1. INTRODUCTION

\( \omega \) Centauri is a fascinating and enigmatic object: it appears to be a globular cluster (GC), but it has a very complex stellar population, and with its unusual mass \( (M \sim 3 \times 10^6 \, M_\odot) \) it has often been suggested to be the remains of a larger stellar system. It has received a large amount of attention; for a review, see Meylan (2003). One of the most interesting results (Bedin et al. 2004) was the discovery that over a range of at least two magnitudes the main sequence splits into red and blue branches. Follow-up spectroscopic studies at medium resolution led to the finding that, contrary to any expectation from canonical stellar models, the bluer branch of the MS is more metal-rich than the red (Piotto et al. 2005). At the moment, the only explanation for the photometric and spectroscopic properties of the double main sequence is that it is all plausible that the bluer branch of the MS has an unusually high helium content (Norris 2004; King et al. 2012).

It has been suggested that this unusual He-rich population might come from material contaminated by the ejecta of massive \( (25 \, M_\odot) \) Norris (2004), or slightly less massive \( (10–14 \, M_\odot) \) Piotto et al. (2005) supernovae, from rapidly rotating low-metallicity massive stars (Maeder & Meynet 2006), or from intermediate-mass asymptotic-giant-branch stars (Izzard et al. 2004).

This double MS was not totally unexpected because Norris et al. (1996) found a bimodal distribution of \([Ca/H]\) for RGB stars based on low-resolution spectra, with a first peak at \([Ca/H] \sim -1.4\) and a second peak at \([Ca/H] \sim -1.0\). This result was partially confirmed in the same period by Suntzeff & Kraft (1996), who, using the calcium triplet method, found an \([Fe/H]\) distribution with a peak at \([Fe/H] \sim -1.7\) and a tail toward higher metallicities.

However, \( \omega \) Centauri is much more complex than that, because more than two stellar populations are present. Sollima et al. (2005) could identify at least four stellar populations on the subgiant branch (SGB) with mean \([Fe/H] = -1.7, -1.3, -1.0, \) and \(-0.6\) dex, respectively, based on CaT abundances. Villanova et al. (2007) photometrically identified at least five stellar populations in the SGB region, and three populations spectroscopically, based on their iron content, at \([Fe/H] = -1.68, -1.37, \) and \(-1.14\).

Several other studies tried to establish the number and iron content of the populations. The first was Calamida et al. (2009), based on Strömgren photometry of the red giant branch (RGB). The authors found six peaks in the iron distribution at \([Fe/H] = -1.73, -1.29, -1.05, -0.80, -0.42, \) and \(-0.07\) dex. On the other hand, Johnson & Pilachowski (2010), based on a metallicity distribution obtained by a large number of high-resolution RGB spectra, identified four groups at \([Fe/H] = -1.75, -1.50, -1.10, \) and \(-0.75\) dex. Recently, Pancino et al. (2011) also suggested the presence of a very metal-poor population at \([Fe/H] = -1.95\), based on high-resolution spectra.

Finally, Marino et al. (2011) found that their metallicity distribution is consistent with the presence of multiple peaks corresponding to \([Fe/H] = -1.75, -1.60, -1.45, \) and \(-1.00\), a broad distribution of stars extending between \(-1.40\) and \(-1.00,\) and a tail of metal-rich stars reaching values of \([Fe/H] = -0.70\).

In addition, Stanford et al. (2006) found that an age range of 2–4 Gyr exists in the cluster, based on the position and metallicity of stars in the TO–SGB region. This result was confirmed by Villanova et al. (2007), who also suggested that a large age spread could affect the cluster. In particular, they found that stars belonging to the most metal-poor group...
([Fe/H] \sim -1.7) span an age range of several gigayears and that, surprisingly, the most metal-rich component is also the oldest.

Based on this brief summary, it is clear that a more complete study is required in order to better determine the number and mean metallicity of subpopulations in \(\omega\) Centauri and its age–metallicity relation, which is the best way to understand the complex star formation history of this intriguing object. Such a study must take care to account for any possible spread in He and CNO that affects the stars of the cluster, as found by Norris (2004) and Marino et al. (2011).

The best region in the CMD for this purpose is the SGB, where the position of a star strongly depends not only on the metallicity, but also on the age. In this way, both age and metallicity can be used to disentangle and identify the subpopulations, as well as to study any possible age spread and age–metallicity relation affecting them.

For this purpose, we collected a large spectroscopic database that covers the entire SGB of the central \(\omega\) Centauri field (see Villanova et al. 2007). In Section 2 we present the observations and data reduction. In Section 3 we discuss the abundance measurements, while in Section 4 we present the results. In Sections 5 and 6 we discuss the implications of the observational facts presented in this paper for the stellar populations in \(\omega\) Centauri, the age spread, the age–metallicity relation, and the origin of this anomalous cluster.

2. OBSERVATIONS AND DATA REDUCTION

The spectroscopic data come from the ESO proposal 082.D-0424(A), and were collected in 2009 January–March with FLAMES@VLT+GIRAFFE. The sky was clear, and the typical seeing was \(\sim\)0.8 arcsec (FWHM). We used the MEDUSA mode, which obtains 132 spectra simultaneously. To have a high enough S/N and spectral resolution, we used the HR13 setup, which gives \(R = 22,500\) in the 6120–6405 Å range.

Our main target was the SGB, where we pointed 450 stars, divided into 7 placements and observed for 4 or 5 hr each. The remaining fibers were placed on HB \((\sim 270)\) and RGB \((\sim 80)\) stars and on the sky (10 fibers for each plate). Results for the RGB targets were already presented in Marino et al. (2011, 2012).

SGB target stars were selected from the \(3 \times 3\) mosaic of \(HST\) fields presented in Villanova et al. (2007) in order to cover the five SGBs of the \(m_{F435W} - m_{F625W}\) CMD identified in that paper. In this paper, we call the five SGBs A, B, C, D, and E (see Figure 1).

Stars were selected for the observations so that there were no neighbors closer than 0.6 arcsec and brighter than \(m_{F625W} + 2.5\) mag, where \(m_{F625W}\) is the magnitude of the target, to avoid possible contamination. Target stars were then further cleaned for any remaining contamination during the data analysis process, as explained in the following section. We also identified our targets in the ground-based photometry by Bellini et al. (2009). This was done to obtain the \(V\) magnitudes needed to estimate the gravity (see the next section). However, in a few cases we found that the \(V\) ground-based magnitude was widely discrepant compared to \(m_{F625W}\), probably because of the crowding. In order to remove this problem, we decided to use an interpolated \(V\) magnitude \((V_i)\). To do that, we plotted \(V\) versus \(m_{F625W}\). The relation is linear, so we fitted a straight line using a \(3\sigma\) clipping rejection algorithm. Finally, we adopted the \(V_i\) obtained from this relation and the appropriate \(m_{F625W}\) magnitude of each star.

