ABUNDANCES ON THE MAIN SEQUENCE OF ω CENTAURI

LAURA M. STANFORD, G. S. DA COSTA, AND JOHN E. NORRIS
Research School of Astronomy and Astrophysics, Australian National University, Weston, ACT 2611, Australia; stanford@mso.anu.edu.au, gdci@mso.anu.edu.au, jen@mso.anu.edu.au

AND

RUSSELL D. CANNON
Anglo-Australian Observatory, Epping, NSW 2121, Australia; rdc@aaoepp.gov.au

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ABSTRACT

Abundance ratios of carbon, nitrogen, and strontium relative to iron, calculated using spectrum synthesis techniques, are given for a sample of main-sequence and turnoff stars that belong to the globular cluster ω Centauri. The variations of carbon, nitrogen, and/or strontium show several different abundance patterns as a function of [Fe/H]. The source of the enhancements/depletions in carbon, nitrogen, and/or strontium may be enrichment from asymptotic giant branch stars of low (1–3 $M_\odot$) and intermediate (3–8 $M_\odot$) mass. Massive rotating stars that produce excess nitrogen without carbon and oxygen overabundances may also play a role. These abundances enable different contributors to be considered and incorporated into the evolutionary picture of ω Cen.

Subject headings: globular clusters: general — globular clusters: individual (ω Centauri)

Online material: machine-readable table

1. INTRODUCTION

The globular cluster ω Centauri is known to have characteristics not shared by other clusters. Its unusual nature was first noted by Woolley et al. (1966) and Cannon & Stobie (1973) who demonstrated that its red giant branch (RGB) has an intrinsic color spread. Early abundance studies of member stars, obtained spectroscopically, have shown a range in metallicity (Freeman & Rodgers 1975; Lloyd Evans 1977; Butler et al. 1978; Cohen & Bell 1986; Francois et al. 1988; Paltoglou & Norris 1989).

In the last decade detailed spectroscopic and photometric work on ω Cen has revealed the large extent of the abundance range within the system.

The cluster metallicity distribution has been studied in more detail recently, using spectroscopic analysis of the Ca ii triplet lines (Norris et al. 1996; Suntzeff & Kraft 1996), photometry (Lee et al. 1999; Pancino et al. 2000; Hilker & Richtler 2000; Sollima et al. 2005), and spectroscopic analysis of the Ca ii K line (Stanford et al. 2006a). These studies found few, if any, stars with $[\text{Fe/H}] < -2.0$. The distribution then rises to a peak at $[\text{Fe/H}] = -1.7$ with a long tail to higher metallicities, up to $[\text{Fe/H}] \approx -0.4$. The distribution also has a second peak at $[\text{Fe/H}] = -1.2$ (Norris et al. 1996).

Three main populations within the cluster have been identified (Norris et al. 1996; Suntzeff & Kraft 1996; Pancino et al. 2002). The bulk of the cluster stars (~70%) has metallicities at $[\text{Fe/H}] \approx -1.7$, the metal-intermediate population has $[\text{Fe/H}] \approx -1.2$ and represents roughly 20% of the stars, and the remaining 5% of the stars are metal-rich, at $[\text{Fe/H}] \approx -0.6$. Sollima et al. (2005) found the RGB to be discrete in nature and identified up to five distinct populations, three of which are within the metal-intermediate population described above. Elemental studies have shown a range in abundances within the cluster members. Carbon, nitrogen, and oxygen exhibit large scatter for a given $[\text{Fe/H}]$ (Persson et al. 1980; Brown & Wallerstein 1993; Norris & Da Costa 1995, hereafter ND95). The α-elements (Mg, Si, Ca, and Ti) have constant values at a given $[\text{Fe/H}]$ for most metallicities (Brown & Wallerstein 1993; Smith et al. 1995, 2000; ND95), but $[\alpha/\text{Fe}]$ decreases at higher metallicities ([Fe/H] > -1.0) (Pancino et al. 2002). As the α-element abundances are constant with iron below $[\text{Fe/H}] \approx -1.0$, they are produced by the same source, most likely supernovae Type II. At higher abundances, decreasing $[\alpha/\text{Fe}]$ is indicative of supernovae Type Ia contributions.

The heavy neutron-capture elements (e.g., Y, Zr, Ba, La, Pr, and Nd) give information on enrichment sources, shedding light on whether a slow or rapid neutron-capture process occurred (or both). ND95 and Smith et al. (1995) found that the s-process abundance ratios with respect to iron increase with increasing $[\text{Fe/H}]$, and then flatten above $[\text{Fe/H}] = -1.2$. These results are in contrast to normal globular clusters and indicate that the stellar winds from asymptotic giant branch (AGB) stars (sources of s-process elements) were involved in the enrichment process of ω Cen. ND95 concluded also that there were no correlations between the abundance ratios with respect to iron for the s-process elements and those for C, N, O, Na, and Al. Eu is an r-process element, and abundances of this element are found to be lower in ω Cen stars than in the field (Smith et al. 1995), and ratios of Ba/La show that the enrichment process is dominated by the s-process (ND95).

Another piece in the ω Cen puzzle is the double main sequence seen in deep photometry of the cluster (Anderson 2002; Bedin et al. 2004). This is thought to be the result of helium variations of the order of $\Delta Y \approx 0.12$ dex between two populations (Norris 2004; Piotto et al. 2005). The source of the large amount of additional helium required may be AGB stars with masses larger than 6 $M_\odot$, stellar winds associated with early evolutionary phases of massive stars, or perhaps Type II supernovae (Norris 2004; Piotto et al. 2005; Maeder & Meynet 2006). Bekki & Norris (2006) suggest that the helium-enhanced population formed from gas ejected by the stellar populations that surrounded ω Cen when it was the nucleus of a dwarf galaxy. Maeder & Meynet (2006) have argued that in models with low metallicity, massive stars with high rotation can produce the large amounts of helium required to explain the blue main sequence (BMS), depending on the slope of the initial mass function. These models also produce a large excess of nitrogen but little carbon, consistent with
the phenomena observed in spectra of the stars in the bMS (Piotto et al. 2005).

Variations of the CNO group, Na, Mg, and Al abundances have been found to different degrees in most normal globular clusters on the RGB. In the last few decades, studies of main-sequence turnoff (MSTO) stars in a number of globular clusters have shown that variations exist in C and N in this region of the CMD as well. These clusters include 47 Tuc (Cannon et al. 1998; Briley et al. 2004b), NGC 6752 (Suntzeff & Smith 1991; Gratton et al. 2001a), M71 (Cohen 1999; Briley & Cohen 2001; Ramirez & Cohen 2002), M5 (Cohen et al. 2002), and M13 (Briley et al. 2004). Anticorrelations between Na and O have been shown to exist on the main sequence (MS) in 47 Tuc (Carretta et al. 2004), NGC 6397, and NGC 6752 (Gratton et al. 2001b). These latter two clusters also have an anticorrelation between Mg and Al (Gratton et al. 2001b).

There are three possibilities for the origin of the abundance variations in ω Cen and other globular clusters: internal processing, accretion of matter onto surface layers, and primordial formation. In regard to the first possibility, internal processing within the individual stars themselves, with the products then being mixed to the surface layers, may be the source of the abundance variations. This may account, in part, for the variations in the RGB stars in some clusters, as the level of C depletion on the RGB increases with decreasing magnitude (e.g., M92; Langer et al. 1986). However, mixing of the internal layers does not occur in the current MS stars (e.g., Da Costa & Demarque 1982). Therefore, internal processing cannot explain all the variations seen in globular clusters. The second option is that the enriched accreted material onto their surface layers from the stellar winds of AGB stars. The stars may have been a part of a binary system or in the vicinity of AGB stars. The accreted material will be on the surface layers only, and, therefore, in a comparison of MS with RGB abundance ratios one should generally find higher abundances for the unevolved stars than are found for the evolved ones because increased convective mixing as the stars evolve up the RGB will dilute the accreted material. Primordial variations account for the third and final possibility. Here the stars formed from material that had been previously enriched from sources such as winds and ejecta of AGB stars, massive rotating stars, and/or supernovae.

