ABSTRACT

In this Letter, the results of our low-resolution spectroscopic survey for identifying hydrogen-deficient stars in the red giant sample of the globular cluster ω Cen are reported. Spectral analyses were carried out on the basis of the strengths of the (0, 0) MgH band and the Mg b triplet. In our sample, four giants were identified with weak/absent MgH bands in their observed spectra, which was unexpected for their well determined stellar parameters. The Mg abundances for the program stars were determined from the subordinate lines of the MgH band to the blue of the Mg b triplet, using the spectral synthesis technique. The derived Mg abundances for the program stars were as expected for the red giants of ω Cen, except for the four identified candidates. The determined Mg abundances of these four candidates are much lower than that expected for the red giants of ω Cen, and are unacceptable based on the strengths of the Mg b triplet in their observed spectra. Hence, a plausible explanation for the weak/absent MgH bands in the observed spectra of these stars is a relatively lower abundance of hydrogen in their atmospheres. These giants may belong to the group of helium-enriched red giants of ω Cen.

Key words: globular clusters: general – globular clusters: individual (Omega Centauri) – stars: chemically peculiar

Online-only material: color figures

1. INTRODUCTION

A rare group of hydrogen-deficient (H-deficient) and carbon-rich supergiants in the order of their increasing effective temperatures are H-deficient carbon (HdC) stars, R Coronae Borealis (RCB) stars, and extreme helium stars (Hema et al. 2012; Pandey et al. 2006). The origins and evolution of these peculiar stars is not yet clear.

The distances are not accurately known to any of the Galactic H-deficient stars. The position of a star on the H-R diagram gives us an idea about its evolution and possibly its origin. To place these stars on the H-R diagram, a survey was conducted to identify new H-deficient stars in the most massive and brightest Galactic globular cluster (GGC): ω Centaurs.

The observed large spread in the metallicity ([Fe/H]) and the other abundance anomalies of ω Cen cluster stars (Johnson & Pilachowski 2010; Marino et al. 2011; Simpson & Cottrell 2013; Sollima et al. 2005), including the existence of multiple stellar populations, the He-normal and He-enhanced or H-poor (Bedin et al. 2004; Piotto et al. 2005), makes it an enigmatic GGC.

The recent spectroscopic studies of Dupree & Avrett (2013) and Marino et al. (2014) confirm the existence of the He-enhanced stars in ω Cen and NGC 2808, respectively. Hence, our survey also explores the H deficiency or the He-enhancement in the sample giants of ω Cen.

2. SAMPLE SELECTION AND OBSERVATIONS

Our survey is based on the Strömgren photometric studies of red giant stars in ω Cen by Calamida et al. (2009). Stars in the GGCs are expected to be homogeneous in metallicities ([Fe/H]). However, there are a few GGCs that show a large dispersion in their metallicities. One of them is the GGC ω Cen, with a range in [Fe/H]: −2.5 < [Fe/H] < +0.5 (Johnson & Pilachowski 2010, and references therein). This spread in metallicity, which is not expected for a GGC, is possibly an indication of the presence of H-deficient stars in ω Cen. Note that the metal lines are much stronger in the spectra of the H-deficient supergiants: the RCB and the HdC stars, when compared with those observed in the spectra of F- and G-type normal supergiants. This is attributed to the lower opacity in the atmosphere due to H deficiency. Hence, H-deficient stars appear more metal-rich than they actually are (Sumangala Rao et al. 2011). Our suspicion was that the metal-rich giants of ω Cen may possibly be H-poor. In this survey, priority was given to the giants in the metallicity range: +0.5 > [Fe/H] > −0.5. However, for the sake of completeness, irrespective of metallicity, all giants brighter than 14.5 y magnitude (Strömgren visual) were considered for our study. The other criterion that was applied to increase the probability of finding H-deficient stars in our sample was the (J − H)0 and (H − K)0 colors (IR-colors). The RCB and the HdC stars’ distributions in the IR-color plot is distinct from normal dwarfs and giants (Feast 1997; Tisserand et al. 2009). The J, H, and K magnitudes and the corresponding Galactic dust reddening for extinction correction were adopted from the Two Micron All Sky Survey Catalogue1 and the NASA/IPAC Infrared Science Archive,2 respectively.

