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Quantitative analysis of carbon isotopic ratios in carbon stars

III. 26 J-type carbon stars including 5 silicate carbon stars

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Abstract. We present the result of a quantitative analysis of $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios in 26 J-type carbon stars. The $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios are determined from lines of the CN red system around 8000 Å, using the iso-intensity method and line-blanketed model atmospheres.

The average of $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios in the 26 stars is 4.7 ± 2.8 (standard deviation). All the stars studied, except for two stars, have $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios smaller than 10. $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios as low as $1 \sim 2$, which are lower than the value at the equilibrium of the CN-cycle, are found for a significant fraction of our sample, suggesting the operation of non-equilibrium nuclear processes. For several stars previously analyzed by other authors, our result shows fair agreement. The serious disagreement of $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios, which we reported for N-type carbon stars in our preceding paper, is not found for J-type carbon stars.

Five silicate carbon stars in our sample show no peculiar $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios among the stars studied in the present work. This result implies that the mechanism responsible for low $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios in silicate carbon stars might be the same with that operating in other J-type carbon stars. In other words, $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios in silicate carbon stars have turned out to give few clues to identify the mechanism responsible for their formation.

Key words: stars: abundances – stars: carbon – stars: fundamental parameters – stars: AGB and post-AGB

1. Introduction

A group of carbon stars can be distinguished for the enormous strength of the absorption due to ^{13}C-bearing molecules, and they were designated as J-type by Bouigue (1954). Such enormous enhancements of ^{13}C-bearing molecules are not observed for N- and SC-type carbon stars. Though SC-type carbon stars were mostly classified as J-type by the earlier classification, Ohnaka & Tsuji (1996, hereafter Paper I) reveal that $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios in 15 SC-type carbon stars are mostly larger than 10.

The enormous strength of the absorption of ^{13}C-bearing molecules in J-type carbon stars implies very low $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios. Besides, unlike N- and SC-type carbon stars, J-type carbon stars do not exhibit the enhancement of the *s*-process elements (Utsumi 1985). These observational facts cannot be interpreted by the scenario considered for the formation of N- and SC-type carbon stars. In the formation of N- and SC-type carbon stars, the thermal pulse and the third dredge-up at the asymptotic giant branch (AGB) are considered to play a crucial role (e.g. Iben 1981, Vassiliadis & Wood 1993, Straniero et al. 1997). Namely, ^{12}C freshly synthesized in the thermal pulse is mixed to the stellar surface by the third dredge-up, resulting in the increases of C/O and $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios. The enhancements of the *s*-process elements observed in N- and SC-type carbon stars (e.g. Utsumi 1985) also indicate the operation of the thermal pulse, where neutrons are expected to be supplied via $^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$. However, this scenario cannot reproduce the enrichment of ^{13}C and the lack of the *s*-process enhancements observed in J-type carbon stars, and the formation of J-type carbon stars still remains unclear. The mixing of CN-cycled material is one of the scenarios considered for the formation of J-type carbon stars, since $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratio is lowered to $3 \sim 4$ at the equilibrium of the CN-cycle. In fact, the operation of the CN-cycle at the bottom of the convective envelope and extra mixing processes have been intensively investigated, but no definitive answer has been given so far.

Carbon stars with the silicate emission at 9.8 μm, which were discovered by Willems & de Jong (1986) and Little-Marenin (1986) in the IRAS Low Resolution Spectra (LRS), are also associated with J-type. Since their discovery, silicate carbon stars have been identified as J-type by Willems & de Jong (1986), Lloyd-Evans (1990), Lambert et al. (1990), and Chan (1993). However, $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios in silicate carbon stars have not well quantitatively been determined yet. The detection of silicate emission suggests that the circumstellar envelopes of these stars should be oxygen-rich, on the contrary to the photospheric chemical compositions characterized by C/O > 1. The detections of OH and H_2O masers (Nakada et al. 1987, 1988; Little-Marenin et al. 1988, 1994) also suggest the existence of oxygen-rich material in the circumstellar envelopes.

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$^{12}C/^{13}C$ ratios in J-type carbon stars reflect nuclear reactions and mixing processes in the stellar interior. A quantitative analysis of ^{13}C enrichments gives us a clue to clarify the nuclear reactions responsible for the formation of J-type carbon stars. As for silicate carbon stars, some peculiar $^{12}C/^{13}C$ ratios which would be associated with the presence of silicate emission may be found. Thus, we have carried out a quantitative analysis of $^{12}C/^{13}C$ ratios, using lines of the CN red system located around 8000 Å, for 26 J-type carbon stars including 5 silicate carbon stars. Our main purpose is to find the distribution of $^{12}C/^{13}C$ ratios in J-type carbon stars. We will also discuss a comparison of the resulting $^{12}C/^{13}C$ ratios with those previously derived by other authors, and possible mechanisms responsible for small $^{12}C/^{13}C$ ratios in J-type carbon stars.

2. Observation

Our program stars are summarized in Table 1. The sample consists of 26 J-type carbon stars, most of which were selected from the lists of carbon stars with the C-classification (Yamashita 1972, 1975), and those with comments on spectral peculiarities (Dean 1976). The IRAS database (NASA) and Stephenson (1973, 1989) are also important references. The silicate carbon stars were selected from the literature such as Willem & de Jong (1986), Little-Marenin (1986), Lloyd-Evans (1990), Lambert et al. (1990), and Chan (1993). Our sample includes five of them: EU And, BM Gem, V778 Cyg, NC 83, and GCCCS 447[1]. We also emphasized such stars for which photometric data are available.

All the observations were carried out using the 74-inch reflector of Okayama Astrophysical Observatory (OAO[2]), during the period between December 1987 and February 1993. The spectrum of each star consists of two adjacent exposures, covering from 7800 to 8030 Å. Each exposure covers 120 Å with an overlap of 10 Å allowed. The measured full widths at half maximum of thorium comparison lines appear to be about 0.4 Å, corresponding to a spectral resolution of about 20,000. The signal-to-noise ratios range from 20 to 800. For some of the program stars, large differences of signal-to-noise ratios are found between two exposures, because of the changes of the integration time and the weather condition. The descriptions of the spectrograph and the way of data reduction are found in Paper I.

3. Model atmospheres

The model atmospheres used in the analysis are based on the code developed by Tsuji (1965). They are constructed with four assumptions: plane-parallel geometry, hydrostatic equilibrium, local thermodynamical equilibrium (LTE), and radiative equilibrium. The code incorporates the effect of the molecular absorption due to CO, C_2, CN, HCN, and C_2H_2 using the Band Model Method. Detailed discussion on our model atmospheres can be found in Paper I and Ohnaka & Tsuji (1998, hereafter Paper II).

Our model atmospheres are specified by a set of four parameters: effective temperature, surface gravity, micro-turbulent velocity, and chemical composition. The determination of effective temperatures will be described in the next section. The surface gravity and the micro-turbulent velocity are estimated in the same way as in the cases of N- and SC-type carbon stars (Paper I); we set $\log g$ = 0.0 and $\xi_{\rm micro}$ = 3.0 km s^{-1}. The chemical composition is assumed to be solar (Anders & Grevesse 1989), except for carbon abundance. Lambert et al. (1986) analyzed the elemental abundances of carbon, nitrogen, and oxygen in four J-type carbon stars[3], and the average of the C/O ratios in the four stars is 1.3. We adopt this value for all our program stars. Table 2 shows the input parameters of the models used in the analysis. Examples of our model atmospheres are shown in Fig. 1, where the models with C/O = 1.1, 1.3, and 2.0 are plotted. The models with C/O = 1.1 and 2.0 are calculated to check the effect of C/O ratio on the resulting $^{12}C/^{13}C$ ratios.

