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

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Globular star clusters are compact and massive stellar systems old enough to have witnessed the entire history of our Galaxy, the Milky Way. While recent results[1,2,3] suggest that their formation may have been more complex than previously thought, they still are the best approximation in nature to a stellar population formed over a relatively short time-scale (less than 1 Gyr) and with virtually no dispersion in the iron content. Indeed, only one cluster-like system (ω Centauri) in

the Galactic Halo is known to have multiple stellar populations with a significant spread in iron abundance and age[4,5]. Similar findings in the Galactic Bulge have been hampered by the obscuration due to thick and varying layers of interstellar dust. Here we report on the discovery of two populations with different iron content and age in Terzan 5, a globular cluster-like system in the Galactic Bulge. This discovery opens a new perspective to our understanding of the Bulge formation: indeed Terzan 5 could be the surviving remnant of one of the primordial building blocks which are thought to merge and form galaxy bulges.

We have recently obtained a set of high-resolution images of Terzan 5 in the K and J bands by using MAD[6], a Multi-Conjugate Adaptive Optics demonstrator instrument installed at the Very Large Telescope of the European Southern Observatory. MAD operates at near infrared wavelengths, thus revealing the only component of stellar radiation that can efficiently cross the thick clouds of dust obscuring the Galactic Bulge. It is able to perform exceptionally good and uniform Adaptive Optics correction over its entire field of view (FoV=1'x1'), thus compensating for the degradation effects to the astronomical images induced by the Earth atmosphere. In particular, we have obtained a set of K-band (2.2μm) images of Terzan 5 close to the diffraction limit (see Figure 1). The exceptional sharpness and uniformity of the images yields very high quality photometry, resulting in a superb ($K, J–K$) colour-magnitude diagram (CMD) even for the very central region of the cluster, and leading to a surprising discovery. We have detected two well-defined red horizontal branch (HB) clumps, separated in luminosity: a bright HB (*bHB*) at $K = 12.85$ and a faint HB (*fHB*) at $K = 13.15$, the latter having a bluer *(J–K)* colour (see Figure 2).

We have carefully considered whether the double HB could be spurious. It is

neither due to instrumental effects (Figure 2), nor to differential reddening[7,8] (as the two HB clumps in the CMD are separated in a direction which is essentially orthogonal to the reddening vector), nor to field contamination (while field stars are expected to be almost uniformly distributed over the MAD FoV, the radial distributions of the stars belonging to the two HB clumps are significantly concentrated toward the cluster centre and are inconsistent with a uniform distribution at more than 5σ level; see Figure 3a and Supplementary Information). We have also found that the radial distributions of the two HB populations are different (see Figure 3a): according to a Kolmogorov-Smirnov test, the *bHB* population is significantly (at $> 3.5\sigma$ level) more centrally concentrated than that of the *fHB*. The stars belonging to the *bHB* are also substantially more numerous than those of the *fHB* near the cluster centre (at $r < 20"$), becoming progressively more rare at greater distance (see Figure 3b).

Once alerted to the existence of the double HB, we have also identified the feature in optical observations obtained with the Advanced Camera for Surveys (ACS) on board the Hubble Space Telescope (HST; see Supplementary Figure 1a). Although the strong differential reddening broadens the colour extension of the HB clumps by ~ 1 mag, the optical (*I, V–I*) CMD still shows a clear bimodal distribution of HB stars in the direction orthogonal to the reddening vector (see Supplementary Figure 1b). A hint of a double HB clump was already visible in a previously published CMD obtained with HST-NICMOS[9-11], although the shorter colour baseline provided by the *J* and *H* band observations did not clearly separate the two clumps.

