Spectroscopic abundance analyses of the ³He stars HD 185330 and 3 Cen A

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Abstract

Abundances of 21 elements in two 3 He stars HD 185330 and 3 Cen A have been analysed relative to the well studied sharp-lined B3 V star ι Her. Six elements (P, Ti, Mn, Fe, Ni, and Br) are over-abundant in these two peculiar stars, while six elements (C, O, Mg, Al, S, and Cl) are under-abundant. Absorption lines of the two rarely observed heavy elements Br II and Kr II are detected in both stars and these elements are both over-abundant. The centroid wavelengths of the Ca II infrared triplet lines in these stars are red-shifted relative to those lines in ι Her and the presence of heavy isotopes of Ca (mass number 44 - 46) in these two stars are confirmed. In spite of these similarities, there are several remarkable differences in the abundance pattern between these two stars. N is under-abundant in HD 185330, as in many Hg-Mn stars, while it is significantly over-abundant in 3 Cen A. P and Ga are both over-abundant in 3 Cen A, while only P is over-abundant and no trace of absorption line of Ga II can be found in HD 185330. Large over-abundances of Kr and Xe are found in both stars, while the abundance ratios Kr / Xe are significantly different between them (– 1.4 dex in HD 185330 and +1.2 dex in 3 Cen A). Some physical explanations are needed to account for these qualitative differences.

Key words: Stars: abundance — Stars: atmosphere — Stars: individual : HD 185330, 3 Cen A, and ι Her

1 Introduction

³He stars, which show abnormally strong absorption components caused by the lighter isotope of helium (3 He), belong to a small group of chemically peculiar B-type (Bp) stars. These stars are also included in the group of He-weak stars. Sargent and Jugaku (1961) discovered the first member of the group 3 Cen A (HD 120709) by measuring accurate wavelengths of 10 He I lines. They found a good correlation between the measured wavelength shifts and the isotope shifts for 3 He. The second star ι Ori B was discovered by Dworetsky (1973).

Hartoog and Cowley (1979) searched for B stars with enhanced ³He and presented lists of eight definite ³He stars and three probable stars. They analysed profiles of He I lines and found that ³He stars have total He abundances 5 to 20 times

lower than normal B-type stars and have ${}^3\mathrm{He}$ / ${}^4\mathrm{He}$ ratios ranging between 0.47 and 2.7. They obtained the fractional ${}^3\mathrm{He}$ content (${}^3\mathrm{He}$ / (${}^3\mathrm{He}$ + ${}^4\mathrm{He}$)) in 11 stars and suggested that the fractional content of ${}^3\mathrm{He}$ appears to increase with increasing effective temperature among the ${}^3\mathrm{He}$ stars. They further noted that ${}^3\mathrm{He}$ stars occupy a narrow strip in the log $T_{\rm eff}$ - log g plane between He-strong stars (hot side) and another group of Heweak stars (cool side) which show no evidence of ${}^3\mathrm{He}$ in their spectra.

The list of Hartoog and Cowley (1979) includes HD 185330 (HR 7467) as a definite ³He star. HD 185330 is a 6-th magnitude B-type star classified as B5 II-III by Cowley (1972). Preston (1976) first recognized the star shows a red-shifted absorption component to the He I line at 6678 Å which is caused

by the lighter isotope of helium. He noted that no two stars out of the four 3 He stars known in 1976 (3 Cen A, ι Ori B, HD 185330, and β Ori B) are spectroscopically alike. He further noted that three stars except for HD 185330 are members of visual binary systems in young stellar associations.

Michaud et al. (1979) carried out detailed radiative acceleration calculations for helium in stellar envelopes of main sequence stars with effective temperatures between 10,000 and 25,000 K and concluded that the observed under-abundances of ⁴He can be explained by diffusion. They also pointed out the occurrence of ³He stars in a narrow range of effective temperature can also be explained by diffusion.

Stateva et al. (1998) carried out analyses of three He I lines (4921, 5876 and 6678 Å) for four stars (HD 58661, HD 172044, HD 185330, and 46 Aql) and confirmed the presence of 3 He in HD 185330. They obtained the isotope ratio 3 He / 4 He to be 0.96 in this star.

Bohlender (2005) analysed profiles of He I lines in 3 Cen A and HD 185330 and provided evidences for different vertical stratification profiles of 3 He and 4 He in these stars. He suggested that 4 He is generally enhanced deep in the photospheres but sharply depleted high in the atmospheres, while 3 He appears to be enhanced in a thin layer above that of 4 He. Recently, Maza et al. (2014) carried out non-LTE computations for the isotopes of 3 He and 4 He in the Hg-Mn star κ Cnc. They found that non-LTE abundances of He obtained from He I lines are lower than LTE values and He is found to be stratified in the atmosphere of κ Cnc. They showed that although the LTE analysis indicates a step-like profile of the He abundance, a gradual decrease with height is indicated by the non-LTE analysis.

Information of chemical abundances of elements heavier than helium in atmospheres of $^3{\rm He}$ stars should provide various boundary conditions in further studies of these peculiar objects. However, detailed abundance analyses of $^3{\rm He}$ stars have been published for only a few stars including 3 Cen A (Jugaku et al. 1961, Castelli et al. 1997, Adelman and Pintado 2000, and Wahlgren and Hubrig 2004) and α Scl (HD 5737) (López-García et al. 2001, Saffe and Levato 2014) . Additional analyses are needed to be carried out for other stars having different physical conditions such as the effective temperature in order to increase the number of sample stars before constructing detailed theoretical models.

In this study, we report chemical abundances of 21 elements (including upper limits of two elements) in HD 185330, together with the prototypical 3 He star 3 Cen A. Analyses have been carried out relative to the well studied sharp-lined normal B3 V star ι Her (HD 160762) (Kodaira and Scholz 1970, Peters and Aller 1970, Pintado and Adelman 1983, Golriz and Landstreet 2017) using spectral data observed with the same instrument. We confirm isotopic shifts in He I lines and detect the presence of heavy isotopes of calcium from IR Ca II

Table 1. Summary of observational data.

