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HIGH-RESOLUTION SPECTROSCOPY OF METAL-RICH GIANTS IN ω CENTAURI: FIRST INDICATION OF TYPE Ia SUPERNOVA ENRICHMENT[1]

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ABSTRACT

We have obtained high-resolution, high signal-to-noise ratio spectra for six red giants in ω Centauri: three belong to the recently discovered metal-rich red giant branch (RGB-a; as defined by Pancino et al.) and three to the metal-intermediate population (RGB-MInt). Accurate iron, copper, and α-element (Ca and Si) abundances have been derived and discussed. In particular, we have obtained the first direct abundance determination based on high-resolution spectroscopy for the RGB-a population, $\langle[\mathrm{Fe/H}]\rangle = -0.60 \pm 0.15$. Although this value is lower than previous estimates based on calcium triplet measurements, we confirm that this population is the most metal-rich in ω Cen. In addition, we have found a significant difference in the α-element enhancement of the two populations. The three RGB-MInt stars have the expected overabundance, typical of halo and globular cluster stars: $\langle[\alpha/\mathrm{Fe}]\rangle = 0.29 \pm 0.01$. The three RGB-a stars show, instead, a significantly lower α-enhancement: $\langle[\alpha/\mathrm{Fe}]\rangle = 0.10 \pm 0.04$. We have also detected an increasing trend of [Cu/Fe] with metallicity, similar to the one observed for field stars by Sneden et al. The observational facts presented in this Letter, if confirmed by larger samples of giants, are the first indication that supernovae Type Ia ejecta have contaminated the medium from which the metal-rich RGB-a stars have formed. The implications for current scenarios on the formation and evolution of ω Cen are briefly discussed.

Subject headings: globular clusters: individual (ω Centauri) — stars: abundances — stars: Population II

1. INTRODUCTION

The globular cluster ω Centauri is the most massive and luminous of all galactic globular clusters, and it is the *only* one that shows undisputed variations in its heavy-element content. For these reasons, ω Cen red giants have been the subject of the largest spectroscopic surveys ever attempted on a globular cluster. Calcium triplet low-resolution studies (Norris, Freeman, & Mighell 1996; Suntzeff & Kraft 1996) have shown that (1) few stars exist on the red giant branch (RGB) with $[\mathrm{Fe/H}] < -1.8$; (2) there is a well-defined peak in the distribution at $[\mathrm{Fe/H}] = -1.6$ with a long, extended tail reaching $[\mathrm{Fe/H}] = -0.5$; (3) the distribution appears bimodal with a second, smaller peak at $[\mathrm{Fe/H}] \sim -1.0$.

In spite of the previous massive observational efforts, the full complexity of the RGB structure of ω Cen has been revealed only recently, thanks to wide-field photometry (Lee et al. 1999; Pancino et al. 2000) that discovered the presence of a previously undetected, anomalous sequence (hereafter RGB-a) on the red side of the main RGB. This newly discovered population is thought to represent the rich end of the metallicity distribution in ω Cen: Pancino et al. (2000) estimated a mean $[\mathrm{Ca/H}] \simeq -0.1$ and $[\mathrm{Fe/H}] \simeq -0.4$ from six RGB-a stars in common with previous surveys (stars ROA 300, 447, 500, 513,[3] 517, and 523; nomenclature from Woolley 1966).

In the framework of a coordinated spectrophotometric project devoted to the study of this puzzling stellar system, we present here the first high-resolution abundance measurements of the most metal-rich giants in ω Cen.

2. OBSERVATIONAL MATERIAL

We selected our targets among the metal-rich giants in ω Cen. Three of them, stars ROA 300, WFI 222068, and WFI 222679, belong to the RGB-a, while the other three belong to the intermediate-metallicity population (RGB-MInt; Pancino et al. 2000). Only star ROA 371 (Table 1) has been observed before with high-resolution spectroscopy ($R \geq 20{,}000$; Paltoglou & Norris 1989; Brown et al. 1991; Vanture, Wallerstein, & Brown 1994; Norris & Da Costa 1995) and for this reason is the ideal comparison object.

