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The ages of the multi-iron populations in Terzan5

D. Massari,[1,2] on behalf of the Cosmic-Lab team

[1] INAF-Osservatorio Astronomico di Bologna, via Ranzani 1, 40127, Bologna, Italy
e-mail: davide.massari@oabo.inaf.it
[2] University of Groningen, Kapteyn Astronomical Institute, NL-9747 AD Groningen, Netherlands

Abstract. We report on the age determination of the two main stellar populations in Terzan 5. Detailed proper motion decontamination and differential reddening correction allowed us to distinguish two separate main-sequence turn-offs in the colour-magnitude diagram. This led to the first accurate determination of the absolute age of Terzan 5 populations, which turned out to be separated in time by ~ 7 Gyr. The analysis of a large spectroscopic sample also revealed the existence of a third, metal-poor [Fe/H$\simeq -0.8$ dex] component. The exceptional properties of Terzan 5 make it a unique system in the Galaxy, and lend further support to the interpretation of the system as a fossil remnant of the Galactic bulge formation epoch.

Key words. Hertzsprung-Russell and C-M diagrams – Stars: abundances – Stars: Population II – globular clusters: individual (Terzan 5) – Galaxy: bulge

1. Introduction

The formation of galaxy bulges is a long-standing issue that has not found a firm solution, yet. Interesting hints can be derived from the investigation of the only bulge whose stellar populations can be resolved: the Galactic bulge.

So far, the observed properties of the Milky Way bulge led to conflicting interpretations. The old age of bulge stars and their observed chemistry suggest that it formed early and rapidly (Matteucci & Romano 1999), in agreement with the prediction of a dissipative collapse model (Eggen et al. 1962). On the other hand the structure and stellar kinematics of the bulge, which appears to be peanut/X-shaped (Nataf et al. 2010) and cylindrically rotating (Howard et al. 2008), is consistent with a purely dynamical evolution of a disk buckling into a bar (Shen et al. 2010).

Another interesting hypothesis (see e.g. Noguchi 1999; Immeli et al. 2004) is that bulges form at high redshift ($z \sim 2-3$) via a combination of disk instabilities and mergers of giant clumps on short dynamical timescales. These clumps have indeed been observed at high redshift (Elmegreen et al. 2008), but the final proof of the validity of this scenario would come from their discovery at $z = 0$. Recently Ferraro et al. (2009) may have discovered the first remnant of one of these objects in our Galaxy: the bulge stellar system Terzan 5.

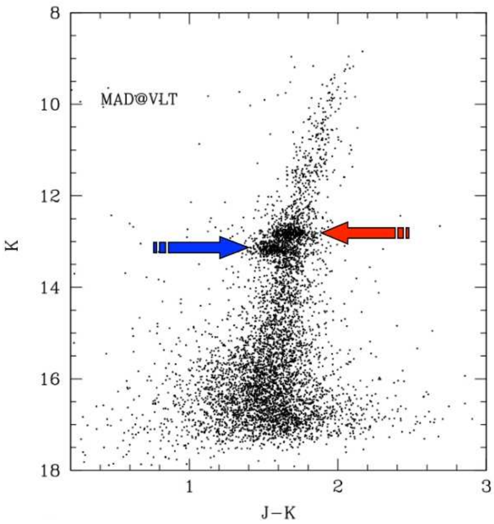

Fig. 1. IR CMD of Terzan 5 as observed with MAD at the VLT. The two discovered RCs are highlighted by the two arrows.

2. Terzan 5: the discovery of its peculiarity

Terzan 5 is a stellar system located in the bulge of our Galaxy at a distance of 5.9 kpc from Earth (Valenti et al. 2010). Because of the large extinction in its direction, the best way to investigate its properties is by means of infrared (IR) observations. Indeed, by using $K-$ and $J-$band observations with the Multi-Conjugate Adaptive Optics Demonstrator (MAD) at the Very Large Telescope (VLT), Ferraro et al. (2009) discovered two well separated red clumps (RCs) in the colour-magnitude diagram (CMD) of Terzan 5 (see Figure 1).

A first high-resolution spectroscopic screening obtained on 33 giants using NIRSPEC at the KeckII telescope demonstrated that the two populations of Terzan 5 share the same average radial velocity (thus confirming their membership), but have quite different metallicity. In particular, the population corresponding to the faint RC has an average [Fe/H]= -0.25 dex, while that corresponding to the bright RC has and average [Fe/H]= $+0.27$ dex (Origlia et al. 2011). Moreover the metal-poor population turned out to be α-enhanced to values of [α/Fe]= $+0.34$ dex, while the metal-rich population resulted to be solar-scaled.

