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The globular cluster NGC 6528 the ferrous side of the Galactic Bulge

E. P. Lagioia[1], A. P. Milone[2], G. Bono[1,3], P. B. Stetson[4], A. Aparicio[5,6], R. Buonanno[1,7], A. Calamida[8], M. Dall'ora[9], I. Ferraro[3], R. Gilmozzi[10], G. Iannicola[3], N. Matsunaga[11], M. Monelli[4,5], P. G. Prada Moroni[12], and A. Walker[13]

[1] Univ. di Roma Tor Vergata, V. Ricerca Scientifica 1, 00133, Roma, Italy
e-mail: eplagioia@roma2.infn.it
[2] ANU, Cotter Road, Weston, ACT, 2611, Australia, e-mail: milone@mso.anu.edu.au
[3] INAF – OAR, Via Frascati 33, 00040 Monte Porzio Catone, Italy
[4] D.A.O, NRC, 5071 West Saanich Road, Victoria, BC V9E 2E7, Canada
[5] Instituto de Astrofisica de Canarias, E-38200 La Laguna, Tenerife, Canary Islands, Spain
[6] Dept. Astroph., Univ. of La Laguna, 38200 La Laguna, Tenerife, Canary Islands, Spain
[7] INAF – OACTe, via M. Maggini, 64100 Teramo, Italy
[8] Space Telescope Science Institute, 3700 San Martin Dr., Baltimore, MD 21218, USA
[9] INAF – OAC, Salita Moiariello 16, 80131 Napoli, Italy
[10] ESO, Karl-Schwarzschild-Straße 2, 85748, Garching, Germany
[11] The University of Tokyo, 10762-30, Mitake, Kiso-machi, Kiso-gun,3 Nagano 97-0101, Japan
[12] Dip. di Fisica, Università di Pisa, Largo E. Fermi, 56127 Pisa, Italy
[13] CTIO, National Optical Astronomy Observatory, Casilla 603, La Serena, Chile

Abstract. We present new and accurate optical photometry of the Bulge globular cluster NGC 6528. The images were collected with ACS at HST and together with WFC3 (UVIS, IR) allowed us to measure the proper motion to separate cluster and field stars. We adopted two empirical calibrators and we found that NGC 6528 is coeval with and more metal-rich than 47 Tuc. Moreover, it appears older and more metal-poor than the super-metal-rich old open cluster NGC 6791. We also performed a preliminary analysis of field stellar populations located around NGC 6528 and NGC 6522 by using ground-based near-infrared photometry collected with SOFI at NTT. The comparison of evolved stellar components (red giant branch, red horizontal branch, red clump stars) indicates that they share similar properties in this region of the Baade's Window.

Key words. globular clusters: general — globular clusters: individual (NGC 6528, NGC 104, NGC 6791) — stars: evolution

1. Introduction

The Bulge is a complex component of the Galactic spheroid whose stellar content shows a broad range of kinematic and chemical components. Different observational campaigns connected either with microlensing events in the direction of the Galactic center (OGLE, EROS, MACHO, (Udalski et al. 1994; Zhao et al. 1995; Alcock et al. 1995; Aubourg et al. 1993), or with near-infrared (NIR) integrated surface photometry from COBE/DIRBE observations (Dwek et al. 1995), or with star counts from the 2MASS survey (López-Corredoira et al. 2005), have found evidence that the Bulge has a boxy/peanut morphology, with the long axis lying onto the Galactic plane at an angle of $\phi_0 \simeq 20°$ from the Sun-Galactic center direction (Rattenbury et al. 2007; Gerhard 2002). More recent investigations based on resolved stellar populations have also found evidence of a bar by analyzing the (bimodal) distribution of the Red Clump (RC) stars in the NIR color-magnitude diagram (CMD) of some Bulge regions located approximately along the Galactic minor axis at $b < 5°$. McWilliam & Zoccali (2010), Nataf et al. (2010) and Saito et al. (2011) found evidence that RC stars are split into two components separated, on average, by 0.65 mag along the line of sight. McWilliam & Zoccali (2010) argue that such a separation can be associated with an underlying X-shaped structure of the Bulge.

