THE TERZAN 5 PUZZLE: DISCOVERY OF A THIRD, METAL-POOR COMPONENT

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ABSTRACT

We report on the discovery of three metal-poor giant stars in Terzan 5, a complex stellar system in the Galactic bulge, known to have two populations at [Fe/H] = −0.25 and +0.3. For these three stars we present new echelle spectra obtained with NIRSPEC at Keck II, which confirm their radial velocity membership and provide an average [Fe/H] = −0.79 dex iron abundance and [α/Fe] = +0.36 dex enhancement. This new population extends the metallicity range of Terzan 5 to 0.5 dex more metal poor, and it has properties consistent with having formed from a gas polluted by core-collapse supernovae.

Key words: Galaxy: abundances – Galaxy: bulge – infrared: stars – stars: abundances – stars: late-type – techniques: spectroscopic

1. INTRODUCTION

Terzan 5 is a complex stellar system in the Galactic bulge. It suffers from huge extinction, its average color excess being E(B − V) = 2.38 (Barbuy et al. 1998; Valenti et al. 2007), and it is also affected by significant differential reddening (ΔE(B − V) ≃ 0.7 mag; Massari et al. 2013). For years, it has been classified as a globular cluster, although soon after its discovery its true nature was already under dispute (see, e.g., King 1972).

Recent high-resolution imaging in the near infrared (NIR) obtained with the Multi-conjugate Adaptive Optics Demonstrator (MAD) at the European Southern Observatory Very Large Telescope (ESO-VLT), revealed the presence of two distinct red clumps that cannot be explained by differential reddening or distance effects (Ferraro et al. 2009). Prompt NIR spectroscopy with NIRSPEC at Keck II demonstrated that the two stellar populations are characterized by very different iron abundances ([Fe/H] = −0.2 and +0.3). Subsequent spectroscopic studies of 33 red giant stars (Origlia et al. 2011) fully confirmed the large metallicity difference between the two populations. The sub-solar component has [Fe/H] = −0.25 ± 0.07 rms and it is α-enhanced, similar to the old bulge population that likely formed at early epochs from a gas enriched by a huge amount of Type II supernovae (SNe II). The super-solar component, which is possibly a few gigayears younger, has [Fe/H] = +0.27 ± 0.04 and an approximately solar [α/Fe] abundance ratio, indicating that it should have originated from a gas polluted by both SNe II and Ia on a longer timescale. Both components show a small internal metallicity spread and the most metal-rich population is also more centrally concentrated (Ferraro et al. 2009; Lanzoni et al. 2010). These observational facts could be accounted for by a proto-Terzan 5 that was more massive in the past than today (its current mass being 2 ∼ 106 M⊙; Lanzoni et al. 2010), which possibly experienced at least two relatively short episodes of star formation with a time delay of a few gigayears.

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There is an interesting chemical similarity between Terzan 5 and the bulge stellar population, which shows a metallicity distribution with two major peaks at sub-solar and super-solar [Fe/H] and a third, minor component with significantly lower ([Fe/H] ≃ −1.0) metallicity (see, e.g., Zoccali et al. 2008; Hill et al. 2011; Johnson et al. 2011; Rich et al. 2012; Utenthaler et al. 2012; Ness et al. 2013a, 2013b, and references therein). These bulge stellar populations show [α/Fe] enhancement up to about solar [Fe/H], and then a progressive decline toward solar values at super-solar [Fe/H]. Such a trend is at variance with both that observed in the thick disk, where the knee occurs at significantly lower values of [Fe/H], and with the rather flat distribution of the thin disk with approximately solar [α/Fe]. Chemical abundances of bulge dwarf stars from microlensing experiments (see, e.g., Cohen et al. 2010; Bensby et al. 2013, and references therein), also suggest the presence of two populations, an old sub-solar one with [α/Fe] enhancement, and a possibly younger, more metal-rich one with decreasing [α/Fe] enhancement with increasing [Fe/H].

This Letter presents the discovery of three red giant stars belonging to Terzan 5, with metallicities far below the sub-solar component observed thus far.

