HIGH-RESOLUTION REDDENING MAP IN THE DIRECTION OF THE STELLAR SYSTEM TERZAN 5*

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ABSTRACT

We have used optical images acquired with the Hubble Space Telescope to construct the first high-resolution extinction map in the direction of Terzan 5, a peculiar stellar system in the inner bulge of our Galaxy. The map has a spatial resolution of $8'' \times 8''$, over a total field of view of $200'' \times 200''$. The absorption clouds show a patchy structure on a typical scale of $20''$ and extinction variations as large as $\delta E(B-V) \sim 0.67$ mag, especially in the direction of the center of the system. These correspond to an absolute color excess ranging from $E(B-V) = 2.15$ mag up to 2.82 mag. After the correction for differential reddening, two distinct red giant branches become clearly visible in the color–magnitude diagram of Terzan 5 and they correspond well to the two sub-populations with different iron abundances recently discovered in this system.

Key words: dust, extinction – Galaxy: bulge – globular clusters: individual (Terzan 5)

1. INTRODUCTION

Terzan 5 is a stellar system commonly catalogued as a globular cluster (GC), located in the inner bulge of our Galaxy (its Galactic coordinates are $l = 3.8395$, $b = 1.6868$, at a distance of 5.9 kpc (Valenti et al. 2007). It is affected by severe differential reddening (Ortolani et al. 1996), with an average color excess $E(B-V) = 2.38$ (Barbuy et al. 1998; Valenti et al. 2007). Ferraro et al. (2009, hereafter F09) discovered the presence of two distinct sub-populations, which define two red clumps (RCs) clearly separated in luminosity in the $(K, J-K)$ color–magnitude diagram (CMD) and show significantly different iron content: the bright RC at $K = 12.85$ is populated by a quite metal-rich (MR) component ([Fe/H] $\gtrsim +0.3$), while the faint clump at $K = 13.15$ corresponds to a relatively metal-poor (MP) population at [Fe/H] $\sim -0.2$. This discovery, such a large difference in the iron content ($\Delta$ [Fe/H] $> 0.5$ dex) was found only in ω Centauri, a GC-like system in the Galactic halo, now believed to be the remnant of a dwarf galaxy accreted by the Milky Way. Origlia et al. (2011) presented a detailed study of the abundance patterns of Terzan 5, demonstrating that (1) the abundances of light elements (like O, Mg, and Al) measured in both sub-populations do not follow the typical anti-correlations observed in genuine GCs; (2) the overall iron abundance and the α-enhancement of the MP component demonstrate that it formed from a gas mainly enriched by Type II supernovae (SNII) on a short timescale, while the progenitor gas of the MR component was further polluted by SNIIa on longer timescales; and (3) these chemical patterns are strikingly similar to those measured in the bulge field stars.

These observational results demonstrate that Terzan 5 is not a genuine GC, but a stellar system that has experienced complex star formation and chemical enrichment histories. Indeed, it is likely to have been much more massive in the past than today (with a mass of at least a few $10^7-10^8 M_\odot$), while its current value is $\sim 10^6 M_\odot$; Lanzoni et al. 2010, hereafter L10), thus to retain the high-velocity gas ejected by violent SN explosions. Moreover, the collected evidence indicates that it formed and evolved in strict connection with its present-day environment (the bulge), thus suggesting the possibility that it is the relic of one of the pristine fragments that contributed to form the Galactic bulge itself. In this context, the extraordinary population of millisecond pulsars (MSPs) also observed in Terzan 5 can find a natural explanation. In fact, the large number of SNII required to account for the observed abundance patterns would be expected to have produced a large population of neutron stars, mostly retained by the deep potential well of the massive proto-Terzan 5. The large collisional rate of this system (Verbunt & Hut 1987; L10) may also have favored the formation of binary systems containing neutron stars and promoted the recycling process responsible for the production of the large MSP population now observed in Terzan 5.