Although the Bulge cannot be considered a single stellar system, the bulk of its stars are mostly old with ages of the order of 10 - 12 Gyr (Clarkson et al. 2008; Sahu et al. 2006; Zoccali et al. 2001) thus suggesting that it is the earliest massive component of Galaxy formed over a short time interval (McWilliam & Zoccali 2010; Meléndez et al. 2008; Zoccali et al. 2003; Ortolani et al. 1995). Recent empirical and theoretical investigations support the working hypothesis that the Bulge, and in particular the inner Bulge, was the first component of the spheroid to be formed and then it served as a nucleus around which the rest of the Galaxy was built. This is the so-called inside-out scenario (Zoccali et al. 2008; Lee 1992). According to this framework, the innermost regions of the stellar halo and of the Bulge were formed by a rapid, dissipative collapse of low-angular momentum material (Eggen et al. 1962). A high-rate of star formation, in the first ~1 Gyr, caused a fast chemical enrichment of the interstellar medium mainly by type II SNe ejecta, as confirmed by the overabundance of α-elements measured in Bulge stars (Zoccali et al. 2006; McWilliam & Rich 1994). More recently, the large spectroscopic survey of the Bulge (ARGOS, Freeman et al. 2013) using RC stars as stellar tracers found that the metal-rich stellar component ([Fe/H] > -0.5) is associated with the boxy Bulge, while the metal-poor one ([Fe/H] < -0.5) is associated with the thick disk. The former component is made of two distinct populations: the metal-poor component ([Fe/H] ≈ -0.25) is uniformly distributed across the selected fields while the metal-rich component ([Fe/H] $\approx$ 0.15) kinematically colder and closer to the plane of the Galaxy. The above components are considered the aftermaths of the instability-driven Bulge formation from the pristine Galactic thin disk (Ness et al. 2013a).

The observation of a radial metallicity gradient in the Bulge (Ness et al. 2013b; Uttenthaler et al. 2012; Zoccali et al. 2008) further support the hypothesis that our Bulge is more a boxy/peanut Bulge than a classical merger-generated Bulge (Ness et al. 2013b; Zoccali et al. 2008). The Bulge GCs clusters play in this context a key role, since they are the relics of the time when the Bulge forming instabilities took place. In the following we briefly discuss the properties of NGC 6528 and four typical Baade's Window regions located around NGC 6528 and NGC 6522.

2. Optical CMD of the globular NGC 6528

One common approach to determine the properties of the Bulge is to study the Bulge globular clusters (GCs), since this sub-system share many dynamical and evolutionary features with the stellar population(s) of the Bulge itself (Valenti et al. 2010, 2007; Ortolani et al. 1995). Among the most studied Bulge GCs there are those located in the Baades Window, namely NGC 6522 and NGC 6528. These two clusters are projected on the same sky area and appear partially overlapping according to recent estimates of their tidal radii (Harris 1996, as updated in 2010). NGC 6528 is an interesting cluster, since it is among the most metal-rich GCs. High-resolution spectroscopy, suggest for this cluster a solar metallicity and a modest α-element enhancement. Carretta et al. (2001) found [Fe/H] = +0.07 ± 0.01 and a marginal α-element enhancement ([α/Fe] $\simeq$ +0.1 ± 0.2), while Zoccali et al. (2004), by using three giants belonging to Horizontal Branch (HB) and to the Red Giant Branch (RGB), found [Fe/H] = −0.1 ± 0.2 and [α/Fe] $\simeq$ +0.1 ± 0.1. In a more recent investigation based on high-resolution NIR spectra Origlia et al. (2005) found [Fe/H] = −0.17 ± 0.01 and a higher α-element enhancement [α/Fe] $\simeq$ +0.33 ± 0.01. According to these results NGC 6528 is an ideal laboratory not only to constrain the α-element enhancement in old metal-rich systems, but also to shed new lights on the possible occurrence of an age-metallicity relation among the most metal-rich GCs (Dotter et al. 2011; Rakos & Schombert 2005). The estimate of both structural parameters and intrinsic properties for NGC 6528 have been partially hampered by the occurrence of differential reddening across the field of view and by the high level of stellar crowding due to field stars. The former problem can be overcome by using NIR bands, the latter one is more complex. The use of optical-NIR color-color planes to separate field and cluster stars (Calamida et al. 2009; Bono et al. 2010) is hampered by the fact that the metallicity distributions of Bulge, thin disk and NGC 6528 stars peak around solar chemical composition. Furthermore, the use of the color-color plane require precise and deep photometry in at least three optical-NIR bands. These are among the main reasons why current estimates of the absolute age of NGC 6528 range from 13 ± 2 Gyr (Ortolani et al. 2001) to 11 ± 2 Gyr (Feltzing & Johnson 2002), to 12.6 Gyr (Momany et al. 2003). The optical and NIR CMDs of NGC 6528 presented below come from space- and ground-based data obtained, respectively, with *HST* and with SOFI images. In particular, the first dataset consists of two groups of images collected eight years apart, between June 2002 and June 2010: the first is composed of optical ACS/WFC images in the filters $F606W$ and $F814W$; the second comprises optical and NIR images taken, respectively, with UVIS ($F390W, F555W, F814W$) and IR ($F110W, F160W$) channel of the WFC3. The temporal baseline of the *HST* dataset allowed us to compute the star proper motions in the NGC 6528 central region corresponding to the ACS Field of View (FoV) and to split, by means of a pure kinematic selection bona-fide cluster members from field stars (Lagioia 2014). The *HST* photometry was, eventually, corrected for differential reddening using the procedure described in Milone et al. (2012). The ground-based dataset is composed of NIR (J and K_S) images, proprietary data, collected with the SOFI camera at the New Technology Telescope of ESO at La Silla, Chile. The pointings cover two FoVs partially overlapping and slightly shifted in the South-West direction with respect to the center of the cluster. Each pointing is roughly $5' \times 5'$ wide.

