Publication Year	2015
Acceptance in OA@INAF	2020-04-14T13:38:11Z
Title	Probing the MSP Prenatal Stage: The Optical Identification of the X-Ray Burster EXO 1745-248 in Terzan 5
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DOI	10.1088/2041-8205/807/1/L1
Handle	http://hdl.handle.net/20.500.12386/24006
Journal	THE ASTROPHYSICAL JOURNAL
Number	807

The Astrophysical Journal Letters, 807:L1 (5pp), 2015 July 1
doi:10.1088/2041-8205/807/1/L1

PROBING THE MSP PRENATAL STAGE: THE OPTICAL IDENTIFICATION OF THE X-RAY BURSTER EXO 1745-248 IN TERZAN 5*

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Received 2015 May 4; accepted 2015 May 27; published 2015 June 24

ABSTRACT

We report on the optical identification of the neutron star burster EXO 1745-248 in Terzan 5. The identification was performed by exploiting *Hubble Space Telescope*/Advanced Camera for Surveys images acquired in Director's Discretionary Time shortly after (approximately one month) the *Swift* detection of the X-ray burst. The comparison between these images and previous archival data revealed the presence of a star that is currently brightened by ~3 mag, consistent with expectations during an X-ray outburst. The centroid of this object well agrees with the position, in the archival images, of a star located in the turn-off/sub-giant-branch region of Terzan 5. This supports the scenario that the companion should have recently filled its Roche Lobe. Such a system represents the prenatal stage of a millisecond pulsar, an evolutionary phase during which heavy mass accretion on the compact object occurs, thus producing X-ray outbursts and re-accelerating the neutron star.

Key words: binaries: close – globular clusters: individual (Terzan 5) – stars: neutron – X-rays: bursts – X-rays: individual (EXO 1745-248)

1. INTRODUCTION

Low-mass X-ray binaries (LMXBs) and radio millisecond pulsars (MSPs) are thought to be, respectively, the starting and the ending stages of a common evolutionary path where a neutron star accretes matter (and angular momentum) from a companion (e.g., Bhattacharya & van den Heuvel 1991; Wijnands & van der Klis 1998). The early phases of this evolutionary path are characterized by active mass accretion accompanied by intense X-ray emission (larger than $\sim 10^{35}$ erg s^{-1}). These systems are observed as LMXBs characterized by a few outbursts in the X-ray due to accretion disk instabilities. These objects are usually called "X-ray transients" (White et al. 1984). When the neutron star is re-accelerated, the system will appear as an MSP in the radio band. Newly born MSPs are therefore expected to have a bloated and tidally deformed companion that is still losing mass from its Roche Lobe. In this case, the system is called "redback" (or "black widow" if the companion is less massive than 0.05 $M_\odot$). Following the canonical scenario, at the end of the evolution, only the degenerate core of the peeled companion (i.e., a helium or carbon–oxygen white dwarf) is predicted to orbit the MSP (a sub-stellar mass object, which is eventually completely evaporated in the case of a black widow). Indeed, the optical searches for the companion stars to binary MSPs performed so far in Galactic globular clusters detected objects belonging to all of these three classes: five bloated stars, companions to redbacks (see Ferraro et al. 2001; Edmonds et al. 2002; Cocozza et al. 2008; Pallanca et al. 2010, 2013), two very low mass object companions to black widows (Pallanca et al. 2014; Cadelano et al. 2015), and eight white dwarf companions to canonical MSPs (Edmonds et al. 2001; Bassa et al. 2003; Ferraro et al. 2003; Sigurdsson et al. 2003; L. R. Sandoval et al. 2015, in preparation; M. Cadelano et al. 2015, in preparation). A new, unexpected link has been added to the chain very recently. Papitto et al. (2013) found that the X-ray transient IGR J18245-2452 in the globular cluster M28 (Eckert et al. 2013) corresponds to MSP-M28I, and the system is currently swinging between accretion-powered and rotation-powered states. This shows that the transition from an LMXB to an MSP passes through an intermediate phase during which the two states cyclically alternate over a timescale of a few years (Papitto et al. 2013). A low-mass main-sequence star, which experienced a strong (~2 mag) luminosity increase, has been identified as the optical counterpart to the system (Pallanca et al. 2013).

