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THE INFRARED SPECTRUM OF THE CARBON STAR Y CANUM VENATICORUM BETWEEN 1.2 AND 30 MICRONS

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ABSTRACT

The infrared spectrum of Y CVn (N3; C4, 5; SR*b* variable) is presented with essentially complete wavelength coverage from 1.2 to 30 μm and mostly at a resolution $\Delta\lambda/\lambda$ of 0.02. The previous identification of C_3 at 5.2 μm by Goebel *et al.* is confirmed. There is no clear evidence for the SiC_2 ν_3 fundamental absorption band at 5.7 μm; but the 11.5 μm SiC particulate emission band is seen. The 11.5 μm band shape is consistent with the laboratory measurements of crystalline SiC made by Dorschner *et al.* Thus both C_3 in the stellar photosphere and circumstellar SiC contribute to the violet opacity in Y CVn, although C_3 is dominant. The power radiated in the circumstellar SiC band is shown to be inadequate to account for the violet opacity in Y CVn, a result which supports the conclusion of Bregman and Bregman. A 7.5 μm absorption band is observed for the first time and attributed to a mixture of HCN and C_2H_2. Opacity between 2.4 and 2.7 μm is observed for the first time and is consistent with the $\Delta v = -1$ C_2 band. The molecules present in the infrared spectrum—CO, CN, C_2, C_3, HCN, and C_2H_2—are generally in agreement with the models of Tsuji, Scalo, Johnson, Beebe, and Sneden, and Querci and Querci. A possible emission feature is observed at 22.5 μm. Its significance and possible origin are discussed. The 1.6 μm H^- opacity minimum is seen, a requirement for detection of the photosphere. With the exception of the 11.5 μm SiC band and the emission feature at 22.5 μm, the photosphere is dominant over circumstellar emission out to 30 μm. This result should limit the amount of carbon-rich material (graphite) which early N type carbon stars similar to Y CVn could be capable of injecting into the interstellar medium.

Subject headings: infrared: spectra — line identifications — stars: carbon — stars: individual

I. INTRODUCTION

The N type carbon star Y CVn (N3; C5, 4; SR*b* variable) is the first star in which the 5.2 μm band of C_3 has been identified (Goebel *et al.* 1978*a*). This molecule is probably the source of the well known violet opacity in many carbon stars (Bregman and Bregman 1978), although particulate SiC may be important in others. The original infrared observations of C_3 used an InSb detector, restricting spectral coverage to wavelengths less than 5.6 μm. Consequently, the presence of the 5.7 μm band of SiC_2, the molecule responsible for the Merrill-Sanford bands and from which SiC particles may condense, could not be addressed.

This paper reports spectrophotometric observations covering the essentially complete wavelength interval 1.2–30 μm. Two new sets of observations were made, the first within a 1 month interval. Previous observations of another carbon star, V Cyg (N; C7, 4e; Mira variable), suggested that dust emission was responsible for most of the flux beyond 4 μm (Forrest, Gillett, and Stein 1975; Puetter *et al.* 1977). In contrast, the flux of Y CVn is apparently dominated by the photosphere out to 30 μm. Our wide spectral coverage also allows the H^- continuum to be examined. These are the first observations from 2.4 to 3.0 μm, 5.5 to 8.0 μm, and 16 to 30 μm of such an unveiled carbon star. The data from 1.2 to 30 μm indicate that the photospheric continuum dominates over any featureless circumstellar radiation out to 30 μm. A newly discovered emission feature at 22.5 μm is interpreted as arising from circumstellar material.

The present observations confirm the identification of the C_3 band at 5.2 μm; and show that if SiC_2 is present, the SiC_2 absorption band at 5.7 μm would be obscured by C_3 at 1% spectral resolution. Silicon carbide (SiC) emission at 11.5 μm exists simultaneously with C_3 absorption at 5.2 μm, requiring a contribution of both species to the violet opacity in Y CVn. The polyatomic molecules HCN and C_2H_2 are expected to have absorption bands of observable strength between 4 and 8 μm, and a band centered near 7.5 μm is attributed to a mixture of HCN and C_2H_2, with a possible contribution from CS allowed.

