The true nature of Terzan 5: the most efficient "furnace" of MSPs in the Galaxy

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Abstract. Terzan 5 is the globular cluster (GC)-like stellar system harboring the largest known population of MSPs. Using the Multi-Conjugate Adaptive Optics demonstrator MAD at the ESO-VLT, we recently obtained a superb \((K, J - K)\) color-magnitude diagram, which has revealed the existence of two horizontal branches (HBs) well separated in magnitude and colour (Ferraro et al. 2009, Nature, 462, 483). A prompt spectroscopic follow-up with NIRSPEC@Keck has shown that the two populations have (1) significantly different iron content \((\text{[Fe/H]} = -0.2 \text{ and } +0.3\) for the faint and the bright HB, respectively), (2) distinct \([\alpha/\text{Fe}]\) abundance patterns and (3) no evidence of the Al-O anti-correlation commonly observed in GCs. All these properties suggest that Ter 5 is far from being a genuine globular. Instead it has experienced the explosion of a huge number of supernovae (SNe), thus accounting for its high metal content and it should have been much more massive in the past than today, thus to retain the SN ejecta within its potential well. The many type II SNe should have also produced a large number of neutron stars (NSs), which could finally explain its exceptionally large population of MSPs.

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Terzan 5 (hereafter Ter 5) was discovered in 1968 and, since then, it was cataloged as a common Globular Cluster (GC) in the Galactic Bulge. While it was early indicated as the GC with the highest collision rate in the Galaxy [1], the astonishing discovery of 31 millisecond pulsars (MSPs) [2] has recently renewed the interest toward this stellar system. The updated list (see http://www.naic.edu/~pfreire/GCpsr.html) now counts 34 such objects, corresponding to 25% of the entire sample of known MSPs in GCs; indeed the MSP population of Ter 5 is the largest ever found in any GCs!

Within a project aimed at studying the properties of GCs harboring MSPs, a few years ago our group started a systematic search of optical companions to MSP in binary systems [3]. This search has led to important results, since 4 (out of the 7) known MSP companions in GCs (see Fig. 1) have been discovered by our group. Within this search, Ter 5 was, of course, one of the top-priority target, and in fact it was the subject of a deep photometric investigation. In particular, our latest survey led to a surprising discovery. Despite the severe extinction \((E(B - V) = 2.4; [4])\) affecting this system, thanks to near-IR observations performed with the Multi-conjugate Adaptive Optics Demonstrator (MAD) at the ESO-VLT, we have obtained a superb \((K, J - K)\) color-magnitude diagram (CMD) even for the very central region of the cluster. This allowed us to reveal the presence of two well-defined red horizontal branch (HB) clumps, clearly separated in luminosity [5]: a bright HB (bHB) at \(K = 12.85\), and a faint HB (fHB) at \(K = 13.15\), the latter having a bluer color (see Fig.2a). Since theoretical models [6] predict that
FIGURE 1. Location in the \((M_U, (U-V)_0)\) plane of the optical companions \((filled squares)\) to binary MSPs detected so far in GCs: COM47TucU and COM47TucW in 47 Tucanae ([20, 21]); COM6397A in NGC6397 [22]; COM6752A in NGC6752 [23]; COM-M4 in M4 [24], COM6266B in NGC6266 [25] and COM−M28H recently discovered in M28 by [26]. The He-WDs \((dashed lines)\) and CO-WD \((solid lines)\) cooling tracks and Main Sequence stars \((small empty circles)\) are plotted for reference.

the HB level gets brighter in the K-band for increasing metallicity, a combination of different metallicities (with the bHB population being more metal-rich than the fHB) could in principle reproduce the observed feature. Prompt medium-resolution, near-IR spectra (acquired with NIRSPEC at the Keck Telescope) have indeed confirmed that the iron content of the stars in the two clumps differs by a factor of 3 (~0.5 dex): the fHB stars have \([\text{Fe/H}]=-0.2\), while the bHB stars have \([\text{Fe/H}]=+0.3\) (Fig.2b). Note that Ter 5 is the first GC-like system ever discovered in the Galactic bulge with a clear iron spread. However, such a different iron content alone, cannot account for the observed split in luminosity of the two HB clumps. Instead, two populations characterized by the measured iron abundances and two different ages \(t=12\) Gyr for the fHB, and \(t=6\) Gyr for the bHB) well reproduce both the luminosity of the two HB clumps and the location of the red giant branches (RGBs). Note that a much smaller age gap is needed if the younger population is enhanced in Helium [10].

Additional high-resolution spectra of a sample of RGB stars [11] confirmed the striking difference in the iron content of the two populations. Moreover, we found indications of distinct \([\alpha/\text{Fe}]\) abundance patterns and no evidence of the Al-O anti-correlation commonly observed in GCs. These chemical properties suggest that Ter 5 is not a genuine GC. Indeed, the co-existence of two stellar populations with different iron content (and probably ages) indicates 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

\[\text{[1]}\] The only other known globular-like stellar system with a significant spread in iron abundance (in a much lower metallicity regime) and multiple stellar populations is \(\omega\) Centauri in the galactic Halo (see [7, 9, 8])
FIGURE 2. Left panel – VLT-MAD (K,J-K) CMD of the central (1′ × 1′) region of Ter 5, with the two HB clumps marked with red arrows. The reddening vector is also plotted. Right panel – Combined spectra near the 1.1973 micron iron line for three fHB (left) and three bHB (right) stars, as obtained with NIRSPEC at Keck II. The measured equivalent widths of the lines and suitable spectral synthesis yield [Fe/H] ≃ −0.2 ± 0.1 and [Fe/H] ≃ +0.3 ± 0.1 iron abundances, respectively.

(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 $\sim 10^7 M_\odot$ [12] with initial masses possibly amounting to a few $10^8 M_\odot$ [13].

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 [11] 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 [14, 15] 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) up to a metallicity [Fe/H] ≃ 0. These 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 [16] 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.

2 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 value is [Fe/H] ≃ −1 in the Old Halo/Disk, while it is significantly higher ([Fe/H] ≃ 0) in the Bulge, testifying a much higher star formation rate in this dense environment.
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 (NSs), most of which would have been retained by the deep potential well of the massive proto-Ter 5 system. Then, the large collision rate of Ter 5 [1, 17] could have favored the formation of binary systems containing NSs and promoted the re-cycling process that finally generated the large population of MSPs we observe today. If such a scenario is correct, many more MSPs still wait to be discovered in this system, and the 34 known objects probably are just the tip of the iceberg. This is also supported by recent high-energy observations with the Fermi Space Telescope that discovered GeV $\gamma$-ray emission from Ter 5 [18] and 47 Tuc [19]. The $\gamma$-ray luminosity attributed to MSPs indicates that Ter 5 may host a factor of 5-20 more MSPs (depending on the actual cluster distance) than 47 Tuc (counting 23 such objects). 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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