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PROBING THE LINK BETWEEN DYNAMICS AND STELLAR EVOLUTION: BLUE STRAGGLER STARS IN GLOBULAR CLUSTERS

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RESUMEN

En esta contribución se revisan las principales propiedades de las estrellas blue straggler (BSS) en cúmulos globulares galácticos. Se presentan y discuten el conjunto de resultados referentes a la frecuencia de BSS, distribución radial y composición química.

ABSTRACT

In this contribution we review the main observational properties of Blue Straggler Stars (BSS) in Galactic Globular Clusters. A flower of results on the BSS frequency, radial distribution, and chemical composition are presented and discussed.

Key Words: binaries: general — globular clusters: general — stars: blue stragglers — stars: evolution

1. INTRODUCTION

The ultra-dense cores of Galactic Globular Clusters (GGCs) are very efficient "furnaces" for generating exotic objects, such as low-mass X-ray binaries, cataclysmic variables, millisecond pulsars, blue straggler stars (BSS), etc. Most of these stars are thought to be the by-products of the evolution of binary systems, possibly originated and/or hardened by stellar interactions. Thus, studying the nature of these exotica and the properties of non-standard sequences in the GC color-magnitude diagrams (CMDs) can serve as a powerful diagnostic of the dynamical evolution of clusters and its effects on the evolution of their stellar population and binary systems (see Bailyn 1995, and references therein). This topic has received strong impulse in the recent years. In this paper we review the main properties of the most known exotic population of GGCs: the so-called BSS.

First discovered by Sandage (1953) in M3, BSS are commonly defined as stars brighter and bluer (hotter) than the main sequence (MS) turnoff, lying along an extension of the MS in the CMD. Thus, they mimic a rejuvenated stellar population and their existence has been a puzzle for many years. Direct measurements (Shara et al. 1997) and indirect evidences show that BSS are more massive than the normal MS stars, pointing toward stellar mergers as possible explanation for their origin. Indeed, their formation mechanisms are not yet completely understood, and the leading scenarios, at present, involve mass transfer (MT) between binary companions (McCrea 1964; Zinn & Searle 1976), possibly up to the complete coalescence of the binary system, or the merger of stars (whether or not in binaries) induced by collisions (COLL; Hills & Day 1976). Hence, BSS certainly represent the link between standard stellar evolution and cluster dynamics (see Bailyn 1995).

2. THE UV APPROACH TO THE BSS STUDY

The observational and interpretative scenario of BSS has significantly changed in the last years. In fact, for almost 40 years since their discovery, BSS have been detected only in the outer regions of GCs or in relatively loose clusters, thus generating the idea that low-density environments were their *natural habitats*. However, this was just an observational bias, and, starting from the early '90, high resolution studies allowed to properly image and discover BSS also in the highly-crowded central regions of dense GCs (see the case of NGC 6397 by Auriere et al. 1990). In particular, the advent of the Hubble Space Telescope (HST) represented a real turning point in BSS studies, thanks to its unprecedented spatial resolution and imaging/spectroscopic capabilities in the ultraviolet (UV; see Paresce et al. 1991; Ferraro & Paresce 1993; Guhathakurta et al. 1994, etc).

In fact, in the optical bands the systematic study of BSS, especially in the central regions of high density clusters, still remains problematic, even if using HST. This is because the optical CMD of old stellar populations is dominated by the cool stellar component. Hence, the observation and the construction of complete samples of hot stars (as BSS, other by-products of binary system evolution, extreme blue

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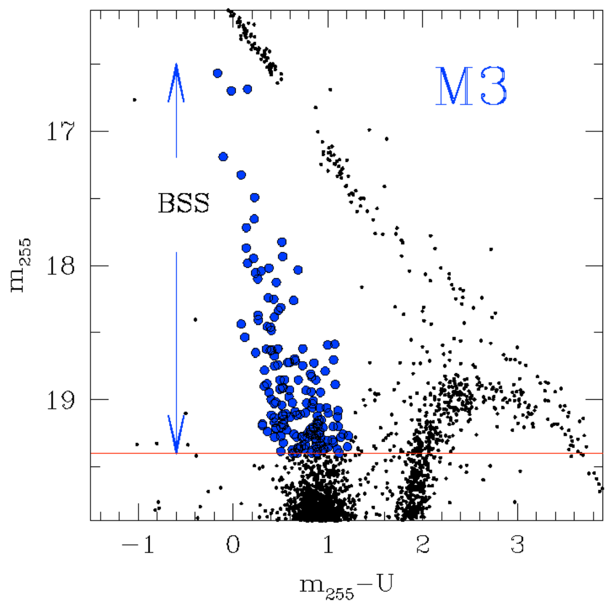

Fig. 1. BSS in the UV: the case of M3. The horizontal line at $m_{255} = 19.4$ is the assumed BSS limiting magnitude, corresponding to $\sim 5\sigma$ above the turnoff level (from F97).

horizontal branch stars, etc.) is "intrinsically" difficult in this plane. Moreover, BSS can be easily mimicked by photometric blends of sub-giant branch (SGB) and red giant branch (RGB) stars in the optical CMDs. Instead, at UV wavelengths RGB stars are very faint, while BSS are among the brightest objects. In particular, BSS define a narrow, nearly vertical sequence spanning ~ 3 mag in the UV plane (see Figures 1 and 2), thus being much more easily recognizable. In the mean time, BSS-like blends are much less severe at these wavelengths because of the relative faintness of SGB and RGB stars. Indeed, the $(m_{255}, m_{255}-\mathrm{U})$ plane is an ideal tool for selecting BSS even in the cores of the densest GCs, and its systematic use allowed to put the BSS study into a more quantitative basis than ever before (e.g., Ferraro et al. 2003; see Figure 3).

