The Age of the Old Metal-poor Globular Cluster NGC 6397
Using WFC3/IR Photometry*

Matteo Correnti1, Mario Gennaro1, Jason S. Kalirai1,2, Roger E. Cohen1, and Thomas M. Brown1

1 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA; correnti@stsci.edu
2 Center for Astrophysical Science, John Hopkins University, Baltimore, MD 21218, USA

Received 2018 February 14; revised 2018 July 16; accepted 2018 July 24; published 2018 September 11

Abstract

Globular clusters (GCs) in the Milky Way represent the ideal laboratory to establish the age of the oldest stellar populations and to measure the color–magnitude relation of stars. Infrared (IR) photometry of these objects provides a new opportunity to accomplish this task. In particular, at low stellar masses, the stellar main sequence (MS) in an IR color–magnitude diagram (CMD) exhibits a sharp “kink” (due to opacity effects in M dwarfs), such that lower mass and cooler dwarfs become bluer in the $F_{110W} - F_{160W}$ color baseline and not redder. This inversion of the color–magnitude relation offers the possibility to fit GC properties using IR imaging, and to reduce their uncertainties. Here, we used the IR channel of the Wide Field Camera 3 on board the Hubble Space Telescope to obtain new, deep high-resolution photometry of the old metal-poor GC NGC 6397. From the analysis of the GC CMD, we revealed below the MS “kink” the presence of two MSs with different chemical compositions. We derived the cluster fiducial line and we compared it with a grid of isochrones over a large range of parameter space, allowing age, metallicity, distance, and reddening to vary freely within reasonable selected ranges. We derived an age of 12.6 Gyr with a random uncertainty $\sigma \sim 0.7$ Gyr. These results confirm that the analysis of the IR color–magnitude of stars provide a valuable tool to measure the GC ages and offers a new venue to determine their absolute age to sub-Gyr accuracy with next generation IR telescopes.

Key words: galaxies: star clusters: individual (NGC 6397) – globular clusters: general

1. Introduction

Globular clusters (GCs) are among the oldest objects in the universe for which accurate ages can be determined. Determining the absolute age of these objects is a measure of when baryonic structure formation occurred in the universe (Spergel et al. 2003), thus providing a strict lower limit on its age. Moreover, it provides robust constraints on the physics adopted in stellar evolutionary models (Salaris & Weiss 1998; Cassisi et al. 1999; Dotter et al. 2008; VandenBerg et al. 2008). Measuring the relative age difference between clusters associated with distinct structural components of the Galaxy also yields the formation and assembly timescale of these parent populations.

Derivation of star cluster ages has primarily relied on the analysis of visible-light color–magnitude diagrams (CMDs) and comparison with stellar evolutionary models. However, uncertainties in the other fundamental parameters have hampered the estimates of absolute GC ages. In addition to the systematic uncertainties related to the different assumption in the stellar models ($\sigma = 0.4$ Gyr—Chaboyer & Krauss 2002; Valle et al. 2013a, 2013b) and the cluster metallicity ($\sigma = 0.5$ Gyr for a 0.2 dex error —Dotter et al. 2008) the largest uncertainty impacting this technique comes from simultaneously “fitting” the age at a given distance and reddening ($\sigma = 1.5$–2 Gyr—Chaboyer 2008).

Recently, a new tool was introduced to measure accurate star cluster parameters based on high-precision infrared (IR) CMDs. Sarajedini et al. (2009) and Bono et al. (2010) demonstrated that the MS in a pure IR CMD exhibits a change in the color–magnitude relation of stars at $\sim 0.5 M_{\odot}$, with color rapidly shifting to the blue (Pulone et al. 1998, 1999; Zoccali et al. 2000; Calamida et al. 2009; Kalirai et al. 2012; Milone et al. 2012b, 2014; Monelli et al. 2015). We will refer to this feature as the MS kink (hereafter MSK). This feature arises from a redistribution of the emerging stellar flux due to a change in opacity caused by the collision-induced absorption of $H_2$ (Linsky 1969; Saumon et al. 1994, and references therein). This feature presents two fundamental characteristics: the MSK luminosity and the bending shape are dependent on metallicity, but are independent of age beyond $\sim 1$ Gyr, allowing to partially break the degeneracy between these two parameters. Furthermore, the shape of the color–magnitude relation, particularly its shift to the blue at magnitudes fainter than the MSK, provides a new opportunity to simultaneously constrain the distance and reddening accurately.

In this context, in Correnti et al. (2016, hereafter C16) we demonstrated the predictive power and the constraints imposed on GC properties by the observation of this feature. We analyzed Hubble Space Telescope (HST) Wide Field Camera 3 IR (WFC3/IR) archival observations of four GCs (namely, 47 Tuc, M 4, NGC 2808, and NGC 6752) for which the data are deep enough to reach at least $\sim 2$ mag below the MSK, allowing us to fully sample the bending of the MS at low masses. From the comparison of the fiducial lines, obtained with an ad hoc fitting method, with a grid of isochrones, we derived the best-fit parameters, we quantified the correlations among them and we obtained the individual uncertainties. From our analysis, we derived random age uncertainties of $\sigma \sim 0.7$–1.1 Gyr. Hence, observing the near-IR MSK offers a new venue to push the absolute age of GCs to sub-Gyr statistical accuracy.

