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Measuring Hydrogen-to-Helium Ratio in Cool Stars

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Abstract

Conventionally, the helium-to-hydrogen ratio for the stars are adopted to be 0.1, as standard, unless, the stars are severely deficient in hydrogen like in RCB-class, or the stars' helium abundance is accurately measured using He I transitions in warm/hotter stars. In our study, the small change in helium-to-hydrogen ratio (from standard value, 0.1) in normal giants were detected from the large difference (> 0.3 dex) in the Mg-abundance measured from Mg I lines and the subordinate lines of (0,0) MgH band. These are the stars that are mildly hydrogen-deficient/He-enhanced. Such stars were spectroscopically discovered for the first time among giants of the globular cluster ω Centauri. The sample selection, observations, methodoloy and results are discussed in detail.

Keywords: Stars: Giants, Chemical abundance, Chemically peculiar

1. Introduction

The universe is vast and mysterious that it always unfolds itself to new, unseen and unknown things hidden in it. The stars that are studied are all abundant in hydrogen, except for a handful of stars that are severely deficient in hydrogen (Asplund et al., 2000; Lambert and Rao, 1994; Hema et al., 2012a,b, 2017; Pandey, 2006; Pandey et al., 2008; Clayton et al., 2005). We conducted a survey for exploring the hydrogen abundance in giants of the massive and brightest Galactic globular cluster (GGC) ω Centauri of our Galaxy, the Milky Way.

The observed large spread in the metallicity ([Fe/H]) and the other abundance anomalies of ω Cen cluster stars (Johnson and Pilachowski, 2010; Marino et al., 2011; Simpson and 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 and 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, but spectroscopically. The observations, methodology, the results and discussions are explained in the following sections.

Table 1: The stellar parameters, metallicities and derived Mg abundances for the program stars in the order of their increasing $T_{\rm eff}$. The stars in italics are the relatively H-poor/He-enhanced.

Star	Star (LEID)	S/N	$T_{\rm eff}$	$\log g$	[Fe/H]	Group	$\log \varepsilon$(Mg)	[Mg/Fe]	He/H
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	0.20
178243	60073	100	3985	0.75	−0.8	First	6.4±0.2	−0.4	...
172980	61067	110	4035	0.85	−1.0	First	7.0±0.2	+0.4	0.1
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	...
166240	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	0.15
251701	32169	100	4285	1.35	−1.0	First	7.0±0.2	+0.4	0.1
193804	35201	80	4335	1.10	−1.0	Third	<6.5±0.2	<−0.1	...
5001638	...	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	...

2. Sample Stars and Observations

In order to investigate this large spread in the metallicity of ω Cen, a survey was conducted among the brightest giants of the cluster. We suspected that, due to different hydrogen-to-helium ratio in these stars, the metallicities appear different. Hence, we selected the brightest giants of different metallicities for our survey.

Note that all the metal-rich giants ($+0.5 >$ [Fe/H] > -0.5 dex) 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 dex) 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. These program stars (11 in number) analyzed for investigating their He-enhancement with their low-resolution spectra are given in Table 1.

Low-resolution optical spectra for these selected red giants of ω Cen were obtained from the 2.34 m Vainu Bappu Telescope (VBT), the Vainu Bappu Observatory, equipped with the

Optomechanics Research spectrograph (Prabhu et al., 1998) and the 1K × 1K CCD camera. These spectra obtained using 600 l mm^{-1} grating centered at the Hα line at 6563 Å, were at a resolution of about 8 Å.

From the low-resolution studies, about four He-enhanced stars were discovered. Out of these, two He-enhanced stars along with their normal comparison stars were analyzed by obtaining the high-resolution spectra. These four stars that are analyzed with their high-resolution spectra are given in italics in Table 1. The high-resolution optical spectra were obtained using the Southern African Large Telescope (SALT) high-resolution spectrograph (HRS). These spectra obtained with SALT–HRS have a resolving power R $(\lambda/\Delta\lambda)$ of 40,000. The spectra were obtained with both blue and red cameras using 2K × 4K and 4K × 4K CCDs, respectively, spanning a spectral range of 370–550 nm in the blue and 550–890 nm in the red. The data reduction and analyses were carried out using the IRAF software package.

