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Galactic Globular Clusters: the stellar laboratory

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Abstract. Galactic Globular clusters represent a fundamental laboratory to study many aspects of the low mass stellar evolution and Galaxy formation. In this paper I briefly discuss some recent results obtained by our group in this framework.

Key words. CM diagram – Stellar populations – Stellar evolution

1. Introduction

Galactic globular clusters (GGCs) are ideal laboratories for a number of crucial *experiments* on stellar evolution, namely *(i)* testing theoretical evolutionary models; *(ii)* tracing the Galaxy formation history, being *fossils* from the early epochs and the only witnesses of the entire evolution; *(iii)* studying how the internal dynamics of stellar systems can effect the *passive* evolution of stars.

Many different groups in Italy are involved in systematic studies of stellar populations in GGCs using different techniques and approaches. Within this context, a few years ago our group started a long-term project devoted to fully exploit the potentiality of this unique stellar system to better understand the structure and the evolutionary history of the Galaxy. In this paper I report a short summary of the most recent results.

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2. Checking theoretical models of stellar evolution

Stellar evolution theory is crucial to yield a reliable clock for dating astrophysical objects. Suitable Color Magnitude Diagrams (CMDs) and Luminosity Functions (LFs) are the most powerful tools to test theoretical models and, in turn, the *running* of the stellar clock. Quantitative analysis and testing of each individual evolutionary sequence in the CMDs of GGCs are fundamental in this respect.

Within this framework, in Ferraro et al. (1999 and 2000, hereafter F99 and F00, respectively) we construct a large database of high quality optical and near-IR CMDs (cf. Figure 1, left panel) for a complete sample of GGCs, spanning a wide range in metallicity. Such a data–base has been used to define a variety of observables and fully characterize the photometric properties of the Red Giant Branch (RGB), namely: *(a)* the location of the RGB in the CMD both in $(J–K)_0$ and $(V–K)_0$ colors at different absolute K magnitudes (–3, –4, –5, –5.5) and in temperature; *(b)* its overall mor-

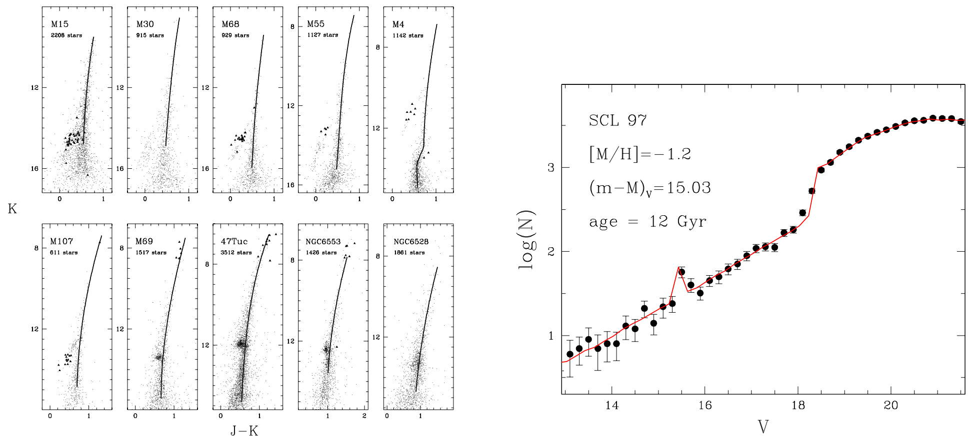

Fig. 1. Left panel: (K,J-K) CMDs for the 10 GGCs presented in F00. The thick lines in each panel are the RGB fiducial ridge lines. Variable stars are plotted as filled triangles. Right panel: Differential RGB/SGB LF for the cluster M3 (Rood et al. 1999). The solid line is the theoretical LF by Straniero, Chieffi & Limongi (1997).

phology and slope; *(c)* the *Bump* and the *Tip* luminosities. All these quantities have been measured with a homogeneous procedures applied to each individual CMD, by adopting the distance modulus scale defined in F99. A set of relations linking the photometric parameters to the cluster global metallicity ($[M/H]$) have been also obtained and used to perform a detailed comparison with the theoretical predictions (for example about the magnitude level of the RGB-bump and the RGB-Tip) and to derive photometric estimates of the metallicity distributions in complex, *i.e.* chemically inhomogeneous, stellar populations as those observed in nearby dwarf galaxies.