Note that all the metal-rich giants (+0.5 > [Fe/H] > −0.5) were selected for observations, irrespective of their IR-colors, and totaled 130 in number. However, the metal-poor giants (−0.5 > [Fe/H] > −2.5) selected for observations, with IR-colors like RCB stars, were 40 in number. Though the sample of red giants from the core of ω Cen were not included in our sample (to avoid confusion in identifying the giants in the crowded field), many of the giants in the periphery were double or multiple objects. The giants that were not clearly resolved were excluded from our observations. Hence, only 34 of the 130 metal-rich stars and about 11 of the 40 metal-poor stars were selected for observations.

Low-resolution optical spectra for these selected red giants of ω Cen were obtained from the 2.34 m Vainu Bappu

1 http://irsa.ipac.caltech.edu/Missions/2mass.html
2 http://irsa.ipac.caltech.edu/applications/DUST1/
Telescope (VBT), the Vainu Bappu Observatory, equipped with the Optomechanics Research spectrograph (Prabhu et al. 1998) and the 1 K × 1 K CCD camera. These spectra obtained using 600 l mm$^{-1}$ grating centered at the H$\alpha$ line at 6563 Å were at a resolution of about 8 Å. The data reduction and analyses were carried out using the IRAF$^3$ software package.

3. ANALYSES AND RESULTS

The observed spectra of all the program stars were continuum normalized. The region of the spectrum (having maximum flux) free of absorption lines is treated as the continuum point, and a smooth curve passing through these points is defined as the continuum. The well defined continuum in the spectrum of the sample metal-poor giant, and in the spectrum of Arcturus with very high signal-to-noise ratio (S/N), is used as a reference for judging the continuum for the sample metal-rich stars in the wavelength window 4900–5400 Å, including the Mg$\beta$ triplet and the complete MgH band. The analyses of the observed spectra of the program stars were carried out based on the strengths of the blue degraded (0, 0) MgH band extending from 5330 to 4950 Å, with the band head at 5211 Å, and the Mg$\beta$ lines at 5167.32 Å, 5172.68 Å, and 5183.60 Å. Based on the strengths of these features in the observed spectra, three groups were identified in our sample: (1) the metal-rich giants with strong Mg$\beta$ lines and the MgH band, (2) the metal-poor giants with weak Mg$\beta$ lines and no MgH band, and (3) the metal-rich giants with strong Mg$\beta$ lines, but no MgH band. To analyze the strengths of the MgH band in the observed spectra of sample stars, the stars with similar ($J$ − $K$)$_0$ colors ($\Delta(J − K)_0$ $\sim ±0.1$), and $y$ magnitudes ($\Delta y$ $\sim ±0.5$) that represent the effective temperatures ($T_{\text{eff}}$) and surface gravities (log $g$), respectively, were selected. The spectra of stars having similar $y$ magnitude and ($J$ − $K$)$_0$ colors were then compared with each other. From this comparison, four stars were identified having a weaker or absent MgH band than expected. Two stars, 178243 and 73170, are from the first group showing the strong Mg$\beta$ lines, but a weaker MgH band than expected for their stellar parameters (see Figure 1). The other two stars, 262788 and 193804, are from the third group showing relatively strong Mg$\beta$ lines, but an absent MgH band which was unexpected for their stellar parameters$^4$ (see Figure 2). Judging by the observed strengths of the Mg$\beta$ lines and the presence/absence of the MgH band expected for their stellar parameters, the spectra of the giants 178243, 73170, 262788, and 193804 suggest that their atmospheres are relatively H-poor. Hence, to confirm this suggestion, the observed strengths of the MgH bands were further analyzed by synthesizing the spectra of these four stars along with the program stars of the first, second, and third groups for their adopted stellar parameters. Note that observed spectra with S/N > 60 were analyzed.