On 2015 March 13, *Swift*/BAT observations detected an X-ray burst in Terzan 5 (Altamirano et al. 2015). The *Swift*/XRT observations promptly following the *Swift*/BAT detection localized the transient source at R.A.(J2000) = $267^\circ\!.0207$, decl.(J2000) = $-24^\circ\!.779$, with a 90% uncertainty of $3''\!.5$ (Bahramian et al. 2015). Moreover, the measured spectrum turned out to be consistent with a relatively hard photon index of 1.0 ± 0.2 and a hydrogen column density of $N_{\mathrm{H}} = (4 \pm 0.8) \times 10^{22}\,\mathrm{cm}^{-2}$. The latter is larger than the typical value measured in Terzan 5 (Bahramian et al. 2014) and well in agreement with the hydrogen column density of the previously known transient EXO 1745-248 (Kuulkers et al. 2003). Indeed, the subsequent position refinement by Linares et al. (2015) centered the system around EXO 1745-248 with a $2''\!.2$ error circle. These data therefore strongly suggest that the new *Swift*/BAT outburst coincides with EXO 1745-248, an X-ray neutron star transient that already showed outbursts in 2000 and 2011 (Degenaar & Wijnands 2012). Such an identification has been also confirmed by radio VLA observations (Tremou et al. 2015), which locate the source position within $0''\!.4$ of the published coordinates of EXO 1745-248 obtained from *Chandra* data (source CX3 in Heinke et al. 2006). The most recent *Swift*/XRT observations indicate

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* Based on observations (GO 14061, GO 12933, GO 9799) with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555.

that the source is probably on the way to transiting to the soft state (Yan et al. 2015).

Such an intriguing object is not uncommon in Terzan 5. In fact, this stellar system is known to harbor several X-ray sources (see, e.g., Heinke et al. 2006) and to be the most efficient furnace of MSPs in the Milky Way: it harbors a total of 34 MSPs, corresponding to $\sim$25% of the entire sample of such objects known to date in Galactic globular clusters (Ransom et al. 2005). Ferraro et al. (2009) recently demonstrated that, at odds with what is commonly thought, Terzan 5 is not a globular cluster, but a system hosting stellar populations characterized by significantly different iron abundances, spanning a total metallicity range of 1 dex (see also Origlia et al. 2011, 2013; Massari et al. 2014). The measured chemical patterns (Origlia et al. 2011, 2013) could be naturally explained in a scenario where Terzan 5 was originally much more massive than today ($\sim 10^6\,M_\odot$; Lanzoni et al. 2010), thus to be able to retain the iron-enriched gas ejected by violent supernova explosions. The large number of type II supernovae required to explain the observed abundance patterns should have also produced a large population of neutron stars, mostly retained into the deep potential well of the massive *proto*-Terzan 5 and likely forming binary systems through tidal capture interactions. Finally, its large collision rate (Lanzoni et al. 2010), the largest among all Galactic globular clusters (see also Verbunt & Hut 1987), could have highly promoted pulsar re-cycling processes, which can explain the production of the large population of MSPs/LMXBs now observed in the system.

Since the X-ray outburst detected by *Swift* is expected to also produce a significant enhancement of the optical luminosity (see Shahbaz & Kuulkers 1998; Charles & Coe 2006; Testa et al. 2012; Pallanca et al. 2014), we successfully applied for *Hubble Space Telescope* (*HST*) Director Discretionary Time to urgently survey the central region of Terzan 5 and thus provide new insights into this still unexplored phase of the LMXB-to-MSP path. Here, we report on the identification of the optical counterpart to EXO 1745-248 obtained from the analysis of these images.

2. OBSERVATIONS AND DATA REDUCTION

To search for the expected optical emission from EXO 1745-248 during its X-ray bursting phase, we submitted an *HST* Director Discretionary Time proposal (GO 14061, PI: Ferraro) asking for two orbits with the Advanced Camera for survey (Advanced Camera for Surveys/WFC). The observations have been promptly performed on 2015 April 20, about one month into the X-ray outburst (continuing at the time of writing). The data set (hereafter Epoch 3, EP3) consists of 5 × 398 s images in F606W, 5 × 371 s images in F814W, and one short exposure per filter (50 and 10 s, respectively; the latter have not been used in the present work).