The most solid tests of stellar evolutionary calculations are based on the comparison between theoretical and observed LFs. In Rood et al. (1999) we presented a high-precision, large-sample LF for the GGC M3. This is the largest observed LF ever obtained in a GGC: indeed, by using a combination of ground-based and Hubble Space Telescope data, the entire radial extension of the cluster has been covered. Figure 1 (right panel) shows the comparison between the observed and the theoretical LF, computed by using Straniero, Chieffi & Limongi (1997) standard theoretical models. An excellent agreement has been found, suggesting that the H profile (and thus the fuel consumed in the earlier stages) is predicted with reasonable accuracy by the standard models.

3. Understanding the formation of the Galactic Halo

The Sagittarius dwarf spheroidal (Sgr dSph) galaxy (Ibata et al. 1994) is an *in vivo* example of an accretion/disruption event of a Galactic satellite: a process that may have been one of the main channel in the Galactic Halo assembly. The study of the stellar content, star formation history and chemical evolution of this disrupting system is thus crucial in order to reconstruct the evolutionary history of the Milky Way. As a part of a long-term project devoted to understand the origin and the evolution of the *building blocks* of the Galactic

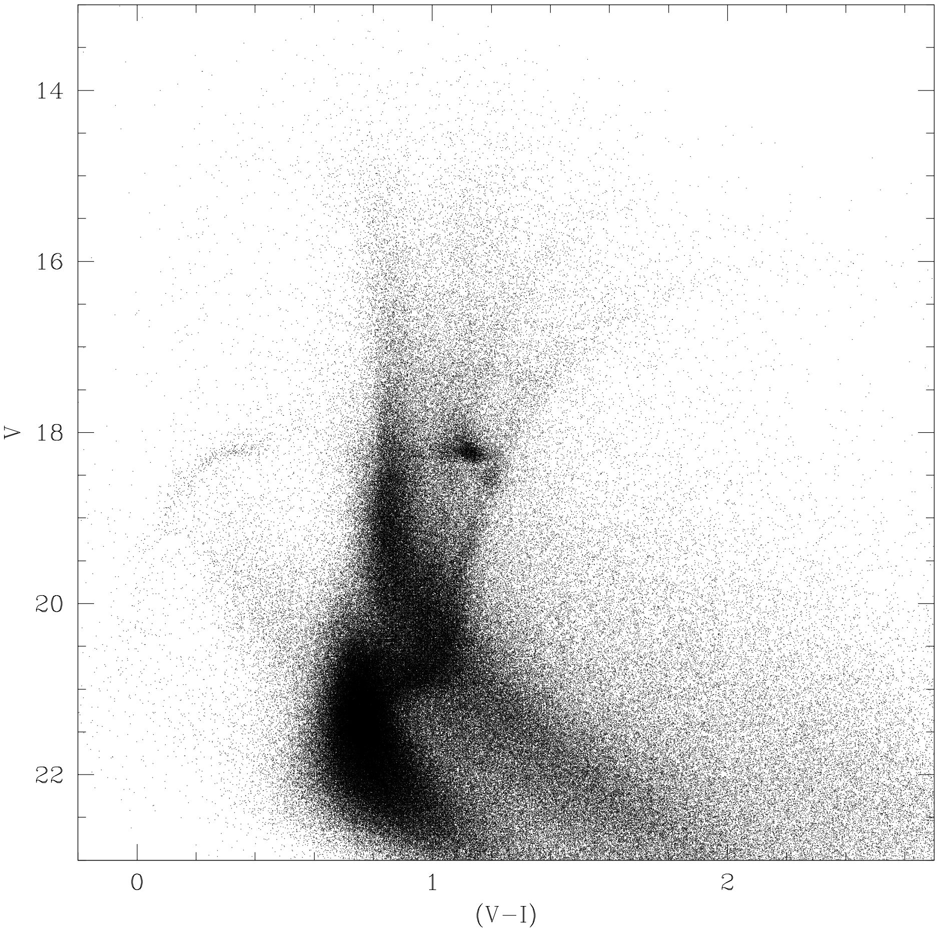

Fig. 2. (V,V-I) CMD for 493,000 stars in a $\sim 1^{\circ} \times 1^{\circ}$ region around the globular cluster M54. Three main populations are clearly visible: field stars, M54, and the Sgr dSph.

Halo, we are performing a detailed study of the stellar population in this disrupting system. The first results of extensive wide-field V,I photometry of the Sgr dSph in a region ($\sim 1^{\circ} \times 1^{\circ}$) around the globular cluster M 54, have been recently published (Monaco et al. 2002).