In order to fix the main properties of NGC 6528 we compared its CMD with that of two metal-rich template clusters used as empirical calibrators, namely 47 Tuc (NGC 104, $t \approx 11$ Gyr, [Fe/H] = −0.8; VandenBerg et al. 2010; Carretta et al. 2009) and NGC 6791 ($t \approx 8$ Gyr, [Fe/H] = +0.3; Brasseur et al. 2010; Boesgaard et al. 2009). For 47 Tuc accurate ACS/WFC photometry is already available ($F606W, F814W$; 47 Tuc, Calamida et al. 2012, Anderson et al. 2008); for NGC 6791 we derived photometry in F606W and F814W by means of the same procedure used for NGC 6528 (see Anderson et al. 2008). In the upper panels of Fig. 1 are shown the CMDs of these two empirical calibrators (47 Tuc at left and NGC 6791 at right), in ACS/WFC optical bands $F606W, F814W$. For both of them we estimated the ridge line (dashed line) and determined the magnitude and color of Red HB in 47 Tuc (RHB, red circle) and of RC stars in NGC 6791 (blue circle) and of the RGB Bump in 47 Tuc (green circle). The Bump was not identified in NGC 6791, since it is younger than typical globulars, and therefore with a limited number of stars along the RGB. The bottom panels of Fig. 1 show the CMD of the candidate cluster stars for NGC 6528 in the same bands of the calibrating clusters. The bottom left panel shows the comparison with the ridge line, the RHB and the RGB Bump of 47 Tuc scaled to NGC 6528 using the true distance modulus and the reddening labeled in the figure. The comparison indicates that NGC 6528 seems more metal-rich than 47 Tuc. In fact the entire MS of the former is systematically bluer than of the latter. Moreover, the RGB in NGC 6528 has a shallower slope than the RGB of 47 Tuc and both the RHB and the RGB bump of 47 Tuc are brighter and bluer than those in NGC 6528. These finding support the evidence that the difference between the two clusters is mainly in chemical composition rather than in age. The comparison between NGC 6528 and NGC 6791 (bottom right panel) indicates that the former cluster is less metal-rich than the latter. The difference between the two depends on both chemical composition and age because the ridge line of NGC 6791 becomes, for magnitudes fainter than $F814W \sim 21$, systematically redder than MS stars in NGC 6528. Moreover, the ridge line of NGC 6791 attains colors in the TO region that are systematically brighter than main sequence turn-off (MSTO) stars in NGC 6528 and the shape and the extent in color of the sub-giant branch region in NGC 6791 is narrower ($F606W - F814W \sim 0.85$ *vs* $F606W - F814W \sim 1.2$) compared to NGC 6528.

