SPECTROSCOPY UNVEILS THE COMPLEX NATURE OF TERZAN 5

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ABSTRACT

We present the chemical abundance analysis of 33 red giant stars belonging to the complex stellar system Terzan 5. We confirm the discovery of two stellar populations with distinct iron abundances: a relatively metal-poor component with [Fe/H] = −0.25 ± 0.07 rms and another component with [Fe/H] = +0.27 ± 0.04 rms, exceeding in metallicity any known Galactic globular cluster (GC). The two populations also show different [α/Fe] abundance ratios. The metal-poor component has an average [α/Fe] = +0.34 ± 0.06 rms, consistent with the canonical scenario for rapid enrichment by core collapse supernovae (SNe). The metal-rich component has [α/Fe] = +0.03 ± 0.04 rms, suggesting that the gas from which it formed was polluted by both type II and type Ia SNe on a longer timescale. Neither of the two populations shows evidence of the [Al/Fe] over [O/Fe] anti-correlation that is typically observed in Galactic GCs. Because these chemical abundance patterns are unique, we propose that Terzan 5 is not a true GC, but a stellar system with a much more complex history of star formation and chemical enrichment.

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

Online-only material: machine-readable table

1. INTRODUCTION

Terzan 5 is commonly cataloged as a globular cluster (GC) located in the inner bulge of our Galaxy. It is heavily reddened, with an average color excess E(B − V) = 2.38 (Barbuy et al. 1998; Valenti et al. 2007) and such a reddening strongly depends on the line of sight (Ortolani et al. 1996; Valenti et al. 2007). This stellar system also harbors an exceptionally large population of millisecond pulsars (MSPs): indeed, the 34 MSPs detected so far in Terzan 5 amount to ~25% of the entire sample of known MSPs in Galactic GCs (Ransom et al. 2005). Recently, a combined photometric and spectroscopic study of Terzan 5 has led to the discovery of two distinct populations, as traced by two well-separated (δK ≈ 0.3) red clumps in the (K, J − K) color–magnitude diagram (CMD), with a ≈ 0.5 dex difference in their iron content (Ferraro et al. 2009, hereafter F09). A conventional isochrone fit is consistent with the two populations of Terzan 5 being separated by a few Gyr (F09), although only a small age gap is needed if the younger population is enhanced in helium (D’Antona et al. 2010).

The findings in F09 appear to be best understood if Terzan 5 was much more massive in the past than today, in order to retain the supernova (SN) ejecta and igniting other star formation episodes. A more massive proto-Terzan 5 would also naturally explain its large population of MSPs and the fact that the metal-rich component is more centrally concentrated than the metal-poor one (F09; see also Lanzoni et al. 2010), a typical feature of stellar systems which are self-enriched in iron, as, e.g., the dwarf galaxies.

With the aim of accurately reconstructing the puzzle of the formation and evolutionary history of Terzan 5, we are currently undertaking a global study of the photometric, chemical, and kinematic properties of its stellar populations. This Letter presents the results of the spectroscopic screening of a suitable sample of giant stars in order to obtain chemical abundances and abundance patterns of key metals, like iron, carbon, aluminum, oxygen, and other α-elements, and constrain the complex chemical enrichment history of Terzan 5.

2. OBSERVATIONS AND ABUNDANCE ANALYSIS

In order to select suitable targets, we used the differential-reddening-corrected optical–IR CMD of Terzan 5 shown in Figure 4 of F09. In this diagram it is possible to recognize not only two red clumps, but also two main red giant branches (RGBs). We therefore selected a sample of red giants mostly located along the two RGBs and spanning the entire luminosity range above the horizontal branch level, with the purpose of fully characterizing their chemical content. High-resolution spectra have been acquired on 2010 July 1–2 by using NIRSPEC (McLean et al. 1998) at Keck II. A slit width of 0.43, giving an overall spectral resolution R = 25,000, and the standard NIRSPEC-5 setting, which covers a large fraction of the 1.5–1.8 μm H band, have been used.