Within this exciting scenario, we are now coordinating a project aimed at reconstructing the origin and the evolutionary history of Terzan 5. However, severe limitations to the detailed analysis of the evolutionary sequences in the optical CMDs are introduced by the presence of large differential reddening. To face this problem here we build the highest-resolution extinction map ever constructed in the direction of Terzan 5.

2. DIFFERENTIAL REDDENING CORRECTION

2.1. The Data Set

The photometric data used in this work consist of a set of high-resolution images obtained with the Wide Field Channel (WFC) of the Advanced Camera for Survey (ACS) on board the Hubble Space Telescope (GO-9799; see F09; L10). The ACS-WFC camera has a field of view (FoV) of $\sim 200'' \times 200''$ with a plate

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The probability that Terzan 5 was accreted from outside the Milky Way (as supposed for ω Centauri) is therefore quite low.

Its 34 MSPs amount to $\sim 25\%$ of the entire sample of MSPs known to date in Galactic GCs (Ransom et al. 2005; see the updated list at http://www.naic.edu/~pfreire/GCpsr.html).

* Based on observations with the NASA/ESA HST, obtained at the Space Telescope Science Institute, which operated by AURA, Inc., under NASA contract NAS5-26555.
scale of 0\'05 pixel$^{-1}$. Both F606W (hereafter $V$) and F814W ($I$) magnitudes are available for a sample of about 127,000 stars. The magnitudes were calibrated on the VEGAMAG photometric system by using the prescriptions and zero points by Sirianni et al. (2005). The final catalog was placed onto the Two Micron All Sky Survey absolute astrometric system by following the standard procedure discussed in previous works (e.g., L10). The ($I, V-I$) CMD shown in Figure 1 clearly demonstrates the difficulty of studying the evolutionary sequences in the optical plane, because of the broadening and distortion induced by differential reddening. In particular, the red giant branch (RGB) is anomalously wide ($\Delta(V-I) \sim 0.8$ mag) and the two RCs appear highly stretched along the reddening vector.

2.2. The Method

The method here adopted to compute the differential reddening within the ACS FoV is similar to those already used in the literature (see, e.g., McWilliam & Zoccali 2010; Nataf et al. 2010). Briefly, the amount of reddening is evaluated from the shift along the reddening vector needed to match a given (reddened) evolutionary sequence to the reference one, which is selected as the least affected by the extinction. Thus, the first step of this procedure is to define the reddening vector in the considered CMD. It is well known that the extinction $A_\lambda$ varies as a function of the wavelength $\lambda$, and the shape of the extinction curve is commonly described by the parameter $R_\lambda = A_\lambda / E(B-V)$. In order to determine the value of $R_\lambda$ at the reference wavelengths of the F606W and F814W filters ($\lambda_V = 595.8$ and $\lambda_I = 808.7$ nm, respectively; see http://etc.stsci.edu/etcstatic/users_guide), we adopted Equations (1), (3a), and (3b) of Cardelli et al. (1989), obtaining $R_V = 2.83$ and $R_I = 1.82$. With these values we then computed the reddening vector shown in Figure 1. A close inspection of the CMD shows that the direction of the distortions along the RCs and the RGB is well aligned with the reddening vector.

As second step, the ACS FoV has been divided into a regular grid of $m \times n$ cells. The cell size has been chosen small enough to provide the highest possible spatial resolution, while guaranteeing the sampling of a sufficient number of stars to properly define the evolutionary sequences in the CMD. In order to maximize the number of stars sampled in each cell, we used the main sequence (MS). After several experiments varying the cell size, we defined a grid of $25 \times 25$ cells, corresponding to a resolution of 8\'0.05 × 8\'0.05. In order to minimize spurious effects due to photometric errors and to avoid non-member stars, we considered only stars brighter than $V = 26.6$ and with $2.7 < (V-I) < 3.7$ colors. We also set the upper edge of the CMD selection box as the line running parallel to the reddening vector (see Figure 2). With these prescriptions the number of stars typically sampled in each cell is larger than 60, even at large distance from the cluster center.