Although the clusters analyzed in C16 provide a fairly good sample to test the predictive power of the MSK, they do not...
cover the entire metallicity regime probed by Galactic GCs, spanning only a limited range ([Fe/H] \(\approx\) \(-0.7\)–\(-1.5\) dex). Unfortunately, our sample lacked a genuine old metal-poor cluster. Age measurements for these old metal-poor stellar systems is of fundamental importance. For example, if it can be established that these objects formed \(\geq\)13 Gyr ago, then they must have formed in very low mass halos and they have been affected by reionization (Bullock & Johnston 2005; Gnedin 2010).

In this context, we obtained new HST WFC3/IR observations of the old metal-poor GC NGC 6397. This cluster represents an ideal candidate to complement our sample, being near \(d \approx 2.3\) kpc (Harris 1996) and one of the most metal-poor clusters in the Milky Way ([Fe/H] \(\approx\) \(-2.0\) dex, Gratton et al. 2003). Performing the same analysis as in C16, we derived the GC best-fit parameters and their uncertainties. This study allows us to obtain an independent and statistically accurate age for the GC NGC 6397. Moreover, adding NGC 6397 to the C16 sample provides a unique opportunity to test the age–metallicity relation of Milky Way GCs. In fact, NGC 6397 data provide a point to anchor the age–metallicity relation in the low metallicity regime.

The remainder of the paper is organized as follows: the data set and reduction is presented in Section 2. In Section 3, we show the cluster CMD and Section 4 describes the method adopted to obtain its fiducial line. In Section 5, we derived the best-fit isochrones and the probability distribution functions, thus obtaining the cluster best-fit parameters and their uncertainties. In Section 6, we show the age–metallicity relation obtained from the whole sample (NGC 6397 and the 4 GCs analyzed in C16). Finally, in Section 7, we summarize and discuss the results.

2. Observations and Data Reduction

NGC 6397 was observed with HST on 2016 March 08 using the IR channel of the WFC3 as part of the HST program 14124 (PI: M. Correnti; MAST data can be found at doi:10.17909/T9P966). The cluster was observed in the two filters F110W and F160W. Four exposures were taken in each filter, with exposure times of \(\sim 250\) and \(\sim 400\) s, respectively. To resample the PSF, mitigate hot pixels, and minimize errors from flat fielding, we used a four-point dither pattern in each filter. To ensure that the confusion limit does not truncate the photometric depth reached in the cluster, observations were taken at approximately 1/3 from NGC 6397’s center.

To reduce NGC 6397 images, we used the following approach: calibrated .flt science images and a drizzled, stacked, distortion-corrected .drz reference image were retrieved from the HST archive. The first are the products of the calwfc3 data reduction pipeline. The latter are the results of the combination of the .flt files using AstroDrizzle with a default parameter set, as provided by the WFC3 Team. The pipeline uses the latest reference files to perform bad pixel flagging and corrections for dark current, nonlinearity, flat fielding, and up-the-ramp fitting of multiple readouts per WFC3/IR exposure. Additional preprocessing and PSF photometry were performed using the latest version of Dolphot\(^3\) (Dolphin 2000, and numerous subsequent updates), which includes preprocessing and photometry modules customized to each camera on board HST as well as precomputed PSFs customized to each filter. Before performing PSF photometry, the WFC3/IR module of Dolphot was used to mask bad pixels and generate a sky frame corresponding to each science image.\(^4\) Iterative PSF photometry was performed simultaneously on the .flt images using the drizzled .drz image as a reference frame for alignment. Dolphot has many parameters governing the details of the image alignment, photometry, and aperture corrections, and a detailed description can be found in Williams et al. (2014). After testing on the NGC 6397 data as well as sets of similar WFC/IR imaging of Galactic bulge GCs (R. E. Cohen et al. 2018, in preparation), using both observed catalogs and Dolphot artificial star tests, we found that the optimal compromise between photometric completeness and ability to reject spurious sources resulted from a hybrid between the parameters used by Williams et al. (2014) and those recommended by the Dolphot manual.

Specifically, the parameters modified from their default values were \texttt{Force} = 1 (which forces all sources to be classified as stars, improving precision in crowded fields at cost of background galaxy discrimination), \texttt{SigFind} = 3, \texttt{Pos-Step} = 0.1, \texttt{RCentroid} = 1, and \texttt{RCombine} = 1.415. With these settings, we achieved optimal image alignment and source detection.

The resulting photometric catalogs contain photometry in the VegaMag system as well as several diagnostic parameters (including sharpness, roundness, and crowding), which are useful to cull remaining artifacts and spurious detections. Based on the aforementioned tests, we found that requiring \([\text{sharp}] \leq 0.1, \text{crowd} \leq 0.25, \text{round} \leq 0.4\) and a photometric quality flag of 2 or less in each filter efficiently eliminated spurious detections while minimizing the loss of well-measured stellar sources. (e.g., Cohen et al. 2014; Dieball et al. 2016). Artificial star tests reveal that our photometry has \(S/N > 100\) and a (spatially integrated) completeness of \(\geq 50\%\) down to \(F160W \sim 20\), nearly 2 mag faintward of the MS kink (for a detailed description of artificial star tests, see Cohen et al. 2018).