Most spectroscopic studies have concentrated on the RGB stars in ω Cen because of their greater brightness. We have obtained spectra of a sample of turnoff stars to examine the relationship between age and metallicity in the cluster (Stanford et al. 2006a), and to determine abundances of several elements and compare them with those found on the RGB. This gives further insights into the evolutionary history of ω Cen and enables us to distinguish between surface enhancement and primordial enrichment scenarios within the cluster.

The present paper describes the analysis of these spectra to determine abundances of C, N, and Sr relative to Fe for the MS and turnoff (TO) sample and attempts to untangle the complex evolutionary history of ω Cen. Early results of this work are given in Da Costa et al. (2005). In §2 we describe the observations and reduction techniques. Section 3 outlines the derivation of metallicities and ages for the sample and discusses the metallicity populations. We describe the techniques used to determine C, N, and Sr abundances in §4. Finally, §5 summarizes the results and discusses a chemical evolutionary history for the cluster.

2. OBSERVATIONS AND REDUCTION

The observations and reduction of our data are described in detail in Stanford et al. (2006a), to which we refer the reader. Sufficient it here to say that the photometry of the cluster was obtained with the 1 m telescope/Tektronix CCD combination at Siding Spring Observatory in the V and B bands. From these data a color-magnitude diagram (CMD) shown in Fig. 1 was constructed for objects within an annulus 15’–25’ from the cluster center. Two regions were defined on the upper MS, with a view to determining the metallicity and age range for the cluster. Stars in each region were observed using the Two Degree Field (2dF) multiobject spectrograph (Lewis et al. 2002) on the Anglo-Australian Telescope. This spectrograph has the capability of simultaneously observing up to 400 objects using a fiber-fed system. 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. Spectra were obtained with 1200 line mm$^{-1}$ gratings used in the spectrographs and covered the wavelength range 3800–4600 Å. They have a resolution of ~2.5 Å FWHM and signal-to-noise ratio (S/N) of 30–50. A final sample of 424 radial velocity–selected members was found. The members are shown as large dots in Figure 1. The small dots represent the photometry of all the remaining objects that do not have membership information.

Data for stars on the MS were also obtained for three other globular clusters: NGC 6397, NGC 6752, and 47 Tuc. These clusters were observed in a similar manner to that used for ω Cen, and membership was determined based on radial velocities and metallicities. The data obtained for the clusters were used to test the reliability of the metallicity calibration and for comparison of abundances.

3. METALLICITIES AND POPULATIONS

The process for calculating metallicities has been described in detail in Stanford et al. (2006a). To summarize, the metallicities were calculated using a combination of two methods (see Beers et al. [1999] for details of these methods briefly described here). The first uses the Ca H K line strength and color of an object to assign a metallicity. Due to the saturation of the Ca H K line these metallicities become uncertain above [Fe/H] ≈ −1.0. The second method uses the weak metal lines in the spectrum. This method
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Fig. 2.—Generalized histograms of the metallicity distribution for the 98/99 (a) and 2002 (b) samples (Gaussian kernel of \(\sigma = 0.15 - 0.20\), based on the individual errors for each metallicity). For comparison, the Norris et al. (1996) RGB distribution is also plotted (\(\sigma = 0.14\)). Indicated on each histogram is the division into three populations with the first having \([\text{Fe/H}] < -1.5\), the second \(-1.5 \leq [\text{Fe/H}] < -1.1\), and the third \([\text{Fe/H}] \geq -1.1\).

The metallicity analysis. For the first and second populations (at \([\text{Fe/H}] = -1.7\) and \(-1.2\), respectively) the \([\alpha/\text{Fe}]\) ratio was taken to be 0.3 (ND95; Smith et al. 1995, 2000). For the most metal-rich population, with a mean \([\text{Fe/H}] = -0.8\), the \(\alpha\) enhancement was taken to be \([\alpha/\text{Fe}] = 0.18\).

3.1. Indices

Indices were measured for the \(G\) band (CH) at \(\sim 4300\) Å, the violet CN band at 3883 Å, the Sr \(\lambda 4077\) and \(\lambda 4215\) lines, and Ba \(\lambda 4554\) for the \(\omega\) Cen members and calibrating cluster stars. The weaker Sr \(\lambda 4215\) line was used as confirmation of the Sr abundance, which was determined primarily from the Sr \(\lambda 4077\) feature. The bandpasses for CH, Sr, and Ba are given in Table 1, with the indices defined following Beers et al. (1999). The CN index is S3839 as defined by Norris et al. (1981). The \(\omega\) Cen data are plotted as a function of metallicity in Figure 4, split into MS (\(V > 18\)) and SGB (subgiant branch; \(V \leq 18\)) samples. The corresponding indices determined for NGC 6397, NGC 6752, and 47 Tuc are represented by box plots showing the area they occupy in \([\text{Fe/H}]-\text{index} \) space, for comparison with the MS \(\omega\) Cen stars, as we do not have data for the SGB stars in these clusters. The center line within the rectangle for each box plot represents the median for each data set. The bottom and top sides of the box represent the first and third quartiles, while the vertical lines extending from the top and bottom edges of the box represent the upper and lower limits of the data. The error bars in the figure represent the standard error of the mean of the indices for individual observations and the derived error in metallicity.

Studying the two CH plots, one can see that the SGB group has, in general, higher indices than on the MS one. This is due to the cooler temperatures on the SGB than on the MS. At lower metallicities on the MS, there are two members that have unusually high C indices. These fall well outside the ranges in \([\text{Fe/H}]\) and the CH index that is occupied by the calibrating clusters. Outliers can also be identified on the SGB. The S3839 index shows several objects that appear to have high abundances of carbon and/or nitrogen in both the MS and SGB groups. The strontium...
index plot shows a large scatter, and several outliers can be identified in both panels. For the SGB group, a least-squares fit to the data was performed, shown by the solid line. This line indicates that there are several objects with considerably higher Sr indices than those of the main population. There is little spread in the Ba index, most likely due to the low sensitivity of our data to the Ba abundance.

The CN-CH bimodality known to exist on the RGB of 47 Tuc is also found on the MS (Cannon et al. 1998; Da Costa et al. 2004). CN-strong and CN-weak stars exist in ω Cen on the RGB but have not yet been seen on the MS in ω Cen. Figure 5 plots the CN index versus the CH one for the ω Cen data and is split into the three metallicity bins as well as into the MS and SGB groups (left and right columns, respectively). Also plotted (open circles) are the 47 Tuc data showing the bimodality within this cluster for comparison with the metal-rich, MS population in ω Cen. The solid line is a fit to the 47 Tuc anticorrelation and is plotted in each panel as a reference. The dotted line is the one used to define the CN weak/CH strong (and vice versa) groups.

4. FIRST-PASS ABUNDANCES

To obtain an initial estimate of the abundance ratios of stars in our sample, in particular for the stars that have enhancements in carbon, nitrogen, and/or strontium, we compared indices obtained from synthetic spectra with those from the observed data. As described in § 3, the ω Cen sample was divided by metallicity into three populations, shown in Figure 3. Isochrones with the mean metallicity and ages of each population were fitted to the data. Discrete points along these isochrones gave a series of stellar parameters (temperature and gravity) that are representative of the observed data for each population.

Kurucz models (1993) were used with atomic line lists from R. A. Bell (2000, private communication) and Kurucz molecular lines lists to generate synthetic spectra to compare with our observations. The spectrum synthesis code was originally developed by Cottrell & Norris (1978). A synthetic spectrum with appropriate stellar parameters was compared with an atlas of the Sun (Beckers et al. 1976). Using an adopted solar C abundance of log \( N / N_{\text{tot}} \) = $-3.36$, we found that the CH feature showed a small difference between the spectrum of the Sun and the synthetic spectrum, and as a result the log \( g_f \)-values were reduced by 0.5 dex. Similarly, for an adopted N abundance of log \( N / N_{\text{tot}} \) = $-4.04$, the synthetic violet CN feature was too strong with respect to the solar spectrum and the log \( g_f \)-values were reduced by 0.25 dex. The log \( g_f \)-values for the blue CN feature (\$4215\$) were reduced by 0.10 dex in a similar manner. The Sr \$4077\$ and \$4215\$ lines and Ba \$4554\$ line were also compared and found to be within acceptable agreement. An observed spectrum of Arcturus ($\alpha$ Boo) was then compared with a synthetic spectrum with appropriate stellar parameters (ND95) and was used as an independent check of the adjusted values. It was found to provide acceptable agreement with abundance studies of this star. Table 2 lists the \( g_f \)-values and solar abundances used here for Sr and Ba.