Object	Obs date	Exposure	Number of images			
		(sec)				
HD 185330	2005:05:19	1200	1			
	2010:12:17	240	4			
	2010:12:19	390	4			
3 Cen A	2005:05:19	300	2			
ι Her	2012:06:25	60	50			

triplet lines. A detailed comparison of their abundance patterns provides information of previously unknown qualitative differences between these two ³He stars.

2 Observational data

Spectral data of three target stars in the visible spectral range (from 3690 to 10480 Å) were obtained with the Echelle Spectro Polarimetric Device for the Observation of Stars (ESPaDOnS)¹ attached to the 3.6 m telescope of the Canada-France-Hawaii Telescope (CFHT) observatory located on the summit of Mauna Kea, Hawaii. Calibrated intensity spectral data were extracted from the ESPaDOnS archive through Canadian Astronomical Data Centre (CADC). The resolving power is R = 65000. Details of observational data used in the present study are summarized in table 1. After downloading individual spectral data, we measured apparent wavelengths of several isolated and unblended absorption lines of C II and N II, and obtained averaged shift in wavelength with respect to the laboratory scale. We converted the wavelength scale of individual spectral data into the laboratory scale. All of the available spectra are then averaged into a mean spectrum. Continuum re-fittings were carried out for each spectral order separately using high order polynomial functions. The signal-to-noise (SN) ratios measured on final products at around 6000 Å are 800, 700, and 1300 for HD 185330, 3 Cen A, and ι Her, respectively.

3 Analysis

Atmospheric parameters ($T_{\rm eff}$ and $\log g$) of HD 185330 have been estimated from uvby and β photometric data taken from Hauck and Mermilliod (1998). We use the empirical calibration of the [c1] and β method given in Nieva and Przybilla (2012) (equations (7) and (9)) and obtain $T_{\rm eff}$ = 16350 K and $\log g$ = 3.80. This temperature is slightly higher than that adopted in Takeda et al. (2010) but coincides within the expected error. We adopt parameters of ι Her given in Nieva and Przybilla (2012) ($T_{\rm eff}$ = 17500 K and $\log g$ = 3.80) and those of 3 Cen A

¹ http://www.cfht.hawaii.edu/Instruments/Spectroscopy/Espadons/

obtained by Castelli et al. (1997) ($T_{\rm eff}$ = 17500 K and log g = 3.80) .

We use ATLAS9 model atmospheres (Kurucz 1993) after interpolating to the selected atmospheric parameters of each object. Analyses of absorption lines were carried out using the WIDTH9 program, a companion to the ATLAS9. For three regions containing merged absorption lines (C II 4267, Mg II 4481 and O I 6156 - 6158), we use a profile fitting program MPFIT which was developed by Takeda (1995). The program calculates a theoretical spectrum in a small spectral region using a specified model atmosphere and a list of atomic lines, and iteratively improves the fitting with the observation by changing the relevant parameters, such as the abundances of specified elements and the macro-turbulent velocity.

Data of atomic transition probabilities (log *gf* values) were taken from the NIST database (Kramida et al. 2015) whenever available. When no data are found in the database, we use log *gf* values given in the VALD3 database (Ryabchikova et al. 2015) (Mn II, Fe III, and Ni II). We can find no data of atomic transition probabilities for two ions Ga II and Xe II in these databases and use data taken from Hubrig et al. (2014) and stellar log *gf* values given in Yüce et al. (2011), respectively. Effects of isotopic or hyperfine structures for Mn II, Ga II, and Hg II have not been taken into acount in this study.

The microturbulent velocity is defined as the non-thermal component of the local gas velocity in the spectral line formation region of the stellar atmosphere (Cowley 1996). However, the validity of this concept has been the subject of debate for decades. For instance, it has been suggested that the use of non-LTE in spectral analysis should eliminate the need for microturbulence. Nieva and Przybilla (2012) carried out extensive non-LTE analyses of high-resolution optical spectra for a sample of early B-type stars including ι Her. Through an iterative process, they have constrained the stellar parameters including the microturbulence. They find a microturbulence of 1 km s⁻¹ in ι Her. We have adopted their result of the microturbulence in ι Her in the present study. The same values of microturbulent velocities are assumed in analyses of the other two stars HD 185330 and 3 Cen A.

4 Results

4.1 Abundances

We have analyzed absorption lines of 21 elements and obtained new abundances for 19 elements and upper limits of two elements (Ga and Hg) in HD 185330. Abundances of 21 and 15 elements have been obtained in 3 Cen A and ι Her, respectively. We confirm the lighter isotope of He and heavier isotopes of Ca in the two peculiar stars. Detailed line-by-line analyses are listed in table 2 (Supplementary data: not shown in this material) . Resulting mean abundances of HD 185330 and 3 Cen A

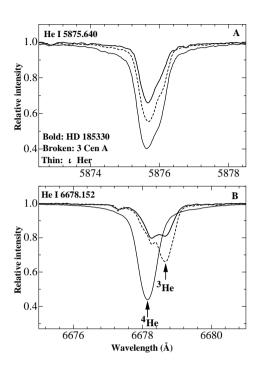
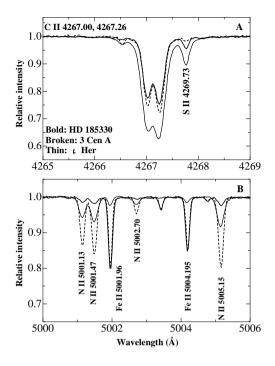


Fig. 1. Comparisons of the He I lines at 5875.64 Å (panel A) and at 6678.15 Å (panel B) for HD 185330 (bold line), 3 Cen A (broken line) and ι Her (thin line). Absorption centers of isotopes 3 He and 4 He are shown by arrows in panel B.

are given in columns 2 and 6 of table 3 and those of the reference star ι Her are given in column 10 of the table.