3. BSS SPECIFIC FREQUENCY AND PRIMORDIAL BINARY FRACTION

Based on these observations, the first catalogs of BSS have been published (e.g., Fusi Pecci et al. 1992; Ferraro et al. 1995, hereafter FFB95), and the most recent collection of BSS counts nearly 3000 candidates i 56 GGCs (Piotto et al. 2004; the most recent results based on this data-set are discussed by Leight in this book).

These works have significantly contributed to form the nowadays commonly accepted idea that

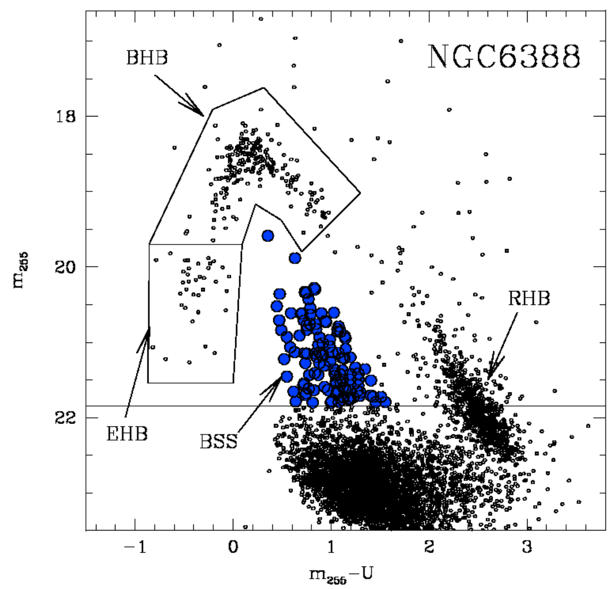

Fig. 2. BSS in the UV: the case of NGC 6388 (from Dalessandro et al. 2008a).

BSS are a normal stellar population in GCs, since they are present in all properly observed clusters. However, according to Fusi Pecci et al. (1992), BSS in different environments could have different origins. In particular, BSS in loose GCs might be produced by the coalescence of primordial binaries, while in high density GCs (depending on survival-destruction rates for primordial binaries) BSS might arise mostly from stellar interactions, particularly those which involve binaries. While the suggested mechanisms of BSS formation could be separately at work in clusters with different densities (FFB95; Ferraro et al. 1999), there are evidences that they could also act simultaneously within the same cluster (as in the case of M3; see Ferraro et al. 1993, 1997, hereafter F93 and F97, respectively).

A number of interesting results have been obtained from cluster-to-cluster comparisons. For this purpose we used the BSS specific frequency, defined as the number of BSS counted in a given region of the cluster, normalized to the number of "normal" cluster star in the same region, adopted as reference (generally we adopted the horizontal branch stars, hereafter HB). The BSS specific frequency has been found to largely vary from cluster to cluster: for the six GCs considered by Ferraro et al. (2003), the BSS frequency varies from 0.07 to 0.92, and does not seem to be correlated with central density, total mass, velocity dispersion, or any other obvious cluster property (see also Piotto et al. 2004). Even "twin" clusters like M3 and M13 harbor a quite different BSS

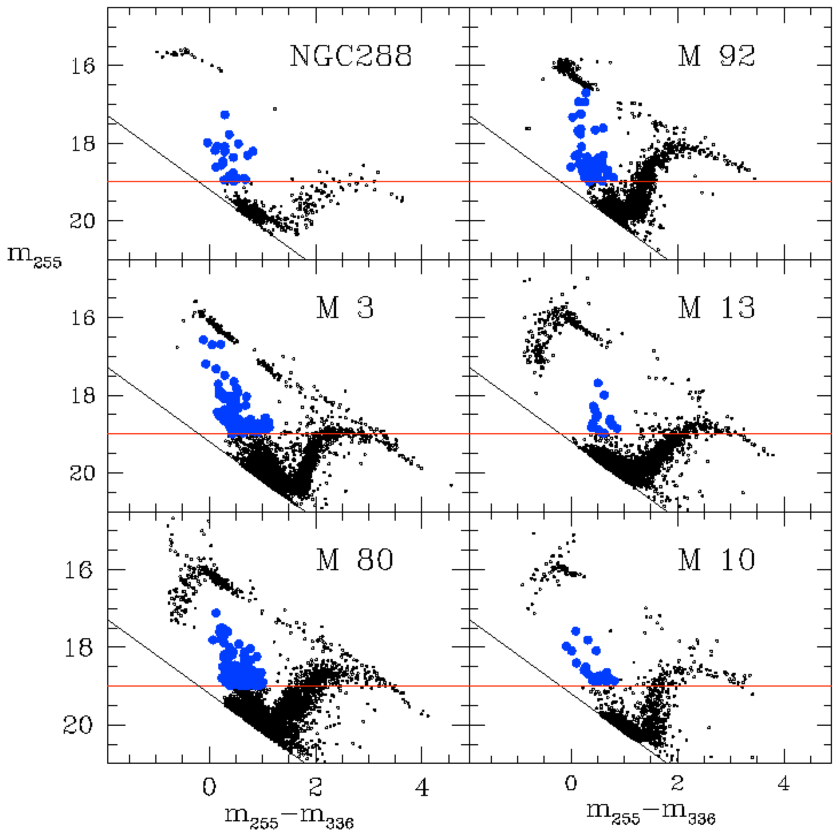

Fig. 3. $(m_{255}, m_{255} - m_{336})$ CMDs for the six clusters discussed in Ferraro et al. (2003). Horizontal and vertical shifts have been applied to all CMDs in order to match the main sequences of M3. The horizontal solid line corresponds to $m_{255} = 19$ in M3. The bright BSS candidates are marked as large filled circles.