Observations were carried out in 2000 June with the Ultraviolet-Visual Echelle Spectrograph (UVES) at the ESO's Very Large Telescope Kueyen at Paranal, Chile, as a backup program while the main targets were not visible. We obtained high-resolution ($R \sim 45{,}000$) echelle spectra with a signal-to-noise ratio (S/N) of ∼100–150 per resolution element. The monodimensional spectra were extracted with the UVES pipeline (Ballester et al. 2000), then continuum normalized and corrected

[1] Based on Ultraviolet-Visual Echelle Spectrograph observations collected at the European Southern Observatory, Paranal, Chile, within the observing program 165.L-0263. Also based on Wide-Field Imager observations collected at La Silla, Chile, within the observing programs 62.L-0354 and 64.L-0439.

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[3] In Pancino et al. (2000), this star was erroneously reported as star ROA 512.

TABLE 1
LITERATURE DATA FOR STAR ROA 371

Parameter	PN89	B91	V94	ND95	This Letter
R	∼17,000	∼17,000	∼20,000	∼38,000	∼45,000
S/N	≤50	∼100	70–150	∼50	140
$T_{\rm eff}$ (K)	4000	4000	4000	4000	4000
$\log g$	0.9	0.9	0.9	0.9	0.7
v_t (km s^{-1})	2.5	1.5	2.2	1.6	1.5
[Fe/H]	−1.37	−0.9	−1.00	−0.79	−0.95

NOTE.—PN89: Paltoglou & Norris 1989; B91: Brown et al. 1991; V94: Vanture et al. 1994; and ND95: Norris & Da Costa 1995.

for telluric absorption bands with IRAF.[4] Radial velocities measured on our spectra confirm membership for all six stars.

The magnitudes and colors of our program stars (see Table 2), used to estimate $T_{\rm eff}$ and $\log g$, are from Pancino et al. (2000) and from unpublished V data obtained during the same observing runs and treated the same way. Dereddened colors and absolute magnitudes were derived, assuming $E(B-V) = 0.12$ and $(m-M)_V = 13.92$ (Harris 1996). Effective temperatures and surface gravities were obtained with the calibration by Montegriffo et al. (1998) for giants, assuming a mass of 0.7 $M_\odot$.

3. ABUNDANCE ANALYSIS

We selected a set of reliable and unblended spectral lines that span a wide range in strength, excitation potential, and wavelength. In particular, the results presented here are based on 94 Fe I lines, 10 Fe II lines, 17 Ca I lines, 10 Si I lines, and the 5782 Å line for Cu I, all in the spectral range ∼5300–6800 Å. Atomic data were taken mainly from the National Institute of Standards and Technology Atomic Spectra Database (Version 2.0)[5] and from Nave et al. (1994) for iron. For copper we used the hyperfine structure line list from the Kurucz database (Bielski 1975).

Equivalent widths (EWs) for Fe, Ca, and Si were measured with IRAF by Gaussian fitting of the line profile on the local continuum. The Gaussian profile is a good approximation for these stars, if one avoids strong lines. For the coolest stars we chose *not* to measure any atomic line inside the prominent TiO bands. The comparison of our EW measurements for ROA 371 with Norris, Da Costa, & Tingay (1995) shows a modest (∼2%) systematic difference that has a negligible impact on the final abundance determination: the results for ROA 371 are, in fact, in good agreement with other literature values (Table 1).