The data were reduced using GIRAFFE pipeline 1.13 (Blecha et al. 2000), which corrects the spectra for bias and flat-fielding. (See http://girbldrs.sourceforge.net/ for documentation on the GIRAFFE pipeline and software.) A sky correction was applied to each stellar spectrum by subtracting the average of 10 sky spectra that were observed simultaneously with the stars (using the same FLAMES plate). The wavelength calibration uses calibration-lamp spectra taken the following day with respect to the observations. Finally, each spectrum was normalized to the continuum. The resulting spectra have a dispersion of 0.05 Å pixel\(^{-1}\) and a typical S/N \(\sim 25–40\), with a median value of 35.

We used the fxcor utility of IRAF to measure the radial velocity, which we then converted to heliocentric. The error in radial velocity is typically \(\sim \)1 km s\(^{-1}\). Considering the mean radial velocity of \(\omega\) Centauri \((\sim 232\) km s\(^{-1}\); Reijns et al. 2006), the velocity dispersion in the inner part of the cluster \((\sim 15\) km s\(^{-1}\); Reijns et al. 2006), and the observational errors, all of the stars with radial velocities in the range 180–300 km s\(^{-1}\) were considered members.

The coordinates, magnitudes, and radial velocities of our members are reported in Table 3. This table reports on the final targets after eliminating binaries and contaminated objects, as explained in the following section.

3. ABUNDANCE MEASUREMENTS

First, we checked for any possible residual contamination of our targets by neighbor stars that can be easily identified in our photometry. To be conservative and avoid any misinterpretation of the data, we finally decided to retain only those targets with no contamination, i.e., those targets with no neighbors brighter than \(m_{F625W} + 2.5\) mag within three times the FWHM of our observations. This guarantees us that the final metallicity is not altered by contamination effects. We had to reject 264 stars.

Second, we checked for possible binaries by looking for radial velocity variations. We expect most binaries to be composed of
an SGB and an MS; such systems should be brighter on average with respect to the single star sequence. For this reason, they would appear younger than they really are. For each target, we have 4/5 radial velocities obtained in different epochs, with an epoch range of a few weeks. Thus, we obtained the rms for each star and finally the rms distribution (not reported here). According to this distribution, we flagged as binaries all those stars that show an rms larger than 7 km s\(^{-1}\). We rejected 14 stars as binaries.

After the contamination and the binary checks, we were left with 172 objects that are plotted in Figure 1.

As in Villanova et al. (2007), we derived effective temperatures (\(T\)\(\text{eff}\)) from the \(m_{\text{F435W}} - m_{\text{F625W}}\) color in the \(HST\) CMD. The relation between color and \(T\)\(\text{eff}\), as a function of [M/H] (by which we mean the global metallicity, including alpha elements), was derived from isochrones by Pietrinferni et al. (2006).\(^4\) Colors were de-reddened using the absorption coefficients listed in Table 3 of Bedin et al. (2005), adopting \(E(B - V) = 0.115\). As a first guess for the [M/H] to be used in the color–[M/H]–temperature relation, we adopted [Fe/H] = −1.5, the mean metallicity of \(\omega\) Cen stars, along with an \(\alpha\)-enhancement of 0.4 dex for all stars (see Johnson & Pilachowski 2010). The [M/H] was derived from the adopted [Fe/H] and the alpha enhancement from the prescription by Salaris et al. (1993), along with the corresponding \(T\)\(\text{eff}\) from the color–[M/H]–temperature relation. Using this value for \(T\)\(\text{eff}\), we calculated \(\log g\) and \(v_t\), and measured a new [Fe/H] abundance as described below. Then for each star the values of \(T\)\(\text{eff}\) and [Fe/H] were changed in an iterative process, until convergence (when \(\log g\) and \(v_t\) change less than 0.02 dex and 0.02 km s\(^{-1}\), respectively).

As noted by Villanova et al. (2007), the effect of variations in helium content on the relation between color and temperature is of the order of \(\sim 10\) K in temperature for SGB stars, which translates into a change of \(\sim 0.01\) dex in metallicity. Such small changes can be neglected.

The gravity \(\log g\) was calculated from the elementary formula

\[
\log \left( \frac{g}{\text{g}_\odot} \right) = \log \left( \frac{M}{M_\odot} \right) + 4 \log \left( \frac{T\text{eff}}{T_\odot} \right) - \log \left( \frac{L}{L_\odot} \right).
\]

The mass \(M/M_\odot\) was derived from isochrone fitting. The luminosity \(L/L_\odot\) was derived from \(V_t\), assuming the absolute distance modulus \((m - M)_0 = 13.75\) found by Van de Ven et al. (2006), and the reddening adopted above. The bolometric correction (BC) was derived from the BC–\(T\)\(\text{eff}\) relation of Alonso et al. (1999). Finally, the microturbulence velocity came from the relation (Gratton et al. 1996):

\[\Delta v_t = 2.22 - 0.322 \log g.\]

The adopted atmospheric \(T\)\(\text{eff}\), \(\log g\), and \(v_t\) are listed in Table 3.

The metal content was obtained by comparison with synthetic spectra calculated using MOOG (Sneden 1973). The model atmospheres of Kurucz (1992), used throughout this paper, assume \(N_{\text{He}}/N_{\text{H}}\ = 0.1\), corresponding to \(Y = 0.28\) by mass. The bMS and the related SGB stars (i.e., stars with the same metallicity as the bMS stars), are thought to have a helium content \(Y \sim 0.38\). As discussed in Piotto et al. (2005), the variation in the atmospheric structure due to this increase in helium introduces an systematic error smaller than 0.03 dex in the metal-abundance determinations, which is negligible.

