THE AGE AND METALLICITY RELATION OF \( \omega \) CENTAURI

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ABSTRACT

We present a metallicity distribution based on photometry and spectra for 442 \( \omega \) Centauri cluster members that lie at the main-sequence turnoff region of the color-magnitude diagram. This distribution is similar to that found for the red giant branch. The distribution shows a sharp rise to a mean of \([\text{Fe/H}]=-1.7\) with a long tail to higher metallicities. Ages have then been determined for the stars using theoretical isochrones enabling the construction of an age-metallicity diagram. Interpretation of this diagram is complicated by the correlation of the errors in the metallicities and ages. Nevertheless, after extensive Monte Carlo simulations, we conclude that our data show that the formation of the cluster took place over an extended period of time: the most metal-rich stars in our sample (\([\text{Fe/H}]=-0.6\)) are younger by 2–4 Gyr than the most metal-poor population.

Subject headings: globular clusters: general — globular clusters: individual (\( \omega \) Centauri)

Online material: machine-readable tables

1. INTRODUCTION

The Galactic globular cluster \( \omega \) Centauri exhibits unusual properties compared to other clusters. The first indication that it was atypical was in the photometric work of Woolley et al. (1966) and Cannon & Stobie (1973), in which the large color width of the red giant branch (RGB) was first established. An internal spread in metallicity was shown to exist from the spectroscopic work of Freeman & Rodgers (1975) using RR Lyrae variables. A large range in metallicity from \([\text{Fe/H}]=-1.8\) to \(-0.4\), and several discrete populations on the RGB, have been shown to exist by many studies over the last decade (Norris et al. 1996, hereafter NFM96; Suntzeff & Kraft 1996; Lee et al. 1999; Pancino et al. 2000; Rey et al. 2004; Sollima et al. 2005a). There also exist ranges in abundance for all the elements studied in the cluster (Norris & Da Costa 1995; Smith et al. 1995, 2000). These studies have primarily concentrated on the RGB stars as they are brighter than main-sequence (MS) or subgiant ones.

There is evidence of an age range in \( \omega \) Cen from the abundance and photometric studies. Specifically, the observed abundance patterns of different elements show the signatures of a variety of enrichment processes (Lloyd Evans 1977; Norris & Da Costa 1995; Smith et al. 1995; Pancino et al. 2002). Contributing sources include Type II supernovae (SNe II), which result from high-mass stars, asymptotic giant branch (AGB) stars that lose their material as stellar winds, and Type Ia supernovae (SNe Ia), which are formed from older stars via mass transfer onto a white dwarf. Enrichment of large-process elements is seen in the RGB stars indicating contributions by low-mass \((1.5–3 M_\odot)\) AGB stars (Lloyd Evans 1977; Norris & Da Costa 1995; Smith et al. 1995, 2000). These AGB stars have lifetimes of the order of 1–3 Gyr, indicating that there was an extended period over which enrichment and formation of the stars occurred in \( \omega \) Cen. Results from Pancino et al. (2002) show a decrease in \([\text{Ca/Fe}]\) at higher metallicities in the cluster. This indicates there are contributions from Type Ia supernovae in the enrichment processes and again that it took place over an extended period.

Using Strömgren photometry, Hughes & Wallerstein (2000) and Hilker & Richtler (2000) examined the metallicity distribution and determined ages for samples of stars near the turnoff region in \( \omega \) Cen. Both studies concluded that the more metal-rich stars in the cluster were younger than the metal-poor ones, with an age range of several gigayears.

Recently, high-precision photometry of the cluster has shown perhaps as many as five discrete RGBs (Rey et al. 2004; Sollima et al. 2005a). An age range of \(~4\) Gyr was determined using population modeling of the horizontal branch (HB) by Rey et al. (2004). Sollima et al. (2005a) obtained an upper limit to the range of 6 Gyr using the RGB bumps that correspond to the different populations. The position of the bump in the RGB luminosity function is a function of metallicity and age (and helium). Ferraro et al. (2004) have shown from their high-resolution images that a distinct metal-rich subgiant branch (SGB) exists (designated SGB-a). Their conclusion from isochrone fitting the main metal-poor population and the SGB-a was that they are of the same age, indicating no age range in the cluster at all. The distinct SGB-a is also present in the photometric data of Bedin et al. (2004). Bedin et al. (2004) also find two distinct main sequences, but surprisingly the red sequence contains \(~75\)% of the stars. On the RGB the majority of the stars lie along the blue side of that branch, and it has been shown that the ratio of metal-poor to metal-rich objects is \(80:20\) (NFM96). This indicates that the bluer main sequence is the more metal-rich population, as has been confirmed spectroscopically by Piotto et al. (2005). The separation between the two sequences can be explained by the populations having significantly different helium abundances \((\Delta \text{Y} \approx 0.12)\) Bedin et al. 2004; Norris 2004; Lee et al. 2005). The source of this unusually high helium abundance in the metal-rich population is not clear.

Hilker et al. (2004) measured abundances of \(~400\) subgiant and turnoff stars using medium-resolution spectra. Their abundance distribution resembles that from the RGB. Ages were derived for each star using its metallicity and position on the color-magnitude diagram (CMD) giving an age-metallicity diagram. They concluded from this diagram that a range of about...
3 Gyr exists in the cluster. Recently, Sollima et al. (2005b) obtained Very Large Telescope (VLT) data of ~250 stars on the subgiant branches in ω Cen. They found an age range of no more than 2 Gyr fitting isochrones to the populations in the cluster.

It has been suggested by Freyhammer et al. (2005) that the stars in the most metal-rich population are actually located in a clump beyond the bulk of the cluster. Photometry for this metal-rich population was fitted with isochrones with metallicities in the range $-1.1 \leq [\text{Fe/H}] \leq -0.8$ and using a larger distance modulus and reddening than are conventionally used for ω Cen. The direct spectroscopic abundance measurements of Sollima et al. (2005b) for stars along the metal-rich subgiant branch found their average metallicity to be $[\text{Fe/H}] \approx -0.6$, casting doubt on the result of Freyhammer et al. (2005).

In order to more accurately define the age range in the cluster, we have observed a sample of MS and MS turnoff (MSTO) stars. This sample enables several new insights into the cluster because we have studied the MS stars spectroscopically. The metallicity distribution on the MS has been compared to that found on the RGB. We have also used these data to compare the abundance patterns and abnormalities found at the MSTO with those found for the RGB stars. A comparison of our MSTO sample with stars on the RGB can show whether the enrichment of $s$-process and CNO elements is due to surface contamination, which would be obliterated by the growing convective envelope as the stars move on to the giant branch, or whether the enrichment is uniform throughout the stars.

The major goal of the present work, however, is to look at the turnoff region of the CMD along with the metallicities for the members and determine a more accurate age range for the cluster. Most previous work at the turnoff region has used only photometric data. A spectroscopic approach coupled with photometry may prove to give a more accurate age range for the cluster and show any age-metallicity relation that exists. In §2 we describe the observations and reduction techniques. Section 3 outlines the derivation of metallicities for the sample. The discussion on the calculation of ages is described in §4, and §5 summarizes the results and comparisons with previous investigations. Preliminary accounts of these results have appeared in Stanford et al. (2004).

2. OBSERVATIONS AND REDUCTION

Photometry for the cluster was obtained with the 1 m telescope/Tektronix CCD combination at Siding Spring Observatory, in the $V$ and $B$ bands. Ten fields with centers approximately $20''$ from the cluster center were observed. Each field was $20'\times 20''$ in area. Exposure times were 500 s for the $V$ band and 900 s for the $B$ band. Typical seeing ranged between $1''8$ and $2''2$. The photometry was carried out using aperture photometry, and the final sample only contained uncrowded stars (i.e., there were no neighbors within $5''$). The fields overlapped slightly in order to calibrate the frames in position and photometry. The photometry calibration used magnitudes from lists in the $B$ and $V$ bands from Cannon & Stobie (1973), Cannon (1981), and Cannon & Stewart (1981) for objects that were in common. The photometric zero-point uncertainties are of the order of 0.02 in both bands, and all errors come from photon statistics.