The derived abundance of C is influenced by the amount of oxygen within the star, as the CO molecule forms preferentially over the CH one. However, for our range of stellar parameters, changing the O abundance was demonstrated to have no effect

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TABLE 1

| Line     | Line Band (Å) | Blue Sideband (Å) | Red Sideband (Å) |
|----------|---------------|-------------------|------------------|
| G band (CH) | 4292.5–4317.5 | 4247.0–4267.0     | 4357.0–4372.0    |
| Sr \$4077\$ | 4074.7–4080.7 | 4048.0–4060.0     | 4085.0–4092.0    |
| Sr \$4215\$ | 4212.0–4218.0 | 4201.0–4211.0     | 4245.0–4257.0    |
| Ba \$4554\$ | 4551.0–4557.0 | 4505.0–4512.0     | 4573.0–4579.0    |

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1 Vizier Online Data Catalog, V/39 (R. Kurucz, 1993).
on our calculations. This result was tested by generating a series of synthetic spectra at metallicities that spanned the ω Cen metallicity range with several temperatures and gravities typical of the observed sample. The oxygen abundance was varied for each one (between $\frac{[O/Fe]}{C}$ = 0.0 and 0.5 dex), and the strength of the G-band was compared between synthetic spectra with the same stellar parameters. It was found that oxygen did not play a significant role in the abundance determined from the CH feature for any of the stellar parameters considered. This test was also conducted for the CN feature, and again no noticeable difference was found with varying oxygen abundance. We have assumed that oxygen follows the general $\alpha$ enhancement trend. That is, $\frac{[O/Fe]}{C}$ = 0.3 for objects with metallicities $[Fe/H] \leq -1.0$, and $\frac{[O/Fe]}{C}$ = +0.18 for the higher metallicity stars. ND95 show that there are a number of stars with oxygen deficiencies (values of $\frac{[O/Fe]}{C} < 0.0$) for RGB stars. This indicates that the ON cycle may have occurred in these objects. Although the assumed $\frac{[O/Fe]}{C}$ abundance does not play a significant role in the abundances determined, in

![Graphs showing indices against metallicity for different elements](image)

**Fig. 4.**—Indices for the G band (CH), CN at ~3883 Å, Sr ii λ4077 and Ba ii λ4554, plotted against metallicity for the MS ($V > 18$) and SGB stars ($V \leq 18$). The boxed regions on the MS plot represent indices calculated for three other globular clusters: NGC 6397 ($[Fe/H] = -1.96$), NGC 6752 ($[Fe/H] = -1.56$), and 47 Tuc ($[Fe/H] = -0.76$).
future studies it would be beneficial to determine the oxygen abundances for individual stars.

The stellar parameters derived from the isochrones were used to generate synthetic spectra for 10 carbon abundances at each point along an isochrone for each population. $G$-band indices were determined for each of these synthetic spectra and plotted along with the indices from the observed spectra for each population. This procedure enabled a mean carbon abundance to be obtained for each population, which was then used when another set of synthetic spectra was generated using the nitrogen abundance as the varying parameter. The S3839 index was measured in these synthetic spectra, and the results for the synthetic spectra...
were again plotted with the observed data to obtain a mean nitrogen abundance for each population. This procedure was followed again, but with varying strontium abundance, and the strontium indices were plotted for the synthetic and observed data. Interpolation between the synthetic isoindex lines for each element and population enabled a first estimate at the abundances of carbon, nitrogen, and strontium for each object. From these abundances the objects with possible enhancements (or in some cases depletions) in carbon, nitrogen, and strontium could be identified for further in depth analysis. The synthetic spectra give an initial estimate of the abundances, but should be viewed with caution, since there is a 0.4–0.6 dex range in [Fe/H] for the member stars of each population, while the isoindex lines are for a fixed abundance. Also, some stars have temperatures and gravities that deviate from those used for the isoindex lines. The larger the difference in [Fe/H], temperature and/or gravity from the isoindex value, the larger the uncertainty in the initial estimate.

The C abundance for the synthetic spectra was varied between \([\mathrm{C}/\mathrm{Fe}] = -0.9\) and +1.8. The G-band index was measured for each spectrum and plotted with the observed data, as shown in the left column of Figure 6. The diamonds represent those stars for which individual abundances were determined, while circles represent all other objects. Lines of common abundance are also plotted for the synthetic spectra. The vertical dashed line represents the cutoff between MS and turnoff stars. See text for details.

![Fig. 6. — G-band indices plotted against absolute magnitude (\(M_V\)) for each of the three populations of \(\omega\) Cen (left panels) and against the calibrating globular clusters (right panels). The diamonds represent those stars for which individual abundances were determined, while circles represent all other objects. Lines of common abundance are also plotted for the synthetic spectra. The vertical dashed line represents the cutoff between MS and turnoff stars. See text for details.](image)
both the MS stars and the SGB stars, and there are two MS stars that have possible enhanced features. The C abundance for the ω Cen stars was calculated by interpolation in luminosity and G-band strength to give an initial approximation to the abundance of that element.

The right column of Figure 6 shows the three calibrating globular clusters (NGC 6397, NGC 6752, and 47 Tuc). NGC 6397 and NGC 6752 bracket the metallicity range of the first population, and their results, as normal globular clusters, can be compared to those found for ω Cen in order to determine which stars are abnormal on the MS of the latter. The error bars in each panel represent errors in measured index and magnitude. They do not include the uncertainty in the inferred abundance induced by an object’s distance in color, magnitude, and metallicity from the isochrone used to generate the isofield lines.

The normal globular clusters show no significant spread (1 σ) in the CH index, while the first population of ω Cen, on the other hand, shows several objects that are outliers from the bulk of the population and a 2 σ spread on the MS and a 4 σ spread on the SGB. NGC 6752 can also be compared with the second population. Again the small spread in the normal GC is in contrast to that seen in ω Cen. The third population can be compared with the results from 47 Tuc, for which the indices have been split according to the CN-CH bimodality for clarity. On close inspection, one sees that the ω Cen results have a similar range in indices to those from 47 Tuc.

The mean C abundance for the bulk of each population was determined and then used when calculating synthetic spectra with varying nitrogen. Again, the CN index was determined for each synthetic spectrum and plotted against the observed data, shown in the left column of Figure 7. Once more, the error bars in each panel represent errors in measured index and magnitude. The diamonds in the plot indicate those stars that had individual N abundances determined (see § 5). As with the plot of the CH indices, the top panel shows the most metal-poor stars, the middle one the intermediate-metallicity population, and the bottom panel the most metal-rich stars. Inspection of the top panel shows that the synthetic lines for CN are closely spaced on the MS, illustrating the low sensitivity of the CN feature at these abundances and temperatures. Consequently, finding any objects with high N abundances is difficult, and any spread is comparable to the measurement errors (1 σ). Determining N abundances becomes a slightly easier task on the SGB, and the presence of several outliers is clear. The outliers are more pronounced in the second population, and there is a large range in apparent N abundance in the third population, with 4 and 9 σ spreads on the MS and SGB, respectively. Initial estimates of the N abundance for each ω Cen star were calculated, and all objects with a first-pass N abundance, [N/Fe], greater than 1.2 dex were included for further study. The low sensitivity of the feature and the relatively large errors on the abundance estimate meant that this included a fair number of objects in the metal-poor, MS category that were subsequently shown to have normal N abundances.

