A Sr-RICH STAR ON THE MAIN SEQUENCE OF ω CENTAURI

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Received 2006 September 28; accepted 2006 November 1; published 2006 December 5

ABSTRACT

Abundance ratios relative to iron for carbon, nitrogen, strontrium, and barium are presented for a metal-rich main-sequence star ([Fe/H] = −0.74) in the globular cluster ω Centauri. This star, designated 2015448, shows depleted carbon and solar nitrogen but, more interestingly, shows an enhanced abundance ratio of strontrium [Sr/Fe] ≈ 1.6 dex, while the barium abundance ratio is [Ba/Fe] ≤ 0.6 dex. At this metallicity one usually sees strontrium and barium abundance ratios that are roughly equal. Possible formation scenarios of this peculiar object are considered.

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

1. INTRODUCTION

The largest globular cluster associated with our Galaxy, ω Centauri, shows substantial ranges in abundance of all elements that are studied (e.g., Norris & Da Costa 1995a; Smith et al. 1995, 2000; Pancino et al. 2002). The iron abundance ranges from [Fe/H] ≈ −2.0 up to ≈ −0.4. A peak at [Fe/H] = −1.7 exists that accounts for approximately 70% of the population, and there is a long tail to higher metallicities (Norris et al. 1996; Suntzeff & Kraft 1996; Lee et al. 1999; Pancino et al. 2000; Stanford et al. 2006).

Studies of individual elements have also shown a range in their abundances within the cluster members. Carbon, nitrogen, and oxygen show large scatters in their abundance ratios for a given [Fe/H] (Persson et al. 1980; Brown & Wallerstein 1993; Norris & Da Costa 1995a). The α-elements (Mg, Si, Ca, and Ti) show a constant value of [α/Fe] ≈ 0.3 below [Fe/H] < −1.0 (Brown & Wallerstein 1993; Smith et al. 1995, 2000; Norris & Da Costa 1995a) but decrease to [α/Fe] = 0.0 at higher metallicities ([Fe/H] > −1.0; Pancino et al. 2002). The constancy with iron at lower abundances indicates they are produced by the same source, most likely Type II supernovae. At the higher metallicities [α/Fe] decreases, consistent with Type Ia supernova contributions.

Sodium and aluminum abundance ratios are correlated, and both are anticorrelated with [O/Fe] (Brown & Wallerstein 1993; Norris & Da Costa 1995a, 1995b; Smith et al. 2000). Smith et al. (2000) also report [Al/Fe] being anticorrelated with [Mg/Fe]. [Cu/Fe] has been found to be constant for [Fe/H] < −0.8 (Smith et al. 2000; Cunha et al. 2002), but Pancino et al. (2002) report a trend of increasing [Cu/Fe] as the metallicity increases from [Fe/H] = −1.2 to −0.5. Studies of the iron-peak elements (Cr, Ni, and Ti) and metals (Sc and V) have shown that there is no trend with respect to iron (up to [Fe/H] ≈ −0.8), consistent with primordial enrichment from Type II supernovae. The heavy neutron capture elements have been shown by Norris & Da Costa (1995a) and Smith et al. (1995) to increase sharply as a function of iron abundance. These results are in contrast to normal globular clusters, and suggest that the stellar winds from asymptotic giant branch (AGB) stars (sources of s-process elements) were involved with the enrichment of ω Cent.

The cluster also has several members that are of distinct classes, such as CH stars, Ba stars, S stars (Lloyd Evans 1983), and stars with strong CO (Persson et al. 1980), to name a few. Here we present another object that has unusual abundance ratios, the formation of which is difficult to explain.

We have obtained observations of a sample of main-sequence and turnoff stars within the cluster for several purposes. First, the possibility of an age-metallicity relation within the cluster’s member stars was investigated (Stanford et al. 2006). We found that an age range of 2–4 Gyr exists between the most metal-poor and metal-rich populations within the cluster, similar to that found by other studies (Hilker et al. 2004; Rey et al. 2004; Sollima et al. 2005). Positions, photometry, metallicities, and ages of the stars in the catalog can be found in the electronic version of Stanford et al. (2006). The second goal was to determine the abundance ratios of carbon, nitrogen, strontrium, and barium, as functions of [Fe/H] (L. M. Stanford et al. 2006, in preparation). In that analysis a metal-rich main-sequence member, 2015448, was found that exhibited unusual s-process abundance ratios. The purpose of this Letter is to detail the abundance analysis for star 2015448 and to propose possible formation scenarios. Section 2 briefly describes the observation and reduction process for our sample of main-sequence and turnoff members. The stellar parameters and analysis are detailed in § 3, while § 4 discusses the possible formation scenarios for this object.