About 40 stars have been observed during the run. Here, we report and discuss the results for 33 giants having radial velocities consistent with the systemic velocity of Terzan 5 (see, e.g., Harris 1996; Origlia & Rich 2004; Ferraro et al. 2009), i.e., likely members of the system.

The raw spectra have been reduced using the REDSPEC IDL-based package written at the UCLA IR Laboratory. Each order...
Table 1
Stellar Parameters and Abundances for the Sample of Observed Giants in Terzan 5

| No. | R.A.     | Decl. | Teff | log g | v_teff | [Fe/H] | [O/Fe] | [Si/Fe] | [Mg/Fe] | [Ca/Fe] | [Ti/Fe] | [Al/Fe] | [C/Fe] |
|-----|----------|-------|------|-------|--------|--------|--------|--------|--------|--------|--------|--------|-------|
| 1   | 267.0182526 | −24.7787234 | 3400  | 0.5   | −85    | 0.18 ± 0.05 | −0.06 ± 0.10 | −0.03 ± 0.16 | 0.12 ± 0.14 | 0.05 ± 0.09 | 0.02 ± 0.14 | 0.12 ± 0.17 | −0.28 ± 0.09 |
| 2   | 267.0176110 | −24.7777213 | 3600  | 0.5   | −101   | 0.32 ± 0.05 | −0.04 ± 0.08 | −0.02 ± 0.16 | 0.08 ± 0.13 | −0.05 ± 0.08 | 0.08 ± 0.13 | 0.27 ± 0.17 | −0.52 ± 0.09 |

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

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

3. RESULTS AND DISCUSSION

By the inspection of the iron abundance distribution (see Table 1), the existence of two populations is clearly evident: a relatively metal-poor component (as traced by 20 giants in our sample) with average [Fe/H] = −0.25 ± 0.07 rms, and a metal-rich component (as traced by 13 giants in our sample) with average [Fe/H] = +0.27 ± 0.04 rms. The two populations therefore show a ∆[Fe/H] ≈ 0.5 dex iron abundance difference, fully confirming first results from F09 based on the observations of a small sample of red clump stars.

Figure 2 shows the various [α/Fe] abundance ratios for the giants observed in Terzan 5 and in other Galactic stellar populations, for comparison. The computed average abundance ratios for the two Terzan 5 components are listed in Table 2. We find an overall average [α/H] ≈ +0.09 and [α/Fe] ≈ +0.34 for the metal-poor, and [α/H] ≈ +0.30 and [α/Fe] ≈ +0.03 for the metal-rich stars. Hence, the two populations show a ∆[α/H] ≈ +0.2 dex and a ∆[α/Fe] ≈ −0.31 differences.

The first important result of this study is that the two populations in Terzan 5 have clearly distinct abundance patterns, the most metal-rich being significantly enriched in iron and moderately enriched in [α/H], with respect to the metal-poor one. These properties have never been observed before in any discussion). More stringent constraints on the stellar parameters have been obtained by the simultaneous spectral fitting of several CO and OH molecular bands, which are very sensitive to temperature, gravity, and microturbulence variations (see Figures 6 and 7 in Origlia et al. 2002). The final values of the adopted stellar parameters, radial velocity, and our best-fit chemical abundances with 1σ random errors are listed in Table 1. We conservatively estimate that the systematic errors in the derived best-fit abundances, due to the residual uncertainty in the adopted stellar parameters, are ≈ ±0.1 dex. However, it must be noted that any variation in the stellar parameters makes all the spectral features under consideration vary in a similar way (although with different sensitivities). Hence, the derived relative abundances are less dependent on the adopted stellar parameters, i.e., they are affected by smaller systematic errors.