3. Color–Magnitude Diagram: An MS split

Figure 1 shows the F160W versus F110W – F160W CMD for NGC 6397. A visual inspection of the cluster CMD shows that above the MS the MS is narrow and there are no evident signs of any large color spread or split. Conversely, at fainter luminosity below the MS, the MS broadens and it seems to be separated in two sequences. The presence of a double MS in NGC 6397 was already reported in Milone et al. (2012a). From the analysis of the multiband HST ACS/WFC and WFC3/UVIS photometry, the authors found that the cluster MS splits into two components: a primordial population, containing \(\sim 30\%\) of the stars, and a second generation with enhanced sodium and nitrogen, depleted carbon and oxygen, and a slightly enhanced helium abundance \((\Delta Y \sim 0.01)\).

The presence of an MS split below the MS in IR CMD is not completely unexpected: as discovered by Milone et al. (2012b, 2014) and confirmed in C16, for the GCs NGC 2808 and M 4, multiple populations, observed at larger masses, in optical bandpasses, are visible also in the IR at low stellar masses, below the MS. The presence of a double MS, below the MKS, is due to a different chemical composition of the subpopulations, with the blue MS representing the first stellar

---

\(^3\) http://americano.dolphinsim.com/dolphot/

\(^4\) We set \texttt{step} = 2 to generate high-resolution sky frames.
generation, having primordial helium and high oxygen, and the redder MS associated with a second generation consisting of stars enhanced in helium, nitrogen, sodium, and depleted in oxygen. Recently, Milone et al. (2017) demonstrated that the morphology of the IR MS below the MSK in the GC ω Cen is even more complex, indicating the presence of multiple sub-populations.

To verify the significance of the MS split suggested by the visual inspection of the CMD, we derived the color distribution of stars, in fixed magnitude intervals, in the region below the MSK. The left panel of Figure 2 shows a zoom-in view of the NGC 6397 CMD, whereas the color distribution of stars in the five magnitude intervals, over the range 18.50 < F160W < 21.00 mag, are shown in the right panel. Figure 2 shows a progressive broadening of the MS as a function of the magnitude, particularly below F160W > 19.50 mag, where the two sequences form two distinct peaks.

To further verify that the observed broadening is not caused by photometric errors, we conducted Monte Carlo simulations of a synthetic cluster with a single stellar population. Our goal is to simulate the most populated red MS and verify that a single population cannot also reproduce the blue sequence observed in the CMD. To do so, we randomly drew star masses using a Salpeter mass function, normalizing to the observed (completeness-corrected) number of stars. To each mass, we associated the corresponding magnitude and color from the best-fit isochrone (derived as described in Section 5.1) and we shift the intrinsic color of the model to match the fiducial line of the red MS (derived as described in Section 4). A component of unresolved binary stars, derived from the same mass function, is added to a fraction of the sampled stars. We use a flat distribution of primary-to-secondary mass ratios and we adopt a binary fraction of ≃15% (Davis et al. 2008). Finally, we add the photometric errors with a distribution derived from the artificial star tests. The derived simulated CMD (blue dots) and the color distribution below the MSK (blue lines) are superimposed in Figure 2 to the observed CMD and observed color distribution.

Our analysis indicates that NGC 6397 hosts a double MS below the MSK, as observed in NGC 2808 and M 4. In particular, the “primordial” population (i.e., the blue MS) is the less populated one, similarly to what is observed in M 4 and in agreement with the results obtained by Milone et al. (2012a).

4. Deriving the Fiducial Line

To obtain the NGC 6397 fiducial line, we follow the same approach used in C16 for the cluster M 4, where the primordial (blue) population is not the predominant one.

Briefly, we used a kernel-density-estimation to estimate the 2D probability density function (PDF) underlying the data in the CMD. We found the PDF global maximum and by moving along the direction of minimum gradient, we traced the ridge line. Then, to ensure the smoothness of the ridge line, we computed the corresponding bezier curve and we used this smooth approximation as the final fiducial line. As demonstrated in C16, this method is not prone to biases due to the presence of binaries and it accurately traces the fiducial line of the most prominent population when multiple MS are present.

Next, we adopted the following empirical approach, specifically customized for the case in which the MS that we want to trace is the less populated. We applied a magnitude–color cut in the CMD and selected stars fainter than F160W ∼ 18.50 mag and redder than (F110W − F160W)\textsubscript{fiducial}, where (F110W − F160W)\textsubscript{fiducial} is the color of the fiducial line that traces the most prominent population. After removing these objects from the catalog, we rederived the fiducial line and its error on the new data set.