\(^4\) http://basti.oa-teramo.inaf.it/index.html

Our [Fe/H] values were obtained from a comparison of each observed spectrum with five synthetic ones (see Figure 2), calculated with different metal abundances. We used the regions at 6136–6138 Å and at 6191 Å for this purpose. These regions contain the only Fe lines not contaminated by telluric absorption and emission features and that are visible in all our spectra due to their S/N and to the \(T\)\(\text{eff}\) and low metallicity of the targets. In the most metal-rich spectra, other iron lines are visible, but to be homogeneous we had to choose only those that are also visible in the most metal-poor targets. \(\log(gf)\) of the lines were calibrated by spectroscopy on the Sun, assuming \(\log(\text{Fe}) = 7.50\) and the solar spectrum by Kurtucz et al. (1984).

The metallicity was obtained by minimizing the rms scatter of the differences between the observed and synthetic spectra. [Fe/H] values derived for our targets are listed in Table 3.

At this point, we must note that the [Fe/H] we obtained is based on the assumption of standard \(N_{\text{He}}/N_{\text{H}}\) content. However, the cluster has a mean He content that varies from \(Y = 0.25\) for the most metal-poor stars, to \(Y \sim 0.39\) for the most metal-rich, according to Joo & Lee (2013). A larger He content implies a lower H content, and by consequence the real [Fe/H] value should be higher than that we obtained. For \(\Delta Y = 0.14\), we should apply a correction of \(\Delta(\text{Fe}/\text{H}) = +0.09\). However, this would make a comparison with the literature difficult, so we prefer to use our current value and just warn the reader about this effect.

Because we have uncontaminated objects, the random internal error is dominated by the noise of the spectra. The S/N ranges from 30 to 40 for most of the stars, while the faintest have S/N \(< 25\) in the worst case. To estimate the error in [Fe/H], we used Monte Carlo simulations. For this purpose, we calculated a spectrum representative of the two most populous and extreme populations, the brightest at [Fe/H] \(~ -1.8\) and the faintest at [Fe/H] \(~ -0.8\). Then, we added noise to each one in order to obtain 1000 new spectra that simulate the real ones. Finally,
we measured the [Fe/H] of each simulated spectrum. For both brighter and fainter targets, we found $\sigma([\text{Fe}/\text{H}]) = 0.08$ dex. This is probably because the decrease in S/N is compensated by the increase in the mean metallicity, which gives stronger spectral lines. Another way to estimate this error is to use the formula from Cayrel (1988):

$$\sigma_{\text{EQW}} \sim 1.06 \times \sqrt{(FWHM \cdot \delta x)/(S/N)}.$$ 

In our case, $FWHM = 0.35$ Å and $\delta x = 0.05$ Å. For the median S/N of our spectra ($\sim 35$), the expected $\sigma_{\text{EQW}}$ is 4 mÅ. This translates to $\sigma([\text{Fe}/\text{H}]) = 0.07$ if we consider that we used three iron lines to estimate abundances, which is close to the value we obtained with the Monte Carlo simulations.

To this error, we should add (in quadrature) the error due to photometric uncertainty in the colors; the error in color is typically of the order of 0.01 mag, which translates to a 0.02 dex error in abundance (see Villanova et al. 2007). Finally, we adopt an overall uncertainty of 0.08 dex for [Fe/H]. This is the internal random error in our metallicity measurement. In addition there can be a systematic error of the order of 0.15–0.20 dex, because of systematic uncertainties in the effective temperature scale, in the model atmospheres, and in the distance and reddening. The systematic errors do not affect the relative metallicities of the different stellar populations of $\omega$ Cen that we will discuss in later sections.

4. RESULTS

First, we plot the iron distribution of the entire sample in Figure 3. Then, in the following plot (Figure 4), we report the iron distribution of the five SGB branches of Figure 1 separately. The first basic thing we note is that according to our analysis, each SGB has a distribution in metallicity with a spread that exceeds the observational errors. Such errors are plotted in Figure 4 as error bars in the top-right part of each panel. In addition, each SGB displays several peaks that allowed us to identify a certain number of sub-populations that form the cluster.

We identified the metallicity-based sub-populations in order to reproduce simultaneously the metallicity distribution of the entire sample and the metallicity distribution of individual SGBs. We could identify six of them, termed

- Pop$_1$ : $[\text{Fe}/\text{H}] = -1.83$
- Pop$_2$ : $[\text{Fe}/\text{H}] = -1.65$
- Pop$_3$ : $[\text{Fe}/\text{H}] = -1.34$
- Pop$_4$ : $[\text{Fe}/\text{H}] = -1.05$
- Pop$_5$ : $[\text{Fe}/\text{H}] = -0.78$
- Pop$_6$ : $[\text{Fe}/\text{H}] = -0.42$.

Their presence and their mean [Fe/H] value are justified by the following analysis.

In the figures, each sub-population was fitted with a Gaussian (blue dashed line) with a $\sigma$ that was allowed to vary up to $\pm 0.02$ dex around our theoretical uncertainty of 0.08 dex in order to obtain a better fit. In each figure, the continuous red line is the sum of all the single Gaussians. We also allowed the mean [Fe/H] value of each sub-population to vary by a few hundredths of a dex in order to obtain the best match possible with the data.

Figure 4 shows that SGB$_A$ is dominated by Pop$_1$ and Pop$_2$, but Pop$_3$ is clearly visible. In addition, there is a faint peak that could correspond to Pop$_4$. The most probable explanation is that this peak corresponds to evolved blue straggler stars (BSSs).

SGB$_B$ is composed of a mix of Pop$_2$ and Pop$_3$.

In SGB$_C$, Pop$_2$ and Pop$_4$ are clearly visible as two well-defined peaks. The histogram also shows a tail with a secondary peak at [Fe/H] $\sim -1.7$. We interpret this as Pop$_5$.

SGB$_D$ is dominated by Pop$_4$, but there is a tail that corresponds to Pop$_5$.

SGB$_E$ is dominated by Pop$_5$, but Pop$_4$ is clearly visible as a well-defined tail, while Pop$_6$, despite containing only two stars, forms a separated peak.

If we consider Figure 3, we can clearly identify Pop$_2$, Pop$_3$, Pop$_4$, Pop$_5$, and Pop$_6$ as well-defined peaks. Pop$_1$ forms a low-metallicity tail and not a peak, but if we remove it we cannot properly fit the iron distribution.

5. COMPARISON WITH THE LITERATURE

We already presented in the introduction the most recent papers that discuss the number and iron content of the sub-populations of $\omega$ Cen. In this section, we discuss how those results can be interpreted in light of what we have found here. We underline the fact that, due to the very extensive literature and to the very different methodologies used to study this cluster, we focus our attention only on those papers that try to identify the number of sub-populations based on their [Fe/H] content.