4. Determination of effective temperatures

To determine the effective temperature of each star, we apply the InfraRed Flux Method (IRFM, Blackwell et al. 1980). We also applied it to the determination of the effective temperatures of N- and SC-type carbon stars in Paper I. The effective temperature can be determined by the ratio of observed bolometric flux ($f_{\rm BOL}$) to infrared flux, once the ratio is calibrated by model atmospheres. The L'-band (3.7 μm) flux is employed as infrared flux, because this band region is least disturbed by molecular absorption in the spectra of carbon stars. Molecular absorption features are dependent on other parameters such as chemical composition, surface gravity, and micro-turbulent velocity as well as effective temperature. However, by using the L'-band flux, we can determine effective temperatures as independently of those parameters as possible. The calibration of the ratio $\log R_{L'} = \log(f_{\rm BOL}/f_{L'})$ is shown in Fig. 2, where the ratios are calculated with the model atmospheres with C/O = 1.1, 1.3, and 2.0. As we mentioned in the previous section, we adopt the $T_{\rm eff} - \log R_{L'}$ relation calculated with C/O = 1.3.

Though the L'-band is relatively free from molecular absorption lines, one concern is the effect of the 3 μm absorption due to HCN and C_2H_2. The effect of this absorption feature is corrected in the empirical way mentioned in Paper I. But the 3 μm absorption is located almost at the edge of the response function of the L' filter, thus its effect on the observed L'-band flux is minor. As discussed in Paper I, other molecular absorption features such as $\nu_1+\nu_2$ bands of HCN and $\nu_2+\nu_5$ bands of C_2H_2 at 3.7 μm are unlikely to have any serious effects on the

[1] A General Catalogue of Cool Carbon Stars (Stephenson 1973). The 2nd edition, A General Catalogue of Cool Galactic Carbon Stars (Stephenson 1989), is designated as GCCGCS.

[2] OAO is a branch of National Astronomical Observatory of Japan (NAOJ). This work was carried out under the common use program of OAO.

[3] Lambert et al. (1986) also analyzed WZ Cas. But since it is classified as SC-type with a C/O ratio very near to unity, we exclude this star from the present work. It has already been discussed in Paper I.

Table 1. Summary of the observations of 26 J-type carbon stars. The first row for each star is the exposure covering from 7800 to 7920 Å, while the second row is that covering from 7910 to 8030 Å

GCCGCS[a]	GCCCS[b]	Name	C-Class[c]	m_V	Date Observed	S/N
36	11	VX And	C4,5J	8.5	1990 Dec 22	700
					1990 Dec 21	200
53	14	NQ Cas	C4,5J	9.7	1990 Dec 27	140
					1990 Dec 25	90
378	110	HD 16115	C2,3J	8.2	1990 Dec 24	100
					1990 Dec 23	20
384	112	VZ Per	C4,5J	11.0	1992 Sep 3	50
					1992 Sep 4	60
608	177	UV Cam	C5,4J	7.9	1990 Dec 22	700
					1990 Dec 21	80
654	197	BO Tau	C4,5J	10.9	1992 Nov 17	60
					1992 Nov 13	120
*1158	447			11.0	1992 Nov 15	120
					1992 Nov 13	100
1290	522	DH Gem	C4,5J	10.0	1991 Mar 6	140
					1991 Mar 3	140
1466	616	UW Aur	C4,5J	10.0	1993 Feb 4	130
					1993 Feb 3	80
1507	645	HD 52432	C4,5J	7.0	1987 Dec 3	100
					1987 Dec 2	100
*1653	716	BM Gem	C5,4J	9.8	1990 Apr 14	120
					1990 Apr 13	100
1891	906	MSB 31	C5:,5J	9.0	1991 Mar 6	200
					1991 Mar 3	80
2153	1126	HD 70138	C5,5J	9.3	1991 Mar 6	80
					1991 Mar 3	40
2301	1260	Lee 99	C3,4J	10.0	1993 Feb 5	30
					1993 Feb 5	36
2331	1290	HD 75021	C5,5J	7.2	1990 Dec 22	60
					1990 Dec 21	300
2449	1403	HD 79319	C4,4J	8.9	1990 Dec 22	160
					1990 Dec 21	300
3283	2030	Y CVn	C5,5J	4.9	1992 Mar 21	800
					1992 Mar 18	120
3313	2047	RY Dra	C4,5J	6.4	1992 Mar 19	240
					1992 Mar 18	600
3558	2208	HD 133332	C4,4J	10.5	1993 Feb 2	110
					1993 Feb 4	100
4217	2717	CG Vul		9.0	1992 Mar 23	160
					1992 Mar 18	50
*4222		NC 83		12.5	1992 Sep 3	60
					1992 Sep 2	60
*4923	2919	V 778 Cyg	C4,5J	9.0	1990 Dec 24	200
					1990 Dec 23	80
5496	3082	RX Peg	C4,4J	7.7–8.6	1992 Nov 14	180
					1992 Nov 13	160
5728	3156	TX Lac	C3:,4J	10.2	1992 Sep 5	43
					1992 Sep 6	35
*5848	3184	EU And		10.0	1990 Dec 22	160
					1990 Dec 21	100
5865	3186	V 353 Cas	C4,5J	9.0	1992 Sep 3	79
					1992 Sep 4	64

[a] A General Catalogue of Cool Galactic Carbon Stars, Stephenson (1989)
[b] A General Catalogue of Cool Carbon Stars, Stephenson (1973)
[c] Yamashita (1972, 1975)
* silicate carbon stars

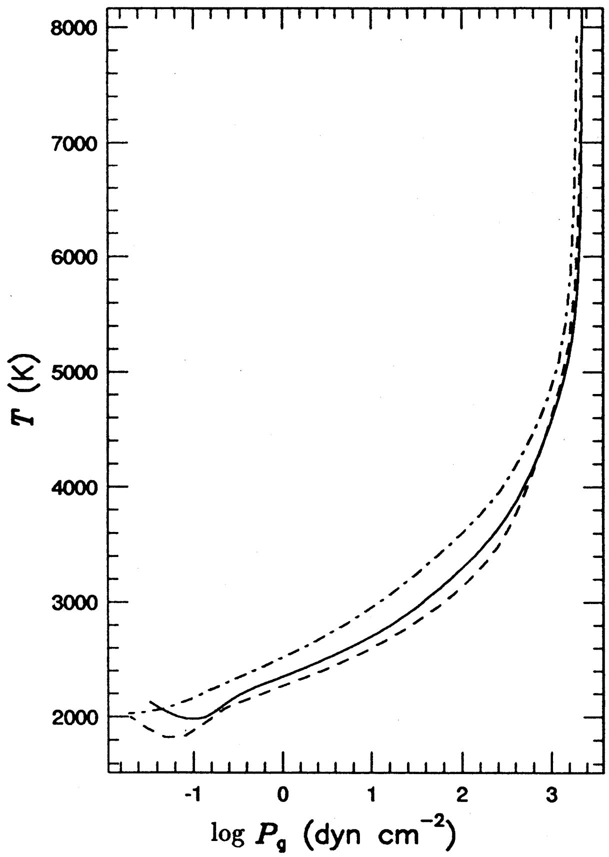

Fig. 1. Examples of the model atmospheres. The models calculated with C/O = 2.0, 1.3, and 1.1, are shown by the dashed-dotted, solid, and dashed lines, respectively. The other parameters are $T_{\rm eff}$ = 3000 K, $\log g$ = 0.0, and $\xi_{\rm micro}$ = 3 km s^{-1}

