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Abundances of the star ROA 276 in ω Cen

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Abstract. A red giant branch star, ROA 276, in the globular cluster ω Centauri has been found to have unusual Sr and Ba abundance ratios. Medium resolution spectra of ROA 276, from the ANU's 2.3m telescope and high resolution spectra obtained with the Magellan Telescope/MIKE spectrograph combination, confirm this result. Calculations of the depletion effect, the potential change in surface abundance that results from the increased depth of the convective envelope as a star moves from the main sequence to the red giant branch, strongly suggest that the observed Sr enhancement in ROA 276 is of primordial origin, rather than originating from a surface accretion event.

Key words. Stars: abundances – Population II – Galaxy: globular clusters – ω Centauri

1. Introduction

Once thought to be a globular cluster, ω Centauri is more widely accepted today as the remnant nucleus of a dwarf galaxy that was disrupted by the Milky Way billions of years ago. The first clue to its unusual nature was seen in the large spread in colour on the red giant branch in the colour-magnitude diagram (CMD) seen by Woolley et al. (1966) and Cannon & Stobie (1973), and more recently in the high precision photometry of Sollima et al. (2005). The CMD of Sollima et al. (2005) revealed distinct red giant branch (RGB) sequences, indicative of distinct populations. Our knowledge and understanding of the formation and evolution of ω Cen is far from complete. Bedin et al. (2004) presented photometry that revealed a double main sequence (MS). This is thought to be the result of enhanced helium abundances in the more metal-rich populations (Norris 2004).

Ranges in abundances ratios for all elements studied have been found in stars on the red giant branch (RGB) (see e.g. Norris & Da Costa 1995; Smith et al. 1995). The *s*-process element abundance ratios, [*s*/Fe], increase with increasing [Fe/H], but then are constant above metallicities greater than [Fe/H] = −1.2 (Norris & Da Costa 1995; Smith et al. 1995). The origin of the *s*-process enrichment may be due to ejecta from asymptotic giant branch (AGB) stars.

The processes that were involved in the enrichment of the stars include: 1) internal mixing within the stars themselves; 2) accretion of matter onto the surface layers from either stellar winds of AGB stars or interstellar material; and/or 3) primordial enrichment, where the stars formed from already enriched material. It is likely that more than one of these scenarios is at play.

A sample of RGB stars in ω Cen was chosen to cover the range in metallicity and several objects were included due to the known enhanced nature of the CH feature, or high *s*-process abundances. Abundances of carbon, nitrogen, strontium and barium were determined. The full analysis and results of this work can be found in Stanford, Da Costa & Norris (2010). From this study an RGB star was discovered that had unusual Sr and Ba abundance ratios. Here we present results for this star, and discuss the possible origins of its abundance patterns.

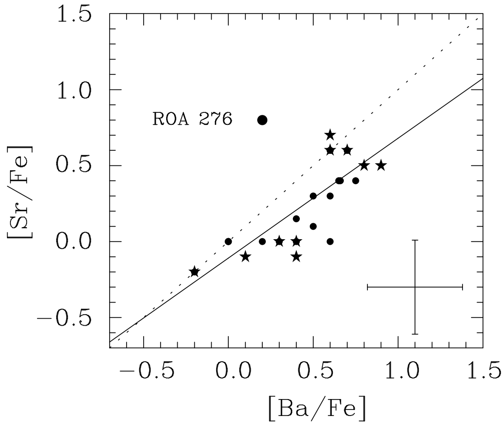

Fig. 1. [Sr/Fe] vs [Ba/Fe]. The dots reprent the higher resolution data R1200, and the stars the lower resolution data R600. Stars in common are averaged. Note ROA 276.