$^3$ The IRAF software is distributed by the National Optical Astronomy Observatory under contract with the National Science Foundation.

$^4$ Note that the contribution of the MgH lines to the Mg$\beta$ line strength makes the latter appear stronger in the first group than in the third group.
The spectra were synthesized from 5100–5200 Å which includes the Mg b lines and the (0, 0) MgH band. For synthesizing the spectra, the atomic lines were compiled from the standard atomic data sources, and all of the atomic lines identified by Hinkle et al. (2000) were included. The (0, 0) MgH molecular line list was adopted from Hinkle et al. (2013). Synthetic spectra were generated by combining the LTE spectral line analysis/synthesis code MOOG (Sneden 1973), and the ATLAS9 (Kurucz 1998) plane parallel, line-blanketed LTE model atmospheres with convective overshoot. Spectrum of Arcturus, a typical red giant, was synthesized to validate the adopted line list for the adopted stellar parameters of Arcturus. Hence, the spectra of the program stars were synthesized following the above procedure. The synthesized spectra, for their adopted stellar parameters and abundances, were then compared with the observed spectra. From the studies of Norris & Da Costa (1995), the average [Mg/Fe] for the red giants of ω Cen is about +0.4 dex over a metallicity range: [Fe/H] = −2.0 to −0.7. Hence, in our synthesis the [Mg/Fe] = +0.4 dex was initially adopted. Since the subordinate lines of the MgH band at about 5167 Å are blended with the saturated Mg b lines, the subordinate lines of the MgH band in the wavelength window 5120–5160 Å were given more weight in our synthesis. The best fit of the spectrum synthesized for the adopted stellar parameters to the observed was obtained by adjusting the Mg abundance, and therefore estimating the Mg abundance6 for the program star (see Figure 3, for example). Note that the derived Mg abundances are in excellent agreement with the two common stars in the Norris & Da Costa (1995) study. The adopted stellar parameters and the derived Mg abundances for the program stars (first, second, and third groups) are given in Table 1. For all the normal first and third group stars, our derived Mg abundances (mean [Mg/Fe] ∼+0.3 dex) for their adopted stellar parameters were as expected for the red giants of ω Cen, with just four exceptions. These four exceptions are 73170 and 178243 from the first group and 262788 and 193804 from the third group, which were identified with the weak/absent MgH bands in their observed spectra. The Mg abundances derived for these four giants are much lower than that expected (for details, see Hema 2014).

4. DISCUSSION

The two stars of the first group with strong Mg b lines and a weaker MgH band are 73170 and 178243. The MgH subordinate lines to the redward and blueward of the Mg b lines are clearly weaker in the observed spectra of 73170 and 178243 when compared with the spectra of stars with similar stellar parameters. Figure 1 shows the spectra of the first group stars in increasing order of $T_{\text{eff}}$ from bottom to top. This comparison clearly shows that the weaker MgH bands in the spectra of these two stars are not as expected for their adopted stellar parameters. If the weaker MgH band is not due to the star’s $T_{\text{eff}}$, log $g$, and [Fe/H], then the reason would be a lower Mg abundance. These stars are metal-rich with strong Mg b lines in their observed spectra, indicating that the Mg abundance in their atmospheres is as expected for their metallicities. Hence, neither the stellar parameters nor the Mg abundance

5. $\log (Mg) = \log (Mg/H) + 12.0$, this convention is used throughout this study.

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abundances are possible reasons for the weaker MgH bands observed in these stars. The only possible reason for the weaker MgH bands would be a lower hydrogen abundance in their atmospheres.