The main results for HD 185330 are the large overabundances of P [+ 1.9]², Mn [+ 1.0], Fe [+ 0.4], Ni [+ 0.5], Br [+ 2.3], Kr [+ 2.2], and Xe [+ 3.6], and under-abundances of C [– 0.6], N [– 0.5], Mg [– 0.5], Al [– 1.1], S [– 0.9], and Cl [– 0.5]. Upper limits of two elements (Ga and Hg) are obtained. Results of 3 Cen A are over-abundances of N [+ 0.4], P [+ 2.0], Mn [+ 1.6], Fe [+ 0.4], Ni [+ 0.5], Ga [+ 3.3], Br [+ 2.7], Kr [+ 3.3], Xe [+ 2.1] and Hg [+ 3.3] and under-abundances of C [– 0.8], O [– 0.6], Mg [– 0.5], Al [– 1.4], S [– 1.4], and Cl [– 0.7]. In ι Her, we obtained abundances of 15 elements from C to Ni and found coincidences with the solar abundance (Asplund et al. 2009) within \pm 0.3 dex, except for Fe II. We obtained a large apparent under-abundance of Fe from Fe II lines in this

 $^{^2}$ Logarithmic abundance of an element relative to the solar abundance of the element. [$N_{\rm elem}$] = log ($N_{\rm elem}$ / $N_{\rm H}$)_{star} - log ($N_{\rm elem}$ / $N_{\rm H}$)_{Sun}.



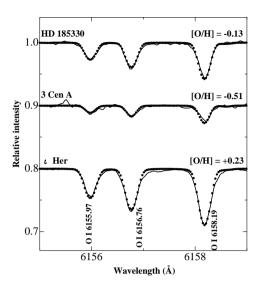


Fig. 2. Comparisons of the C $\scriptstyle\rm II$ doublet lines near 4267Å (panel A) and N $\scriptstyle\rm II$ lines near 5000 Å (panel B) in three target stars.

star.

Because the abundances found for HD 185330 and 3 Cen A are quite different from the solar abundances (Asplund et al. 2009), we computed plane parallel ATLAS12 models³ for both stars with the same atmospheric parameters. Abundances of individual elements obtained above are used in computations. Next, we tried to obtain new abundances with ATLAS12 models using the same equivalent widths and $\log gf$ values. Resulting ATLAS12 abundances for Fe II and Fe III show small apparent changes ($\sim +0.08$ dex and ~ -0.02 dex for Fe II and Fe III, respectively) from those obtained using ATLAS9 models in both stars. These changes are comparable to errors resulting from observational noise or those coming from errors in $\log gf$ values and in the adopted atmospheric parameters. Based on these experiments, we decided to adopt results obtained with ATLAS9 models in the present study.

We find several large (qualitative) differences in abundances

Fig. 3. Analyses of three O $\scriptstyle\rm I$ lines near 6157 Å in three target stars. Observed profiles (dotted line) and the best fit computed profiles (continuous line) are shown. Best fit LTE abundances of O are indicated for each star

between these two stars. N is under-abundant in HD 185330, while it is significantly over-abundant in 3 Cen A. P and Ga are both over-abundant in 3 Cen A, while only P is over-abundant but no trace of absorption line of Ga II can be found in HD 185330. We notice a large difference in the abundance ratio Kr / Xe between the two stars. No signature of the Hg II line at 3983 Å is found in HD 185330, while the Hg II line is clearly present and it is over-abundant in 3 Cen A.

Below we discuss briefly on individual elements.

He: Profiles of two He I lines at 5875.64 Å and at 6678.15 Å in three target stars HD 185330, 3 Cen A, and ι Her are compared in figures 1A (upper panel) and 1B (lower panel), respectively. The line at 6678 Å clearly shows absorption component of the lighter isotope 3 He. In 3 Cen A, the 3 He component is stronger than that of 4 He, while the 3 He component is weaker than that of 4 He in HD 185330. We have not carried out detailed analyses

³ Programs were downloaded from http://www.astro.utoronto.ca/ lester/programs.htm/l the He abundances or the isotope ratios ³He / ⁴He and refer

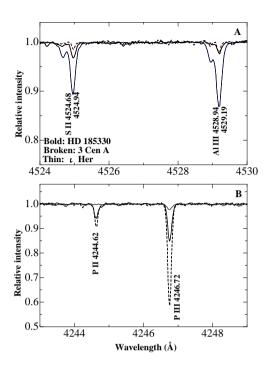


Fig. 4. Comparisons of S $\scriptstyle\rm II$ and Al $\scriptstyle\rm III$ lines (panel A) and P $\scriptstyle\rm II$ and P $\scriptstyle\rm III$ lines (panel B) in three target stars.

to works reported in Hartoog and Cowley (1979) and in Stateva et al. (1998).

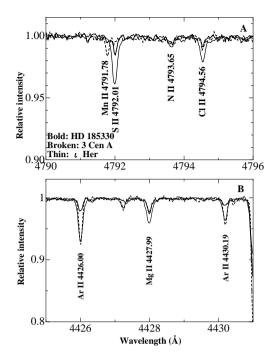
C, N and O: Observed profiles of C II lines at 4267.00 Å and at 4267.26 Å and N II lines near 5000 Å are compared in figures 2A and 2B, respectively. The C II lines in HD 185330 and in 3 Cen A are both weaker than in ι Her and we conclude that C is definitely under-abundant in both stars. On the other hand, N II lines are remarkably weaker in HD 185330 than in 3 Cen A. A difference in the abundance of N by nearly 1 dex is concluded between these two stars. Line profile analyses of the three O I lines between 6155 Å and 6159 Å are displayed in figure 3. When we apply the non-LTE corrections of ~ -0.2 dex for O I given in Takeda et al. (2010), we obtain underabundances of O in HD 185330 [-0.3] and in 3 Cen A [-0.8], and the solar abundance of O in ι Her. Wahlgren and Hubrig (2004) reported an over-abundance of O [+ 0.15] from O I and an under-abundance [-0.5] from O II lines in 3 Cen A. In these line profile analyses, we assume a rotational velocity $(v \sin i)$

