NMSU ASTRONOMY CUME 361, April 2011 **Jon Holtzman**

Read the paper "Spectroscopy Unveils the Complex Nature of Terzan 5", by Origlia et al. ApJL 726, L20 (2011).

I expect a passing grade will be 70-75 percent.

1 solar mass = 2×10^{33} gm. 1 pc = 3.086×10^{18} cm

1. (22 points) The paper suggests that Terzan 5 is a relic of a larger system.
   (a) (2) What is the main reason that the authors come to this conclusion?
   (b) (8) Quantitatively demonstrate whether you would expect a globular cluster to be able to retain elements produced in supernovae.
   (c) (2) One possibility is that Terzan 5 has been tidally stripped of material. Are there any other examples of systems you know of around the Milky Way that show evidence of disruption?
   (d) (10) Imagine you have a dwarf galaxy companion to the Milky Way that has a mass of 10^8 solar masses with a half-mass radius of 1 kpc. Estimate how close it would need to come to the center of the Milky Way to be significantly tidally stripped.
2. (20 points) Abundances
   (a) (3) Quantitatively define what the equivalent width of a line is.
   (b) (3) When the paper discusses deriving abundances, it talks about deriving photospheric parameters. What are the main photospheric parameters they are talking about (there are usually three, with two very important ones) that affect the equivalent width of lines? Why do the photospheric parameters need to be determined to measure abundances?
   (c) (2) What other photospheric parameters might affect the shape/width of the lines (but not the equivalent width)?
   (d) (3) What is the standard explanation for why the α/Fe ratio is enhanced in globular clusters relative to the Sun?
   (e) (3) Would you expect that α/Fe is enhanced in open clusters in the Milky Way? Why or why not?
   (f) (3) The paper discusses the aluminum and oxygen abundances in Terzan 5. One of the main proposed explanations (which is not discussed in this paper) for the anticorrelation between Al and O in globular clusters is related to the anticorrelation observed between N and O. Discuss why you might expect a N-O anticorrelation.
   (g) (3) The ratio of Fe mass to H mass in the Sun is roughly $10^{-4.5}$. What is the ratio (Fe/H) in the two different populations of Terzan 5?
3. (8 points) Reddening
   (a) (2) The paper states that Terzan 5 is heavily reddened, with an average color excess of E(B-V)=2.38. Define E(B-V).

(b) (6) About how much fainter in the V band is Terzan 5 than it would be if it was seen without any intervening material? How about the H band? Express your answers both in magnitudes as well as in flux units.

4. (15 points) Color-magnitude diagram

(a) Based on the discussion in the introduction, make an annotated sketch on the included page of what you expect the observed (K,J-K) color-magnitude diagram of Terzan 5 to look like. The diagram should include:

i. labelled axes with at least two numerical values noted on each axis. Remember, you are sketching an observed CMD. Describe how you determined your numbers;

ii. a group of points representing each of the different populations observed in Terzan 5. Ideally, use two different colors or different symbols for the two main populations, and clearly identify which population is which;

iii. something that roughly indicates the relative number of points from one region of the diagram to another;

iv. labelling of the main observed stages of stellar evolution, with a brief note (on the side) about what is going on inside the star at each stage.

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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] $= -0.25 \pm 0.07$ rms and another component with [Fe/H] $= +0.27 \pm 0.04$ 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] $= +0.34 \pm 0.06$ rms, consistent with the canonical scenario for rapid enrichment by core collapse supernovae (SNe). The metal-rich component has [α/Fe] $= +0.03 \pm 0.04$ 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)[5].

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 ($\delta K \simeq 0.3$) 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

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[5] See the updated list at http://www.naic.edu/~pfreire/GCpsr.html.

Table 1
Stellar Parameters and Abundances for the Sample of Observed Giants in Terzan 5

No.	R.A.	Decl.	$T_{\rm eff}$	log g	v_r[a]	[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.)

