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# Terzan 5: the relic of a primordial fragment of the Galactic Bulge

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**Abstract.** Using the Multi-Conjugate Adaptive Optics demonstrator MAD at the VLT, we recently obtained exceptionally high quality near-IR images of Terzan 5, a stellar system in the Galactic Bulge commonly catalogued as a globular cluster. The MAD ($K$, $J-K$) color-magnitude diagram has revealed the existence of two horizontal branches (HBs) well separated in magnitude and colour. A prompt spectroscopic follow-up with NIRSPEC@Keck has shown that the two populations have significantly different iron content ([Fe/H]= $-0.2$ and $+0.3$ for the faint and the bright HB, respectively). This is the first time that a stellar system with different iron content is found in the Bulge. Additional evidences indicate that the two populations may have significantly different ages and that the system was more massive in the past. Such a discovery opens a new perspective into our understanding of the Bulge formation: Terzan 5 could be the relic of one of the primordial building blocks which are thought to merge and form galaxy bulges.

**Key words.** Stars: abundances – Globular clusters: individual (Terzan 5)— Stars: evolution – Stars: Population II – Galaxy: globular clusters – Galaxy: abundances

## 1. Introduction

Globular clusters (GCs) are compact and massive stellar systems old enough to have witnessed the entire history of our Galaxy. Increasing evidences of multiple evolutionary sequences and a significant spread in the abundance patterns of a few light-elements (as Na, O, Al, etc) have been recently collected (see references in Piotto 2009 and Carretta et al. 2010), thus suggesting that GC formation may have been more complex than previously thought. However, the striking homogeneity of the iron content within most GCs indicates that their stellar populations formed over a relatively short time-scale (less than 1 Gyr). The only clear exception known to date (Norris & Da Costa 1995; Sollima et al. 2005, Ferraro et al. 2004) is $\omega$ Centauri in the Galactic Halo. This system is widely thought to be the remnant of a disrupted dwarf galaxy which has been accreted by the Milky Way, and it is therefore considered to be a crucial palimpsest for a deep understanding of the formation and evolutionary history of our galaxy. Similar findings in the Bulge have been always hampered by the severe reddening conditions of this region of the Galaxy. Recently, however, we have discovered that a system similar to $\omega$ Centauri also orbits the Bulge (Ferraro et al. 2009, herefater F09): Terzan 5 (Ter 5), which was commonly catalogued as

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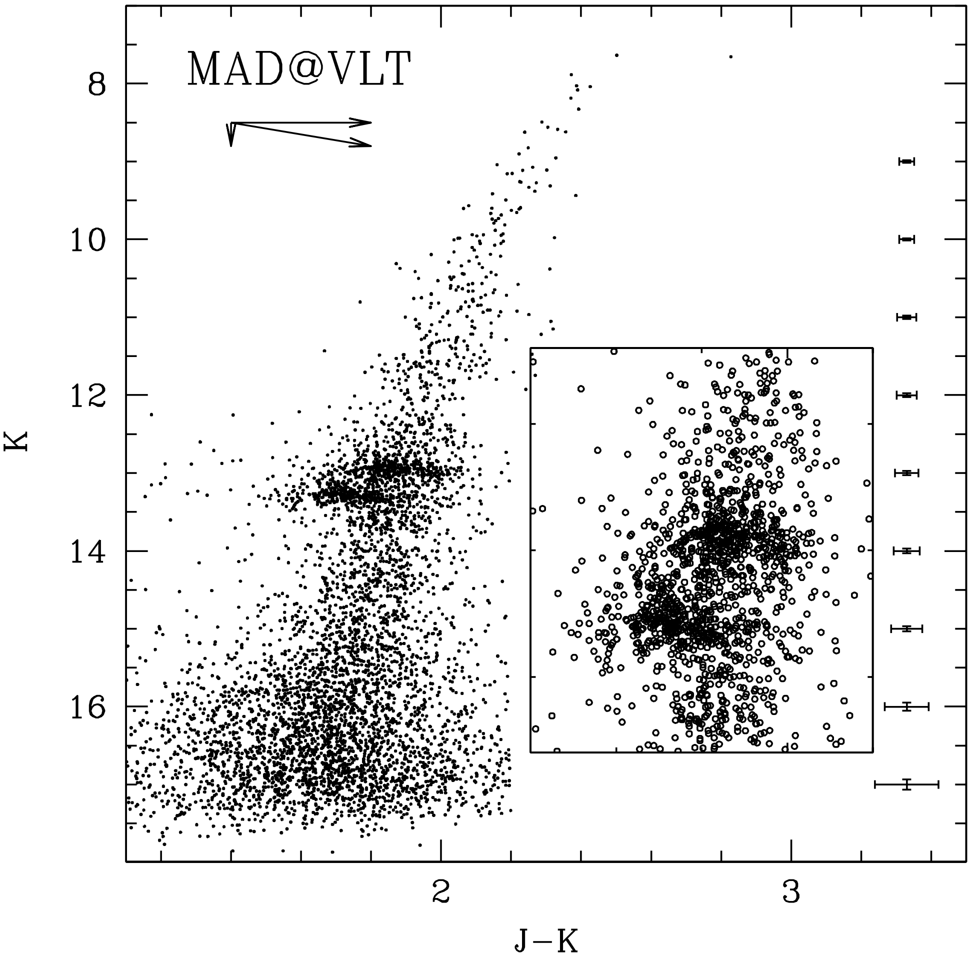