of 5 km s⁻¹ in all three stars. Considering the resolving power of observational data, we conclude that rotational velocities of three target stars are equal to or smaller than $\sim 5 \text{ km s}^{-1}$. This is in agreement with the result for ι Her ($v \sin i = 6 \pm 1 \text{ km s}^{-1}$) given in Nieva and Przybilla (2012). Sigut et al. (2000) reported a very low rotational velocity ($v \sin i \le 2 \text{ km s}^{-1}$) using high resolution ($R \sim 120000$) spectral data. Bohlender (2005) obtained low rotational velocities ($v \sin i = 3 \text{ km s}^{-1}$) in both HD 185330 and in 3 Cen A. The rotational velocity of HD 185330 is lower than that ($v \sin i = 15 \text{ km s}^{-1}$) given in Abt et al. (2002).

Ne, Mq, Al and Si: Equivalent widths of 21 lines of Ne I are used to derive LTE abundances of Ne in three target stars. We obtain an apparent over-abundance of \sim [+ 0.6] in ι Her. Using non-LTE corrections given in Takeda et al. (2010) for the two Ne I lines at 6143.06 Å and 6163.59 Å for HD 185330 and ι Her, we obtain slight over-abundances of Ne [+0.4] and [+0.3]in these two stars. Abundances of Mg are obtained from five Mg II lines including the 4481 Å doublet. Our results show nearly the same under-abundances of Mg [-0.45] in both stars. Profiles of an Al III line at 4529.19 Å in three target stars are compared in figure 4A. We can see the Al III line is strikingly weak in the two peculiar stars. Abundances of Al have been derived from four Al III lines and Al is under-abundant by \sim [– 1.4] in both stars. Abundances of Si are derived from seven Si II and seven Si III lines. Si shows normal abundance [0.0] in both HD 185330 and 3 Cen A.

P: Both HD 185330 and 3 Cen A show very strong lines of P II and P III as illustrated in figures 4B and 7B. We use 33 lines of P II and four lines of P III in the abundance analyses. We obtain large over-abundances of P [+ 1.9] in HD 185330 and [+ 2.0] in 3 Cen A, from P II lines. A significantly lower abundance of P is obtained from P III lines in HD 185330. We notice large mean square errors in the resulting abundances from P II lines for both stars (around \pm 0.3 dex). Furthermore, abundances of P obtained from P II lines show apparent dependences on equivalent widths in both HD 185330 and 3 Cen A. We tried to reduce the dependence by changing the value of the microturbulent velocity from 1 km s⁻¹ to 5 km s⁻¹, and found that the dependence could not be eliminated. When a large microturbulent velocity is used, mean square errors in the abundances of other elements such as Si II and Fe II become too large.

S,Cl and Ar: We find 13 S II lines in HD 185330. Comparisons of S II lines in three target stars can be found in figures 2A, 4A and 5A. S II lines in HD 185330 and 3 Cen A are weaker than in ι Her and we obtain under-abundances [– 0.9] and [– 1.4] in these two stars, respectively. We identified two Cl II lines and an example is displayed in figure 5A. Cl II lines are weaker than in ι Her and we obtain under-abundances [– 0.5] and [– 0.7] in HD 185330 and 3 Cen A, respectively. Two Ar II lines at 4426.00 Å and at 4439.19 Å are displayed in figure 5B. Ar II lines in 3



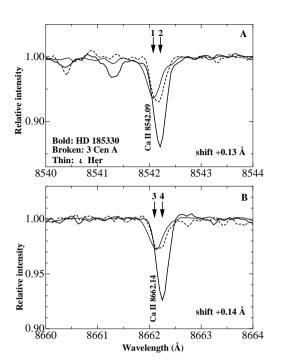


Fig. 5. Comparisons of S $\scriptstyle\rm II$ and Cl $\scriptstyle\rm II$ lines (panel A) and Ar $\scriptstyle\rm II$ and Mg $\scriptstyle\rm II$ lines (panel B) in three target stars.

Cen A show nearly the same strengths as in ι Her, while Ar II lines in HD 185330 are weaker. Using eight Ar II lines, we obtain under-abundance of Ar [– 0.2] in HD 185330 and normal abundances [0.0] in both 3 Cen A and in ι Her. Castelli et al. (1997) reported normal abundances of S, Cl, and Ar in 3 Cen A. Adelman and Pintado (2000) obtained an under-abundance of S [– 1.4] in this star, which is coincident with our result.

Ca II IR triplet: Profiles of the two Ca II triplet lines at 8542.09 Å and at 8662.14 Å are displayed in figures 6A and 6B, respectively. Both these lines are located near the line centers of H I Paschen lines (P15 and P13). We adopt the broad wings of the Paschen lines to be the local continuum and normalized them to unity in these figures. We have adjusted the wavelength scale by using the two strong and isolated Ne I lines at 8495.36 Å and at 8654.38 Å. We find that the line centers of both Ca II lines in HD 185330 and 3 Cen A are definitely red-shifted relative to those of ι Her. Differences in wavelength of the observed line centers are \pm 0.14 Å and \pm 0.11Å for HD 185330 and 3 Cen

Fig. 6. Comparisons of two Ca $\scriptstyle\rm II$ line at 8542.09 Å (panel A) and at 8662.14 Å (panel B) in three target stars. Arrows 1, 3 and 2, 4 show observed line centers in $\scriptstyle\rm \iota$ Her and HD185330 for the two Ca $\scriptstyle\rm II$ lines, respectively.