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II. OBSERVATIONS

The data discussed here represent the combined observations of the Ames group (1.2–4.0 μm, 1.2–5.5 μm, and 8.0–13.5 μm), the San Diego group (2.1–4.0 μm, 4.3–8.0 μm, and 8.0–13.5 μm), and the Cornell group (16–30 μm), and are displayed in Figure 1 as Spectra II and III. The data set of 1976 December 14 (Spectrum I) was discussed by Goebel *et al.* (1978*a*). Table 1 lists the pertinent observational parameters. The method of data reduction to absolute spectrophotometry of the Ames group is discussed in detail by Strecker, Erickson, and Witteborn 1979. The San Diego group's method is discussed by Puetter *et al.* (1979). Both techniques produce calibrated spectrophotometry through reference to established secondary standards, which in turn are calibrated against an α Lyrae flux curve. The Cornell group's method is discussed by Forrest, McCarthy, and Houck (1979).

The observations taken between 1978 January 4 and February 18 are combined into Spectrum II, Figure 2. The vertical scale of Figure 2 may be called normalized deviations from the Planck function. Since Y CVn is an SR*b* variable, it is necessary to observe the different wavelength intervals nearly simultaneously. The calibrated spectrophotometry can be recovered from Figure 2 by multiplication of each point by a function

$$F_\lambda = N_F{}^{-1} B(T_{\rm BB}, \lambda)\,,$$

where $B(T_{\rm BB}, \lambda)$ is the Planck function of temperature $T_{\rm BB}$ at the wavelength λ, and N_F is a normalization constant. N_F and $T_{\rm BB}$ are listed in Table 1 for all the observations. $T_{\rm BB}$ will be considered an infrared color temperature $T_{\rm IR} = T_{\rm BB}$. The data in Figure 2 are plotted with a logarithmic vertical axis. This allows the data from the three spectral regions to be shifted vertically to normalize them, while preserving the spectral shape. The vertical shifts are only a few percent. The logarithmic horizontal axis transforms constant resolving power (50) into a constant linear measurement on the page across the entire range of wavelengths.

The observations taken between 1978 April 5 and June 26 were combined into Spectrum III. The 16–30 μm flux was calibrated by comparison with several standard stars, which were observed during the same flight series, and is believed to be accurate to approximately ±15%. The shape of the spectrum and the air mass corrections necessary shortward of 17 μm due to terrestrial CO_2 were derived using our unpublished spectrum of Mars, the spectrum of IRC +10420 (Forrest, McCarthy, and Houck 1979), and laboratory blackbody spectra obtained before and after the flight series. Because of the low signal-to-noise in the original 0.2 μm resolution spectrum, the data have been binned into 1 μm (from 18.5 to 25.4 μm) and 2 μm (at 17 μm, 27 μm, and 29 μm) bandpasses and averaged. There were from 40 to 100 individual measurements in each bin. The data shown in Figure 1 have $\pm 1\ \sigma_{\rm mean}$ error bars. Within the errors, the 16–30 μm flux is a smooth continuation of the shorter wavelength data.

There is an important difference between the data reproduced here and that of Goebel *et al.* (1978*a*). That work approximated the standard star (β Gem, K0 III) flux curve by a 4700 K blackbody. The procedure was justified because no spurious molecular features were introduced, and spectroscopy of molecular constituents was the subject of discussion. But that method is inadequate for the determination of any continuous opacity sources unless the standard is free of H^- opacity (β Gem is not). The standards have now been referenced to α Lyr, permitting the nature of any continuous opacity to be examined.

III. INTERPRETATION

a) The Photospheric Continuum

There are a variety of opacity sources which might form the continuum level which is observed here (Querci, Querci, and Tsuji [QQT] 1974), e.g., molecular lines, H^-, and photospheric or circumstellar dust. We argue that H^- dominates the continuous photospheric opacity in Y CVn. A direct comparison should be made of Spectrum II (Fig. 2) and Spectrum I

TABLE 1

INFRARED OBSERVATIONS OF Y CANUM VENATICORUM

Date of Observation	Wavelength Range (μm)	Composite Spectrum Number	Observatory	Detector Type	T_{BB} (°K)	N_F	Standard Star	Observers
1976 Dec 14....	1.2–2.4, 2.9–5.6	I	KAO	InSb	2900	2.67×10^{19}	β Gem	Ames
1978 Jan 4......	1.2–4.0	II	Learjet	InSb	2750	2.50×10^{18}	β And	Ames
1978 Feb 2......	4.3–8.0	II	KAO	PbSnTe	2750	2.50×10^{18}	α Tau	UCSD
1978 Feb 18.....	8.0–13.5	II	NASA–UA Mt. Lemmon	Si:As	2750	3.05×10^{18}	3000 K (α Boo)	Ames
1978 May 23....	4.3–8.0	III	KAO	PbSnTe	2800	2.50×10^{18}	α Boo	UCSD
1978 Jun 26.....	2.1–4.0	III	UCSD–UM Mt. Lemmon	InSb	2800	2.3×10^{18}	η UMa	UCSD
1978 Apr 5.....	8.0–13.5	III	UCSD–UM Mt. Lemmon	Si:As	2800	2.50×10^{18}	α Boo (4000 K)	UCSD
1978 May 6.....	16–30	III	KAO	Si:Sb	2800	2.25×10^{18}	IRC +10420	Cornell

