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IDENTIFICATION OF NEW INFRARED BANDS IN A CARBON-RICH MIRA VARIABLE

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ABSTRACT

For the first time, we present complete 0.75–13 μm spectrometry of a carbon-rich, Mira-class variable star. Although the near-infrared is dominated by photospheric absorption bands of the CN red system, the infrared becomes progressively dominated by the bands of the polyatomic molecules HCN and C_2H_2. Since the band at 3.1 μm is known to be due to HCN and C_2H_2, we are able to associate bands at 1.04, 1.53, 1.85, 2.5, 2.7, 3.56, 3.85, 4.8, and 7.1 μm with HCN and C_2H_2. The spectrum indicates that radiative transfer in the carbon Mira class cannot be discussed quantitatively without the inclusion of HCN and C_2H_2 opacity. From a consideration of the carbon star models of Querci and Querci, it is deduced that the abundance ratio of HCN to C_2H_2, $A(\mathrm{HCN})/A(C_2H_2)$, can be used to indicate whether 3α-processed or CNO-processed material is in the outer atmosphere. $A(\mathrm{HCN})/A(C_2H_2) \gg 1 \Rightarrow \mathrm{CNO}$; $A(\mathrm{HCN})/A(C_2H_2) \leq 1 \Rightarrow 3\alpha$. An 11.3 μm SiC dust-emission feature is present, although it is significantly different from the 11.7 μm SiC feature in Y CVn. A featureless emission is present from 4 to 13 μm and can be ascribed to optically thin graphite grains with a temperature of 450 K.

Subject headings: infrared: spectra — line identification — molecular processes — stars: abundances — stars: carbon — stars: long-period variables

I. INTRODUCTION

The star V Coronae Borealis (V CrB; C6, 2) represents a type of carbon star intermediate in its color temperature between the SR*b* variables and the dust-enveloped CW Leo (IRC +10216) class of objects. Previous interpretations of such stars have relied on broad-band photometry (Mendoza and Johnson 1965; Forrest, Gillett, and Stein 1975, hereafter FGS; and Merrill 1977), or on incomplete spectrophotometry (Frogel and Hyland 1972; and Merrill and Stein 1976, hereafter MS) as a data base. Generally, the flux curve of cool carbon stars has appeared too broad for description by a single blackbody; hence, the conclusion may be drawn that photospheric radiation is being redistributed at longer wavelengths (Frogel and Hyland 1972). The above argument must certainly be true for the Mira V Cyg (FGS; Puetter *et al.* 1977), while Merrill (1977) suggests that the radiation we are observing from the Mira R Lep is from its cold photosphere. Apparently all Miras do not behave in the same way.

In this paper we present the 0.75–13 μm infrared spectrum of V CrB. This is the first such complete infrared spectrophotometry of a carbon-rich Mira-type variable. In the near-infrared, V CrB displays strong CN red-system ($\Delta v = 2$, 1, and 0) bands, indicating photospheric-dominated radiation. Beyond 1.2 μm, the spectral characteristics of V CrB change dramatically. We will argue that its spectrum is dominated by bands of HCN and C_2H_2 molecules. The domination is so extensive that radiative transfer calculations (model atmospheres) cannot be attempted for this star, or for any other cold carbon star, without the inclusion of HCN and C_2H_2 opacities. The HCN and C_2H_2 opacities are analogous to H_2O steam opacity in oxygen-rich, cool Mira stars.

The presence of large column densities of HCN and C_2H_2 may lessen the amount of graphite necessary to explain carbon Mira flux curves, as is outlined below. The previously accepted conclusion that the emergent flux of all carbon Miras is redistributed by dust will require modification in light of the present data, as (1) the previous analysis did not include polyatomic opacity, (2) the polyatomics compete with graphite for free carbon, and (3) the opacity effects of the strong CN bands were not considered. We will not provide the model solution to the problem; rather, we will show that these effects can no longer be ignored if further progress in modeling this class of stars is anticipated.

II. OBSERVATIONS

The infrared spectrophotometry of V CrB is presented in Figure 1. The spectrum is a composite of four different spectral regions taken with four different instruments. Each region was reduced independently and the flux density plotted. No attempt has been made to shift regions to attain agreement, as there are no overlapping spectral regions.