populations: the specific frequency in M13 is the lowest ever measured in a GC (0.07), and it turns out to be 4 times lower than that measured in M3 (0.28). Which is the origin of this difference? The paucity of BSS in M13 suggests either that the primordial population of binaries in M13 was poor, or that most of them were destroyed. Alternatively, as suggested by F97, the mechanism producing BSS in the central region of M3 is more efficient than that in M13, because the two systems are in different dynamical evolutionary phases.

In this respect, the most surprising result is that the largest BSS specific frequency has been found in two GCs which are at the extremes of central density values in our sample: NGC 288 and M80, with the lowest and the highest central density, respectively. This suggests that the two formation channels can have comparable efficiency in producing BSS in their respective typical environment.

Given the role of binary systems in both the MT and the COLL scenarios, one of the most important ingredient necessary to properly understand the BSS formation process certainly is the fraction of primordial binaries in each cluster. Indeed, by analysing the color distribution of the MS stars, we recently derived the fraction of binary systems in a sample of 13 low-density GGCs (Sollima et al. 2007). The estimated global fractions of binary systems range from 10 to 50 per cent depending on the cluster. Interestingly enough, this fraction has been found to nicely correlate with the BSS frequency (see Sollima et al. 2008, Figure 4). This is the cleanest evidence ever obtained that the unperturbed evolution of primordial binaries is the dominant BSS formation process in low-density environments.

4. THE BSS RADIAL DISTRIBUTION

M3 has played a fundamental role in the BSS history, because it is the system where not only the BSS have been first identified, but also their radial distribution has been studied over the entire cluster extension for the first time. In fact by combining UV HST observations of the cluster central region (F97) and wide field ground-based observations in

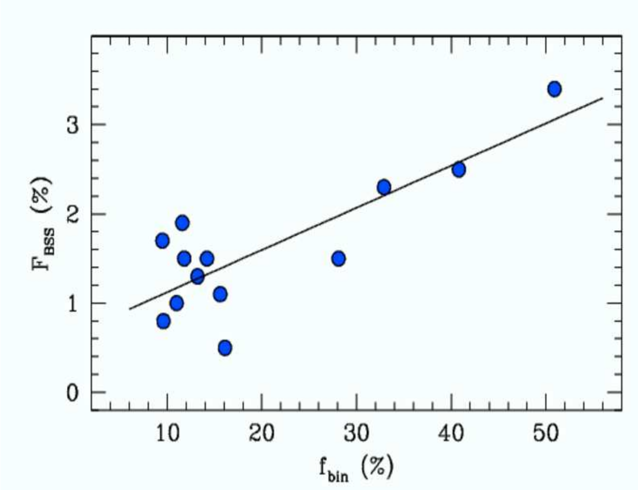

Fig. 4. The correlation between the BSS specific frequency and the binary fraction for 13 low-density clusters.

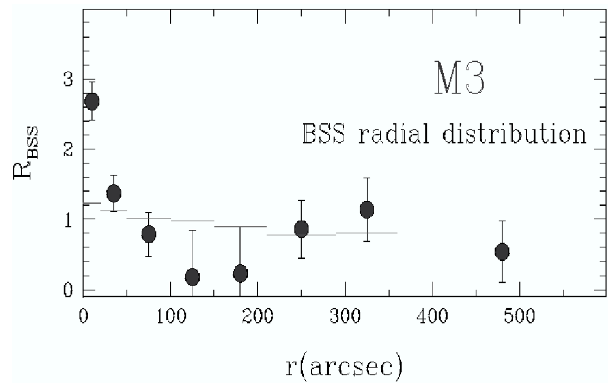

Fig. 5. The BSS double-normalized relative frequency $R_{\rm BSS}$ (*filled circles*) in M3. The horizontal segments show the relative frequency of the RGB stars used as reference population. (From F97).

the optical bands (Buonanno et al. 1994, F93), F97 presented the BSS radial distribution of M3 all over its radial extent ($r \sim 6'$). The resulting distribution was completely unexpected: BSS appeared to be more centrally concentrated than RGB stars in the central regions, and less concentrated in the cluster outskirts.

For further investigating such a surprising result, F97 divided the surveyed area in a number of concentric annuli, and counted the number of BSS and RGB stars normalized to the sampled luminosity in each annulus, according to the following relations (F93):

$$R_{\rm BSS} = \frac{(N_{\rm BSS}/N_{\rm BSS}^{\rm tot})}{(L^{\rm sampled}/L_{tot}^{\rm sampled})}$$

and

$$R_{\rm RGB} = \frac{(N_{\rm RGB}/N_{\rm RGB}^{\rm tot})}{(L^{\rm sampled}/L_{\rm tot}^{\rm sampled})},$$

respectively. The result is shown in Figure 5 and it clearly shows that the radial distribution of BSS in M3 is bimodal: it reaches maximum at the center of the cluster, shows a clear-cut dip in the intermediate region (at $100'' < r < 200''$), and rises again in the outer region (out to $r \sim 60'$).