Hence, we conclude that the existence of the two HB clumps is a real feature and the differing radial distributions may indicate different physical origins of the two populations. In particular, a combination of different metallicity and age, with the population in the *bHB* clump being more metal-rich and younger than the fainter one,

could in principle reproduce the observed features (see Supplementary Figure 2). The only direct information previously available on the metal content of individual stars in Terzan 5 was from 4 bright giants near the Tip of the red giant branch (RGB), giving an average [Fe/H] = −0.2 with a negligible dispersion[12]. Hence, we quickly secured medium-resolution near IR spectra of 6 HB stars (3 in each clump) at the Keck Telescope[13]. The derived radial velocities for the two groups of stars (−85 Km/s in both cases) are fully consistent with the previous measures[12] and the systemic velocity of Terzan 5 quoted in the currently adopted globular cluster (GC) catalogue[14]. This confirms that all of the observed stars are cluster members and suggests that there is no significant kinematical difference between the two populations (this is also confirmed by proper motion studies; see Supplementary Information). Furthermore, we have found that the iron content of the stars in the two clumps differs by a factor of 3 (~ 0.5 dex): the *fHB* stars have [Fe/H] = − 0.2, while the *bHB* stars have [Fe/H] = +0.3 (see Figure 4a).

To date, beside a significant spread in the abundance patterns of a few light-elements (as Na, O, etc)[1], the chemical composition of all GCs in the Galaxy is known to be extremely uniform in terms of iron content, with the only exception being ω Centauri[4,5] in the Galactic Halo. Hence, Terzan 5 is the first stellar aggregate with GC-like properties but with the signatures of a much more complex star formation history, ever discovered in the Bulge.

To further investigate this issue, we have performed a differential reddening correction[15] on the optical ACS catalogue and combined it with the near infrared data, thus obtaining the (*K, V−K*) CMD shown in Figure 4b. The presence of two distinct populations with a double HB and (possibly) two separate RGBs can be seen in this CMD. The RGB of the most metal rich population appears to be more bent (as expected, because of the line blanketing due to a higher metal content). The observed

features can be reproduced with two populations characterized by the observed metallicities and two different ages: t = 12 Gyr for the *fHB* and a significantly younger age (t = 6 Gyr) for the *bHB*.

Using the number of HB stars found in the combined MAD and ACS samples (see Supplementary Information for details), we estimate that the cluster harbours about ~ 800 *fHB* stars and 500 *bHB* stars in total. This is even larger than the global HB population of 47 Tucanae[16], thus suggesting that Terzan 5 is more massive than previously thought (see Supplementary Information).

The evidence for two distinct stellar populations and for a very large total mass suggests that Terzan 5 has experienced a quite troubled formation history. It might be the merger-product of two independent stellar aggregates[17]. While such a possibility seems to be unlikely for GCs belonging to the Galactic Halo, the chance of capturing a completely independent stellar system should be significantly larger if the orbits are confined within the Bulge. In this scenario, however, it is not easy to explain why the metal rich population is more centrally concentrated than the metal poor one. Moreover, GCs younger than 10 Gyr are very rare in our Galaxy[18]. Rather, Terzan 5 could be a complex ω Centauri-like system[4,5] or the nuclear remnant of a disrupted galaxy, similar to the M54-Sagittarius system[19,20] or the Carina dwarf spheroidal[21] in the metal rich regime. The remnant of a disrupted dwarf galaxy would naturally present a larger central concentration of the metal rich (and younger) population[22], as commonly observed in the satellites of the Milky Way and M31. On the other hand, the strict similarity in iron abundance between Terzan 5 and the Bulge population is fully compatible with the hypothesis that the (partial) disruption of its progenitor has contributed to the Bulge formation[23].

Possible relics of the hierarchical assembly of the Galactic Halo have been

recently identified at high Galactic latitudes[24]. Terzan 5 may be the first example of the sub-structures that contributed to form the Galactic Bulge. Indeed our discovery could be the observational confirmation that galactic spheroids originate from the merging of pre-formed, internally-evolved stellar systems and that other similar objects might be hidden into the heavily obscured central region of the Galaxy.