Preliminary positions were based on an early version of the US Naval Observatory catalog. These were then used to match stars from the SuperCosmos scan of a UK Schmidt plate centered on ω Cen, and positions of all stars were found. The final catalog positions from the SuperCosmos scan have an accuracy of $\sim 0''2$.

From these data a CMD, shown in Figure 1, was constructed for objects within an annulus $15''-25''$ from the cluster center. As there is no membership information, Figure 1 contains objects that belong to both ω Cen and the field. The Yonsei-Yale ($Y^2$) isochrones (Yi et al. 2001) were plotted along with the data and have metallicities $[\text{Fe/H}] = -1.7, -1.2, -0.6$; all have an age of 13.5 Gyr. Abundance studies have determined that the different stellar populations in ω Cen show $\alpha$-enhancement (Norriss & Da Costa 1995; Smith et al. 1995, 2000; Pancino et al. 2002; Origlia et al. 2003). For metallicities $[\text{Fe/H}] = -1.7$ and $-1.2$, $[\alpha/\text{Fe}]$ was taken to be 0.3, and for $[\text{Fe/H}] = -0.6$, $[\alpha/\text{Fe}] = 0.18$ was used. In Figure 1 a reddening $(B - V) = 0.11$ (Lub 2002) and distance modulus $(m - M)_V = 14.10$ were assumed. This value of the distance modulus comes from Rey et al. (2004) and when fitting isochrones best reproduces the data. Mean photometric errors as a function of $V$ magnitude from the aperture photometry are shown in Table 1.

In 1998 an area on the CMD was defined on the upper MS $(18.05 \leq V \leq 18.55; 0.30 \leq B - V \leq 0.72)$ with a view to determining the metallicity range. Stars in this region were observed using the Two Degree Field (2dF) Multiobject Spectrograph on the Very Large Telescope (VLT) in combination with the Siding Spring multiobject spectrophotometer to determine the metallicities of stars in this region.

### Table 1: Photometry Errors for the ω Cen Data

| $V$ (mag) | Error in $V$ | Error in $(B - V)$ |
|-----------|--------------|-------------------|
| 16.0........ | 0.002        | 0.004             |
| 16.5........ | 0.002        | 0.005             |
| 17.0........ | 0.004        | 0.007             |
| 17.5........ | 0.005        | 0.009             |
| 18.0........ | 0.008        | 0.012             |
| 18.5........ | 0.011        | 0.016             |
| 19.0........ | 0.017        | 0.025             |
| 19.5........ | 0.024        | 0.034             |
| 20.0........ | 0.031        | 0.045             |
the Anglo-Australian Telescope (Lewis et al. 2002). This spectrograph has the capability of simultaneously observing up to 400 objects using a fiber-fed system. In 2002 a second region was defined at the turnoff (17.25 ≤ V ≤ 18.5; 0.6 ≤ B − V ≤ 1.1) to look at the most metal-rich stars in the cluster and to determine the age range in the cluster, since the age degeneracy of the isochrones for a given metallicity can best be broken at the turnoff region. The first sample was observed in 1998 May and 1999 April (hereafter 98/99 sample) and the second in 2002 March (hereafter 2002 sample). Figure 1 shows the two boxes from which candidates were selected.

Although 2dF is able to observe 400 objects at once, for our sample the maximum number of objects we were able to observe per configuration was about 280. This was due to the compact nature of our fields relative to the large field of view of the instrument, as well as the limit on fiber-to-fiber spacing. Twelve hundred line mm$^{-1}$ gratings were employed, and the spectra obtained covered the useful wavelength range 3800−4600 Å, with a scale of either 0.9 or 1.1 Å pixel$^{-1}$. They have a resolution of $\sim$2.4 Å (FWHM).

As the number of probable members in the 1998 sample was high, these objects were observed in one configuration for several hours. For the 1999 observations, the small number of nonmembers found in the previous run were removed and other candidates added to the configuration along with the confirmed members. This single configuration was again observed for several hours.

A slightly more complicated approach was taken for the 2002 observations. This sample extended to much redder colors to ensure that any high-metallicity cluster members were included but consequently had higher field star contamination. In order to completely observe our 2002 sample of 900 objects, a number of fiber configurations were needed, and each of these contained successively fewer new stars due to crowding. The first step in the observing process was to determine which stars were members of $\omega$ Cen. This cluster has a large radial velocity of 232 ± 0.7 km s$^{-1}$ (Dinescu et al. 1999), while the field stars have velocities $\sim$0 ± 50 km s$^{-1}$. This information was used to determine membership of the cluster. Each configuration was observed until a signal-to-noise ratio (S/N) per pixel of about 10 was reached. The exposure time depended on the weather and seeing, although the average was 1–2 hr per field. The observations were carried out in 30 minute exposures to facilitate removal of cosmic rays. These data were then reduced and wavelength calibrated using the standard 2dF reduction software available at the telescope. The reduced fields were co-added and the individual spectra were then extracted using the FIGARO routine extract. Once reduced and extracted, the spectra were cross-correlated with a spectrum of a previously confirmed $\omega$ Cen member in the IRAF package RV using fxcor to obtain velocities. These were plotted as a histogram and membership was classified within a generous velocity cutoff limit.

Once we had observed all stars in our sample, the cluster members were reobserved with 2dF for $\sim$3–5 hr in order to obtain higher S/N spectra for more detailed analysis. The spectra were again cross-correlated, this time with a synthetic spectrum, to obtain velocities to confirm membership and obtain more accurate velocities. Analysis of twilight sky observations taken at the same time showed an offset in the velocities between the two CCD cameras of $\sim$11 km s$^{-1}$. A correction was applied to the spectra to account for the offset, and the individual spectra were then co-added. The final heliocentric velocity histogram is shown in Figure 2. The narrow peak at 235 km s$^{-1}$ comprises the $\omega$ Cen members, while the broader peak at lower velocities contains the field stars. The standard deviation was determined by an iterative $\pm 3 \sigma$ cutoff process (where $\sigma = 13$ km s$^{-1}$). The velocity dispersion in the outer regions of the cluster is low ($\sim$9 km s$^{-1}$; Merritt et al. 1997), and the standard deviation is driven by both the velocity error measurement and the dispersion. The mean velocity errors are typically 8 km s$^{-1}$. The standard deviation of the field stars was 53 km s$^{-1}$.

The 98/99 and 2002 samples were observed to completeness levels of 37% and 94%, respectively, where the completeness level is defined as the ratio of number of objects observed to the number that had the potential to be observed. To be classed as “observable” each star underwent a visual inspection on the CCD images to ensure there were no contaminating objects within 5$''$.

These processes yielded a final sample of 442 members from some 850 observed candidates near the turnoff in the CMD of $\omega$ Cen. A CMD showing the members is shown in Figure 3 (large filled circles). The small filled circles represent the photometry as in Figure 1. The isochrones are the same as in Figure 1. Figure 3 shows that there are a number of very red, presumably metal-rich, stars in $\omega$ Cen at the turnoff region. Objects that were classified as radial velocity nonmembers of the cluster in the 2002 sample are shown in Figure 4. This diagram shows that the candidates were positioned fairly uniformly over the 2002 region on the CMD. It also makes clear that while we found no members in the bottom right corner of the box in Figure 3, candidates were observed there. Tables 2 and 3 briefly list the members and nonmembers, respectively. Table 2 details the identification (col. [1]), right ascension (col. [2]), and declination (col. [3]) of each cluster member, along with the $V$ magnitude (col. [4]) and color ($B − V$; col. [5]). Column (6) lists the heliocentric velocity. Columns (7) and (8) list the determined metallicity ([Fe/H]) and the error associated with it ($\sigma_{[\text{Fe/H}]}$). Columns (9) and (10) give the age assigned to each star and its error. Finally, column (11) informs the reader on which run the star was observed, where “1” is for the 98/99 sample and “2” for 2002. Table 3 gives the identification (col. [1]), right ascension (col. [2]), and declination (col. [3]) of the nonmembers and photometry information. Column (6) lists the heliocentric velocity, and column (7) states on
which observing run the star was observed ("1" for the 98/99 sample, "2" for 2002).

