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Exotic populations in Galactic globular clusters

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Abstract. Recent high-resolution observations of the central region of Galactic globular clusters have shown the presence of a large variety of exotic stellar objects whose formation and evolution may be strongly affected by dynamical interactions. In this paper I review the main properties of two classes of exotic objects: the so-called Blue Stragglers stars and the optical companions to Millisecond pulsar. Both these classes of objects are invaluable tools to investigate the binary evolution in very dense environments and are powerful tracers of the dynamical history of the parent cluster.

Key words. Globular clusters; Stars: blue stragglers; millisecond pulsar

1. Introduction

Ultra-dense cores of Galactic Globular Clusters (GCs) are very efficient "furnaces" for generating exotic objects, such as low-mass X-ray binaries, cataclysmic variables, millisecond pulsars (MSP), blue stragglers (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 exotic objects and the properties of artificial sequences, as that of BSS, in the color-magnitude diagrams (CMDs) of GCs can serve as a powerful diagnostic of the dynamical evolution of clusters, and of its effects on the evolution of their stellar population and binary systems (see Bailyn 1995 and reference therein).

This topic has received strong impulse in the recent years. In this paper I review the main properties of the most known *exotic population* of GCs: the so-called BSS, that describe the very first sequence of exotic objects discovered in the CMD and the most recently discovered *anomalous sequence*: the one defined by MSP companions.

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2. Blue straggler stars

BSS, first discovered by Sandage (1953) in M3, are commonly defined as stars brighter and bluer (hotter) than the main sequence (MS) turnoff (TO), lying along an apparent extension of the MS, and thus mimicking a rejuvenated stellar population. The existence of such a population has been a puzzle for many years, and even now its formation mechanism is not completely understood, yet. At present, the leading explanations involve mass transfer between binary companions, the merger of a binary star system or the collision of stars (whether or not in a binary system). Direct measurements (Shara et al. 1997) and indirect evidence show that BSS are more massive than the normal MS stars, pointing again towards collision or merger of stars. Thus, BSS represent the link between classical stellar evolution and dynamical processes (see Bailyn 1995).

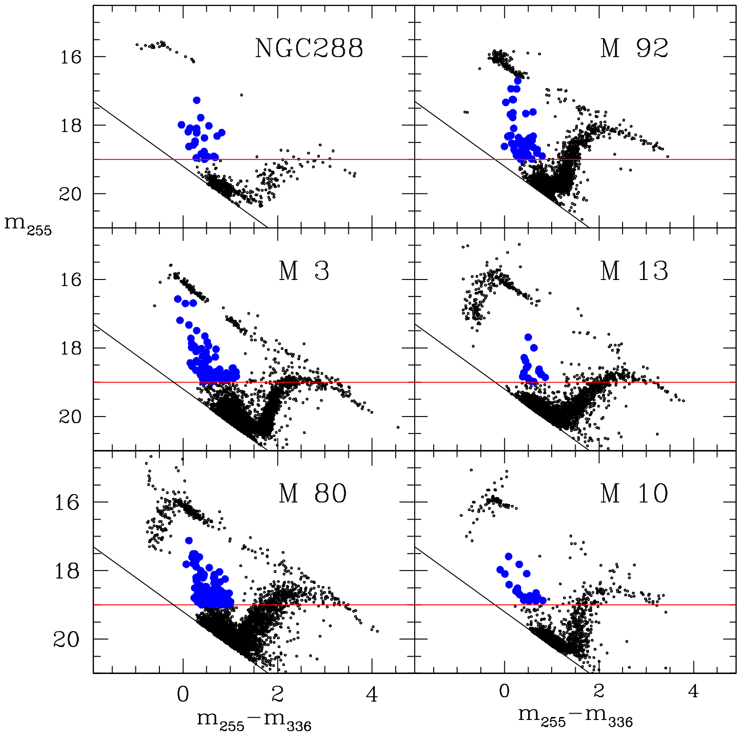

Fig. 1. ($m_{255}, m_{255} - m_{336}$) CMDs for the six clusters discussed in F03a. Horizontal and vertical shifts have been applied to all CMDs in order to match the main sequences of M3. The horizontal solid line corresponds to $m_{255} = 19$ in M3. The bright BSS candidates are marked as large filled circles.