Figure 1 Portion of the NIRSPEC H-band spectra of two red giants of Terzan 5 with similar Teff ≈ 3800 K, but different chemical abundance patterns (solid line for the metal-poor star, dotted line for the metal-rich one). A few atomic lines and molecular bands of interest are marked.
Galactic GC. In fact, all GCs are characterized by an extremely high homogeneity in the iron abundance. The only notable exception (but in a significantly lower metallicity regime) is the halo globular-like system ω Centauri (Norris & Da Costa 1995; Sollima et al. 2005; Johnson & Pilachowski 2010), which is, for this reason, currently believed to be the remnant of an accreted and partially disrupted dwarf galaxy (Bekki & Freeman 2003). Indeed, observational evidence of tidal debris from ω Centauri already exist (see, e.g., Wylie-de Boer et al. 2010, and references therein).

The overall iron abundance and the [α/Fe] enhancement of the Terzan 5 metal-poor component is consistent with what is measured in bulge stars (see Figure 2). This suggests that, as the bulk of the bulge population, this component in Terzan 5 likely formed from a gas mainly enriched by type II SNe on a short timescale. When compared to the metal-poor component, the larger [α/H] overall abundance of the metal-rich one can be explained with an additional enrichment by type II SNe, whose ejecta must have been retained within the potential well in spite of the violent explosions. Moreover, the Solar [α/Fe] abundance ratio indicates that its progenitor gas was also polluted by type Ia SNe explosions on longer timescales. Among GC-like stellar systems, such a signature of type Ia SNe enrichment has been observed only in the most metal-rich population of ω Centauri (see, e.g., Pancino et al. 2002; Origlia et al. 2003; Johnson & Pilachowski 2010).

Figure 2 also shows the [Al/Fe] versus [Fe/H] abundance distribution, indicating that Aluminum behaves like α-elements. Figure 3 shows the [Al/Fe] versus [O/Fe] abundance ratios. As a whole, the stars of Terzan 5 display a clear positive correlation between [Al/Fe] and [O/Fe], at variance with the anti-correlation shown by ordinary GCs. In fact, it is well known that even genuine, single-metallicity GCs show large (up to ∼1 dex) star-to-star variations in the abundance of light elements (like Na, O, Mg, and Al) that are not observed in the Galactic field stars, nor in the field of nearby dwarf galaxies (see, e.g., Carretta et al. 2010c). In particular, [Na/Fe] and [Al/Fe] abundances are seen to anti-correlate with [O/Fe] in all GCs that have been surveyed till the present day, both in the Galaxy and beyond (see Letarte et al. 2006; Carretta et al. 2009; Mucciarelli et al. 2009, and references therein). This chemical fingerprint is so specific to GCs that it has been proposed as the benchmark to classify a stellar system as a GC (Carretta et al. 2010a). Yet, neither the population as a whole nor the two sub-components of Terzan 5 show the Al–O anti-correlation. Moreover, each of the two populations shows spreads (∼0.1 dex) in both [O/Fe] and [Al/Fe] not exceeding the 1σ measurement errors (see Table 2), again at odds with the relatively large (several tenths of dex) cosmic spreads measured in GCs of any metallicity (Gratton et al. 2004).

Hence, a second important result from our study is that Terzan 5 experienced a chemical enrichment history which is...
different from the path typically leading to the development of the Al–O anti-correlation and the presence of multiple stellar populations in GCs (see also D’Ercole et al. 2008, 2010). In this respect, it is also interesting to note that the stars in ω Centauri, while sharing with Terzan 5 a significant spread in iron, clearly exhibit anti-correlation signatures, both as a whole, and within each metallicity sub-group, the only possible exception being the most metal-rich stars (Johnson & Pilachowski 2010). This may suggest that the chemical enrichment history of Terzan 5 differs also from the one of ω Centauri.

Finally, Tables 1 and 2 show that [C/Fe] is depleted with respect to the Solar value in both populations. Such a carbon depletion is commonly measured in the bulge giants (see, e.g., Rich et al. 2007; Origlia et al. 2008) and it indicates that some extra-mixing processes are at work during the evolution along the RGB even at metallicities close to Solar.

4. CONCLUSIONS

The main observational evidences from the photometric and spectroscopic studies performed so far on Terzan 5 can be summarized as follows.