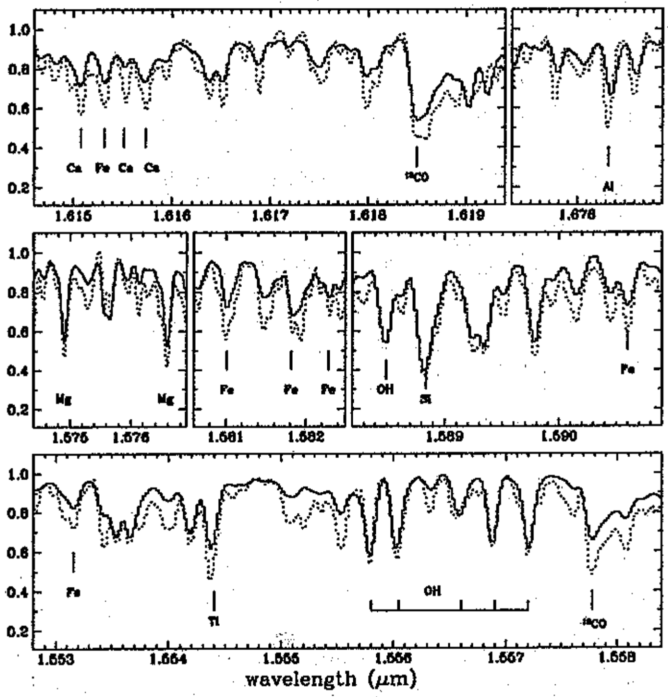

Figure 1 Portion of the NIRSPEC H-band spectra of two red giants of Terzan 5 with similar $T_{\rm eff} \approx 3800$ K, but different chemical abundance patterns (solid line for the metal-poor star, dotted line for the metal-rich one). A few atomic lines and molecular bands of interest are marked.

Table 2
Average Abundance Ratios of the Two RGB Populations in Terzan 5

Abundance Ratio	Metal-poor Population	Metal-rich Population
[Fe/H]	−0.25 ± 0.07	+0.27 ± 0.04
[O/Fe]	+0.34 ± 0.06	−0.04 ± 0.04
[Ca/Fe]	+0.32 ± 0.05	+0.02 ± 0.03
[Si/Fe]	+0.36 ± 0.08	+0.02 ± 0.10
[Mg/Fe]	+0.33 ± 0.10	+0.08 ± 0.06
[Ti/Fe]	+0.34 ± 0.10	+0.06 ± 0.06
[Al/Fe]	+0.52 ± 0.13	+0.13 ± 0.13
[C/Fe]	−0.35 ± 0.12	−0.38 ± 0.08

has been sky subtracted by using nodding pairs and flat-field corrected. Wavelength calibration has been performed using arc lamps and a second-order polynomial solution, while telluric features have been removed by using an O-star featureless spectrum observed during the same nights. The signal-to-noise ratio of the final spectra is always larger than 30. Figure 1 shows an example of the observed spectra.

A grid of suitable synthetic spectra of giant stars has been computed by varying the photospheric parameters and the element abundances, by using an updated version of the code described in Origlia et al. (1993). By combining full spectral synthesis analysis and equivalent width measurements of selected lines, we have derived abundances for Fe, C, O, Ca, Si, Mg, Ti, and Al. Our line list and details of the analysis are given in Origlia et al. (2002) and Origlia & Rich (2004). Reference solar abundances are from Grevesse & Sauval (1998).

Stellar temperatures have been first estimated from the $(J-K)_0$ colors, by using the $E(B-V) = 2.38$ average reddening and the color–temperature transformation by Montegriffo et al. (1998), specifically calibrated on GC giants. Gravity has been estimated from theoretical evolutionary tracks, according to the location of the stars on the RGB, while for the microturbulence velocity an average value of 2 km s^{-1} has been adopted (see Origlia et al. 1997, and references therein for a detailed 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 $\approx \pm 0.1$ 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.