For the derived Mg abundance of 73170, the [Mg/Fe] is about −0.2. This value is about +0.6 dex lower than the average, and about +0.4 dex lower than the minimum [Mg/Fe], derived for the ω Cen giants at the star’s metallicity of [Fe/H] = −0.65, as reported by Norris & Da Costa (1995). For the derived Mg abundance of 178243, the [Mg/Fe] is about −0.4. This value is about +0.8 dex lower than the average, and about +0.6 dex lower than the minimum [Mg/Fe] derived for the red giants of ω Cen at the star’s metallicity of [Fe/H] = −0.8 (Norris & Da Costa 1995). Nevertheless, going by the observed strengths of the Mg b lines and the expected Mg abundance for the stars’ metallicity, our derived low Mg abundances for these two stars are unacceptable. Hence, we emphasize that the weaker MgH bands in these two stars are not due to the stellar parameters and the Mg abundances, but most likely due to a relatively lower abundance of hydrogen in their atmospheres. The typical errors of about ±100 K on Teff, determined from the high-resolution spectroscopic studies of red giants, were adopted. Note that the syntheses of the MgH bands for the upper limit of the Teff for these two stars do not provide a fit to the observed spectrum (see Figure 3, for example).

Figure 3. Observed spectrum and the synthesized spectra for the star 178243. The spectrum synthesized for the best-fit value of [Mg/Fe] and for different Teff for the expected [Mg/Fe] of ω Cen red giants are shown in the figure—see the key on the figure.

(A color version of this figure is available in the online journal.)

Table 1

| Star  | Star (LEID)a | S/N | Teff  | log g | [Fe/H] | Group | log ε(Mg) | [Mg/Fe] |
|-------|-------------|-----|-------|-------|--------|-------|-----------|---------|
| 269309| ···          | 70  | 3760  | 0.90  | −0.5   | First | 7.1 ±0.2  | 0.0     |
| 73170 | 39048       | 100 | 3965  | 0.95  | −0.65  | First | 6.75 ±0.2 | −0.2    |
| 178243| 60073       | 100 | 3985  | 0.75  | −0.8   | First | 6.4 ±0.2  | −0.4    |
| 172980b| 61067     | 110 | 4035  | 0.85  | −1.0   | First | 7.0 ±0.2  | +0.4    |
| 178691| 50193       | 110 | 4075  | 0.65  | −1.2   | First | 6.6 ±0.2  | +0.2    |
| 271054| ···          | 100 | 4100  | 1.40  | −1.0   | First | 6.7 ±0.2  | +0.1    |
| 40867 | 54022       | 110 | 4135  | 1.15  | −0.5   | First | 7.2 ±0.2  | +0.1    |
| 250000| ···          | 90  | 4175  | 1.40  | −1.0   | First | 6.9 ±0.2  | +0.3    |
| 131105| 51074       | 80  | 4180  | 1.05  | −1.1   | First | 6.9 ±0.2  | +0.4    |
| 166240b| 55101     | 60  | 4240  | 1.15  | −1.0   | First | 6.8 ±0.2  | +0.2    |
| 262788| 34225       | 110 | 4265  | 1.30  | −1.0   | Third | <6.0 ±0.2 | <−0.6   |
| 251701| 32169       | 100 | 4285  | 1.35  | −1.0   | First | 7.0 ±0.2  | +0.4    |
| 193804| 35201       | 80  | 4335  | 1.10  | −1.0   | Third | <6.5 ±0.2 | <−0.1   |
| 5001638| 150       | 150 | 4400  | 1.6   | −0.5   | First | 7.3 ±0.2  | +0.2    |
| 270931| ···          | 100 | 4420  | 1.25  | −0.5   | First | 7.2 ±0.2  | +0.1    |
| 214247| 37275       | 60  | 4430  | 1.45  | −1.5   | Third | 6.5 ±0.2  | +0.4    |
| 216815| 43475       | 80  | 4500  | 1.85  | −0.6   | First | 7.3 ±0.2  | +0.3    |
| 14943 | 53012       | 100 | 4605  | 1.35  | −1.8   | Second| <6.7 ±0.2 | <+0.9   |

Notes.

a Stellar parameters are from Johnson & Pilachowski (2010) for the giants with LEID identification.

b Common stars with the sample of Norris & Da Costa (1995). Norris & Da Costa report [Mg/Fe] of 0.53 and 0.27 for 172980 and 166240, respectively.
The strong Mg b lines in the spectra of 262788 and 193804 clearly indicate that the Mg abundance is normal or as expected for the stars’ metallicity. Hence, the stellar parameters and the lower Mg abundances are ruled out as possible reasons for the absence of the MgH band in the spectra of these twins. The only possibility could be a relatively lower abundance of hydrogen in their atmospheres.