Example spectra of a metal-poor subgiant, whose metallicity is representative of the majority of the cluster population, and one of the more unusual metal-rich members are shown in Figure 5. Noticeable differences between the two spectra are the increased G band between 4300 and 4310 Å, CN at 3883 and 4215 Å, and numerous metal lines in the more metal-rich star. A paper on the analysis of the abundances of carbon, nitrogen, strontium, and barium for all members, including the more peculiar objects, is in preparation.

Spectra with 2dF were also obtained for main-sequence stars in four other globular clusters, NGC 6397, M55, NGC 6752, and 47 Tuc. These clusters were observed in a manner similar to that for ω Cen. The data obtained for the clusters were used here to test the reliability of the metallicity calibration. Observing dates and parameters used are given in Table 4. Abundance standards were also observed for calibrations during each 2dF cluster run.

3. METALLICITIES

3.1. Abundance Calibration

Metallicities were calculated using a combination of two methods following Beers et al. (1999). The first uses the Ca ii K line strength (in the form of a pseudo-equivalent width) and \((B-V)_0\). In order to take into account the large range in K line strength, three different on-feature bandwidths were used. These were 6, 12, and 18 Å and formed indices designated K6, K12, and K18, respectively. The line bands and sidebands for these indices are defined as in Beers et al. (1999). The final index, \(K'\), is given by

\[
K' = \begin{cases} 
K6, & K6 \leq 2.0, \\
K12, & K6 > 2.0, K12 \leq 5.0, \\
K18, & K12 > 5.0. 
\end{cases}
\]  

This metallicity determination becomes more uncertain at higher metallicities due to the saturation of the Ca ii K line. Another uncertainty arises from \((B-V)_0\), as this color index may be affected by anomalous CN absorption not found in the calibrating objects. At fixed \(K'\) and for a \((B-V)_0\) typical of the more metal-rich stars that show strong CN absorption, a change of \((B-V)_0\) of ±0.02 mag results in an abundance change of ±0.08 dex.

The second method used a technique known as the autocorrelation function (ACF) method, which utilizes the strength of the metal lines in the spectrum. The wavelength range used in this technique is 4000–4285 Å exciting the CN band and hydrogen lines in the process (from 4166 to 4216 and 20 Å centered on Hδ). The main drawback of this calibration is that the spectra need to have a sufficient signal-to-noise ratio (at least S/N ≥ 20) so that the method is not seriously affected by noise.

To quantify the usefulness of the two indices, tests were performed to determine cutoff limits in S/N and in \((B-V)_0\) for which only \(K'\), only ACF, or the combination of both would be used. The cutoff limits were determined from spectra of 15 high proper motion stars chosen from the lists of Giclas (see, e.g., Carney et al. 1996) to cover the range in metallicities found in ω Cen. Spectra of these objects, which are all dwarfs, were obtained with Australian National University’s 2.3 m telescope at Siding Spring Observatory and have a resolution of 1.2 Å (FWHM) and S/N ∼ 100. The spectra were convolved to have the same resolution as our 2dF sample, and five different levels of noise were introduced to the spectra to cover the S/N range in our sample. The convolved and noise-added spectra were then analyzed with our metallicity determination technique, and the resulting abundances compared, as a function of color and S/N, with the abundances that result from applying our technique to the original higher resolution, high-S/N spectra. As expected, objects with higher metallicities showed larger errors when using the \(K'\) index, while the metal-poor stars had larger scatter when ACF was employed.
This procedure also found a systematic offset in the ACF abundance in the sense that the abundances derived from the convolved noise-added spectra were higher than those for the original spectra. The offsets were a function of metallicity, color, and S/N, with bluer objects having larger offsets than redder ones for a given S/N. Given the similarity between the convolved noise-added spectra of the Giclas dwarfs and those of our ω Cen stars, we applied these corrections, again as a function of metallicity, color, and S/N, to the initial ω Cen star ACF metallicity determinations to account for this systematic effect. The corrections ranged in size from −0.1 to −0.3 dex.

We also analyzed 2dF observations of a number of field dwarfs with known metallicities chosen from the lists of Carney et al. (1996) and Beers et al. (1999). Approximately half of these spectra were obtained during our cluster observing runs, while the remainder were obtained from other runs using the same instrumental setup. Our K′ and ACF abundances derived from these spectra generally agreed well with the literature values: the mean differences were ∼−0.1 dex for [Fe/H] < −1.0, but somewhat higher (∼0.2–0.3 dex) for the more metal-rich objects.

The existence of 2dF spectra for substantial samples of main-sequence stars in four globular clusters (NGC 6397, M55, NGC 6752, and 47 Tuc) allows a further investigation of our abundance determinations. These spectra have S/N values similar to those of our ω Cen sample. We applied our technique to the cluster main-sequence star spectra, and the resulting abundance histograms for [Fe/H]K′ and [Fe/H]ACF are shown in Figures 6 and 7, respectively. In the case of [Fe/H]K′, we found that the mean abundances for the clusters from our technique are systematically lower by 0.2–0.3 dex than the accepted metallicities (Harris 1996). We also note that the distribution for 47 Tuc is considerably broader than for the other three clusters. This results from the saturation of the Ca ii K line at higher metallicities, which, in turn, causes a larger uncertainty in the final [Fe/H]K′. Furthermore, we verified that the possible bimodality of the 47 Tuc abundance distribution in Figure 6 is not correlated with the known bimodality in CN strengths on the cluster main sequence.

For the ACF metallicity, despite use of the offsets defined from the analysis of the Giclas star spectra, the values for NGC 6397 and 47 Tuc are higher than the accepted values by ∼0.2 dex. No [Fe/H]ACF values were derived for the M55 and NGC 6752 stars as the spectra generally do not possess sufficient counts to apply the technique. We also note that the width of the NGC 6397 [Fe/H]ACF distribution is quite broad. This is a consequence of the relatively low sensitivity of the ACF method at low abundance.

### Table 2

#### ω Cen Members

| ID     | R.A. (J2000.0) | Decl. (J2000.0) | V (mag) | B − V | Velocity (km s⁻¹) | [Fe/H] | σ[Fe/H] | Age (Gyr) | σAge (Gyr) | Run¹ |
|--------|---------------|----------------|---------|-------|-------------------|--------|---------|-----------|------------|------|
| 1000258 | 13 25 49.30   | −47 15 35.1    | 18.49   | 0.52  | 200               | −1.76  | 0.19    | 12.8      | 2.7        | 1    |
| 1000812 | 13 25 47.00   | −47 17 23.0    | 17.47   | 0.61  | 227               | −1.64  | 0.19    | 12.3      | 1.3        | 2    |
| 1002064 | 13 25 41.80   | −47 18 39.6    | 18.29   | 0.57  | 197               | −1.41  | 0.17    | 14.7      | 2.1        | 2    |
| 1002884 | 13 25 38.00   | −47 19 46.6    | 17.49   | 0.60  | 206               | −1.76  | 0.19    | 12.8      | 1.2        | 2    |
| 1004374 | 13 25 31.00   | −47 19 24.9    | 17.50   | 0.62  | 212               | −1.72  | 0.19    | 13.0      | 1.1        | 2    |
| 1005088 | 13 25 27.60   | −47 13 33.8    | 17.39   | 0.73  | 224               | −1.58  | 0.22    | 17.5      | 3.9        | 2    |
| 1005184 | 13 25 26.70   | −47 19 50.2    | 17.28   | 0.72  | 225               | −1.93  | 0.30    | 19.0      | 2.1        | 2    |
| 1005758 | 13 25 23.70   | −47 17 26.6    | 17.38   | 0.80  | 211               | −1.37  | 0.28    | 19.0      | 3.2        | 2    |
| 1005096 | 13 25 21.80   | −47 25 48.1    | 17.32   | 0.72  | 223               | −1.49  | 0.24    | 12.4      | 4.3        | 2    |
| 1006065 | 13 25 22.30   | −47 12 09.1    | 17.51   | 0.65  | 226               | −1.62  | 0.20    | 13.0      | 1.6        | 2    |

**Notes.**—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Table 2 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.

