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CO IN THE INFRARED AND RADIO SPECTRA OF CARBON STARS*

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ABSTRACT

Spectral scans from 2.0 to 2.5 μ of many of the reddest sources in the Two-Micron Sky Survey have resulted in the identification of eight new carbon stars, five of which have subsequently been identified by other observers. These and other known carbon stars have been searched for 2.6-mm CO emission. A broad emission line, similar to that in IRC+10216, has been found in IRC+40540. IRC−20131 and IRC+50338 (V Cyg) show narrow CO lines whose origin is probably interstellar.
Subject headings: carbon stars — infrared sources — molecules

I. INTRODUCTION

The $J = 1 \to 0$ rotational line of carbon monoxide at 2.6 mm has been found in the spectra of two carbon stars (Solomon *et al.* 1971; Wilson *et al.* 1973) which have relatively large amounts of circumstellar material. The existence of such material can be inferred from infrared photometric (Gillett *et al.* 1971) and infrared spectroscopic (Frogel and Hyland 1972) observations of carbon stars. For previously unclassified infrared sources, however, photometric data alone cannot easily distinguish between carbon-rich and oxygen-rich stars. On the other hand, scans in the 2.0–2.5 μ region with a resolution of 32 or 65 Å mm^{-1} can be used to make this distinction (Frogel and Hyland 1972; Hyland *et al.* 1972).

For the present study such scans were used to select the carbon stars from some of the previously unidentified, reddest 2.2-μ sources in the Two-Micron Sky Survey (Neugebauer and Leighton 1969). Several of these unidentified sources were subsequently independently identified as carbon stars by other authors from shorter wavelength spectroscopic data. We then observed these and other carbon stars at 2.6 mm in an attempt to find additional stellar sources of CO emission.

II. OBSERVATIONS AND RESULTS

The 2.0–2.5 μ scans of eight previously unidentified IRC sources were made at a resolution of 65 Å mm^{-1} with an 0.5-m Ebert–Fastie spectrometer (McCammon *et al.* 1967) during 1969 and 1970. The spectrometer was attached to the Cassegrain foci of the 60-, 100-, and 200-inch (1.5, 2.5, and 5 m) telescopes of the Hale Observatories. Telluric absorption features were removed, and the scans were placed on an absolute flux scale by either direct or indirect comparison with α Lyrae. Details of this procedure are given in Frogel (1971) and summarized in Hyland *et al.* (1972). The Journal of Observations of the eight IRC sources plus two comparison objects is given in Table 1. Also indicated in Table 1 are the identifications of IRC sources with stars in the General Catalogue of Cool Carbon Stars (Stephenson 1973) made by Baumert (1974), and the identification of IRC+20370 as a carbon star by Vogt (1973). Monitoring with the 62-inch infrared telescope on Mount Wilson of the 2.2-μ brightness of all sources except IRC−20131 and IRC+20326 (Becklin, private communication) over several years indicates that they are long period variables. Two of these, +30219 and +50030, have been independently classified as long-period variable carbon stars by Lockwood and Zinter (1973). The scans of all eight are shown in Figure 1, together with two comparison spectra.

The carbon star identification is determined simply by a comparison with similarly obtained scans of known carbon stars, including IRC+10216 (Frogel and Hyland 1972; Becklin *et al.* 1969). In particular, carbon-rich stars can be easily distinguishable from oxygen-rich stars of similar temperature by at least two of the following features: (*a*) the absence of the 1.9-μ H_2O absorption band; (*b*) the near zero or positive slope of the spectrum (log F_λ versus λ) in the 2.0–2.3 μ region; (*c*) the appearance of the 2.29-μ CO bands; (*d*) the appearance of several characteristic, weak absorption features, including a broad (0.06 μ), shallow depression at $\sim$2.18 μ. (Compare the carbon star spectra published in Frogel and Hyland 1972 with the oxygen star spectra published in Hyland *et al.* 1972.) The features noted in (*d*) may arise from a blending of the 1–3, 2–4, and 3–5 band heads of the

* The infrared data presented in this paper were obtained while JAF and ARH were at Hale Observatories, Carnegie Institution of Washington, and California Institute of Technology.