The $(V, V-I)$ CMD counting ∼493,000 stars measured in the entire field of view is shown in Figure 2. At least three main populations can be easily distinguished: (i) the RGB of the Sgr's metal-rich population is visible on the red side of the diagram, extending to very red (V-I)≈ 2.7 color. The corresponding red HB clump is also clearly visible at $V \sim 18.22$. The RGB-bump of the Sgr is the clump of stars along the RGB at $V \sim 18.5$ and $(V-I) \sim 1.2$.

(ii) a second, much steeper RGB is barely visible at (V-I)≈ 1.1, belonging to the much metal-poorer population of

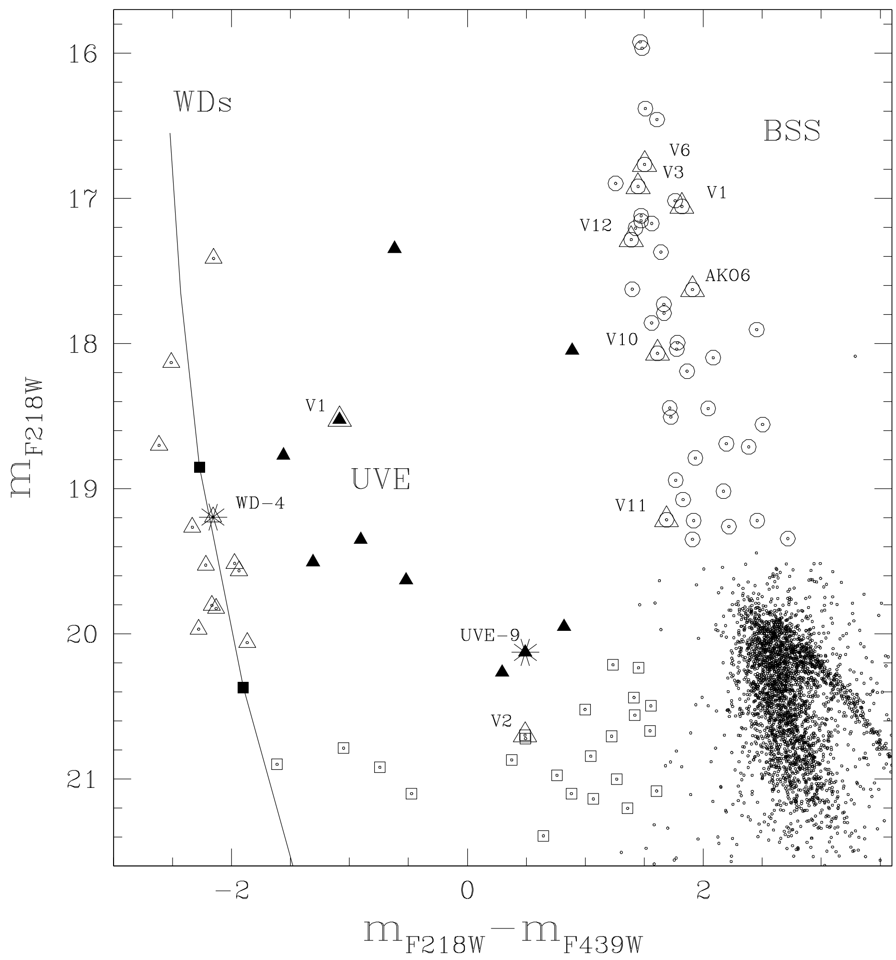

Fig. 3. Zoom of the ($m_{F218W}, m_{F218W} - m_{F439W}$) CMD showing the blue populations in the core of 47 Tuc. BSSs are plotted as large empty circles (variables are highlighted by large empty triangles and labelled with their names). WDs candidates are plotted as open triangles. The theoretical WD cooling sequence from Wood (1995) models has been overplotted to the data. UVE stars are plotted as filled triangles. The large population of *faint* UVE stars (empty squares) is also shown. Peculiar objects are indicated by larger open triangle and labelled with their names. The three blue objects (namely WD-4, BSS-26 (V11) and UVE-9) which have been found to be close to the three binary MSPs are marked with a large asterisk and labelled with their names.

M 54. Its blue HB is clearly seen at (V,V-I)=(18.2,0.2).

(*iii*) the field population defines a nearly vertical sequence around V-I=0.8 and, at slightly redder colors (V-I≈1.1), the more evolved field stars are also visible.

Thanks to the large sample of stars measured, we have been able to detect for the first time the RGB-bump in the Sgr dSph. The photometric properties of the Sgr RGB and the position of the RGB-Bump have been used to constrain the range of possible ages and metallicities of this population: the most likely solution give $-0.6 \leq [M/H] \leq -0.4$ and 4 $Gyr \leq age \leq 8$ Gyr.