¹ Observed in 98/99 (1) or in 2002 (2).

### Table 3

#### Nonmembers in the 2002 Observing Box

| ID     | R.A. (J2000.0) | Decl. (J2000.0) | V (mag) | B − V | Velocity (km s⁻¹) | Run¹ |
|--------|---------------|----------------|---------|-------|-------------------|------|
| 1001938 | 13 28 47.01   | −47 34 48.40   | 17.960  | 0.745 | 83.82             | 2    |
| 1002364 | 13 28 20.23   | −47 27 21.50   | 17.454  | 0.935 | −69.53            | 2    |
| 1004333 | 13 28 31.77   | −47 19 56.80   | 17.256  | 0.988 | −69.60            | 2    |
| 1006419 | 13 26 52.11   | −47 11 47.70   | 17.963  | 0.957 | 19.28             | 2    |
| 1006806 | 13 26 56.74   | −47 05 01.60   | 17.773  | 0.725 | 51.16             | 2    |
| 1006842 | 13 26 40.69   | −47 05 41.80   | 17.567  | 0.785 | 2.03              | 2    |
| 1007176 | 13 26 02.32   | −47 07 48.90   | 18.112  | 0.979 | −5.43             | 2    |
| 1007243 | 13 25 26.06   | −47 13 03.70   | 18.387  | 0.725 | −36.33            | 2    |
| 1002751 | 13 24 59.11   | −47 19 47.20   | 17.850  | 0.931 | −15.36            | 2    |
| 1008138 | 13 24 53.74   | −47 26 40.90   | 17.625  | 0.828 | −66.73            | 2    |

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¹ Observed in 98/99 (1) or in 2002 (2).
It is not clear why the clusters give systematic offsets in the $[\text{Fe/H}]_{K'}$ and $[\text{Fe/H}]_{\text{ACF}}$ abundances while the standard stars do not, although it may be due to uncorrected scattered light in the crowded multifiber spectra, which affects the absorption lines. Our preference is to use the cluster data rather than those of the standard stars given the much larger sample sizes in each cluster at a given $[\text{Fe/H}]$ (hundreds vs. a few). It is also preferable to use objects that were similar in magnitude and color and were observed and reduced in the same manner as the $\omega$ Cen stars.

Comparisons between the mean $K'$ metallicities for each cluster and the accepted $[\text{Fe/H}]$ values are shown in Figure 8, along with a similar comparison for the ACF metallicities. The median of the distributions for 47 Tuc and for NGC 6397 ($[\text{Fe/H}]_{\text{ACF}}$) were used here. In these plots the dotted lines are 1:1 relations. Error bars were also included. The vertical bars come from the standard deviation from the mean of the abundance histograms, while the horizontal error bars come from Harris (1996). In the top panel, the solid line is the least-squares fit to the data, while the bottom panel’s solid line is an offset of 0.2 dex from the 1:1 line. Corrections to the $K'$ metallicities were constructed based on a linear fit from the calibrating clusters and were applied to the $\omega$ Cen data. The ACF correction used was a 0.2 dex offset from the 1:1 line. Fitting a straight line to the ACF data might not give an accurate correction as there are only two data points, and to err on the side of caution, we instead used an offset. This was determined from the offset of 47 Tuc, as the ACF data are more

![Fig. 5.—Spectra of two stars in our sample. Top, Subgiant from the metal-poor population; bottom, subgiant from one of the more metal-rich populations. These spectra have a resolution of ~2.4 Å. Noticeable differences are the increased G band at ~4300 Å, CN at 3883 and 4215 Å, and stronger metal lines in the more metal-rich star.](image)

![Fig. 6.—$K'$ metallicity generalized histograms for the members of the calibrating clusters NGC 6397, M55, NGC 6752, and 47 Tuc. The dotted line in each panel indicates the accepted $[\text{Fe/H}]$ value (Harris 1996), which is consistently of higher metallicity than the mean $[\text{Fe/H}]$ value determined here.](image)
accurate at this metallicity than at that of NGC 6397. Final values are given by

$$[\text{Fe/H}]_{K^0} = \frac{[\text{Fe/H}]_{K^0} + 0.17}{1.06},$$

(2)

$$[\text{Fe/H}]_{ACF} = [\text{Fe/H}]_{ACF} - 0.2.$$  

(3)

The $K^0$ calibration is more reliable for metal-poor stars due to the saturation of the Ca II K line at higher metallicities. The ACF method, on the other hand, is more reliable for the metal-rich objects due to the loss of sensitivity at lower abundances. Therefore, limits were put in place at metal-poor and metal-rich ends of our metallicity range to use only the method that suited best. The final metallicity of the $\omega$ Cen stars is given by

$$[\text{Fe/H}] = \begin{cases} 
[\text{Fe/H}]_{K^0}, & \text{if } [\text{Fe/H}]_{K^0}, [\text{Fe/H}]_{ACF} \leq -2.0, \\
[\text{Fe/H}]_{ACF}, & \text{if } [\text{Fe/H}]_{K^0}, [\text{Fe/H}]_{ACF} \geq -0.8, \\
\langle [\text{Fe/H}] \rangle, & \text{otherwise}.
\end{cases}$$

(4)

The weighted mean of the two metallicities was calculated using

$$\langle [\text{Fe/H}] \rangle = \frac{[\text{Fe/H}]_{K^0} \sigma_{K^0}^2 + [\text{Fe/H}]_{ACF} \sigma_{ACF}^2}{1/\sigma_{K^0}^2 + 1/\sigma_{ACF}^2}.$$  

(5)

The error estimates associated with the initial $K^0$ and ACF determinations were derived from two sources. The first is from the Beers formulation itself, where an error estimate is assigned for the $K^0$ and ACF metallicities individually as described in Beers et al. (1999). The convolved and noise-added spectra of field dwarfs, described above, that were used to quantify the accuracy of the indices were also used to assign a second error source to the metallicities. The effect of noise is to increase the ACF index and hence leads to systematic overabundances. As noted above, corrections were applied appropriate to the star’s metallicity, color, and S/N. These simulations were also used to determine the errors.
metallicity error by the same amount. For both K
0 calibration instead of the combination of the ACF and K
0 metallicities the standard deviation for K
0 was lower at higher metallicities than the boundary limits. This technique was used between the two metallicities to assign errors at all metallicities between our boundary limits. The overall error associated with a given metallicity was taken as the average of the two separate estimates. The final adopted error was taken as the average of the two separate estimates. The overall error associated with a given metallicity was taken as the individual errors associated with either the K' or ACF metallicities if only one was used or the quadratic sum for the weighted mean metallicity, given by

\[ \frac{1}{\sigma_F^2} = \left( \frac{1}{\sigma_{K',c}^2} + \frac{1}{\sigma_{ACF,c}^2} \right). \]  

(6)

3.2. Metallicity Distribution

Figure 9a shows the resulting metallicity distributions obtained for the 98/99 and Figure 9b those for the 2002 samples. The distributions are compared with that found for the RGB of the cluster, taken from NFM96. To convert their [Ca/H] distribution to [Fe/H], [Ca/Fe] was assumed to be 0.3 for [Fe/H] ≤ −1.0 (Smith et al. 1995; Pancino et al. 2000), declining linearly from [Ca/Fe] = 0.3 at [Fe/H] = −1.0 to [Ca/Fe] = 0.0 for [Fe/H] = 0. The distributions have been normalized by area, and the RGB distribution has been convolved with a wider Gaussian kernel (σ = 0.14) than in NFM96 due to the larger errors associated with our metallicities. The metallicity errors for our sample are ~0.15–0.2 dex, compared with 0.05 dex for that of NFM96. The generalized histograms for the 98/99 and 2002 samples use the individual σ-value associated with each metallicity.