Because of its period of 357.8 days, an effort was made

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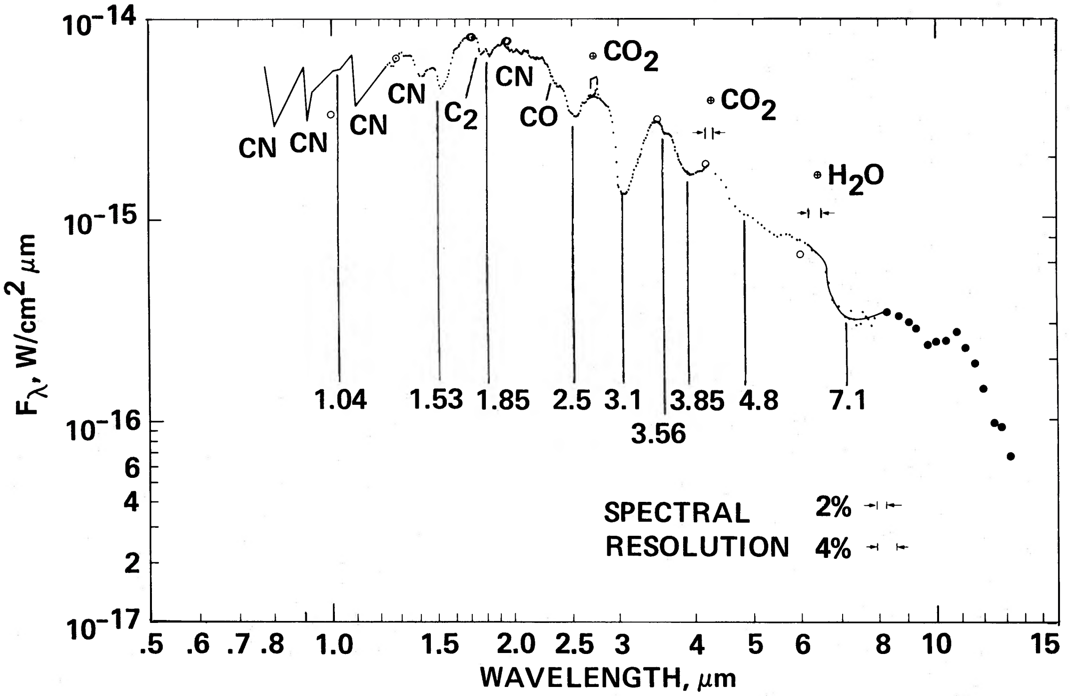

FIG. 1.—Spectrophotometry of the carbon star V CrB (C6, 2e) between 0.75 and 13 μm. Regions of atmospheric interference at 2.7, 4.3, and 6.3 μm are indicated. Data points between 0.75 and 1.1 μm are connected with straight lines. The solid line between 6 and 8 μm is a hand-drawn average of data points done for clarity. The open circles are computed 1675 K blackbody fluxes.

to observe V CrB nearly simultaneously in each of the separate spectral regions. The inherent difficulties in coordinating this effort made this goal impossible. But as can be seen from Table 1, the times are close enough that unification into a single spectrum is reasonable for all but the shortest wavelength region.

The 0.75–1.1 μm spectrum was observed on two nights by B.J.T. using the 0.9 m (36-inch) Crossley telescope of Lick Observatory. Selected Wing bands (Wing 1967) at 7812, 8116, 9044, 9190, 9316, 10104, 10400, 10834, and 10964 Å were used. The spectral resolution was 32 Å. The averaged data from the two nights are given here; their signal-to-noise ratio exceeds 50 at all wavelengths. For one night, atmospheric extinction was determined from two observations each of β Leo and α Ser; for the other, standard extinction was used. The passbands and standards are from Wing (1967); the correction of the latter, from the Oke (1964) to the Hayes and Latham (1975) system, is small and was not applied.

The 1.23–4.2 μm spectrum was taken from the NASA Ames Research Center Kuiper Airborne Observatory (KAO), using the instrument and techniques described by Strecker, Erickson, and Witteborn (1979, hereafter SEW). The secondary standard used was α Boo, assumed to have

TABLE 1

OBSERVATIONS OF V CRB

Wavelength range (μm)	Date (UT)	Telescope	Instrument	Standard Star	Spectral Resolution	Mira Phase[a]
0.75–1.1................	1979 June 12 1979 June 13	UCLO Crossley 36 inch (91 cm)	UCLO single channel scanner with trimetal phototube	β Leo α Ser	0.4%	0.74
1.23–4.6................	1979 April 19	NASA KAO 36 inch (91 cm)	NASA ARC filter spectrometer with InSb detector	α Boo	2%	0.59
4.0–8.0................	1979 April 11	NASA KAO 36 inch (91 cm)	UCSD filter wheel spectrometer with PbSnTe detector	α Lyra α Boo	2%	0.57
8.0–13.0..............	1979 May 11	NASA Mount Lemmon 60 inch (1.5 m)	NASA ARC filter wheel spectrometer with Si : As detector	α Boo	4%	0.65

[a] Mattei, J. A., private communication.

the flux distribution given by SEW. The spectral resolution is 1.5%. Because we oversample resolution elements, the scatter between adjacent data points is a measure of signal to noise.

The 4.4–8.0 μm segment was taken from the KAO utilizing the University of California at San Diego spectrophotometer (Puetter *et al.* 1981). The methodology of observation and data reduction was the same as that of SEW in the 1.2–4.2 μm region. Both α Lyr and α Boo were observed on another night, so the flux of α Boo could be determined directly on that night from the model of Schild, Peterson, and Oke (1971) for α Lyr. Because of an atmospheric correction problem at 6.3 μm, the data displayed are in two segments. From 4.4 to 6 μm, V CrB is ratioed directly to α Lyr. From 6 to 8 μm, V CrB is ratioed to α Boo, whose flux is known from its ratio to α Lyr as described above. In order to enhance signal-to-noise in the 6–8 μm region, each spectral point has been averaged with a three-point slit function. This causes only a small loss of spectral resolution, since the spectrum is oversampled. The resulting spectral resolution is 2%.

The 8–14 μm spectrum was taken with the NASA Mount Lemmon 1.5 m (60 inch) telescope. The standard star used was α Boo. The observational method is described by Bregman and Witteborn (1980). The spectral resolution is 4%.