3. Methodology 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 *b* 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 *b* 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 *b* lines and the MgH band, (2) the metal-poor giants with weak Mg *b* lines and no MgH band, and (3) the metal-rich giants with strong Mg *b* lines, but no MgH band (see Fig. 1). To analyze the strengths of the MgH band in the observed spectra of sample stars, the stars with similar $(J-K)_0$ colors ($\Delta(J-K)_0 \sim \pm 0.1$), and y magnitudes ($\Delta y \sim \pm 0.5$) that represent the effective temperatures (T_{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 *b* lines, but a weaker MgH band than expected for their stellar parameters (see Fig. 1 of Hema and Pandey (2014)). For all the program stars listed in Table 1, the stellar parameters and the metallicities derived from the high-resolution spectra were adopted from Johnson and Pilachowski (2010).

The other two stars, 262788 and 193804, are from the third group showing relatively strong Mg *b* lines, but an absent MgH band which was unexpected for their stellar parameters. Judging by the observed strengths of the Mg *b* lines and the presence/absence of the MgH band expected for their stellar parameters, the spectra of the giants 178243, 73170, 262788, and

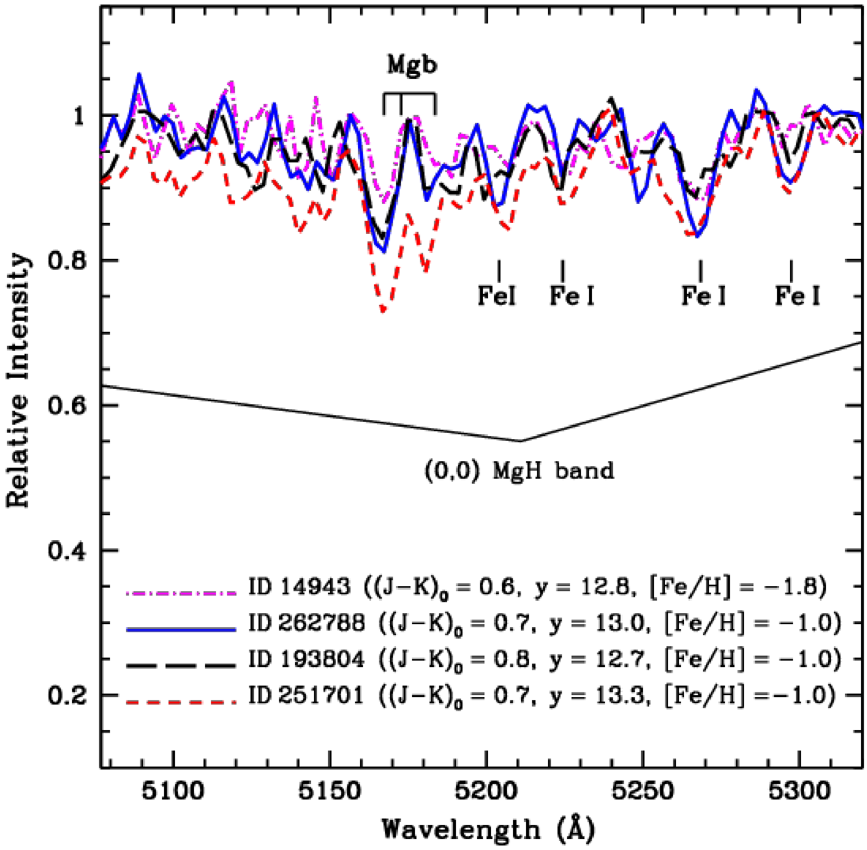

Figure 1: The observed spectrum of 262788 (in thick blue line) and 193804 (in black long dashed line), the third group stars, compared with the observed spectrum of 251701 (in red dashed line), the first group star. Also shown is the observed spectrum of 14943 (in magenta dash dotted line), the second group star. These stars have similar $(J-K)_0$ colour and y magnitudes. The key features such as Mg *b* lines, the MgH band and the Fe I lines are marked. The [Fe/H] values are from Johnson and Pilachowski (2010).