Such a peculiar chemistry suggests that Terzan 5 experienced a complex chemical evolution, where the metal-poor population probably formed from a gas mainly enriched by Type-II supernovae, while the metal-rich component likely formed from a gas further polluted by Type-Ia supernovae. This means that Terzan 5 initial mass had to be significantly larger than the current one ($\sim 10^6 M_\odot$; Lanzoni et al. 2010) thus to retain the iron-enriched supernovae ejecta.

All these peculiar features make Terzan 5 a unique system, clearly not compatible with the definition of genuine globular cluster. To better understand its nature, our group performed a series of detailed photometric and spectroscopic studies with the final aim of determining its precise star formation history (SFH).

3. Terzan 5: photometric properties

The precise determination of Terzan 5 SFH requires the accurate measurement of the absolute ages of its populations. Since one of the best absolute age indicators is the magnitude of the main-sequence turn-off (MSTO), the separation of the evolutionary sequences of Terzan 5 at the MSTO level is necessary. Such an ambitious goal requires to deal with two sources of complexity: the contamination by fore- and background stars, and the differential reddening effect.

The best way to decontaminate a CMD from non-member sources is by means of proper motions (PMs). An accurate PM analysis has been performed in Massari et al. (2015), and proved to be very efficient in selecting likely-member stars, cleaning the CMD from spurious sequences and providing the final proof of the actual membership of both the RCs.

Differential reddening causes the stars in the CMD to move along the reddening vector direction depending on their extinction, and this results in a severe mixing and distortions of the evolutionary sequences (e.g., Ortolani et al. 1996). By exploiting deep *Hubble Space Telescope* (HST) data, Massari et al. (2012)

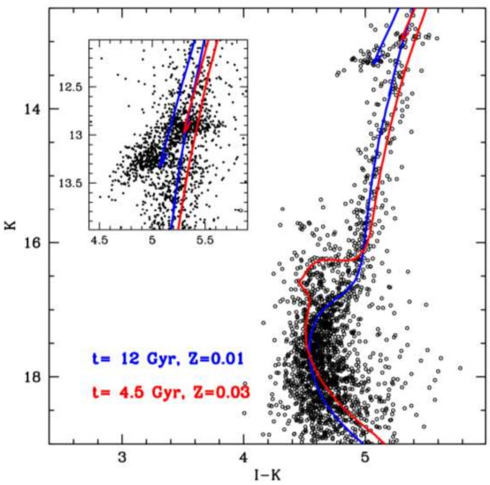

Fig. 2. $(K, I-K)$ CMD of Terzan 5, after PM decontamination and differential reddening correction. The separation of two MSTOs becomes evident, and the best-fitting isochrones reveal an age difference of about ∼ 7 Gyr.

built a high-resolution differential reddening map that allows to correct each star photometry for its own value of the colour excess $E(B-V)$. The reddening map is publicly available at `www.cosmic-lab.eu`.

By combining the information on the stellar membership from PMs, with the differential reddening correction, in Ferraro et al. (2016) we were finally able to obtain the "cleanest" CMD of Terzan 5 so far, and clearly detect a double MSTO. Such a surprising CMD is shown in Figure 2, where a bright MSTO and sub giant branch (SGB) clearly separate from a fainter SGB. Given the measured metallicities, the two peculiar photometric features are best fitted by two theoretical isochrones (from Pietrinferni et al. 2004, 2006) that are 12 Gyr and 4.5 Gyr old, respectively. No peculiar Helium enhancement is required to explain the double MSTO, at odds with what previously suggested based only on the RC separation (D'Antona et al. 2010; Lee et al. 2015). Such an astonishing age difference of ∼ 7 Gyr makes Terzan 5 *unique* among all of the other stellar systems in the Galaxy.

4. Terzan 5 spectroscopic properties

The first spectroscopic screening on Terzan 5 stars was obtained on a sample of 33 giants. To better describe the cluster SFH, and to probe its entire metallicity distribution, a larger sample is needed. To this aim we analysed a sample of more than 1600 stars in the direction of Terzan 5, observed with the spectrographs GIRAFFE/FLAMES at the VLT and DEIMOS at the KeckII telescope, to measure radial velocities and iron abundances [Fe/H].

First, we characterised the sample of bulge stars surrounding Terzan 5, selected as all the objects located farther than the cluster tidal radius. The results of the analysis are described in detail in Massari et al. (2014a), and they represent one of the few kinematical *and* chemical characterisation of bulge stars at very low Galactic latitude.