The abundance calculations were made using an extension of the OSMARCS grid of plane-parallel, LTE model atmospheres for M giants and supergiants calculated by Plez (1992; B. Plez 1995, private communication). First estimates of the microturbulent velocity v_t and of [Fe/H] were derived from curves of growth for Fe I and Fe II. We then explored the parameter space around our first estimates and refined them by enforcing simultaneously the following conditions: (1) v_t was determined by imposing that strong and weak Fe I lines give the same abundance; (2) the temperature was constrained by imposing excitation equilibrium on Fe I; and (3) the surface gravity was refined by imposing ionization equilibrium between Fe I and Fe II. As a final test, we checked that [Fe/H] was not changing with λ. The resulting best parameters for the six program stars are shown in Table 2: temperatures and gravities are close to the photometric estimates, and we adopted them to derive the abundances of the other elements (Ca and Si). For copper we computed the line profile with a spectral synthesis technique to take into account the hyperfine structure of the 5782 Å line (Bielski 1975).

Table 3 shows the final abundances, together with their uncertainties: the first figure quoted is the random uncertainty, obtained by averaging the abundances from single lines. In the case of copper, the error reflects the goodness of the spectral synthesis fit. The uncertainty in parentheses is instead an estimate of the internal systematics, obtained by altering the values of $T_{\rm eff}$ (by ± 100 K), $\log g$ (by ± 0.2), and v_t (by ± 0.2 km s^{-1}) and by evaluating the impact of such changes on the resulting abundances. To give an idea of the (external) systematic uncertainties we analyzed the spectrum of Arcturus (α Boo), taken with the Universtiy College London Echelle Spectrograph at the Anglo-Australian Telescope (M. S. Bessel 1995, private communication) with the same procedure used for the program stars, obtaining: $T_{\rm eff} = 4300$ K, $\log g = 1.6$, $v_t = 1.4$ km s^{-1}, and [Fe/H] $= -0.43$. This can be used, together with the abundance analysis of ROA 371 (Table 1), to place our results in a more general context.

4. RESULTS

The three RGB-a stars are the first members of this population ever analyzed with high-resolution spectroscopy. By taking a straight average of their abundances (from Table 3), we found [Fe/H] $= -0.60 \pm 0.15$ and [Ca/H] $= -0.49 \pm 0.16$, confirming that the RGB-a population is the most metal-rich component of the ω Cen stellar mix. The RGB-a abundance obtained here is lower than the previous estimate ([Ca/H] ~ -0.1) based

[4] IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

[5] See http://physics.nist.gov/cgi-bin/AtData/main_asd.

TABLE 2
PROGRAM STARS

ROA (1)	WFI (2)	V (3)	M_V (4)	$(B-V)_0$ (5)	$T_{\rm eff}$ $(B-V)$ (6)	$\log g$ (M_V) (7)	$T_{\rm eff}$ (Fe) (8)	$\log g$ (Fe) (9)	v_t (10)	[Fe/H] (11)
300	221132	12.71	−1.21	1.48	3800	0.7	3900	0.7	1.4	−0.77
	222068	12.95	−0.97	1.42	3900	0.9	4000	1.1	1.3	−0.49
	222679	13.26	−0.66	1.26	4100	1.2	4100	1.2	1.4	−0.54
211	619210	12.43	−1.49	1.37	3950	0.8	4000	0.8	1.9	−1.02
371	617829	12.71	−1.21	1.34	4000	0.9	4000	0.7	1.5	−0.95
	618854	13.26	−0.66	1.00	4600	1.6	4600	1.2	1.5	−1.20

NOTE.—Col. (1): The Royal Astronomical Observatory number from Woolley 1966; col. (2): WFI catalog number from Pancino et al. 2000; cols. (3)–(5): V magnitude, M_V absolute magnitude, and $(B-V)_0$ dereddened color (see text); cols. (6) and (7): photometric estimates of $T_{\rm eff}$ in kelvins and $\log g$, based on Montegriffo et al. 1998; cols. (8)–(11): stellar parameters $T_{\rm eff}$ in kelvins, $\log g$, v_t in kilometers per second, and [Fe/H], derived from our abundance analysis (see text).