While the bimodality detected in M3 was considered for years to be *peculiar*, the most recent results demonstrated that this is not the case. In fact, the same observational strategy adopted by F97 in M3 has been applied to a number of other clusters, with the aim of studying the BSS radial distribution over the entire cluster extensions. Bimodal distributions with an external upturn have been detected in several cases (see Figure 6): 47 Tuc (Ferraro et al. 2004), NGC 6752 (Sabbi et al. 2004), M55 (Zaggia et al. 1997; Lanzoni et al. 2007c), M5 (Warren et al. 2006; Lanzoni et al. 2007a), NGC 6388 (Dalessandro et al. 2008a), M 53 (Beccari et al. 2007), NGC 5466 (Beccari et al., in preparation). Originally, F97 argued that the bimodal distribution of BSS in M3 could be the signature of the two formation mechanisms acting simultaneously in the same cluster: the *external* BSS would arise from MT activity in primordial binaries, while the *central* BSS would be generated by stellar collisions leading to mergers. Sigurdsson et al. (1994) offered another explanation for the bimodal BSS distribution in M3. They suggested that all BSS were formed in the core by direct collisions and then ejected to the outer regions by the recoil of the interactions. Those BSS which get kicked out to a few core radii would rapidly drift back to the center of the cluster due to mass segregation, thus leading to the central BSS concentration and a paucity of BSS in the intermediate regions (around a few core radii). More energetic recoils would kick the BSS to larger distances and, since these stars require much more time to drift back toward the core, they may account for the overabundance of BSS in the cluster outskirts. We are currently using Monte-Carlo dynamical simulations in order to discern between the different possibilities. Mapelli et al. (2004, 2006) and Lanzoni et al. (2007a,b) modeled the dynamical evolution of BSS in a number of clusters, by using a modified version of the code described by Sigurdsson et al. (1995). Their results demonstrate that the observed BSS bimodal distributions cannot be explained within a purely collisional scenario in which all BSS are generated in the core through stellar interactions. In fact, an accurate reproduc-

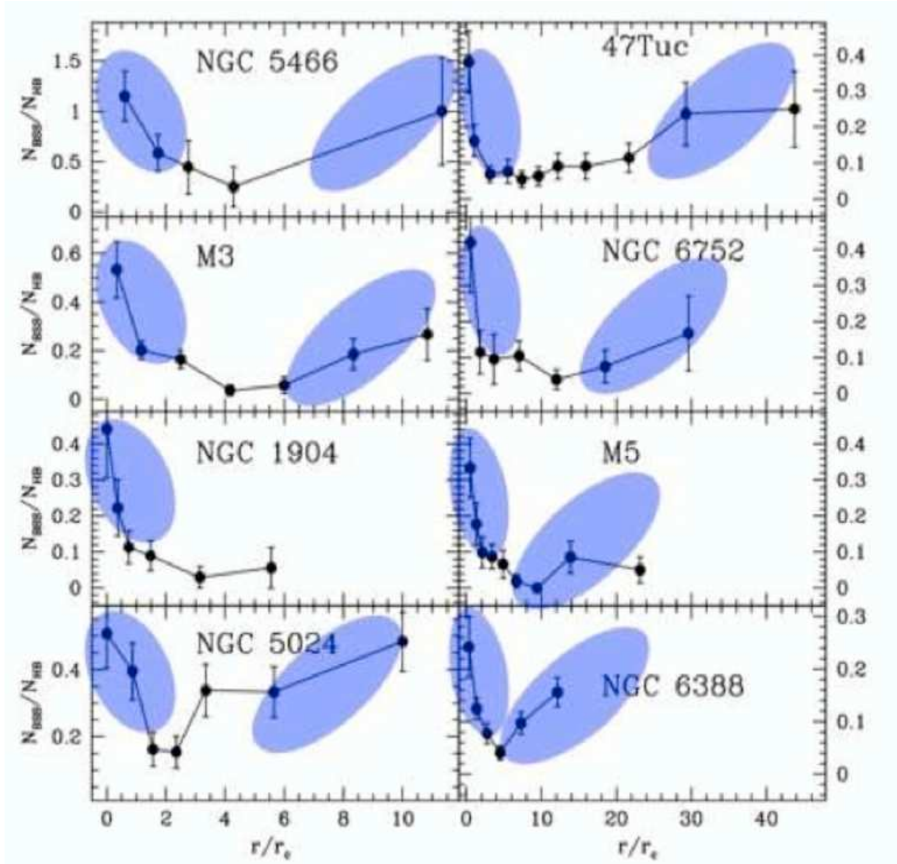

Fig. 6. The BSS radial distribution observed in 8 GGCs. In all cases, but NGC 1904, the distribution is clearly bimodal, with a peak in the center, a dip at intermediate radii, and an upturn in the external regions.

tion of the external upturn of the BSS radial distribution can be obtained only by requiring that a sizable ($\sim 20-40\%$) fraction of BSS is generated in the peripheral regions, where primordial binaries can evolve in isolation and experience mass transfer processes without suffering significant interactions with other cluster stars.