The 98/99 spectra were of hotter and fainter objects. The range of S/N for the 2002 sample was ~30–70, while for the 98/99 spectra it was ~20–40. The lower S/N for the 98/99 sample and the fact that the majority had metallicities calculated using the K' calibration instead of the combination of the ACF and K' calibrations made their metallicity determinations slightly more uncertain. Since it is the 2002 sample, in particular the brighter stars at the turnoff, that gives us the most information about the age range in the cluster, the larger errors in abundance on the main-sequence stars are not a great concern for the age determinations.

The data from our two subsamples were not combined due to the 2002 set being incomplete at the metal-poor end and biased toward the metal-rich populations. The 98/99 sample is unbiased with respect to the distribution of members in the CMD (except for a small number of stars with B − V > 0.72), while the 2002 one is biased against the metal-poor sample. This can be seen in the offset between the 2002 sample and the NFM96 data, as no corrections have been made for selection effects. There have also been no evolutionary corrections made to the distributions, although these are likely to be minor.

The distributions have a steep rise at [Fe/H] = −1.7, with tails to higher metallicities. We find 25% (44/174) and 15% (39/254) of stars with metallicities [Fe/H] < −1.7 for the 98/99 and 2002 samples, respectively. Stars with [Fe/H] > −1.0 account for 4% (11/254) for the 2002 sample and 5% (8/174) for the 98/99 sample. In the NFM96 data 25% of stars have [Fe/H] < −1.7 and 6% of stars have [Fe/H] > −1.0. The reader should note that the NFM96 sample covers the whole region of the cluster, while our sample covers the outer region between 15′ and 25′. We conclude that the metallicity range found for the turnoff region is qualitatively similar to that found for the giant branch.

A Kolmogorov–Smirnov two-sample test was performed on the 98/99 and NFM96 distributions. The null hypothesis was that the two samples came from the same distribution. This test was also repeated using the data sets from Suntzeff & Kraft (1996) in place of that of NFM96. Their data for ω Cen comprise two groups, one of subgiant branch objects and the other of red giant branch stars. These three sets of data were tested against our 98/99 data separately. For the 98/99 data, we found that the null hypothesis could not be rejected. Not surprisingly given the
biased selection, the 2002 data set showed a different result, and the null hypothesis was rejected for each of the three tests.

To check the accuracy of the metallicities, the members falling into the 2002 turnoff box were separated into three groups based on their photometry as shown in the bottom panels of Figure 10. This figure illustrates the differences in metallicity as a function of position on the CMD. The solid lines indicate where the regions of interest lie. These lines are based on an isochrone, where the first (left to right) has parameters of \( \frac{\text{Fe}}{\text{H}} = -1.2 \), age = 13.5 Gyr, and arbitrarily offset in \( V \) by -0.14 mag and in \( B-V \) by -0.062 mag to divide the data into separate groups. The second solid line is the same isochrone but offset by \( V = 12 \) mag and \( B-V = 0.12 \) mag.

Corresponding metallicity histograms for each group are shown in the top panels. The first group has a mean \( \frac{\text{Fe}}{\text{H}} \) = -1.61 \( \pm \) 0.13, the second \( \frac{\text{Fe}}{\text{H}} \) = -1.48 \( \pm \) 0.17. The third group has a mean \( \frac{\text{Fe}}{\text{H}} \) = -1.28, but note the small number of objects in this group. The errors in abundance for the third group are large (0.3 dex), evident by the large width of the histogram.

4. AGES

When determining the ages using theoretical isochrones, it is best to use the turnoff region, since this is where the isochrones are more sensitive to age variations. For the present investigation only the members with \( V \leq 18 \) were used, and these stars came from the 2002 sample.

Two methods were used to calculate the age range of the cluster. The first involved assigning individual ages to each star based on its position on the CMD and metallicity using theoretical isochrones. The second method involved the construction of synthetic CMDs from a specified metallicity distribution, age range, and theoretical isochrones, followed by comparison between synthetic and observed CMDs.

The isochrones used were the Yonsei-Yale (Y2) isochrones (Yi et al. 2001; Kim et al. 2002). These isochrones permit interpolation between age, metallicity, and \( \alpha \)-elemental abundance to generate the required isochrone. A grid of isochrones was used that spans the metallicity range \( -2.6 < \frac{\text{Fe}}{\text{H}} < 0.3 \) in 0.05 dex increments. For each metallicity there were 34 isochrones for ages 2–19 Gyr in 0.5 Gyr steps. Alpha enhancement was taken to be constant \( \langle \alpha/\text{Fe} \rangle = 0.3 \) for \( \frac{\text{Fe}}{\text{H}} \leq -1.0 \) and declining linearly for higher \( \frac{\text{Fe}}{\text{H}} \) until it reached the solar value at \( \frac{\text{Fe}}{\text{H}} = 0 \).

The RGB metallicity distribution from NFM96 was used as the input into all simulations when requiring synthetic CMDs in the following sections. This distribution was shown in the previous section to be similar to that found on the main sequence. As the NFM96 distribution is for \( \frac{\text{Ca}}{\text{Fe}} \) rather than \( \frac{\text{Fe}}{\text{H}} \), it was scaled using constant \( \frac{\text{Ca}}{\text{Fe}} = 0.3 \) for \( \frac{\text{Fe}}{\text{H}} < -1.0 \) and linearly decreasing \( \frac{\text{Ca}}{\text{Fe}} \) to 0.0 at \( \frac{\text{Fe}}{\text{H}} = 0 \) for \( \frac{\text{Fe}}{\text{H}} > -1.0 \).

4.1. Method 1: Assigning Individual Ages to Stars

To assign an age to each star, its metallicity was used to select the nearest isochrone in our grid. The isochrones with this metallicity but with differing ages were then compared to the star’s \( (B-V)_0 \) and \( M_V \) on the CMD to find the closest one.
Usually a star’s position did not fall directly on one isochrone, and linear interpolation in color or magnitude was performed between the two closest isochrones to determine its age.

An error associated with the age was obtained using the errors in $B/C0_V$ and metallicity. The errors associated with the individual $V$ magnitude contribute a very small amount to the final error and were therefore ignored here. Typical errors in $V$ give an error in the age of $\sim 0.1$ Gyr. This is shown in Figure 11, where one of the stars in our sample is plotted with isochrones of the same metallicity but with a range of ages. The inset shows the boxed region around the star with magnitude and color error bars, showing the significance of the errors in both directions and their impact on the age. To find the error, the age calculation was repeated for a positive and negative change in color using the values given in Table 1. Similarly, the metallicity was modified using $\pm 1\sigma$ errors to obtain the corresponding error in age. The range in age determined by the metallicity errors and that determined by the photometry errors were quadratically summed and halved to give the final estimate of the age error.

Total errors in the age calculation were up to $\pm 4$ Gyr for stars below the turnoff, where the isochrones are close together, and up to $\pm 2$ Gyr for objects above the turnoff. There were some stars that did not fit any of the isochrones in the grid for their metallicity. These were given the maximum (or minimum) age in the range, i.e., 19 (or 2) Gyr, and represented $\sim 7\%$ of the sample. An age of 19 Gyr for an object in a globular cluster is not believable, nor is one of 2 Gyr. This discrepancy is most likely due to $3\sigma$ errors in the photometry, which then propagate to errors in the metallicity.

Figure 12 shows the age-metallicity diagram (AMD) resulting from this method. The top panel in this plot show only those stars with $V < 18$, as this is the area of the CMD that is most sensitive to age. The solid line is a fit by eye to the data, while the dashed line is a least-squares fit taking errors in both coordinates into consideration. Middle: Observed age-metallicity diagram for $\omega$ Cen for comparison with the simulations in Fig. 13. This is the same as the top panel, but without the error bars or 19 Gyr old stars. Bottom: Box plots of the binned data.

