69. Possible Presence of the Forbidden [CI] λ 8727 Line in Carbon Stars

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In carbon stars it seems needless to say that the abundance of carbon acts an important role in discussing theoretical problems connected with dissociative equilibrium of atomic elements and molecular compounds. It has been, however, very difficult to find any available lines of atomic carbon in the photographic spectral region of cool carbon stars. Recently Lambert and Swings (1967) discussed forbidden [CI] lines and assigned λ 8727.13 line in the solar spectrum to a [CI] forbidden line ($^1D_2 - ^1S_0$) with a large value of transition probability. Spinrad and Wing (1969) suggested the possibility of this line to be identified also in carbon stars.

Though this paper is somewhat of preliminary nature so far as it is concerned with this problem, it will be of some importance if more detailed and careful quantitative analysis could be carried out.

Investigation was tried on some infrared spectrograms of thirteen carbon stars in the spectral region around λ 8727, which have been obtained by a spectrograph giving a dispersion of 8 Å/mm at the Coudé focus of the 188 cm reflector of the Okayama Astrophysical Observatory. For the check of identification some echelle spectrograms of Y CVn and 19 Psc giving a dispersion of 3 Å/mm were also studied.

In the spectral region around λ 8727, spectra of carbon stars are mainly characterized by $A^2\Pi - X^2\Sigma$ CN lines (Davis and Phillips, 1963) as is shown in Table I and schematically in Fig. 1.

Table I

λ	Transition	Assignment	Rotational quantum number
8724.81	5,3	P ₂	30
25.89	6,4	Q ₂	6
26.20	5,3	R ₁	44
26.78	4,2	R ₂	60
28.40	5,3	Q ₁	36

As it is clearly seen from Fig. 1, no blending effect of other lines seems considerable to disturb the λ 8727 [CI] line. Even if the EuI λ

Fig. 1. Schematic diagram of $A^2\Pi-X^2\Sigma$ CN lines around λ 8727.

C10-920 Y CVn

Fig. 2. Microphotometric tracing of Y CVn in the spectral region around λ 8727.

8727.77 line (King, 1939) and the SiI λ 8728.38 line (multiplet number 79) (Moore, 1945) exist, they are impossible to affect the [CI] line in a spectrogram of such a dispersion as 8 Å/mm. The possibility of the FeI λ 8727.10 line (multiplet number 999) affecting the [CI] line is also excluded because FeI lines with multiplet number larger than 983 seems absent in cool carbon stars (Fujita and Yamashita, 1963). An example showing the identification features of spectral lines around λ 8727 referring to a microphotometric tracing of Y CVn is illustrated in Fig. 2. It should be mentioned that the [CI] λ 8727 line is clearly identified and its measured wavelength gives 8727.16 showing good coincidence with the value obtained by Lambert and Swings (1967).

Thus the feature of the [CI] λ 8727 line was investigated on microphotometric tracings of thirteen carbon stars and the different appearance of this line from star to star was recognized. Another example which indicates a weak [CI] λ 8727 line is illustrated in Fig. 3.

C10-736 ST Cam

Fig. 3. Microphotometric tracing of ST Cam in the spectral region around λ 8727.

Table II

Star	C-Subtype	C ₂ Percentage	[CI] λ 8727 Eye estimation
RY Dra	C4 ₄	0.366	4
Y CVn	C5 ₄	0.326	5
W Ori	C5 ₄	0.297	4
S Sct	C5 ₄	0.292	5
ST Cam	C5 ₄	0.290	2
X Cnc	C6 ₄	0.278	2
Y Tau	C7 ₄	0.236	1
U Hya	C7 ₃	0.232	2
DS Peg	C6 ₃	0.229	3
UU Aur	C5 ₄	0.220	3
UX Dra	C7 ₃	0.208	2
BL Ori	C6 ₃	0.197	2
19 Psc	C7 ₃	0.147	1

Question is how to evaluate quantitatively the intensity of the [CI] λ 8727 line. As a first and preliminary trial, eye estimation of the intensity of this line was tried referring to nearby CN lines and fictitious continuous background with five intensity grades ranging from 1 (weakest) to 5 (strongest). The results of estimation are shown in Table II.

