54. *Abundance Analyses of Thirty Cool Carbon Stars**

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(Communicated by Yoshio FUJITA, M. J. A., May 13, 1985)

Introduction. Identification of spectral lines in the visual region for two cool carbon stars U Hya (C6, 3) and Y CVn (C5, 5) was made by Utsumi (1967), and it was found that the molecular bands cause no serious effects in the spectral regions from 4750 Å to 4900 Å, and from 4400 Å to 4500 Å, and physical parameters and abundances of the elements can be obtained from the atomic lines in these regions. Curve-of-growth analyses for twenty-two cool carbon stars were made by Utsumi (1970), and it was found that in J-type cool carbon stars, Sr, Y, Zr and Ba show nearly normal abundances, while rare-earth elements are overabundant by factors of 10~100, and in normal cool carbon stars, all s-process elements were over-abundant by factors of 10~100. These results were obtained by the use of the absolute gf-values by Corliss and Bozman (1962), and by Corliss and Warner (1964), and cosmic abundance by Aller (1961) as a standard. The gf-values by Corliss and Bozman and those by Corliss and Warner were found to contain large systematic errors, and as a result, the solar photospheric abundances were revised. Our previous result, therefore, must be revised by using new gf-values, and abundance analyses will be extended for as many carbon stars as possible.

Observations. We have obtained about two hundred spectrograms of sixty-two carbon stars (forty-eight stars later than C4, fourteen stars earlier than C3) in the spectral region from 4400 Å to 5000 Å with a dispersion of 13.7 Å/mm, with the coude spectrograph attached to the 188 cm reflector of the Okayama Astrophysical Observatory. Some of the spectrograms were obtained by Prof. Y. Yamashita. Logarithmic intensity tracings were made with a Nalumi microphotometer of the Department of Astronomy, University of Tokyo by Prof. Y. Yamashita, and with a Nalumi microphotometer of the Department of Astronomy, Hiroshima University by Utsumi. We have made analyses of thirty cool carbon stars which include eight stars of C4~C6 in addition to twenty-two stars studied before. Four R-type stars of C4~C5 are included among the eight stars newly studied. It was difficult to measure lines on the short-wavelength side of 4750 Å on the tracing of RY Dra, Y CVn, and V Aql on account of the UV-depression of carbon stars, which is believed to be due to C₃ molecules.

For each star, about 170 lines, which were almost free from blends, were selected from the identification table for U Hya by Utsumi (1967).

The equivalent widths were obtained through the relation between equivalent width and central depth, since the effect of blends on central depths seems to be small.

Curve of growth. The differential curve-of-growth method is improper for cool carbon stars because the spectral region which is almost free from molecular

*) A summarized version of this paper was read by Professor Y. Fujita at the Strasbourg Colloquium on "Cool Stars with Excesses of Heavy Elements" (1984).

absorption is different for M-type stars and for cool carbon stars, and appropriate atomic lines of cool carbon stars in common with those of K-type or Ba II stars are very few. For this reason, we constructed empirical curves of growth for fourteen elements using the equivalent widths and absolute gf-values. Absolute gf-values were mainly taken from the Table by Kurucz and Peytremann (1975).

Atmospheric parameters were derived from the plots of Fe I and Ti I lines so as to show the best fitting to Unsold's (1955) theoretical curve-of growth. In the present study, the ionization degree was determined by using Ti I and Ti II lines, since Ti I and Ti II lines were found stronger and less blended than Y I and Y II lines which were used in our previous study. We assumed that $\theta_{\text{ion}} = \theta_{\text{ex}} - 0.1$ and derived the electron pressure using Saha's formula.

Results. Excitation temperature $\theta_{\text{ex}} = 5040/T$, kinetic velocities ξ_0 , and electron pressures $\log P_e$ of thirty cool carbon stars thus derived are given in Table I, together with the spectral type by Yamashita (1972, 1975).