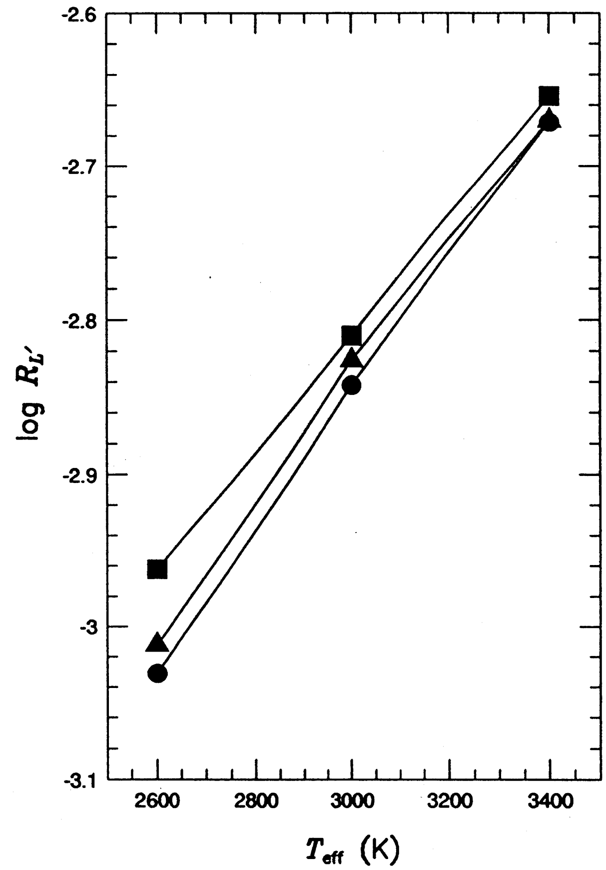

Fig. 2. The calibration of $R_{L'}$ against $T_{\rm eff}$ with different C/O ratios. The filled squares, triangles, and circles correspond to the models with C/O = 1.1, 1.3, and 2.0, respectively

Table 2. Stellar parameters adopted for the model atmospheres used in the analysis

Parameter	Values
$T_{\rm eff}$ (K)	2500, 2600, 2800, 3000, 3200, 3400, 3600, 3800
$\log g$ (cm s^{-2})	0.0
$\xi_{\rm micro}$ (km s^{-1})	3.0
C/O	1,1, 1.3, 2.0

observed L'-band flux. Regarding the CS first overtone bands at 3.9 μm, Aoki et al. (1998) have recently analyzed the spectra acquired with the Infrared Space Observatory (ISO), and have identified strong CS absorption in 3 SC stars. But they also reveal that the CS absorption is very weak in N-type carbon stars. Probably this is also the case for J-type carbon stars. In fact, the spectrum of the J-type carbon star Y CVn obtained by Goebel et al. (1980) does not show any strong absorption at 3.9 μm. Therefore, it is also unlikely that the determination of the effective temperatures of J-type stars is affected by the CS absorption.

Photometric data from U or B-band throughout to L or L'-band are available in the literature (Mendoza & Johnson 1965, Noguchi et al. 1981, and Walker 1979) for four of our program stars: RY Dra, BM Gem, HD75021, and VX And. The photometric data are de-reddened, using A_v estimated based on the works by Sharov (1964) and by FitzGerald (1968). Then the bolometric fluxes are obtained by integrating the monochromatic fluxes throughout the relevant spectral region. With the bolometric fluxes and infrared fluxes evaluated in this way, we determine the effective temperatures, using the $T_{\rm eff} - \log R_{L'}$ relation. The effective temperatures determined in this way are indicated by asterisks(*) in the third and seventh columns of Table 3. The uncertainty of $T_{\rm eff}$ is about 5%, or about 150 K for $T_{\rm eff}$ = 3000 K. The detail of the origins of the uncertainty is discussed in Paper I.

Concerning the stars for which photometric data throughout the whole spectral region are not available, we determine the effective temperatures by the use of the $(J - L')_0 - T_{\rm eff}$ relation. Dr. K. Noguchi kindly obtained the photometric data of J, H, K, and L'-bands of our program stars, except for those available in the literature (Noguchi et al. 1981, Noguchi et al. 1995). In Fig. 3, we plot the effective temperatures of the four stars, determined directly with the IRFM, against $(J - L')_0$. The effective temperatures of N- and SC-type carbon stars, which were determined directly with the IRFM in Paper I, are also plotted. The effective temperatures of the four J-type carbon stars (filled

Table 3. Effective temperatures and $^{12}C/^{13}C$ ratios

Star	$(J-L')_0$	T_{eff} (K)	$^{12}C/^{13}C$	Star	$(J-L')_0$	T_{eff} (K)	$^{12}C/^{13}C$
VX And	1.95	2890*	12 ± 2	Lee 99	1.18	3360	1.9 ± 0.5
NQ Cas	1.62	3090	5.3 ± 0.9	HD 75021	1.53	3150*	1.7 ± 0.7
HD 16115	0.57	3720	4.4 ± 1.4	HD 79319	1.50	3160	3.0 ± 0.3
VZ Per	1.97	2880	4.8 ± 1.2	Y CVn	2.01	2860	2.0 ± 0.5
UV Cam	1.19	3350	2.9 ± 0.4	RY Dra	1.76	3010*	1.9 ± 0.2
BO Tau	1.07	3420	2.1 ± 0.7	HD 133332	1.66	3070	3.0 ± 0.5
GCCCS 447**	2.40	2620	5.6 ± 1.4	CG Vul	2.48	2570	1.9 ± 1.1
DH Gem	1.87	2940	5.3 ± 0.9	NC 83**	2.71	2490	3.0 ± 1.0
UW Aur	2.22	2730	3.6 ± 0.7	V 778 Cyg**	1.92	2910	4.8 ± 0.8
HD 52432	2.07	2818	12 ± 2	RX Peg	1.96	2890	7.6 ± 2.4
BM Gem**	2.18	3010*	4.8 ± 0.8	TX Lac	1.12	3390	4.8 ± 1.2
MSB 31	1.90	2920	9.1 ± 1.5	EU And**	1.86	2950	5.3 ± 0.9
HD 70138	1.62	3090	2.8 ± 0.7	V 353 Cas	2.09	2810	6.9 ± 1.2

* T_{eff} is determined directly with the IRFM.
** silicate carbon stars

circles) seem to be marginally higher than those of N- and SC-type carbon stars (open squares and open triangles, respectively) with the same $(J-L')_0$ color. However, given the accuracies of T_{eff}, it seems safer to use the $(J-L')_0$ – T_{eff} relation based on all the three types of carbon stars than to use that based on only four J-type carbon stars. Thus, we derive the $(J-L')_0$ – T_{eff} relation by the linear least square fit, including all the three types of carbon stars, and determine effective temperatures for the rest of our program stars. The effective temperatures determined are summarized in the third and seventh columns of Table 3. The uncertainties of the effective temperatures determined from the $(J-L')_0$ – T_{eff} relation are about 200 K, as discussed in Paper I.