The Mira phase in Table 1 has been kindly provided by the American Association of Variable Star Observers (AAVSO) (Mattei, private communication). AAVSO observations dating back to 1967 show visual maxima ranging from 7.5 to 6.9 and the minima from 12.2 to 11.0. No trend toward brighter maxima or fainter minima is indicated by their data, and the average amplitude is 4.9 mag. Our data were taken near visual minimum ($m_v \approx 10.8$), except for the 0.75–1.1 μm portion, which was taken at about three-quarters phase, i.e., at the beginning of the steeply rising portion of the visual light curve. As the shortest wavelength range is nearest the visible, and is therefore the most variable, we have not included it in Figure 2.

III. DISCUSSION

Because of the lack of simultaneity, certain problems cannot be addressed, such as the precise nature of the underlying photospheric continuum or the exact amount of overlying "graphite" dust. In this discussion, we will therefore avoid conclusions which are strongly dependent upon simultaneity. Similarly, since the phase was chosen for temporal convenience, no problems relating to variability can be addressed, such as phase dependence of band strengths or infrared color temperature. This latter type of problem is addressed in detail by Bregman and Witteborn (1980).

The infrared color temperature T_{IR} is defined (see

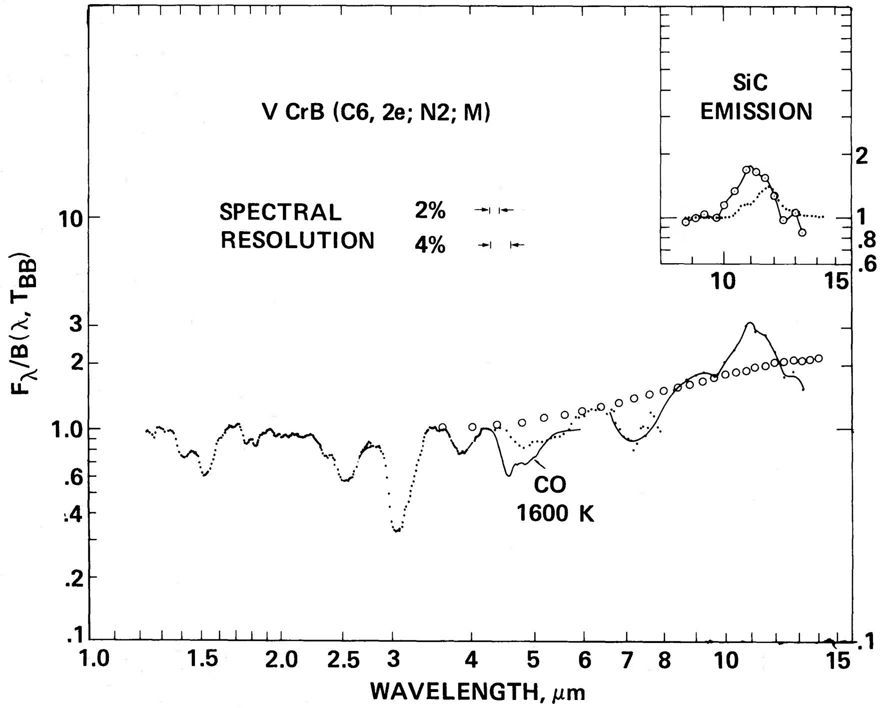

FIG. 2.—The data of Fig. 1 are normalized to a 1675 K blackbody curve between 1.2 and 13 μm. The solid line beyond 6 μm is a hand fit of the data for clarity. The solid line between 4 and 6 μm is the CO fundamental vibration-rotation band opacity of a single slab at 1600 K in absorption against a continuum level of 1.0. The open circles are the graphite excess emission at 450 K as explained in the text. The upper right-hand corner insert is a relative comparison of the present V CrB data (*circled dots*) and the laboratory measurements of Dorschner, Friedemann, and Gürtler (1977) (*dots*) as taken from Goebel *et al.* 1980.

Goebel *et al.* 1978*a*) to be that of the best-fitting blackbody flux curve $B(\lambda, T_{\rm BB})$, $T_{\rm IR} = T_{\rm BB}$, in the wavelength range from 1.2 to 6 μm. For V CrB, $T_{\rm IR} = 1675$ K when our data were obtained. The $T_{\rm IR}$ changes with phase for carbon Miras (Goebel *et al.* 1977). Upon division by $B(\lambda, T_{\rm BB})$, the spectrum is as shown in Figure 2. For purposes of spectroscopy, Figure 2 is the preferred way to present data over such a broad wavelength range. The spectral portion below 1.2 μm has been deleted in Figure 2, as it was the least simultaneous observation, and that region is most sensitive to temperature.

Throughout the infrared spectrum, absorption bands appear which cannot be explained by the most abundant diatomics CN, C_2, and CO. The diatomic band positions and shapes are well known for warmer carbon stars like Y CVn, for which $T_{\rm IR} = 2800$ K (Goebel *et al.* 1978*a* and references therein). Temperature and abundance can modify the CN, C_2, and CO band shapes and centers, but these effects are well understood and are not important to the bands under discussion. We will discuss each band individually. The bands are listed in Table 2 with associated molecules and their vibrational bands in the region of interest.

a) Molecular Bands

i) *The 1.04 Micron Band*

Although CN opacity at 10400 Å is smaller than in the stronger band head regions (Wing 1967), it is not completely negligible in carbon stars. At 10400 Å, some of the carbon stars observed by Wing show a possible opacity other than CN, as he recognized at that time. Our spectrophotometry was at selected bandpasses only, and we cannot say definitively that a polyatomic band is present in V CrB. But it appears, from a comparison of our observations of V CrB with those of other carbon stars observed by Wing, that a polyatomic band is a possible contributor at 10400 Å. Complete scanner spectra are needed in this region (e.g., Faÿ and Honeycutt 1972), preferably at a phase in the V CrB light curve when the polyatomic bands are stronger. It would then be possible to compare the observed spectrum with CN band computations.