A, respectively. Using the isotopic shifts of the Ca II IR triplet lines (Nörtershäuser et al. 1998), we interpret that $^{44}\mathrm{Ca}$ and $^{46}\mathrm{Ca}$ are dominating in the atmosphere of HD 185330, while $^{44}\mathrm{Ca}$ is the mainly contributing isotope in 3 Cen A. Inspecting lists of stars in which wavelength shifts of infrared triplet lines of Ca II are observed (Cowley et al. 2007 and Cowley et al. 2009), we notice that 3 Cen A is presently the hottest star ($T_{\rm eff}$ = 17500 K) and the second hottest star is the HZB star Feige 86 ($T_{\rm eff}$ = 16400 K) .

Ti, Cr and Mn: Equivalent widths of 11 lines of Ti II and four lines and Cr II are measured in HD 185330. A slight overabundance [+ 0.35] and a slight under-abundance [- 0.2] are obtained for these two elements. In 3 Cen A, our measurements resulted in a slight over-abundance [+ 0.3] and a normal abundance of Ti and Cr, respectively. We use four Mn II lines in both stars to obtain definite over-abundances of Mn by [+ 1.0] and [+ 1.6] in HD 185330 and in 3 Cen A, respectively. The abundance of Mn obtained in 3 Cen A nearly coincides with published re-

Table 3. Summary of abundances.

Ion		HD 185330					2 Can A			ι Her			Colon
1011	log (N)	RMS	N	[N/H]	log (NI)	RMS	3 Cen A N	[N/H]	log (N)	RMS	N	[N/H]	Solar
C II a	7.82	0.04	6	-0.61	log (N) 7.68	0.04	6	-0.75	log (N) 8.38	0.03	4	-0.05	8.43
			18				18		8.38 7.86		4 19	0.03	
N II O I ^a	7.32	0.16	3	-0.51	8.27	0.18		0.44		0.07	3		7.83
	8.56	0.04		-0.13	8.18	0.04	3	-0.51	8.92	0.04		0.23	8.69
O II	8.28	0.14	16	-0.41	8.11	0.10	16	-0.58	8.80	0.07	12	0.11	8.69
Ne II	8.73	0.14	21	0.80	8.50	0.12	21	0.57	8.54	0.20	21	0.61	7.93
$Mg II^a$	7.13	0.13	7	-0.47	7.10	0.15	7	-0.50	7.60	0.15	7	0.00	7.60
Al II	5.32	0.28	4	-1.13	5.08	0.14	4	-1.37	6.58	0.11	3	0.13	6.45
Si II	7.39	0.3	7	-0.12	7.36	0.22	5	-0.15	7.50	0.12	5	-0.01	7.51
Si III	7.39	0.11	4	-0.12	7.65	0.08	4	0.14	7.92	0.15	4	0.41	7.51
P II	7.28	0.28	33	1.87	7.42	0.27	33	2.01	5.45	0.25	9	0.04	5.41
P III	6.63	0.22	4	1.22	7.36	0.18	4	1.95	5.40	0.04	3	-0.01	5.41
S II	6.25	0.19	13	-0.87	5.71	0.19	12	-1.41	7.26	0.13	11	0.14	7.12
Cl II	4.98		2	-0.52	4.77		2	-0.73	5.25		2	-0.25	5.50
Ar II	6.22	0.26	8	-0.18	6.44	0.14	8	0.04	6.69	0.24	8	0.29	6.40
Ti II	5.30	0.14	11	0.35	5.27	0.17	6	0.32	4.79	0.12	6	-0.16	4.95
Cr II	5.43	0.14	4	-0.21	5.72	0.09	4	0.08	5.57	0.04	3	-0.07	5.64
Mn II	6.47	0.17	4	1.04	7.03	0.04	4	1.60					5.43
Fe II	7.95	0.16	33	0.45	7.92	0.14	31	0.42	7.13	0.12	19	-0.37	7.50
Fe III	7.75	0.11	12	0.25	7.86	0.08	9	0.36	7.55	0.05	9	0.05	7.50
Ni II	6.70	0.13	18	0.48	6.68	0.18	18	0.46	5.95	0.21	9	-0.27	6.22
Ga 11	≤ 3.75	••••	2	< 0.71	6.33	0.21	6	3.29					3.04
Br II	4.87	0.07	3	2.33	5.19	0.05	3	2.65					2.54
Kr II	5.40	0.02	4	2.15	6.54	0.08	4	3.29	••••				3.25
Xe II	5.83	0.18	9	3.59	4.32		2	2.08	••••				2.24
Hg II	≤ 3.30		1	≤ 2.13	4.47		1	3.30					1.17

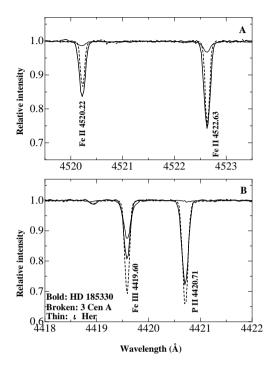
a: Includes results of line profile analyses.

sults (Castelli et al. 1997: [+1.4], Adelman and Pintado 2000: [+1.8], and Wahlgren and Hubrig 2004: [+1.6]).