4. Tracing stellar dynamics

Ultra-dense cores of GGCs are very efficient "kilns" for generating exotic objects, such as low-mass X-ray binaries, cataclysmic variables, millisecond pulsars (MSPs), blue straggler stars (BSSs), etc. Most of these objects are thought to result from the evolution of various kinds of binary systems, whose nature and even existence can be strongly affected by stellar dynamics in the cluster cores.

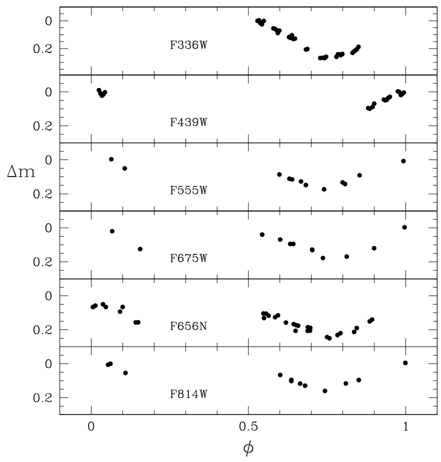

Fig. 4. Light curves of COM J1740−5340 in different HST filters and epochs as a function of the MSP phase.

4.1. UVE stars in 47 Tuc

In Ferraro et al. 2001a, we presented UV–CMDs for $\sim$ 4 000 stars detected within the Planetary Camera (PC) field of view in the core of 47 Tuc. We have pinpointed a number of interesting objects: *(i)* 43 BSSs, including 20 new candidates; *(ii)* 12 bright (young) cooling white dwarfs (WDs) at the extreme blue region of the UV-CMD; *(iii)* a large population of UV-excess (UVE) stars, lying between the BSS and the WD sequences. The UVE stars discovered in the core of 47 Tuc represent the largest population of anomalous blue objects ever observed in a globular cluster. If the existence of such a large population is confirmed, we have finally found the long-searched population of interacting binaries predicted by theory. A zoom of the $(m_{F218W}, m_{F218W} - m_{F439W})$ CMD is shown in Figure 3: there are at least a dozen of UVE stars (plotted as filled triangles) lying between the WD and the BSS sequences and a large population of faint UVE (small empty squares). The true nature of these *anomalous* UVE stars cannot be satisfactorily assessed yet, since several different evolutionary mechanisms involving stellar collisions and interactions could account for them. High resolution, deeper imaging and spectroscopic observations in the UV are required to discriminate among the various models. However, the large number of positional coincidences with X-ray sources (from the recent CHANDRA catalog by Grindlay et al. 2001) indeed suggests that part of them could be interacting binaries. In particular, a significant number of X-ray sources ($\sim$ 30%) have been found to be possibly associated with the *faint UVE* population, supporting the existence of a large population of faint cataclysmic variables in the core of this cluster.

4.2. The MSP in NGC6397

Among the collisional by-product zoo, the MSPs are invaluable probes to study cluster dynamics. MSPs are formed 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 GCC 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. In an ultradense stellar environment like the core region of globular clusters dynamical interactions can lead to the formation of several different binary systems, suitable for recycling neutron stars. In this framework, we have started a program specifically devoted to search for optical counterparts to companions of binary MSPs in GGCs, in order to better understand their formation channel.

Up to now, our search for optical counterpart to MSP companion in binary systems in GGCs has been very fruitful: two optical counterpart candidates have been identified in the core of 47 Tuc (see Ferraro et al., 2001a) using deep HST observations in the UV. However, the most surprising result is the identification of the optical counterpart to a MSP companion (COM J1740−5340) in the globular cluster NGC 6397 (Ferraro et al., 2001b, Ferraro et al. 2003).

This system is the first example of a binary MSP in which the optical light curve of the companion shows tidal distortions (see Figure 4), providing strong evidence that the MSP is orbiting a companion whose Roche lobe is completely filled. Such an exotic companion could represent the first detection of a new-born MSP. The discovery of this system, thanks to the unusual brightness of COM J1740−5340 (V$\approx$ 16.6), has also allowed unprecedented detailed spectroscopic observations, thus opening a new unexplored window to the study of MSPs in clusters.

Indeed, this system represents an unique laboratory to study the formation mechanism of the MSP binary formation in GCs. In this contest, we are now coordinating a spectro-photometric programme using the current instrumentation available at ESO in a prompt attempt to shed light on the structure and the true origin of this exotic system (Ferraro et al. 2003, Sabbi et al. 2003). As a final result this project will clarify whether this is a primordial binary or the result of an exchange interaction in the cluster core and it will allow to understand the mechanisms of mass transfer driving both the spin up of a neutron star and the possible evaporation of the companion.

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