2. Observations

The initial observations of the RGB stars were obtained on the ANU's 2.3m telescope at Siding Spring Observatory in 2002 and 2003 with the Double Beam Spectrograph using the 600 and 1200 line/mm gratings. Spectra for 18 RGB stars were obtained with the 600 line/mm grating, and 39 with the 1200 I grating, 8 of which were in common. The low resolution (R600) data covered a wavelength range of 3500–5400Å, with a resolution of 2.2Å FWHM. The high resolution (R1200) spectra covered a wavelength range of 3700–4600Å with a resolution of 1.2Å FWHM. Reduction and wavelength calibration were performed using standard routines in IRAF and Figaro.

After analysis of these data, it became apparent that one object in the sample required further, higher resolution abundance analysis: ROA 276. Spectra were obtained for this star, and comparison objects ROA 46 and 150, with the Magellan Telescope/MIKE spectrograph combination during 2007 June 22-23 using a 0.5 arcsec slit, yielding a resolving power of 47,000, and a resolution of 0.12 Å FWHM.

3. Analysis

Stellar parameters for our sample were obtained primarily from the literature (Norris & Da Costa 1995; Persson et al. 1980). For the RGB stars with no literature information, [Fe/H] was determined using [Ca/H] from Norris, Freeman & Mighell (1996) where [Fe/H] = [Ca/H] − [Ca/Fe]. Following Smith et al. (1995) we adopt the following [Ca/Fe] relation: [Ca/Fe] = 0.3 for [Fe/H] ≤ -1.0, and $-0.3 \times$ [Fe/H] for $-1.0 \leq$ [Fe/H] ≤ 0.0. The temperature and gravity were interpolated from the parameters of other stars with similar metallicity, in $(B-V) - T_{\rm eff}$ and V–log g space, respectively. As most RGB stars have a microturbulent velocity of around 2.0 km s^{-1}, this value was assumed for these objects.

The abundance analysis used spectrum synthesis techniques for each of the objects, adopting the stellar parameters as described above. Kurucz (1993) stellar models were employed with atomic line lists from Bell (2000, private communication) and Kurucz molecular lines lists. The synthesis code developed by Cottrell (Cottrell & Norris 1978) was used to generate synthetic spectra and broadened to match the observed higher and lower resolution data. The Sr II 4077Å, Sr II 4215Å and Ba II 4554Å features were analyzed. The solar abundances and gf values for Sr II 4077Å, Sr II 4215Å and Ba II 4554Å used in Stanford et al. (2007) were again employed. An error analysis was performed by varying the stellar parameters and redetermining the abundances for several stars in both the R600 and R1200 samples.