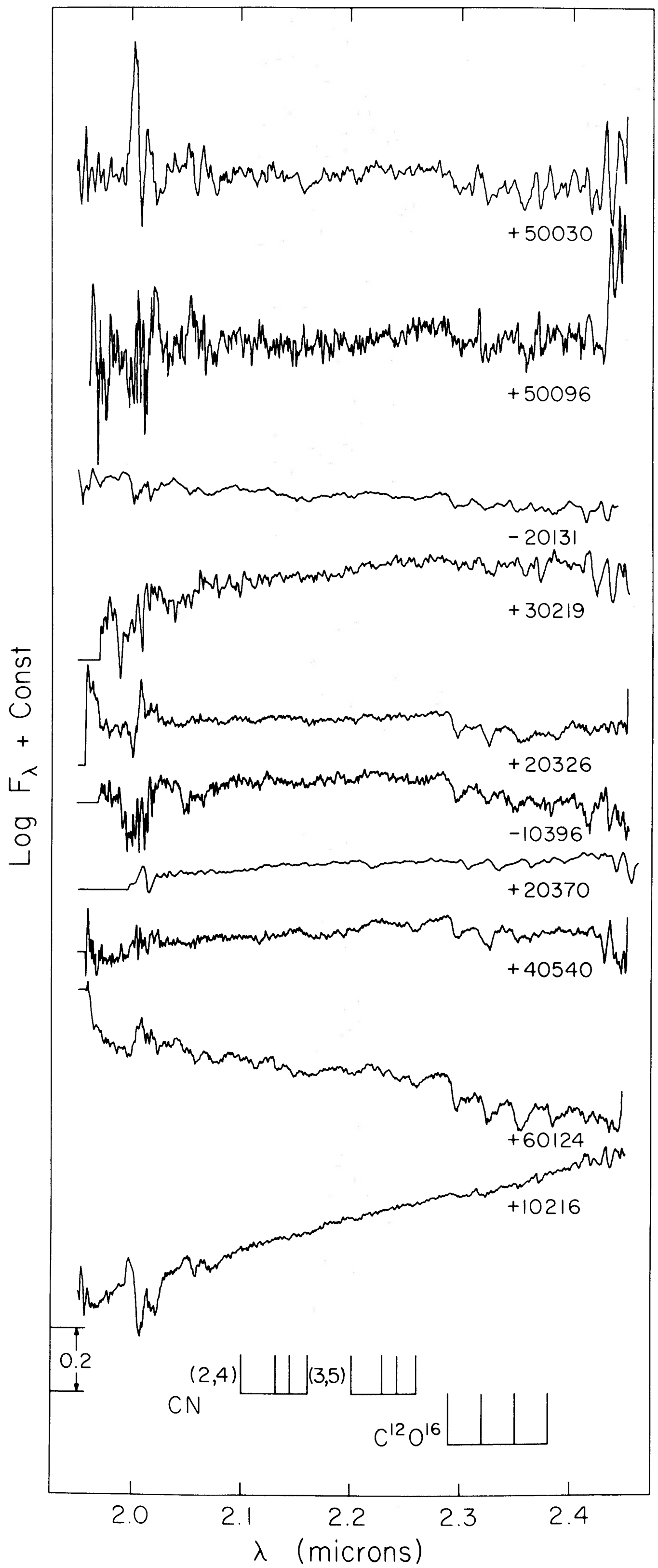

FIG. 1.—Spectra of carbon stars with telluric absorption features and the instrumental sensitivity function removed

TABLE 1

INFRARED SPECTROSCOPIC OBSERVATIONS

IRC	Date	Telescope	$I-K$	$\log F_{\rm cont}/F_{\rm CO2.3\mu}$	2.6-mm Emission	Notes†
+50030..........	1970 Jan 17	60″	6.08	0.075	No	CCS#56
+50096..........	1969 Aug 28	60	6.39	0.069	No	CCS#142
−20131..........	1970 Jan 26	200	6.08	0.047	Yes	CCS#776
+30219..........	1969 May 24	60	7.54	0.031	Yes	CCS#1641
+20326..........	1969 June 22	200	5.56	0.078	No	New
−10396..........	1969 June 13	100	7.50	0.086	No	New
+20370..........	1969 June 21	200	4.91	0.037	No	Vogt 1973
+40540..........	1969 June 22	200	6.73	0.062	Yes	New
+60124*.........	1969 Nov 22	60	4.27	0.103	No	CCS#154
+10216*.........	1969 Apr 24	60	6.15	0.022	Yes	

* The spectra of these stars are included for comparison.