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] $= -0.25 \pm 0.07$ rms, and a metal-rich component (as traced by 13 giants in our sample) with average [Fe/H] $= +0.27 \pm 0.04$ rms. The two populations therefore show a Δ[Fe/H]≈ 0.5 dex iron abundance difference, fully confirming first results by 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]$\approx +0.09$ and [α/Fe]$\approx +0.34$ for the metal-poor, and [α/H]$\approx +0.30$ and [α/Fe]$\approx +0.03$ for the metal-rich stars. Hence, the two populations show Δ[α/H] $\approx +0.2$ dex and a Δ[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

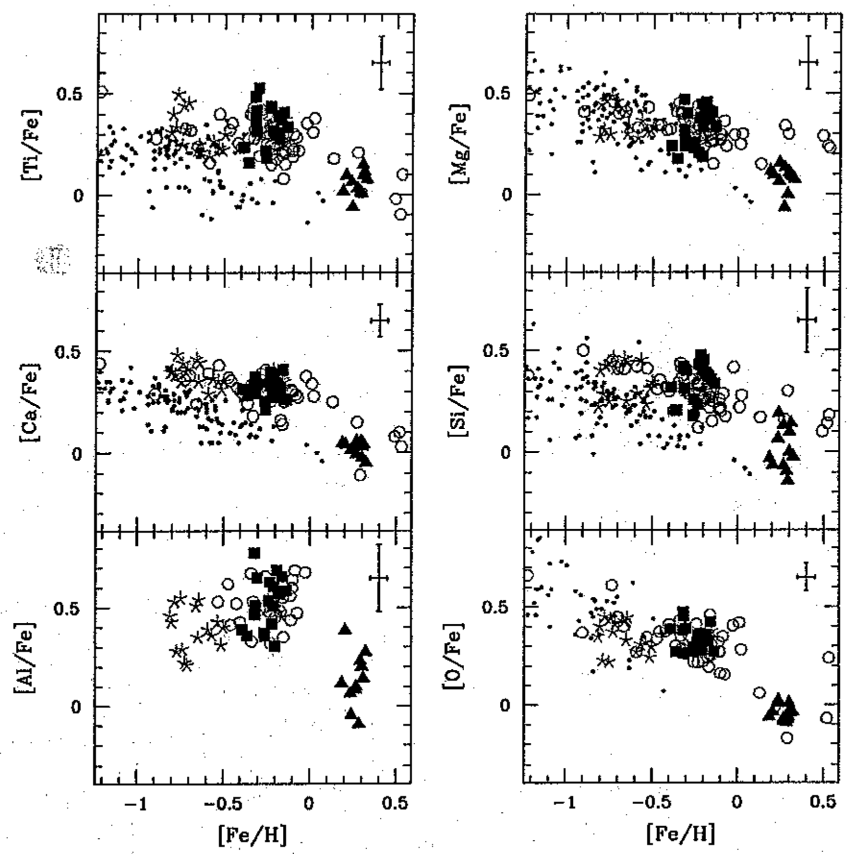

Figure 2 Individual [α/Fe] and [Al/Fe] abundance ratios as a function of [Fe/H] for the 20 metal-poor (solid squares) and the 13 metal-rich (solid triangles) giants in our observed sample. Included are also the four metal-poor giants observed by Origlia & Rich (2004). Typical error bars are plotted in the top right corner of each panel. The abundance patterns of bulge field (open circles) and GC (asterisks) giants (see, e.g., Rich et al. 2007; Fulbright et al. 2007; Origlia et al. 2008, and reference therein) and those of disk and halo (gray dots; Gratton et al. 2003) stars are also plotted for comparison.

Galactic GC.[6] In fact, all GCs are characterized by an extremely high homogeneity in the iron abundance.[7] 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

[6] Only the old, populous, disk open cluster NGC 6791 has iron and chemical abundance patterns (e.g., Origlia et al. 2006) very similar to the Terzan 5 metal-rich population.

[7] Recent claims of the detection of much smaller (≃0.1 dex) iron dispersion have been reported in the literature for M22 (Marino et al. 2009; Da Costa et al. 2009), NGC 1851 (Carretta et al. 2010b), and M54 (Carretta et al. 2010c).