The solid line shown in the middle panel is a constant age line drawn at 13.5 Gyr. This line shows that there are more stars below this age than above it at metallicities greater than $[\text{Fe}/\text{H}] = -1.3$, illustrating the existence of the age-metallicity relation.

The bottom panel of Figure 12, the data were divided into several metallicity bins and represented using box plots. The line in the box represents the median value of the data within the bin. The top and bottom edges of the box indicate the interquartile range, and the ends of the vertical lines represent the minimum and maximum values of the data. As there were only two stars with $[\text{Fe}/\text{H}] > -1.0$, these were plotted as individual values. This plot suggests that up to $[\text{Fe}/\text{H}] = -1.2$ it is unclear whether there is an age range. Objects with $[\text{Fe}/\text{H}] > -1.2$, on the other hand, appear to have consistently lower ages than those with lower metallicities.
To test the age range found above we performed Monte Carlo simulations of a population that had the metallicity distribution taken from NFM96. The synthetic population of stars occupied the same position on the CMD as the $\omega$ Cen turnoff stars in our sample and had the same sample size. Four different age ranges were considered, 0, 2, 4, and 6 Gyr between metallicities $[\text{Fe/H}] = -1.7$ and $-0.6$, with a linear interpolation in age between these metallicities. The oldest population in each case was assigned an age of 13.5 Gyr and $[\text{Fe/H}] = -1.7$. For example, the ages for the 2 Gyr age range simulation was calculated as follows:

$$
\text{Age} = \begin{cases} 
13.5, & [\text{Fe/H}] \leq -1.7, \\
-1.82[\text{Fe/H}] + 10.41, & -1.7 < [\text{Fe/H}] < -0.6, \\
11.5, & [\text{Fe/H}] \geq -0.6.
\end{cases}
$$

(7)

Photometric errors were included that were representative of the observed sample (see Table 1). We also included an error on the abundance determination ($\sigma = 0.15$ dex) when simulating the populations. We then determined ages for all stars in each of the populations in the same manner as was done for the observed data. The goal was to test how well we could recover the input parameters given the errors on photometry and metallicity.

The resulting AMDs are shown in Figure 13. In these plots, each point represents a simulated star and was assigned an age depending on the input parameters. Simulation 1 has no age range; simulations 2, 3, and 4 have age ranges of 2, 4, and 6 Gyr, respectively, between metallicities $[\text{Fe/H}] = -1.7$ and $-0.6$. Any stars that have abundances beyond those values have the maximum or minimum ages assigned to them. The dot-dashed line in each plot indicates the input age-metallicity relation before any photometric or metallicity errors were included. The solid line is the least-squares fit to the data, which takes errors in both coordinates into consideration.

The first thing to note in Figure 13 is that errors induce an age-metallicity relation. Figure 13a, which has an input age range of 0 Gyr, shows an apparent age range of 3.9 Gyr. As the input age range becomes larger, the calculated age range comes more into line with it. The simulations with 4 and 6 Gyr age spreads do not accurately reproduce the observed AMD for $\omega$ Cen, which can be seen by comparing Figure 13 with the observations in the middle panel of Figure 12. For these simulations, the correlation between age and metallicity is too tight when compared with that of the $\omega$ Cen plot. The two simulations with age ranges of 0 and 2 Gyr show a scatter that is similar to that of $\omega$ Cen and have similar slopes. This shows that while the observational data indicate an age range of $\sim 5$ Gyr, this number drops considerably when the errors in metallicity and photometry are taken into account. From this we conclude that the age range in $\omega$ Cen lies between 0 and 2 Gyr. To summarize: errors in metallicity and photometry have the potential to induce an unreal age-metallicity relation or to make a small one appear larger.

These simulations also show the evolutionary effects for different metallicities and ages. Simulations with higher age ranges have more metal-rich objects than those with no or small age ranges. This is due to our choice of turnoff box and to metal-rich young stars spending a longer period within the box than the older metal-rich objects. As only a small number of metal-rich objects were found in our observed sample, the above result strengthens the case for a low age range within the cluster.

To further check the age range found, we plotted the data within metallicity ranges on the CMD and fitted isochrones of appropriate
It has been suggested that large helium variations ($\Delta Y \sim 0.12$) play a key role in understanding the bimodality of the MS (Bedin et al. 2004; Norris 2004; Piotto et al. 2005). It is therefore important to see what effect helium variations have at the turnoff region of the CMD and the ages calculated for our sample. Unfortunately, the $Y^2$ isochrones (as well as most other sets of published isochrones) do not present results for sufficiently large ranges of helium for a given $Z$. Those that do cover the required range in helium and $Z$ are the Revised Yale Isochrones (RYIs; Green et al. 1987). While these models do not contain the most up-to-date physics, they are adequate to show the relative effects of helium variations.

To test the effect of helium we assumed our sample had two populations: the first had $[\text{Fe}/\text{H}] \leq -1.45$ while the second had $[\text{Fe}/\text{H}] > -1.45$. The standard value of $Y = 0.23$ was applied to the first population, and helium for the second population would then be 0.35 (for $\Delta Y = 0.12$). Although we wished to use $Y = 0.23$ and 0.35 (for $\Delta Y = 0.12$) for the first and second groups, respectively, the RYIs are incomplete above $Y = 0.3$ and isochrones with a full set of desired ages cannot be calculated. Therefore, values of $Y = 0.2$ and 0.3 were used to show the relative effect (using $\Delta Y = 0.10$). To test the effect of helium on the ages, two sets of isochrones were used. Both covered a metallicity range of $-2.6 < [\text{Fe}/\text{H}] < -0.5$ and an age range of 6–20 Gyr. All the isochrones in the first set had $Y = 0.2$. For isochrones in the second set that had $[\text{Fe}/\text{H}] \leq -1.45$, helium was taken to be 0.2, and for those with $[\text{Fe}/\text{H}] > -1.45$, $Y = 0.3$. Ages were calculated using these isochrones for each of our members in the cluster in the same manner as described in § 4.1.

The results are shown in Figure 15. Figures 15a and 15b show the AMDs for $\Delta Y = 0.0$ and 0.1, respectively. Figure 15c compares the ages determined with and without helium variations. These plots show that there is little variation at the turnoff region for a particular star when changing its assumed helium abundance. Although there is a significant difference between the positions on the CMD at the MS and RGB, the turnoff region difference is very small. We conclude that the possible enhancement of helium in the second population does not significantly affect the ages calculated at the turnoff region. There is one star in which the ages do differ by a significant amount (age =15 Gyr for $Y = 0.2$ and age =20 Gyr for $Y = 0.3$). This is due to its position on the CMD. It is at the SGB as opposed to the turnoff region, and here the isochrones lie very close together and small variations in position of the isochrones for the two sets induce a large age variation.

**Method 2: Synthetic Color Magnitude Diagrams**

The second method to determine the age range in $\omega$ Cen utilized only the photometric information. No use was made of the spectroscopy data other than that they support the use of NFM96
the metallicities $[\text{Fe/H}] = -1.7$ and $-0.6$. Any points that had metallicities outside this range were assigned the maximum or minimum value, with the maximum age being 13.5 Gyr in each simulation. Errors in photometry were assigned to each point, in accordance with the data in Table 1. Each simulation had $N = 80,000$. These simulations did not include binary stars.

Four of the CMDs obtained from these simulations are shown in Figure 16. Each CMD shows the synthetic points, with the objects with $V \leq 18$ falling in the 2002 turnoff box as larger symbols. Figure 17 shows the $\omega$ Cen data and is for comparison purposes. Figure 16a is for a simulation with no age spread; Figures 16b, 16c, and 16d are for age spreads of 2, 4, and 6 Gyr, respectively, between metallicities $[\text{Fe/H}] = -1.7$ and $-0.6$. In order to objectively test which simulation represented our observed sample best, a $\chi^2$ test was performed. This involved dividing the CMD in which our objects lie into smaller boxes. A grid of $3 \times 5$ boxes (three in $V$ magnitude and five in $B-V$) was used in this case, and each box was given equal weighting. We established, through a series of tests using different numbers of boxes, that the $3 \times 5$ grid gave the best chance of finding the age range.