† "New" indicates previously unpublished identification.

CN red system. The weakness of the 2.29-μ band in all of the spectra of Figure 1 is taken as evidence for a circumstellar emission filling in this normally strong photospheric absorption feature (Frogel and Hyland 1972). The extreme redness of the $I-K$ color (Table 1) and of the emission at longer wavelengths (Frogel, unpublished data) is independent evidence for such circumstellar emission.

We have observed these stars, plus other known carbon stars not observed by Wilson *et al.* (1973), in an attempt to find additional stellar sources of CO emission at 2.6 mm. IRC+30219 has already been detected as a CO source by Wilson *et al.* (1973). Radio observations were made on the 11-m telescope of the National Radio Astronomy Observatory,[1] Kitt Peak, Arizona, with supplemental work done on the 5-m paraboloid of the Millimeter Wave Observatory,[2] Fort Davis, Texas.

At NRAO the receiver was operated in the total-power mode with the telescope switching on- or off-source every 30 s. In Texas, frequency switching was used in addition to moving the telescope at half-minute intervals. Care was taken to make sure there was no background CO signal in the off-source position. Both receivers used a crystal diode mixer with a 1390-MHz first IF coupled to an L-band parametric amplifier. The NRAO system used 256 quarter-megahertz filters, the Texas receiver used 40 two-megahertz filters. Single-sideband temperature was approximately 1500 K at NRAO, about 1700 K at Texas. Calibration was provided by a chopper wheel, and pointing was checked daily on Jupiter (NRAO) and the Sun (Texas).

Table 2 lists those stars searched for 2.6-mm CO emission. Line parameters are given for those stars in which we detected emission. The line of +40540 (Fig. 2) is similar to the lines in +10216 and +30219, namely, wide (~20 km s^{-1}) and relatively flat (Wilson *et al.* 1973). Two off positions measured 3′ away from +40540 give an upper limit (3 σ) of ~0.3 K to any background component to the line. (IRC+10216 is a star which has a large expanding circumstellar cloud, as shown by radio and infrared observations [Wilson *et al.* 1971; Toombs *et al.* 1972].)

The CO emission lines in +50338 (V Cyg) and −20131 are quite narrow and unlike the lines found in the other carbon stars. Off-source spectra suggest that these lines are interstellar in origin.

III. DISCUSSION

The infrared properties of the three broad-line CO emission stars are quite uniform and represent one extreme of the continuum of values these properties can assume:

1. They are at the end of the color scale, $I-K > 6$. Data at longer wavelengths (Gillett *et al.* 1971; Frogel, unpublished data) are consistent with this.
2. The 2.0–2.5 μ scans indicate that the 2.29-μ CO absorption bands are weak or absent, presumably because of the presence of substantial circumstellar emitting material. Table 1 contains a quantitative

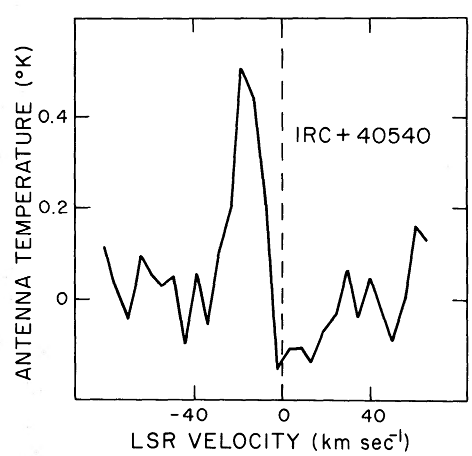

FIG. 2.—Spectra of the 2.6-mm CO emission line in IRC+40540.

[1] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

[2] The Millimeter Wave Observatory is operated by the Engineering Research Laboratory, University of Texas at Austin, with support from the National Aeronautics and Space Administration, the National Science Foundation, and McDonald Observatory.