TABLE 3
RESULTING ELEMENT ABUNDANCES

Star	[Fe/H]	[Ca/Fe]	[Si/Fe]	[Cu/Fe]	Population
ROA 300	−0.77 ± 0.02 (±0.10)	0.12 ± 0.07 (±0.15)	0.01 ± 0.11 (±0.11)	−0.32 ± 0.13 (±0.04)	RGB-a
WFI 222068	−0.49 ± 0.02 (±0.12)	0.15 ± 0.06 (±0.16)	0.11 ± 0.10 (±0.11)	−0.15 ± 0.12 (±0.05)	RGB-a
WFI 222679	−0.54 ± 0.02 (±0.11)	0.06 ± 0.05 (±0.14)	0.08 ± 0.10 (±0.11)	−0.33 ± 0.11 (±0.08)	RGB-a
ROA 211	−1.02 ± 0.01 (±0.08)	0.28 ± 0.04 (±0.14)	0.28 ± 0.07 (±0.10)	−0.45 ± 0.09 (±0.12)	RGB-MInt
ROA 371	−0.95 ± 0.01 (±0.09)	0.30 ± 0.03 (±0.14)	0.26 ± 0.11 (±0.11)	−0.33 ± 0.07 (±0.04)	RGB-MInt
WFI 618854	−1.20 ± 0.01 (±0.12)	0.28 ± 0.04 (±0.05)	0.30 ± 0.06 (±0.10)	−0.41 ± 0.04 (±0.07)	RGB-MInt

on calcium triplet surveys (see § 1). However, calcium triplet calibrations are usually rather uncertain in the high-metallicity regime (see Norris et al. 1996).

Our most interesting and surprising result, however, is the different α-element enhancements found for the two subpopulations. We obtained [Ca/Fe] $= 0.29 \pm 0.01$ and [Si/Fe] $= 0.28 \pm 0.02$ for the three RGB-MInt stars, which is the expected value for the α-enhancement of halo and globular cluster stars. Instead, the three RGB-a stars have only [Ca/Fe] $= 0.11 \pm 0.05$ and [Si/Fe] $= 0.07 \pm 0.05$. If we compute [α/Fe] for each star with a weighted average of their Ca and Si abundances, the RGB-MInt and RGB-a populations α-enhancements turn out to be [α/Fe] $= 0.29 \pm 0.01$ and 0.10 ± 0.04, respectively.

This is the first indication that a population of stars with a significantly lower α-enhancement exists in ω Cen: both Norris & Da Costa (1995) and Smith et al. (2000), who analyzed giants in ω Cen with metallicities of up to [Fe/H] $= -0.78$ and -0.95, respectively, found *no evidence* of a decrease in calcium, silicon, or in any other α-element enhancement.

The effect is illustrated in Figures 1*a* and 1*b*, where the calcium and silicon enhancements are plotted as a function of [Fe/H]. The shaded areas mark the region where the measurements by Norris & Da Costa (1995) and Smith et al. (2000) lie, while the solid lines represent the Galactic [α/Fe] relation as can be derived from Edvardsson et al. (1993) and Gratton (1999). The six stars analyzed here are plotted as filled circles: as can be seen, the three RGB-MInt stars show enhancements that are in good agreement with previous determinations for ω Cen, while the three RGB-a stars are clearly less overabundant in both elements. We would like to note at this point that even if some small systematic differences may be present among the various studies (most probably due to a different choice of atomic data and log gf, especially in the case of copper), the use of trends in the abundance ratios is particularly reliable since it is based on relative, differential measurements.