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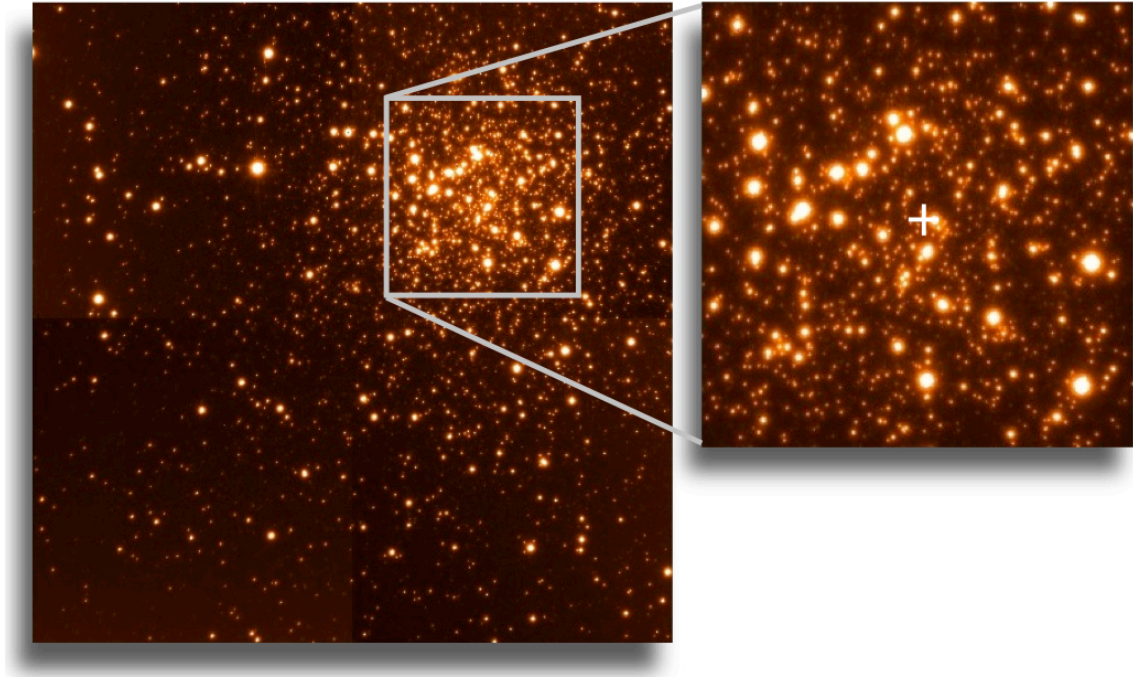
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**Figure 1. The extraordinary MAD image of Terzan 5 in the *K*-band.**
Observations were performed at the ESO-VLT (Paranal, Chile) on August 2008,
through *J* and *K* filters. Exposure times were of about two minutes in each filter.
The figure shows the best image obtained in the *K* band (the image size is 1'x1',
North is up, East is left). The measured Full Width half Maximum (FWHM) of
stars is 0.1", the Strehl ratio ranges between 15% and 24% over the entire FoV.
The quality of the *J* image is slightly worse (FWHM $\approx$ 0.24" and Strehl ratio
below 10%), but still much better than normally obtained with ground-based
observations. A small (16" x 16") portion of the *K* image sampling the very
central region of Terzan 5 is also shown. The cluster centre of gravity (marked
with the white cross) has been determined by averaging the positions of the
resolved stars and following the same procedure adopted in previous studies[25].
It is located at α = 17^h 48^m 4.85^s, δ= –24° 46' 44.6", which is ~ 3" South-East
from the centre listed in the most commonly adopted globular cluster
catalogue[14], but in good agreement (within the errors $\Delta\alpha \approx \Delta\delta \approx$ 0.5") with the