The accurate inspection of the MS population in each cell allowed us to identify the one with the lowest extinction (i.e., where the MS population shows the bluest average color): it is located in the southeast region of the cluster at a distance $r \approx 80''$ from its center. The stars in this cell are shown in the left panel of Figure 2 and those enclosed in the selection box have been used as reference sequence for evaluating the differential reddening in each cell. As a “guide line” of this sequence we used an isochrone of 12 Gyr and metallicity $Z = 0.01$ (from
For each cell of the grid we determined the mean \((V - I)\) color and \((V)\) magnitude. A sigma-clipping rejection at 2σ has been adopted to minimize the contribution of Galactic disk stars (typically much bluer than those of Terzan 5) and any other interloper. Each cell is then described by the \((<V - I>, <V>)\) color–magnitude pair, which defines the equivalent cell-point in the CMD (as an example, see the cross marked in the right panel of Figure 2). The relative color excess of each \(i\)th cell, \(\delta[E(V - I)_i]\), is estimated by quantifying the shift needed to move the equivalent cell-point onto the reference sequence along the reddening vector (as an example, see the right panel of Figure 2). From the value of \(\delta[E(V - I)_i]\), the corresponding \(\delta[E(B - V)_i]\) is easily computed using the relation

\[
\delta[E(B - V)_i] = \frac{\delta[E(V - I)_i]}{(R_V - R_I)},
\]

where \(i = 1, m \times n\) and \(m \times n = 625\) is the total number of cells in our grid. The \(V\) and \(I\) magnitudes of all stars in the \(i\)th cell are then corrected by using the derived \(\delta[E(B - V)_i]\) and a new CMD is built. The whole procedure is iteratively repeated and a residual \(\delta[E(B - V)_i]\) is calculated after each iteration. The process stops when the difference in the color excess between two subsequent steps becomes negligible (=0.02 mag). The final value of the relative color excess in each cell \(\delta[E(B - V)_i]\) is thus given by the sum over all the iterative steps. For robustness, we applied this procedure in both the \((I, V - I)\) and \((V, V - I)\) planes. The difference between the two estimates turned out to be always smaller than ~0.01 mag and the average of the two measures was then adopted as the final estimate of the differential reddening in each cell.

### 2.3. Error Estimate and Caveats

Our estimate of the error associated to the color excess in each cell is based on the method described by von Braun & Mateo (2001; see also Alonso-García et al. 2011). We considered the uncertainty on the mean color of the \(i\)th cell as the main source of error on the value of \(\delta[E(B - V)_i]\). This latter was then computed as the ratio between the 1σ dispersion of the mean color and the parameter \(a = \cos(180 - \theta)\), where \(\theta\) is the angle between the reddening vector and the color axis. Geometrically, this is equivalent to measuring the difference between the values of \(\delta[E(B - V)_i]\) of the first and last contact points of the color error bar when moved along the reddening vector to match the reference line. We did not consider the error on the mean magnitude because, since the reference line is almost vertical, its contribution is negligible. Following these prescriptions, we obtain a typical formal error of about 0.03 mag on each color excess value \(\delta[E(B - V)_i]\).

A potential problem with this procedure to quantify the differential reddening of Terzan 5 is the presence of two stellar populations with distinct iron abundances. Indeed, the MR population is expected to be systematically redder than the MP one in the CMD, and we therefore expect that at least a fraction of stars with redder colors along the MS are genuine MR objects, and not MR stars affected by a larger extinction. However, by using the Girardi et al. (2010) isochrones, the
expected intrinsic difference in the \((V - I)\) color between the MR and MP populations is only \(\delta (V - I) \sim 0.05\) mag. Moreover, the MR population has been found to be more centrally segregated than the MP one (F09; L10). Hence, we expect the former to become progressively negligible with increasing radial distance from the cluster center. On the other hand, the uncertainties due to the photometric errors are dominant in the central region of the system, where the two populations are comparable in number. Finally, the use of average values for the color and magnitude in each cell \((\langle V - I \rangle \text{ and } \langle V \rangle)\), with the addition of a sigma-clipping rejection algorithm, should reduce the effect of contamination by MR stars. Thus, an overall error of 0.05 mag on the color excesses \(\delta [E(B - V)]_i\) is conservatively adopted to take into account any possible residual effects due to the presence of a double population in Terzan 5.