With this information it was then possible to statistically decontaminate the sample of likely members stars, selected according to their location within Terzan 5 tidal radius and their radial velocity within $\pm 3\sigma$ from Terzan 5 systemic velocity ($RV_{\mathrm{Ter5}} \simeq -87.5$ km/s). The stars surviving such a decontamination describe a very peculiar [Fe/H] distribution: it is extremely broad, spanning more than 1 dex in iron abundance, and multi-modal, with the presence of *three* components (see Massari et al. 2014b). The two dominant components correspond very well those found in Origlia et al. (2011), both in terms of average [Fe/H] and in terms of relative numbers. Moreover, three stars belonging to the third small component were also observed at higher resolution with NIRSPEC, and were found to have an average [Fe/H]$\simeq -0.8$ dex and to be α-enhanced (Origlia et al. 2013).

5. Discussion

The combination of these findings allowed us to obtain first hints on the SFH of Terzan 5 (see Figure 3).

The overall age and metallicity spreads clearly put Terzan 5 in a completely different context with respect to that of Galactic globular clusters. *What is Terzan 5, then?* Ferraro et

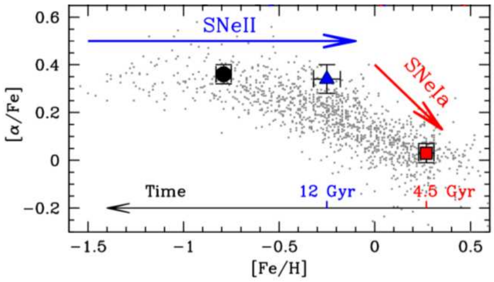

Fig. 3. The chemical properties of the three sub-populations of Terzan 5 (large symbols) are compared to those of bulge field stars (grey dots). The formation epoch of the two major sub-populations in Terzan 5 is labelled. The action of the two main types of supernovae is also sketched.

al. (2016) suggested the possibility that Terzan 5 is the $z = 0$ remnant of a massive clump similar to those observed at high redshift, that may have contributed to form the Galactic bulge. Only another alternative interpretation would still fit in the global observational picture: Terzan 5 could be the nuclear star cluster of one of the massive Milky Way satellites that contributed to the assembly of the Milky Way bulge via repeated mergers (e.g. Hopkins et al. 2010). We stress that in both the proposed scenarios Terzan 5 would be a fossil remnant of the bulge formation epoch, thus representing the only direct link between the current times and the still obscure infancy of the Milky Way.

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References

D'Antona, F., Ventura, P., Caloi, V., et al. 2010, ApJ, 715, L63
Eggen, O. J., Lynden-Bell, D., & Sandage, A. R. 1962, ApJ, 136, 748
Elmegreen, B. G., Bournaud, F., & Elmegreen, D. M. 2008, ApJ, 688, 67
Ferraro, F. R., Dalessandro, E., Mucciarelli, A., et al. 2009, Nature, 462, 483
Ferraro, F. R., Pallanca, C., Lanzoni, B., et al. 2015, ApJ, 807, L1
Ferraro, F. R., Massari, D., Dalessandro, E. et al. 2016, ApJ, 828, 75
Hopkins, P. F., Croton, D., Bundy, K., et al. 2010, ApJ, 724, 915
Howard, C. D., Rich, R. M., Reitzel, D. B., et al. 2008, ApJ, 688, 1060
Immeli, A., et al. 2004, A&A, 413, 547
Lanzoni, B., Ferraro, F. R., Dalessandro, E., et al. 2010, ApJ, 717, 653
Lee, Y.-W., Joo, S.-J., & Chung, C. 2015, MNRAS, 453, 3906
Massari, D., Mucciarelli, A., Dalessandro, E., et al. 2012, ApJ, 755, L32
Massari, D., Mucciarelli, A., Ferraro, F. R., et al. 2014, ApJ, 791, 101
Massari, D., Mucciarelli, A., Ferraro, F. R., et al. 2014, ApJ, 795, 22
Massari, D., Dalessandro, E., Ferraro, F. R., et al. 2015, ApJ, 810, 69
Matteucci, F., & Romano, D. 1999, Ap&SS, 265, 311
Nataf, D. M., et al. 2010, ApJ, 721, L28
Noguchi, M. 1999, ApJ, 514, 77
Origlia, L., Rich, R. M., Ferraro, F. R., et al. 2011, ApJ, 726, L20
Origlia, L., Massari, D., Rich, R. M., et al. 2013, ApJ, 779, L5
Ortolani, S., Barbuy, B., & Bica, E. 1996, A&A, 308, 733
Pietrinferni, A., et al. 2004, ApJ, 612, 168
Pietrinferni, A., et al. 2006, ApJ, 642, 797
Shen, J., Rich, R. M., Kormendy, J., et al. 2010, ApJ, 720, L72
Valenti, E., Ferraro, F. R., & Origlia, L. 2010, MNRAS, 402, 1729