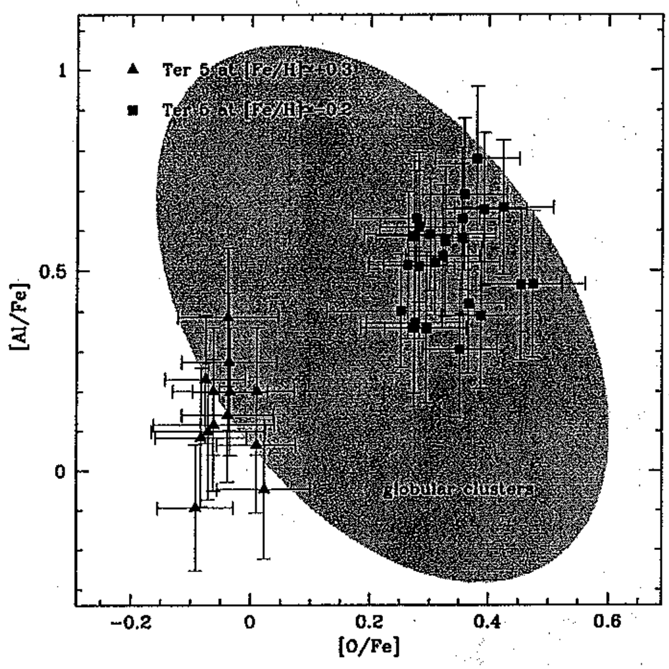

Figure 3 [Al/Fe] vs. [O/Fe] abundance ratios of the observed giants in Terzan 5. Symbols are as in Figure 2. The gray ellipse indicates the range of values measured in Galactic GCs (see, e.g., Carretta et al. 2010a).

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).[7] 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] $\simeq -0.2$) 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] $\simeq +0.3$), 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

[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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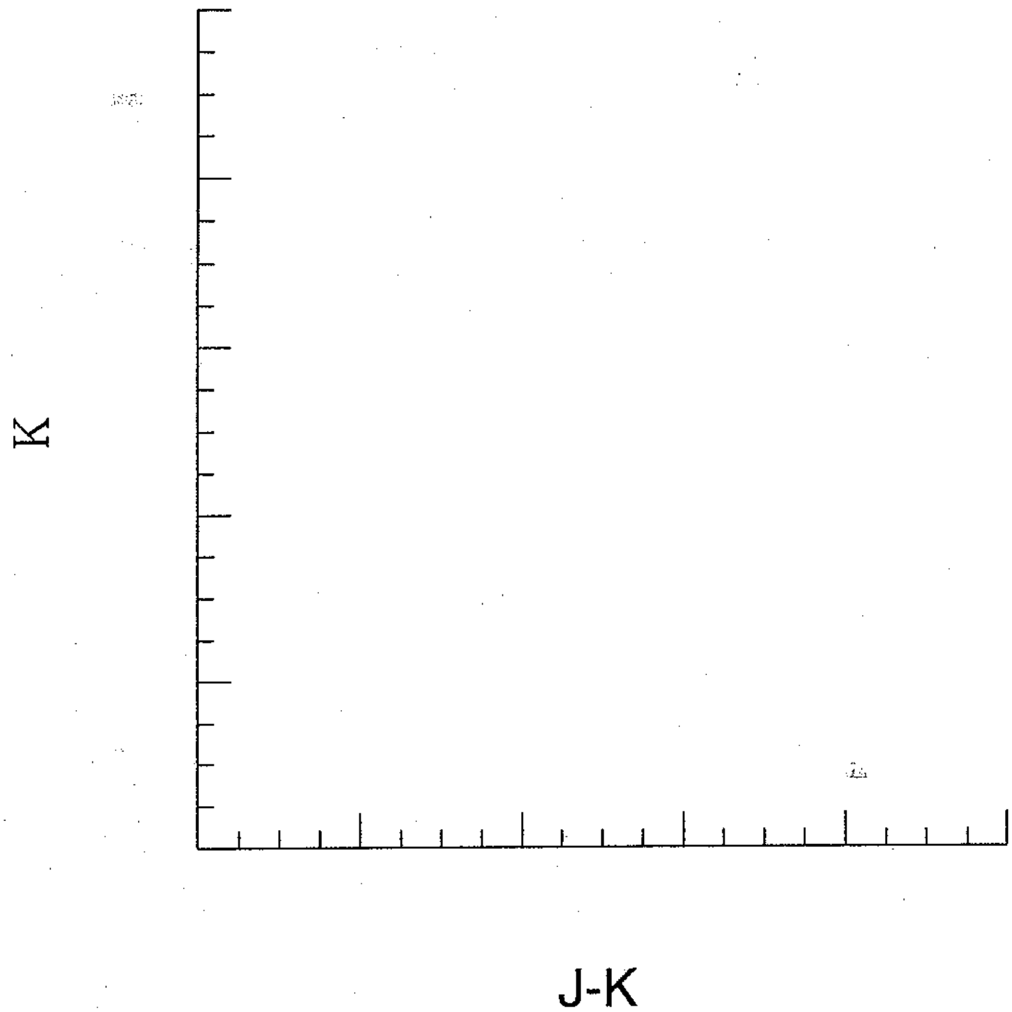