In order to accurately interpret the results of the $\chi^2$ fitting we first tested our simulations and statistical calculations. The first test involved using a sample from one of the simulations to represent our observed data. The objects were chosen randomly and had the same sample size as our observed sample ($N = 222$). This was repeated five times to check the consistency of the results. Four representative samples were chosen with age spreads of 0, 2, 4, and 6 Gyr. These were tested against all the other, larger $N$ simulations in the same manner as the observed sample to see which simulation was the “best fit.” The best result in these cases would of course be the input age range. For example, the 2 Gyr representative sample should be best reproduced by the 2 Gyr simulation. The results of these tests are shown in Figure 18. For the representative sample with no age range, Figure 18a, the statistical test seems to find the correct result, although an age range of 2 Gyr cannot be definitively ruled out. The 2 Gyr representative sample (Fig. 18b) does not have a clear solution as to which simulation is best represented by it, and the test shows that it could be anywhere between 0 and 4 Gyr. The test does reproduce an age range of 4 Gyr for the 4 Gyr representative sample (Fig. 18c), but again there is an uncertainty of $\pm 2$ Gyr. The representative sample with a 6 Gyr age spread seems to be the most clearly defined result and accurately predicts an age range of 6 Gyr for the sample (Fig. 18d). These tests indicate that the higher the age range the more likely it will be recovered by this statistical test. This effect was also seen in the simulations done in § 4.1 and shown in Figure 13. Lower age ranges are harder to identify than larger ones.

The $\chi^2$ results for $\omega$ Cen are shown in Figure 19. Comparing these to the tests performed on the representative samples, we can see that the $\omega$ Cen results are similar to the 4 Gyr results. Both have an age range of 4 Gyr as the lowest $\chi^2$ value, and both have small values for the 6 Gyr simulation as well. The $\chi^2$ result for the 2 Gyr age range is somewhat higher than in the 4 Gyr graph and resembles the 6 Gyr representative sample results with a steep slope at low age ranges. The shape of the curve indicates that the age range is neither 0 nor 2 Gyr but could possibly be up to 6 Gyr. We can rule out large age ranges (of the order of 6 Gyr) as the $\omega$ Cen data do not show a distinct result for it in these simulations nor in § 4.1.

### 4.4. Simulations with No Age-Metallicity Relation

Simulations were also produced that had the $\omega$ Cen metallicity distribution and a range in ages but no age-metallicity relation, examples of which are shown in Figure 20. The ages were chosen

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**Fig. 15.—Age-metallicity relations resulting from ages obtained using (a) constant He abundance ($Y = 0.2$) and (b) varied helium abundance ($Y = 0.2$ for $[\text{Fe/H}] \leq -1.45$ and $0.3$ for $[\text{Fe/H}] > -1.45$ for $V < 18$). (c) Comparison between the ages calculated using the two different sets of isochrones. See text (§ 4.2) for details.**
randomly for each object and as such had a flat distribution. This figure shows four simulations with age ranges of 0, 2, 4, and 6 Gyr. The 2002 CMD limits are also shown, and the simulated objects falling in this area are highlighted. The solid line in the figures represents the blue edge fiducial of the $\omega$ Cen data (see Fig. 17).

These simulations did not match the 2002 sample. In particular, the old metal-rich stars and young metal-poor stars were found in the simulations but are not seen in the observational data. The young metal-poor stars in the simulations are seen in the bluer and brighter turnoff region, which have no counterpart in the observed sample as shown in Figure 17. The old metal-rich stars are found in the bottom right corner of the 2002 box in the CMD, and again none of these stars were found in the 2002 sample. This last result cannot be explained by a lack of candidate members being observed in this area. The simulated stars were well distributed across this region, but no members of $\omega$ Cen were found in that area. Although some of these simulations might be considered as fitting the observed data, it is the presence of young metal-poor stars at and above the turnoff that excludes this scenario. This does indicate that there is a clear age-metallicity relation in the cluster with the younger stars being more metal-rich.

5. DISCUSSION

5.1. Age Range

We have shown using several different methods that there is a difference in ages within the stars of $\omega$ Cen of between 2 and 4 Gyr. Our first method of assigning individual ages to stars initially seemed to indicate quite a large age range of 5 Gyr. It was found, however, through simulations of the populations in $\omega$ Cen that this large age range was most probably induced by the observational errors, which led to an enhanced age-metallicity correlation. Our simulations indicated that the actual age range in the cluster was $2 \pm 2$ Gyr. Simulations of the CMDs, using only the photometric information, showed that the age range is $4 \pm 2$ Gyr.

Although our results do not give a definitive value for the age range in $\omega$ Cen, they can be used, along with other data, to strongly constrain it. Previous results for the existence of an age range in $\omega$ Cen, and the methods employed, are summarized in Table 5. Considering these studies, an age range of $\geq 6$ Gyr is most likely to be too high. On the other hand, although a zero
age range cannot be ruled out completely, it seems unlikely to be the case, particularly given the results for the element abundance ratios in the metal-rich populations. We therefore conclude that the most likely value for the age spread in Cen is 2–4 Gyr.

Two results in the literature are most relevant to this work. The first is that of Hilker et al. (2004). They used Strömgren photometry and metallicities to determine an age range of 3 Gyr. Their result is consistent with what we found here.

The second result is from Sollima et al. (2005b) using two sets of photometry and metallicities derived from spectra. They find little, if any, age range (0–2 Gyr) in their isochrone fits to the CMDs. As we have found an age range of 2–4 Gyr these results are not entirely inconsistent but do differ enough to warrant further investigation. Part of the explanation for this difference may come from the two different regions of the cluster that we and Sollima et al. (2005b) have observed. Our photometric data come from the outer regions of the cluster between 15' and 25' from the center, while the Sollima et al. (2005b) data originated from fields centered on the cluster out to 10'. The metal-rich population is more centrally concentrated (NFM96), and we might not be sampling enough of these objects to make a conclusive statement on the ages of the most metal-rich population. In apparent disagreement with there being no age range, however, is the lack of /C11-enhancement in the most metal-rich population (Pancino et al. 2002) suggesting SNe Ia involvement in the enrichment of the stars. Kobayashi et al. (1998) found that the progenitors of SNe Ia may take ≤1 Gyr to evolve, which is in agreement with the result of Sollima et al. (2005b). However, Yoshii et al. (1996) found that the lifetime of SNe Ia progenitors is most likely to be 0.5–3 Gyr, which supports both the result found here and that of Sollima et al. (2005b). An abundance study of the s-process elements by Pancino (2003) for the most metal-rich stars shows enrichment on the same scales as the metal-intermediate population ([s/Fe] ∼ 1.0 dex; Norris & Da Costa 1995; Smith et al. 1995, 2000). The sources of these enrichment processes (AGB stars) take several gigayears to mature (Smith et al. 2000; Romano et al. 2005 and references therein).

Examining Figures 3 and 5 from Sollima et al. (2005b), which are relevant to their Wide Field Imager (WFI) data, one finds that an age range of about 3 Gyr is possible. Using isochrones with slightly different metallicities from those plotted by Sollima et al. (2005b; for example, [Fe/H] = −1.85 for the MP population and [Fe/H] = −1.2 for the MINT2 population, suggested...
by the mean abundance in the sample range determined from their Fig. 3), ages of 17 and 14 Gyr are required to fit the MP and MINT2 data, respectively, giving an age range of 3 Gyr. Furthermore, the outliers in the right panel of their Figure 5, which are explained by Sollima et al. (2005b) as possibly due to photometric or spectroscopic errors, may instead require a much younger age. It would be interesting to know how far from cluster center these objects lie. A possible conclusion might be that there is a bimodality in age in the most metal-rich population in which the older metal-rich group resides primarily in the center of the cluster, while the younger metal-rich group is more widely distributed. Given the metallicity errors in both Sollima et al. (2005b) and our data sets, it is not possible at present to obtain a definitive answer to this possibility.