Previous optical images of Terzan 5 acquired with the same instrument in the same filters were already present in the *HST* Archive: GO 12933 (PI: Ferraro) performed on 2013 August 18 (hereafter EP2) and GO 9799 (PI: Rich) performed on 2003 September 9 (hereafter EP1). We already used these data to construct the deepest optical color–magnitude diagram (CMD) of Terzan 5 (see Ferraro et al. 2009; Lanzoni et al. 2010; Massari et al. 2012).

For the present study, all the data sets have been homogeneously analyzed, applying standard IRAF procedures for pixel-area-map (PAM) correction on the (flc) images corrected for charge transfer efficiency. The photometric analysis has been carried out by using the DAOPHOT package. For each image, we modeled a Moffat point-spread function (PSF) by using 150–200 bright and nearly isolated stars. Afterward, we performed source detection in each image imposing a 3σ threshold over the background level. By using all the sources detected and PSF fitted in at least 1 out of 2 images in EP1 and 3 out of 10 images in EP2 and EP3, we then created a catalog for every epoch. In spite of including sources detected in only one filter, such an approach allowed us to avoid losing very faint (but possibly real) objects, while safely discarding spurious detections, such as cosmic rays and detector artifacts. The obtained master lists (one for every epoch) then have been used to identify the stellar sources in each single frame and the PSF model has been applied to derive the final magnitudes. As a final step, to build the EP2 and EP3 catalogs, we considered all the stars with a magnitude measured in both filters in at least three out of five images, while the EP1 catalog obviously consists of the objects detected in both the available images. For each star, the magnitudes estimated in different images of the same filter have been homogenized (see Ferraro et al. 1992) and their weighted mean and standard deviation finally have been adopted as the star magnitude and photometric error. The magnitude calibration to the VEGAMAG system has been performed by using the catalog by Massari et al. (2012) as the reference.

To precisely determine the star coordinates, we first applied the equations reported by Meurer et al. (2002) and corrected the instrumental positions for the known geometric distortions affecting the ACS images. Through cross-correlation with the catalog of Massari et al. (2012), which had been placed onto the 2MASS system, we then obtained the absolute coordinates for each star, with a final astrometric accuracy of $\sim 0''.2$ in both right ascension and declination.

3. RESULTS

The photometric analysis of our data set in a region around the position of EXO 1745-248 immediately revealed in EP3 the presence of a bright star that was not visible in EP1 and EP2 images (see Figure 1). The comparison of the three epochs unequivocally identifies the bright object (hereafter COM-EXO 1745-248) as the optical counterpart to EXO 1745-248. The absolute position of the optical source is R. A. (J2000) = $17^{\rm h}48^{\rm m}05^{\rm s}.23$, decl. (J2000) = $-24°46'47''.6$. This is consistent at 1σ with the VLA position quoted by Tremou et al. (2015; see the red and the green circles in Figure 2). Instead, the star previously suggested as the possible optical counterpart to this X-ray transient (Heinke et al. 2003) is located $\sim 0''.7$ to the west (cyan square in the figure).

After the astrometric transformations, the centroid position of the bright object in EP3 is within 0.05 pixels from the centroid of a fainter star clearly detected in EP1 and EP2 (see Figure 3). This could be the optical counterpart caught in quiescence. The probability that the true counterpart is a fainter, non-detected star aligned (within 0.05 pixels) along the line of sight is very low ($P \sim 0.4\%$).[4] In addition, the

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[4] To estimate the probability of a chance superposition with a star fainter than the proposed counterpart, the number of stars down to 5 mag below the turn-off level at the same distance ($\sim 5''$) from the cluster center is needed. Since no data set available for Terzan 5 reaches such a faint magnitude limit, we adopted as the reference the luminosity function of 47 Tucanae derived from deep *HST* observations (Sarajedini et al. 2007). Star counts have been normalized to the number of Terzan 5 stars counted between the turn-off level and 2 mag above in a ring of $2''$ width, centered at $5''$ from the center.