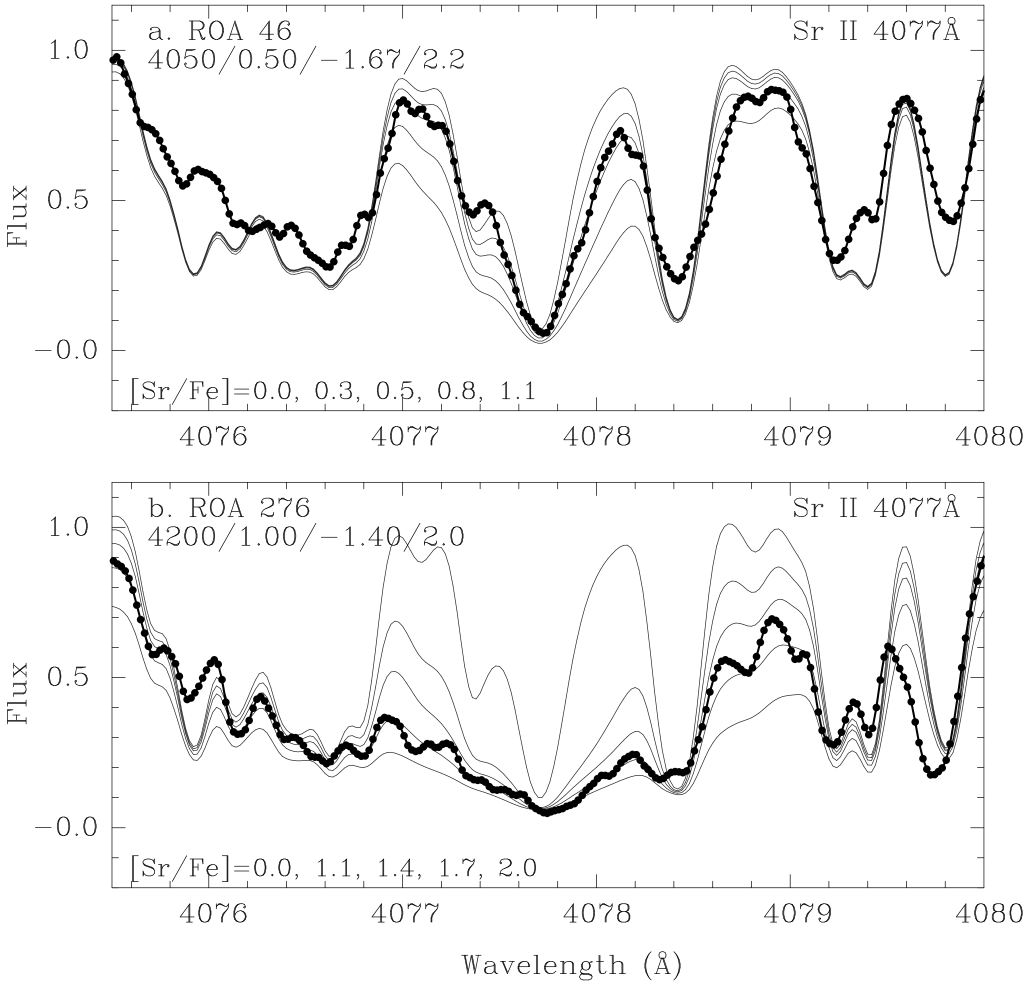

Fig. 2. Observed and synthetic spectra of Sr ii 4077Å for ROA 46 (for comparison) and ROA 276.

Fig. 1 shows the resulting [Sr/Fe] against [Ba/Fe]. Two things are immediately clear. Firstly, most stars have Sr and Ba abundance ratios that are very similar, and these two elements are correlated. The dotted line in the figure represents the 1:1 line, while the solid line is the least square fit to the data. The second thing to note is the star that lies off the trend, marked as ROA 276. It has a high [Sr/Fe] value, but a lower than expected [Ba/Fe] value. A similar star was found in ω Cen in our previous study of abundances in stars on the main sequence turn-off (Stanford et al. 2006, 2007)

The stellar parameters for ROA 276 were derived by interpolation of $T_{\rm eff}$ and $\log g$ given its metallicity converted from [Ca/H] from Norris, Freeman & Mighell (1996). When analyzing the Sr ii 4077Å feature in the spectra it was noticed that many of the neighboring lines were too strong, indicating the metallicity was too high or the temperature too low. By decreasing the metallicity to [Fe/H] = −1.4, and redetermining the temperature to be 4200K (as opposed to 4000K), an improved fit to these lines was found. Despite the change in stellar parameters the unusual [Ba/Sr] ratio is still