TABLE 2

PROPOSED IDENTIFICATION OF BANDS IN V CrB

λ	HCN	C_2H_2	CS	References
	$G'(v)$ $G(v)$	$G(v')$ $G(v)$		
1.04 μm[a]	300–000	0030^00^0–0000^00^0	…	(1), (2)
9620 $\rm cm^{-1}$	…	1112^00^0–0000^00^0	…	…
1.53 μm	200–000	1010^00^0–0000^00^0	…	(1), (3)
6540 $\rm cm^{-1}$	21^10–01^10	1011^10^0–0001^10^0	…	…
1.85 μm	101–000	…	…	(1)
5410 $\rm cm^{-1}$	11^11–01^10	…	…	…
2.5 μm	002–000	0011^10^0–0000^00^0	…	(1), (4)
4000 $\rm cm^{-1}$	11^10–000	1000^01^1–0000^00^0	…	…
	12^20–01^10	0102^01^1–0000^00^0	…	…
	12^00–01^10	1001^11^1–0001^10	…	…
		0100^03^1–0000^00^0	…	
2.8 μm	…	1000^01^1–0001^10^0	…	(4)
3570 $\rm cm^{-1}$	…	…	…	…
3.1 μm	100–000	0101^11^1–0000^00^0	…	(1), (4)
3230 $\rm cm^{-1}$	11^10–01^10	0102^01^1–0001^10^0	…	(5), (6)
	others	0011^10^0–0001^10^0	…	…
		0010^00^0–0000^00^0	…	…
3.56 μm	01^1–000	…	…	(1)
2810 $\rm cm^{-1}$	02^01–01^10	…	…	…
3.85 μm	100–01^10	0100^01^1–0000^00^0	$\Delta v = 1$	(1), (4)
2600 $\rm cm^{-1}$	…	0100^02^0–0000^01^1	…	(7)
	…	0101^11^1–0001^10^0	…	…
	…	0010^00^0–0001^10^0	…	…
	…	1000^00^0–0000^01^1	…	…
	…	0003^11^1–0000^00^0	…	…
4.8 μm	001–000[b]	…	CO $\Delta v = 0$	(1)
2100 $\rm cm^{-1}$	03^10–000	…	(see text)	…
7.1 μm	020–000	0001^11^1–0000^00^0	$\Delta v = 0$	(1), (4)
1410 $\rm cm^{-1}$	…	…	…	…

[a] Band at 1.04 is an association, not an identification.

[b] Raman band, but weakly infrared active due to Coriolis interaction.

REFERENCES: (1) Rank *et al.* 1960; (2) Ghersetti, Adams, and Rao 1977; (3) Varanasi and Bangaru 1975; (4) Bell and Nielsen 1950; (5) Wiggens, Plyler, and Tidwell 1961; (6) Ridgway, Carbon, and Hall 1978; (7) Bailey, private communication.

Opacity other than CN may also be present elsewhere in 0.75–1.1 μm region (Wing 1967). Possible detections of HCN bands in this region have been reported by Faÿ, Fredrick, and Johnson (1968) and Giguere (1973) in much warmer carbon stars. Additional lines attributed to HCN in the 7900–8600 Å range have been reported by Querci and Querci (1970) in another carbon star, UU Aur.

Nearly all the stars examined previously have been rather warm and without very strong 3.1 μm polyatomic bands. Based upon our spectrum of V CrB and the spectra of cooler carbon stars shown in Wing's thesis (1967), we suggest these bands may be found in cool carbon Miras with scanner spectra and are probably due to HCN and C_2H_2, although, according to Ghersetti, Adams, and Rao (1977), the C_2H_2 band may be weak compared with the bands discussed below.

ii) *The 1.53 Micron Band*

This band is quite distinct, even though it is seen against the CN $\Delta v = -1$ red-system band. It does not appear at our 2% spectral resolution nor at higher spectral resolution (McCammon, Münch, and Neugebauer 1967) in carbon stars of infrared color temperatures ($T_{\rm IR}$) greater than 2500 K. Connes *et al.* (1968) may have observed individual lines from C_2H_2 and HCN in Y CVn. To date, it has only appeared in the spectra of the cold Mira-type stars such as V CrB, R Lep, S Cep, U Cyg, and SS Vir. At filter wheel resolution, the fully developed band was first noticed by Goebel *et al.* (1977) in S Cep, but could not be identified at that time. Goebel *et al.* (1978*b*) showed that the band increased with decreasing infrared color temperatures. The band is strongest in V CrB, which has the coldest $T_{\rm IR}$ yet measured in a carbon Mira (1675 K). Oddly, it has the same band shape as the CO second overtone but is displaced a full 0.1 μm shortward of the CO band center's position.