K
J-K

NMSU ASTRONOMY CUME 361, April 2011 **Jon Holtzman**

Read the paper "Spectroscopy Unveils the Complex Nature of Terzan 5", by Origlia et al. ApJL 726, L20 (2011).

I expect a passing grade will be 70-75 percent.

1 solar mass = 2×10^{33} gm. 1 pc = 3.086×10^{18} cm

1. (22 points) The paper suggests that Terzan 5 is a relic of a larger system.

   (a) (2) What is the main reason that the authors come to this conclusion?

   They measure two populations in Terzan 5 with different heavy element abundances. Heavy elements could only be retained in a system if it had significantly more mass than the present mass of Terzan 5.

   (b) (8) Quantitatively demonstrate whether you would expect a globular cluster to be able to retain elements produced in supernovae.

   Calculate escape velocity $v = \sqrt{2GM/r^2} \sim 3km/s(\frac{M}{10^6 M_{sun}})\left(\frac{r}{10pc}\right)^{-1}$. *This is much smaller than typical SN ejecta velocity, e.g.* $v \sim \sqrt{(2E/m)}$ *with* $E \sim 10^{51}$ *ergs and* $m \sim 10 M_{sun}$.

   (c) (2) One possibility is that Terzan 5 has been tidally stripped of material. Are there any other examples of systems you know of around the Milky Way that show evidence of disruption?

   Sagittarius is the best example. Pal 5 is a GC example. Several likely streams have been identified. Magellanic stream is a maybe.

   (d) (10) Imagine you have a dwarf galaxy companion to the Milky Way that has a mass of 10^8 solar masses with a half-mass radius of 1 kpc. Estimate how close it would need to come to the center of the Milky Way to be significantly tidally stripped.

$$2GM_{mw}R/d^3 = GM_{dwarf}/R^2$$

   gives $d \sim 12kpc$ *for* $M = 10^{11}$ *and* $d \sim 6kpc$ *for* $M = 10^{10}$ *(note that mass interior to satellite is smaller than total halo mass).*

2. (20 points) Abundances

   (a) (3) Quantitatively define what the equivalent width of a line is.

   EW width is rectangular width corresponding to area of line:

$$EW = \int (F_{cont} - F)/F_{cont} d\lambda$$

   (b) (3) When the paper discusses deriving abundances, it talks about deriving photospheric parameters. What are the main photospheric parameters they are talking about (there are usually three, with two very important ones) that affect the equivalent width of lines? Why do the photospheric parameters need to be determined to measure abundances?