2. OBSERVATIONS AND CHEMICAL ABUNDANCE ANALYSIS

In the context of an ongoing spectroscopic survey with VLT-FLAMES and Keck-DEIMOS of the Terzan 5 stellar populations, aimed at constructing a massive database of radial velocities and metallicities (D. Massari et al. in preparation; F. R. Ferraro et al. in preparation), we found some indications of the presence of a minor (∼3%) component significantly more metal-poor than the sub-solar population of Terzan 5. We acquired high resolution spectra of three radial velocity candidate metal-poor giant stars, members of Terzan 5. Observations using NIRSPEC (McLean et al. 1998) at Keck II were undertaken on 2013 June 17. We used the NIRSPEC-5 setting to enable observations in the H-band and a 0.′43 slit width that provided an overall spectral resolution of R = 25,000.

Data reduction was performed by using the REDSPEC IDL-based package developed at the UCLA IR Laboratory. Each spectrum was sky subtracted by using nod pairs, corrected
Figure 1. Portion of the NIRSPEC $H$-band spectra of two red giants of Terzan 5 with similar temperatures ($T_{\text{eff}} \approx 3800$ K), but different chemical abundance patterns (solid line for the metal-poor star 243, dotted line for a sub-solar star at $[\text{Fe}/\text{H}] \approx -0.22$ from Origlia et al. 2011). The metal-poor giant 243 has significantly shallower features. A few atomic lines and molecular bands of interest are noted.

3. RESULTS

Our provisional estimate for the systemic velocity of Terzan 5, as inferred from our VLT-FLAMES and Keck-DEIMOS survey, is $-82$ km s$^{-1}$ with a velocity dispersion of $\approx 15$ km s$^{-1}$.

From the NIRSPEC spectra we first measured the radial velocity of the three stars under study and confirmed values within $\approx 1\sigma$ from the systemic velocity of Terzan 5 (see Table 1). These stars are located in the central region of Terzan 5, at distances between 13$''$ and 71$''$ from the center (see Table 1). Our VLT-FLAMES and Keck-DEIMOS survey shows that in this central region, the contamination by field stars with similar radial velocities and metallicity is negligible (well below 1%). Preliminary analysis of proper motions also indicates that these stars are likely members of Terzan 5.
We then measured the chemical abundances of iron, \(\alpha\)-elements, carbon, and aluminum. Our best-fit estimates of the stellar temperature and gravity, radial velocity, and chemical abundances with 1\(\sigma\) random errors are listed in Table 1. In the evaluation of the overall error budget, we also estimated that systematics due to \(\Delta T_{\text{eff}} \approx 200\) K, \(\Delta \log g \pm 0.5\) dex, and \(\Delta V \pm 0.5\) km s\(^{-1}\) variations in the adopted stellar parameters can affect the inferred abundances by \(\approx \pm 0.15\) dex. However, the derived abundance ratios are less dependent on the systematic error, since most of the spectral features used to measure abundance ratios have similar trends when varying the stellar parameters, and at least some degeneracy between abundance and the latter is canceled out.

We find the average iron abundance \([\text{Fe/H}] = -0.79 \pm 0.04\) rms to be significantly lower (by a factor of \(\sim 3\)) than the value of the sub-solar population \([\text{Fe/H}] = -0.25\), pointing toward the presence of a distinct population in Terzan 5, rather than to the low metallicity tail of the sub-solar component.

As shown in Figure 2, our newly discovered metal-poor population has an average \(\alpha\)-enhancement (\([\alpha/\text{Fe}] = +0.36 \pm 0.04\) rms) similar to that of the sub-solar one, indicating that both populations likely formed early and on short timescales from a gas polluted by SNe II.

Like the stars belonging to the sub-solar component, these other giants with low iron content also show an enhanced \([\alpha/\text{Fe}]\) abundance ratio (average \([\alpha/\text{Fe}] = +0.41 \pm 0.18\) rms) and no evidence of Al–Mg and Al–O anti-correlations, and/or large \([\text{O/Fe}]\) and \([\text{Al/Fe}]\) scatters, although no firm conclusion can be drawn with only three stars.

We also measured some \([\text{C/Fe}]\) depletion (at least in stars 243 and 262), as commonly found in giant stars and explained by mixing processes in the stellar interiors during the evolution along the RGB.