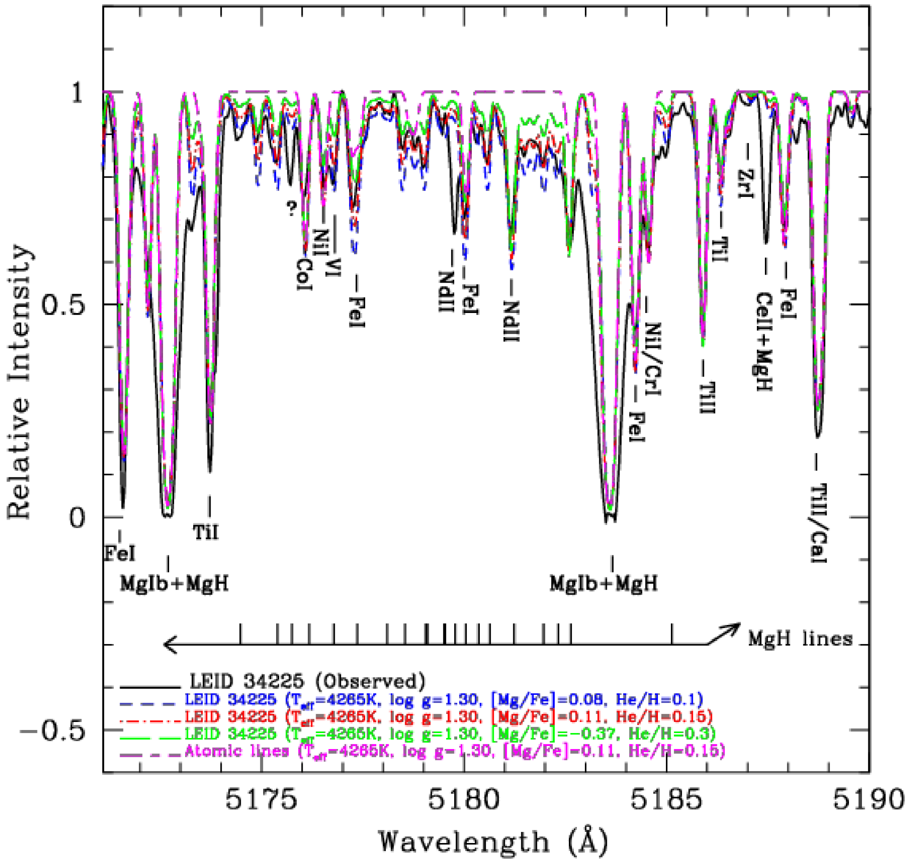

Figure 2: Observed and the synthesized MgH bands for LEID 34225 are shown. The spectra synthesized for the Mg abundance derived from the Mg I lines and the best-fit value of the He/H ratio are shown by the red dashed-dotted line. The synthesis for the two values of He/H are also shown.

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.

From the studies of Norris and 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 dex. 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 abundance for one of the program stars LEID 34225 (see Fig. 2, for example). Note that the derived Mg abundances are in excellent agreement with the two common stars in the Norris and 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] $\sim$ +0.3 dex) for their adopted stellar parameters were