Fe and Ni: Equivalent widths of 33 low excitation (excitation potential \leq 3.23 eV) Fe II lines and those of 12 Fe III lines are used to obtain the Fe abundance in HD 185330 and overabundances of [+ 0.45] and [+ 0.25] are found from Fe II and Fe III, respectively. For 3 Cen A, we use 31 Fe II lines and nine Fe III lines and obtain over-abundances [+ 0.42] from Fe II and [+ 0.36] from Fe III. The abundance of Fe in 3 Cen A obtained in this study is in agreements with those reported earlier (Castelli et al. 1997: [+ 0.2], Adelman and Pintado 2000: \sim [+ 0.25], and Wahlgren and Hubrig 2004: \sim [+ 0.35]). We obtain somewhat discordant results of the Fe abundance in ι Her. Figures 7A and 7B illustrate profiles of Fe II and Fe III lines used in the abundance analyses in three target stars and we can see that the two Fe II lines near 4520 Å are very weak in t Her. Figure 2B illustrates profiles of two high excitation (10.27 eV) lines of Fe II. These lines are strikingly weak in ι Her. Because of the weakness of Fe II lines, we use 19 lines and obtain an under-abundance [- 0.37] and a normal abundance [+ 0.05] from Fe III lines in this star. The difference amounts to 0.42 dex, well larger than the rms errors (smaller than 0.15 dex). The discrepancy in abundances of Fe derived from Fe II and Fe III lines in ι Her had been pointed out in several papers (e.g.

Kodaira and Scholz (1970), Peters and Aller (1970), Pintado and Adelman (1983) and Golriz and Landstreet (2017)). They all concluded that a higher abundance of Fe is obtained from Fe III lines than from Fe II lines.

We use 18 Ni II lines in both HD 185330 and 3 Cen A to derive the abundance of Ni and found Ni is over-abundant by \sim [+ 0.45] in both stars. On the other hand, absorption lines of Ni II in ι Her are very weak and we obtain an underabundance of Ni [- 0.3] using nine lines. Differences in the Ni abundances by ~ 0.7 dex between the two peculiar stars and t Her strongly suggest enhancements of Ni in these two stars. We note some comments on the abundance of Ni in these two stars. Hg-Mn stars generally show under-abundances of Ni. Ghazaryan and Alecian (2016) lists 48 Hg-Mn stars in which abundances of Ni have been determined. Only four stars show over-abundances of Ni among them. Saffe and Levato (2014) reported an under-abundance of Ni [-0.9] in a He-weak star α Scl. Under-abundances of Ni have been reported in HD 175640 [- 0.4] (Castelli and Hubrig 2004b) and in HR 6000 [- 0.4] (Castelli et al. 2017). In HD 19400, a normal or a slight overabundance of Ni have been reported in Hubrig et al. (2014) and in Alonso et al. (2003), respectively. In the two He-weak stars HD 34797 and HD 35456, Alonso et al. (2003) obtained slight over-abundances of Ni \sim [+ 0.3].



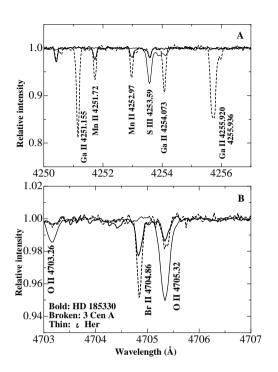


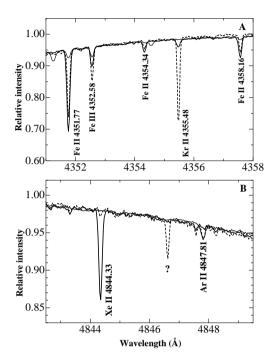
Fig. 7. Comparisons of the two Fe $\scriptstyle\rm II$ lines near 4521 Å (panel A) and an Fe $\scriptstyle\rm III$ and a P $\scriptstyle\rm II$ lines near 4705 Å (panel B) in three target stars.

Fig. 8. Comparisons of three Ga $\scriptstyle\rm II$ lines near 4254 Å (panel A) and a Br $\scriptstyle\rm II$ line at 4704.86 Å (panel B) in three target stars.

Ga: We find remarkable differences in the observed strengths of Ga II lines between HD 185330 and 3 Cen A. Figure 8A shows that three Ga II lines near 4254 Å are prominent in 3 Cen A, while these lines are absent in HD 185330. From equivalent widths of six Ga II lines, we obtained an over-abundance of Ga [+3.3] in 3 Cen A. This is in agreement with results obtained by Takada-Hidai et al. (1986) and by Castelli et al. (1997) based on ultraviolet IUE spectra of 3 Cen A. We set upper limits of the two strong lines of Ga II (at 4262.01 Å and 6334.07 Å) in HD 185330 to be 0.5 mÅ and obtained an upper limit of [+0.7]. The difference in the abundance of Ga between the two stars amounts to at least 2.6 dex.

Br, Kr and Xe: Absorption lines of the two ions Br II and Kr II are rarely observed in stellar spectra. Castelli and Hubrig (2004b) analysed two lines of Br II in HD 175640 and obtained an over-abundance of Br [+ 2.3] in this star. Cowley and Wahlgren (2006) obtained an over-abundance of Br [+ 2.6] in 3 Cen A from three lines of Br II. Profiles of the Br II line at

4704.86 Å in three our target stars are shown in figure 8B. From measurements of equivalent widths of three Br II in HD 185330 and in 3 Cen A, we obtain over-abundances of Br [+ 2.3] and [+ 2.6] in these stars, respectively. As to Kr II, Hardorp et al. (1968) analysed the profile of a Kr II line at 4355.48 Å in 3 Cen A, and obtained an over-abundance of Kr [+ 3.1]. Castelli et al. (1997) obtained an over-abundance of Kr [+ 3.3] from ultraviolet IUE spectra of 3 Cen A. Interestingly, we find that the Kr II line at 4355.48 Å is clearly present but strikingly weaker in HD 185330 than 3 Cen A (figure 9A). Using equivalent widths of four absorption lines of Kr II, we obtained over-abundances of [+ 2.2] and [+ 3.3] in HD 185330 and 3 Cen A, respectively. Castelli et al. (1997) reported an over-abundance of Kr [+3.3] in 3 Cen A which is in agreement with our result. The difference in the abundance of Kr between these two stars is larger than 1.0 dex. Profiles of an absorption line of the next heavy noble gas Xe II at 4844.33 Å is compared in figure 9B. In this case, the Xe II line is strikingly stronger in HD 185330 than in



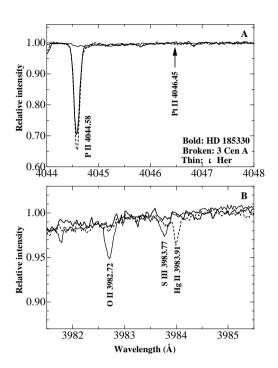


Fig. 9. Comparisons of a Kr $\scriptstyle\rm II$ line at 4355.48 Å (panel A) and a Xe $\scriptstyle\rm II$ line at 4844.33 Å (panel B) in three target stars. A question mark in panel B shows an unidentified line in 3 Cen A.