3. RESULTS

The final differential reddening map in the direction of Terzan 5 is shown in Figure 3, with lighter colors indicating less obscured regions and the center of gravity and core radius (L10) also marked for reference. We find that, within the area covered by the ACS-WFC, the color excess variations can be as large as \(\delta E(B - V) = 0.67\) mag. This is consistent with the value of 0.69 mag estimated by Ortolani et al. (1996) from the elongation of the RC. The obscuring clouds appear to be structured in two main dusty patches: the first one is located in the northwestern corner of the map at 30°–35° from the center, with an average differential extinction \(\delta E(B - V) > 0.4\) mag and a peak value of 0.67 mag. The second one is placed in the southeastern corner, with typical values of \(\delta E(B - V) \sim 0.3\) mag. These two regions seem to be connected by a bridge-like structure with \(\delta E(B - V) \gtrsim 0.2\)–0.3 mag.

We used this map to correct our photometric catalogue. Figure 4 shows the comparison between the observed (left panel) and the differential-reddening-corrected (right panel) CMDs in the \((V, V - I)\) plane. After the correction, both the color extension of the RC and the RGB width are significantly reduced by 40% and >50%, respectively, and V magnitudes become \(\sim 0.5\) mag brighter. To properly quantify the effect of such a correction on the MS width, we selected the stars along an almost vertical portion of MS and compared their color distributions before and after the correction. To this end, we selected stars with \(25 < V < 25.5\) in the observed CMD, and 0.5 mag brighter in the corrected one (see the dashed lines in Figure 4). The result is shown in the bottom panels of the figure. Before the correction the MS color distribution is well represented by a Gaussian with a dispersion \(\sigma = 0.18\), significantly larger than the photometric error at this magnitude level \((\sigma_{\text{phot}} \sim 0.13)\). Instead, the intrinsic width of the corrected MS is well reproduced by the convolution of two Gaussian functions separated by 0.05 mag in color, with a ratio of 1.6 between their amplitudes, and each one having \(\sigma = 0.13\) equal to the photometric error. Such a color separation corresponds to what expected for two stellar populations with metallicities equal to those measured in Terzan 5 (see Section 2.3). The adopted ratio between the amplitudes corresponds to the number counts ratio between MP and MR populations (L10). Hence, these two Gaussian functions correspond to the two sub-populations at different metallicities observed in Terzan 5. Note that the corrected MS color distribution shows an asymmetry toward the redder side, which is more pronounced in the center of the system and decreases at progressively larger distances. The highest amplitude Gaussian (corresponding to the MP population) is unable to properly account for this feature, while the convolution with the reddest and lowest amplitude Gaussian (corresponding to the MR population, which is observed to decrease in number...
Figure 4. Comparison between the optical CMDs of Terzan 5 before (left panel) and after (right panel) the differential reddening correction. Only stars located at a distance $20'' < r < 80''$ are plotted for sake of clarity. All the sequences in the corrected CMD are much less stretched along the reddening vector. The bottom panels show the color distributions (gray histograms) for a nearly vertical portion of MS at $25 < V < 25.5$ in the observed CMD, and at $24.5 < V < 25$ in the corrected one (see the dashed lines in the two upper panels). Before the correction, the color distribution is well represented by a Gaussian with $\sigma = 0.18$ (while the photometric error is $\sigma_{\text{phot}} \sim 0.13$). After the correction, the distribution is well fitted by the convolution of two Gaussian functions with $\sigma = 0.13$, separated by 0.05 mag in color and with an amplitude ratio of 1.6. The solid Gaussian corresponds to the MP population of Terzan 5, while the dotted one represents the MR component (Section 3).

with increasing distance from the center) provides an excellent match.