Finally, the actual value for the fiducial line and its uncertainty is derived adopting a bootstrap approach. We drew 1000 samples from the cluster catalog (after the magnitude–color cut), using the same total number of stars, and allowing for repetitions. The fiducial line for each bootstrap catalog is calculated using the procedure outlined above. We then divided the ensemble of 1000 fiducial realization into 0.05 mag bins in F160W. We estimated the fiducial value and its error, assuming the bin center as the F160W fiducial value and half the bin size as its error. For the F110W − F160W color, we adopted the mean and standard deviation over the ensemble of fiducials, using the points that fell within each magnitude bin.

Figure 3 shows the cluster CMD with the superimposed fiducial line obtained as described above, whereas in Figure 4 we show the same zoom-in of the region below the MSK (as in Figure 2) and the corresponding color distribution in the five magnitude bins, to better illustrate the shape of the new fiducial line in this portion of the CMD. The mean fiducial color (red line) and its mean error (light red region) are reported in each bin. This comparison demonstrates that the newly derived fiducial line reproduces quite well the peak of the blue population.

To test the robustness of the obtained measure, we performed the following tests: we iterated the procedure by applying different magnitude cuts through a ±0.25 mag step with respect to the default value quoted above (i.e., F160W = 18.50). Then, we verified that the derived fiducial lines are consistent with each other within the errors and that the shape is not altered by the different selection choices.
Furthermore, for each bootstrap catalog we derived the mean color in the five magnitude bins of Figure 2, applying a smoothed naive estimator (Silverman 1986) to be insensitive to a particular binning starting point. To estimate the final fiducial magnitude and color values, we adopted the same procedure described above (i.e., the fiducial magnitude F160W is the bin center and the fiducial color is the mean over the different realization). As pointed out in C16 for the cluster M 4, due to the empirical procedure applied to derive the fiducial line, we acknowledge that the uncertainties derived in Section 5.3 could be slightly underestimated.

5. Constraints on the GC Parameters

5.1. Isochrones Fitting: Deriving the GC Age

To derive the cluster best-fit parameters in terms of age, metallicity, distance, and reddening, we followed the same approach as in C16. We compared the fiducial line with a set of stellar models from the Victoria–Regina evolutionary code (VandenBerg et al. 2014). We transformed the models to the WFC3/IR filter system by means of synthetic photometry using the MARCS library of stellar spectra (Gustafsson et al. 2008) and the most updated WFC3/IR throughputs and zero points. To take into account the extinction, we applied the Fitzpatrick (1999) extinction law to the spectra, before integrating them under the throughput curves.

We then built a grid of isochrones over a large range of the parameter space, allowing age, metallicity, distance, and reddening to vary freely over reasonable uniform priors that are consistent with the literature. The reference value and the adopted intervals are reported in Table 1. In detail, we used a fixed age range (i.e., from 11 to 15 Gyr), an interval of ±0.20 dex for the metallicity, and an interval of ±0.20 and 0.10 mag for distance and reddening, respectively. During the analysis, we iteratively readjusted the parameter range in order to center the derived best-fit results in the new interval and to ensure that the marginal probability in each variable falls to zero well within the ranges. The grid is obtained by adopting steps of 0.1 Gyr for the age, ±0.20 dex for the metallicity, and ±0.10 mag for distance and reddening.

As in C16, the only a priori fixed parameters are the [α/Fe] ratio, the helium abundance, and the extinction coefficient RV. For the [α/Fe] ratio, we adopted the value [α/Fe] = +0.4 dex (spectroscopic measures indicate [α/Fe] = +0.36 dex,
Table 1
GC Prior Parameters and Ranges

| Age\(_{\text{range}}\) | [Fe/H] | \(\Delta\) [Fe/H] | Reference | \((m - M)_b\) | \(\Delta (m - M)_b\) | \(E(B-V)\) | \(E(B-V)_{\text{range}}\) | Reference |
|-----------------|--------|-----------------|----------|--------------|-----------------|------------|-----------------|----------|
| 11.0–15.0       | –2.02  | ±0.20           | 1        | 12.12        | ±0.25           | 0.18       | ±0.10           | 2        |

Note. Columns (1): age interval (Gyr). (2): metallicity reference value (dex). (3): metallicity interval (dex). (4): reference for the metallicity value (4) Kraft & Ivans (2003). (5): distance modulus reference value (mag). (6): distance modulus interval (mag). (7): reddening reference value (mag). (8): reddening interval (mag). (9) reference for distance modulus and reddening values (2) Reid & Gizis 1998.

Figure 5. \(F160W\) vs. \(F110W - F160W\) for GC with the fiducial line (black line) and the best-fit isochrone (red line) derived as described in Section 5.1 superimposed. Best-fit parameters are reported in Table 2.

Figure 6. Residual of the fit between the best-fit isochrone and the fiducial line. Dark and light gray regions represent the 1\(\sigma\) and 2\(\sigma\) fiducial color errors.

Table 2
GC Best-fit Parameters

| Age | \(\sigma\) | [Fe/H] | \(\sigma\) | \((m - M)_b\) | \(\sigma\) | \(E(B-V)\) | \(\sigma\) |
|-----|----------|--------|----------|--------------|----------|------------|----------|
| 12.6| \(\pm 0.6\) | \(\pm 0.7\) | 1.88     | \(\pm 0.4\) | 12.02    | \(\pm 0.03\) | 0.22     | \(\pm 0.015\) |

Note. Columns (1): Age (Gyr). (2): Age uncertainty (Gyr, 68% confidence interval). (3): Metallicity (dex). (4): Metallicity uncertainty (dex, 68% confidence interval). (5): Distance modulus (mag). (6): Distance modulus uncertainty (mag, 68% confidence interval). (7): Reddening (mag). (8): Reddening uncertainty (mag, 68% confidence interval).