Most normal carbon stars indicate $\theta_{\text{ex}} \sim 1.8$, and R-type stars C4J~C5J $\theta_{\text{ex}} \sim 1.6$. Excitation temperatures of N-type stars of C4J~C5J (Y CVn and RY Dra) are difficult to determine, because lines of 4400 Å~4500 Å region cannot be used in curve-of-growth analysis due to strong molecular bands and UV-depression. However, from intensities of lines in 4400 Å~4500 Å region of Y CVn and RY Dra, $\theta_{\text{ex}} \sim 1.8$ can be indicated.

The ionization degree was determined by using Ti I and Ti II lines. Thus, we determined the relative abundances of the following elements; Ca, Sc, Ti, V, Cr, Mn, Fe, Sr, Y, Zr, Ba, La, Nd, and Sm for thirty cool carbon stars. The effect of blendings was taken into account in the determination of the relative shift of the curve of growth. On account of strong molecular bands and blending of both molecular and atomic lines, the accuracy of the result is different from element to element. In C4J~C5J stars, lines of Sc II and La II are seriously blended with molecular bands. The logarithmic relative abundances with respect to Fe, normalized by the cosmic abundance by Allen (1976), $[M/\text{Fe}]$ for thirty stars are given in Table II. The accuracy is estimated to be about 0.4 dex, though it may be larger for rare-earth elements. The logarithmic abundances with respect to Fe in the previous (I) and present (II) studies, and the cosmic abundances on a scale on which $\log N = 12$ for hydrogen by Aller (I) and by Allen (II) are given in Table III.

In normal cool carbon stars of C4~C8, heavy metals are overabundant by factors of 10~100, and rare-earth elements are overabundant by a factor of about 10. J-type cool carbon stars consisted of three groups: R-type stars represented by HD 52432, N-type stars represented by Y CVn, and Li stars represented by WZ Cas (Yamashita 1972, 1975).

It may be said that in all the groups of J-type cool carbon stars, abundances of s-process elements with respect to Fe are nearly normal.

Discussion. In connection with heavy metals relative to Fe and Ti, the present results are not so different from the previous ones. In connection with abundances of rare-earth elements relative to Fe and Ti, the present results are smaller by a factor of about 3 in an average for normal cool carbon stars, and smaller by a factor of about 10 for J-type cool carbon stars than the previous ones.

Such discrepancies are believed to be mainly due to the effect of blending in J-type cool carbon stars. It is found that abundances of Ce II and Pr II cannot be determined accurately because lines of Ce II and Pr II are so seriously

Table I

Star	Type	θ_{ex}	$\xi_{\odot}$	log Pe	Star	Type	θ_{ex}	$\xi_{\odot}$	log Pe
HD79319	R4; C4,4J	1.6	10.0	-2.1	U Hya	N2; C6,3	1.8	6.7	-3.3
HD19557	R5; C4,5J	1.6	10.0	-2.0	VY UMa	NO; C6,3	1.8	7.5	-3.3
HD52432	R5; C4,5J	1.6	8.7	-2.0	DS Peg	N1; C6,3	1.8	8.2	-3.4
HD168227	R5; C4,5J	1.7	10.0	-2.6	Y Tau	N2; C6,4	1.8	6.0	-3.1
UV Cam	R8; C5,4J	1.6	8.2	-1.9	TU Gem	N3; C6,4	1.8	7.5	-3.1
RY Dra	N4; C4,5J	1.8	8.2	-3.6	UU Aur	N3; C6,4	1.8	6.5	-3.3
Y CVn	N3; C5,5J	1.8	8.2	-3.3	S Sct	N3; C6,4	1.8	6.0	-3.1
RV Mon	Nb; C4,4	1.8	8.7	-3.3	V Aql	N6; C6,4	1.8	6.0	-3.3
AQ And	Nb; C5,4	1.8	12.0	-3.5	HD180953	N2; C6,4	1.8	7.5	-3.5
ST Cam	Nb; C5,4	1.8	8.7	-3.3	Z Psc	NO; C7,2	1.8	7.5	-3.4
W Ori	N5; C5,4	1.8	6.5	-3.1	19 Psc	Nb; C7,2	1.8	10.9	-3.1
X Cnc	N3; C5,4	1.8	6.0	-3.4	UX Dra	NO; C7,3	1.8	6.9	-3.3
SS Vir	Np; C5,3e	1.8	7.5	-3.1	RR Her	K5ep; C8,1e	2.0	8.2	-4.2
HD59643	R9; C6,2	1.8	7.5	-3.4	RS Cyg	NOpe; C8,2	2.0	7.5	-4.7
BL Ori	Nb; C6,3	1.8	8.6	-3.3	WZ Cas	N1p; C9,2J Li	2.0	7.5	-4.8