**Fig. 1.** MAD ($K$, $J-K$) CMD of the central ($1' \times 1'$) region of Ter 5. The inset show a zoom in the HB region with the two HB clumps clearly visible. The reddening vector is also plotted.

a globular cluster (GC), contains instead two stellar populations with different iron contents and (probably) ages. Indeed it might represent the observational proof that even the innermost part of galactic spheroids may form from the accretion/merging of small pre-formed and internally-evolved stellar systems. Here we describe the main findings about this puzzling stellar system obtained in the last months, and the overall scenario that is emerging (from F09 and Lanzoni et al. 2010).

## 2. The discovery

Ter 5 is commonly catalogued as a globular cluster (GC) located in the inner Bulge of our Galaxy. It is difficult to observe because of the heavy differential reddening along its line of sight (the average color excess is $E(B-V) = 2.38$; Ortolani et al. 1996; Barbuy et al. 1998; Valenti et al. 2007). Ter 5 has an exceptionally large population of millisecond pulsars (MSPs): indeed, its 33 MSPs amount to about 25% of the en-

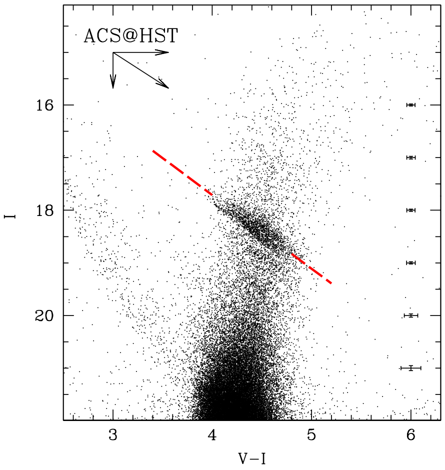


**Fig. 2.** ACS ($I$, $V - I$) CMD of Ter 5. Error bars (1 s.e.m) are plotted at different magnitude levels. The reddening vector and a dashed line parallel to it are also plotted.

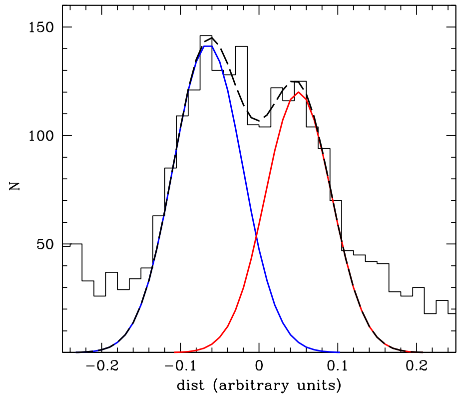


**Fig. 3.** Distribution of the geometrical distances of HB stars from the dashed line marked in Fig.2. Two well-defined peaks corresponding to the bHB and the fHB are clearly visible and nicely reproduced by two Gaussians (in red and blue, respectively; the black dashed line is the combination of the two Gaussian distributions).

tire sample of known MSPs in Galactic GCs (Ransom et al. 2005; see the updated list at `www.naic.edu/~pfreire/GCpsr.html`).