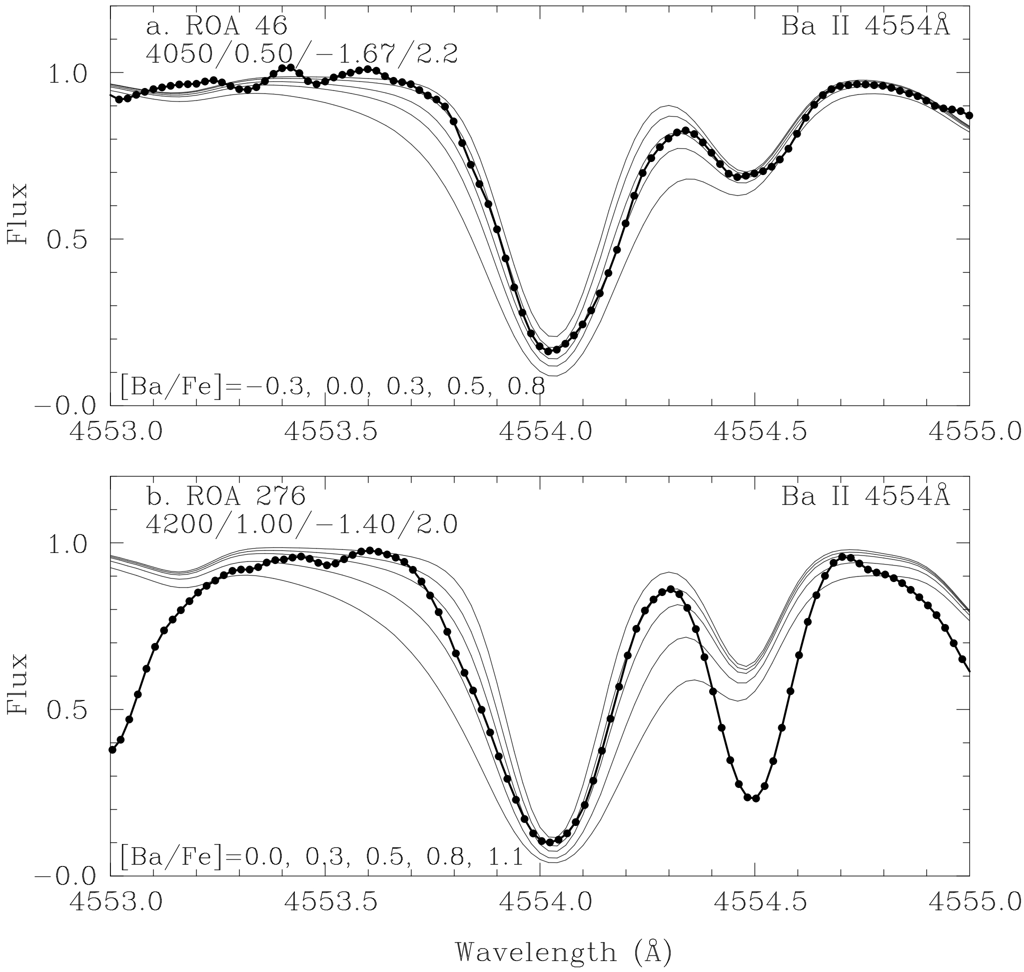

Fig. 3. Observed and synthetic spectra of Ba II 4554Å for ROA 46 (for comparison) and ROA 276.

present. It should be kept in mind that the temperature and metallicity have been estimated and require more accurate determination.

As a consequence of the abundance result obtained with the intermediate resolution spectra, higher resolution data were obtained for ROA 276 along with two other ω Cen RGB stars, ROA 46 and ROA 150. These data were obtained with the Magellan (Clay) telescope/MIKE echelle spectrograph combination[1] described above. Here we concentrate on the wavelength regions that cover the Sr II 4077Å and the Ba II 4554Å lines. Hyperfine splitting for the Ba II 4554Å line was taken into account and followed the *s*-process abundance pattern from Arlandini et al. (1999).

Fig. 2 shows the Sr 4077Å line for ROA 40 (panel a), and 276 (panel b). The results for the Ba 4554Å line for these stars are shown in Fig. 3. For comparison, in both figures a synthetic spectrum with stellar parameters $T_{\rm eff}$ = 4200 K, $\log g$ = 1.0, [Fe/H] = −1.40 and v_t = 2.0 km s^{-1} have been plotted for a range of [Sr/Fe] and [Ba/Fe] values against the observed ROA 276 spectrum. The resulting abun-

[1] `http://www.ucolick.org/~rab/MIKE/usersguide.html`

dance ratios for ROA 276 are [Sr/Fe] = 1.6 and [Ba/Fe] = 0.4. It is clear from the MIKE high resolution data that ROA 276 has an unusual [Ba/Sr] ratio, and that further study of this star is warranted.