Carretta et al. 2010). The original helium abundance in the stellar models was obtained using Equation (1) and Equation (2) from Gennaro et al. (2010), after the ratio between [Fe/H] and [M/H] was taken into account using Equation (3) from Salari et al. (1993). We assumed the solar mixture from Asplund et al. (2009), a primordial helium abundance of \(Y_p = 0.2485\) from Izotov et al. (2007) and Peimbert et al. (2007), and a ratio of \(\Delta Y / \Delta Z = 1.5\). Finally, for the extinction coefficient, \(R_V\), we adopted the value \(R_V = 3.1\).

The best-fit isochrone has been obtained comparing the fiducial line with the isochrone grid and deriving for each isochrone the posterior PDF. Due to choice of uniform priors in our parameters, the posterior PDF is proportional to the likelihood \(L\), which is calculated using the following equation:

\[
L \approx \exp \left( -\frac{1}{2} \chi^2 \right),
\]

where the term \(\chi^2\) in Equation (1) is defined as:

\[
\chi^2 = \sum_{i=1}^{N} \frac{(\Delta\text{col}_i)^2}{\sigma_i^2},
\]

where \(\Delta\text{col}\) is the difference in color between the isochrones and the fiducial (i.e., \((F110W - F160W)_{\text{iso}} - (F110W - F160W)_{\text{fiducial}}\)), calculated at each point in the fiducial line. \(\sigma\) is the error associated with the fiducial color points, derived as described in Section 3. The best-fit isochrone is the one that maximizes the joint PDF for the four parameters.

Figure 5 shows the GC CMD with the fiducial line (black line) and the best-fit isochrone (red line) superimposed. The derived parameters and uncertainties from the best-fit isochrone (obtained as described in Section 5.3) are reported in Table 2. The fit residuals (i.e., the term \(\Delta\text{col}\) from Equation (2)) as a function of the magnitude \(F160W\) are shown in Figure 6. The best-fit isochrone reproduces the fiducial line quite well, with some discrepancies in the subgiant branch (SGB) region and below the MSK. For the bright portion of the CMD, a similar trend was observed also in C16, where all of the isochrones were slightly redder (\(\Delta\text{col} \sim 0.02–0.04\) mag) than the fiducial line in the SGB and red giant branch region. We note that the same behavior was pointed out also in VandenBerg et al. (2013) in their analysis of visible-light photometry. This difference can be caused by a series of factors: small zero-point or systematic errors in the color–\(T_{\text{eff}}\) relations, problems in the stellar models concerning diffusion, convection, and/or the atmospheric boundary conditions (see VandenBerg et al. 2013, for a detailed discussion). Similar discrepancies between models and observations in the red giant branch, over a broad metallicity baseline, were also found by Cohen et al. (2015) from the analysis of wide field ground-based IR (\(J-K_s\)) photometry of 12 Galactic GCs.
Below the MSK, the fiducial line exhibits a change with respect to the “expected” color trend, bending slightly toward the red at $F160W \sim 19$ mag, before turning back toward bluer colors at $F160W \sim 20$ mag, producing a step in the fiducial shape that is not present in the isochrone. The low density of stars in this region of the CMD, coupled with the intrinsic shape of the fiducial line, can produce this deviation from a smooth shape for the fiducial. To verify if the results obtained are influenced by this particular shape of the fiducial line, we derived the best-fit parameters using the fiducial line obtained from the mean color in the five magnitude bins below the MSK (i.e., using only five data point below $F110W = 18.50$ mag). This method is less prone to small-scale variations and attributes less weight to this portion of the CMD when the fiducial line is compared with the isochrones’ grid. Adopting this fiducial, we obtained the following values for the best-fit parameters: age $= 12.80$ Gyr, metallicity $[\text{Fe/H}] = -1.87$ dex, distance modulus $(m - M)_0 = 12.01$ mag, and reddening $E(B-V) = 0.21$ mag.

Finally, we also derived the best-fit parameters using the fiducial lines obtained with the different magnitude cuts (i.e., ±0.25 mag step with respect to the default value $F160W = 18.50$ mag). In this case, we obtained variations of ±0.2 Gyr for the age, ±0.02 dex for the metallicity, ±0.01 mag for the distance modulus, and ±0.01 mag for the reddening.