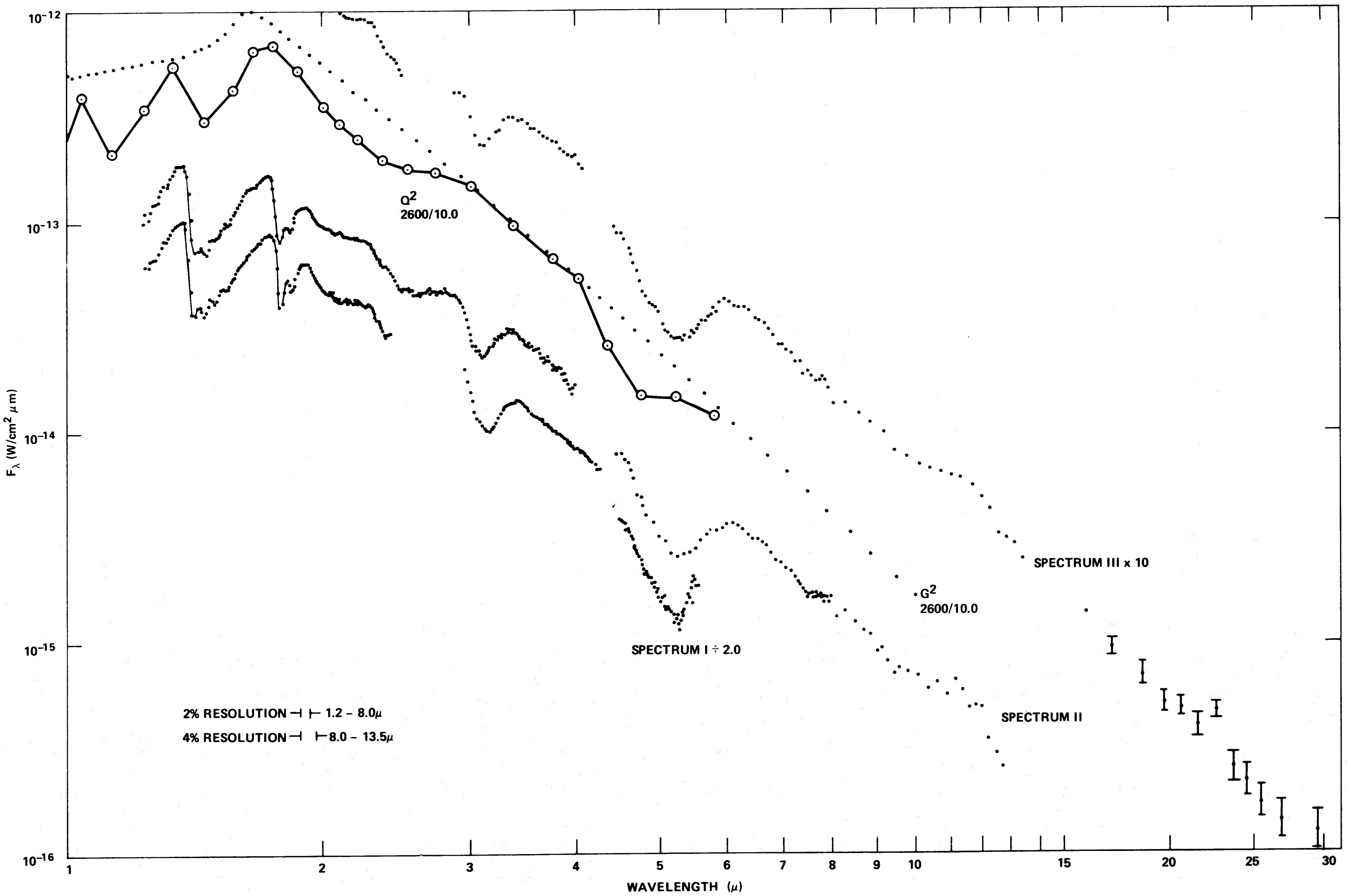

FIG. 1.—The absolute spectrophotometry of Y CVn taken on the dates listed in Table 1 and combined into three composite spectra. Although Spectrum III has been shifted vertically by a factor of 10, it does not overlie Spectrum II, but is slightly higher across the entire spectrum. The variability can be attributed to a combination of temperature and size changes. From 16 to 30 μm the data has been spectrally averaged to obtain a higher S/N. Below 16 μm the resolution is oversampled, so differences between adjacent datum points is a measure of noise. The curve labeled Q^2 2600/10.0 is a model carbon star of $T_{\rm eff}$ = 2600 K and g = 10.0 cm s^{-2} from Querci and Querci (1974). The curve G^2 2600/10.0 is explained in the text.