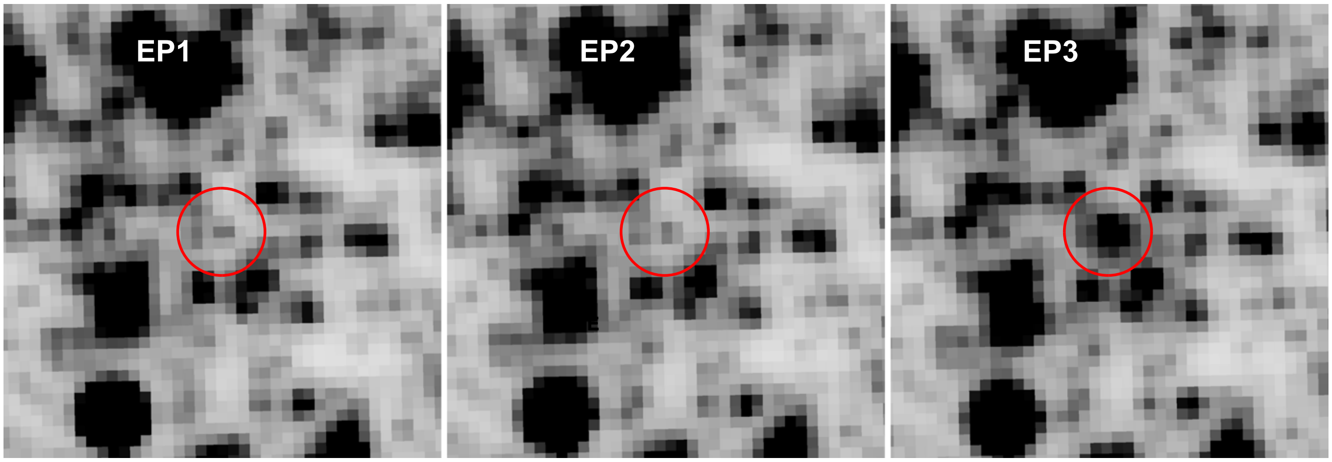

Figure 1. *HST*/ACS drz combined images of the 2″ × 2″ region around EXO 1745-248, in the F814W filter, for the three epochs (EP1, EP2, EP3, from left to right, respectively). The source (highlighted with a red circle) is visible as a faint star during the quiescent epochs EP1 and EP2, while it is observed in an outburst stage during EP3. North is up; east is to the left.

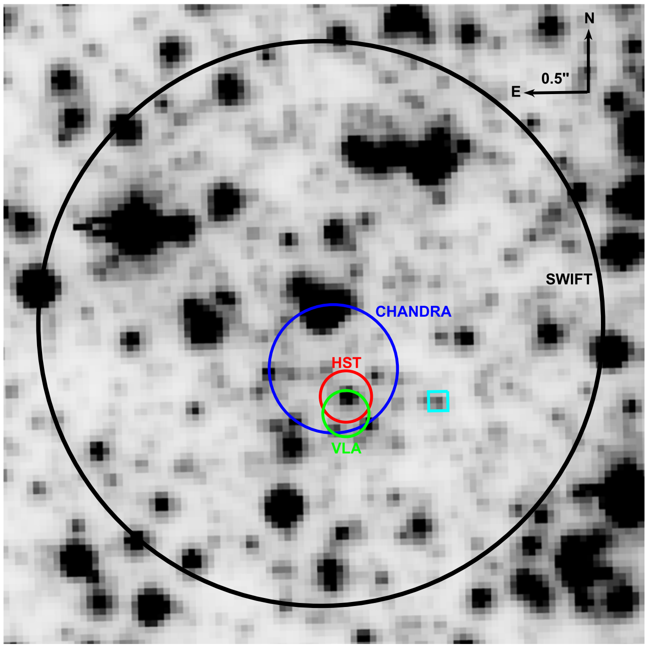

Figure 2. F814W-band drz combined image of the 5″ × 5″ region around EXO 1745-248 in the EP3 exposure. The source positions and uncertainties obtained from the various observational campaigns are marked: the *Swift*/XRT 2.″2 radius error circle is shown in black, the *Chandra* error circle in blue, the VLA measure in green, and the *HST* optical determination in red. The cyan square marks the star previously proposed (Heinke et al. 2003) as the possible optical counterpart to EXO 1745-248.

brightness profile of this star does not show any significant deviation from symmetry, thus supporting the hypothesis that it is a single object. Hence, the most natural conclusion is that the identified star is indeed the counterpart in quiescence. The identified object passed from observed magnitudes $m_{\rm F606W} = 24.74$ and $m_{\rm F814W} = 21.74$ during quiescence (EP1 and EP2),[5] to $m_{\rm F606W} = 21.77$ and $m_{\rm F814W} = 18.88$ in the outburst state (EP3), thus experiencing a brightening of 3 mag (corresponding to a factor of 16 in luminosity). Because