For 262788, the derived [Mg/Fe] < −0.6. This is about +1.0 dex lower than the average, or about +0.8 dex lower than the minimum [Mg/Fe] value as derived by Norris & Da Costa (1995) for the star’s metallicity, [Fe/H] = −1.0. For 193804, the derived [Mg/Fe] < −0.1. This value is about +0.5 dex lower than the average, or about +0.3 dex lower than the minimum [Mg/Fe] value, as reported by Norris & Da Costa (1995), for the star’s metallicity [Fe/H] = −1.0. Hence, going by the observed strengths of the Mg b lines and the expected Mg abundance for the stars’ metallicity, our derived low Mg abundances for these two stars are unacceptable. This rules out the effects of stellar parameters and the lower Mg abundances as possible reasons for the absence of the MgH band in the observed spectra of 262788 and 193804. The only possible reason for the absence of the MgH band could be a relatively lower abundance of hydrogen in their atmospheres. The spectra synthesized for the upper limit of the T_{\text{eff}} for the stars 262788 and 193804 do not provide a fit to the observed spectra. The observed weak/absent MgH band in 214247, of the third group, is as expected for the star’s warmer T_{\text{eff}} and metallicity. The derived Mg abundance is as expected for the star’s metallicity.

The weak/absent MgH band in the observed spectra of these four giants despite the presence of strong Mg b lines may not be due to the uncertainty in the adopted stellar parameters or a lower Mg abundance. The only plausible reason is a relatively lower abundance of hydrogen in their atmospheres. Hence, we report the discovery of four giants with relatively lower abundances of hydrogen in their atmospheres. These giants may belong to the group of helium-enriched (n_{He}/n_{H} \sim 0.16–0.2) red giants of ω Cen, similar to those found in the studies of Dupree et al. (2011), for which the blue main sequence (bMS) stars may be the progenitors. The double main sequence, the red main sequence (rMS) and the bMS, in ω Cen was discovered by Anderson (1997). The bMS stars differ from rMS stars by their helium enrichment up to Y \sim 0.38 with the range 0.35 < Y < 0.45 (Norris 2004; Piotto et al. 2005). The Y value for rMS stars is about 0.25 (Norris 2004; Piotto et al. 2005). From the studies of Marino et al. (2011), unlike the observed Na–O anticorrelation for the metal-poor giants of ω Cen, the number of giants with Na-enrichment increases with the metallicity ([Fe/H]). Note that 11 stars of our metal-rich sample, including the 4 reported H-poor or He-rich stars, show Na-enhancement (Marino et al. 2011; Johnson & Pilachowski 2010). One star, however, is Na-normal. For rest of our metal-rich sample of five stars, Na abundances are not available. However, no obvious trend is seen in Al–Mg, as the Al–Mg anticorrelation provides a further clue for the He-enrichment in the metal-rich giants (D’Ercole et al. 2010).

None of these newly discovered H-deficient giants show the carbon features as seen in the spectra of RCB stars and they do not exhibit RCB IR-colors. Hence, these are not the H-deficient stars of RCB-type. To ascertain a range in H-deficiency or the helium enrichment of these newly discovered giants and the analyzed metal-rich sample, it is essential to study these stars by obtaining their high-resolution spectra.

We thank the referee for a constructive report. We thank David L. Lambert, H. C. Bhatt, B. E. Reddy, and S. Giridhar for fruitful discussions. We thank the VBO staff for assistance.

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7 Note that the expected n_{He}/n_{H} ratio and Y for the normal giants are about 0.1 and 0.25, respectively.