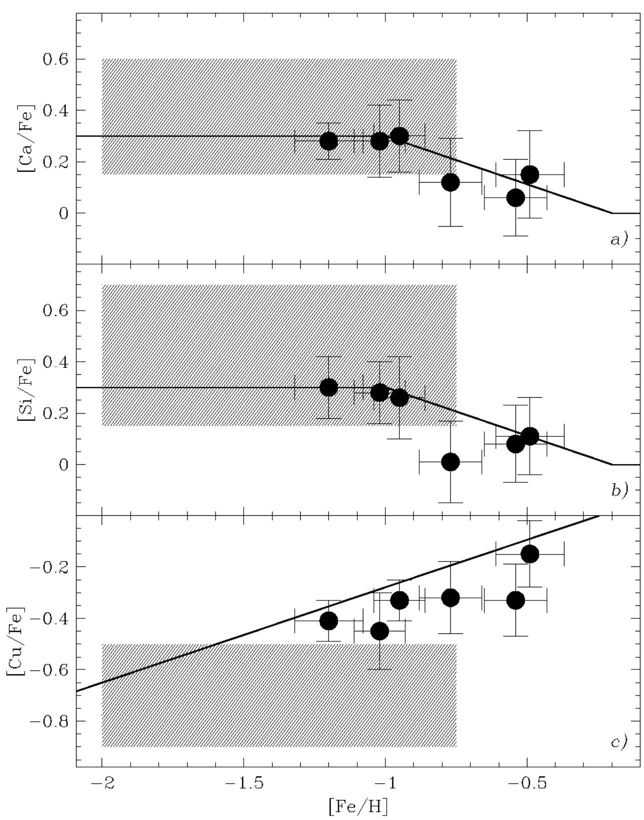

FIG. 1.—Element ratios for (*a*) [Ca/Fe], (*b*) [Si/Fe], and (*c*) [Cu/Fe]. Our results are plotted as filled circles, while shaded areas mark the regions where previous high-resolution measurements for ω Cen giants lie, and solid lines represent the corresponding trends in our Galaxy (see text for references).

Figure 1*c* shows our results for [Cu/Fe]. Our stars are plotted as filled circles, the shaded area covers the region where the Smith et al. (2000) measurements lie, and the solid line represents the trend found by Sneden, Gratton, & Crocker (1991) for field stars. The increasing trend in our data is more compatible with the results by Sneden et al. (1991) than with the behavior of the metal-poor stars in ω Cen. As discussed by Smith et al. (2000), copper is thought to be produced mainly by Type Ia supernovae (SNe Ia) and only marginally by Type II supernovae (SNe II; see also Matteucci et al. 1993), as required to explain the trend observed in the Galaxy. For the metal-poor and -intermediate stars in ω Cen, Smith et al. (2000) found a very low and constant value of [Cu/Fe] $= -0.6$, in agreement with the idea that SNe Ia have *not* contributed to the enrichment of these two populations.

If the results shown in Figure 1 are confirmed by larger samples of metal-rich stars, then *we have found the first evidence that SNe Ia ejecta have contaminated the medium from which the RGB-a stars have formed.*

5. DISCUSSION

A detailed discussion on the chemical evolution of ω Cen is beyond the purpose of this Letter; however, some obvious implications of the new results presented here deserve a short comment. There are two main scenarios that have been proposed to explain the variety of stellar populations observed in ω Cen, both based upon nonnegligible observational evidences: the *self-enrichment* scenario and the *merging* scenario. Let us discuss the impact of our result on the two separately, while recalling that the actual evolutionary path of ω Cen may well be the result of a combination of both scenarios.

The self-enrichment scenario.—The most popular explanation is that ω Cen has been somehow able to retain the ejecta of previous generations of stars and to self-enrich during its star formation history. This requires that ω Cen was formerly a more complex and larger stellar system, with a deeper potential well, possibly a dwarf galaxy (Freeman 1993; Dinescu, Girard, & van Altena 1999; Hilker & Richtler 2000; Hughes & Wallerstein

2000), that lost most of its stars (and gas) in the interaction with the Milky Way, as the Sagittarius dwarf spheroidal is doing presently.