Sollima et al. (2005) found four stellar populations at [Fe/H] = $-1.7, -1.3, -1.0$, and $-0.6$. Looking at their Figure 4,
we can suggest that their population at $-1.7$ is a mixture of Pop$_1$ and Pop$_2$, at $-1.3$ is our Pop$_3$, at $-1.00$ is our Pop$_4$, and at $-0.6$ is our Pop$_5$.

Villanova et al. (2007) found three stellar populations at $[\text{Fe}/\text{H}]$ = $-1.68$, $-1.37$, and $-1.14$. Looking at their Figure 15, the population at $-1.68$ can be identified as a mixture of Pop$_1$ and Pop$_2$, while that at $-1.37$ is our Pop$_3$. The group at $-1.14$ is our Pop$_4$.

Calamida et al. (2009) found six peaks in the iron distribution at $[\text{Fe}/\text{H}]$ = $-1.73$, $-1.29$, $-1.05$, $-0.80$, $-0.42$, and $-0.07$ dex. Looking at their Figure 17, the group at $-1.73$ can be identified as a mixture of Pop$_1$ and Pop$_2$. In particular, Pop$_1$ is visible as a peak at $[\text{Fe}/\text{H}] \sim -1.8 \div -1.9$, not pointed out by the authors. The peak at $-1.29$ is our Pop$_3$, while the peak at $-1.05$ is our Pop$_4$. Their peaks at $-0.80$ and $-0.42$ are our Pop$_5$ and Pop$_6$, respectively. In particular, the identification of the same population at $[\text{Fe}/\text{H}] = -0.42$ in two independent data sets makes us confident that Pop$_6$ is real. However, we do not have any trace of their peak at $-0.07$. An explanation could be that the corresponding population forms a weak SGB branch fainter than SGB$_E$, so we did not recognize it in our CMD and we did not point any fiber on its stars, or that it is too centrally concentrated, so we missed it in the fiber pointing.

Johnson & Pilachowski (2010) identified four groups at $[\text{Fe}/\text{H}] = -1.75$, $-1.50$, $-1.10$, and $-0.75$. Looking at their Figure 8, the populations at $-1.75$, $-1.10$, and $-0.75$ can be identified with our Pop$_1$+Pop$_2$, Pop$_4$, and Pop$_5$, respectively. Their peak at $-1.50$ does not correspond to any of our populations.

We do not confirm the presence of a very metal-poor population ($[\text{Fe}/\text{H}] \sim -1.9$), as suggested by Pancino et al. (2011). However, our data do not have the required accuracy and statistics to identify such a feature.

Finally, we compare our results with Marino et al. (2011). These data show clear peaks at $[\text{Fe}/\text{H}] = -1.76$, $-1.60$, $-1.00$, and $-0.76$ that correspond to our Pop$_1$, Pop$_2$, Pop$_4$, and Pop$_5$, respectively. Pop$_3$ is visible as a tail of Pop$_2$.

6. THE AGE SPREAD AND THE AGE–METALLICITY RELATION

After determining the sub-populations that form the cluster and their distribution on the SGB, we can discuss the implications of our results on the age spread that, according to Villanova et al. (2007), affects the cluster and that should be of the order of several gigayears. This is a controversial topic, because some authors suggest that $\omega$ Cen does not have any age spread at all (e.g., Sollima et al. 2005).

We start by estimating the range in magnitude that each sub-population covers at the level of the SGB. We do not consider peaks identified as BSSs.

In order to visualize the spread in magnitude of each population, we plot in Figure 5 their position on the SGB. The membership of each star was decided based on which Gaussian dominates at its metallicity in Figure 4. The $[\text{Fe}/\text{H}]$ interval assigned to each population changes from one SGB to the other in order to minimize the contamination due to measurement errors. Of course some contamination remains, but with the given
error in metallicity it is impossible to separate completely the six groups of stars. For the following discussion, we assume that each population has no intrinsic [Fe/H] spread, and that the enlargement associated with each peak in the [Fe/H] distribution histograms is totally due to the measurement error. This is justified by the fact that Gaussians with a σ of 0.08 dex (which is our internal measurement error) well fit the total [Fe/H] distribution of Figure 3.

Pop1 forms only SGB_A. Pop2 forms part of SGB_A, SGB_B, and maybe SGB_C, so its spread is of the order of 0.2–0.4 mag. Pop3 forms part of SGB_A, SGB_B, and SGB_C, so its spread is of the order of 0.4 mag. Pop4 forms SGB_C, SGB_D, and SGB_E, so its spread is of the order of 0.7 mag. Pop5 forms SGB_E and maybe SGB_D, so its spread is <0.4 mag. Pop6 does not show any spread and all its stars belong to SGB_E.

The correspondence between the populations and the five SGBs is given in Table 1.

Before giving an estimation of the age spread of each population, we must address some further considerations.

The first concerns the interval in age that corresponds to a Δm_{F,435W} of 0.1 mag on the SGB. In Villanova et al. (2007), we already performed this exercise, and it turns out that the exact value depends both on metallicity and helium content. However, a good approximation is ∼1 Gyr per 0.1 mag.

The second concerns the total CNO content of each population. NGC 1851 has a double SGB (Milone et al. 2008), where the two populations are separated by about 0.1 mag in luminosity. This implies an age difference of about 1 Gyr if the two populations have the same CNO. However, Cassisi et al. (2008) showed that a CNO difference of 0.3 dex can reduce the age difference to 100 Myr.

To investigate this point, we plotted in Figure 6 the total CNO content as a function of the metallicity ([Fe/H]) using data from Marino et al. (2012, crosses), D’Orazi et al. (2011, open circles), and S. Villanova et al. (2014, in preparation, filled points). Marino et al. (2012) and S. Villanova et al. (2014, in preparation) well sample the region below [Fe/H] = −1.0, while we use D’Orazi et al. (2011) and S. Villanova et al. (2014, in preparation) to sample the more metal-rich part above [Fe/H] = −1.0. The mean trend is represented by the black continuous line, while the black dashed lines are the mean trend shifted vertically by ±0.08 dex, that is, the mean rms of the data (see below). We notice that the mean CNO content has two different linear trends. The first, from [Fe/H] ∼ −2.0 to [Fe/H] ∼ −1.5, has a slope of ∼0.76, while the other, from [Fe/H] ∼ −1.5 to [Fe/H] ∼ −0.5, is flatter, with a slope of ∼0.12. After that, we calculate the spread of the points around the mean trend, and found that the dispersion of [CNO/Fe] is σ = 0.08 dex. This is a small value, comparable with the typical measurement error of any chemical abundance determination procedure (e.g., Villanova et al. 2011), so we can assume that any intrinsic spread in CNO (at a given metallicity), if present at all, is negligible. A more straightforward procedure would be a direct calculation of the measurement error on the [C+N+O/Fe] quantity, which depends on the error on the temperature, gravity, metallicity, microturbulence, and S/N, but this is out of the scope of this paper. Our conclusion is that we can assume a constant CNO content within each sub-population.