Even if the number of the clusters surveyed to date is low, the bimodal radial distribution first found in M3 and thought to be *peculiar* seems instead be the *natural* one. However, generalizations cannot be made from a sample of a few clusters only, and such a statement needs to be characterized on a much more solid statistical base. Indeed, a few exceptions are already known: NGC 1904, which does not present any external upturn (Lanzoni et al. 2007b), and ω Cen (Ferraro et al. 2006a) and NGC 2419 (Dalessandro et al. 2008b; see Figure 7) which show a completely flat BSS radial distribution.

The latter two cases deserve specific comments: by using a proper combination of high-resolution HST data and wide-field ground-based observations sampling the entire radial extension of the cluster, Ferraro et al. (2006a) have detected the largest population of BSS ever observed in any stellar system: more than 300 candidates have been identified. At odds with all the GCs previously surveyed, the BSS population in ω Cen has been found not to be centrally segregated with respect to the other cluster stars (see Figure 8). This is the cleanest evidence ever found that ω Cen is not fully relaxed, even in the central regions, and it suggests that the observed BSS are the progeny of primordial binaries, whose radial distribution is not yet significantly altered by stellar collisions and by the dynamical evolution of the cluster.

A similar result has been recently found in the remote cluster NGC2419, where the BSS population has been studied over the entire cluster extension by using a proper combination of high resolution ACS/HST images and wide-field ground based data (Dalessandro et al. 2008b; Figure 7). The distribution of the selected BSS turns out to be essentially equal to that of the other cluster stars (Figure 9).

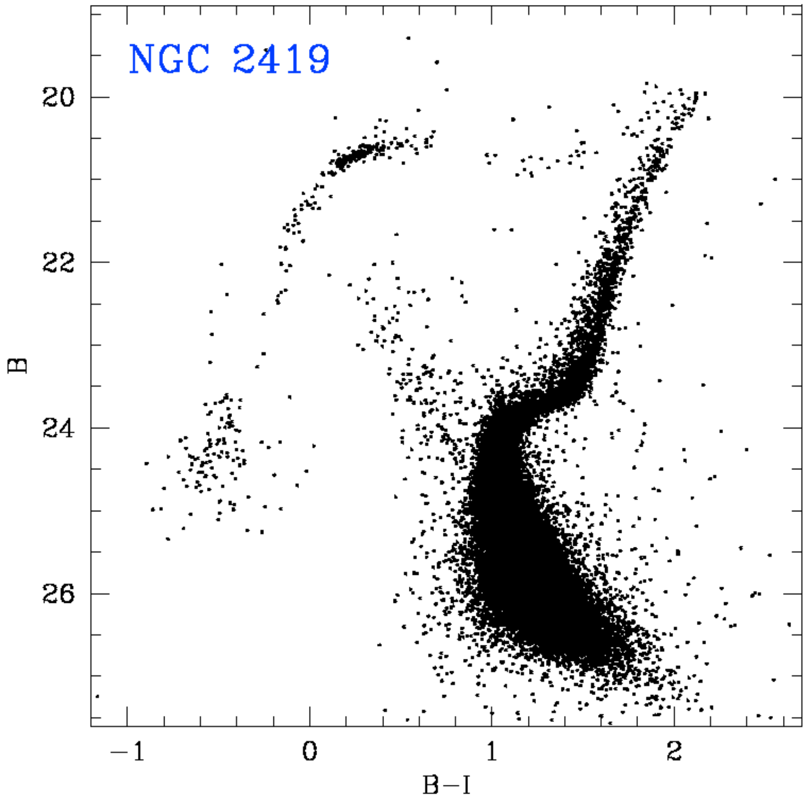

Fig. 7. CMD of the remote cluster NGC 2419. Note the large population of BSS.

As in the case of ω Cen, this evidence indicates that NGC 2419 is not yet relaxed even in the central regions. This observational fact is in agreement with the estimated half-mass relaxation time, which is of the order of the cluster age.

Our dynamical simulations (Mapelli et al. 2004, 2006; Lanzoni et al. 2007a,b) have also shown that the radial position of the dip of the BSS radial distribution sensibly depends on the dynamical friction efficiency within the cluster, while flat BSS distributions indicate little or no dynamical evolution of the system. Even at an early stage, our investigation is very promising and suggests that *precious information about the cluster dynamical evolution are imprinted in the BSS radial distribution.*

It is crucial now to extract these information for a large sample of clusters spanning the entire range of structural/dynamical properties. We are therefore leading a HST Large Programme (granted with 177 orbits) aimed at securing high-resolution UV observations of the central regions of 46 GGCs. By combining these data with coordinated Galaxy Evolution Explorer (GALEX) and ground-based photometry of the cluster exteriors we will be able to make a significant jump forward in the comprehension of the BSS properties and their dependence on the cluster characteristics.

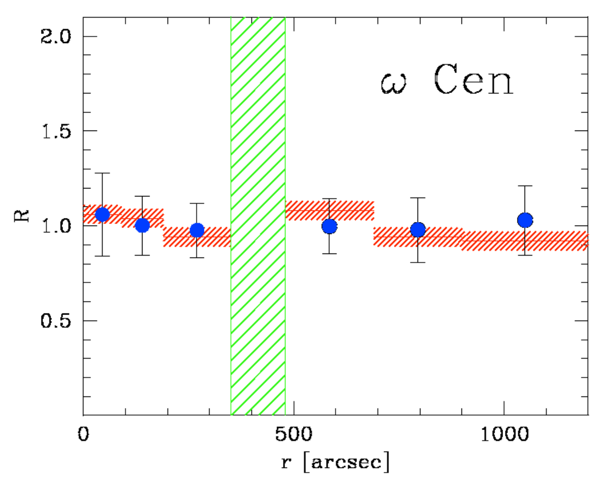

Fig. 8. The BSS double-normalized relative frequency (*filled circles*) in ω Cen. The shaded area marks the cluster region that we excluded in order to avoid incompleteness problems. The horizontal segments show the relative frequency of the RGB stars used as reference population (from Ferraro et al. 2006a).