4. Discussion

The source of these unusual abundance patterns is unlikely to be AGB stars. At this metallicity AGB stars produce [Sr/Fe] and [Ba/Fe] abundances in roughly equal amounts (Gallino et al. 1998). Massive stars may have contributed to the enrichment, in particular massive rotating objects. These objects have been speculated to be the cause of the He enrichments in the cluster, as they produce the helium and nitrogen in their stellar winds without carbon and oxygen overabundances (Maeder & Meynet 2006). These stars may be able to account for the abundances found on the RGB. As yet *s*-process element yields for rotating, massive stars at this metallicity have not been published and therefore definitive conclusions regarding the enhancement sources cannot be made.

The low [Ba/Sr] value for ROA 276 is similar to that found for the main sequence star S2015448 (Stanford et al. 2006), which has [Sr/Fe] = 1.6, [Ba/Fe] < 0.6 and [Ba/Sr] < −1.0. While the relative frequencies of such large Sr enhancements on the MSTO and RGB are not well determined, and must await further work, the existence of such objects on both the MS and RGB places an important constraint on the origin of the enhancement. Unless accretion provides a large fraction of the mass of the observed star, a primordial origin for the enhancements is required. An estimate of the dilution due to convection as an enhanced MS star evolves up the RGB leads to a reduced relative abundance, [Sr/Fe] = 0.35. Conversely, given the same assumptions, one would conclude that ROA 276 would have had the enormous value, [Sr/Fe] $\approx$ 2.3, when it was on the main sequence if its surface was contaminated rather than primordially enhanced. While not outside the realm of possibility, this is unlikely.

As noted, ROA 276 stood out against all other members of our RGB sample. For our initial adopted metallicity of [Fe/H] = −0.57, we obtained [Ba/Sr] = −1.2 from our high-resolution MIKE spectra. We also found that this value is quite insensitive to uncertainties in atmospheric parameters. In contrast, the [Ba/Fe] value was found to be equal to or greater than [Sr/Fe] for every other star analyzed.

Further analysis of this object is required to accurately determine its stellar parameters and to confirm the *s*-process abundance pattern found here, as well as to estimate abundances for many other elements in order to understand the origin of the unusual abundance patterns.

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References

Arlandini, C., et al. 1999, ApJ, 525, 886
Bedin, L. R., et al. 2004, ApJ, 605, L125
Cannon, R. D., & Stobie, R. S. 1973, MNRAS, 162, 207
Cottrell, P. L., & Norris, J. 1978, ApJ, 221, 893
Gallino, R., et al. 1998, ApJ, 497, 388
Kurucz, R. 1993, CD-ROM 13, ATLAS9 Stellar Atmosphere Programs and 2 km/s Grid (Cambridge: SAO), 13
Maeder, A., & Meynet, G. 2006, A&A, 448, L37
Norris, J. E., & Da Costa, G. S. 1995, ApJ, 447, 680
Norris, J. E., 2004, ApJ, 612, L25
Norris, J. E., Freeman, K. C., & Mighell, K. J. 1996, ApJ, 462, 241
Persson, S. E., et al. 1980, ApJ, 235, 452
Smith, V. V., Cunha, K., & Lambert, D. 1995, AJ, 110, 2827
Sollima, A., et al. 2005, MNRAS, 357, 265
Stanford, L. M., et al. 2006, ApJ, 653, L117
Stanford, L. M., Da Costa, G. S., & Norris, J. E. 2007, ApJ, 667, 911
Stanford, L. M., Da Costa, G. S., & Norris, J. E. 2010, ApJ, 714, 1001
Ventura, P., D'Antona, F., & Mazzitelli, I. 2002, A&A, 393, 215
Woolley, R. v. d. R. 1996, R. Obs. Ann., No 2