We can now translate the magnitude spread into an age spread. The results are reported in Table 1. Three populations (Pop2, Pop3, and Pop4) have an age spread of at least 2 Gyr. Pop4 shows a surprisingly large age spread.
Pop₁ and Pop₆ do not show an age spread. On the other hand, Pop₃ possibly also occupies SGB₂, but its number of possible stars is so small (a total of 2) that we prefer to leave the question open and assign it an age spread of 0, and to put its possible membership to SGB₂ and the corresponding age spread within parentheses in Table 1. Also, Pop₂ suffers the same problem and its membership to SGB₂ is uncertain, so we decided again to put it within parentheses in Table 1, together with the relative age spread.

Thus, we conclude that α Centauri shows clear evidence of a significant age spread in at least three of its populations when they are identified based on metallicity alone.

The next step is to transform all the information we have, i.e., the metallicity and magnitude of each star, to an age–metallicity relation, taking advantage of the fact that the SGB is the place in the CMD most sensitive to age effects. The aim is to transform the $F435W$ magnitude of each star into an age. However, there are several effects that can be taken into account using isochrones (Pietrinferni et al. 2006). The most obvious one is the fact that stars of the same age but different metallicity have different $F435W$ magnitudes, with the most metal-rich also being the faintest. We found that a difference of 1.0 dex in metallicity corresponds to a $F435W$ difference of 0.64 mag on average, keeping the other parameters constant. On the other hand, the α-enhancement is not an issue because all stars have the same α content at all metallicities (Johnson & Pilachowski 2010, Figure 13). A further effect to take into account is the He content. In Piotto et al. (2005), we showed that stars with $[\text{Fe}/H] \sim -1.7$ have a normal He content ($Y \sim 0.25$), while stars with $[\text{Fe}/H] \sim -1.4$ are He-enhanced ($Y \sim 0.38$). Recently, Joo & Lee (2013) published a more detailed He trend that we adopted here. According to this trend, all stars with $[\text{Fe}/H] < -1.55$ have $Y \sim 0.25$, all stars with $[\text{Fe}/H] > -1.31$ have $Y \sim 0.39$, and for stars in between, $Y$ linearly increases from $[\text{Fe}/H] \sim -1.55$ to $[\text{Fe}/H] \sim -1.31$. Again, using isochrones with different He content, we found that $\Delta Y = +0.1$ corresponds to an increase in $F435W$ of $\sim 0.05$ mag, keeping the other parameters constant. We note that the large uncertainty on the He–$[\text{Fe}/H]$ relation is compensated for by the small effect of $Y$ on the $F435W$ magnitude (much lower than that due to the metallicity). The CNO trend was already discussed above. We take it into account using the relation published by Marino et al. (2012, Section 5) that is valid for $[\text{Fe}/H] < -1$. In this iron regime, the effect of CNO enhancement is independent of metallicity. For $[\text{Fe}/H] \sim -0.4$ (the upper limit of our metallicity range), isochrones show that the effect of CNO enhancement on age is three times larger than for the $[\text{Fe}/H] < -1$ regime, keeping the other parameters constant. We linearly interpolated in between.

Finally, as already said, for a given metallicity, He content, and C+N+O content, a 0.1 mag difference in $F435W$ corresponds to an age difference of $\sim 1$ Gyr, keeping the other parameters constant. We also verified that all the quantities we assumed in order to transform $F435W$ into age, apart from the CNO content (i.e., 0.64 mag dex$^{-1}$ for the metallicity, 0.05 mag for a change of 0.1 in $Y$), are fairly constant over the entire interval of ages and metallicities covered by our stars. They are reported in Table 2 for reference.

In order to also take into account the SGB tilt (see Figure 1), we proceeded as in Villanova et al. (2007), i.e., we fitted a straight line to the upper SGB and calculated the distance of each star with respect to this line. We note that the five SGBs of Figure 1 are not perfectly parallel to each other, but this does not affect our final result in a significant way. All the quantities discussed before (i.e., 0.64 mag dex$^{-1}$, 0.05 mag for a change of 0.1 in $Y$, and 0.1 mag Gyr$^{-1}$) are related to a vertical difference in the magnitude $F435W$ in the CMD, and for this reason they were transformed to this new reference system parallel to the upper SGB.

The error on the final age is a function of the $[\text{Fe}/H]$ difference between two stars. For targets of the same metallicity and, as a consequence, of the same He and CNO content, it is dominated by the error on the magnitude and $[\text{Fe}/H]$ value. To estimate the error in this case, we used a Monte Carlo simulation. We took an artificial star representative of the entire sample and assigned it a metallicity of $[\text{Fe}/H] = -1.50$, a magnitude $m_{F435W} = 18.5$, and a color $m_{F435W} - m_{F625W} = 1.12$. After that, we generated 10,000 stars according to a random Gaussian distribution centered on these values and with a dispersion $\sigma$ of 0.01 mag on $m_{F435W}$ and $m_{F625W}$ (the typical photometric error for an SGB star), and of 0.08 dex on the metallicity. Finally, we estimated the age of these 10,000 stars using the same method described above for the real stars. The results are the errors reported in Figure 7 as contours. The inner contour is the $1\sigma$ error, the contour in the middle is the $2\sigma$ error, and the outer contour is the $3\sigma$ error.