5.2. Comparison with Literature Estimates

To test that the isochrone fitting procedure provides reasonable values for the best-fit parameters, we compared our results with several literature estimates. Due to its proximity, NGC 6397 has been thoroughly observed and analyzed in many studies, which derived its age using different methods and tracers. In this context, large discrepancies exist in the age determination, with values ranging from 11.47 (Hansen et al. 2007) to 13.9 Gyr (Gratton et al. 2003). A nice summary of the main literature age estimates is provided in Table 2 in Torres et al. (2015). For the metallicity, spectroscopic measures in the literature yield $[\text{Fe/H}] \simeq -2.0$ ([Fe/H] = $-2.03 \pm 0.05$ dex, Gratton et al. 2003, [Fe/H] = $-2.02 \pm 0.07$ dex, Kraft & Ivans 2003, [Fe/H] = $-1.99$ dex, Carretta et al. 2009, and [Fe/H] = $-2.10$ dex, Husser et al. 2016, and references therein). From the analysis of the GC white dwarf cooling sequence, Hansen et al. (2013) derived $[\text{Fe/H}] = -1.8$ dex, while Anthony-Twarog & Twarog (2000), from the analysis of the GC CMD using Stromgren photometry, obtained $[\text{Fe/H}] = -1.84$ dex. As in C16, the most direct comparison is with the results obtained in VandenBerg et al. (2013), which, using the same stellar evolutionary code, although with slightly different prescriptions for the isochrone computation, derived the cluster best-fit parameter from the analysis of HST ACS visible-light photometry. VandenBerg et al. (2013) derived an...
The age estimate is in good agreement with the value obtained in this work, while our metallicity is slightly higher, although consistent, within 2σ, with the literature values. For the true distance modulus, literature values span the interval 12.03–12.13 mag (Reid & Gizis 1998; Gratton et al. 2003; Hansen et al. 2007), whereas the reddening is $E(B-V) = 0.18 \pm 0.01$ mag (Reid & Gizis 1998; Richer et al. 2008, and references therein). While the derived value for the distance modulus is in good agreement with previous works, our estimate of the reddening $E(B-V)$ is slightly higher (of the order of 0.02–0.04 mag). However, literature values translate to an apparent distance modulus $(m-M)_V = 12.59$–12.68 mag, in agreement within the errors with our estimate ($(m-M)_V = 12.70$ mag).

Finally, during the review process, Brown et al. (2018) published a paper in which they obtained a direct trigonometric parallax of NGC 6397, exploiting the HST/WFC3 spatial scanning mode. The authors obtained a true distance modulus $(m-M)_0 = 11.89 \pm 0.07 \pm 0.09$ mag and an absolute cluster age of $13.4 \pm 0.7 \pm 1.2$ Gyr. Their distance modulus is shorter than our estimate (and literature estimates) at a level of 1σ–2σ, although consistent with recent dynamical analysis (Watkins et al. 2015). Despite using the same stellar evolutionary code, the age estimate is slightly higher than the one derived by Vandenberg et al. (2013) and by this work (+0.4 and +0.8 Gyr, respectively), although consistent within 1σ with both works.

5.3. Posterior PDF: Deriving Age Uncertainties

To measure the uncertainties for each best-fit parameter we derived, for each isochrone of the grid, the joint posterior PDF. The latter, due to choice of uniform priors for our parameters, is proportional, within the specified prior ranges, to the likelihood $L$, obtained from Equations (1) and (2). Then, to derive the 1D posterior PDF for each parameter (1D $P(X)$), we marginalized the 4D PDF ($P(X,Y,W,Z)$ where $X$, $Y$, $W$, and $Z$ are age, metallicity, reddening, and distance modulus) over the remaining three parameters (i.e., $Y$, $W$, and $Z$). Each individual uncertainty is obtained from the cumulative distribution of the marginalized 1D distribution. 1σ (2σ) confidence intervals are defined as the area enclosed within 16% (2.5%) and 84% (97.5%) of each
cumulative distribution. This would correspond to the true 1σ and 2σ uncertainties if the 1D PDFs were Gaussian. Figure 7 shows the derived random uncertainties for the four parameters. In particular, we obtain that random age uncertainties are of the order of σ ~ 0.7 Gyr.

Considering the uncertainties in the best-fit parameters when a different fiducial line is adopted (i.e., when a different magnitude cut is applied or a different method for tracing the faint part below the MSK), we acknowledge that the derived age uncertainties could be underestimated. Taking into account the age range derived in Section 5.1 and considering the uncertainties in the method, we estimate that the value σ ~ 1.0 is more representative of the GC age uncertainty.

To illustrate the correlations and interdependencies between the various parameters, we show in Figure 8 the 2D posterior PDFs of all the parameters. These 2D PDFs are obtained by the marginalization of the 4D PDF over two parameters instead of three.

Finally, we note that the quoted uncertainties only take into account random noise (number statistics and measurement errors). We acknowledge that the total uncertainty on GC parameters is further increased by the presence of a systematic component due to, e.g., the choice of the stellar evolution library, stellar atmospheres, and possible zero-point offsets (as well as other, more subtle, possibly unknown sources of uncertainty). Moreover, it is important to keep in mind that the results obtained in this study, as well as in C16, are strictly model-dependent. Adopting a different set of stellar models can produce different results in terms of best-fit parameters (for a detailed discussion, see Saracino et al. 2018). However, such issues are common for most age derivations of GCs. Our results demonstrate that using the IR photometry and the MSK as an age diagnostic represent a new venue to determine a GC’s age.