The right column of Figure 7 shows the results for the calibrating globular clusters. Both NGC 6397 and NGC 6752 show little scatter in their indices, as would be expected when the synthetic indices are taken into account. There is very little sensitivity in this feature at these metallicities, temperatures, and gravities. As was found for the G band, ω Cen shows several stars with CN indices that are higher than the mean, even with the low sensitivity in this area. The indices for 47 Tuc are again split into the CN-CH bimodality. Two sets of synthetic lines were plotted for these data, with different mean C abundance. We see a larger range in the ω Cen data than we do in the 47 Tuc indices.

Sr and Ba were analyzed simultaneously, although the Ba index was too weak to obtain meaningful results. The synthetic Sr indices are plotted in the left column of Figure 8 along with the ω Cen data, where the error bars in each panel represent errors in measured index and magnitude. A large spread of the Sr index is apparent in Figure 8, which is mainly due to the low S/N and intermediate resolution of our spectra. The spread in the measured index is comparable to the measurement error in the first two populations. The third population shows a 3 σ spread in comparison with the measured errors. Nevertheless, we are able to identify objects that may have large Sr enhancements and use these for individual spectrum synthesis analysis. The diamonds represent those objects that had individual Sr abundances calculated, which are discussed in § 5.

None of the normal globular clusters show Sr enhancement, and any scatter is comparable (of the order of 1 σ) to the measurement errors of the index. The cluster 47 Tuc shows several objects that may be considered to have higher Sr abundance ratios, but closer inspection reveals that these objects have higher indices due to low S/N. ω Cen, in all cases, shows larger scatter than the normal globular clusters, with several stars having higher indices being objects of particular interest. Inspection of spectra shows these results are not due to the lower S/N.

The choice of isochrones used for each of the three populations in the first-pass abundance analysis was determined from the mean metallicity and ages of the respective populations. The impact of a different choice of parameters for the three sets of isochrones was evaluated. The first population was assigned an isochrone with |Fe/H| = −1.9 and age = 15 Gyr (as against −1.7 and 13.5 Gyr), the second population an isochrone with |Fe/H| = −1.2, age = 11 Gyr (cf. −1.4 and 13.0 Gyr), and the third an isochrone with |Fe/H| = −0.6 and age = 9 Gyr (cf. −0.9 and 12 Gyr). Most stars showed differences in first-pass carbon abundances of less than 0.5 dex. Strontium abundances were calculated with differences less than 0.8 dex. Differences in nitrogen values were affected the most of the three elements, with differences ranging up to ±2.0 dex in the most extreme case and ±1.0 on average. In practice, the result for the nitrogen abundances was not significant, as objects with enhanced N selected for further analysis were determined using the S3839 index rather than the derived N abundance, as described in the following section. The use of a different distance modulus and reddening were also investigated, and the differences in derived abundance was found to be less than 0.2 dex for carbon and nitrogen, and less than 0.5 dex for strontium. These differences are all within the error margins placed on the selection of stars with possible enhancements in C, N, or Sr.

5. INDIVIDUAL ABUNDANCE ANALYSIS

5.1. Abundance Determination of [C/Fe], [N/Fe], and [Sr/Fe]

Following the analysis in § 4, the subsample of stars with possibly enhanced C, N, or Sr abundances was individually analyzed using spectrum synthesis techniques. These objects were chosen according to their first-pass abundances. For carbon, if a star’s interpolated abundance was [C/Fe] > 0.3, it was included. The cutoff for Sr was [Sr/Fe] > 0.8. The CN index was more complicated due to the weakness of the feature and hence its low sensitivity to C and N. Any interpolated abundance had very large error bars due to the small separation between isoindex lines. Therefore, these objects were chosen based on the S3839 index rather than interpolated abundance, and the cutoff imposed was S3839 > −0.05. All objects in the third population were included for individual analysis.
Stars with $[\text{C}/\text{Fe}] < -0.75$ from the first-pass abundance estimation were also included from the first two populations. However, it was found from the comparisons of observed and synthetic spectra for individual stars that in most instances there was not sufficient sensitivity in the data to reliably measure depletions. The low sensitivity of the CN and Sr features on the MS also meant that it was not possible to measure such depletions in N and Sr, respectively, and as a result we cannot say anything about whether depletions exist among these populations.

An age was assigned to each star based on its position on the CMD and its metallicity using theoretical isochrones (Yi et al. 2001), as described in Stanford et al. (2006a). It was relatively straightforward to also obtain temperatures and gravities from the isochrones simultaneously with the ages. A grid of isochrones was used that spans the metallicity range $-2.6 < [\text{Fe/H}] < 0.3$ in 0.05 dex increments. For each metallicity there were 34 isochrones with ages 2–19 Gyr in 0.5 Gyr steps. Alpha enhancement was taken to be constant ($[\alpha/\text{Fe}] = 0.3$) for $[\text{Fe/H}] \leq -1.0$, declining linearly for higher $[\text{Fe/H}]$ until it reached the solar value at $[\text{Fe/H}] = 0$. 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 $M_V$-values on the CMD to find the one closest. Usually a star’s position did not fall directly on one isochrone, so linear interpolation in color or magnitude was performed between the two closest ones to determine its age, along with the temperature and gravity. In almost every case the derived temperature and gravity are not the same as those from the
average isochrones used in Figure 3. Comparisons were made with temperatures obtained from color temperature relations in Alonso et al. (1996). These were, on average, smaller by 100 K. This value is within the 150 K uncertainty in temperature used in the error analysis. Microturbulence was assumed to be 1.0 km s\(^{-1}\).

Each candidate had the abundances of C, N, and Sr determined. The C feature (CH) at \(\lambda 4300\) was analyzed first. Figure 9 gives examples of a MS star (top) and SGB star (bottom) with enhancements in carbon. The heavy lines depict the observed spectrum, while the light lines show the synthetic spectra. The carbon abundance ratio was modified in the synthetic spectra, while all other parameters were held constant. The determined carbon abundance ratio is plotted, along with two others bracketed the value by \pm 0.3\, dex. A synthetic spectrum having \([C/Fe] = 0.0\) is also shown for comparison.

Given \([C/Fe]\), the CN feature at \(\sim 3883\) Å was used to obtain the N abundances. It proved to be quite difficult to obtain accurate abundances at the resolution of our spectra. There was little sensitivity of the feature at abundances lower than \([N/Fe] > 1.0\) dex, especially for objects with low \([Fe/H]\). Therefore, abundances were only recorded when \([N/Fe] \geq 1.0\) dex. Figure 10 gives examples of a MS star (top) and SGB star (bottom) with enhancements in nitrogen. The heavy lines indicate the observed spectrum, while the light lines show the synthetic spectra. The determined nitrogen abundance ratio is plotted, along with two others bracketing the value by \pm 0.3\, dex. A synthetic spectrum with \([N/Fe] = 0.0\) is also shown for comparison.
The Sr abundance was obtained from the Sr II λ4077 line. However, at the S/N of the data it was indistinguishable from the noise at low abundances, and results were only recorded when [Sr/Fe] \( \geq 1.0 \) dex. Further, the abundance obtained from this line was only accepted if the (weaker) Sr II λ4215 line confirmed the abundance of the first line. The Ba II λ4554 line was also examined. However, its sensitivity was too low to obtain reliable abundances in most cases. It was possible to use it as an extra confirmation of the Sr abundance, as the Ba abundance is expected to be strongly correlated with that of Sr at these metallicities. Figure 11 gives examples of a MS star (left column) and SGB star (right column) with enhancements in strontium. The heavy lines indicate the observed spectrum, while the light lines show the synthetic spectra. The top panels show the Sr II λ4077 line, the middle panels the Sr II λ4215 one. The strontium abundance ratio determined for these stars is plotted, along with two others bracketing the value by ±0.3 dex. A synthetic spectrum with [Sr/Fe] = 0.0 is also shown for comparison. The bottom panels show the Ba II λ4554 Å line with the same enhancements in [Ba/Fe] as the ones used for [Sr/Fe].