2. OBSERVATIONS

The observations and reduction of our data are described in detail in Stanford et al. (2006), to which we refer the reader. Briefly, photometry for the cluster was obtained in the V and B bands, and samples were chosen within an annulus 15′–25′ from the cluster center. Two regions were defined near the main-sequence turnoff, shown in Figure 1, and spectra were obtained for objects within these color-magnitude diagram regions using the Two Degree Field Spectrograph on the Anglo-Australian Telescope (Lewis et al. 2002). Figure 1 shows the color-magnitude diagram of all objects with no membership information as dots, the sample of 420 radial velocity members as circles, and the object that is the topic of this Letter as a star. This object, 2015448, has V = 18.22 and B − V = 0.69. This star immediately stood out in a visual inspection of the spectra due to the anomalously strong Sr lines, seen in Figure 2. Its position is R.A. = 13h24m49.10s, decl. = −47°40′34.7″ (J2000.0).
With a radial velocity of 228 ± 11 km s⁻¹, star 2015448 is likely to be a member of the cluster, as ω Cen has a radial velocity of 232 ± 0.7 km s⁻¹ (Dinescu et al. 1999).

The observations were carried out in half-hour exposures, and, as several such exposures were needed to obtain the required signal-to-noise ratio of ~30 for each star, there are several individual observations for star 2015448. Also, this object was observed in 1998, 1999, and 2002 in different fibers and spectrographs. This gives an independent check on the relative strengths of the Sr and Ba features. It was found that the two Sr features were present in all observations, while Ba was not clearly detected in any of our spectra.

A spectroscopic abundance analysis of the full sample is detailed in L. M. Stanford et al. (2006, in preparation). Abundances relative to iron of C, N, and Sr were determined using spectrum synthesis techniques. The CH feature at 4300 Å was used to determine the [C/Fe] abundance for each star. This [C/Fe] was then adopted when the CN feature at 3883 Å was analyzed to find [N/Fe]. The Sr abundance ratio was determined using the two Sr lines at 4077.71 and 4215.52 Å. When possible, [Ba/Fe] was also determined from the feature at 4554.03 Å.

3. STELLAR PARAMETERS AND ANALYSIS

The process for calculating metallicities is described in detail in Stanford et al. (2006). The Sr-rich star has a metallicity of [Fe/H] = −0.74 ± 0.23 dex, determined solely from the autocorrelation function method (Beers et al. 1999), and an age of 14.5 ± 2.2 Gyr. This age is consistent with the mean age of the bulk of the stars in the cluster. The ages for the individual stars in the sample were calculated by fitting an isochrone to each object using the magnitude, color, metallicity, and [α/Fe] abundance (Y2; Yi et al. 2001, Green color transformation table). This also enabled an individual temperature and gravity to be assigned to each star. A temperature of 5820 K and log g = 4.2 (cgs) were adopted for this object. A reddening E(B − V) = 0.11 (Lub 2002) and distance modulus (m − M)₀ = 14.10 were assumed. Although the star’s color is redder than the bulk of the population in the cluster, it is also more metal-rich than that population. The hydrogen-line strengths in the observed spectrum are consistent with those expected on the basis of the star’s color.

Synthetic spectra were obtained using the stellar models of R. L. Kurucz,¹ atomic line lists of R. A. Bell (2000, private communication), and molecular line lists of Kurucz. The spectrum synthesis code was developed by Cottrell & Norris (1978). More details of this process are given in L. M. Stanford et al. (2006, in preparation).

3.1. Abundance Ratios

Figure 3 shows the synthetic spectrum fits to the CH, CN, Sr, and Ba features. The G band at ~4300 Å was analyzed first and gave a C abundance of [C/Fe] = −0.5 ± 0.3 dex. This feature loses its sensitivity for abundances less than [C/Fe] = −0.5, shown by the close proximity of the [C/Fe] = −0.8 and −0.5 dex synthetic lines. As we have no information on O, which affects the C abundance obtained from the CH feature, a value of [O/Fe] = 0.18 dex was assumed. This star was assumed to have [C/Fe] = −0.5, which was then used when determining [N/Fe]. Synthesis of the CN feature at ~3883 Å led to a N abundance ratio of [N/Fe] < 0.5 dex. A range of N abundance ratios is shown in the synthetic spectra, enabling an upper limit to be placed. The CN feature in Figure 3 shows that abundance ratios of [N/Fe] = 1.5 and 1.0 are too high. However, this feature loses its sensitivity as smaller N abundance ratios are considered, and only an upper limit can be determined.