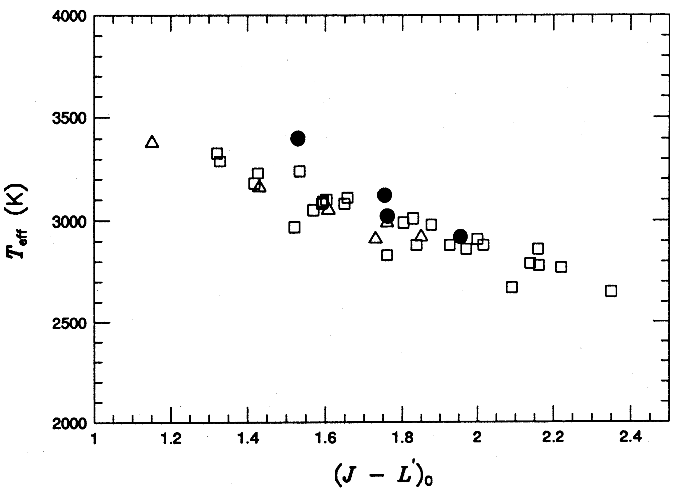

Fig. 3. $(J-L')_0$ – T_{eff} relation based on the effective temperatures determined with the IRFM. The filled circles represent the J-type carbon stars. The N- and SC-type carbon stars analyzed in Paper I are represented by the open squares and the open triangles, respectively

5. Analysis

Figs. 4a–d show four examples of the observed spectra. A glance of the figures reveals that the spectra are heavily line-blanketed by the absorption due to ^{12}CN together with the strong absorption due to ^{13}CN. The spectra shown in the figures are normalized by the fictitious continuum level, which is drawn so that it should travel through the highest point in the region observed and assumed to be constant over the region. In fact, the change of flux level predicted by the blackbody of 3000 K is 3% over 230 Å, and therefore, this assumption is reasonable.

The line positions of the ^{12}CN red system are given in Davis & Phillips (1963). For ^{13}CN, Wyller (1966) analyzed (2,0) and (3,1) bands of the red system and listed the positions of 437 lines. The lines of ^{13}CN are located at the wavelengths by about 40 Å longer than the corresponding lines of ^{12}CN due to the isotope effect. The gf-value of each ^{12}CN line is calculated as described in Paper I. The gf-values of ^{13}CN lines are reasonably assumed to be identical with those of the corresponding ^{12}CN lines.

We determine $^{12}C/^{13}C$ ratios using the iso-intensity method. For lines due to ^{12}CN and ^{13}CN, the logarithms of central depths normalized by the fictitious continuum level are plotted against $\log(gf\Gamma)$, where Γ is a line intensity predicted using the weighting function method (e.g. Cayrel & Jugaku 1963). Γ can approximately be written in the form of $\Gamma(\chi) = \Gamma(0) - \chi\langle\theta_{ex}\rangle$, where χ is the lower excitation potential (LEP) of a line, and $\langle\theta_{ex}\rangle$ is a kind of weighted mean of the reciprocal excitation temperature in the line forming region. Paper II discusses the calculation of Γ and the effects of model atmospheres on it in detail, and we will not repeat them here. Fig. 5 shows examples of the iso-intensity method. The horizontal shift between the two curves for ^{12}CN and ^{13}CN gives the ratio of the abundance of ^{12}CN to that of ^{13}CN, namely, $^{12}C/^{13}C$ ratio. The two curves for ^{12}CN and ^{13}CN are quite close to each other, demonstrating that $^{12}C/^{13}C$ ratios in J-type carbon stars are very low. As Fig. 5 shows, we selected about 10 lines of ^{12}CN and 2 lines of ^{13}CN which are expected not to have their central depths affected by the adjacent lines.

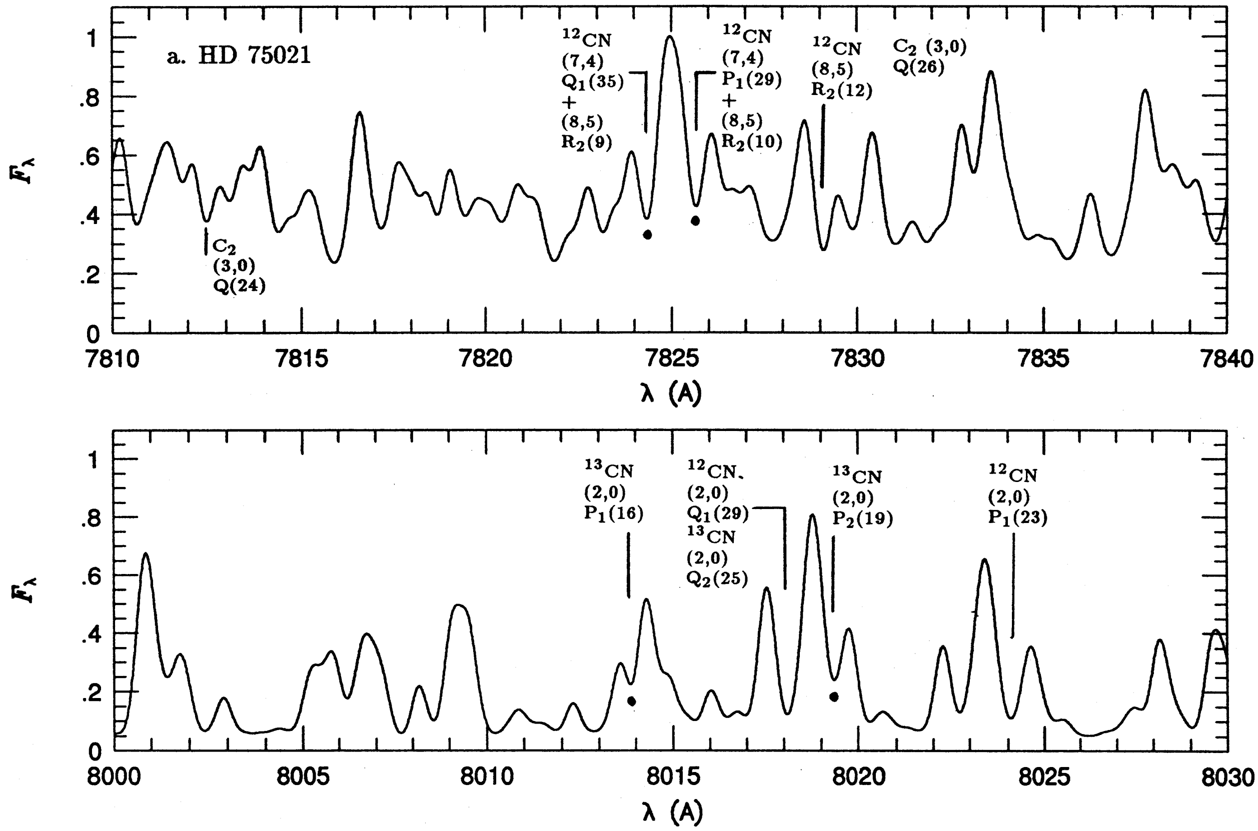

Fig. 4a. The observed spectrum of HD 75021. The lines used in the analysis are indicated by the filled circles