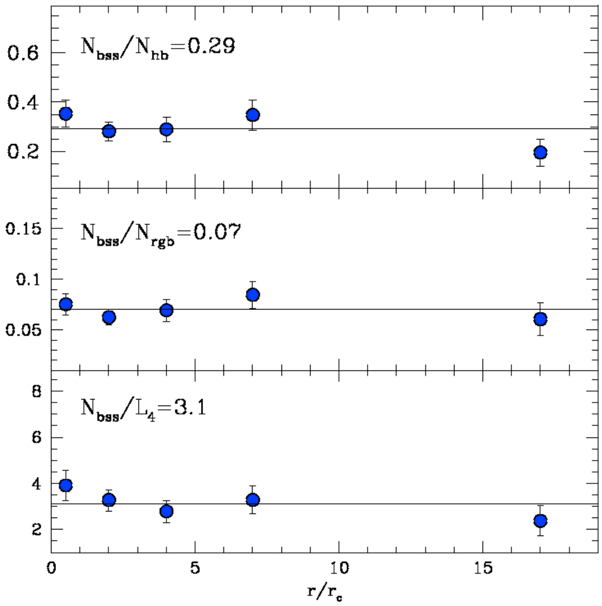

Fig. 9. BSS radial distribution in NGC 2419: the BSS specific frequency is shown with respect to HB stars (top), RGB stars (middle) and the sampled luminosity in units of 10^4 $L_\odot$ (lower panel).

5. SEARCHING FOR THE CHEMICAL SIGNATURES OF THE BSS FORMATION PROCESSES

Theoretical models still predict conflicting results on the expected properties of BSS generated by different production channels. For instance, Benz & Hills (1987) predict high rotational velocities for COLL-BSS, whereas Leonard & Livio (1995) have shown that a substantial magnetic braking could occur, and the resulting BSS are *not* fast rotators. In the case of BSS formed through the MT production channel, rotational velocities larger than those of typical MS stars are predicted (Sarna & de Greve 1996). Concerning the chemical surface abundances, hydrodynamic simulations (Lombardi et al. 1995) have shown that very little mixing is expected to occur between the inner cores and the outer envelopes of the colliding stars. On the other hand, signatures of mixing with incomplete CN-burning products are expected at the surface of BSS formed via the MT channel, since the gas at the BSS surface is expected to come from deep regions of the donor star, where the CNO burning was occurring (Sarna & de Greve 1996).

Spectroscopic observations have recently begun to provide the first set of basic properties of BSS (effective temperature, mass, rotation velocity, etc.; see the recent work by De Marco et al. 2005). However, with the exception of a few bright BSS in the open cluster M67 (Mathys 1991; Shetrone & Sandquist 2000), an extensive survey of BSS surface abundance patterns is still lacking, particularly in GCs. In this context the advent of 8 meter class telescopes equipped with multiplexing capability spectrographs is giving a new impulse to the study of the BSS properties. By using FLAMES at the ESO VLT we are currently performing extensive surveys of surface abundance patterns for representative numbers of BSS in a sample of GGCs. The first results of this search have lead to an exciting discovery (Ferraro et al. 2006b): by measuring the surface abundance patterns of 43 BSS in 47 Tuc, we discovered a sub-population of BSS with a significant depletion of Carbon (C) and Oxygen (O), with respect to the dominant population (see Figure 10). This evidence is interpreted as the presence of CNO burning products on the BSS surface, coming from the core of a deeply peeled parent star, as expected in the case of the MT formation channel. Thus, our discovery in 47 Tuc could be the first detection of a chemical signature clearly pointing to the MT formation process for BSS in a GC.

Indeed, the acquired data-set is a gold-mine of information. In fact, our observations have shown that (1) most of the BSS are slow rotators and only 10 BSS have rotational velocities larger than $v \sin i > 10$ km s^{-1} (see Figure 11), at odds with the predictions of canonical models; (2) the CO-depleted BSS and the few BSS with $v \sin i > 10$ km s^{-1} appear to be "less evolved" than the others: they all lie within a narrow strip at the faint-end of the BSS luminosity distribution in the CMD (see Figure 12); (3) some of them are WUma binary systems suggesting that the evolution of these systems could be a viable channel for the formation of BSS in GCs.

In the Galactic field W UMa objects are binary systems losing orbital momentum because of magnetic braking. These shrinking binary systems, initially detached, evolve to the semi-detached and contact stages (when mass-transfer starts) and finally merge into a single star (Vilhu 1982). In dense cluster environments stellar interactions can drive binaries toward merger: these systems could reasonably be expected to display W UMa characteristics, although the evolutionary time scales could be very different.