5.1.1. Errors

Typical errors were calculated for several objects with different metallicities. The temperature, gravity, and metallicity were varied independently. The measured index was also varied by its errors and included in the error calculations. The temperature was varied by 150 K, determined by reassigning an isochrone to an individual star based on the error in photometry. The gravity varied by 0.2 dex (determined in a similar way as for the uncertainty in temperature), and the metallicity by the individual abundance error for the star being analyzed. The error contributions were added in quadrature. Typical errors were 0.27 dex for the C abundance, 0.37 dex for the N abundance, and 0.38 dex for Sr.

Note that these errors refer only to the objects that had abundances determined for them.

Abundances were also calculated for a small number of normal stars across the three metallicity populations to verify that we would obtain unenhanced abundances for these objects. This was found to be the case, but again the limited sensitivity of the CN and Sr features may not reveal possible enhancements of N and Sr, respectively.

5.1.2. Results

Our abundances are presented in Table 3, which gives the identification number for each star in column (1), and the \( V \) magnitude and \( B - V \) in columns (2) and (3). The temperature, gravity, and metallicity are listed in columns (4)–(6). In columns (7)–(10) indices for the G band (CH), S3839 (CN), Sr II λ4077, and Ba II λ4554 are listed. Abundance ratios of C, N, and Sr relative to iron are given in columns (11), (12), and (13), respectively, if calculated. To untangle the abundance patterns, each metallicity population was treated separately and abundance information then compared between populations. The positions, photometry, metallicity, and ages for these stars are available in the electronic version of Table 2 in Stanford et al. (2006a).

When performing the spectrum synthesis analysis, comparisons by eye between the Ca II K line in the observed and synthetic spectra were used as a check on the metallicities and temperatures. In a small number of cases there was a large discrepancy between the observed and synthetic values, and therefore those stars were not considered further. In total, 32 stars did not have an abundance analysis performed due to unreliable metallicities and/or ages. It is unclear whether the source of the error is driven by the metallicities, related to a 3 \( \sigma \) error in the photometry, or both. After excluding these stars, this left a total of 392 stars in our sample.

Table 4 gives the number and percentage of normal, C, N, and Sr enhancements for each metallicity population. Due to the
varying sensitivity of the CH, CN, and Sr features, the emphasis of this paper is on objects with enhancements \( [\text{C}/\text{Fe}] \geq 0.5 \) dex, \( [\text{N}/\text{Fe}] \geq 1.0 \) dex, and \( [\text{Sr}/\text{Fe}] \geq 1.0 \) dex, even though abundance ratios were calculated \( \sim 1 \sigma \) below these values. These limits were put in place to ensure that we had complete numbers of objects in our sample above these values. There are objects with enhancements in carbon and/or nitrogen, and strontium, which therefore are counted in both the C/N-enhanced and Sr-enhanced groups. This means the percentages often sum to more than 100%.

Using a Gaussian distribution with a kernel equal to the error in each abundance, the effect of errors on the number of objects found to be enhanced was investigated. The first distribution was centered at \( [\text{C}/\text{Fe}] = 0.0 \), with \( \sigma_{\text{C}} = 0.27 \) dex, and produced 5% of the sample as enhanced objects under our criteria of \( [\text{C}/\text{Fe}] \geq 0.5 \). This is comparable to the percentage of enhanced objects found on the MS. However, the two metal-poor objects on the MS (9005309 and 7007334, with \( [\text{C}/\text{Fe}] = 1.30 \) and 1.35, respectively) have \( \sim 5 \sigma \) C enhancements and are not likely to be the result of the uncertainties. The number of objects on the SGB that were found to be enhanced is significantly higher than 5%, but this may be due to the bias against the bulk of the metal-poor objects in the SGB sample introduced by the blue cutoff at \( (B - V) = 0.6 \) for the 2002 sample.

A similar procedure was employed for the nitrogen and strontium abundances, using \( \sigma_{\text{N}} = 0.37 \) dex and \( \sigma_{\text{Sr}} = 0.38 \) dex. Both the N and Sr simulations indicated that it would be unlikely that any objects would be included in the enhanced sample as spurious detections, since less than 1% of the simulated sample had abundances greater than the criteria of \( [\text{N}/\text{Fe}] \geq 1.0 \) dex and \( [\text{Sr}/\text{Fe}] \geq 1.0 \) dex.

Table 5 lists the abundance patterns found on the MS and SGB. One should note that often when we do not find any stars of

![Observed and synthetic spectra showing a MS object, 7007295, in the left panels. The right panels show a SGB star, 8007880, with enhanced s-process elements. The top panel in each column shows the Sr II \( 4077 \) line, the middle shows Sr II \( 4215 \), and the bottom shows Ba II \( 4554 \).]
a particular abundance pattern, it is due to the low sensitivity of the relevant observed features. The table only lists numbers of a particular abundance pattern, it is due to the low sensitivity of unusual stars on the SGB than on the MS.

Due to these selection effects, there are probably more detections redder than the bulk of the metal-poor population in the cluster. and SGB are not possible. The blue color limit for the SGB box is redder than the bulk of the metal-poor population in the cluster. Due to these selection effects, there are probably more detections of unusual stars on the SGB than on the MS.

### 5.2. Abundance Patterns

Figure 12 plots the abundance ratios relative to iron of carbon, nitrogen, and strontium for each of the three populations as a function of luminosity. Care must be taken in the interpretation of this diagram. The shaded regions in the figure show the areas of limited sensitivity and are plotted below the cutoff values by an amount of $\sigma/2$. Consequently, we do not detect all the enhancements/depletions that are potentially present in our sample. Therefore, only a few conclusions can be drawn from the recorded abundance ratios. Stars have been plotted with different symbols in order to better facilitate the comparisons between different elements and abundances. For the first and second populations the open triangles represent those stars that are enriched in carbon ($[\text{C/Fe}] \geq 0.5$) and strontium ($[\text{Sr/Fe}] \geq 1.0$). Objects that are enhanced in both nitrogen and strontium are shown by filled stars. The one object with enhancements in carbon, nitrogen, and strontium, 8001811, is represented by a plus sign inside a circle. All other stars are represented by filled dots with no cross-referencing between panels. Since all stars in the third population have abundance determinations, the symbols are used to show the corresponding object between carbon of any value with enhanced Sr and unenhanced N (open triangles) or enhanced N and enhanced Sr (filled stars). Filled triangles represent stars with carbon abundances and nitrogen enhancements that do not have high Sr enhancements.

#### 5.2.1. Carbon

Figures 12a, 12b, and 12c show the $[\text{C/Fe}]$ abundances for each population. The objects in Figure 12 with individual abundance determinations are shown as diamonds in the carbon, nitrogen, and strontium indices plots (Figs. 6, 7, and 8). The reader is reminded that the spectrum synthesis was performed for the entire third-population sample, but only for a select group of enhanced objects for the first and second populations. Inspection of the C-enhanced objects in the first population (Fig. 12a) shows that there are relatively more objects with elevated abundances on the SGB than on the MS. This same effect is seen to a lesser degree in the second-population data in Figure 12b. If the process that led to the formation of the C-rich stars was primordial (i.e., they formed from matter already enhanced in C and therefore have uniform abundances throughout), one would expect equal numbers of these objects on the MS and SGB. On the other hand, if these objects had elevated C abundances due to the accretion of material onto their surface layers, as they move off the MS and onto the SGB the convective layer deepens and such enhancements become diminished. Consequently, one would expect