As part of a project (Ferraro et al. 2001a,b, 2003; Cocozza et al. 2008) aimed at studying the properties of stellar populations harbouring MSPs, we obtained a set of high-resolution images of Ter 5 in the $K$ and $J$ bands using the multi-conjugate adaptive optics (AO) demonstrator MAD (Marchetti et al. 2007) temporarily installed at the ESO-VLT. A small subset of these images was obtained with an exceptionally good and uniform AO correction: the measured FWHM in the $K$ images is $\approx 0.1''$ over the entire $1' \times 1'$ field of view (FoV). The exceptional sharpness and uniformity of the images allowed us to obtain a superb ($K$, $J - K$) colour-magnitude diagram (CMD) even for the very central region of the cluster, leading to a surprising discovery (F09). *We have detected two well-defined red horizontal branch (HB) clumps, clearly separated in luminosity*: a bright HB (bHB) at $K = 12.85$ and a faint HB (fHB) at $K = 13.15$, the latter having a bluer ($J - K$) colour (see Fig.1).

The existence of a double HB is also confirmed by the ($I$, $V - I$) CMD obtained from optical ACS/HST observations (Fig.2), in spite of the strong differential reddening which highly distorts all the evolutionary sequences. Although being stretched along the direction of the reddening vector, two HB clumps of Ter 5 are still distinguishable (also see Fig.3). A vague indication of this double clump was already visible also in the ($J$, $J - H$) CMD obtained from HST/NICMOS observations by Cohn et al. (2002, see their Fig.4), although their shorter wavelength baseline did not allow such a clear separation of the two clumps.

From number counts, proper motion and radial distribution studies we exclude any significant contamination of the HB samples from the Galactic field stars. In particular, while field stars are expected to be almost uniformly distributed over the MAD FoV, the radial distribution of the stars belonging to both the HB clumps is inconsistent with a uniform distribution at more than $5\sigma$ level (Fig.4). Furthermore, the radial distributions of the two HB populations are also different: the bHB population is significantly (at $> 3.5\sigma$ level) more centrally concentrated than the fHB one. This is further confirmed by the ACS data (Fig.5), which also indicate that the

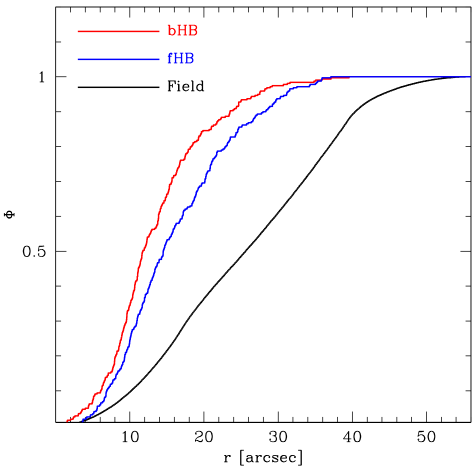


**Fig. 4.** Cumulative radial distribution of the observed bHB stars (red line) and the fHB population (blue line), compared to that of field stars (solid black line), as a function of the projected distance from the cluster centre of gravity. The field distribution has been obtained from a synthetic sample of 100,000 points uniformly distributed in X and Y over the MAD field of view.

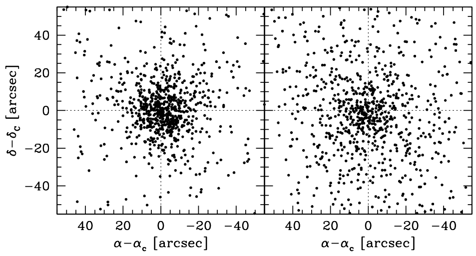


**Fig. 5.** Map of the bright (*left panel*) and faint (*right panel*) HB populations selected from the ACS dataset on the basis of the star position in the ($I$, $V-I$) CMD. The star coordinates ($\alpha$ and $\delta$) are plotted with respect to those of the cluster gravity centre ($\alpha_c$ = 17$^h$ 48$^m$ 4.85$^s$, $\delta_c$ = −24° 46′ 44.6″; Lanzoni et al. 2010).

barycentres of the two HB populations could be slightly different, with the fHB centre being located ≈ 3″ south-east from that of the bHB stars, which almost coincides with the cluster gravity centre. We stress however that, while the optical selection allowed us to improve the statistics and increase the radial coverage of the samples at most, it does not guarantee a proper separation of the two groups of stars. Hence, before confirming such a finding it is necessary to perform a more robust and clean selection of the two HB populations, based on (currently not available) near-IR data covering a much larger area than the MAD FoV.