Which is the scenario emerging from these observations? In the early stage of mass transfer in W UMa systems (*Stage-1*), the transferred mass could come from the unprocessed material and the resulting star would have normal C-O abundances

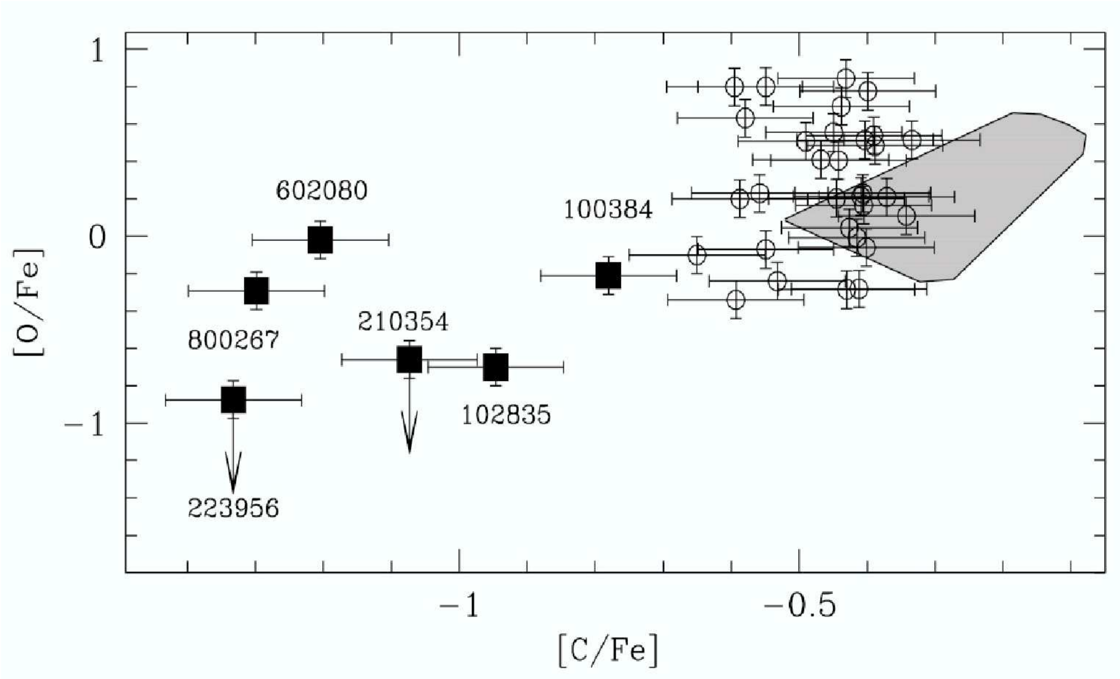

Fig. 10. [O/Fe] ratio as a function of [C/Fe] for the BSS observed in 47 Tuc. Normal BSS are marked with *empty circles*, while CO-depleted BSS are marked with *filled squares* and their names are also reported. The gray regions correspond to the location of the 12 turnoff stars in 47 Tuc analyzed by Carretta et al. (2005).

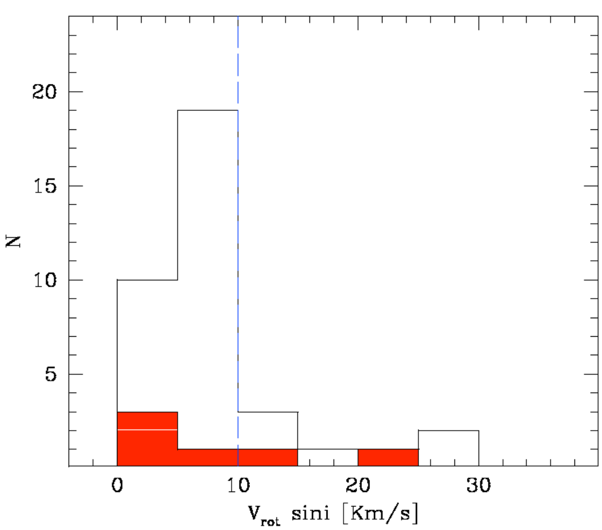

Fig. 11. Distribution of rotational velocities for "normal" BSS (*empty histogram*), compared to that of CO-depleted BSS (*filled histogram*). The vertical *dashed line* marks the separation between slow and the "fast" rotators (with $v \sin i > 10$ km s^{-1}).

(see Figure 13). As the transfer continues reaching into the region of CNO processing, first C and then both C and O would appear depleted (*Stage-2*). Thus it is possible to find depleted C, normal O BSS/W UMa stars. After the merger the star would appear as a CO-depleted non-variable BSS (*Stage-3*). In our sample we have found 2 or 3 stars in *Stage-2*, and 4 in *Stage-3*. Classical MT binaries would also result in BSS with CO depletion, perhaps with a low mass He white dwarf companion. Since the donor star is evolving off the MS, the transferred mass might be more heavily processed. The resulting BSS would be very similar to a *Stage-3* W UMa BSS.

The number of BSS with CO depletion and the presence of W UMa systems show that the MT channel is active even in a high-density cluster like 47 Tuc: at least 10–20% of the BSS are being produced by the MT channel. This finding is in good agreement with the results of dynamical simulations (Mapelli et al. 2004) which have shown that a significant contribution of BSS (25%) generated by the natural evolution of primordial binaries is needed in order to reproduce the BSS bimodal radial distribution observed in this cluster (Ferraro et al. 2004). However, the vast majority (90%) of BSS in our spectroscopic sample is located in the external region of the cluster. Hence, according with Mapelli et al. (2004, 2006), they should mainly be MT-BSS (since COLL-BSS are expected to be strongly segregated in the cluster centre). Thus, most of them should show CO-depletion, at odd with what is observed.