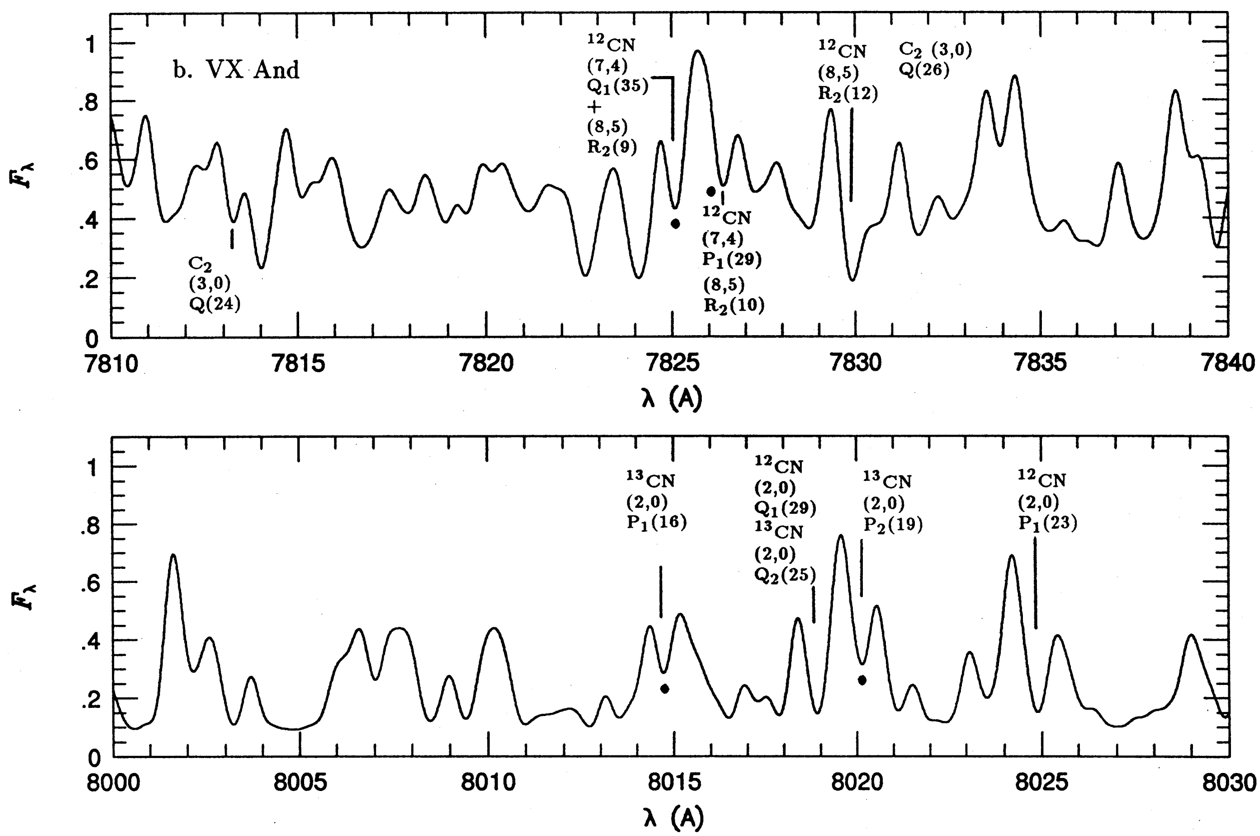

Fig. 4b. The observed spectrum of VX And. See also the legend to Fig. 4a

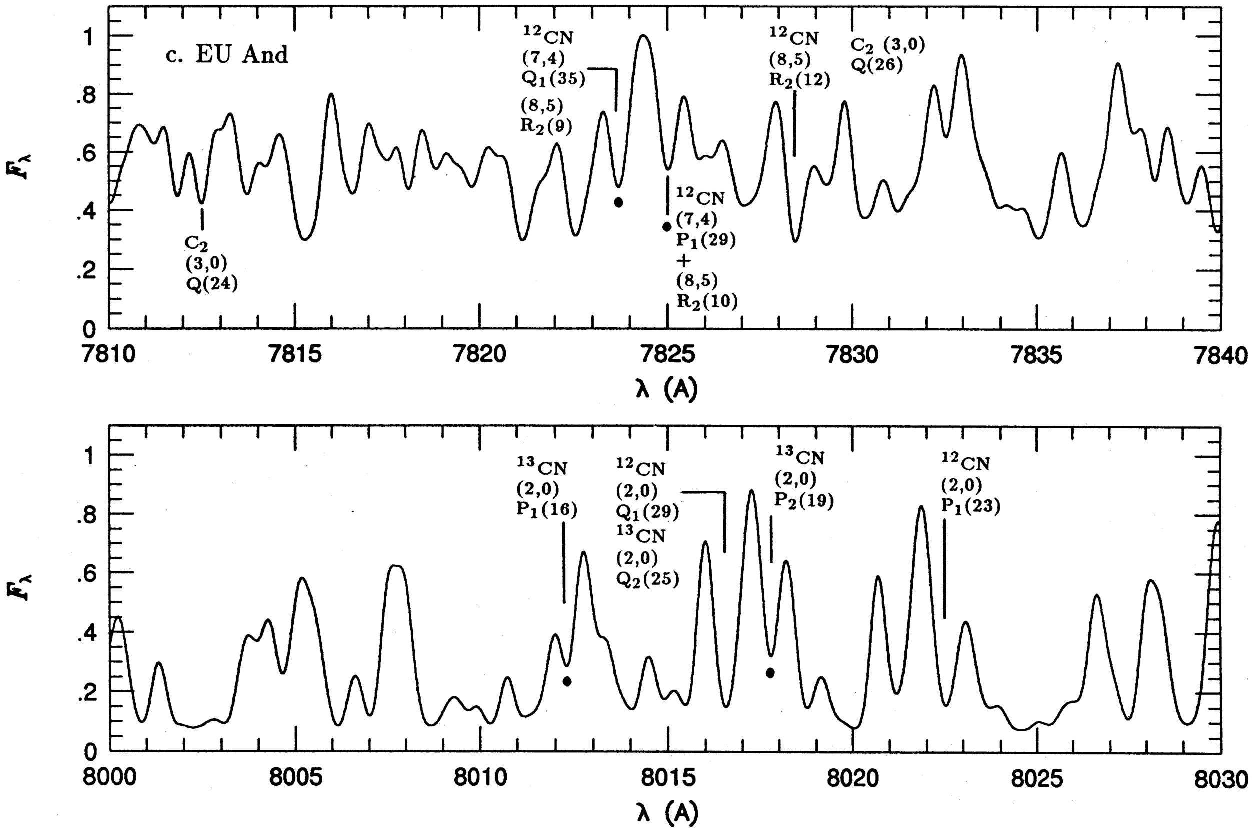

Fig. 4c. The observed spectrum of EU And. See also the legend to Fig. 4a

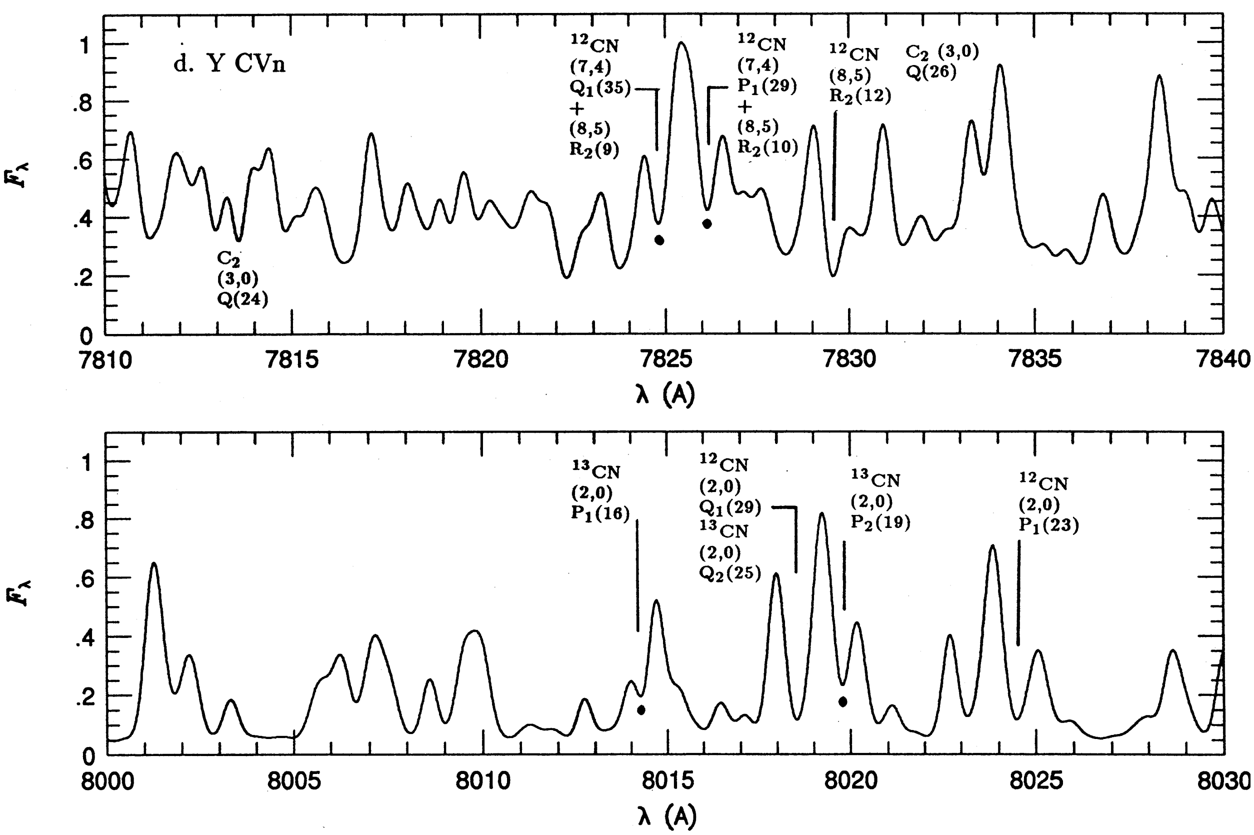

Fig. 4d. The observed spectrum of Y CVn. See also the legend to Fig. 4a

However, only several lines could be found for the stars whose spectra show very strong ^{13}CN lines. Some lines are blended with other lines of the same isotopic species at almost the same wavelength. We used such lines, if the blending lines are weak enough, considering their gf-values and LEP's.

It is very difficult to determine the true continuum level in such heavily line-blanketed spectra as shown in Figs. 4a–d. It should be kept in mind, however, that $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios are derived from the horizontal shifts between the two curves of ^{12}CN and ^{13}CN, namely, the ratios are determined basically from the lines of ^{12}CN and ^{13}CN with the same intensity. In other words, the absolute values of central depths, which should be measured with respect to the *true* continuum, do not matter. The point is that the central depths measured with respect to the *fictitious* continuum level is a kind of measure of line intensities, and that they serve to recognize that the lines of ^{12}CN and ^{13}CN are of *iso*-intensity. Thus, the resulting $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios are not affected by the location of the fictitious continuum level, as long as it is assumed to be constant over the region observed. The spectral synthesis method, which is often used in the analyses of complicated spectra, is not applied in the present work. In fact, such analyses cannot be justified unless a spectral range wide enough to reach some points of the true continuum is used, since synthetic spectra are usually normalized by the true continuum.

The uncertainties of the resulting $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios amount to about 20%. For several stars, the uncertainties are much larger, about 50%. The internal errors, which result from the scattering of the lines plotted in the curves-of-growth, dominate the total errors. The effect of changing model parameters is quite minor. An increase or decrease in the effective temperature by 200 K leads to no noticeable change in the resulting $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios. The adoption of the models with C/O = 1.1 and 2.0, instead of C/O = 1.3, neither gives any noticeable changes.

6. Result

The resulting $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios in our program stars are given in the fourth and eighth columns of Table 3. The histogram of the $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios is shown in Fig. 6, and it shows a rather broad peak from 1 to 6. The average of the $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios is 4.7 ± 2.8 (standard deviation). Two exceptions in our sample are VX And and HD 52432, both of which have a ratio of 12. It should also be noted that some of the stars have $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios less than 3∼4, the value expected at the equilibrium of the CN-cycle. Especially, Lee 99, HD 75021, RY Dra, and CG Vul have extremely low $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios less than 2. Though the uncertainties of the $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios are relatively large for some of those stars, such low $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios cannot be explained by the operation of the CN-cycle in equilibrium.