Since theoretical models predict that the HB level gets brighter in the $K$ band for increasing metallicity (e.g., Pietrinferni et al. 2004), a combination of different metallicities (and possibly ages), with the bHB population being more metal-rich (and younger) than the fainter one, could in principle reproduce the split in $K$-luminosity observed for the two HB clumps. In order to verify this possibility, we promptly secured medium-resolution near-IR spectra of 6 HB stars (3 in each clump) with NIRSPEC at the Keck Telescope. We found that indeed the iron content of the stars in the two clumps differs by a factor of 3 (∼ 0.5 dex): the fHB stars have [Fe/H]= −0.2, while the bHB stars have [Fe/H]= +0.3 (Fig.6). Note that *Ter 5 is the first GC-like system showing a spread in the iron content ever discovered in the Galactic Bulge.* From the measured spectra we also derived the stellar radial velocities and found an average value of −85 km/s ($\sigma$ = 9 km/s) and −85 km/s ($\sigma$ = 10 km/s) for the fHB and bHB stars, respectively (the typical uncertainty on the individual measure is of the order of 3 km/s). These values are fully consistent with the previous measurements (Origlia & Rich 2004; Harris 1996), thus confirming that the HB stars for which we have secured spectra are cluster members, and suggests that there is no significant kinematical difference between the two populations.

With this information in hand we further investigated the possibility that Ter 5 harbours stellar populations with different ages. For this reason we have performed a preliminary differential reddening correction (A. Mucciarelli 2010, in preparation) on the optical ACS catalogue and combined it with the near-infrared data, thus obtaining the ($K$, $V-K$) CMD shown in Fig.7. The presence of two distinct populations with a double HB and (possibly) two separate red giant branches (RGBs) can be seen

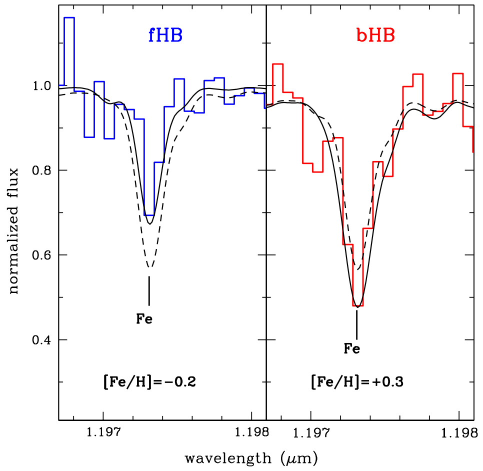


**Fig. 6.** Combined J-band spectra near the 1.1973 $\mu$m iron line for three fHB (left) and three bHB (right) stars, as obtained with NIRSPEC at Keck II (coloured lines). The measured equivalent widths of the lines and suitable spectral synthesis yield iron abundances [Fe/H]= $-0.2 \pm 0.1$ and [Fe/H]= $+0.3 \pm 0.1$, respectively. The black solid lines correspond to the best-fit synthetic spectra obtained for temperatures and gravities derived from evolutionary models reproducing the observed colours of the horizontal branch stars: Teff = 5000 K and log g = 2.5 for the fHB stars, Teff = 4500 K and log g = 2.0 for the bHB stars. For sake of comparison, we also plot (as black dashed lines) the synthetic spectra obtained by adopting the same atmospheric parameters, but [Fe/H]= +0.3 for the fHB and [Fe/H]= −0.2 for the bHB.