The fundamental piece of evidence in favor of this scenario is the constancy of the α-enhancement with metallicity ([α/Fe] $\sim +0.3$) for all stars with [Fe/H] ≤ -0.8 (Norris & Da Costa 1995; Smith et al. 2000). This requires that the major responsibles for the enrichment of these stars are SNe II: at least part of their gas must have been retained by ω Cen in order to explain the iron abundance spread. The timescales of this process are thought to be relatively short ($\lesssim$1 Gyr), in contradiction with the timescales required to explain the observed dramatic increase of the *s*-process element overabundance with metallicity (Norris & Da Costa 1995; Smith et al. 2000; Lloyd Evans 1983). The major responsibles of the *s*-process element enrichment are intermediate-mass asymptotic giant branch stars that act on a timescale of at least 1–5 Gyr (Busso, Gallino, & Wasserburg 1999).[6] Thus, we are still far from assessing robust timescales for the various enrichment processes in ω Cen.

The α and *s*-process element trends, together, have been taken as evidence that no significant contributions by SNe Ia have enriched the (metal-poor and -intermediate) stars in ω Cen (Smith et al. 2000). This has been explained either with a star formation process short enough to end before the onset of SNe Ia or by assuming that SNe Ia winds efficiently removed most of their own products (Recchi, Matteucci, & D'Ercole 2001). However, if we assume that the detailed chemical composition of *all* giants in ω Cen can be explained by pure self-enrichment, then the evidence presented here indicates that ω Cen was able to retain part of the SNe Ia ejecta as well, complicating the picture.

If this is the case, then the RGB-a stars must be younger, possibly resulting from the last burst of star formation in ω Cen. Indeed, an age spread of 3–5 Gyr has been claimed to explain the morphology of the subgiant branch turnoff (Hilker & Richtler 2000; Hughes & Wallerstein 2000). In fact, we would have detected the "knee" of the [α/Fe] relation, a very valuable constraint to the chemical evolution of the whole stellar system (McWilliam 1997). The canonical interpretation of such a feature is that it marks the onset of the SNe Ia pollution. While the timescales of this enrichment process are generally believed to be short ($\lesssim$1 Gyr), they are still quite uncertain since they depend on several factors (Matteucci & Recchi 2001).

[6] An alternative explanation for the *s*-process enrichment is proposed by Ventura et al. (2001), who examine the possibility of surface pollution for stars in globular clusters.

The merging scenario.—The reason why this alternative scenario (Searle 1977; Icke & Alcaino 1988) is not ruled out yet lies mostly in the dynamical and structural properties of ω Cen. In particular, the unusually high ellipticity of ω Cen, which has been demonstrated to be sustained by rotation (Merritt, Meylan, & Mayor 1997), is compatible with the flattened shapes resulting from the merger of two globular clusters (Makino, Akiyama, & Sugimoto 1991). Moreover, Norris et al. (1997) showed that only stars with [Fe/H] ≤ -1.2 in ω Cen do rotate, while the more metal-rich ones show no evident sign of rotation. Finally, Pancino et al. (2000) showed that while the metal-poor population exhibits the well-known east-west elongation, the two metal-rich populations show a more pronounced ellipticity, but with an elongation in the north-south direction. These pieces of evidence point toward a different dynamical origin for the various subpopulations in ω Cen.

There are some problems with this scenario, however. According to Norris et al. (1996) and Smith et al. (2000), the simple merging of two or more single metallicity clusters cannot account for the broad metallicity distribution of the RGB. Also, the high speed of ordinary, already formed globular clusters in the potential well of the Milky Way makes this kind of merging quite unlikely. However, the possibility still remains that some of the present stellar components may have formerly belonged to an external, smaller system that merged with ω Cen.

Within this framework, one of the most promising ideas seems to be the so-called *merger within a fragment scenario* (Norris et al. 1997). According to this scenario, the RGB-a population could originally have been a satellite system that fell into the potential well of the larger stellar system (a small galaxy), whose final remnant is the ω Cen that we observe today. In this case, our results add the evidence that the accreted subsystem has previously been enriched by SNe Ia, as opposed to the main body of ω Cen. Thus, the original environments from which the subpopulations have formed must have had different chemical enrichment histories.

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