We now turn our attention to the silicate carbon stars. Willems & de Jong (1986) proposed that all silicate carbon stars might have enhanced ^{13}C abundances, noting that at least two of the silicate carbon stars they identified are J-type. Later, Lloyd-Evans (1990) identified seven stars which show the 9.8 μm silicate emission feature and the photospheric spectra of carbon stars. He showed that five of the seven stars are J-type and the classification of the others remained to be further examined. Lambert et al. (1990) identified these two questionable stars as J-type, based on the spectroscopic observation at the K-band. We confirm these previous identifications more quantitatively. The $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios are 5.6 ± 1.4 for GCCCS 447, 4.8 ± 0.8 for BM Gem, 3.0 ± 1.0 for NC 83, 4.8 ± 0.8 for V 778 Cyg, and 5.3 ± 0.9 for EU And. These results are perfectly consistent with their previous identifications as J-type. Moreover, it is worth noting that the five silicate carbon stars have the $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios which are the most common in our sample. In other words, these stars exhibit no peculiar $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios which would be associated with the presence of the silicate emission feature.

Our sample includes seven stars previously analyzed by other authors. Table 4 shows a comparison with the previous results. Y CVn and RX Peg were analyzed by Fujita et al. (1969) and Fujita & Tsuji (1977), and their results are $^{12}\mathrm{C}/^{13}\mathrm{C} = 8$ for Y CVn and $^{12}\mathrm{C}/^{13}\mathrm{C} = 6$ for RX Peg. They determined the excitation temperatures so that the lines due to different bands should form as smooth a curve-of-growth as possible,

Table 4. Comparison with the results derived by the previous authors

Sources	$^{12}\mathrm{C}/^{13}\mathrm{C}$	Molecular System	Type of Analysis
		Y CVn	
Fujita et al. (1969)	8	CN red, Δv = 2, 3	curve-of-growth
Lambert et al. (1986)	3.4 ± 0.4	CN red, $\Delta v = -2$	curve-of-growth
	3.0 ± 0.3	CO, Δv = 3	curve-of-growth
	4.1 ± 0.8	CO, Δv = 2	curve-of-growth
Abia & Isern (1997)	4	CN red, ~ 8000 Å	spectral synthesis
This work	2.0 ± 0.5	CN red, Δv = 2, 3	curve-of-growth
		RX Peg	
Fujita & Tsuji (1977)	6	CN red, Δv = 2, 3	curve-of-growth
This work	7.6 ± 0.4	CN red, Δv = 2, 3	curve-of-growth
		RY Dra	
Lambert et al. (1986)	3.7 ± 0.5	CN red, $\Delta v = -2$	curve-of-growth
	2.7 ± 0.4	CO, Δv = 3	curve-of-growth
	4.0 ± 1.0	CO, Δv = 2	curve-of-growth
Abia & Isern (1997)	3	CN red, ~ 8000 Å	spectral synthesis
This work	1.9 ± 0.2	CN red, Δv = 2, 3	curve-of-growth
		VX And	
Lambert et al. (1986)	13 ± 3	CN red, $\Delta v = -2$	curve-of-growth
	6.5 ± 1.5	CO, Δv = 3	curve-of-growth
	13 ± 3	CO, Δv = 2	curve-of-growth
Abia & Isern (1997)	8	CN red, ~ 8000 Å	spectral synthesis
This work	12 ± 2	CN red, Δv = 2, 3	curve-of-growth
		UV Cam	
Abia & Isern (1997)	6	CN red, ~ 8000 Å	spectral synthesis
This work	2.9 ± 0.4	CN red, Δv = 2, 3	curve-of-growth
		BM Gem	
Abia & Isern (1997)	9	CN red, ~ 8000 Å	spectral synthesis
This work	4.8 ± 0.8	CN red, Δv = 2, 3	curve-of-growth
		V 353 Cas	
Abia & Isern (1997)	7	CN red, ~ 8000 Å	spectral synthesis
This work	6.9 ± 1.2	CN red, Δv = 2, 3	curve-of-growth