6. Age–Metallicity Relation

Adding NGC 6397 to the C16 sample allows us to provide a first estimate of the age–metallicity relation obtained from IR photometry. Although the sample is limited to five GCs, it spans a significant range of metallicity (from [Fe/H] ~ −1.9 dex to [Fe/H] ~ −0.7 dex). The slope of this relation is of fundamental importance to test high-resolution N-body simulation of galaxy formation, and inform the mass-merger history that leads to the build up of Milky Way–type halos (Mackey & Gilmore 2004; Font et al. 2011; Beers et al. 2012).

Figure 9 shows the age–metallicity relation derived using the five GCs in our sample (red dots), superimposed on the age–metallicity relation derived by VandenBerg et al. (2013) from their analysis (gray dots). VandenBerg et al. (2013) measures for the clusters in common are reported as black dots. The two age–metallicity relations are in good agreement, with a similar slope and normalization. We note that age uncertainties in VandenBerg et al. (2013) have been derived using a different approach with respect to our method. They are defined as the difference between the best-fit ages obtained by the different authors that independently determined the GCs distance moduli and ages. Hence, the error arising from the fitting of the horizontal branches and isochrones is ±0.25 Gyr. When uncertainties associated to the GC distances and chemical compositions are taken into account, the error is of the order of ~±1.5–2.0 Gyr.

The results from this project can be greatly enhanced with next generation space IR telescopes, such as the James Webb Space Telescope (JWST, see Kalirai 2018, for a detailed discussion). JWST offers increased photometric sensitivity, redder wavelength coverage, higher resolution, and larger fields of view compared to HST/WFC3-IR. This will enable high-precision detection and characterization of the MSK in stellar populations out to larger distances (e.g., clusters over a range of ages and metallicities) and toward extincted sightlines such as the Galactic bulge. Such data will yield new constraints on the age–metallicity relation of stars. Additionally, JWST can easily measure this feature in all Milky Way dwarf satellites and greatly enhance studies of their ancient star formation histories.

7. Summary and Conclusion

In this study, we analyzed new, deep, HST WFC3/IR observations of the old metal-poor GC NGC 6397. Following the work presented in C16, we exploited the constraints imposed on GC properties by leveraging the shape of the MS color–magnitude relation in pure IR CMDs.

We discovered the presence of at least two MS, being the bluer, less populated MS, the one corresponding to the first stellar generation. We used an ad hoc fitting method to derive the fiducial line of the cluster and we compared it with a grid of isochrones over a large range of parameter space. Age, metallicity, distance, and reddening can vary freely within reasonably selected ranges. From the comparison between the fiducial line and the isochrones, we calculated the joint posterior 4D PDF and we derived the best-fit isochrone by maximizing the 4D PDF. We measure a cluster age of 12.6 Gyr, in reasonable agreement with the results obtained by VandenBerg et al. (2013), who used the same stellar evolution code to analyze visible-light ACS photometry of NGC 6397.
Age uncertainty is derived by calculating the 1D posterior PDF. This involves marginalizing the 4D PDF over metallicity, distance, and reddening. The random age uncertainty is of the order of $\sim0.7$ Gyr. Taking into account the different values for the GC parameters obtained with the different fiducials and the uncertainties in the method, we estimate that an uncertainty of $\sigma \sim 1.0$ Gyr is more representative of the true random uncertainty.

Our results confirm that the IR color–magnitude relation and the MSK in the lower MS represents a promising tool to obtain absolute ages of GCs with sub-Gyr accuracy.

Orcid iDs

Matteo Correnti  https://orcid.org/0000-0001-6464-3257
Mario Gennaro  https://orcid.org/0000-0002-5581-2896
Thomas M. Brown  https://orcid.org/0000-0002-1793-9968