Table II

Star	[M/Fe]												
	Ca	Sc	Ti	V	Cr	Mn	Sr	Y	Zr	Ba	La	Nd	Sm
HD79319	-0.1	-0.1	0.1	0.2	0.2	0.1	<1.2	0.3	0.4	0.0	<1.1	0.7	0.4
HD19557	-0.1	-0.2	0.0	-0.1	-0.2	-0.2	<0.7	0.8	0.0	0.5	0.5	0.3	0.3
HD52432	-0.4	-0.3	0.2	0.1	0.1	0.0	<1.4	0.0	0.4	0.3	<1.4	0.9	0.6
HD168227	-0.2	-0.3	0.1	0.0	-0.2	-0.2	<1.0	0.1	0.4	0.0	<1.4	0.9	0.5
UV Cam	-0.1	-0.1	0.0	0.0	0.2	0.0	0.3	0.4	0.1	-0.2	<0.8	0.5	0.3
RY Dra	-	-	0.0	-0.4	0.0	-0.2	<0.6	0.6	0.1	-0.7	<0.9	0.2	-0.2
Y CVn	0.4	-0.1	-0.1	0.2	0.0	0.0	<0.9	0.2	0.2	0.2	<1.0	0.5	0.3
RV Mon	0.4	-0.7	-0.1	-0.2	0.0	-0.3	1.5	2.6	1.9	2.6	1.6	1.6	1.8
AQ And	<0.9	-0.2	0.2	0.3	0.1	-0.2	2.7	2.1	2.3	1.0	1.9	1.1	1.3
ST Cam	0.7	0.4	0.1	0.3	0.3	0.2	2.1	1.8	1.9	1.0	1.3	0.6	0.7
W Ori	0.0	-0.1	0.1	-0.1	0.4	-0.4	1.9	1.6	1.4	1.5	1.1	1.0	1.0
X Cnc	0.4	1.0	0.0	0.0	0.1	-0.1	2.6	2.3	1.7	2.1	1.9	1.2	1.1
SS Vir	0.4	0.4	0.0	0.0	-0.4	-0.2	0.4	1.6	1.8	1.0	1.2	0.7	0.7
HD59643	0.3	-0.1	0.3	0.4	0.4	0.0	1.6	1.6	1.2	2.1	1.9	1.1	1.4
BL Ori	<1.0	0.1	0.0	-0.2	0.1	-0.4	1.8	1.6	1.5	1.5	1.3	1.1	1.2
U Hya	-0.1	-0.2	0.0	-0.1	0.0	-0.2	2.0	1.8	1.5	1.2	1.4	1.0	1.2
VY UMa	-0.5	-0.6	0.0	-0.1	0.3	-0.3	2.6	1.9	1.7	1.4	1.0	0.7	0.8
DS Peg	0.8	0.1	0.0	0.0	0.3	-0.1	2.2	1.7	1.8	1.1	1.4	1.3	1.1
Y Tau	-	0.0	0.0	0.0	0.0	-0.4	2.1	1.5	1.4	0.4	2.1	1.4	0.6
TU Gem	0.3	0.3	0.1	0.1	0.4	0.1	1.3	2.3	2.5	1.5	1.5	0.8	1.0
UU Aur	0.6	0.2	0.0	-0.1	0.2	-0.2	1.2	1.7	1.5	1.3	1.0	0.8	0.9
S Sct	0.5	0.2	-0.1	-0.1	0.0	-0.3	2.2	2.5	2.0	2.1	1.4	1.0	0.9
V Aql	-	0.0	0.0	0.0	0.1	-0.3	1.9	1.9	1.8	-	2.0	1.3	1.0
HD180953	0.4	0.4	0.0	0.2	0.3	-0.1	2.0	1.6	1.1	1.5	1.1	1.3	1.1
Z Psc	0.5	0.3	0.1	-0.1	0.1	-0.3	1.9	2.4	1.9	2.1	1.2	1.4	1.8
19 Psc	0.6	-0.3	0.0	-0.2	0.0	-0.4	2.5	1.8	1.4	2.2	0.9	0.9	1.0
UX Dra	0.6	-0.4	0.0	-0.1	0.2	-0.3	1.9	1.7	1.5	1.1	1.1	1.1	1.2
RR Her	0.2	0.5	-0.2	0.0	-0.1	-0.3	1.0	1.6	1.3	1.0	0.7	0.6	0.9
RS Cyg	<1.2	<1.2	0.0	0.2	0.2	0.0	2.9	2.5	1.9	1.8	0.6	0.6	0.6
WZ Cas	0.7	-0.1	0.0	-0.1	0.4	-0.2	<2.0	0.5	0.5	0.1	0.0	0.0	0.4