Herzberg (1945) lists an HCN band at 1.53 μm ($2\nu_2$) and a C_2H_2 band at 1.54 μm ($\nu_1 + \nu_3$). Other bands of HCN and C_2H_2 also occur near this wavelength and are listed in Table 2 along with literature references. There is no convenient published spectrum of either molecule at our resolution. We have measured C_2H_2 with a Beckman DK2A spectrometer (Fig. 3) and find a band at 1.52 μm with a half-width of 0.25 μm at 300 K. The intensity measurements of the C_2H_2 bands at 1.53 μm by Varanasi and Bangaru (1975) indicate the band is moderately strong.

The most abundant polyatomic species at temperatures below 2500 K are HCN and C_2H_2 according to most dissociation equilibrium models: Tsuji (1964); Johnson, Beebe, and Sneden (1975); Scalo (1973); and Querci and Querci (1974). Furthermore, as listed by Herzberg, none of the other molecules expected to be abundant in carbon stars has bands reasonably nearby 1.53 μm. For another species to give rise to the band, an unusually strong band strength per molecule would be required. We think this to be quite unlikely. Hence, HCN and C_2H_2 are the most plausible contributors to this band.

iii) *The 1.85 Micron Band*

This band is relatively weak. It might have gone unnoticed except for its effect on the (1, 1) band head of the $\Delta v = 0$ Ballik-Ramsay band of C_2. In all other carbon stars observed to date, the (0, 0) band head at 1.78 μm is noticeably stronger than the (1, 1) band head. In V CrB,

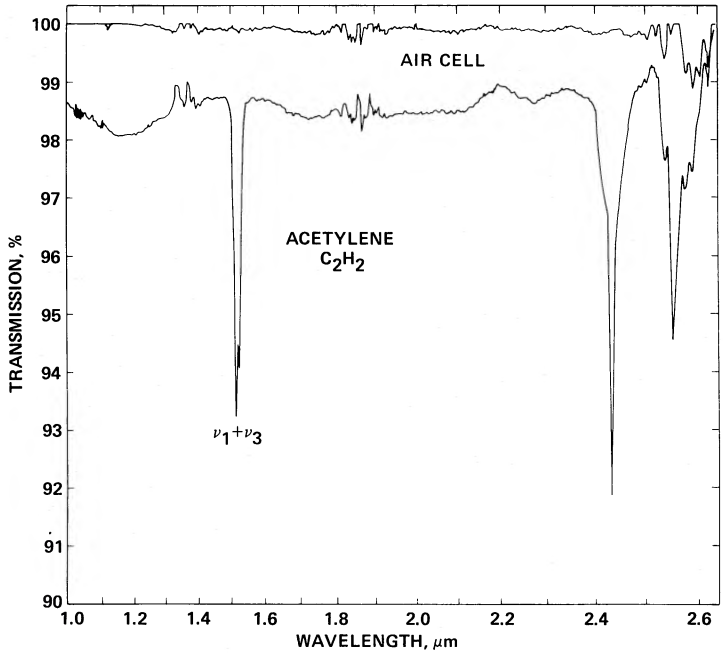

FIG. 3.—A laboratory spectrum of C_2H_2 in absorption at 300 K taken using a Beckman DK2 double-beam spectrometer. The curve labeled "air cell" had the same experimental arrangement but lacked C_2H_2. The 1.5 μm band shows a *P*-branch and *R*-branch but no *Q*-branch. The bands at 2.43 and 2.56 μm contribute to the 2.5 μm absorption discussed in the text.

however, the reverse occurs. Herzberg (1945) lists a medium-strength band $\nu_1 + \nu_3$ at 1.85 μm for the HCN molecule. Even though there is a telluric water-vapor band at 1.85 μm, telluric water cannot be the cause because this spectral region is quite transparent from the KAO, and our calibration procedure does not produce this effect in any of the dozens of stars of various spectral types which we have observed. By itself, this band is insignificant; but coupled with the other polyatomic bands, it serves to strengthen our conclusions concerning the importance of polyatomic opacity.

iv) *The 2.5 Micron Band*

This band was first noticed by Merrill and Stein (1976) as a continued depression of the stellar flux beyond the CO first overtone. The depression could not be clearly observed from the ground because of telluric water beyond 2.5 μm. A 2.5 μm band is not confined to Mira variables only, and this served to confuse identification. Goebel *et al.* (1980) have shown that the 2.5 μm band in SR*b*-type carbon variables is due mostly to C_2 Ballik-Ramsay $\Delta v = 1$ opacity. However, in V CrB, the C_2 Ballik-Ramsay $\Delta v = 0$ band is weak, so the strong 2.5 μm band cannot be due to C_2. Both HCN and C_2H_2 have significant bands in this region. (See, for example, Rank *et al.* 1960; Bell and Nielsen 1950; and Fig. 3.) Ridgway *et al.* (1976) identified the $\nu_1 + \nu_5{}^1$ *Q*-branch of C_2H_2 in this region in IRC +10216, a carbon star with an extensive circumstellar shell. Therefore, we associate this band with HCN and C_2H_2. No other abundant molecules have bands at this wavelength.

v) *The 2.8 Micron Band*

This region of our spectrum is not exceptionally clear because of the telluric CO_2 band. The atmospheric CO_2 band has not been completely corrected for extinction between V CrB and the standard star, and the band heads at 2.69 and 2.77 μm are still apparent. Since these band heads are no more than 1 resolution-element wide in our spectrum, we can interpolate the stellar spectrum through them. The result is that the 2.6–2.9 μm stellar flux is depressed relative to all the high points in the spectrum by about 20%. This is to be expected if C_2H_2 is present in strength, as the 3.1 μm band indicates (Bell and Nielson 1950). A 2.8 μm opacity is present in all Mira-type carbon stars observed to date (Goebel *et al.* 1978*b*).