4. DISCUSSION AND CONCLUSIONS

New spectroscopic observations of three stars, members of Terzan 5, have provided a further evidence of the complex nature of this stellar system and of its likely connection with formation and evolution history of the bulge.

We find that Terzan 5 hosts a third, more metal-poor population with an average \([\text{Fe/H}] = -0.79 \pm 0.04\) rms and \([\alpha/\text{Fe}]\) enhancement. From our VLT-FLAMES/Keck-DEIMOS survey, we estimate that this component represents a minor fraction (a few percent) of the stellar populations in Terzan 5.

Notably, a similar fraction (\(\approx 5\%\)) of metal-poor stars (\([\text{Fe/H}] \approx -1\)) has also been detected in the bulge (see, e.g., Ness et al. 2013a, 2013b, and references therein). This metal-poor population shows a kinematics typical of a slowly rotating spheroidal or a metal weak thick disk component.

Our discovery significantly enlarges the metallicity range covered by Terzan 5, which amounts to \(\Delta [\text{Fe/H}] \approx 1\) dex. Such a value is completely unexpected and unobserved in genuine globular clusters. Indeed, within the Galaxy, only another globular-like system, namely \(\omega\) Centauri, harbors stellar populations with a large (>1 dex) spread in iron (Norris & Da Costa 1995; Sollima et al. 2005; Johnson & Pilachowski 2010; Pancino et al. 2011). This evidence strongly sets Terzan 5 and \(\omega\) Centauri apart from the class of genuine globular clusters, and suggests a more complex formation and evolutionary history for these two multi-iron systems.

It is also interesting to note that detailed spectroscopic screening recently performed in \(\omega\) Centauri revealed an additional sub-component significantly more metal-poor (by \(\Delta [\text{Fe/H}] \sim 0.3–0.4\) dex) than the dominant population (Pancino et al. 2011). The authors suggested that this is best accounted for in a self-enrichment scenario, where these stars could be the remnants of the first stellar generation in \(\omega\) Centauri.

### Table 1

| No. | R.A. (2000) | Decl. (2000) | \(T_{\text{eff}}\) | \(\log g\) | \(v_r^a\) | \(\rho^b\) | \[Fe/H\] | \[O/Fe\] | \[Si/Fe\] | \[Mg/Fe\] | \[Ca/Fe\] | \[Ti/Fe\] | \[Al/Fe\] | \[C/Fe\] |
|-----|------------|-------------|-----------------|----------|--------|--------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| 243 | 267.0088362 | -24.7951362 | 3800            | 1.0      | -74    | 71     | -0.78       | +0.36        | +0.53        | +0.30        | +0.38        | +0.35        | +0.24        | -0.12       |
| 262 | 267.0210698 | -24.7755223 | 4000            | 1.0      | -64    | 13     | -0.83       | +0.26        | +0.22        | +0.46        | +0.39        | +0.31        | +0.39        | -0.47       |
| 284 | 267.0194897 | -24.7724098 | 3800            | 0.5      | -92    | 24     | -0.75       | +0.25        | +0.44        | +0.33        | +0.36        | +0.55        | +0.60        | -0.05       |

Notes:

\(^a\) Heliocentric radial velocity in km s\(^{-1}\).

\(^b\) Radial distance from the center of Terzan 5 in arcseconds.
The three populations of Terzan 5 may also be explained by some self-enrichment. The narrow peaks in their metallicity distribution could be the result of quite bursty star formation activity in the proto-Terzan 5, which should have been much more massive in the past to retain the SN ejecta and progressively enrich its gas in metals. However, Terzan 5 might also be the result of an early merging of fragments with sub-solar metallicity at the epoch of the bulge/bar formation, and with younger and more metal-rich sub-structures following subsequent interactions with the central disk.

However, apart from the similarity in terms of large iron range and possible self-enrichment, ω Centauri and Terzan 5 likely had quite different origins and evolution. It is now commonly accepted that ω Centauri may be the remnant of a dwarf galaxy accreted from outside the Milky Way (e.g., Bekki & Freeman 2003). At variance, the much higher metallicity of Terzan 5 and its chemical similarity to the bulge populations suggests some symbiotic evolution between these two stellar systems.

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