3. NIR CMD of four Baade's Window fields

The ground based NIR images of NGC 6528 collected with SOFI at NTT are affected by extreme crowding in the center of the cluster. We also collected homogeneous NIR photometry of three other fields located in the Baade's Window. The PSF photometry of the four fields was homogeneously performed (see Lagioia 2012). Fig. 2 displays the NIR (K_S, $J - K_S$) CMDs of all the four pointings. The CMD of the fields centered on NGC 6528 and on NGC 6522 are plotted, respectively, in the bottom-left and in the top-right panel. Note that in these CMDs we only plotted stars located outside a circle of $3'$ from the cluster center. This means that the above CMDs are dominated by field stars, since the half mass radius of the two quoted clusters are 0.38 arcmin (NGC 6528) and 1 (NGC 6522) arcmin (Harris 1996), respectively. The 'field 1' (top-left) is located slightly North-West of NGC 6528, in the outskirts of the tidal radius of NGC 6528 and NGC 6522 [1], while the 'field 2' (bottom-right) is located southward of NGC 6522 center, in the outer part of its tidal radius.

Data plotted in the four panels show well-defined RGBs, but current photometry do not allow us to perform an accurate estimate of the MSTO position. Note that the sky area covered by the fields located around the two GCs are similar, while the sky areas of 'field 1' and 'field 2' are ~ 2.5 times smaller. We adopted as a reference sequence the CMD of the field located around NGC 6522. A glance at the CMD of this field shows a well-defined concentration of stars ranging from $K_S \simeq 13$ to $K_S \simeq 14$ mag and $J - K_S \simeq 0.95$ mag. This stellar overdensity is a mix between Red HB (RHB), typical of an old stellar population (fainter, $t \gtrsim 10$ Gyr) and RC, typical of an intermediate-age stellar population (brighter, $1 \lesssim t < 10$ Gyr). This means that we are dealing with the typical stellar populations of the Galactic Bulge (Saito et al. 2011; McWilliam & Zoccali 2010; Ortolani et al. 2001).

We estimated the fiducial line of the 'field NGC 6522' RGB and an upper limit to the magnitude of the RHB+RC stars. They are plotted in the four panels of the same figure as a red line and a black square. The mean reddening in the four fields is quite similar, but the 'field 1' for which we applied a shift in color of -0.03 mag in color. The comparison with the 'field NGC 6528' shows a large spread in color along the RGB and in the upper main sequence. Thus suggesting that stars located in this region might be affected either by differential reddening or by a spread in metal abundance or both. On the other hand, the comparison with the 'field 1' and 'field 2' CMDs indicates that field stellar populations are quite similar. This applies not only to RGB and RHB+RC stars, but also to the blue main sequence stars located between $K_s \sim 13$ and $K_s \sim 16$ mag and $J - K_s \sim 0.3$ - 0.6 mag, i.e. the tracer of the Galactic thin disc ($t \gtrsim 8$ Gyr;

[1] The tidal radii of NGC 6528 and NGC 6522 are: 16.57 and 16.44 arcmin (Harris 1996).