The interpretation of the 2.8 μm opacity as being due to C_2H_2 offers an alternative to the recent interpretation by Krassner, Smith, and Hilgeman (1979) regarding this opacity observed in IRC +10216. Their claim is that opacity observed in IRC +10216 in this region may be due to an HN–X bond. Except for the strong dust continuum, the molecular bands present in the 3 μm region of IRC + 10216 (Witteborn *et al.* 1980) are little different from any of the other carbon Miras which we have observed. Specifically, the 2.9 μm flux is depressed relative to other continuum points even though the 3.1 μm band is weaker in IRC +10216 than in Miras. Ridgway, Carbon, and Hall (1978) discuss specifically the 3.1 μm band at very high resolution in IRC +10216 and include a portion of the region shortward of 2.9 μm. Their spectrum shows no outstanding features other than those directly attributable to HCN and C_2H_2. Thus, the 20% depression is explainable without invoking an HN–X bond.

vi) *The 3.1 Micron Band*

The 3.1 μm band is well known and studied at high and low resolution (Ridgway, Carbon, and Hall 1978; MS; and Noguchi *et al.* 1977). The predominant species contributing to the band are known to be HCN and C_2H_2, with the relative abundances varying from star to star. Except for the ν_5 fundamental of C_2H_2 at 13.7 μm, the 3.1 μm band is the strongest band in the infrared both in the laboratory (Varanasi and Bangaru 1975) and in the series of bands we are discussing in the V CrB spectrum. Because of the great depth and width of the band, it is evident that it is formed far out in the colder regions of the atmosphere. In V CrB the band cannot be filled in by thermal reradiation of dust, as is the case in IRC +10216. The contention that there is little dust reradiation in the 2–3 μm region of V CrB is supported by the presence of the CO first overtone at 2.3 μm, C_2 Ballik-Ramsay at 1.8 μm, and the CN $\Delta v = -2$ red-system opacity in the 2 μm region of V CrB.

vii) *The 3.56 Micron Band*

The presence of the band in carbon star spectra was first pointed out by Goebel *et al.* (1978*a*) and is associated with the HCN molecule ($\nu_1{}^1 + \nu_3$). It appears as a weak band in conjunction with the 3.1 and 3.85 μm bands.

viii) *The 3.85 Micron Band*

The 3.85 μm band was first studied by MS who observed it in the Mira-type variables. Bregman, Goebel, and Strecker (1978) found it to be correlated with the 3.1 μm band and identified it with a complex of C_2H_2 bands and CS. There may be problems associating the 3.85 μm band with C_2H_2 as Ridgway has failed to detect C_2H_2 lines in the carbon Mira S Cep (Wing, private communication). Generally, the 3.85 and 3.56 μm bands are well separated, unconfused with other molecular bands, and have well-defined band shapes. If their relative strengths can be established from laboratory measurements at elevated temperatures, it may prove possible to utilize these two bands for column density measurements of HCN and C_2H_2 in the Mira carbon stars. Both bands are in the 3.5 μm atmospheric window; therefore, ground-based, high-resolution measurements of individual lines should be possible.

ix) *The 4.8 Micron Band*

At the phase of observation, V CrB had no strong CO fundamental at 4.6 μm. In fact, the flux at 4.6 μm forms part of the continuum on which our estimate of $T_{\rm IR} = 1675$ K is based. There is an apparently rising continuum level between 6.0 and 6.7 μm which is different from that seen between 2 and 4 μm. In order to verify the apparent absence of CO, we have computed the CO fundamental band profile in absorption with respect to unity for isothermal 1600 K CO, as shown in Figure 2.

Clearly the band shape in V CrB does not imitate the 1600 K CO fundamental in that the star shows no absorption shortward of 4.6 μm, although it has opacity extending from 4.6 μm out to about 5.8 μm. If the band were dominated by C_3, as in Y CVn (Goebel *et al.* 1978*a*), then the band center should be at about 5.2 μm. Similarly, SiC_2 should be at 5.7 μm (Treffers, private communication), and C_2H should be at 5.4 μm. HCN has bands near 4.7 μm (Herzberg 1945), which are shown by Rank *et al.* (1960). Band intensity measurements by Kim and King (1979) indicate the HCN bands to be about 500 times weaker than the 3.1 μm band, so this band is not likely to be due to HCN.

In spite of the apparent discrepancy in the band shape, CO may cause the observed absorption. Wing (private communication) has suggested that if reemission in the CO fundamental band is present, then the emission intensity is likely to be greatest at the band head near 4.6 μm and decline in strength to longer wavelengths. The CO absorption band head could then be weakened relative to the 5.0 μm wing of the band. This interpretation requires a fairly strong fundamental band, i.e., a large column density of CO, and that is not ruled out by our observations of other carbon stars. This, like all other identifications proposed, is directly subjectable to future verification with observations at high spectral resolution.