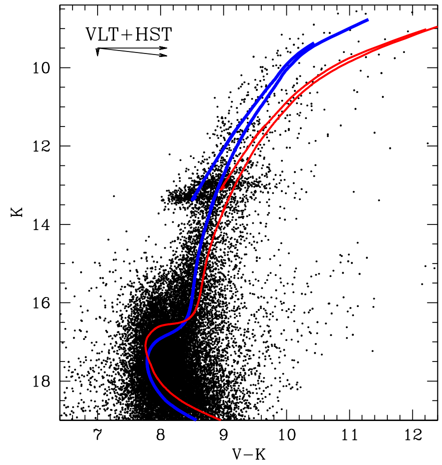


**Fig. 7.** ($K$, $V-K$) CMD of Ter 5 obtained by combining VLT-MAD and HST-ACS data preliminary corrected for differential reddening. Two isochrones with [Fe/H]= −0.2 (heavy element mass fraction Z=0.01, and helium mass fraction Y=0.26) and $t$ = 12 Gyr (blue line), and with [Fe/H]= +0.3 (Z=0.03, Y=0.29) and $t$ = 6 Gyr (red line) are overplotted to the data by adopting a colour excess $E(B-V) = 2.38 \pm 0.05$ and a distance d = $5.9 \pm 0.5$ kpc.

in this CMD. The RGB of the most metal-rich population appears to be more bent (as expected, because of the line blanketing due to a higher metal content). As shown in the figure, two isochrones characterized by the observed metallicities and two different ages ($t$ = 12 Gyr for the fHB and $t$ = 6 Gyr for the bHB) well reproduce not only the luminosity difference of the two HB levels, but also the locations of the RGB stars. On the other hand, D'Antona et al. (2010) suggested that the two clump levels can be also reproduced by two populations with the observed metallicities, a negligible difference in age (just $\sim$ 100 Myr) and a difference $\delta Y \sim 0.07$ in the helium abundance. While a different helium content can certainly contribute to mitigate the age gap between the two populations, a precise age estimate can be derived only from deep IR observations able to properly measure the main-sequence turn-off level, and, for the moment, these scenarios should be regarded as the two possible extremes.

In any case, these evidences suggest that *Ter 5 is not a genuine GC, but rather a stellar system with a much more troubled star formation history.*

## 3. Star density profile and structural parameters

To get deeper insights into the nature of this puzzling stellar system, we have determined its projected density profile using direct star counts on the available datasets. For the innermost part of the profile we have exploited the high-resolution (MAD and ACS) datasets, while for $r > 100''$ we have used the WFI sample and complementary data from the 2MASS survey, thus covering radial distances out to $r = 1700''$. To avoid incompleteness biases, different limiting magnitudes have been adopted for the four datasets: $K = 13$, $I = 20$, $I = 19$, and $K = 12.5$ for the MAD, ACS, WFI, and 2MASS samples, respectively. By also adopting the colour cuts $(V - I) > 3.4$ and $(J - K) > 1.3$ we have excluded from the analysis the contribution of the stars belonging to the Galactic disk main sequence. With these limits we have computed the four portions of the density profile corresponding to each dataset. By following the procedure described in Ferraro et al. (1999), we have then obtained the overall projected density profile shown in Fig.8 (empty squares). The outermost ($r \gtrsim 175''$) measures from the WFI and 2MASS samples have an almost constant value, and their average has been used to estimate the Galactic Bulge and Disk contamination level. The subtraction of this background yields the profile shown in the figure as filled dots. This is well fit all over its radial extension by an isotropic, single-mass King model (King 1966) with core radius $r_c = 9.0''$, half-mass radius $r_h = 31''$, tidal radius radius $r_t = 277'' = 4.6'$, and intermediate concentration ($c = 1.49$). While the size of the core radius is consistent with the most recent determination ($r_c = 7.9''$; Cohn et al. 2002), the concentration is significantly smaller than that ($c \approx 2$) suggested by those authors, and the ratio between the core and the half-mass radius is a factor of two larger in our case.