blended. In J-type cool carbon stars, most lines of rare-earth elements are weak and blended, and especially La II lines are so seriously blended that only upper limits of abundances can be determined. On the other hand, such discrepancies are believed to be partly due to the difference of the ionization degree, in both normal and J-type cool carbon stars.

Abundances of s-process elements are determined mainly in relation to that of Ti. In the atmospheres of cool carbon stars, Fe is nearly neutral, Sr, Ba, and rare-earth elements are nearly ionized, and Ti, V, Cr, and Zr are partially

Table III

	[M/Fe]													
	Ca	Sc	Ti	V	Cr	Mn	Sr	Y	Zr	Ba	La	Nd	Sm	
U Hya (I)	0.1	0.0	-0.2	0.1	-0.2	-0.4	1.5	0.9	0.9	1.9	1.5	1.1	1.5	
U Hya (II)	-0.1	-0.2	0.0	-0.1	0.0	-0.2	2.0	1.8	1.5	1.2	1.4	1.0	1.2	
Y CVn (I)	0.0	-0.2	-0.4	-0.3	-0.8	-0.6	0.3	0.0	0.0	0.4	2.1	1.4	1.6	
Y CVn (II)	0.4	-0.1	-0.1	0.2	-0.2	0.0	< 0.9	0.2	0.2	0.2	≤ 1.0	0.5	0.3	
	Cosmic Abundance													
	Ca	Sc	Ti	V	Cr	Mn	Fe	Sr	Y	Zr	Ba	La	Nd	Sm
(I)	6.0	2.9	4.6	4.2	5.0	4.8	6.8	2.6	3.2	2.7	2.5	2.0	1.9	1.6
(II)	6.3	3.2	5.1	4.4	5.9	5.4	7.6	2.9	1.8	2.5	2.0	1.6	1.8	1.5

(I) Utsumi (1970), Aller (1961). (II) Present study, Allen (1976).

ionized. In the previous study, the ionization degree of Ti was underestimated, and as a result, the abundance of Ti was underestimated by a factor of about 2. Since abundances of rare-earth elements are determined by ionized lines, they are little affected by the difference of ionization.

In conclusion, it may be said that in normal cool carbon stars heavy metals are overabundant by factors of 10~100, and rare-earth elements are overabundant by a factor of about 10, and in J-type cool carbon stars, C^{12}/C^{13} ratio is smaller, C_2 and CN bands and Li 6708 are stronger than in normal cool carbon stars (Fujita *et al.* 1966; Yamashita 1972, 1975), and abundances of s-process elements with respect to Fe are nearly normal.

The author wishes to express his hearty thanks to Prof. Y. Yamashita for making the observational material on which it was based available to him, and for helpful discussions. His hearty thanks are also due to Prof. Y. Fujita, M. J. A., for his advice and constant encouragement.

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