   Effective temperature, surface gravity, and microturbulence. Temperature and gravity affect ionization and populations of levels,

(c) (2) What other photospheric parameters might affect the shape/width of the lines (but not the equivalent width)?

Rotation, magnetic fields, radial velocity.

(d) (3) What is the standard explanation for why the α/Fe ratio is enhanced in globular clusters relative to the Sun?

GCs form early in the history of the MW, before the timescale for type Ia SNe to add extra Fe into the gas

(e) (3) Would you expect that α/Fe is enhanced in open clusters in the Milky Way? Why or why not?

No, because open clusters form later in the history of the MW, so gas out of which they form has been enriched by both type II and type Ia SNe.

(f) (3) The paper discusses the aluminum and oxygen abundances in Terzan 5. One of the main proposed explanations (which is not discussed in this paper) for the anticorrelation between Al and O in globular clusters is related to the anticorrelation observed between N and O. Discuss why you might expect a N-O anticorrelation.

Main explanation for N-O anticorrellation is dredged up regions of CNO processing. In CNO cycle, N is the bottleneck, so N will be enhanced at the expense of O. Na-Al anticorrelation may reflect a similar thing from another nuclear reaction cycle.

(g) (3) The ratio of Fe mass to H mass in the Sun is rougly $10^{-4.5}$. What is the ratio (Fe/H) in the two different populations of Terzan 5?

From definition of [Fe/H], two populations withh have ratios $10^{-4.5-0.25}$ *and* $10^{-4.5+0.27}$

3. (8 points) Reddening

(a) (2) The paper states that Terzan 5 is heavily reddened, with an average color excess of E(B-V)=2.38. Define E(B-V).

Difference between observed (B-V) and unreddenned (B-V). Equivalently, $E(B-V) \equiv A_B - A_V$

(b) (6) About how much fainter in the V band is Terzan 5 than it would be if it was seen without any intervening material? How about the H band? Express your answers both in magnitudes as well as in flux units.

For $E(B-V) = 2.38$, $A_V = 3.1E(B-V) = 7.4$ *mags, or flux ratio of 912. Extinction at H roughly 1/6th that at V, so* $A_H = 1.2$ *or flux ratio of 3.*

4. (15 points) Color-magnitude diagram

(a) Based on the discussion in the introduction, make an annotated sketch on the included page of what you expect the observed (K,J-K) color-magnitude diagram of Terzan 5 to look like. The diagram should include:

i. labelled axes with at least two numerical values noted on each axis. Remember, you are sketching an observed CMD. Describe how you determined your numbers;

ii. a group of points representing each of the different populations observed in Terzan 5. Ideally, use two different colors or different symbols for the two main populations, and clearly identify which population is which;

iii. something that roughly indicates the relative number of points from one region of the diagram to another;

iv. labelling of the main observed stages of stellar evolution, with a brief note (on the side) about what is going on inside the star at each stage.

Was looking for an observed CMD with apparent mag on y axis and apparent color on x axis. For apparent mag, take distance modulus about 14.5 plus ~ 1 *mag of extinction. Colors in* $(J-K)$ *between 0 and 1, plus some reddening. Only recently recognized that population is bimodal, so two different populations should be close to each other. More metal-rich population should be slightly redder, but also since younger age is inferred, could have slightly more luminous/bluer turnoff. Horizontal branches should be very red (clumps on RGB) at these high metallicities. More metal rich HB clump should be 0.3 mag brighter. Should have many more MS stars than RGB stars. Should identify MS as core H burning, RGB as shell H burning, HB, as core He burning.*