Dissociative equilibrium of C, C₂ and other molecules which are possible to combine with C in carbon stars is one of interesting theoretical problems. To help the understanding in connection with this problem, it may be worthwhile to see the correlation of the intensity of the [CI] λ 8727 line and the intensity of C₂ molecular lines. As the absorption percentage of (1, 0), (0, 0), and (0, 1) bands of the C₂ Swan System was obtained from spectral scanning in some carbon stars (Fujita, 1967 and 1969), it seems plausible to compare the total absorption percentage of those three sequences in thirteen carbon stars (Table II) with the eye estimation above described. The results are shown in Fig. 4 and for reference the correlation between the intensity of the [CI] λ 8727 line and the spectral subtype is shown in Fig. 5. If the intensity of the CN (4, 2) R₂ (60) line is strong in one star the intensity of the [CI] line might be underestimated and if that of the same CN line is weak in another star the intensity of the [CI] line might be overestimated. And thus, the eye estimation of the [CI] line will be dependent on the intensity of the neighbouring CN (4, 2) R₂ (60) line. It was, however, shown that the intensity of the CN Violet System is weak and almost independent of C subdivision in cool carbon stars (Shane, 1928; Bidelman, 1956) and spectral scanning also has the similar tendency (Fujita, 1967 and 1969). Though the situation is not the same because the eye estimation here refers to the infrared A²II-X² Σ CN band, the effect above described would not be necessary to be taken so seriously into consideration.

Fig. 4. Intensity of the [CI] λ 8727 line versus absorption percentage of (1, 0), (0, 0), and (0, 1) bands of the C₂ Swan System.

Fig. 5. Intensity of the [CI] λ 8727 line versus spectral subtype.

Table III

Transition	C ¹² N ¹⁴		C ¹³ N ¹⁴		Assign- ment	Rotational quantum number
	λ	Wave number	λ	Wave number		
4,2	8697.18	11494.83	8718.64	11466.53	Q ₁	50
	8698.55	11493.01	8719.96	11464.79	R ₁	58
	8703.67	11486.26	8724.86	11458.36	P ₂	44
	8706.84	11482.07	8727.90	11454.36	Q ₂	51
	8709.25	11478.89	8730.22	11451.32	R ₂	59
	8712.11	11475.13	8732.95	11447.74	P ₁	44
5,3	8694.07	11498.93	8721.20	11463.16	Q ₁	33
	8695.12	11497.55	8722.20	11461.85	Q ₂	34
	8700.11	11490.95	8726.98	11455.57	P ₂	28
	8700.94	11489.86	8727.78	11454.52	P ₁	27
	8702.30	11488.07	8729.46	11452.32	R ₁	42
	8705.17	11484.28	8731.83	11449.21	Q ₁	34

As it can be seen in Fig. 4, the intensity of the [CI] line is generally proportional to the C₂ band intensity in those thirteen carbon stars. As those belong to cool stars, the correlation shown in Fig. 4 seems quite reasonable from theoretical study of dissociative equilibrium developed by Tsuji (1964). His calculation shows that the concentration of atomic carbon decreases in parallel with that of molecular C₂ toward the lower temperature side from around $\theta=2.0$. Though (1, 0), (0, 0), and (0, 1) bands of the C₂ Swan System are originated from a normal state and the [CI] line from the excited state, the tendency

above described will not change. Another rather difficult problem is how to make quantitative estimation of the [CI] λ 8727 line intensity in order to lead to the direct knowledge of the carbon abundance.

Now, we must pay attention to isotopic $C^{13}N^{14}$ lines of (4, 2) and (5, 3) transitions of the infrared $A^2\Pi-X^2\Sigma$ CN band in the spectral region around λ 8727. The calculated values of those lines by applying the approximation formula $\nu_r^1 = \rho^2 \nu_r$ are shown in Table III. Errors of those values by our approximation cannot be estimated as the comparison of those values with laboratory values is not yet possible. Assuming those calculated wavelengths are displaced from observed ones, we may, however, check if the wavelength coincidence of the [CI] λ 8727 line to any line of $C^{13}N^{14}$ or the blending of the [CI] λ 8727 line by any line of $C^{13}N^{14}$ is possible in the spectra of Y CVn in which the C^{13}/C^{12} ratio is estimated comparatively high (Fujita *et al.*, 1966, 1967, and 1969). The microphotometric tracing shows that the wavelength coincidence of the λ 8727 line to any line of $C^{13}N^{14}$ or the blending of the λ 8727 line by any line of $C^{13}N^{14}$ seems improbable.

Finally we can suggest that the presence of the [CI] λ 8727 line is quite possible in spectra of carbon stars.

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