In Figures 4 and 6 of Sollima et al. (2005b), which pertain to a different, higher spatial resolution data set, one does not find a similar age difference, except to say there is a large range in metallicities (shown in the top panels of their Fig. 4) for each population. This might indicate that there is a range of ages in each population. The lack of spread in the CMD for each metallicity group, however, suggests that the single metallicity isochrone fits to these data are an appropriate choice.

Throughout this work we have assumed the age-metallicity relation to be a linear one. This might not be the case. We know that ω Cen has at least three (and possibly up to five) distinct populations. The length of time between the formation of these populations might not in fact be linear. Unfortunately, our data do not have the required accuracy to address this question. More accurate metallicities are required, for which higher resolution spectra are needed, as well as larger samples of the most metal-rich population, to more accurately determine the age range in the cluster.

5.2. Cluster Origins

The origin of ω Cen is not well understood. Due to its unique metallicity and age ranges it is unlikely to have formed in the same manner as other globular clusters. From the enrichment of its member stars, one concludes that it was massive enough to retain ejecta from AGB stars and supernovae. Tsujimoto & Shigeyama (2003) discuss the formation of globular clusters as the result of cloud-cloud collisions. These collisions trigger star formation, and chemical evolution in the resulting cluster depends on the relative velocity of the initial clouds. Those with low velocities trigger star formation involving less than 1% of the gas and promote star formation episodes induced by supernovae, as would be the case in ω Cen. On the other hand, collisions between clouds with higher velocities do not retain enough gas to form later generations after the initial star formation episode, resulting in “normal” globular clusters.

Alternatively, ω Cen may be the result of mergers of several globular clusters with discrete metallicities within the halo of the Milky Way. However, several globular clusters of discrete metallicities do not accurately reproduce the metallicity distribution seen on the RGB (NFM96; Smith et al. 2000), and the probability of several clusters colliding and merging in the halo is low. This scenario is also not consistent with the s-process enhancements seen in the more metal-rich populations. A different twist to this hypothesis is the “merger within a fragment” scenario (Searle 1977; Searle & Zinn 1978). In the context of ω Cen, the more metal-rich component may have been another smaller cluster associated with the parent dwarf galaxy that merged with the nucleus (Norris et al. 1997; Ferraro et al. 2002).

Current evidence suggests that ω Cen is most likely to be the remnant nucleus of a dwarf spheroidal galaxy that was consumed.
by the Milky Way (Freeman 1993), similar to the Sagittarius dwarf spheroidal galaxy (dSph), which is currently in the process of being stripped. The similarities between Cen and dSph galaxies were noted initially by Norris & Bessell (1978). Consistent with this scenario, Cen shows self-enrichment over a timescale of several gigayears. The current orbit of Cen within the Galaxy is at odds with cluster enrichment over a long timescale, suggesting that this is not where it initially formed. Specifically, frequent disk crossings of the current orbit would not have allowed such self-enrichment to take place; any gas would have been stripped from the cluster on short timescales. The retrograde motion and small apocentric radius (Dinescu et al. 1999) are unusual properties for a globular cluster and further suggest that it did not originally form in its current orbit.

Bekki & Freeman (2003) have demonstrated using a self-consistent dynamical model that Cen could have been formed from a nucleated dwarf galaxy that interacted and merged with the young Galactic disk over a period of some 3 Gyr. This model assumes that there is very little gas in the Galactic disk at these times. The central nucleus survives tidal stripping due to its compactness, and extended star formation is induced by the Galactic tidal forces causing radial inflow that triggers repetitive starbursts. Their Figure 4 shows that star formation is enhanced slightly at several different epochs. This is consistent with the age range found here for Cen and the distinct populations found in the cluster.

Numerical simulations have been used to analyze the dynamical evolution of simulated dwarf galaxies that evolve to have the present-day kinematic characteristics of Cen (Mizutani et al. 2003; Chiba & Mizutani 2004; Meza et al. 2005). As the disruption occurs, these systems may deposit large fractions of their stars into the thick disk component of the Galaxy, leaving the nucleus to orbit it. As Mizutani et al. (2003) note, the debris from the progenitor may have already been found in the observations showing signatures of merging events in the Milky Way (Gilmore et al. 2002). Analysis of data from various surveys (such as the Sloan Digital Sky Survey [York et al. 2000] or Radial Velocity Experiment [Steinmetz 2003]) may find the debris from the progenitor of Cen in the thick disk, giving a more comprehensive picture of the evolution of the cluster.

Abundance studies of the Sagittarius dwarf spheroidal galaxy have shown similar patterns to those found in Cen for some elements (McWilliam & Smecker-Hane 2005a, 2005b), further supporting the idea that the cluster was associated with an accreted dwarf galaxy. Deficiencies in copper are seen in both systems (McWilliam & Smecker-Hane 2005a; Cunha et al. 2002; Pancino et al. 2002), and abundance patterns of other elements (e.g., La and Y) are also similar. However, [$\alpha$/Fe], Na, and Al exhibit different patterns. This last result indicates that although both systems share a similar history, as one might expect evolutionarily differences exist between them. Care should be taken, however, when comparing Cen with dSph galaxies, as the relative sizes between the two systems are quite different. Despite this, comparisons can still be made between the systems, since Cen, as the nucleus of a dSph, may have had gas inflow from the parent dSph outer regions that was incorporated into later generations of cluster stars (Bekki & Norris 2006).

The Carina and Fornax dSph galaxies show large ranges in both metallicity and age (Mateo 1998 and references therein). The Carina dwarf spheroidal galaxy is known to have two, possibly three, episodes of star formation (Smecker-Hane et al. 1994; Hurley-Keller et al. 1998; Monelli et al. 2003). These results are qualitatively similar to those found for Cen: star formation over relatively large timescales, once again supporting the idea that this cluster is the nucleated remnant of a dSph galaxy.

Another property of Cen is the dependence of kinematics on abundance. Norris et al. (1997) showed that the metal-rich component in the cluster is centrally concentrated and has a lower velocity dispersion than the metal-poor population. Sollima et al. (2005b) not only find that the metal-intermediate populations have a lower velocity dispersion than the metal-poor component, in agreement with Norris et al. (1997), but further find that the most metal-rich population has a higher velocity dispersion than the metal-intermediate one but not as large as the metal-poor one. Anderson (2003) did not find any evidence of proper-motion variations between three SGB populations in Cen, including the most metal-rich one. Furthermore, Piotto et al. (2005) found the mean radial velocities of the blue and red main sequences to be essentially the same. The Sculptor dSph galaxy shows the similar characteristic of dependence of kinematics on abundance (Tolstoy et al. 2004). This dSph has two distinct populations, one metal-rich ([$Fe/H]=−1.4$) and the other metal-poor ([$Fe/H]=−2.0$). The higher metallicity stars show lower velocity dispersion than the metal-poor component and are also more centrally concentrated, just as reported for Cen. Tolstoy et al. (2004), however, found no evidence of different systemic rotation between the two components. In contrast, in Cen the metal-poor component exhibits systemic rotation while the metal-rich one does not (Norris et al. 1997), showing that there are still many differences between the systems that are yet to be explained.
6. CONCLUSIONS

Interpretation of our age-metallicity diagram is complicated by correlated errors in metallicity and age, but after extensive simulations an age range of 2–4 Gyr is found to exist in ω Cen. We find an age-metallicity relation for which the younger stars are those that are more metal-rich. These results strengthen the likelihood that the origin of the unusual properties of this cluster is connected with the evolution of a more massive system such as a nucleated dwarf galaxy that was subsequently captured and disrupted by the Milky Way.

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