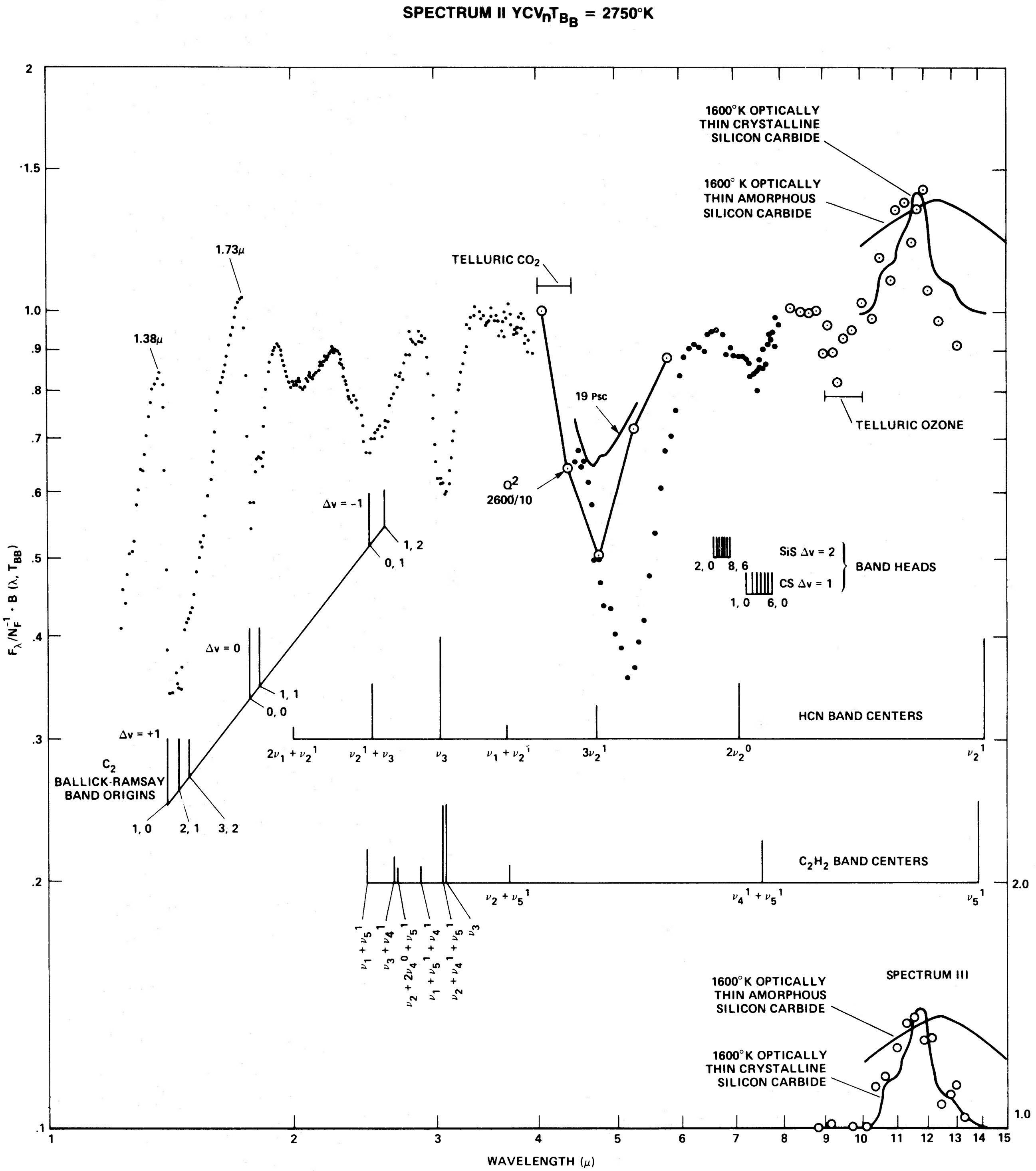

FIG. 2.—The normalized deviations from a Planck function of T_{BB} = 2750 K for the carbon star Y CVn. The three wavelength intervals covered by the observers are: *small dots*, 1.2–4.0 μm; *large dots*, 4.3–8.0 μm; *circled small dots*, 8.0–13.5 μm. The resolution out to 8.0 μm is about 2%; from 8.0 to 13.5 μm, it is 4%. The fundamental absorption band as observed in 19 Psc is indicated by a smooth heavy line between 5 and 6 μm. The band heads, origins, and centers of various species discussed in the text are positioned below the spectrum at their measured or computed wavelength. The relative height of HCN and C_2H_2 band indicators gives a crude measure of intrinsic band strength. The gap at 4.2 μm is due to telluric CO_2 interference. The apparent absorption at 9.5 μm is attributed to telluric ozone. The 11.5 μm emission band is compared with the properties of amorphous and crystalline SiC, as discussed in the text. The curve labeled Q^2 2600/10.0 is as in Fig. 1, but with the continuum removed by G^2 2600/10.0.

(Figure I of Goebel *et al.* 1978*a*). The point to note is that in Spectrum I, the 1.38 μm level of Y CVn is not depressed relative to the 1.73 μm level. The H^- present in β Gem (K0 III) causes a depression of its own 1.38 μm level relative to its 1.73 μm level when comparison is made directly with a blackbody of temperature (4700 K) appropriate to wavelengths longward of 1.6 μm. Thus one can conclude that there is H^- opacity present in Y CVn in an amount nearly equal to that observed in β Gem, if the effect in question cannot be attributed to other opacity sources.

Photospheric dust could cause opacity throughout the entire 1.0–2.5 μm range but is not expected in an atmosphere with a $T_{\rm eff}$ of 2500 K. Circumstellar extinction, which produces absorption of the 1.38 μm radiation relative to the 1.73 μm radiation, also causes unacceptably large extinction in the visible. Dust can contribute very little to the effect being considered.