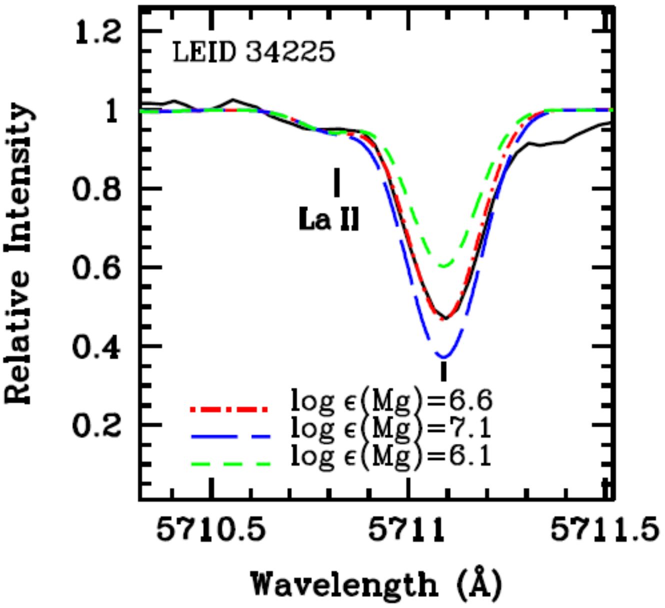

Figure 3: The Mg abundance derived from the $\lambda\lambda$5711 Å Mg I lines for the program stars. The best fit synthesis is shown with the red-dash dotted line.

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 (see Table 1).

The high-resolution optical spectra obtained from SALT, South African Astronomical Observatory (SAAO) were obtained for two of the four metal-rich, mildly hydrogen-poor or helium-enhanced giants, LEID 39048 (73170) and LEID 34225 (262788), along with their comparison normal (hydrogen-rich) giants, LEID 61067 (172980) and LEID 32169 (251701). The stellar parameters and the elemental abundances for the program stars were derived from the equivalent widths measured from these high-resolution spectra. The strengths of the MgH bands in the spectra of these program stars were analyzed with these derived stellar parameters. The observed spectra of the sample (hydrogen-poor) stars (LEID 39048 and LEID 34225) show weaker MgH bands, unlike in the spectra of the normal comparison giants (LEID 61067 and LEID 32169), as observed in the low-resolution spectral studies (Hema and Pandey, 2014). The accurate Mg abundances were derived from the weaker atomic Mg I lines (see Fig. 3). Note that the Mg *b* lines are very strong and are saturated in the spectra of our program stars, and hence these lines are not used for estimating the Mg abundance from the Mg I line or MgH band. And, the Mg abundance from the MgH band is derived using the clean subordinate lines of the MgH molecular band that are not blended with the strong Mg *b* lines. The spectra of the program stars were synthesized using their derived stellar parameters and the elemental abundances as discussed in Section 3 of Hema et al. (2018).

Uncertainty on the $T_{\rm eff}$ and ξ_t is estimated by changing the $T_{\rm eff}$ in steps of 25 K and ξ_t in steps of 0.05 km s^{-1}. The changes in $T_{\rm eff}$ and ξ_t and the corresponding deviations in abundance, from the zero slope abundance, of about $1\,\sigma$ error, is obtained. This change is adopted as the uncertainty on these parameters. The adopted $\Delta T_{\rm eff} = \pm 50$ K and $\Delta \xi_t = \pm 0.1\,{\rm km\,s^{-1}}$ (see Fig. 2 of Hema et al. (2018)). The uncertainty on $\log g$ is the standard deviation from the mean value of the $\log g$ determined from different species, which is about ± 0.1 (cgs units). The rms error due to these parameters along with the standard deviation in the abundances due to line-to-line scatter is the uncertainty adopted for the metallicity and Mg abundance from Mg I and MgH band (please see Table 5 of Hema et al. (2018).

For the first group stars the best fit synthesis for the MgH bands were obtained for the Mg abundance derived from the Mg I lines within the uncertainties. But for the third group stars, LEID 39048 and LEID 34225, the Mg abundance for the best fit synthesis of MgH bands requires about 0.4 dex less Mg abundance than that derived from the Mg I lines. This is perfectly in line with our studies Hema and Pandey (2014). Further, the ATLAS12 opacity-sampling stellar model atmospheres that were iterated and generated for different He/H ratios were used Kurucz (2014) to conduct the detailed abundance analysis, and also to retaliate the difference in Mg abundance from Mg I and MgH lines by changing the He/H ratios (Hema et al., 2020). For the program stars, LEID 39048 and LEID 34225, the derived He/H ratio is about 0.2 and 0.15, respectively. For the detailed results of abundance analysis for the corresponding He/H ratios, please see Hema et al. (2020).