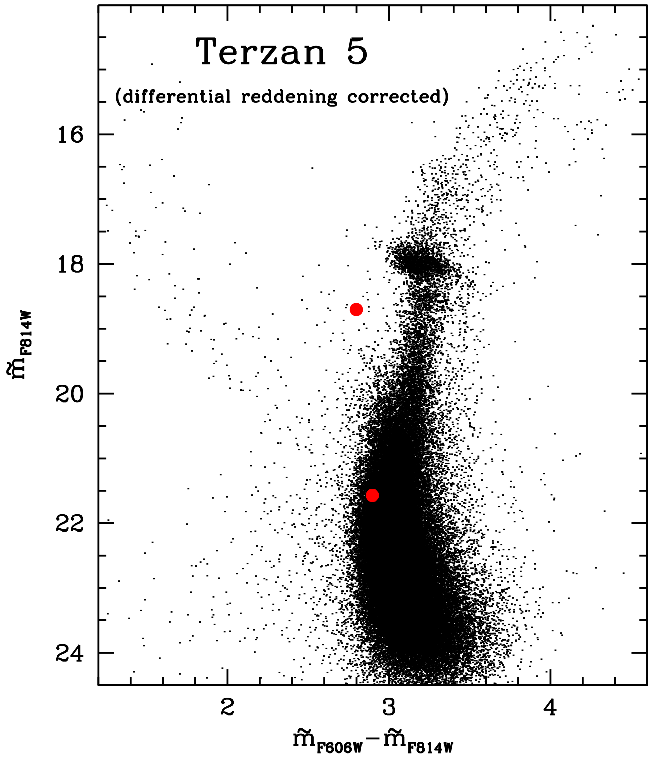

Figure 3. ($m_{\rm F814W}$, $m_{\rm F606W}-m_{\rm F814W}$) CMD of Terzan 5 corrected for differential reddening (according to Massari et al. 2012). The position of the optical counterpart to EXO 1745-248, in the outburst and in quiescent states, is marked with large red circles.

of its location in the inner Galactic bulge, Terzan 5 is affected by a large extinction, with an average color excess $E(B-V) = 2.38$ (Barbuy et al. 1998; Valenti et al. 2007), showing strong variations up to $\delta E(B-V) = 0.67$ mag within the ACS field of view (Massari et al. 2012). We therefore applied the high-resolution differential reddening map obtained by Massari et al. (2012) to correct the observed magnitudes (in the following, the notation $\widetilde{m}$ indicates magnitudes corrected for differential reddening). Figure 3 shows the position of COM-EXO 1745-248 in the differential reddening corrected CMD during the two states. We found $\widetilde{m}_{\rm F606W} = 24.47$ and $\widetilde{m}_{\rm F814W} = 21.57$ during EP1 and EP2, while $\widetilde{m}_{\rm F606W} = 21.50$

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[5] The magnitudes of the star in the EP1 ($m_{\rm F606W} = 24.7 \pm 0.1$; $m_{\rm F814W} = 21.6 \pm 0.1$) and EP2 ($m_{\rm F606W} = 24.74 \pm 0.04$; $m_{\rm F814W} = 21.7 \pm 0.1$) quiescent stages are fully consistent within the errors.

and $\widetilde{m}_{\rm F814W} = 18.70$ in EP3, corresponding to a small (0.1 mag) color variation, which is within the errors. No variability has been detected over the period of ~50 minutes covered by each *HST* orbit in EP3 and EP2. It is worth mentioning that EP3 data were acquired on 2015 April 20, almost simultaneously to the X-ray observations (Yan et al. 2015), suggesting that the system is transiting from a hard to a soft state.

An estimate of the orbital period of the system can be obtained by following Shahbaz & Kuulkers (1998), who report a relation between the orbital period and the *V*-band luminosity variation. Since we observe $\Delta V \sim 3$ mag in the case of EXO 1745-248, the orbital period turns out to be $P \sim 1.3$ days. On the other hand, for LMXBs, van Paradijs & McClintock (1994) proposed an empirical relation between the absolute *V* magnitude in outburst and the parameter Σ, which depends on the ratio between the X-ray and the Eddington luminosities ($L_{\rm X}/L_{\rm Edd}$) and the orbital period. By assuming $L_{\rm X}/L_{\rm Edd} \sim 0.5$ (Yan et al. 2015) and $M_V = 1.37$ (in Johnson *V* magnitude) for EXO 1745-248, we obtain $P \sim 0.1$ days. From these estimates, the orbital period of the system is likely to be between 1.3 and 0.1 days.

