessandro et al. 2009).

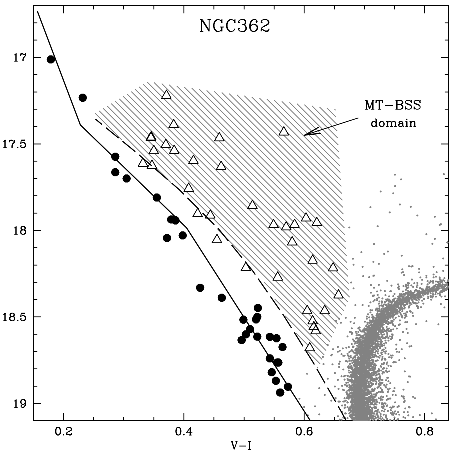

Fig. 2. Zoomed view of the $(V, V-I)$ CMD of NGC 362 on the BSS region. Filled circles are blue-BSSs, while open triangles are red-BSSs. The gray shaded area ("MT-BSS domain") approximately indicates the region populated by MT binaries in Xin et al. 2015 translated into the CMD of NGC 362. The solid black line is a 0.2 Gyr collisional isochrone (Sills et al. 2009).

The identification of evolved BSSs is crucial to constrain BSS formation and evolution models. In fact, the collection of complete samples of these objects in GCs allows the determination of meaningful population ratios from which characteristic evolutionary timescales can be empirically constrained. Moreover, since evolved BSSs are 20 times more luminous than their progenitors, detailed spectroscopic follow-up studies are largely facilitated.

Recently, by using the high resolution spectrograph UVES-FLAMES at the ESO-VLT, Ferraro et al. 2016 observed three stars (hereafter named bHB1 bHB2 and E-BSS1) located in a region of the CMD slightly brighter than the red clump, in the massive GC 47 Tucanae (see Fig. 3). We used the detailed comparison between chemical abundances derived separately from neutral and from ionized spectral lines as a powerful stellar *weighing device* to measure stellar masses. In fact, abundances obtained from neutral lines are independent of the adopted gravity, while those ob-

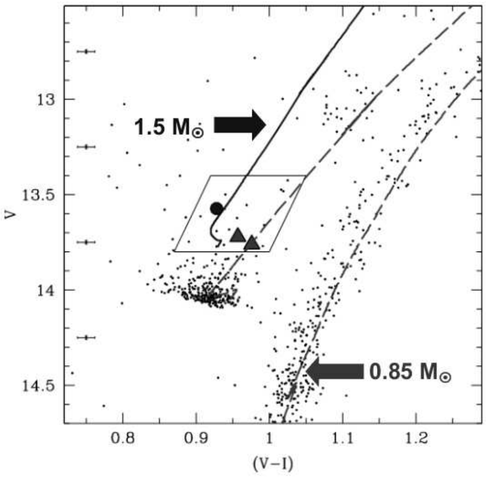

Fig. 3. Portion of the $(V, V-I)$ CMD of 47 Tucanae around the horizontal branch. The large circle marks the position of E-BSS1, while triangles correspond to the reference targets (bHB1 and bHB2). The dashed line corresponds to the evolutionary track of a single $0.9M_{\odot}$ star. The solid line is the evolutionary track, from the HB to the AGB, for a star with a MS mass of $1.5M_{\odot}$.

tained from ionized absorption lines are quite sensitive to gravity. The measurements of iron and titanium abundances performed separately from neutral and ionized lines reveal that two targets (bHB1 and bHB2) have stellar parameters fully consistent with those expected for low-mass post-HB objects, while for the other target (E-BSS1) the elemental ionization balance is obtained only by assuming a mass of $\sim 1.4M_{\odot}$, which is significantly larger than the MSTO mass of the cluster ($\sim 0.85M_{\odot}$). The comparison with theoretical tracks suggest that this is a BSS descendant possibly experiencing its core helium burning phase. The large applicability of the proposed approach to most of the GCs in the Galaxy opens the possibility to initiate systematic searches for evolved BSSs, thus giving access to still unexplored phases of their evolution.

Take home messages:

(i) *BSSs are crucial and powerful gravitational test particles*

(ii) *E-BSSs can now be distinguished form their low-mass sisters*

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