4. Discussion

Since, hydrogen and helium are the most abundant elements in the stars' atmospheres, it is almost impossible to measure their accurate abundances. Only in the hotter stars, where helium transitions are seen, the helium abundance can be estimated. But, in cool stars, there are no direct measurements of helium. For Sun, the helium is estimated by sampling the solar wind. Primordial He-abundance and that from local H II regions and B-type stars set the floor/ceiling for He-abundance. Measurements of He/H ratio in cool stars are essential to derive accurate elemental abundances including the He-abundance. For cool stars, elemental abundances are derived by adopting a "standard" He/H ratio of 0.1.

By Sumangala Rao et al. (2011), an LTE abundance analysis conducted for SAO 40039, a warm post-AGB star whose spectrum is known to show surprisingly strong He I lines for its effective temperature. On the assumption that the He I lines are of photospheric and not chromospheric origin, a He/H ratio of approximately unity was found by imposing the condition that the adopted He/H ratio of the model atmosphere must equal the ratio derived from the observed He I triplet lines at 5876, 4471 and 4713 Å, and singlet lines at 4922 and 5015 Å.

There are stars that are severely deficient in hydrogen which are called the R Coronae Borealis stars, with the related groups the extreme helium (EHe) stars and the hydrogen-deficient carbon (HdC) stars. These stars are having very weak/absent hydrogen-Balmer lines or the presence of He lines in hotter EHe stars. Hence, the helium abundance could be measured from these hot EHe stars.

But for cooler stars, where neither the He lines could be seen nor the small changes in hydrogen abundance could be measured from the hydrogen-Balmer lines as these are very strong and saturated.

Hence, the method of using Mg I lines and the MgH molecular band for measuring even smallest change in the He-abundance in the spectrum of cool stars is a very useful and robust method. For the respective He/H ratios of the He-enhanced stars, the elemental abundances are also affected. Please see discussion of Hema et al. (2018, 2020). Our study Hema and Pandey (2014); Hema et al. (2018, 2020) in the giants of ω Cen is the first ever spectroscopic confirmation of He-enhancement. The abundance analysis conducted by deriving the actual He/H ratio, not only provide the solutions to abundance anomalies observed in stars of the globular cluster but also for the peculiar stars of the Galactic field. Many normal stars are studied with the assumption of standard He/H ratio of 0.1, which may not be the actual value. Hence, more and more studies for deriving the actual He/H ratio and in different stellar groups are much needed to address the He-enhancement, the abundance anomalies and the peculiarities, to understand their origin and evolution.

5. Conclusion

The low-resolution spectroscopic survey conducted by Hema and Pandey (2014) resulted in the discovery of four mild H-deficient/He-enhanced giants in the Galactic globular cluster ω Cen. For two out of four giants along with their comparison stars the high-resolution spectra were obtained from the SALT. Using their high-resolution spectra and the ATLAS12 model atmospheres iterated for different He/H ratios, the detailed abundance analysis were carried out (Hema et al., 2018). Deriving the accurate Mg abundances, the MgH bands were synthesized with model atmospheres with different He/H ratios. For the two He-enhanced giants: LEID 39048 and LEID 34225, the same Mg abundances from Mg I and MgH bands were obtained for the He/H ratios of 0.2 and 0.15, respectively (Hema et al., 2020). And, the comparison stars, the derived He/H ratios were 0.1, as expected. This is the first ever spectroscopic confirmation for the presence of He-enhanced giants in ω Cen. The approach of identifying the He-enhanced stars with the difference in Mg abundance from Mg I and MgH band is very novel and robust method. Our studies bridges the evolutionary track of the metal-rich, He-rich population of ω Cen.

And it is also essential to explore the origin/processes responsible for the He-enhancement. As said, "In light of the impossibility of direct detection of He-lines in photospheric spectra of cool stars, one is led to wonder if mildly He-rich cool stars exist, how they might be detected, and how they might arise (diffusion, internal nucleosynthesis and mixing, binary interactions, etc?)" by Lambert (1996).

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Further Information

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Author contributions

This work is part of a collective effort with contributions from all the co-authors.

Conflicts of interest

The authors declare no conflict of interest.

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