In order to more deeply investigate the nature of COM-EXO 1745-248 in the quiescent state under the assumption that the disk contribution to the observed magnitude is negligible, we identified the star in the *K*-band adaptive optics images obtained with ESO/MAD, which were used by Ferraro et al. (2009) to discover the two main multi-iron populations hidden in this system. We first corrected the combined (K, $m_{\rm F606W} - K$) CMD for differential reddening. Then, we transformed it into the absolute plane by assuming the average color excess quoted above and the distance modulus $(m - M)_0 = 13.87$ corresponding to a distance of 5.9 kpc (Valenti et al. 2007). The result is shown in Figure 4, where the position of COM-EXO 1745-248 in the quiescent state is marked. A more detailed characterization of the nature of COM-EXO 1745-248 is strongly hampered by the complexity of the stellar populations harbored in Terzan 5. The comparison with a 12 Gyr old isochrone (Girardi et al. 2010) well reproducing the main metal-poor sub-population of Terzan 5 at [Fe/H]= −0.3 dex[6] suggests that COM-EXO 1745-248 could be a sub-giant-branch (SGB) star. On the other hand, the metal-rich sub-population could be significantly (a few gigayears) younger than the main metal-poor component (see Ferraro et al. 2009). Thus, if COM-EXO 1745-248 belongs to the metal-rich component, it would be located below the SGB in a position where companions to redback MSPs have been found (see, e.g., the case of COM-MSP6397A in Ferraro et al. 2001). Since no spectroscopic information on the metallicity of this star is available, both possibilities are equivalently valid. While in the case of redbacks any prediction on the stellar parameters based on the observed photometric properties can be difficult (see the case of COM-MSP6397A), this is possible for an SGB star belonging to the metal-poor population. In this case, the following stellar parameters are obtained: mass $M = 0.9\,M_\odot$, effective temperature $T_{\rm eff} = 5440$ K, surface gravity $\log g = 3.9$, and luminosity $\log L/L_\odot = 0.35$. The corresponding stellar radius, therefore, is $R \sim 1.7\,R_\odot$. Hence, by assuming that the star has completely filled its Roche Lobe and adopting a canonical value for the neutron star mass ($\sim 1.4\,M_\odot$), we derive an orbital separation of $a \approx 5.2\,R_\odot$ and a period of $P_{\rm orb} \sim 0.9$ days for the binary system, fully in agreement with the range estimated above. We estimate that the radial velocity variations of such a binary system should have an amplitude of $\sim 170 \sin i$ km s^{-1} (i being the system inclination angle), which could be detectable through a dedicated spectroscopic follow-up.