The derived reddening correction was also applied to the $(K, V - K)$ CMD obtained from the combination of the ACS and near-infrared data (see F09). Figure 5 shows the corrected CMD with two well-separated RGB sub-populations and the two distinct RCs. The ratio between the number of stars counted along the two RGBs is $\sim 1.5$, in very good agreement with the value from the RCs (see above and L10).

The differential-reddening-corrected CMD can be finally used to estimate the absolute color excess in the direction of Terzan 5. Different values of $E(B - V)$ are provided in the literature, ranging from 1.65 (estimated by Armandroff & Zinn 1988 from the strength of an interstellar band at 8621 Å), up to 2.19 and 2.39, derived from optical or infrared photometry (Barbuy et al. 1998; Cohn et al. 2002; Valenti et al. 2007). However, all these estimates are average values and do not take into account the presence of differential reddening. Here, instead, we want to build a two-dimensional map of the absolute reddening and, to this end, we shifted the corrected $(V, V - I)$ CMD of Terzan 5 along the reddening direction until it matches

Figure 5. Brightest portion of the differential-reddening-corrected $(K, V - K)$ CMD of Terzan 5, with error bars also reported. Beside the two RCs, also two well-separated RGBs are clearly distinguishable. The solid and dashed lines correspond to the mean ridge lines of the MP and the MR sub-populations, respectively.

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8 A free tool providing the color excess values at any coordinate within the ACS-WFC FoV can be found at the Web site http://www.cosmic-lab.eu/Cosmic-Lab/.
the CMD of 47 Tucanae, adopted as reference cluster since it is metal-rich, low extincted and with a well-determined distance modulus. In particular, we looked for the best match between the RC of the MP population of Terzan 5 and the RC of 47 Tucanae. We adopted the color excess $E(B-V) = 0.04$ and the distance modulus $\mu_0 = 13.32$ for 47 Tucanae (from Ferraro et al. 1999), and $\mu_0 = 13.87$ for Terzan 5 (Valenti et al. 2007). From the Girardi et al. (2010) model, in the $(V, V-I)$ plane, the RC of 47 Tucanae turns out to be 0.02 mag brighter and 0.03 mag bluer than the MP one of Terzan 5 because of a difference in their metallicity ([Fe/H] = −0.70 for 47 Tucanae and [Fe/H] = −0.27 for the MP population of Terzan 5; see Ferraro et al. 1999 and Origlia et al. 2011, respectively). Taking into account these slight differences, a nice match of the two RCs is obtained by adopting $E(B-V) = 2.15$ mag. Since the corrected CMD is, by construction, referred to the bluest cell, the absolute color excess within the ACS-WFC FoV varies from $E(B-V) = 2.15$ up to $E(B-V) = 2.82$ mag. In order to check the reliability of these estimates, we compared it with the values found by Gonzalez et al. (2012) from the Vista Variable in the Via Lactea survey. In a $2' \times 2'$ region centered on Terzan 5, these authors found an extinction $A_K = 0.80$ mag. Using the Cardelli et al. (1989) coefficients to convert $E(B-V)$ to $A_K$, our estimate varies from $A_K = 0.75$ to $A_K = 0.98$ mag, in nice agreement with Gonzalez et al. (2012) result.

Moreover, we looked for a possible correlation between the color excess and the dispersion measures for 34 MSPs of Terzan 5 studied by Ransom (2007). In this case we did not find a strong correlation, probably because mostly (75%) of the MSP sample is situated within the inner 20'' of the system, where the estimate of $E(B-V)$ is more uncertain (see Section 2.3).

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