### Table 3

**Stellar Parameters, Indices, and Abundances for ω Cen Sample**

| ID             | $V$ Mag (2) | $B - V$ (3) | $T_{\text{eff}}$ (4) | log $g$ (5) | $[\text{Fe/H}]$ (6) | $G$ Band (7) | S3839 (8) (4077 Å) | Sr (4554 Å) (10) | $[\text{C/Fe}]$ (11) | $[\text{N/Fe}]$ (12) | $[\text{Sr/Fe}]$ (13) |
|----------------|-------------|-------------|----------------------|-------------|---------------------|-------------|-------------------|------------------|-------------------|-------------------|-------------------|
| 1000812........ | 17.470      | 0.610       | 5874                 | 3.8         | -1.64               | 1.42        | -0.06             | 0.10             | 0.09              | 0.07              | 0.00              |
| 1002064........ | 18.290      | 0.570       | 6066                 | 4.3         | -1.41               | 2.42        | -0.06             | 0.28             | 0.09              | 0.07              | 0.00              |
| 1002884........ | 17.490      | 0.600       | 5901                 | 3.8         | -1.76               | 1.51        | -0.11             | 0.11             | 0.19              | 0.17              | 0.00              |
| 1004374........ | 17.500      | 0.620       | 5883                 | 3.8         | -1.72               | 2.71        | -0.14             | 0.18             | 0.20              | 0.50              | 0.00              |
| 1005088........ | 17.390      | 0.730       | 5443                 | 3.6         | -1.58               | 5.79        | -0.06             | 0.18             | 0.29              | 0.07              | 0.00              |
| 1005996........ | 17.320      | 0.720       | 5572                 | 3.7         | -1.49               | 4.95        | -0.10             | 0.37             | 0.24              | 0.10              | 0.00              |
| 1006065........ | 17.510      | 0.650       | 5761                 | 3.8         | -1.62               | 2.48        | -0.01             | 0.11             | 0.04              | 0.07              | 0.00              |
| 1006286........ | 17.380      | 0.710       | 5564                 | 3.7         | -1.49               | 4.64        | -0.04             | 0.29             | 0.28              | 0.07              | 0.00              |
| 1006625........ | 17.540      | 0.610       | 5869                 | 3.8         | -1.78               | 2.07        | -0.11             | 0.06             | 0.19              | 0.07              | 0.00              |
| 1006759........ | 18.120      | 0.510       | 6282                 | 4.2         | -1.71               | 0.73        | -0.10             | 0.07             | 0.22              | 0.07              | 0.00              |
| 1006812........ | 17.430      | 0.640       | 5772                 | 3.8         | -1.49               | 2.71        | -0.07             | 0.07             | 0.25              | 0.07              | 0.00              |
| 1006962........ | 17.870      | 0.670       | 5672                 | 3.9         | -1.59               | 4.43        | -0.11             | 0.41             | 0.29              | 0.40              | 0.50              |
| 1007266........ | 18.430      | 0.530       | 6179                 | 4.3         | -1.50               | 0.74        | -0.13             | -0.09            | 0.08              | 0.07              | 0.00              |
| 1007362........ | 17.450      | 0.680       | 5681                 | 3.7         | -1.65               | 4.29        | -0.10             | 0.29             | 0.12              | 0.50              | 0.00              |
| 1007414........ | 17.840      | 0.630       | 5869                 | 3.9         | -1.44               | 2.89        | -0.13             | 0.25             | 0.27              | 0.07              | 0.00              |

*Note.—* Table 3 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.

### Table 4

**Enhancement of C, N, and Sr Statistics**

| SAMPLE          | TOTAL NO. | NORMAL (%) | $[\text{C/Fe}] \geq 0.5$ (%) | $[\text{N/Fe}] \geq 1.0$ (%) | $[\text{Sr/Fe}] \geq 1.0$ (%) |
|-----------------|-----------|------------|-----------------------------|-----------------------------|-----------------------------|
| MS              | 195       | 88.2       | 4.1                         | 6.2                         | 5.1                         |
| SGB             | 197       | 65.0       | 16.8                        | 16.2                        | 14.2                        |
| MS              | 116       | 97.4       | 1.7                         | 0.0                         | 0.9                         |
| SGB             | 118       | 75.4       | 14.4                        | 8.5                         | 9.3                         |
| MS              | 61        | 80.3       | 8.2                         | 9.8                         | 8.2                         |
| SGB             | 73        | 49.3       | 21.9                        | 26.0                        | 19.2                        |
| MS              | 18        | 55.6       | 5.6                         | 33.3                        | 22.2                        |
| SGB             | 6         | 50.0       | 0.0                         | 50.0                        | 50.0                        |

*1st population: $[\text{Fe/H}] < -1.5$; 2nd population: $-1.5 \leq [\text{Fe/H}] < -1.1$; 3rd population: $[\text{Fe/H}] \geq -1.1$.*
not to find as many SGB objects with C enhancements, contradicting the results found here. Instead, the result may be due to the diminished sensitivity of the CH feature on the MS compared with the SGB, preventing detection of enhanced C in MS objects.

The metal-poor objects on the MS with large carbon enhancements are possible counterparts of the CH stars found on the SGB. Two objects on the MS, 7007334 and 9005309 (C/Fe = 1.35) and 9005309 (C/Fe = 1.30), seen in Figure 12a, show the largest carbon enhancement in our sample, with no other metal-poor MS objects showing any enhancement. These objects also show no detectable enhancements of nitrogen or strontium. The study by Bell & Dickens (1974) found that for two of the CH giants in ω Cen (ROA 55 and 70), C/H ~ -0.8 and [N/H] ~ 0.0. Adopting [Fe/H] = -1.9 for ROA 70 (Gratton 1982), this gives C/Fe ~ 1.1 and [N/Fe] ~ 1.9. The carbon enhancements are similar to the values found here, although the N enhancement is apparently not, noting, however, that our N sensitivity at this abundance is low. As for the s-process elements, Gratton (1982) found s/Fe = 1.1 for ROA 70 (where s represents the averaged abundances of the s-process elements), but for our MS stars we do not detect any enhancement of Sr above [Sr/Fe] = 1.0 dex. A metal-poor SGB star, 8001811, shows enhancements in carbon, nitrogen, and strontium, similar to those found for RGB CH stars in ω Cen. This star may also be similar to the “subgiant CH” stars reported by Luck & Bond (1991) in the field, which exhibit C and s-process enhancement.

Figure 6 indicates that there are some stars in each of the three populations with possible C depletions. Upon further investigation it was found that in the first population, with the lowest metallicities, C abundances could not be reliably determined below [C/Fe] = 0.0 for the majority of candidates. For the second metallicity population, with −1.5 ≤ [Fe/H] < −1.1, [C/Fe] started to lose its sensitivity around −0.2. C abundances for the most metal-rich population, with [Fe/H] ≥ −1.1, were able to be determined down to [C/Fe] ~ −0.7.

It is significant that we only find one object in the third population with C enhancements greater than 0.0 dex. All objects in the third population went through the individual abundance determination process, although again the CN and Sr features of some objects were not useful for abundance determination. Most of the objects in the third population were C depleted, as can be seen in Figure 12c. Some of these C-depleted stars have various large N and/or Sr enhancements. However, it is interesting to note that we find several objects (4/9) with C depletions that do not have corresponding N and/or Sr enhancements. This may be due to the low sensitivity of the CN and Sr features.

5.2.2. Nitrogen

The middle column of Figure 12 shows the [N/Fe] abundance ratios as functions of luminosity for each of the three populations. The limited sensitivity of the CN feature is indicated by the shaded regions, and for this reason only the extremely N-enhanced objects are identified. Regarding the SGB in the metal-poor and metal-intermediate populations, it can be seen that there is a fraction (∼20%) of N-enhanced objects with [N/Fe] up to ~2.0 dex. Similarly, the third population contains a significant fraction of objects with N enhancements, of the order of 50%. These N enhancements are ~0.5–1.0 dex higher than those found for RGB stars in ND95, and up to ~0.75 dex higher than in the analysis of RGB stars of Brown & Wallerstein (1993). This large discrepancy between the present work and other studies may be due to differing analysis techniques. Analysis of RGB stars using the method employed here would be useful in resolving this discrepancy.