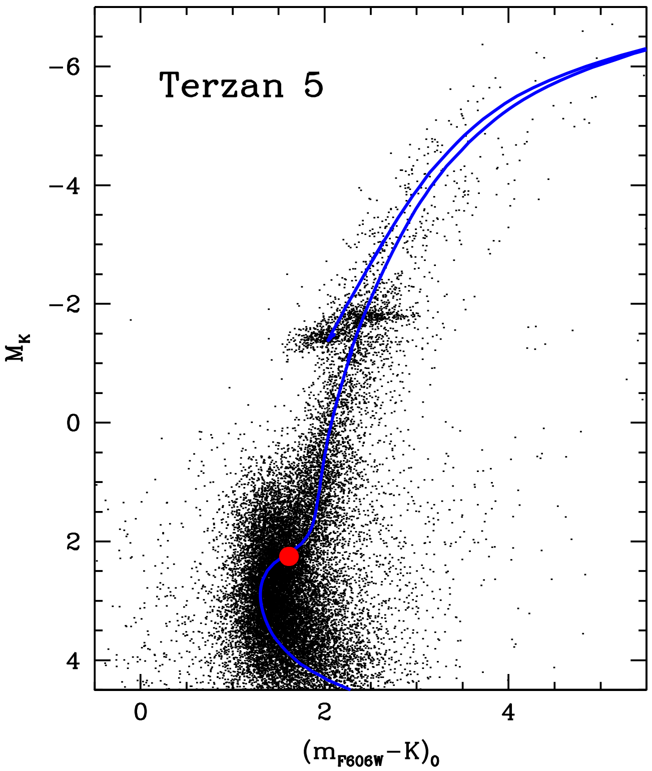

Figure 4. Absolute (M_K, $m_{\rm F606W} - K$)$_0$ CMD of Terzan 5 obtained from a combination of *HST*/ACS and ESO/MAD observations. The position of COM-EXO 1745-248 in the quiescent state is marked with the large red circle. The blue line corresponds to a 12 Gyr isochrone with [Fe/H] = −0.3 (from Girardi et al. 2010), well reproducing the main metal-poor sub-population of Terzan 5.

4. DISCUSSION AND CONCLUSIONS

By using high-resolution images obtained with the *HST*/ACS during three different epochs, we have identified the optical counterpart to the neutron star transient EXO 1745-248 in Terzan 5. With respect to the two previous epochs, this object shows a current brightening of ~3 mag. In the quiescent state it is an SGB star, i.e., an object that is experiencing its first envelope expansion while evolving toward the red giant branch stage.

Very interestingly, the X-ray emission of EXO 1745-248 during quiescence was found to be highly variable both on short and long timescales (Degenaar & Wijnands 2012), and Linares et al. (2014) recently underlined that these properties are impressively similar to those observed for MSP-M28I, the system occasionally swinging between accretion-powered and rotation-powered emission (Papitto et al. 2013). This evidence suggests that EXO 1745-248 could be another system belonging the rare class of objects caught shortly before the

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[6] As discussed in Massari et al. (2014), this population consists of ~62% of the total, while a super-solar component at [Fe/H] = +0.3 dex accounts for ~29%, and an even metal-poorer component at [Fe/H] = −0.8 dex, recently detected by Origlia et al. (2013), corresponds to ~5% of the total. The CMD plotted in Figure 4 nicely shows two distinct red clumps at $M_K = -1.5$ and $M_K = -1.81$, corresponding to the two major sub-populations first discovered in the system by Ferraro et al. (2009).

formation of a radio MSP, possibly in a stage immediately preceding the swinging phase in which MSP-M28I has been observed.

The characterization of EXO 1745-248 offers the opportunity of adding an additional link to the evolutionary chain connecting LMXBs to MSPs. In fact, from the analysis of the data currently available, we can speculate that EXO 1745-248 is experiencing the very early phase of the mass accretion stage when an expanding star (an SGB object) is filling its Roche Lobe and transferring material that eventually spins up the neutron star. Indeed, the few outbursts in the X-ray occurring during this stage unambiguously indicate that heavy mass accretion on the neutron star is taking place. As time passes, the mass accretion rate will decrease and the system will enter into the phase characterized by a cyclic alternation between accretion- and rotation-powered emission, as observed in the case of MSP-M28I (Papitto et al. 2013). Thus, in the future, EXO 1745-248 is expected to possibly start swinging between the LMXB and the MSP states. At later stages, when the neutron star has been sufficiently re-accelerated, the emission is powered by the rotating magnetic field, preventing further significant mass accretion. The system will be observable as a redback, i.e., a radio MSP with a highly perturbed companion, with the Roche Lobe filled and some material still falling toward the neutron star. Indeed, the prototype of this class of objects is MSP-A in NGC 6397 (Ferraro et al. 2001; see also Burderi et al. 2002), which shows a light curve dominated by tidal distortions (in agreement with the fact that the companion is a bloated, highly deformed star), prominent Hα lines (confirming the existence of diffuse gas outside the companion Roche Lobe; Sabbi et al. 2003), and peculiar chemical patterns (as expected for a deeply peeled star; Mucciarelli et al. 2013). The final fate will be that of a "canonical MSP," i.e., an NS in a binary system with a WD companion (the stripped core of the donor star).[7]

We warmly thank the referee, Craig Heinke, for careful reading of the manuscript and useful suggestions that helped improve the paper. This research is part of the project *Cosmic-Lab* (Web site: http://www.cosmic-lab.eu) funded by the European Research Council (under contract ERC-2010-AdG-267675).

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[7] Note that unexpected features have been observed also in this case, the most notable example being the optical variability of the WD companion to the pulsar 6752A in NGC 6752 (Cocozza et al. 2006).