TABLE 2

2.6 MILLIMETER OBSERVATIONS

IRC	Other Designations	$I-K$	T_{ant} (K)	Velocity (lsr) (km s^{-1})	Width (km s^{-1})	Upper† Limit (K)	Velocity Range Searched (km s^{-1})
50030*.....	HV Cas	6.08	...	...	...	1.00	−9 to 198
50096*.....	...	6.39	...	...	...	0.45	−83 to 83
−10080......	R Lep	5.03	...	...	...	0.45	−53 to 113
30114......	S Aur	6.25	...	...	...	0.40	−83 to 83
−20131*.....	...	6.08	1.5	76	3	...	... ...
−20199......	Y Hya	3.68	...	...	...	0.50	−83 to 83
−10242......	U Hya	3.46	...	...	...	0.50	−83 to 83
−20218......	V Hya	4.62	...	...	...	0.45	−83 to 83
00217......	SS Vir	3.57	...	...	...	0.35	−83 to 83
50219......	Y CVn	3.60	...	...	...	0.45	−83 to 83
40273......	V CrB	4.94	...	...	...	0.35	−198 to −32
20326*.....	...	5.56	...	...	...	0.60	−83 to 83
60255......	T Dra	5.51	...	...	...	0.60	−83 to 83
−10396*‡....	...	7.50	...	...	...	0.90	−83 to 83
20370*.....	...	4.91	...	...	...	0.45	−83 to 83
40321......	T Lyr	4.44	...	...	...	0.50	−83 to 83
80036......	UX Dra	2.99	...	...	...	0.45	−83 to 83
50324......	U Cyg	4.62	...	...	...	0.50	−83 to 83
50338......	V Cyg	6.27	2.5	−3	3	...	... ...
40540*.....	...	6.73	0.6	−20	17	...	... ...
10216§.....	...	6.15	1.6	−24	22	...	... ...
30219*§....	RW Lmi	7.54	0.4	0	22	...	... ...
00382§.....	...	6.62	0.8	14	6	...	... ...

* These stars have 2.2-μ spectra reproduced in this paper.

† Effective peak-to-peak temperature for 2-MHz resolution per channel.

‡ Upper limit for CO is less than 1.5 K from −83 km s^{-1} to −115 km s^{-1}.

§ These stars were observed by Wilson *et al.* 1973.

estimate of the 2.3-μ $^{12}C^{16}O$ band head with respect to the extrapolated continuum.

3. The stars for which appropriate data are available are all long-period variables.

These conditions appear necessary, but not sufficient, for 2.6-mm CO emission.

Apart from the obvious differences in the (C/O) abundance ratio, the optical and infrared characteristics of the CO emission stars are similar to the characteristics of the stellar OH and H_2O sources discussed by Hyland *et al.* (1972), Wilson *et al.* (1972), Frogel (1971), and Dickinson *et al.* (1973). They are all late spectral type (photospheric temperatures <2500 K), are variable, and have a large infrared excess. Such similarity is not unexpected: cool photospheric temperatures allow the formation of molecules (cf. Tsuji 1964), and variability may provide the energy necessary to expel the molecules into extended circumstellar regions and, perhaps pump the maser emission of OH and H_2O (Frogel 1971; Dickinson *et al.* 1973). The infrared excess confirms the presence of extensive circumstellar material and hence an outward flow of mass from the photosphere.

There are interesting differences, however, between oxygen-rich and carbon-rich stellar microwave sources. Calculations by Tsuji (1964) show that the partial pressure of CO is similar in the photospheres of both oxygen- and carbon-rich stars and, further, its value is close to that of the H_2O partial pressure for the oxygen-rich stars. Why, then, has CO emission not been detected in the oxygen-rich stars that are H_2O sources? Second, the presence of an infrared excess in the CO stars is evident at wavelengths as short as 2.2 μ (Frogel and Hyland 1972; Frogel, unpublished data), whereas in H_2O and OH emitters the excess is usually present only for $\lambda > 3.5\ \mu$. This may be due to intrinsic properties of the carbon grains (Neugebauer *et al.* 1971). It is also true that the three CO stars are all long-period variables, whereas some OH and H_2O stars are semiregular or irregular variables. This difference, of course, is tentative, given the paucity of CO stars.

Perhaps CO emission requires a more extensive circumstellar envelope and, consequently, greater column densities. Since long-period variability is the most energetic phenomenon associated with noncataclysmic variables, it may be required to supply the environment in which CO emission can take place. Observations of more stars to more sensitive levels should help shed light on these problems.

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