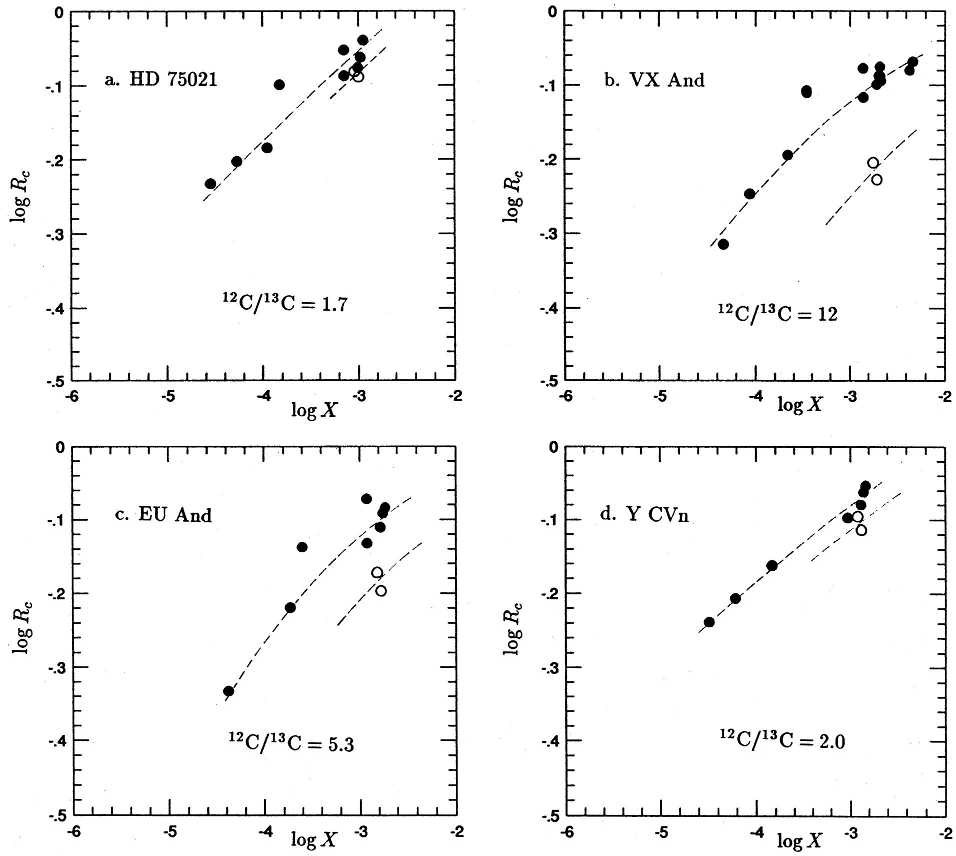

Fig. 5a–d. Examples of the iso-intensity method applied to J-type carbon stars. The ordinates are the logarithms of central depths normalized by the fictitious continuum level, while the abscissas are $\log X = \log(gf\Gamma)$. See also the text. **a** HD 75021. **b** VX And. **c** EU And. **d** Y CVn

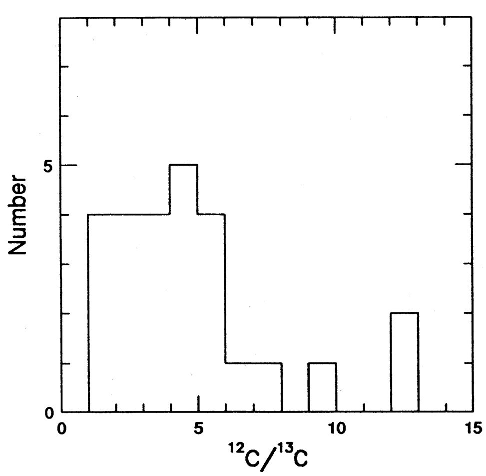

Fig. 6. Histogram of the resulting $^{12}C/^{13}C$ ratios

and the uncertainties of the $^{12}C/^{13}C$ ratios are reportedly about a factor of 2. Thus, given the accuracies of the results and the difference about how to determine excitation temperatures, our results should be preferred to theirs. Our sample also includes three stars analyzed by Lambert et al. (1986) (Y CVn, RY Dra, and VX And). The $^{12}C/^{13}C$ ratios derived by both authors show fair agreement, though our result tends to be somewhat smaller than theirs, except for the value for VX And determined from the CO $\Delta v = 3$ lines. Abia & Isern (1996, 1997) derived $^{12}C/^{13}C$ ratios in 11 J-type carbon stars from CN lines in almost the same wavelength region as we observed, but using the spectral synthesis method. Six stars on the list of Abia & Isern (1997) are included in our sample. The agreement is rather fair, except for UV Cam and BM Gem. Our results are 2.9 ± 0.4 for UV Cam and 4.8 ± 0.8 for BM Gem, while theirs are 6 and 9, respectively. The reason for the disagreement remains to be further investigated. Lambert et al. (1990) estimated that the $^{12}C/^{13}C$ ratios of EU And, V 778 Cyg, NC 83, and BM Gem might be similar to that of VX And ($^{12}C/^{13}C$ = 13 by Lambert et al. 1986 and $^{12}C/^{13}C = 12 \pm 2$ by the present work). But their estimates are based only on the mean equivalent widths of ^{12}CN and ^{13}CN lines located around 2 μm, while our analysis is done on a line-by-line basis, using the model atmospheres in order to take into account the correction for the excitation effect. Therefore, our quantitative analysis finally confirms these silicate carbon stars as J-type.

This agreement of $^{12}C/^{13}C$ ratios among the authors shows a marked contrast to the case of N-type carbon stars discussed in Paper I, where our results of $^{12}C/^{13}C$ ratios are by a factor of 2 to 3 smaller than those derived by Lambert et al. (1986). We pointed out in Paper I that the difference of the model atmospheres used in the analyses might be the reason for the disagreement. However, as we have demonstrated in Paper II, it cannot explain the disagreement. In the case of J-type carbon stars, the enormous strength of ^{13}CN lines might help us measure equivalent widths or central depths relatively accurately both in their analysis and in ours. It might minimize the effect of blending, whether $^{12}C/^{13}C$ ratios are determined by the use of equivalent widths or central depths, while it might have an effect on the analyses of the spectra of N-type carbon stars to some extent. Moreover, thanks to the ^{13}CN lines as strong as the ^{12}CN lines, the $^{12}C/^{13}C$ ratios can be determined from lines with almost the same excitation potentials in the case of J-type carbon stars. The iso-intensity method can best be applied to the case where the line intensities are truly the same. It is also easy for any other method to interpret the lines with similar intensities in terms of abundance ratios. This might be one of the reasons for the agreement of the resulting $^{12}C/^{13}C$ ratios derived by both authors.