The realization that BSS are the ideal diagnostic tool for a quantitative evaluation of the dynamical interaction effects inside star clusters has led to a remarkable burst of searches and systematic studies, using UV and optical broad-band photometry and mainly exploiting the exceptional spatial resolution capability of the Hubble Space Telescope (HST). Based on these observations, the first catalogs of BSS have been published (e.g., Fusi Pecci et al. 1992 ; Ferraro, Fusi Pecci & Bellazzini 1995,hereafter FFB95), until the most recent collection of BSS which counts nearly 3000 candidates in 56 Galactic GCs by Piotto et al. (2004). These works have significantly contributed to form the nowadays commonly accepted idea that 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 and/or mass transfer (hereafter MT) process, while in high density GCs (depending on survival-destruction rates for primordial binaries) BSS might arise mostly from stellar collisions (hereafter COL-BSS), particularly those which involve binaries. While the suggested mechanisms of BSS formation could be 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. 1997, hereafter F97).

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 (see Figure 1) considered by Ferraro et al. (2003a, hereafter F03a), 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 as M3 and M13 harbor a quite different BSS 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 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 the F03a 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.

2.1. The BSS radial distribution

M3 has played a fundamental role in the BSS history, because it is the GC not only where BSS have been first identified, but also where the BSS radial distribution has been studied for the first time over the entire cluster extension. F97 presented the BSS radial distribution of M3 all over its radial extent ($r \sim 6'$) showing 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 $r \sim 360''$).

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, in the last years 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 extension. Bimodal distributions with an external upturn have been detected in several cases (see Figure 2): 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. 2007), NGC 5466 (Beccari et al. 2007, in preparation). Mapelli et al. (2004, 2006) and Lanzoni et al. (2007a) modeled the dynamical evolution of BSS in a number of clusters, by using a modified version of the code described by Sigurdsson & Phinney (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 reproduction 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 surveyed clusters is low, the bimodal radial distribution first found in M3 and thought to be *peculiar* could 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, two exceptions are already known: NGC 1904, which does not present any external upturn (Lanzoni et al. 2007b), and ω

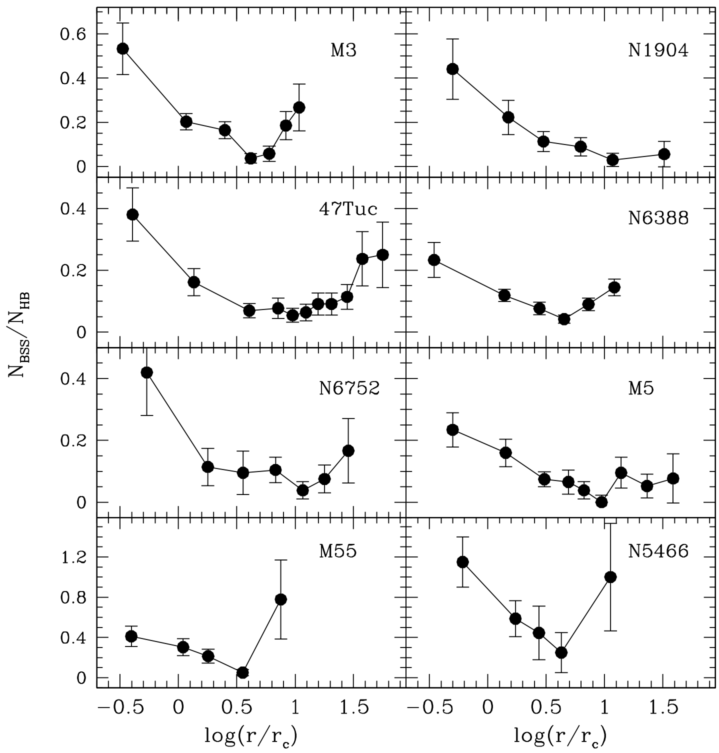

Fig. 2. The BSS radial distribution observed in 8 GCs. In all cases, but NGC 1904, it is clearly bimodal, with a peak in the center, a dip at intermediate radii, and an upturn in the external regions

Cen (Ferraro et al. 2006a), which shows a completely flat BSS radial distribution.

The case of ω Cen deserves specific comments: indeed, at odds with all the GCs previously surveyed, BSS in ω Cen have been found not to be centrally segregated with respect to the other cluster stars. 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 was not yet significantly altered by stellar collisions and by the dynamical evolution of the cluster. Hence, most of these objects should have been produced essentially by MT processes, and *the population of BSS in ω Cen could represent the purest and largest population of non-collisional BSS ever observed.* Thus, ω Cen represents the best laboratory for studying the physical and chemical properties of MT-BSS.