determination obtained from HST-NICMOS observations[9]. The barycenters of the two HB populations are coincident with the gravity centre within the errors.
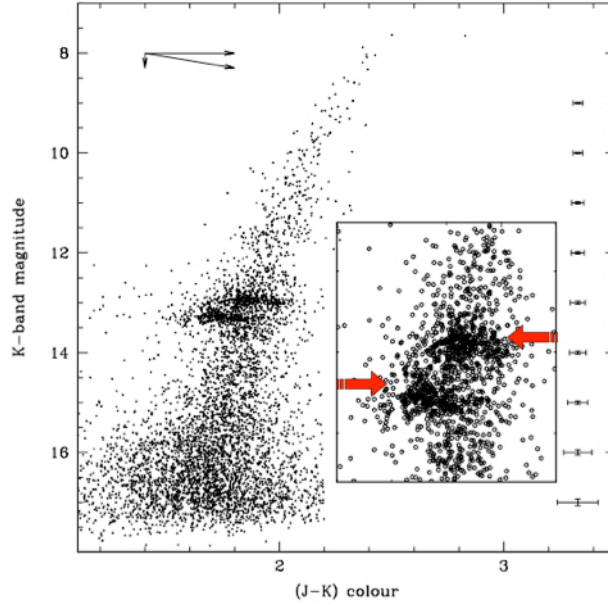
Figure 2. The two Horizontal Branch clumps of Terzan 5. MAD (K, J–K) CMD of the central region of Terzan 5. The inset shows a zoom in the HB region, with the two HB clumps marked with red arrows. Terzan 5 is heavily obscured by thick clouds of dust (this effect is commonly called "reddening") intervening between the system and the observer, in a way that strongly depends on the direction of the line of sight ("differential reddening")[7,8]. The effect of reddening on the K magnitude and the J-K colour is indicated by the reddening vector plotted in the main panel. Several tests have been performed on the images and the catalogue to exclude any possible spurious effect from the instrument or the reduction procedure. Stars in the two clumps do not show any peculiar spatial distribution on the detector. Moreover, the two clumps are not spuriously produced by the variation in size and shape of the Point Spread Function, or the local level of the background. Error bars, 1 s.e.m are plotted at different magnitude levels.

The contamination from Bulge field stars in this CMD is negligible. In the 1 arcmin^2 field of view of MAD, we estimate (see Supplementary Information) that 11 and 8 field stars should contaminate the faint and bright HB selection boxes (while we count 299 faint-HB stars and 310 bright-HB stars in the entire MAD sample).
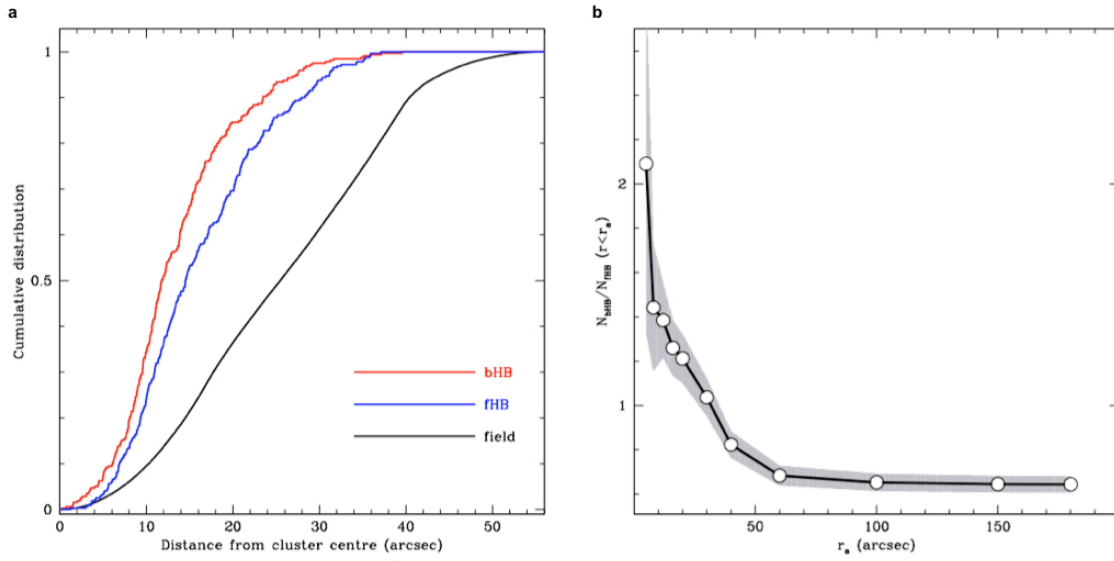
Figure 3. Radial distribution of the two HB populations in Terzan 5.