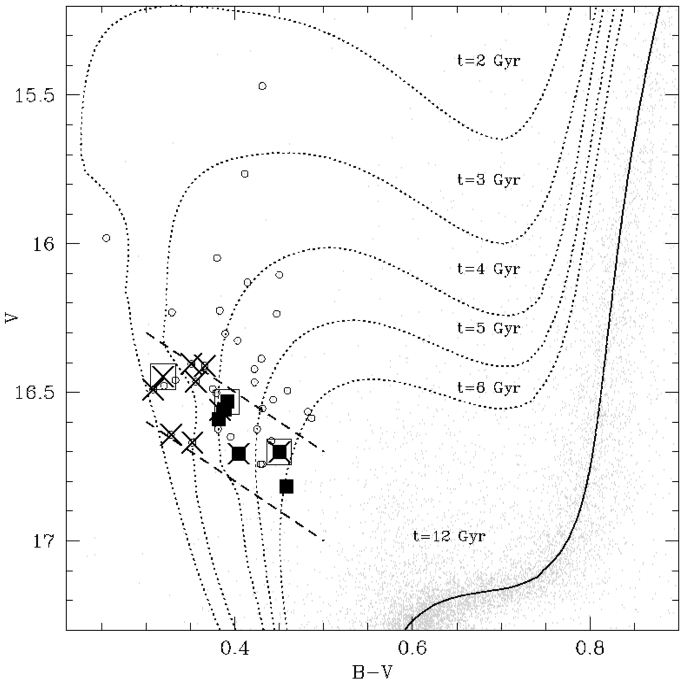

Fig. 12. Zoomed CMD of 47 Tuc in the BSS region. Normal BSS are marked with *open circles*, while CO-depleted BSS are shown as *filled squares*. Isochrones of different ages (from 2 to 12 Gyr) from Cariulo et al. (2003) are overplotted for comparison. The three W UMa systems and the 10 BSS rotating with $v \sin i > 10$ km s^{-1} are highlighted with *large empty squares* and *large crosses*, respectively.

However, since the CO-depleted BSS lie in the CMD where newly formed BSS should lie (see the region between the dashed lines in Figure 12), this may indicate that the following evolution converts C-O abundances back to normal. Certainly, once C and O have been processed into N producing CO-depletion, further nuclear processing would not restore normal C-O abundances during the BSS phase. Instead, mixing processes could play a role in this game.

Indeed, the distribution of rotational velocities provides a clue. Most BSS in our sample are slow rotators, with velocities compatible with those measured in unperturbed turnoff (TO) stars (Lucatello & Gratton 2003). In particular, among the three BSS identified as W UMa systems, we have found a rapid rotator and two intermediate-slow rotators. This seems at odds with what expected, especially for W UMa systems which are predicted to be rapid rotators. Perhaps this arises because we are seeing the systems at different inclination angles; perhaps not. In any case, from their location in the CMD, all of our fastest BSS are presumedly the most recently born. This is also the region of C-O depletion and the W UMa behavior. The cooler, older BSS rotate more slowly and have “normal” C-O. Hence,

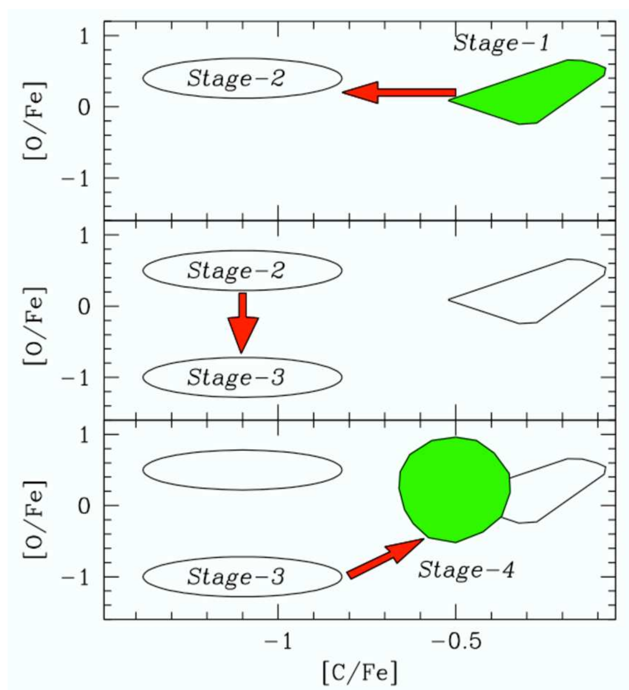

Fig. 13. Suggested evolution of BSS in the [O/Fe]-[C/Fe] diagram. The four different stages discussed in the text are shown.

this might suggest that during the evolution the rotation slows down, and, as that happens, mixing is induced. While rotational mixing ordinarily increases CNO anomalies, in MT-BSS the C-O depleted material overlies the material with normal C-O. Hence, the result of mixing would be to push C-O back toward "normalcy". C and possibly O would still be low, but less so than a MT-BSS at birth. Indeed, we do find that the bulk of our sample has C roughly one half of that of the TO stars. This could be due to systematics (since C in TO stars have been measured from different lines from BSS) or it could also be a real effect. It is now crucial that we understand which.

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