### Table 2

The Sensitivity of the $F435W$ Magnitude on Metallicity, $Y$, and Age (First Three Rows), and the Sensitivity of Age on CNO Content (Last Two Rows)

| Parameter          | Variation $\Delta$ | $F435W$/Age Variation |
|--------------------|--------------------|------------------------|
| $\Delta[\text{Fe}/H]$ | $\pm 1.0$ dex      | $\pm 0.64$ mag         |
| $\Delta Y$         | $+0.10$            | $\pm 0.05$ mag         |
| $\Delta$ Age       | $\pm 1.0$ Gyr      | $\pm 0.10$ mag         |
| $\Delta\text{CNO}([\text{Fe}/H] < -1.0)$ | $\pm 1.0$ dex | $\mp 3.3$ Gyr          |
| $\Delta\text{CNO}([\text{Fe}/H] = -0.4)$ | $\pm 1.0$ dex | $\mp 9.9$ Gyr          |

Figure 7. Age–metallicity relation for $\alpha$ Centauri. Contours represent the $1\sigma$, $2\sigma$, and $3\sigma$ errors, respectively. Red points are data from Villanova et al. (2007), while blue points are data from Hilker et al. (2004). See the text for more details. (A color version of this figure is available in the online journal.)
For completeness, we should add the random error due to a possible He spread for a given Fe abundance that overlaps the He–Fe relation obtained by Joo & Lee (2013). If we take a hypothetical star in the middle of the He range we assumed, i.e., a star with $Y = 0.32$, then consequently, [Fe/H] $= -1.43$. A difference in its He abundance from the adopted value would not influence its age directly because the dependence of age on He is very weak, but it would affect its age determination through its [Fe/H] value. In fact, a larger He content implies a lower H $\Delta$ value. In fact, a larger He content implies a lower H $\Delta$ value. It is $\sim 0.07$ around $(0.08 \pm 0.045$ dex. This is negligible compared to our error on [Fe/H] of 0.08 dex. It is also an overestimation, because we should not use $\Delta Y = 0.07$ for our purposes, but the $\sigma$ of the He spread that, if the He distribution is a Gaussian, is about $0.14/6 = 0.02$. This makes the impact of any possible He spread for a given metallicity totally negligible compared with the error shown in Figure 7.

For stars at the extremes of the [Fe/H] interval, uncertainties in the He and CNO trends must also be considered. While the impact of the He trend uncertainty is negligible, the impact of the CNO trend uncertainty will be discussed in the next subsection.

We underline the fact that the ages obtained so far are relative ages, and the errors we estimated are errors on the relative ages. Absolute ages were obtained by applying a rigid shift to the whole sample so that the oldest stars are the age of the universe. The systematic error on the absolute ages is surely larger than the impact of any possible He spread for a given metallicity.

### Table 3: Parameters of the Observed Stars

| ID     | R.A.          | Decl.         | $m_{F385W}$  | $m_{F625W}$  | $T_{eff}$  | log$(g)$ | $v_t$  | [Fe/H]  | RV      | Age      |
|--------|---------------|---------------|-------------|-------------|-----------|----------|-------|----------|---------|----------|
|        | (deg)         | (deg)         | (mag)       | (mag)       | (K)       | (dex)    | (km s$^{-1}$) | (dex)  | (km s$^{-1}$) | (Gyr)   |
| SGB1   | 201.60146667  | -47.55916667 | 18.072      | 16.976      | 5592      | 3.69     | 0.99  | -1.67    | 225.5   | 8.5      |
| SGB1   | 201.58411667  | -47.42861111 | 18.107      | 17.104      | 5821      | 3.78     | 0.97  | -1.62    | 221.9   | 7.2      |
| SGB1   | 201.60875000  | -47.41194444 | 18.069      | 16.985      | 5611      | 3.69     | 0.99  | -1.71    | 232.9   | 8.6      |
| SGB1   | 201.56883333  | -47.43730556 | 18.112      | 17.118      | 5829      | 3.78     | 0.97  | -1.71    | 232.8   | 7.9      |
| SGB1   | 201.59787500  | -47.54888889 | 18.213      | 17.235      | 5909      | 3.85     | 0.95  | -1.49    | 229.6   | 6.8      |
| SGB1   | 201.76162500  | -47.42775000 | 18.102      | 17.081      | 5813      | 3.78     | 0.97  | -1.43    | 255.1   | 6.2      |
| SGB1   | 201.74654167  | -47.42536111 | 18.109      | 17.059      | 5767      | 3.77     | 0.97  | -1.32    | 225.4   | 6.2      |
| SGB1   | 201.68729167  | -47.42155556 | 18.059      | 16.994      | 5652      | 3.70     | 0.99  | -1.72    | 238.3   | 8.4      |
| SGB1   | 201.56879167  | -47.42063111 | 18.050      | 16.955      | 5603      | 3.68     | 0.99  | -1.63    | 225.5   | 8.0      |
| SGB1   | 201.70537500  | -47.41897222 | 18.070      | 16.973      | 5588      | 3.68     | 0.99  | -1.68    | 241.2   | 8.6      |
| SGB1   | 201.70050000  | -47.54366667 | 18.073      | 17.028      | 5701      | 3.72     | 0.98  | -1.71    | 229.4   | 8.2      |
| SGB1   | 201.61179167  | -47.41819444 | 18.059      | 17.006      | 5708      | 3.72     | 0.98  | -1.58    | 206.8   | 7.1      |
| SGB1   | 201.68179167  | -47.41636111 | 18.148      | 17.145      | 5853      | 3.81     | 0.96  | -1.45    | 244.4   | 6.4      |
| SGB1   | 201.63141667  | -47.41597222 | 18.068      | 17.021      | 5748      | 3.74     | 0.98  | -1.45    | 234.2   | 6.4      |

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

We underline the fact that the ages obtained so far are relative ages, and the errors we estimated are errors on the relative ages. Absolute ages were obtained by applying a rigid shift to the whole sample so that the oldest stars are the age of the universe. Absolute ages were obtained by applying a rigid shift to the whole sample so that the oldest stars are the age of the universe. The systematic error on the absolute ages is surely larger than 1 Gyr, but for our purposes it is not a concern.

The final product of this procedure is the age–metallicity relation presented in Figure 7. Ages derived for our targets are listed in Table 3. Our data (black points) appear to follow five well-defined strips. This is not a real effect but a consequence of our target selection that was focused on the five SGBs. The correspondence between the five SGBs and the five strips is indicated by the five letters that identify the SGBs in Figure 1. Red points are the age–metallicity relation by Villanova et al. (2007). We apply a vertical shift to our points in order to match the age of the three old metal-rich stars ([Fe/H] $\sim -1.15$, age $\sim 13.7$ Gyr). We note that red points in the $-1.8 < [\text{Fe/H}] < 1.3$ regime are older than black points. This is because in Villanova et al. (2007), we did not take into account the effect of the C+N+O content.