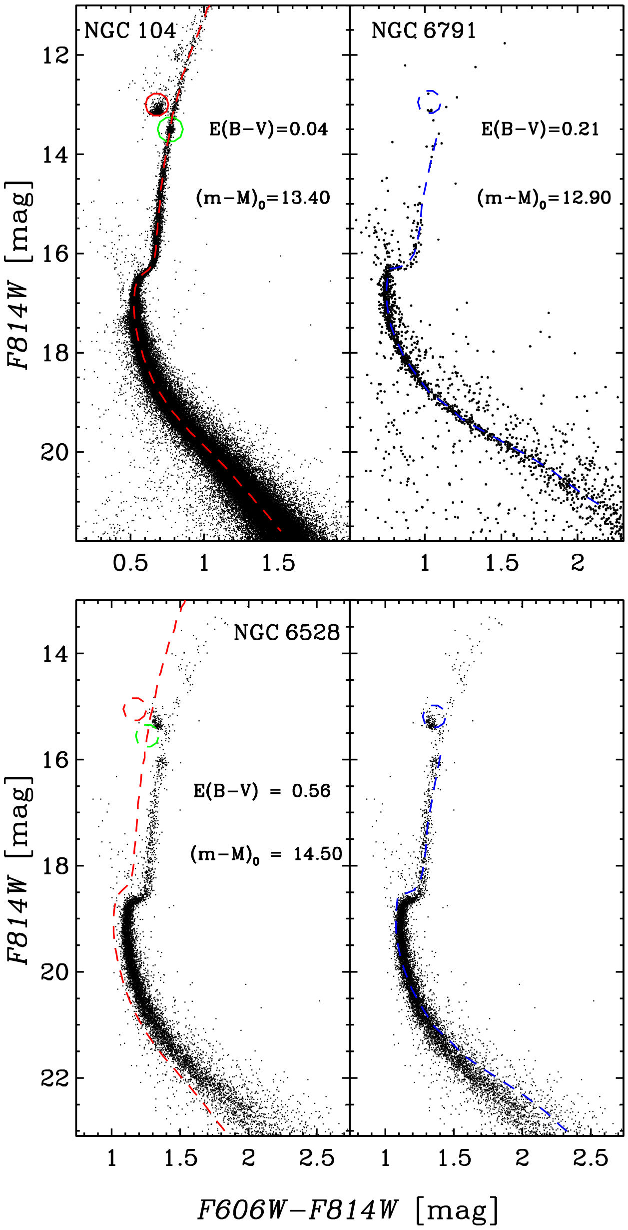

Fig. 1. Top-left: *F*814*W*, *F*606*W* − *F*814*W* CMD of 47 Tuc based on ACS/WFC@HST data. The red and green circles mark, respectively, the RHB and the RGB bump, while the dashed line represent the cluster ridgeline. Top-right: Same as the left, but for the old, metal-rich cluster NGC 6791. The blue circle marks the position of red clump stars. Bottom: Comparison between the *F*814*W*, *F*606*W* − *F*814*W* CMD of NGC 6528, and the ridgelines of 47 Tuc (left) and NGC 6791 (right). The CMD of NGC 6528 contains only stars that, on the basis of our proper motion selection, are cluster members and is corrected for differential reddening. The adopted true distance modulus and reddening (Harris 1996) are also labeled in each panel.

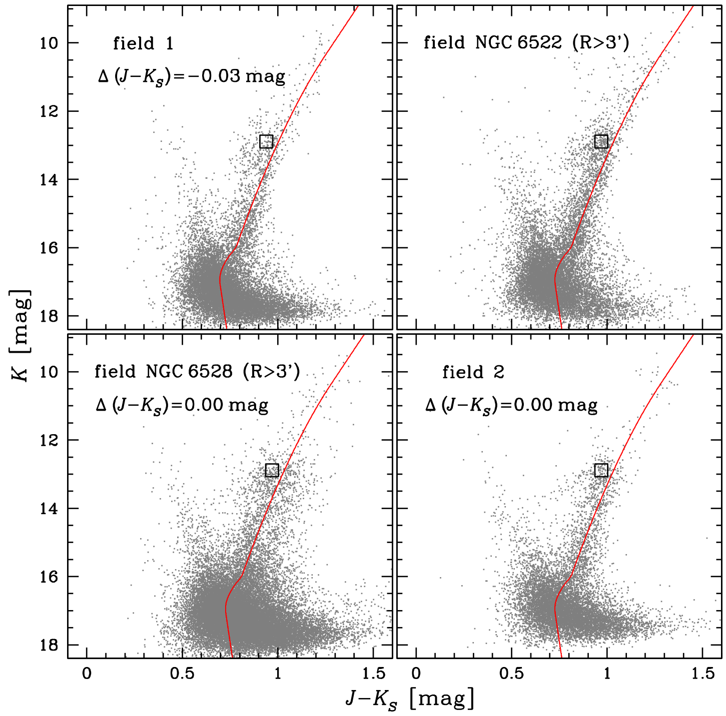

Fig. 2. K_S, $J - K_S$ CMDs of four Bulge fields: NGC 6528, 1, 2 and NGC 6522 (see text for more details). The fiducial (red solid) line of the Bulge sample of the 'field NGC 6522' and the relative RHB+RC position (empty black square) is overplotted on the CMD of the other fields. To account for the difference in mean reddening the ridge line in the top left panel was shifted in color by −0.03 mag.

Calamida et al. 2011; McWilliam & Zoccali 2010).

Our analysis further supports the evidence that high-accuracy deep photometry is not enough for a comprehensive study of stellar populations in the low-reddening regions of the Bulge. The complementary use of other diagnostics (radial velocities, proper motions, spectroscopic determination of iron content) is mandatory to overcome the severe degeneracy (age-metallicity-reddening) of the CMDs.

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