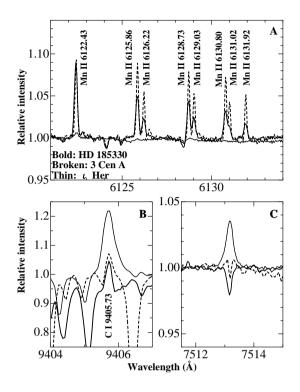
Fig. 10. Comparisons of the Pt $\scriptstyle\rm II$ line at 4046.45 Å (panel A) and the Hg $\scriptstyle\rm II$ line at 3983.91 Å (panel B) in three target stars. No trace of the Pt $\scriptstyle\rm II$ line can be detected.

3 Cen A. This is just the opposite intensity ratio to the case of Kr II line. From nine clearly visible Xe II lines, we obtained an over-abundance of Xe [+ 3.6] in HD 185330. In 3 Cen A, we could measure equivalent widths of only two weak lines and obtained an over-abundance [+ 2.1] in this star.

Pt and Hg: We have examined the strongest Pt II line at 4046.45 Å in both HD 185330 and 3 Cen A, but could not find any trace of the line (figure 10A). The Hg II line at 3983.93 Å is observed in 3 Cen A, while the line is completely absent in both HD 185330 and in ι Her (figure 10B). From the measured equivalent width, we obtain an over-abundance of Hg [+ 3.3] in 3 Cen A. Because of the weakness of the Hg II line in 3 Cen A, we can say nothing about the isotopic composition of Hg in this star. An over-abundance of Hg [+ 4.5] is reported in Castelli et al. (1997) from an analysis of ultraviolet IUE spectra of 3 Cen A. In HD 185330, we could obtain an upper limit of [+ 2.1], assuming an upper limit of 0.5 mÅ.

4.2 Emission lines

Wahlgren and Hubrig (2004) published extensive lists of emission lines observed in 3 Cen A. Here, we compare several emission lines in 3 Cen A with those observed in HD 185330. We compare in figure 11A emission lines of Mn II between 6120 Å and 6133 Å. These emission lines were discovered in 3 Cen A by Sigut et al. (2000) and they are clearly present in HD 185330, while most of them are weaker in HD 185330 than 3 Cen A except for the strongest line at 6122.43 Å. In ι Her, a very weak emission line can be seen at 6122.43 Å. We notice that no counterpart of the emission line of Hg II at 6149.48 Å can be found in HD 185330. Figure 11B illustrates profiles of the C I emission line at 9405.73 Å. Alexeeva et al. (2016) analysed this emission line in ι Her and concluded that their non-LTE calculations can reproduce the observation. The C I emission line is weakly present in both HD 185330 and 3 Cen A. Profiles of an Fe II line at 7513.16 Å is compared in figure 11C. In this



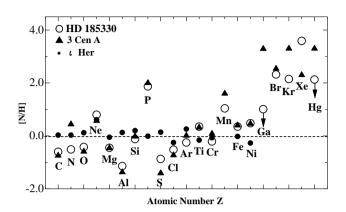


Fig. 11. Weak emission lines in target stars. Panel A shows Mn $\scriptstyle\rm II$ emission lines near 6125 Å. Panels B and C display emission lines of C $\scriptstyle\rm I$ at 9405.73 Å and of Fe $\scriptstyle\rm II$ at 7513.16 Å , respectively.

case, the line is observed as an emission line in ι Her, while the line appears as an absorption line in HD 185330. The line shows double peaked emission components and a sharp central absorption component in 3 Cen A. We refrain from further discussions on metallic emission lines observed in these stars here and will report further data in a forthcoming paper.

5 Discussion

We have determined abundances of 21 elements (including two upper limits) in 3 He stars HD 185330 and 3 Cen A and those of 15 elements in the reference star ι Her. We have confirmed that these two stars belong to the 3 He subgroup. We demonstrated that profiles of the two Ca II triplet lines at 8542.09 Å and at 8662.14 Å are red-shifted relative to those in the reference star ι Her for the first time, and have shown that heavy isotopes of Ca

Fig. 12. Abundance patterns of HD 185330 (open circles), 3 Cen A (filled triangles), and ι Her (dots). Abundances relative to the Sun obtained in this study are plotted against the atomic number. Downward arrows indicate upper limits.

(⁴⁴Ca and ⁴⁶Ca) are present in the atmospheres of HD 185330 and 3 Cen A. Differences in obtained abundances with respect to the solar abundances are plotted against the atomic number in figure 12. Hereafter, we focus on apparent differences in the observed abundances between HD 185330 and 3 Cen A and the possible stratification effect of P suggested by observations of P II lines in these two stars.