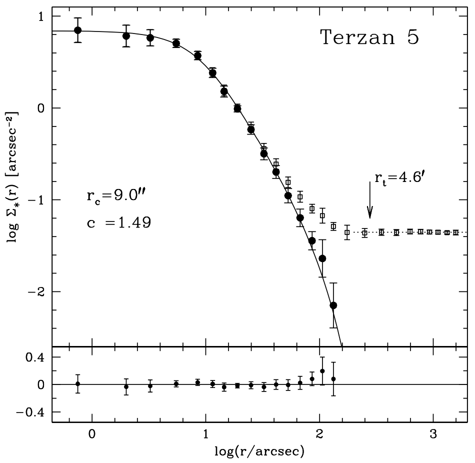


**Fig. 8.** Newly determined star density profile of Ter 5, obtained from resolved star counts in the combined (MAD, ACS, WFI and 2MASS) photometric dataset. Empty squares represent the observed profile, while solid dots are obtained after subtraction of the field background density (marked with the dotted line). The best-fit single-mass King model is shown as a solid line and the corresponding structural parameters (core radius $r_c$, concentration $c$ and tidal radius $r_t$) are labelled in the figure. The lower panel shows the residuals between the observations and the fitted profile at each radial coordinate.

## 4. The current mass of Terzan 5

The star density profile can be used to derive the integrated luminosity of the cluster. From the best-fit King model we estimate that the percentage of total cluster light contained within regions of radius $r = 15''$, $18''$, and $20''$ are roughly 30%, 36% and 40%, respectively. Using aperture photometry on the MAD images, we obtain integrated-light values of $K(r < 15'') = 3.44$, $K(r < 18'') = 3.3$ and $K(r < 20'') = 3.2$ mag, respectively. Adopting the color excess $E(B - V) = 2.38$, the distance modulus $(m-M)_0 = 13.87$ (Valenti et al. 2007, corresponding to a distance of $d = 5.9 \pm 0.5$ kpc) and the bolometric correction $BC_K = 2.4$ appropriate for a population of intrinsic color $(J - K)_0 = 0.8$ (Montegriffo et al. 1998), we estimate that the corresponding bolometric luminosity in the considered regions is: $L_{\rm bol}(r < 15'') = 3 \times 10^5 L_\odot$, $L_{\rm bol}(r < 18'') = 3.4 \times 10^5 L_\odot$ and $L_{\rm bol}(r < 20'') = 3.7 \times 10^5 L_\odot$. Considering the fraction of light sampled in each region we find that the total luminosity of the system is $L_{\rm bol} = 9.5 \pm 0.3 \times 10^5 L_\odot$.

An independent estimate of this value can be derived by using a simple relation (Renzini & Buzzoni 1986) linking the number of stars ($N_j$) observed in a given post-main sequence evolutionary stage $j$ and the luminosity of the entire parent cluster ($L_T$): $N_j = B \times t_j \times L_T$, where $B$ is the specific evolutionary flux (for intermediate/old stellar populations $B = 2 \times 10^{-11}$ stars yr$^{-1} L_\odot^{-1}$) and $t_j$ is the duration of the evolutionary stage.

The number of HB stars counted in the two clumps by F09 is quite large: a total of about 1300 (with 800 and 500 belonging to the fHB and the bHB, respectively). This population is comparable to (or even larger than) that observed in the largest Galactic GCs, like 47 Tucanae (Beccari et al. 2006a) and NGC 6388 (Dalessandro et al. 2008), thus suggesting that the overall size of Ter 5 (in terms of luminosity and mass) is comparable to that of these systems. For a quantitative estimate, we insert the observed number of HB stars in the above relation and adopt $t_{\rm HB} = 10^8$ yr. This provides a luminosity of $4\times10^5 L_\odot$ and $2.5\times10^5 L_\odot$ for the two parent populations, and a total luminosity of $6.5\times10^5 L_\odot$ for the entire stellar system. This estimate, which is distance and reddening independent, is quite consistent with the previous one, thus confirming that Ter 5 has a considerable total luminosity (hereafter we adopt the average value $L_{\rm bol} = 8\times10^5 L_\odot$), significantly higher than previously thought. By comparison, adopting the values of distance and reddening quoted above and a bolometric correction $L_{\rm bol} \simeq 1.4\,L_V$, the total bolometric luminosity corresponding to the integrated magnitude ($V_t = 13.85$) quoted by Harris (1996) would be only $L_{\rm bol} \simeq 10^5 L_\odot$. The discrepancy is most probably due to the strong (differential) reddening affecting the system, especially in the optical bands. This effect is greatly reduced for our new estimate, since it is based on the observed $K$-band integrated magnitude and the number of HB stars. By assuming a mass-to-light ratio $M/L_{\rm bol} = 3$ (e.g., Maraston 1998), the total stellar mass of this system is $M_{\rm T} \simeq 2\times10^6 M_\odot$.