Emission near the first CO overtone band head was seen in the Becklin-Neugebauer (BN) object (Scoville *et al.* 1979); the emission was postulated to be caused by a shock. Although the BN object is a very different type of object than V CrB, Mira variables are likely to have shocks in their atmospheres (Cohen 1980). Similar band-head emission has been seen for SiO in oxygen-rich Miras (Ridgway *et al.* 1977). If the CO mechanism is correct, it may not be sufficient to explain the absorption between 5.5 and 5.8 μm.

One of the more abundant polyatomic species (Tsuji 1964) predicted in low-temperature carbon stars is C_2N_2. With strong bands at 3.76, 3.90, and 4.65 μm and a weak band at 4.78 μm (Herzberg 1945), it might also contribute to the 3.85 μm band. We think this unlikely, as the 4.65 μm band should be stronger than the 4.78 μm band. This is not the kind of 4.8 μm band we see in V CrB. Hence, we can say there is no substantial column density of C_2N_2 in V CrB.

x) *The 7.1 Micron Band*

This is the strongest example of the 7.1 μm band we have seen to date in any type of carbon star. The band is more nearly centered on the HCN band center than the C_2H_2 band center. It is difficult to attribute the band to only one of the two species, although HCN may be dominant. As shown by Goebel *et al.* (1980), this region may also be confused by CS, an abundant diatomic. The best that can be done at our resolution is to attribute the band to both HCN and C_2H_2 with possible CS, and leave the quantitative measurements to high-resolution spectroscopy. The long wavelength wing of this band (the C_2H_2 wing) is apparently the cause of the 8 μm turndown noted in the 8–14 μm spectra of carbon-star Miras taken from the ground some years ago (Forrest, Gillett, and Stein 1975).

xi) *The Molecules* HCN *and* C_2H_2

The knowledge that the 3.1 μm band is caused by HCN and C_2H_2, combined with (1) the presence of the 1.53, 1.85, 2.5, 2.7, and 3.56, 3.85, 4.8, and 7.1 μm bands at wavelengths appropriate to HCN and C_2H_2, and (2) the appropriate relative band strengths and bandwidths, leads to the conclusion that HCN and C_2H_2 are the opacity sources of the bands mentioned above. An inspection of the V CrB flux curve shows that, at wavelengths > 1 μm, the flux spectrum becomes increasingly dominated by these polyatomic bands. The effect is so severe that the radiative transfer process in the atmosphere of V CrB becomes dominated by the polyatomic bands. There are no models to date which take this fact into account. We note that the analogous M star models using H_2O steam opacity have been the subject of continued modeling efforts (Auman 1969; Johnson 1974; and Tsuji 1966, to name a few). This lack of previous modeling is a hindrance to the further understanding of both the stellar atmospheric structure in carbon Miras and the question of how much graphite is being produced in the atmosphere.

The best models to date of carbon stars are those of Querci, Querci, and Tsuji (1974) and Querci and Querci (1974) which cover the range of effective temperatures between 2200 K and 4200 K. They point out correctly that the polyatomic opacities need to be included below 2600 K. For effective temperatures above 2600 K, their models provide a good description of both infrared flux curves and angular diameters (Goebel and Goorvitch 1979). In spite of the fact that none is exactly appropriate to V CrB, we intend to discuss the properties of C_2H_2 and HCN in the warmer models insofar as they relate to the 3α and CNO nuclear burning processes.

xii) *Nuclear Processes*

The relative partial pressures of HCN and C_2H_2 may indicate the type of nuclear processing a star has undergone. For the CNO cycle, $[C] \approx [O] \ll [N]$, while for 3α, $[C] \gtrsim [O] \approx [N]$ (Querci 1974). Thus for 3α production and plume-type mixing, HCN and C_2H_2 abundances are about equal, while for equilibrium CNO-cycle abundances and deep envelope mixing, HCN is far more abundant. The abundances can be estimated from detailed models for particular stars, but, because the dissociation energies are similar, relative abundances can probably be determined by comparing individual unsaturated lines at nearby wavelengths from the two molecules. Hence, it should be possible to deduce which nuclear process dominates the stellar interior by observing the outer atmosphere, with spectral resolution sufficient to resolve the individual lines, provided there is efficient mixing.

Under this scheme, the observations of Ridgway, Carbon, and Hall (1978) would imply that TX Psc, UU Aur, and Y Tau are dominated by CNO processing since only HCN was detected without any C_2H_2. On the other hand, T Lyr, which is dominated by C_2H_2, could be a 3α star.

Querci and Querci (1975) have suggested another method for determination of the dominant nuclear process. They noted that the 3α process preferentially enhanced the carbon abundance, while the CNO process depleted the carbon abundance with respect to the solar value. Thus stars with extensive dust envelopes (e.g., V Cyg) should be 3α dominated; stars without extensive envelopes (e.g., TX Psc) should be CNO dominated. It would be interesting to compare the results of their suggestions with more results of spectroscopy at higher resolution.

b) *Circumstellar Dust*

We would like to know how much graphite (or other carbon-rich dust or soot) is being expelled from the atmosphere of the star. The discussion above indicates that the presence of the many strong polyatomic absorption bands severely modifies the spectral flux distribution in the infrared. This new interpretation implies that dust reradiation in the infrared, to which had previously been ascribed the role of spectral redistribution, plays a lesser role in many stars. As indicated, a quantitative answer will have to wait for models which take the polyatomic bands into account in the 1–8 μm range. When the photospheric energy distribution is better known, the role of graphite (soot) can be more clearly understood.