Under-abundances of light elements (C, O, Mg, Al, S, and Cl) are observed in both HD 185330 and 3 Cen A. The case of N should be noted separately. N shows definite under-abundance [-0.5] in HD 185330, while it shows an opposite anomaly [+0.44] in 3 Cen A. The difference of ~ 1.0 dex is far larger than the expected error (\pm 0.2 dex) in the analysis. Ghazaryan and Alecian (2016) lists 14 stars in which abundances of N have been determined in their catalog of Hg-Mn stars. We find only one star (21 Aql) with a positive value of [+0.47]. However, 21 Aql is included in Yüce and Adelman (2014) as a B8 II-III

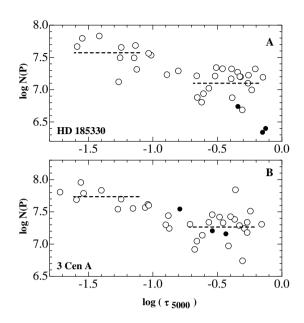


Fig. 13. Possible stratification effects of P in HD185330 (panel A) and 3 Cen A (panel B). Open and filled circles show P II and P III lines, respectively. Horizontal dashed lines indicate approximate mean abundances of P in two layers in stellar atmospheres.

normal star and not as a Hg-Mn star. If we exclude 21 Aql, values of [N/H] of 13 Hg-Mn stars are all negative (ranging from – 0.3 to – 2.3). In a remarkable He-weak star HD 65949, which shows extraordinary strong lines of Re II, Cowley et al. (2010) reported a deficiency of N [– 2.32], which is the lowest among the 13 Hg-Mn stars. In a non-magnetic Bp star HR 6000, Castelli et al. (2017) obtained an under-abundance of N [– 1.02]. Abundances of N in He-weak stars have been determined in several stars. Alonso et al. (2003) obtained over-abundances of N in HD 19400 [+0.35] and in HD 35456 [+ 0.75] and López-García et al. (2001) obtained a slight over-abundance of N in α Scl [+ 0.14]. These He-weak stars are cooler than $T_{\rm eff}$ = 14000 K (Alonso et al. 2003). Thus, N appears under-abundant in Hg-Mn stars, while it shows higher abundance among He-weak stars. If this is the case, HD 185330 might be an exception

among He-weak stars.

We find that the abundances of P in both HD 185330 and 3 Cen A obtained from P II lines have a dependence on the optical depth τ , where lines formed in the upper atmosphere show larger abundances than lines formed in the deeper layer. Abundances of P obtained from P II and P III lines are plotted against log (τ_{5000}) in figure 13A (HD 185330) and 13B (3 Cen A). We can see increasing trends of abundances of P toward the upper atmospheric layer in both stars. Nearly the same trends of P abundances from P II and P III lines are found in HR 6000 (Castelli et al. 2017). They listed five spectroscopic observational evidences for the vertical abundance stratification in stellar atmospheres. We find two signs among the five evidences in HD 185330. They are 1) violation of LTE ionization balance, and 2) disagreement between the abundances derived from strong and weak lines of the same ion. The large scatter in the abundance of P could be resulting from the vertical abundance stratification of P in both HD 185330 and 3 Cen A. The stratification effects of Mn and Hg in 3 Cen A had been discussed in Wahlgren and Hubrig (2004).

Next, we compare the pair of P and Ga, because a small group of PGa stars sometimes appear in papers (e.g. Hubrig et al. 2014) in which both P and Ga are observed to be enhanced. We find in the present study that both P and Ga are definitely over-abundant in 3 Cen A (P [+ 2.0] and Ga [+ 3.3]) while in HD 185330 only P is over-abundant [$\sim + 1.8$]. We obtain only an upper limit of Ga in this star. There is a large difference in abundance of Ga (at least 2.6 dex) between 3 Cen A and HD 185330. We can find similar examples in some slightly cooler Bp stars. Castelli et al. (2017) obtained an over-abundance of P [+ 2.1] while only a slight over-abundance of Ga [+ 0.36] in HR 6000. In contrast to HR 6000, Castelli and Hubrig (2004b) obtained a slight over-abundance of P [+ 0.31] and a large overabundance of Ga [+ 3.7] in HD 175640. Interestingly, in a PGa star HD 19400, both P and Ga show large over-abundances of P [+ 2.3] and Ga [+ 3.8] (Hubrig et al. 2014). Thus, we find large scatters in the abundance ratio of P to Ga among Bp stars and there must be some controlling mechanisms to account for observations.

Abundances of two rarely observed halogens Cl and Br have been obtained in both HD 185330 and 3 Cen A. Cl is underabundant, [-0.5] and [-0.7] in HD 185330 and 3 Cen A, respectively. There are only two Hg-Mn stars in which abundances of Cl have been obtained (Ghazaryan and Alecian 2016). They are χ Lup A [-1.40] and HD 46886 [-0.36]. Castelli et al. (2017) obtained an under-abundance of Cl in HR 6000 $[\le -1.20]$. Our results of Br abundances are over-abundances of [+2.3] and [+2.6] in HD 185330 and 3 Cen A, respectively. The result of 3 Cen A coincides with that given in Cowley and Wahlgren (2006). An over-abundance of Br [+2.29] has been reported in HD 175640 (Castelli and Hubrig 2004b).

Finally, we focus on abundances of the two heavy elements Kr and Xe. The abundance of Kr has been obtained only in one star 3 Cen A (Hardorp et al. 1968). We use four absorption lines of Kr II and obtained over-abundances of Kr in both stars ([+ 2.2] in HD 185330 and [+ 3.3] in 3 Cen A). We also obtained over-abundances of Xe in these two stars ([+ 3.6] in HD 185330 and [+ 2.1] in 3 Cen A). It is interesting to find that the abundance ratios Kr / Xe are reversed in these two stars (figure 12). The abundance of Kr found in HD 185330 is ~ 1.1 dex lower than that in 3 Cen A, while the abundance of Xe is higher by ~ 1.5 dex. Cowley et al. (2010) reported abundances of both Kr [+ 2.9] and Xe [+ 4.4] in the He-weak star HD65949. This star shows nearly the same abundance ratio of Kr / Xe as in HD 185330. This interesting contrast in the abundance trends between Kr and Xe in these stars needs a physical interpretation. However, because we have now only a few sample stars in which abundances of Kr have been reported, further observations are needed before constructing any models.

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