Blue points are the age–metallicity relation by Hilker et al. (2004). Again, we shifted these data vertically in order to match the black points.

The easiest way to interpret Figure 7 is to divide our points into two shaded areas, one that follows the trend shown by metal-poor stars (A1), and another that follows the trend shown by metal-rich stars (A2). Although the A2 group is less populated than A1, its presence is definitively proven by our results, which is one of the most surprising results of this paper. In both cases, the progenitors of each relation appear to be a quite old group of stars, which for A1 have [Fe/H] $\sim -2.0$ and an age of $\sim 11.0$ Gyr and for A2 have [Fe/H] $\sim -1.2$ and an age of almost 14 Gyr. Because of their ages and metallicity differences, it is very unlikely that the second derives from the first by some kind of chemical evolution, so they should be assumed to be two independent primordial objects. Then, in each area stars appear to evolve toward higher metallicities following the arrow labeled “age–metallicity evolution.” We underline the fact that the age–metallicity evolution we draw is only a first interpretation. Future works could significantly change the scenario we are proposing.

The age–metallicity relation within A1 was already presented in Hilker et al. (2004), as shown by the blue squares. That within A2 is shown here for the first time due to our much more complete SGB sample. The presence of two age–metallicity relations can easily explain the age spread of Pop$_1$, which appears to be very large. It simply comes from the superposition of the two age–metallicity relations in the range $-1.20 < [\text{Fe/H}] < -0.90$.

The fact that the oldest population is more metal-rich compared to most of the metal-poor stars in a globular-cluster-like object is something that goes against common sense. One would have expected a monotonically decreasing age–metallicity relation, or at least that the most metal-poor and metal-rich stars were coeval, if the initial chemical enrichment had occurred on a short timescale ($< 1$ Gyr). The only way to rejuvenate A2 stars and place them on top of A1 is to assume a total CNO that is $\sim 1.8$ dex larger than its actual value, i.e., all stars...
belonging to the A2 group should have \([\text{C+N+O}/\text{Fe}] \sim 2.3\) dex, which is a much higher value than anyone observed not only in \(\omega\) Cen, but in any Galactic object. Only some very metal-poor stars (Sivarani et al. 2006) show extremely enhanced C, N, and O (with \([\text{N}/\text{Fe}]\) up to \(~+3.0\)), but in this case it is attributed to contamination by an AGB or massive fast-rotating companion.

To complete our interpretation, it is remarkable that each relation has an age difference (difference between the youngest and oldest star, including also the errors) of \(\sim 3\) Gyr for a given \([\text{Fe}/\text{H}]\) value.

At this point, it is natural to propose that \(\omega\) Centauri is the result of the merging of two independent objects (dwarf galaxies?) or of two independent parts of a single larger object, the first with the oldest stars being more metal-poor (\([\text{Fe}/\text{H}] \sim -2.0\)), and the second with the oldest stars being more metal-rich (\([\text{Fe}/\text{H}] \sim -1.2\)). Each object or part had its own independent evolution in the age–metallicity plane, at least down to 10 Gyr. The evolution ended at \(~6\) Gyr for both of them. If they merged before or after the full evolution of the stars in the age–metallicity plane, and if and how they interacted, is very hard to say.

6.1. The Impact of the Uncertainty of the \([\text{C+N+O}/\text{Fe}]\) versus \([\text{Fe}/\text{H}]\) Relation on the Age–Metallicity Relation

As discussed in Marino et al. (2012), the total CNO content can heavily influence the final age of a star and, in our case, the age–metallicity relation. For this reason, we performed the following test in order to check how an incorrect estimation of the \([\text{C+N+O}/\text{Fe}]\) trend as a function of \([\text{Fe}/\text{H}]\) presented in Figure 6 can alter the final result. We first estimated the two most extreme fits of the data, the first with the highest \([\text{C+N+O}/\text{Fe}]\) value at \([\text{Fe}/\text{H}] \sim -2.0\) and that with the lowest at \([\text{Fe}/\text{H}] > -1.5\). This is plotted as a blue dashed line in Figure 6. The second had the lowest \([\text{C+N+O}/\text{Fe}]\) value at \([\text{Fe}/\text{H}] \sim -2.0\) and the highest at \([\text{Fe}/\text{H}] > -1.5\). This is plotted as a red dashed line in Figure 6. We underline that those fits are completely unreliable, but we want to check whether or not in the worst case our conclusions about the age–metallicity relation are supported. We report the result of this test in Figure 8. The panel on the left was obtained with the blue fit, and the one on the right with the red fit.

We see that the presence of the two independent relations A1 and A2 is confirmed. In the panel on the left, the oldest stars in A1 are as old as the oldest stars in A2, while in the one on the right, the oldest stars in A1 are \(~4\) Gyr younger. This test confirms our hypothesis of the presence of two old, unrelated populations in \(\omega\) Centauri with very different iron contents. On the other hand, each relation shows an age difference of \(4\) Gyr (in the first case) or \(3\) Gyr (in the second case) for a given \([\text{Fe}/\text{H}]\) value.

To check the impact of the uncertainty in the CNO content on the age spread for a given \([\text{Fe}/\text{H}]\), we assume that the spread of \(0.08\) dex we estimated for \([\text{C+N+O}/\text{Fe}]\) around the mean trend of Figure 6 is totally intrinsic and not due to measurement errors. We lack any information about CNO for our stars, so we must proceed in a statistical way. In the previous section, we showed that for a given metallicity the age difference is \(~3\) Gyr. A spread \((\sigma)\) of \(0.08\) dex corresponds to a maximum interval in the \([\text{C+N+O}/\text{Fe}]\) value of \(~0.5\) dex (i.e., \(6\times\sigma\)), which translates...
to an age interval of \(\sim 1.5\) Gyr. If we subtract this value from the age difference, we are left with \(1.5\) Gyr. This means that the age difference is real and larger than \(1.5\) Gyr (very likely \(\sim 3\) Gyr because the spread of 0.08 dex in the CNO trend is almost totally due to measurement errors).

7. CONCLUSIONS

In this paper, we analyzed 172 stars belonging to the SGB region of \(\omega\) Centauri, in order to study the age and metallicity dispersion and the age–metallicity relation to find further clues of how this object was formed. For this purpose, we obtained medium-resolution spectra \((R = 22500)\) in the 6120–6405 Å range and measured the iron content of our stars using the same general approach as Villanova et al. (2007).