a, Cumulative radial distribution of the observed *bHB* stars (red line) and the *fHB* population (blue line), compared to that of field stars (solid black line), as a function of the projected distance from the cluster centre of gravity. The field distribution has been obtained from a synthetic sample of 100,000 points uniformly distributed in *X* and *Y* over the MAD FoV.

b, Ratio between the number of observed *bHB* and *fHB* stars computed over areas of increasing radius r_a. Points with $r_a < 30''$ refer to the MAD sample, those corresponding to larger radii have been computed by using also the ACS data. The grey area around the black line represents the 1σ uncertainty region. *bHB* stars are substantially more numerous than *fHB* stars in the cluster centre and they rapidly vanish at $r_a > 50''$.
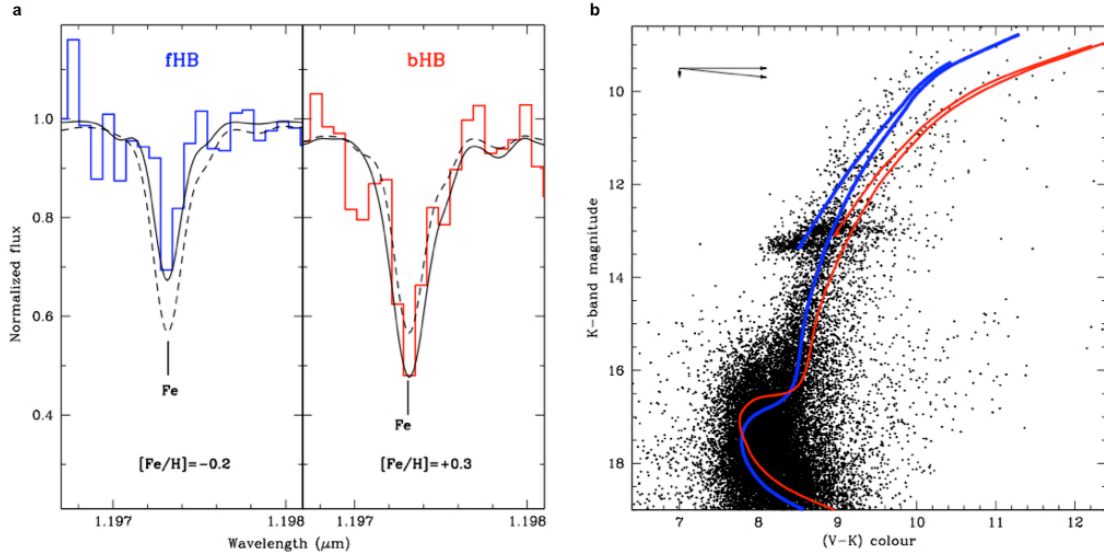
Figure 4. Iron abundance and ages of the two populations.

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 July 2, 2009. 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 solid lines correspond to the best-fit synthetic spectra obtained for temperatures and gravities derived from evolutionary models reproducing the observed colours of the HB stars: T_{eff} = 5000 K and log *g* = 2.5 for the *fHB* stars, T_{eff} = 4500 K and log *g* = 2.0 for the *bHB* stars. For sake of comparison, we also plotted (as 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 (σ = 9 km/s) and −85 km/s (σ = 10 km/s) for the *fHB* and *bHB* stars, respectively (the typical uncertainty on the individual

measure is of the order of 3 km/s). These values are fully consistent with the previously measured radial velocities of 4 giants (V_r = –93±2 km/s)[12] and the value (V_r = –94±15 km/s) listed for Terzan 5 in the currently adopted GC catalogue[14]. This observational fact confirms that the HB stars for which we have secured the 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 (Z=0.01, 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 to 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 reproduced by two isochrones with the measured metallicities and the same age. Due to the large scatter at the turn-off level, we estimate that the uncertainty on the younger component age is of about 2 Gyr.