The Sr and Ba lines were analyzed together. There were two Sr lines used, Sr ii at 4077.71 Å and Sr ii at 4215.52 Å. The Ba ii λ4554.03 line was used to constrain the Ba abundance ratio. The two Sr lines are in agreement and yield [Sr/Fe] = 1.6 ± 0.1 dex. It can be seen clearly that a solar Sr abundance ratio does not fit the observed spectrum. The CN band head at ~4216 Å can affect the abundance ratio obtained for the Sr λ4215 feature. However, with an assumed solar N abundance ratio, there is little effect on the Sr line. While the N abundance ratio could be as high as [N/Fe] = 0.5 dex, spectrum synthesis calculations show this does not affect the Sr λ4215 line significantly and does not alter the abundance ratio obtained. Using the same enhancement for Ba that was found for Sr, one finds the predicted strength to be too high to fit the observed

¹ Vizier Online Data Catalog, 6039 (R. L. Kurucz, 1993).
The sensitivity of the Ba feature is low up until abundance ratios of [Ba/Fe] = 0.6 dex, and an upper limit can be placed at this value.

3.2. Errors

The stellar parameters of temperature, gravity, and metallicity for star 2015448 were varied individually by their uncertainties to give an estimate of the error in our determined abundance ratios. These were then added in quadrature. The error in temperature comes from Δ(B − V) and the reddening, equating to ±100 K uncertainty in temperature. This propagated to errors of ±0.2 dex in C and ±0.1 dex in Sr. Gravity was changed by ±0.2 dex and did not lead to any significant errors in the final abundance ratios. The uncertainty in metallicity propagated to errors in abundance ratios for ΔC of ±0.2 dex and ΔSr of ±0.1 dex. The CN feature used to determine N, adopting the previously determined C abundance ratio for 2015448, did not show any change with the above changes in temperature, gravity, and metallicity, or the determined error in the C abundance ratio, due to the low sensitivity of this feature. To determine the effect of the assumed oxygen abundance, [O/Fe] = 0.0 and +0.3 were used and the CH feature reanalyzed. It was found to have no noticeable effect on the [C/Fe] abundance determined.

4. DISCUSSION

This peculiar star in ω Cen shows [C/Fe] = −0.5, [N/Fe] < 0.5, enhanced [Sr/Fe] = 1.6, and [Ba/Fe] < 0.6. The formation process that created it was unusual, as there are no similar objects yet found within the cluster. We do find main-sequence objects with high Sr, but these also have similar enhancements in Ba. This star was one out of 420 stars studied on the main-sequence turnoff. Given that it is a metal-rich star, and we only found 25 such objects, a more extensive search of other areas of the cluster, particularly the center, may prove fruitful in determining if there are more of these objects. On the red giant branch (RGB), at a metallicity of [Fe/H] = −0.8, most stars have [Ba/Fe] ≈ 0.6 (Norris & Da Costa 1995a), which is consistent with the upper limit found for star 2015448. Norris & Da Costa (1995a) did not observe Sr, and a direct comparison cannot be made. However, they did investigate other light s-process elements such as Y and Zr. Both of these elements have abundance ratios equal to or less than 0.6, and no stars on the RGB exhibit s-process abundances as high as is found here for [Sr/Fe].

There are at least two possibilities that lead to the formation of this star. First, it may have been in a binary system with a companion that underwent unusual s-process enrichment and transferred mass to the star we see today. At present we have no evidence that this star is in a binary system: the individual velocities from the 1998, 1999, and 2002 observations are consistent to within the measurement errors of ∼10 km s⁻¹. A second possibility is that the Sr-rich star formed out of already enriched material.

AGB stars of low and intermediate mass dredge up ¹²C to the surface via helium shell thermal pulses. In general, if the star is more massive than ∼3 M☉, the ¹³C is processed to ¹⁴N via the CN cycle (Ventura et al. 2002). The main s-process is thought to occur within the ¹³C pocket, where the neutron source is the ¹³C(α, n)¹⁶O reaction (e.g., Lattanzio & Karakas 2001). To generate the abundance ratio seen here it would seem necessary for the s-process to occur only for the light s-process elements, perhaps up to the peak at Zr, rather than progressing.
through to heavy s-process elements, including Ba. This may be due to the neutron density not being high enough, as higher neutron densities, assuming all other parameters being equal, will produce larger amounts of heavier nuclei, such as Ba or La, relative to the lighter ones (Smith 2005).