Cyanogen (CN) is the only abundant molecule which has absorption bands at 1.38 and 1.73 μm. In order to check the effect of weak CN lines at 1.38 and 1.73 μm when large column densities are present, we computed the opacity at 1% spectral resolution for column densities of up to 10^{26} CN molecules per cm^2 (a typical model atmosphere will have less than 10^{25} molecules per cm^2 of H_2 and less than 10^{19} of CN [Johnson, Beebe, and Sneden 1975]). *All* known weak lines were included (Augason and Bailey 1978, private communication); between 1.35 and 1.75 μm there are over 12,000 lines. Only column densities greater than 10^{24} depressed the 1.38 and 1.73 μm levels significantly. A relative depression of only 9% could be produced with 10^{26} molecules/cm^2, less than half the observed depression.

Querci, Querci, and Tsuji (1974) and Querci and Querci (1974, hereafter Q^2) have produced carbon star models with $T_{\rm eff}$ as low as 2200 K. A depression shortwards of 1.6 μm similar to that being discussed here is characteristic of the models. A synthesis of their spectra using continuum sources only for comparison with a variety of carbon stars (Goorvitch and Geobel 1980, hereafter G^2) shows that H^- bound-free opacity dominates the continuous opacity sources at wavelengths less than 1.6 μm in the models. Addition of CN red system opacity using the band model of Johnson, Marenin, and Price (1972) did not change this conclusion, even though this band model produces CN bands much stronger than those in real stars, principally because of their use of the straight mean band model (Carbon 1974).

The flux curve of the 2600 K/10.0 cm s^{-2} model of Q^2 has been reproduced in Figure 1. Although it is not exactly appropriate to Y CVn, it does illustrate the H^- opacity effect under discussion. Even though the CN bands are strong, the underlying continuum sources are evident, specifically the H^- peak. The H^- peak has been shifted to a longer wavelength because of the presence of the CN and CO bands, a fact noted by F. Querci in his thesis (1969). A $T_{\rm eff}$ of 2500 K might be more appropriate to Y CVn and might produce stronger C_2 bands than are apparent in the 2600 K model. It would be very valuable to create a denser grid of models of the Querci type for carbon stars in terms of $T_{\rm eff}$, N_C/N_O, and perhaps g than is presently available, as well as extending them to lower temperatures.