Supplementary Information

Field contamination: In order to estimate the impact of field star contamination on the selected HB populations, the MAD and ACS samples have been supplemented with optical (*V* and *I*) wide-field (30' × 30') images retrieved from the ESO-Archive. Those HB stars, as selected in the MAD *(K, J–K)* plane, which are in common with the ACS sample have been used to define the *fHB* and *bHB* selection boxes in the *(I, V– I)* CMD. By counting the number of stars beyond the cluster tidal radius and falling within the HB selection boxes in the wide-field sample we estimate that 11±3 and 8±3 stars/arcmin^2 may contaminate the faint and the bright HB populations, respectively. Since we count 809 *fHB* stars and 521 *bHB* stars in the combined MAD and ACS data set, which samples an area of ~ 11.3 arcmin^2, the above estimates indicate that ~ 16% of the observed stars are field contamination: this yields ~ 685 true *fHB* stars and 450 *bHB* stars. By considering that the MAD+ACS data set samples 88% of the total cluster luminosity, we estimate that the entire cluster contains a total number of ~800 *fHB* stars and 500 *bHB* stars.

Proper motions: To further verify the physical association between the *fHB* and *bHB* populations, we have computed the proper motions of the HB stars using archived NICMOS *J* images[9] and our own MAD *K* image, which are separated by a temporal baseline of ≈ 10 yrs. The NICMOS field of view (19" x 19") is smaller than that of MAD. Hence the analysis has been carried out only on a subset of the HB populations: we counted 175 *fHB* stars and 130 *bHB* stars in the common region. By using the *fHB* as reference to place the two images into the same astrometric system, we computed (a) the residuals between the positions of the *fHB* stars during the two epochs (this sets the internal accuracy of the measures), and (b) the proper motions residuals for the *bHB* population, which traces the relative motion between the two sets of stars. The results of this analysis can be summarized as follows:

1. The systemic tangential velocities of the two sets of stars are identical within the uncertainties. In particular, the difference in tangential velocity is ≈ 0.05 ± 1.08 mas/yr, which corresponds to 0.0 ±30 km/s, adopting a distance *d* = 5.9 Kpc for Terzan 5.

2. The dispersion in tangential velocity is 1.08 mas/yr for the *fHB* population and 1.25 mas/yr for the *bHB*. This must be compared with the tangential dispersion of the red

clump stars in the Galactic field, which amounts to 3.7 mas/yr (following the Besancon Galactic model[27] in the direction of Terzan 5). Hence both the *fHB* and the *bHB* populations are significantly dynamically colder than the surrounding Bulge: $\sigma \approx 25$ km/s vs. $\sigma \approx 105$ km/s.

3. By deconvolving the tangential dispersion of the *fHB* population (which corresponds to the observational noise) from that of the *bHB* population, we find that the true one-dimensional dispersion of the latter is $\sigma \approx 13$ km/s, in good agreement with the velocity dispersion of the cluster in the radial direction ($\sigma \approx 10$ km/s).

All the above results provide further support to the conclusion that both HB populations do belong to Terzan 5.