2.2. Searching for the chemical signature of the BSS formation process

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 COL-BSS, whereas Leonard & Livio (1995) have shown that a substantial magnetic braking could occur, and the resulting BSS are *not* fast rotators. In the

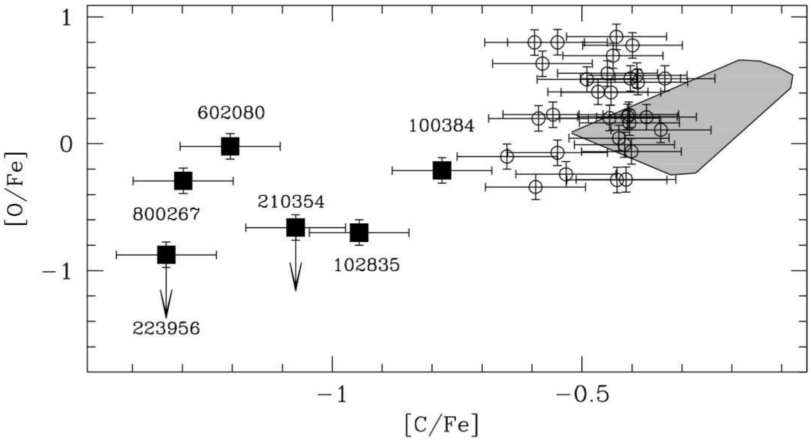

Fig. 3. [O/Fe] ratio as a function of [C/Fe] for the BSS observed in 47 Tuc. Normal BSS are marked with *empty circles*, while CO-depleted BSS are marked with *filled squares* and their names are also reported. The gray regions correspond to the location of the 12 turnoff stars in 47 Tuc analyzed by Carretta et al. (2005).

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).

On the observational side, 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 Galactic GCs. The first results of this search have lead to an exciting discovery: 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 3). This evidence is interpreted as the presence of CNO burning products on the BSS surface, coming from 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 informations. In fact, our observations have shown that (1) only 10 BSS have been found to show rotational velocities larger than $v \sin i > 10$ Km/s, while most of the BSS are slow rotators at odds with what canonical models predict; (2) BSS with CO depletions and the few BSS with $v \sin i > 10$ Km/s appear "less evolved" than the others: they all lie within a narrow strip at the faint-end of the BSS luminosity distribution in the CMD; (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.

3. MSP companions in GCs

Among the possible collisional by-products, MSPs are invaluable probes to study cluster dynamics: they form in binary systems containing a neutron star (NS) which is eventually spun up through mass accretion from the evolving companion. Despite the large difference in total mass between the disk of the Galaxy and the GC system, about 50% of the entire MSP population has been found in the latter. This is not surprising since in the Galactic disk MSPs can only form through the evolution of primordial binaries, while in GC cores dynamical interactions can lead to the formation of several different binary systems, suitable for recycling NS.

The search for optical counterpart to MSP companion in GCs is a relatively recent branch of this research, since the first identification has been done only a few years ago in the core of 47 Tuc. Edmonds et al (2001) identified U_{opt}, the companion to PSR J0024−7203U: this object turned out to be a faint blue variable whose position in the CMD is consistent a cooling helium WD. This is fully in agreement with the MSP recycling scenario, where the usual companion to a binary MSP is an exhausted star.

3.1. The surprising companion to the MSP in NGC6397

A major surprise came from the optical identification of the companion to the binary MSP PSR J1740-5340 (D'Amico et al 2001) in NGC6397. By using high resolution multiband HST observations and the position of the MSP inferred from radio timing, Ferraro et al (2001) identified a bright variable star (hereafter COM J1740-5340) as the optical counterpart to the MSP companion, whose optical modulation nicely agrees with the orbital period of the MSP itself. The optical counterpart shows a quite anomalous position in the CMD since it is located at the luminosity of the TO point but it has an anomalous red color (see Figure 4).

A wealth of intriguing scenarios have flourished in order to explain the nature of this binary (see Orosz & van Kerkwijk 2003, Grindlay et al. 2002 for a review). In particular, Burderi et al. (2002) suggested that the position of COM J1740-5340 in the CMD is consistent with the evolution of an (slightly) evolved Sub Giant Branch (SGB) star orbiting the NS and loosing mass. The future evolution of this system will generate a He-WD/MSP pair. COM J1740-5340 could be a star acquired by exchange interaction in the cluster core or alternatively the same star that spun up the MSP and still overflowing its Roche lobe. The latter case suggests the fascinating possibility that PSR J1740-5340 is a new-born MSP, the very first observed just after the end of the recycling process. This is the first example ever observed of a MSP companion whose light curve is dominated by ellipsoidal variations, suggestive of a tidally distorted star, which almost completely fills (and is still overflowing) its Roche lobe. Thanks to the unusual brightness of the companion ($V \sim 16.5$), this system represents an unique laboratory to study the formation mechanism of binary MSP in GCs, allowing unprecedented detailed spectroscopic observations. A number of interesting results have been obtained from followup studies:

- The determination of the radial velocity curve allowed an accurate measure of the mass ratio of the system (M_{PRS}/M_{COM} = 5.83 ± 0.13) which suggests a mass of $M_{COM} \sim 0.25 M_{\odot}$ by assuming $M_{PSR} \sim 1.4 M_{\odot}$. (Ferraro et al 2003b).
- The H_{α} emission from the system was already noted by Ferraro et al (2001) and fully confirmed by the high-resolution spectra (Sabbi et al 2003a). In particular, the complex structure of the H_{α} line suggests the presence of a matter stream exaping from the companion towards the NS. Note that because of the radiation flux from the pulsar, the material would never reach the NS surface, creating a cometary-like gaseous tail which feeds the presence of (optically thin) hydrogen gas outside the Roche lobe.

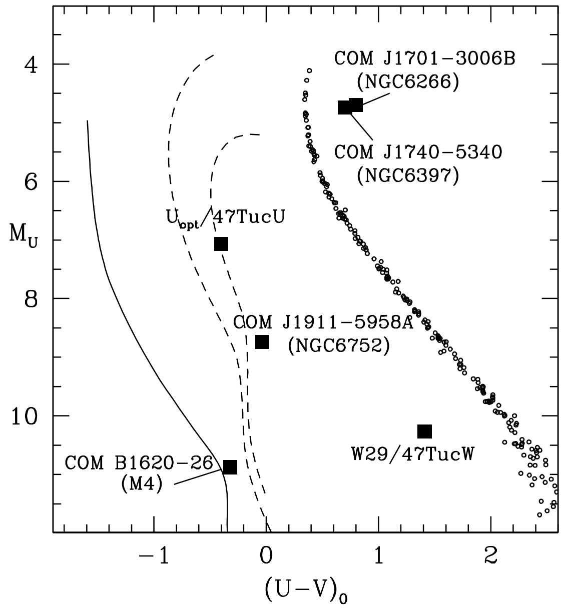

Fig. 4. Optical companions to MSP detected in GCs in the $(M_U, (U-V)_0)$ absolute plane. Six optical companions to binary MSPs have been discovered up to now in 5 Galactic GCs. U_{opt} and W29 in 47 Tuc (Edmonds et al. 2001, 2002); COM J1740−5340 in NGC 6397 (Ferraro et al. 2001); COM J1911−5958A in NGC 6752 (Ferraro et al. 2003c); COM B1620−26 in M4 (Sigurdsson et al. 2003), COM J1701-3006B in NGC6266 (Cocozza et al 2007, in preparation). The cooling tracks for He-WD from Serenelli et al. (2002) are shown as *dashed lines* and the CO-WD cooling sequence from Wood (1995) is plotted as a *heavy solid line*. Main sequence stars *(small empty circles)* are also plotted for reference.

– The unexpected detection of strong He I absorption lines implies the existence of a region at $T > 10,000K$, significantly hotter than the rest of the star (Ferraro et al 2003b, Sabbi et al 2003a,b). The intensity of the He I line correlates with the orbital phase, suggesting the presence of a region on the companion surface, heated by the millisecond pulsar flux.

– COM J1740-5340 has been found to show a large rotation velocity ($V sini = 50 \pm 1 Kms^{-1}$). The derived abundances are found fully consistent with those of normal unperturbed stars in NGC 6397, with the exception of a few elements (Li, Ca, and C). In particular, the lack of C suggests that the star has been peeled down to regions where incomplete CNO burning occurs (Sabbi et al. 2003b), favoring a scenario where the companion is a SGB star which has lost most of its mass (see also Ergma & Sarna 2003).

3.2. Photometric properties of MSP companion in GCs

Since the first discovery of U_{opt}, in 47 Tuc (Edmonds et al 2001), the zoo of the optical MSP counterparts in GCs is rapidly enlarging. Figure 4 shows a comparison of the photometric properties of the available optical identifications of MSP companions hosted in GCs.

The latest discovery in this field is the identification of COMJ1701-3006B in NGC6266 by Cocozza et al (2007): the observed properties of this object closely resemble those of COMJ1740-5340 in NGC6397. Hence, now 2 out of the 6 sources are peculiar, bright objects (being as luminous as the turn off stars and shows quite red colors), perhaps lying along their evolutionary path which will lead to the final stage of a low-mass He-WD. Indeed, U_{opt} in 47 Tuc and COMJ1911-5958A in NGC6752 lie nearly on the same mass $\sim 0.2\ M_{\odot}$ He-WD cooling sequence. If further supported by additional cases, this evidence could confirm that a low mass $\sim 0.15 - 0.2\ M_{\odot}$ He-WD orbiting a MSP is the favored system generated by the recycling process of MSPs in GCs (Rasio et al 2000).

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