From the presence of the 2.5 μm polyatomic band and CN $\Delta v = -2$ red-system band, it is clear that the CO first overtone at 2.3 μm should be weakened by those bands alone. The weakening effect of CN was first explained by Wing and Spinrad (1970). A similar effect occurs in Y CVn, a graphite-free carbon star (Goebel *et al.* 1980). In the past, such weakening has also been attributed to dust alone (Frogel and Hyland 1972). If the CO first overtone were weakened in V CrB because of dust, then the CO fundamental should be absent or nearly absent. This may be the case in V CrB in our spectrum. But we see nearly 20% absorption in the CO fundamental at other phases in V CrB (Bregman and Witteborn 1980). To see that much absorption by the CO fundamental, we cannot be observing through an extensive dust shell which redistributes the radiation at 2.5 μm. Furthermore, the infrared band strengths of the other diatomics CN and C_2 can be adequately interpreted in terms of association into polyatomics, CN into HCN, and C_2 into C_2H_2 (Goebel *et al.* 1978*b*), rather than by dust veiling.

To be sure, there is support for some dust about V CrB, both from our data and elsewhere. In our spectrum, the flux curve never achieves Rayleigh-Jeans slope out to 14 μm, although it does closely fit a 1675 K blackbody between 1.5 and 4 μm. Beyond 4 μm, the flux levels exceed the 1675 K blackbody increasingly as the wavelength increases (Fig. 2). At 11.3 μm, V CrB also displays the SiC dust feature. Interestingly, the SiC band in V CrB is sensibly different from the SiC band in Y CVn (cf. Fig. 2). In Y CVn the peak is at 11.7 μm, rather than 11.3 μm, and the shape of the 11.7 μm band was well described by the polytrope assembly of Dorschner, Friedemann, and Gürtler (1977). A possible interpretation is that the polytrope mixture is sensitive to formation temperature, which may be different in the two stars. Perhaps the polytrope assembly is sensitive to other parameters like pressure or the Si to C abundance ratio, or perhaps the grain size and shape differ in Y CVn and V CrB. This effect could account for a different band shape (Gilra 1972). Most carbon stars appear to have an 11.3 μm like V CrB (FGS; Puetter *et al.* 1977; MS).

Emission by dust composed of SiC cannot explain the rising continuum between 4 and 14 μm because (1) it is confined to the 10–13 μm range in all carbon stars (FGS), (2) it is observed in carbon stars without rising continua (Goebel *et al.* 1980), and (3) no laboratory data exist which show crystalline SiC bulk absorption coefficients to be significant outside the 11.3 μm band (Dorschner, Friedemann, and Gürtler 1977). If one interpolates through the bands at 4.8 and 7.2 μm, then the rising continuum appears to be featureless. For graphite, this is what one expects. In Figure 2, we show an emission shell contribution which we calculated for the optically thin case in excess of the 1675 K blackbody using a graphite optical depth normalized to 10^{-3} at 10 μm and based on the graphite $\tau/\tau_{10\,\mu\mathrm{m}}$ given by Jones and Merrill (1976). Using a shell temperature of 450 K, this calculation gives a reasonable description of the interpolated 4–14 μm rising continuum. The value 450 K is not an optimized single slab temperature, nor has there been any endeavor to adjust temperature gradients (nonexistent in our calculation) or particle size distribution (0.1 μm assumed by Jones and Merrill). There is no significant thermal contribution by the shell below 4 μm.

The existence of such a shell has several implications. First, the SiC and graphite are probably in the same spatial region. If so, the SiC temperature is similar to the graphite temperature, as it is also seen in emission in the same spectral region. This is consistent with the theoretical models of Jones and Merrill (1976). A 450 K temperature would cause the SiC emission band to be shifted to longer wavelengths than the 11.75 μm band in Y CVn, which was described by a 1600 K band temperature. Since the SiC band in V CrB is peaked at 11.3 μm, rather than 11.75 μm, we can eliminate temperature as a single cause of the differing SiC band profiles in the two stars. Probably something more fundamental is occurring, as suggested above.

Second, the graphite shell emission should continue to rise to longer wavelengths above the 1675 K blackbody. Potentially, this future observation should provide a test of the material constants assumed by Jones and Merrill (1976) in their analysis of thick circumstellar shells.

Third, the 7.1 μm band is seen in absorption against the 450 K continuum. If the band is formed below the 450 K dust shell and is partly filled in by emission, the intrinsic depth of the band relative to the photosphere must be larger than is apparent. Since CS is a diatomic molecule, it probably needs the entire atmospheric column density to contribute significantly to the band. The CS abundance is down from CO considerably, while the CO fundamental band may be absent. Therefore, we suggest that the CS contribution is minimal. The most likely carriers of the 7.1 μm band are then HCN and C_2H_2.

Thus, V CrB appears to have very large polyatomic column densities and an optically thin graphite and SiC dust shell. The thinness of the shell may find explanation in the ratio of C to O for V CrB, which is 1.23 according to Kilston (1975). According to Scalo (1973), at temperatures less than 2200 K, C_2H_2 competes very effectively with graphite for free carbon. If most of the carbon in V CrB's outer atmosphere and shell is bound in C_2H_2 and CO, then a small graphite abundance is expected.

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