The accuracy of our measurements coupled with the age sensitivity of the SGB allowed us to find that each of the five SGBs of the cluster has a distribution in metallicity with a spread that exceeds the observational errors. In addition, each SGB displays several peaks that indicate the presence of several sub-populations. We could identify six of them based on their [Fe/H] value.

Taking advantage of the age sensitivity of the SGB, we showed that, first of all, at least half of the sub-population have an age spread of at least \(2\) Gyr. These results are indeed very surprising, and we urge confirmation with additional data.

Then, considering all the possible contributors, we transformed the magnitude of each star into a relative age, obtaining an age–metallicity relation. We underline the fact that we do not use absolute ages but values that consider only the differential SGB luminosity corrected for the differential He, [Fe/H], and CNO contents of each star. Because of this, our final error on age is significantly reduced.

Our relation agrees well with those published previously, which, however, cover the age–metallicity space only partially.

The interpretation of the age–metallicity relation is not straightforward, but it is very likely that the cluster (or what we can call its progenitor) was initially composed of two old populations, but with different metallicities. The most metal-poor had [Fe/H] \(\sim -2.0\), while the most metal-rich had [Fe/H] \(\sim -1.2\), but the oldest stars in the metal-rich regime appear to be several Gyrs older than their oldest metal-poor counterparts. Because of their ages and metallicity, it is very unlikely that the second derived from the first through some kind of chemical evolution, so they should be assumed to be two independent primordial objects. Afterward, at first order, each one evolved chemically with iron, which linearly increases with age, according to our interpretation. This evolution stopped at \(\sim 6\) Gyr. In any case, they remain separated in the age–metallicity plane at least down to 10 Gyr. In addition to this, each object shows an age spread of \(> 2\) Gyr for a given metallicity. These conclusions are not altered by any possible uncertainty on the [C+N+O/Fe] versus [Fe/H] relation.

These two primordial progenitors could correspond to two dwarf galaxies that, at a given unknown time, merged to form what is known today as \(\omega\) Centauri. Whether they merged before or after the full evolution of the stars in the age–metallicity plane, and if and how they interacted, is very hard to say. Clearly, much further work on this enigmatic object is required to help solve some of its mysteries.

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REFERENCES

Alonso, A., Arribas, S., & Martinez-Roger, C. 1999, A&AS, 140, 261
Bedin, L. R., Cassisi, S., Castelli, F., et al. 2005, MNRAS, 357, 1038
Bedin, L. R., Piotto, G., Anderson, J., et al. 2004, ApJ, 605, 125
Bellini, A., Piotto, G., Bedin, L. R., et al. 2009, A&A, 493, 959
Blecha, A., Cayatte, V., North, P., Royer, F., & Simond, G. 2000, Proc. SPIE, 4008, 467
Calamida, A., Bon, G., Stetson, P. B., et al. 2009, ApJ, 706, 1277
Cassisi, S., Salaris, M., Pietrinferni, A., et al. 2008, ApJ, 672, 1158
Cayrel, R. 1988, in IAU Symp. 132. The Impact of Very High S/N Spectroscopy on Stellar Physics, ed. G. Cayrel de Strobel & M. Spite (Dordrecht: Kluwer), 345
D'Orazi, V., Gratton, R. G., Pancino, E., et al. 2011, A&A, 534, 29
Gratton, R. G., Carretta, E., & Castelli, F. 1996, A&A, 314, 191
Hilker, M., Kayer, A., Richtler, T., & Willemson, P. 2004, A&A, 422, 9
Izzard, R. G., Tout, C. A., Karakas, A. I., & Pols, O. R. 2004, MNRAS, 350, 407
Johnson, C., & Pilachowski, C. A. 2010, ApJ, 722, 1373
King, I. R., Bedin, L. R., Cassisi, S., et al. 2012, AJ, 144, 5
Kurucz, R. L. 1992, in IAU Symp. 149, The Stellar Populations of Galaxies, ed. B. Barbuy & A. Renzini (Cambridge: Cambridge Univ. Press), 225
Kurucz, R. L., Furenlid, I., Braa', J., & Testerman, L. 1984, Solar Flux Atlas from 296 to 1300 nm, National Solar Observatory Atlas (Sunspot, New Mexico: National Solar Observatory)
Maeder, A., & Meynet, G 2006, A&A, 448, 37
Marino, A. F., Milone, A. P., Piotto, G., et al. 2011, ApJ, 731, 64
Marino, A. F., Milone, A. P., Piotto, G., et al. 2012, ApJ, 746, 14
Meylan, G. 2003, in ASP Conf. Ser. 296, New Horizons in Globular Cluster Astronomy, ed. G. Piotto, G. Meylan, S. G. Djorgovski, & M. Riello (San Francisco, CA: ASP), 17
Milone, A. P., Bedin, L. R., Piotto, G., et al. 2008, ApJ, 673, 241
Norris, J. E. 2004, ApJ, 612, 25
Norris, J. E., Freeman, K. C., & Mighell, K. J. 1996, ApJ, 462, 241
Pincus, E., Mucciarelli, A., Sbordone, L., et al. 2011, A&A, 527, 18
Pietrinferni, A., Cassisi, S., Salaris, M., & Castelli, F. 2006, ApJ, 642, 797
Piotto, G., Villanov, S., Bedin, L. R., et al. 2005, ApJ, 621, 777
Rejins, R. A., Seitzer, P., Arnold, R., et al. 2006, A&A, 445, 503
Salaris, M., Chieffi, A., & Straniero, O. 1993, ApJ, 414, 580
Seok-Joo, J., & Young-Wook, L. 2013, ApJ, 762, 36
Sivaran, T., Beers, T. C., Bonifacio, P., et al. 2006, A&A, 459, 125
Sneden, C. 1973, ApJ, 184, 839
Sollima, A., Pancino, E., Ferraro, F. R., et al. 2005, ApJ, 634, 332
Stanford, L. M., Da Costa, G. S., Norris, J. E., & Cannon, R. D. 2006, ApJ, 647, 1075
Suntzeff, N. B., & Kraft, R. P. 1996, AJ, 111, 1913
van den Ven, G., van den Bosch, R. C. E., Verolme, E. K., & de Zeeuw, P. T. 2006, A&A, 445, 513
Villanova, S., & Geisler, D. 2011, A&A, 535, 31
Villanova, S., Piotto, G., King, I. R., et al. 2007, ApJ, 663, 296