7. Discussion – possible scenarios of the formation of J-type carbon stars

$^{12}C/^{13}C$ ratios have been derived for 26 J-type carbon stars and the average is 4.7. The low $^{12}C/^{13}C$ ratios of J-type carbon stars have often been attributed to the mixing of CN-cycled material, since $^{12}C/^{13}C$ ratio is lowered to $3 \sim 4$ at the equilibrium of the CN-cycle. In other words, $^{12}C/^{13}C$ ratios can be $3 \sim 4$, if the photospheres of J-type carbon stars consist of pure CN-cycled material. This is the case expected if the CN-cycle operates at the bottom of the convective envelope (Hot Bottom Burning, HBB). Massive stars, $M > 4 \sim 5M_{\odot}$, develop deep convective envelopes with very high base temperature, leading to the operation of the CN-cycle (Sugimoto 1971, Iben 1975, Scalo et al. 1975, Renzini & Voli 1981, Blöcker & Schönberner 1991). However, the operation of the CN-cycle leads to the conversion of carbon into nitrogen, therefore, prevents stars from becoming carbon-rich. In fact, the HBB is a possible mechanism to keep massive stars from becoming carbon stars, and has been investigated as a way to interpret the absence of massive carbon stars in the Magellanic Clouds.

The extra mixing process suggested by Boothroyd et al. (1995) and Wasserburg et al. (1995) is of interest for understanding low $^{12}C/^{13}C$ ratios in J-type carbon stars. They introduce deep circulation currents below the bottom of the standard convective envelope. The bottom of the convective envelope remains cool, while the circulation currents mix material down to hot layers where the CN-cycle operates (cool bottom processing). Wasserburg et al. (1995) show that $^{12}C/^{13}C$ ratio is lowered to ~ 4 in a $1\ M_{\odot}$ model, while C/O ratio exceeds 1 at a certain time on the AGB by addition of ^{12}C synthesized in the thermal pulse. This prediction is consistent with the $^{12}C/^{13}C$ ratios we have derived here. But their model also predicts large nitrogen enrichments by a factor of 3 to 6. Lambert et al. (1986) determined nitrogen abundances from CN lines in the infrared region for four J-type carbon stars (RY Dra, T Lyr, VX And, and Y CVn), and their result shows that the nitrogen abundances in these stars are sub-solar. They conclude that the CN-cycle is inadequate for explaining low $^{12}C/^{13}C$ ratios in J-type carbon stars, while they also mention that RY Dra and Y CVn are relatively nitrogen-rich, and therefore that the operation of the CN-cycle might be possible. For our program stars, nitrogen abundances have not been determined, except for the four stars analyzed by Lambert et al. (1986). Because most of nitrogen atoms are locked up into N_2 molecules, it is not likely that the uncertainty of nitrogen abundance has a large effect on the temperature stratifications of the models or the resulting $^{12}C/^{13}C$ ratios. Nevertheless, it is highly desirable to determine nitrogen abundances in more J-type carbon stars in order to clarify the origin of low $^{12}C/^{13}C$ ratios and their evolutionary status.

A significant fraction of the stars studied here show $^{12}C/^{13}C$ ratios as low as $1 \sim 2$, which are lower than the value at the equilibrium of the CN-cycle. Though the uncertainties of the $^{12}C/^{13}C$ ratios are relatively large for some of those stars, this result implies that those J-type carbon stars may have experienced non-equilibrium processes or the hot CNO-cycle on their way of evolution.

Another possible scenario of the formation of J-type stars is that they evolve from R-type carbon stars, which also have small $^{12}C/^{13}C$ ratios, $8 \sim 9$ (Dominy 1984). A statistical parallax study (Vandervort 1958) shows that R-type carbon stars have $\sim 100\ L_{\odot}$, which is the luminosity achieved by the He-core burning (Scalo 1976), while Dominy (1984) shows that their effective temperatures are as high as 4000–5000 K. Namely, their locations on the HR diagram correspond to those of the horizontal branch stars. It means that the change of the photospheric composition from oxygen-rich to carbon-rich should take place by the time they come to the horizontal branch. Dominy (1984) suggests that the mixing at the He-core flash could turn oxygen-rich atmospheres to carbon-rich. It will be interesting to perform theoretical calculations of the further evolution of R-type carbon stars, to examine whether the abundances and the isotope ratios observed in J-type carbon stars can be reproduced.

The formation of silicate carbon stars is also controversial. At present, the most plausible scenario may be the binary model proposed by Morris (1987, 1990), Lloyd-Evans (1990), and Lambert et al. (1990). The picture depicted by this scenario is that the material shed by an oxygen-rich primary star, possibly at the He-core flash, is stored in the accretion disk around a low mass companion until the primary becomes a carbon star. Barnbaum et al. (1991) show that the variations of radial velocities observed for EU And, BM Gem, and V 778 Cyg are consistent with motion in binary systems. Recently Kahane et al. (1998) detected a narrow feature of CO emission (J = 1−0 and 2−1) toward BM Gem, and they suggest that it is attributable to a circumbinary disk which is distorted or puffed-up. However, as Lambert et al. (1990) point out, a critical issue for this model is the stability of the accretion disk. Namely, if it is formed when the primary star is on the horizontal branch, it must survive until the primary becomes a luminous carbon star. It is impossible to verify this scenario based on our result of $^{12}C/^{13}C$ ratios alone. However, as the previous section shows, the $^{12}C/^{13}C$ ratios in the five silicate carbon stars studied in the present work show no peculiar values as compared with those of other J-type carbon stars. This implies that the mechanism responsible for low $^{12}C/^{13}C$ ratios in silicate carbon stars might be the same with that working in other J-type carbon stars. It might be inferred that the progenitors of silicate carbon stars and other J-type carbon stars are the same, R-type carbon stars for example, and that some descendants could be observed as silicate carbon stars when the conditions for the stability of the accretion disk, such as the mass ratio of the primary to the companion, the separation, etc., are met.

8. Concluding remarks

The major result of this work is that $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios have quantitatively been determined for a large sample of J-type carbon stars. The distribution of the $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios shows a rather broad peak from 1 to 6. A significant fraction of the program stars have $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios smaller than the value expected at the equilibrium of the CN-cycle. Two stars, VX And and HD 52432, are found to have moderately high $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios.

The cool bottom processing seems to be adequate for explaining the low $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios derived here, but nitrogen abundances should be analyzed for more J-type carbon stars, in order to examine this scenario further. The analysis of the elemental abundances of carbon and oxygen as well as oxygen isotope ratios is also important in the understanding of the nuclear mechanism responsible for the formation of J-type carbon stars.

The five silicate carbon stars in our sample show no peculiar $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios as compared with other J-type carbon stars. This result suggests that the mechanism which lowers $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios in silicate carbon stars might not be different from that operating in other J-type carbon stars. Though the scenario in which the oxygen-rich material shed at the He-core flash is stored in the accretion disk around the companion has still some drawbacks, it might be possible that some of R-type carbon stars would evolve and be observed as silicate carbon stars, when the conditions for the survival of the accretion disk are met.

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