Nitrogen enhancements are not seen in the first population on the MS, although such stars are seen on the SGB at this metallicity and on the MS for the higher abundance groups. Whether this is due to the low sensitivity of the CN feature at the resolution and S/N used here, and our subsequent inability to detect the objects with overabundances in N, or is a real effect remains unclear. That said, canonical stellar evolution results do not predict the processing of C to N between the MS and SGB phases of such low-mass stars. Only one star on the SGB was found with [N/Fe] ≥ 2.0. Therefore, the fact that no enhancements of [N/Fe] > 2.0 were seen for MS stars may be a statistical effect. Higher resolution data are needed to address this question. Piotto et al. (2005), in a study of the double main sequence, found nitrogen enhancements of [N/Fe] = 1.0 for the metal-intermediate bMS and [N/Fe] < 1.0 for the metal-poor red main sequence (rMS). Therefore, it seems likely that our technique, which could only measure enhancements above [N/Fe] = 1.0, did not have the required sensitivity to measure any enhancements in N on the main sequence.

5.2.3. Strontium

For Sr there is an abundance trend similar to that found for N across the three populations, as can be seen in Figure 12 (right column). Here one finds a significant number of objects that show Sr enhancement in all three metallicity populations. In particular, we draw attention to the most Sr-rich object, the main-sequence star 2015448, which has [Sr/Fe] = 1.6. This object has the added anomalous behavior that while the abundance of Ba usually tracks that of Sr in heavy-neutron-capture-enhanced objects, we do not detect Ba, and estimate [Ba/Fe] < 0.6. This object is discussed in more detail in Stanford et al. (2006b).

5.2.4. Metal-rich Population

The third population differs from the other two populations in that there were essentially no enhancements in C across the MS....
or SGB. One third-population object, 2016543, was identified with mild C enhancement. This object had no N or Sr enhancements.

Figure 13 shows an example of a more typical member of the third population, which has depleted carbon ([C/Fe] = −0.4). This object was used to obtain a N abundance from the CN features at 3883 and 4215 Å, yielding [N/Fe] = 1.7 (middle panels). It also has enhanced Sr and Ba, shown in the bottom panels. Another star in our sample, 3001426, has similar stellar parameters and abundances.

6. DISCUSSION

The abundance patterns found here, while somewhat limited, when taken together with the data for the red giants, have the potential to constrain putative sources of enrichment. We begin with a short discussion of possible sources of enrichment and follow with constraints that the present results place on the enrichment processes.

The origin of the abundance enhancements found here is most likely primordial or the result of accretion events. These abundance patterns are unlikely to have been generated within the MS stars themselves, as the small convective region does not mix processed materials from the stellar interior to its surface. Comparing these results with those found on the RGB (Smith et al. 1995; ND95) seems to suggest that we are finding similar abundance enhancements in N and the light s-process elements, at least on the SGB. However, most stars studied on the RGB are C depleted, or near solar, and N is enhanced by ∼1.0 dex (Cohen & Bell 1986; Paltoglou & Norris 1989; Brown & Wallerstein 1993; ND95). In RGB stars, where the C is depleted and N enhanced, the CN and ON cycles have been at work. Whether this took
place in the stars themselves, in nearby objects whose material was accreted, or occurred in objects, the eject from which these stars formed is unclear. However, primordial or accretion of C and/or O is needed to explain the CO-strong stars that exist on the RGB (Persson et al. 1980). While the details of the cluster chemical evolution remain in question, we discuss the various type of objects that might have been responsible for the nucleosynthesis of the various elements that are varying within the system.

6.1. Possible Sources of Enrichment

6.1.1. Low-Mass AGB Stars

Low-mass (1–3 $M_\odot$) AGB stars undergo dredge-up episodes that bring C and s-process elements into the convective region (Gallino et al. 1998). Because of their low mass, these objects do not have hot bottom-burning (HBB) episodes, which would produce N and reduce C via the CNO cycle. The amount of s-process elements that is produced depends on neutron density and the availability of the seed Fe nuclei (Smith 2005). The neutron source is the $^{13}$C($\alpha$, n)$^{16}$O reaction. The s-process is believed to occur in a $^{13}$C pocket, which is produced at the third dredge-up episode (Gallino et al. 1998; Lattanzio & Lugaro 2005). Specifically, hydrogen downflow from the envelope penetrates the $^{12}$C intershell region and at H reignition a $^{13}$C enhanced zone is formed. This $^{13}$C source releases neutrons, giving rise to efficient s-processing that depends on the mass fractions of H, $^4$He, $^{13}$C, $^{14}$N, and metallicity. For the C-enhanced stars, in which we do not detect any Sr enhancement (s-process), it may be that we simply do not have the sensitivity to detect any enrichment. Alternatively, if there were little or no $^{13}$C pocket, there would be no source of neutrons for the s-process to occur. Thus, depending on the size and efficiency of the $^{13}$C pocket, these AGB stars may

Fig. 13.—Observed and synthetic spectra of star 2014590 from the most metal-rich population, with [Fe/H] = −1.0 dex. The top left panel shows the spectrum of this object in the range 3800–4600 Å. The top right panel shows the observed spectrum (heavy line), with synthetic spectra (light lines) in the region of the G band. The middle two panels show the CN features at ∼3883 Å (left) and ∼4216 Å (right). The bottom left panel shows the Sr ii 4077 line and the bottom right panel shows Ba ii 4554.
account for the enhancements of C with and without Sr found in our sample.

6.1.2. Intermediate-Mass AGB Stars

Intermediate-mass (3–8 $M_\odot$) AGB stars are more likely to have HBB, thereby producing a site for the operation of the CN cycle and the processing of C into N (Ventura et al. 2002). Production of $s$-process elements is not expected to be very high in these objects due to the shorter duration of the $^{13}$C pocket (Lattanzio et al. 2004). Added to this is lower neutron density from the $^{22}$Ne($\alpha$, n)$^{25}$Mg reaction as the convective region becomes smaller in more massive stars. These stars may account for the objects with N enhancements with little or no $s$-process element enhancements.

6.1.3. Massive Stars

Maeder & Meynet (2006) have recently presented models of rotating massive ($\sim$60 $M_\odot$) stars. These objects produce stellar winds with large excess of He and N, but no C or O excess. Their products are consistent with the abundances seen on the bMS (see Piotto et al. 2005) and may be responsible for some of the enhanced objects found here. Recently, abundance patterns of C, N, O, Na, and Li obtained from models of fast-rotating, massive stars were shown by Decressin et al. (2006) to be similar to the chemical anomalies observed in normal globular cluster stars. Whether these two sets of models also synthesize $s$-process elements is unclear, but they may account for objects with enhancements in N.

Smith (2006) discussed the possibility of Wolf-Rayet and OB stars being enrichment sources for globular cluster anomalies. These objects (WN) may produce large amounts of nitrogen, but a top-heavy stellar mass function is required to generate the large amounts of N needed to explain the observations in globular clusters. A similar scenario is needed in the Maeder & Meynet (2006) models.

6.2. Observational Constraints on the Enrichment of $\omega$ Cen

Similarities exist between the carbon-rich objects found on the MS and those found on the RGB. Here two stars out of 195 ($\sim$1%) were found to have $[C/Fe] > 1.0$ (these are the metal-poor stars 7007334 and 9005309). There is one possible subgiant CH star, 8001811, which translates to $\sim$0.5% of the total number of SGB stars with CH star properties. These percentages are similar to those found for RGB stars brighter than $V \sim 13$ in the Woolley et al. (1966) catalog, where there are four CH stars (55, 70, 279, and 577; see, e.g., ND95) out of a possible $\sim$600, equating to 0.7%. This finding suggests that one might expect to find an approximately 1% incidence of CH stars in any sample at most stages of evolution in the cluster (i.e., excluding BHB objects) and indicates that the CH stars are not limited to a particular evolutionary phase.

It is interesting that the C-rich ($[C/Fe] \geq 0.5$) stars occur predominately at low metallicities, and we find virtually none in the third population. This may result from small-number statistics. In the first and second populations we find that 10% of objects have enhanced C. If the same percentage applies to the third population, this would equate to only two stars, and it is not outside the realm of possibility that they were simply not found in our search. On the other hand, the nondetection may be a result of the material from which these stars formed being low in C to begin with. The source of the carbon enrichment could be low-mass AGB stars or perhaps SNe II. In the latter case, the outer layers escaped while the material close to the iron core did not. Low-mass AGB stars also produce $s$-process elements, depending on initial mass and metallicity. Therefore, they are able to account for the range in $s$-process enhancement seen in many of the C-rich stars.