**Implications for the population of millisecond pulsars (MSPs):**

The scenarios discussed in the paper on the possible origin of Terzan 5 have direct implications for the exceptional population of MSPs discovered in this cluster[28]. In fact, if Terzan 5 is the relic of a more massive structure, the deeper potential well of the original system could have favoured the retention of a larger number of (supernova kicked) neutron stars.
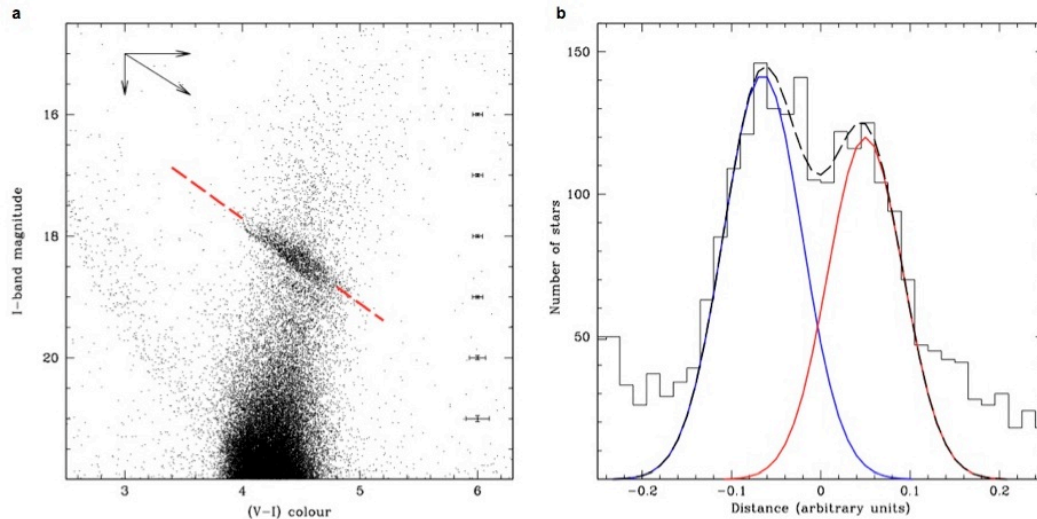
Supplementary Figure 1. Optical (*I, V− I*) CMD of Terzan 5 from deep HST images.

a, This CMD demonstrates the difficulty affecting the optical studies of star clusters located in the direction of the Galactic Bulge. In fact, these clusters suffer for heavy dust obscuration, and the reddening effect is to distort all the evolutionary sequences in the CMD: in particular, the two HB clumps of Terzan 5 appear to be stretched along the direction of the reddening vector (shown in the upper left). Still, two different parallel structures are distinguishable above and below the dashed line, which is parallel to the reddening vector. Error bars, 1 s.e.m are plotted at different magnitude levels.

b, The distribution of the HB star geometrical distances from the dashed line marked in panel **a** is shown. Two well-defined peaks corresponding to the *bHB* and the *fHB* are clearly visible and nicely reproduced by two Gaussians (in red and blue, respectively; the black dashed line is the combination of the two Gaussian distributions).
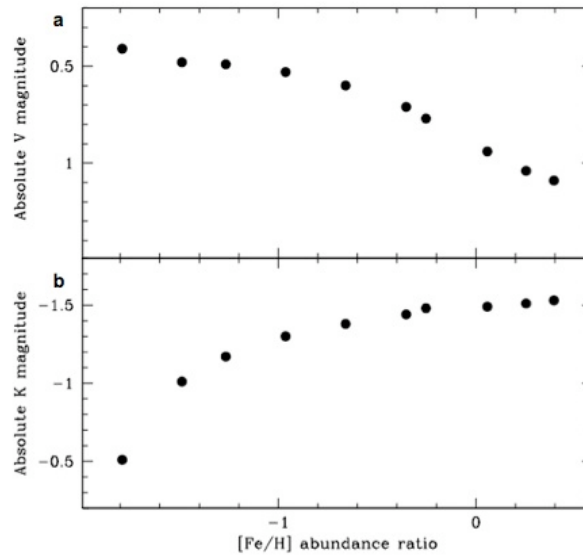
Supplementary Figure 2. Theoretical expectations for the dependence of the HB magnitude level on stellar metallicity.

a, The prediction of theoretical stellar models[26] for the HB magnitude level in the *V* band is plotted as a function of metallicity.

 b, As in panel **a**, but for the *K* band.

As apparent and at odds with the behaviour in the optical bands, a metal-rich population is expected to have a brighter HB than a metal-poor one in the near-infrared. However, for the two observed HB clumps (with [Fe/H] = −0.2 and [Fe/H] = +0.3) the expected difference is only δK ~0.17 mag, i.e. significantly smaller than the observed one (δK ~ 0.3 mag). In order to reproduce the observations it is necessary to hypothesize that the metal rich population is younger than the metal-poor one. Note that in principle also a significant enhancement of Helium abundance could produce more luminous HB stars. However, even at these metallicities, a high helium content would move the HB stars at the extreme blue tail of the HB.

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