References

Anthony-Twarog, B. J., & Twarog, B. A. 2000, AJ, 120, 3111
Asplund, M., Grevesse, N, Sauval, A. J., & Scott, P. 2009, ARA&A, 47, 481
Beers, T. C., Carollo, D., Ivezic, Z., et al. 2012, ApJ, 746, 34
Bono, G., Stetson, P. B., VandenBerg, D. A., et al. 2010, ApJL, 708, L74
Brown, T. M., Casertano, S., Strader, J., et al. 2018, ApJ, 856, 6
Bullock, J. S., & Johnston, K. V. 2005, ApJ, 635, 931
Calamida, A., Bono, G., Stetson, P. B., et al. 2009, in IAU Symp. 258, The Ages of Stars (Cambridge: Cambridge Univ. Press), 189
Carretta, E., Bragaglia, A., Gratton, R. G., et al. 2009, A&A, 505, 117
Carretta, E., Bragaglia, A., Gratton, R. G., et al. 2010, A&A, 516, 55
Cassisi, S., Castellani, V., & the AGB Collaboration, 2009, A&A, 505, 134, 103
Chaboyer, B. 2008, in IAU Symp. 248, A Giant Step: From milli- to Micro-arcsecond Astrometry (Cambridge: Cambridge Univ. Press), 440
Chaboyer, B., & Krauss, L. 2002, ApJ, 567, 45
Cohen, R. E., Hempel, M., Mauro, F., et al. 2015, AJ, 145, 176
Cohen, R. E., Mauro, F., Geisler, D., et al. 2014, AJ, 148, 18
Cohen, R. E., Mauro, F., Alonso-Garcia, J., et al. 2018, AJ, 156, 41
Correnti, M., Gennaro, M., Kalirai, J. S., Brown, T. M., & Calamida, A. 2016, ApJ, 823, 18
Davis, D. S., Richer, H. B., Anderson, J., et al. 2008, AJ, 135, 2155
Dieball, A., Bedin, L. R., Knigge, C., et al. 2016, ApJ, 817, 48
Dolphin, A. E. 2000, PASP, 112, 1383
Dotter, A., Chaboyer, B., & Ivezic, Z., et al. 2008, ApJ, 681, 89
 Fitzpatrick, E. L. 1999, PASP, 111, 63
Font, A. S., McCarthy, I. G., Crane, R. A., et al. 2011, MNRAS, 416, 2802
Gennaro, M., Prada Moroni, P. G., & the AGB Collaboration, 2010, A&A, 518, 13
Gnedin, O. Y. 2010, in IAU Symp. 266, Star Clusters: Basic Galactic Building Blocks throughout Time and Space (Cambridge: Cambridge Univ. Press), 250
Gratton, R. G., Bragaglia, A., Carretta, E., et al. 2003, A&A, 408, 529
Gustafsson, B., Edvardsson, B., Eriksson, K., et al. 2008, A&A, 486, 951
Hansen, B. M. S., Anderson, J., Brewer, J., et al. 2007, ApJ, 671, 380
Hansen, B. M. S., Kalirai, J. S., Anderson, J., et al. 2013, Natur, 500, 51
Harris, W. R. 1996, AJ, 112, 1487
Husser, T., Kamann, S., Dreizler, S., et al. 2016, A&A, 588, 148
Izotov, Y. I., Thuan, T. X., & Stasińska, G. 2007, ApJ, 662, 15
Kalirai, J. S. 2018, ConPh, 59, 251
Kalirai, J. S., Richer, H. B., Anderson, J., et al. 2012, AJ, 143, 11
Kraft, R. P., & Ivans, I. I. 2003, PASP, 115, 143
Linsky, J. L. 1969, AJ, 156, 989
Mackey, A. D., & Gilmore, G. F. 2004, MNRAS, 355, 504
Milone, A. P., Marino, A. F., Bedin, L. R., et al. 2014, MNRAS, 439, 1588
Milone, A. P., Marino, A. F., Bedin, L. R., et al. 2017, MNRAS, 469, 800
Milone, A. P., Marino, A. F., Cassisi, S., et al. 2012b, ApJL, 754, L34
Milone, A. P., Marino, A. F., Piotto, G., et al. 2012a, ApJ, 745, 27
Monelli, M., Testa, V., Bono, G., et al. 2015, ApJ, 812, 25
Peimbert, M., Luridiana, V., & Peimbert, A. 2007, ApJ, 666, 636
Pulone, L., de Marchi, G., & Paresce, F. 1999, A&A, 342, 440
Pulone, L., Salaris, M., Weiss, A., & Buonanno, R. 1998, A&A, 336, 77
Reid, N. I. & Gizis, J. E. 1998, AJ, 116, 2929
Richer, H. B., Dotter, A., Hurley, J., et al. 2008, AJ, 135, 2141
Salaris, M., Chieffi, A., & Straniero, A. 1993, ApJ, 414, 580
Salaris, M., & Weiss, A. 1998, A&A, 335, 943
Sarajedini, A., Dotter, A., & Kirkpatrick, A. 2009, ApJ, 698, 1872
Saumon, D., Bergeron, P., Lunine, J. I., Hubbard, W. B., & Burrows, A. 1994, ApJ, 424, 333
Silverman, B. W. 1986, Density Estimation for Statistics and Data Analysis (London: Chapman and Hall)
Spigel, D., Verde, L., Peiris, H. v., et al. 2003, ApJS, 148, 175
Torres, S., Garcia-Bero, E., Althaus, L. G., & Camisassa, M. E. 2015, A&A, 581, 90
Valle, G., Dell’Omodarme, M., Prada Moroni, P. G., & Degl’Innocenti, S. 2013a, A&A, 549, 50
Valle, G., Dell’Omodarme, M., Prada Moroni, P. G., & Degl’Innocenti, S. 2013b, A&A, 554, 68
Vandenberg, D. A., Bergbusch, P. A., Ferguson, J. W., & Edvardsson, B. 2014, ApJ, 794, 72
Vandenberg, D. A., Brogaard, K., Leaman, R., & Casagrande, L. 2013, ApJ, 775, 134
Vandenberg, D. A., Edvardsson, B., Eriksson, K., & Gustafsson, B. 2008, ApJ, 675, 746
Watkins, L. L., van der Marel, R. P., Bellini, A., & Anderson, J. 2015, ApJ, 812, 149
Williams, B. F., Lang, D., Dalcanton, J. J., et al. 2014, ApJS, 215, 9
Zoccali, M., Cassisi, S., Frogel, J. A., et al. 2000, ApJ, 530, 418