Another source of s-processing, known as the weak s-process, occurs in massive stars (Prantzos et al. 1990). The $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction is the source of the neutrons. Most of the neutrons produced from this reaction are captured by the light elements, and only a small fraction are captured by the $^{56}\text{Fe}$ seed nucleus, a process known as “self-poisoning.” This is the reason for the limited efficiency of the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ source for the s-process. It allows for the production of only light s-process nuclei with mass numbers $65 < A < 90$, and Sr, with a mass number of 87, falls into this range. Ba, on the other hand, with a mass number of 137, does not, and little of this element is produced by this process (Prantzos et al. 1990). It is unclear whether massive stars could also produce the necessary C and N abundance pattern that may have originated from these objects.

The r-process occurs in an environment that is rich in neutrons, and the mean time between successive neutron captures is very short compared with the time to undergo $\beta$-decay. This scenario as the enrichment source also requires the presence of supernova products such as calcium and iron, or to have the Sr-enriched material transferred, but not any supernova products.

Using the abundance yields for the r- and (main) s-process (occurring in low- to intermediate-mass AGB stars) from Cameron (1982) and normalizing to [Sr/Fe], one finds a difference greater than 1 dex between predicted and observed abundances for Ba. For the main s-process the predicted abundance is $[\text{Ba/Fe}] = 1.68$, while the r-process predicts $[\text{Ba/Fe}] = 1.84$. Both of these values are obviously too large, confirming the unusual nature of the source of the abundance patterns found in star 2015448. However, it should be noted that AGB star yields do not explain the abundance anomalies of Na, Mg, Al, and O found in other stars of $\omega$ Cen or normal globular clusters (see, e.g., Fenner et al. 2004). This may be due to the inadequacy of the models used to calculate yields for these objects.

From weak s-process yields in massive stars (Prantzos et al. 1990), using an initial metallicity of $Z/Z_\odot = 10^{-3}$ and mass of $16 M_\odot$, we derive $[\text{Sr/Fe}] = 1.8$ and $[\text{Ba/Fe}] = 0.7$, in good agreement with the Sr abundance and upper limit of the Ba one obtained here. This indicates the weak s-process is the more favorable option for the source of enrichment in star 2015448.

This star is also highly unusual when compared to observations of field stars. Studies of n-capture elements in samples of field stars for a range of metallicities show a spread in abundance ratios of Sr and Ba at low metallicities ($[\text{Fe/H}] < -2.0$), with most stars having $[\text{Sr/Fe}]$ or $[\text{Ba/Fe}] < 0.0$ (McWilliam 1998; Burris et al. 2000; Honda et al. 2004). At higher metallicities, the abundances are within $\pm 0.5$ of the solar abundance.

A cool field giant, U Aquarii, has enhanced $[\text{Sr/Fe}]$ and $[\text{Y/Fe}]$ abundances and low $[\text{Ba/Fe}]$ (Bond et al. 1979). This star is a faint R Corona Borealis variable star and shows no CH features but strong $^{12}\text{C} \rightarrow$ bands. Bond et al. (1979) concluded that U Aqr is a hydrogen-deficient carbon star with enhanced abundances of the light s-process elements Sr and Y (by a factor of $\sim 100$) and little or no Ba. It is now a He-C core of an evolved star of $\sim 1 M_\odot$ that ejected its H-rich envelope at the He core flash. Bond et al. (1979) postulated that a single neutron exposure occurred at the flash, resulting in a brief neutron irradiation producing only the light s-process elements. A similar giant, known as Sakurai’s Object (Asplund et al. 1997), shows similarly enhanced C and light s-process elements and is H-deficient. These types of stars may be responsible for the abundance pattern found in star 2015448. However, a significant difference is the C-rich nature of the giants compared with the carbon-depleted nature of star 2015448.

Our results provide a challenging puzzle to determine the source of the abundance patterns found for this star. That said, the resolution of our data is inadequate to address this question. Higher resolution spectra with high signal-to-noise ratio are needed to analyze as many elements as possible, in particular the s-process ones, to be able to obtain an accurate history for the evolution of star 2015448.

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