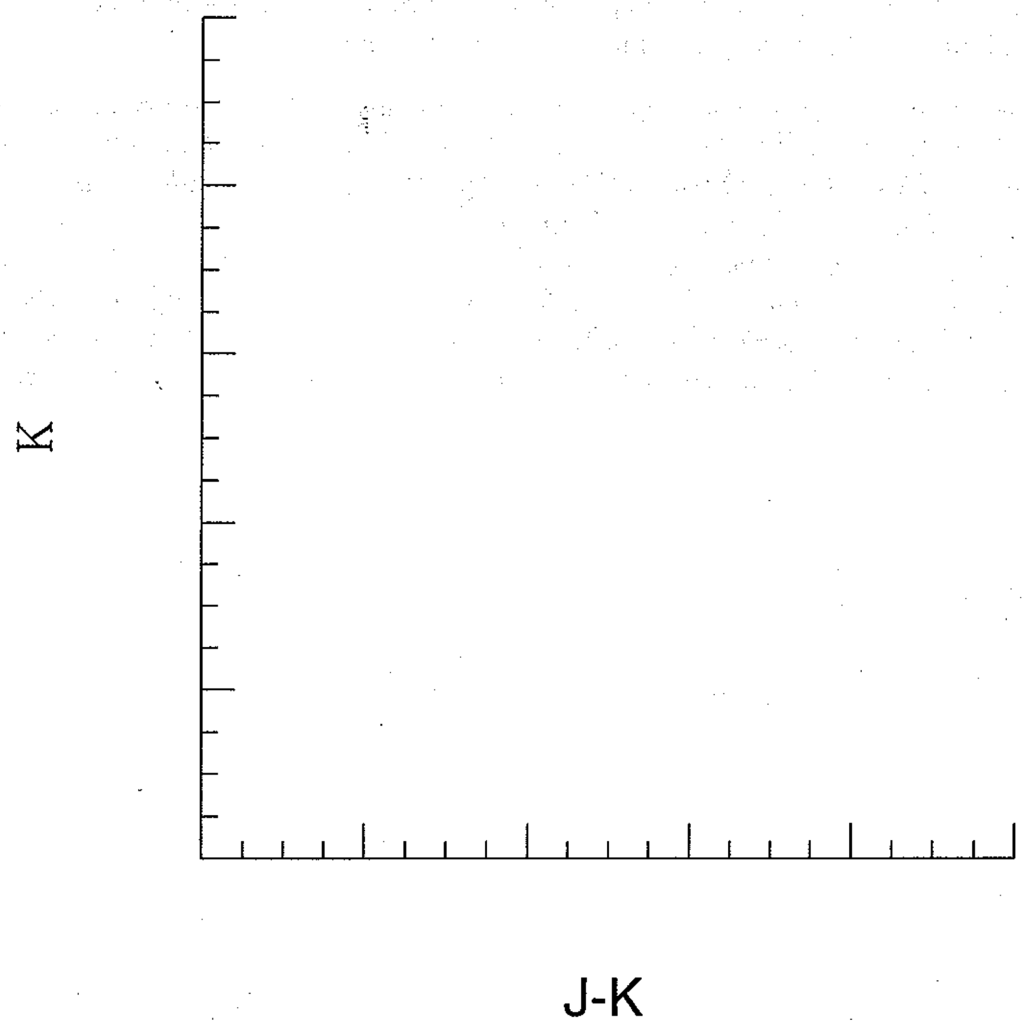

K
J-K

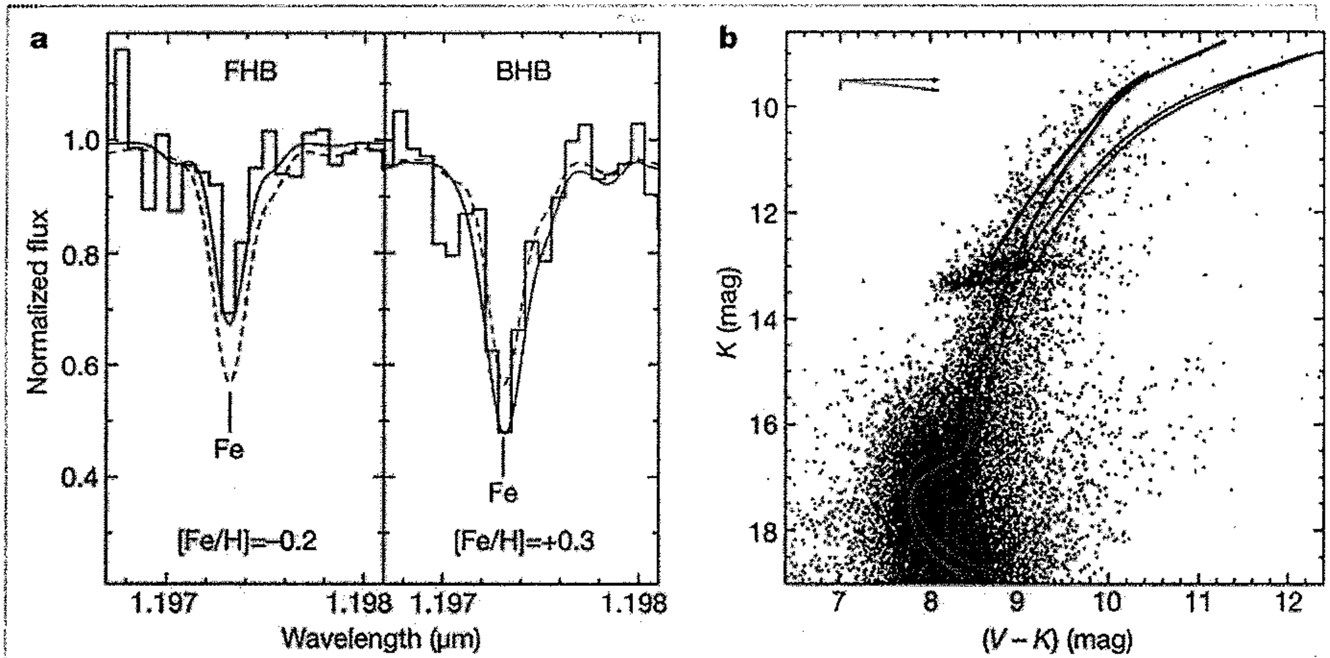
FIGURE 4. Iron abundance and ages of the two populations.

From the following article:

The cluster Terzan 5 as a remnant of a primordial building block of the Galactic bulge

F. R. Ferraro, E. Dalessandro, A. Mucciarelli, G. Beccari, R. M. Rich, L. Origlia, B. Lanzoni, R. T. Rood, E. Valenti, M. Bellazzini, S. M. Ransom & G. Cocozza

Nature **462**, 483-486(26 November 2009)
doi:10.1038/nature08581



a, Combined J-band spectra near the 1.1973 μm iron line for three FHB (left) and three BHB (right) stars, as obtained with NIRSPEC at Keck II on 2 July 2009 (coloured lines). The measured equivalent widths of the lines and suitable spectral synthesis[12] yield iron abundances [Fe/H] ≈ -0.2 ± 0.1 and [Fe/H] ≈ +0.3 ± 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: T_{eff} = 5,000 K and log g = 2.5 for the FHB stars, T_{eff} = 4,500 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. From the measured spectra, we also derived the stellar radial velocities and found an average value of -85 km s^{-1} (σ = 9 km s^{-1}) and -85 km s^{-1} (σ = 10 km s^{-1}) for the FHB and BHB stars, respectively (the typical uncertainty on the individual measure is of the order of 3 km s^{-1}). These values are fully consistent with the previously measured radial velocities of four giants (V_r = -93 ± 2 km s^{-1})[12] and the value (V_r = -94 ± 15 km s^{-1}) listed for Terzan 5 in the currently adopted globular cluster catalogue[14]. This observational fact confirms that the horizontal branch stars for which we have secured spectra are cluster members, and suggests that there is no significant kinematical difference between the two populations. **b**, (K, V - K) CMD of Terzan 5 obtained by combining VLT-MAD and HST-ACS data corrected for differential reddening. Two isochrones[26] 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 on the data by adopting a colour excess[8] $E(B - V)$ = 2.38 ± 0.05 and a distance[8] d = 5.9 ± 0.5 kpc. Note that the CMD cannot be