Figure 12 and Table 4 show that $\sim$10% of the total sample (excluding the two metal-poor CH stars) has $[C/Fe] \geq 0.5$. This is unusual when compared with the RGB abundances in $\omega$ Cen, as previous studies have not found any stars (excluding CH stars) with carbon enhancements at these levels. Carbon abundances of MS and SGB stars in other globular clusters also do not show such enhancements. Carretta et al. (2005) studied carbon, nitrogen, and oxygen in dwarfs and SGB stars in NGC 6397, NGC 6752, and 47 Tuc. For dwarfs, carbon abundances were less than $[C/Fe] = 0.50$ for NGC 6397, $[C/Fe] = 0.2$ for NGC 6752, and $[C/Fe] = -0.1$ for 47 Tuc. The subgiants showed abundance levels of $[C/Fe] \leq 0.15$ for NGC 6397 and $[C/Fe] \leq -0.10$ for NGC 6752 and 47 Tuc.

These C-enhanced objects on the MSTO of $\omega$ Cen may be the evolutionary precursors to the CO-strong objects on the RGB (Persson et al. 1980). Of the stars investigated in Persson et al. (1980), 28 come from the unbiased sample of Cannon & Stobie (1973). The CO-strong stars represent 8 out of these 28 stars, or $\sim$30% of RGB objects. If the 10% of C-rich ($[C/Fe] \geq 0.5$) stars found on the MSTO are the evolutionary precursors, one would expect that more of these objects should have been found. However, our choice of the C-rich cutoff (at $[C/Fe] = 0.5$) is arbitrary, and it is not known what the link is between CO-strong status and carbon abundance on the MSTO. If the C-rich cutoff were lower, we would have found a higher percentage of objects that are C-rich on the MSTO. It would be useful in future investigations to determine carbon abundances for the whole sample to confirm the connection between the C-enhanced objects at the MSTO and the CO-strong objects on the RGB.

The carbon abundances found here in the third population are low when compared with those determined for dwarfs by Carretta et al. (2005) in NGC 6397, NGC 6752, and 47 Tuc. The lowest abundances found for NGC 6752 and 47 Tuc were $[C/Fe] = -0.2$ and $[C/Fe] = -0.13$, respectively. The origin of these depletions for the most metal-rich group is not well understood. Pancino (2003) did not investigate carbon abundances for the most metal-rich RGB sample in $\omega$ Cen, and for the few metal-rich RGB stars studied by ND95 carbon abundances were found to be $[C/Fe] \sim -0.3$. If evolutionary mixing on ascent of the RGB occurred, one would expect even lower carbon abundances than those found on the MS, but for the two metal-rich RGB stars studied by ND95 this was not found to be the case. Estimates of the level of carbon depletions for the first and second populations would be of great interest because they could be compared not only with those found in the third population but also with those on the RGB. Piotto et al. (2005) found $[C/Fe] = 0.0$ for both the metal-poor and metal-intermediate main sequences (rMS and bMS, respectively) using composite spectra of stars belonging to both populations.

The nitrogen enrichments seen at the MSTO across all three populations are quite substantial, with $[N/Fe]$ as large as 2.2. These abundances are slightly larger than those seen in other clusters (Carretta et al. 2005). The nitrogen enhancements in NGC 6752 reach $[N/Fe] = 1.7$ for dwarfs and $[N/Fe] = 1.3$ for subgiants. The maximum N enhancements for 47 Tuc are lower, reaching only $[N/Fe] = 1.1$ for the subgiants, while our third population shows enhancements greater than $[N/Fe] = 1.1$ for 37.5% of the group. Piotto et al. (2005) investigated the two distinct main sequences in $\omega$ Cen and found abundances of C, N, and Ba using composite spectra of a number of stars in each sequence. They found $[N/Fe] \sim 1.0$ for the bMS, which is equivalent in
metallicity to the second population discussed here. This finding is lower by a factor of 3–10 for the abundances of N found here, which may be due to a systematic offset in the abundances found here compared with those found by Piotto et al. (2005). On the ω Cen RGB, ND95 also found N abundances to be less than those found here, by ~0.7 dex.

While Sr abundances have not been extensively investigated on the RGB, lines of other light s-process elements, such as Y and Zr, have been analyzed (ND95; Smith et al. 1995, 2000). In general, it was found that the abundance of the s-process elements relative to iron increased as a function of metallicity. There are no correlations of s-process elemental abundances with other light elements in which variations are seen, such as C, N, O, Na, and Al (ND95). Qualitatively, this result is similar to what is found here. The incidence of Sr enhancement relative to iron increases as a function of metallicity (see Table 4). This increase fits in with the idea that low- to intermediate-mass AGB stars contributed to the gas from which the later generations of stars formed. A comparison between the Sr abundances found for RGB and MS stars will be discussed further in a forthcoming paper (L. M. Stanford et al. 2007, in preparation).

It is not clear whether intermediate-mass AGB stars are responsible for the enhancements seen in Sr, as s-processing is not very efficient in these objects. To account for the N- and Sr-enhanced stars, favorable conditions for N and s-process element production in intermediate-mass AGB stars are needed. Alternatively, the enriched objects may be accounted for by several different sources. For instance, massive rotating stars may account for the N overabundances, while low-mass AGB may account for the s-process enrichment. This latter scenario is supported by the fact that no strong correlation is seen between nitrogen and strontium (s-process) abundances.

Other globular clusters with no evidence of metallicity (i.e., iron) spreads show variations in the abundances of light elements to varying degrees, as described in § 1. Several clusters show CN-CH bimodality not only on the RGB but also on the MS (Cannon et al. 1998; Briley et al. 2004, 2004; Suntzeff & Smith 1991; Gratton et al. 2001a; Cohen 1999; Briley & Cohen 2001; Ramírez & Cohen 2002; Cohen et al. 2002; Da Costa et al. 2004). In this respect, the spread in C and N on the MSTO of ω Cen is not unique, and these results demonstrate that the variations are a product of environment, since field stars do not show similar patterns. Variations in other light elements such as Na, O, Mg, and Al are also found on the MS in some clusters (Gratton et al. 2001b). These elements have yet to be studied on the MS in ω Cen to determine whether the same effect is seen in this cluster. The theoretical yields of AGB stars at present fail to explain the abundance patterns seen in the light elements in globular clusters (see, e.g., Fenner et al. 2004). That is, there is more to the enrichment scenario in other clusters that is yet to be explained, and this complication may also be the case for ω Cen.

6.2.1. Constraints on the Role of Binarity

If the enhancements are due to past accretion events as part of binary systems, the fraction of objects with overabundances indicates that ω Cen should have a large binary fraction, on the order of ~20%. In a radial velocity study of red giants in ω Cen spanning over a decade, Mayor et al. (1996) estimated that the global binary frequency is 3%–4%. Further, they reported that most of the giants with known chemical peculiarities, such as Ba, CH, and S stars, have constant velocities, suggesting that they are not members of binary systems. However, there is the possibility that these objects may have been former binaries that were disrupted by close encounters with nearby stars. The same argument can be applied to the MS stars, where the fraction of C-, N-, and Sr-enhanced stars exceeds the observed binary frequency for giants in the cluster.

7. CONCLUSION

A low-resolution spectroscopic abundance analysis of a sample of 392 ω Cen members revealed objects enhanced in carbon, nitrogen, and/or strontium. These enhanced objects were analyzed in detail, and abundance ratios of carbon, nitrogen, and strontium relative to iron determined. The abundances revealed patterns that can possibly be explained by low- and intermediate-mass AGB and/or rotating massive-star nucleosynthesis. The enhancements are either primordial or from accretion events, rather than evolutionary. Higher resolution, and higher S/N, data are needed to further constrain the possible sources of these abundances anomalies. From such data, abundances of a large number of elements, such as the light elements (O, Na, Mg, and Al), other light and heavy s-process elements, and iron peak elements, will be essential in obtaining another piece of the ω Cen puzzle.

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