Verbunt & Hut (1987) first suggested that the collision rate ($\Gamma$) of Ter 5 is the highest among the Galactic GCs. We can now recompute $\Gamma \propto \rho_0 \times r_c^{0.5}$, with $\rho_0$ being the central mass density (Verbunt & Hut 1987), by adopting the newly determined parameters and using equation (7) of Djorgovski (1993). We find that the collision parameter of Ter 5 is between 5 and 10 times higher than that of Liller 1 and of other massive clusters for which structural parameters have been recently re-determined (NGC6388, NGC6266, 47Tuc; Dalessandro et al. 2008; Beccari et al. 2006b; Mapelli et al. 2006, respectively). Hence we confirm that, even with the new structural parameters (suggesting a lower concentration and a larger mass than previously thought), Ter 5 still has the largest known collision rate of any stellar aggregate in the Galaxy.

## 5. Conclusions

The co-existence of two stellar populations with different iron content (and probably ages) suggests that the original mass of Ter 5 was significantly larger in the past than observed today, large enough to retain the iron-enriched gas that, otherwise, would have been ejected out from the system by the violent supernova (SN) explosions. Indeed, the smallest systems with solid evidences of a spread in the iron content (and ages) are significantly more massive than GCs: the dwarf spheroidal satellites of the Milky Way typically have masses of $\sim 10^7 M_\odot$ (Strigari et al. 2008; see also Battaglia et al. 2008) and, following recent chemo-dynamical models well reproducing the observations, their initial masses amounted to a few $10^8 M_\odot$ (Revaz et al. 2009).

The exceptionally high metallicity regime of the two stellar populations found in Ter 5 also suggests a quite efficient enrichment process, that could have a relevant role in the origin of its population of MSPs. In particular, both the iron and the [$\alpha$/Fe] abundance ratios measured in Ter 5 (Origlia & Rich 2004, Rich et al. 2010, in preparation) show a remarkable similarity with those of the Bulge stars. *This strongly suggests that Ter 5 and the Galactic Bulge shared the same star formation and chemical enrichment processes.* The many observations of Bulge stars (e.g., Meléndez et al. 2008; Origlia et al. 2008; Ryde et al. 2009, and references therein) indicate that they are all characterized by an old age, a high (close to solar) average metallicity [Fe/H], and an [$\alpha$/Fe] ratio which is enhanced (due to SNII enrichment)[1] up to a metallicity [Fe/H]$\simeq$ 0. These

[1] The [$\alpha$/Fe]–[Fe/H] relation shows a down-turn at a value of [Fe/H] which depends on the star formation rate: the higher the latter, the higher the metallicity at which the down-turn occurs. Such a

constraints suggest a scenario where the dominant stellar population of the Bulge formed early (thus explaining the old age), rapidly and with high efficiency from a gas mainly enriched by SNII (thus explaining the [$\alpha$/Fe] enhancement up to high iron contents). Also chemical evolution models (e.g., Ballero et al. 2007; McWilliam et al. 2008) indicate that the abundance patterns observed in the Bulge require a quite high star formation efficiency and an initial mass function flatter than that in the solar neighbourhood, thus to rapidly enrich the gas up to about solar metallicity through an exceptionally large amount of SNII explosions.

The assumption of a similar scenario for Ter 5 would naturally explain its extraordinary population of MSPs, since the expected high number of SNII would produce a large population of neutron stars, most of which would have been retained by the deep potential well of the massive proto-Ter 5 system. Then the high collision rate could have favoured the formation of binary systems containing neutron stars and promoted the re-cycling process that finally generated the large population of MSPs now observed in Ter 5. If such a scenario is correct, many more MSPs still wait to be discovered in this system (see also Ransom et al. 2005), the 33 known objects probably being just the tip of the iceberg. Future deeper pulsar searches of Ter 5, perhaps with larger telescopes such as the Square Kilometer Array, will shed additional light on the nature of this system.

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value is [Fe/H]$\simeq -1$ in the Old Halo/Disk, while it is significantly higher ([Fe/H]$\simeq$ 0) in the Bulge, testifying a much higher star formation rate in this dense environment.

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