1. Terzan 5 shows at least two stellar populations (as traced by both red clump and RGB stars) with distinct iron content and [α/Fe] abundance patterns. The metal-poor population ([Fe/H] ≃ −0.2) is α-enhanced and closely resembles the bulk of the old bulge population (except for the extremely small spread in iron), which formed early and quickly from a gas mainly polluted by type II SNe. The metal-rich population has a metallicity ([Fe/H] ≃ +0.3), and an approximately scaled Solar [α/Fe] ratio, requiring a progenitor gas further polluted by both type II and type Ia SNe on a longer timescale. It is difficult to place the chemistry of Terzan 5 within the framework of known GCs. Indeed, while no genuine Galactic GC displays such a large difference in the iron content, and even remotely resembles the metallicity regime of the two stellar populations of Terzan 5, stars with similar iron content have been observed in the bulge field (see Rich et al. 2007; Fulbright et al. 2007; Zoccali et al. 2008).

2. Neither Terzan 5 as a whole nor the two populations separately show evidence of the Al–O anti-correlation. As soon as the anti-correlation is also effective at Solar metallicity and above, this further suggests that Terzan 5 as a whole is not a genuine GC, and also that it cannot be the merging of two globulars.

3. Its current mass of a few $10^6$ M$_\odot$ (Lanzoni et al. 2010) is not sufficient to retain the SN ejecta and the large population of neutron stars which, thanks to an exceptionally high stellar collision rate (Verbunt & Hut 1987; Lanzoni et al. 2010), could have been recycled into the multitude of MSPs that we observe today.

In order to draw more firm conclusions about the origin of Terzan 5 and its possible bimodal nature it is necessary to (1) complete the chemical screening of its populations, by also sampling stars that, in the CMD, are located between the two main RGBs, (2) perform and analyze ultra-deep IR imaging to accurately measure the luminosity of the main sequence turn-off point(s) and derive the ages of each component, and (3) combine radial velocity and proper motion measurements to properly determine the kinematics of the system. However, considering the information available so far, we venture the following speculations.

The complex stellar population of Terzan 5 and the higher central concentration of the most metal-rich component (see F09; Lanzoni et al. 2010) could be naturally explained within a self-enrichment scenario. An originally more massive proto-Terzan experienced the explosions of a large number of type II and type Ia SNe, whose ejecta have been retained within the potential well and which could also have wiped out the anti-correlation signatures typical of GCs. In such a scenario, the Terzan 5 evolution should have been characterized by two main and relatively short episodes of star formation, thus accounting for the small metallicity spread of both populations.

In addition, the striking chemical similarity between Terzan 5 and the bulge population can also suggest a strong evolutionary link between these two stellar systems and possibly a common origin and evolution. The current view (Kormendy & Kennicutt 2004; Immeli et al. 2004; Shen et al. 2010) for the formation of a bulge structure suggests a range of physical processes that can be grouped in two main scenarios: (1) rapid formation occurring at early epochs (as a fast dissipative collapse, mergers of proto-clouds/sub-structures, evaporation of a proto-disk, etc.), generating a spheroidal bulge populated by old stars, and (2) evolution of a central disk/bar and its possible interaction with other sub-structures on a longer timescale. Within this framework, Terzan 5 might well be the relic of a larger sub-structure that lost most of its stars, probably because of strong dynamical interactions with other similar systems at the early epoch of the Galaxy formation, and/or later on with the central disk/bar. While most of the early fragments dissolved/merged together to form the bulge, for some (still unclear) reasons Terzan 5 survived the total disruption. Note that within this scenario, while the oldest population of Terzan 5 would trace the early stages of the bulge formation, the younger one could

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7 However, note that while the most metal-rich GC where anti-correlations have been searched and found is NGC 6388 at [Fe/H] ≃ −0.4 (Carretta et al. 2009), both the populations of Terzan 5 lie in a metallicity range which has no direct counterpart among Galactic GCs.
contain crucial information on its more recent chemical and dynamical evolution. The metal-rich sub-component of Terzan 5 stands as a remarkable stellar population, worthy of more study.

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