In Figure 3 we make a direct comparison between Spectrum I and the Q^2 band model with $T_{\rm eff} = 2600$ K and $g = 10.0$ cgs units along with the continuum only calculation of G^2 for the same values of $T_{\rm eff}$ and g. Except for the C_2 Ballik-Ramsay $\Delta V = 0$ band at 1.8 μm, the polyatomic band at 3.1 μm, and the C_3 band at 5.2 μm, the Q^2 flux curve comes quite close to the measured curve. (In fact, the angular diameter θ determined from the ratio of stellar flux F^* and model flux F^M at 3.7 μm is $\theta = [(4/\pi)(F^*/F^M)]^{1/2} = 13.1$ milli-arcsec, a very reasonable value.) The bands weaken the H^- peak, but have little effect on the 1.35 μm continuum level. It is the H^- opacity minimum which gives rise to the depression of the 1.35 μm level in Figure 2 compared to the 1.73 μm level. If, in Figure 2, we had chosen to divide the flux by a blackbody passing through 1.35 μm and 3.6 μm, then the 1.73 μm level would have been greater than 1.0, and therefore would have been an apparent emission feature.

Thus H^- is the dominant source of the observed relative depression of the 1.35 and 1.73 μm levels in Spectrum II. Since the H^- opacity effects can be seen, we can conclude that we are observing the photospheric continuum in Y CVn.

From Spectrum III, there is no featureless infrared excess above what we are interpreting to be the photospheric continuum of Y CVn, at least out to 30 μm. Broad-band photometry (Jones and Merrill 1976) of early N type stars and N type spectra at our disposal indicate the lack of large featureless excesses in the early N type carbon stars, at least to N3. Thus it appears that photospheric continuum with superposed molecular absorptions dominate the spectra of early N type carbon stars to N3, i.e., those with $T_{\rm IR}$ greater than 2800 K.

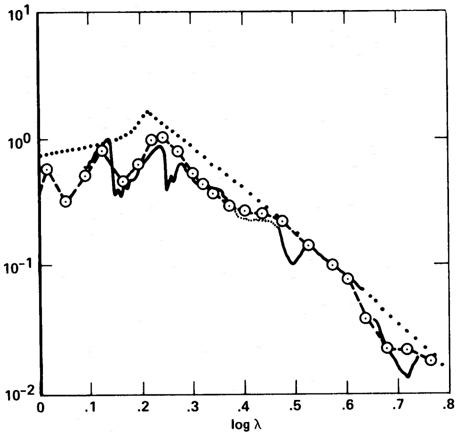

FIG. 3.—A direct comparison of the observed Spectrum I of Y CVn (*solid line*) with the flux spectra of the Q^2 2600 K/10.0 cm s^{-2} model atmosphere (*circled dots* connected with *dashes*) and the G^2 2600 K/10.0 cm s^{-2} model (*dots*). The lack of agreement in certain bands is discussed in the text.

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b) CO, C_3, *and* SiC_2

With extension of spectral coverage out to 8 μm in Spectrum II, we confirm the upturn, in Spectrum I, of the 5.2 μm absorption band at wavelengths greater than 5.2 μm. In fact, the upturn proceeds to essentially a continuum level at 6.6 μm. In Figure 2, the CO fundamental of 19 (TX) Psc (N0; C6, 4) has been superposed. The star 19 Psc has a higher T_{IR} (4000 K) than Y CVn (2800 K). Hence the CO fundamental of 19 Psc should extend to longer wavelengths than that of Y CVn. The extraordinary difference in band profiles between the two stars requires another source of opacity in Y CVn. The observational indications of C_3 are confirmed by the Q^2 model discussed above. In Figure 2 are plotted the CO fundamental values of Q^2 2600/10.0. Again the differences require some other molecule than CO. The C_3 molecule quite adequately accounts for the difference (Treffers and Gilra 1975). On the basis of temperature alone (Tsuji 1964), C_3 is expected to be abundant in Y CVn and not in 19 Psc. A 5.2 μm band profile similar to Y CVn has also been observed in UU Aur and RY Dra (Goebel, unpublished data). The C_3 molecule is expected to be abundant in the latter stars, because of their temperatures.

On the long-wavelength side of the 5.2 μm band there is a small inflection between 5.8 and 6.0 μm. From the preliminary high-temperature laboratory data of Treffers and Gilra (Treffers, private communication), the SiC_2 ν_3 fundamental is expected between 5.6 and 6.0 μm. But on the basis of a dissociation equilibrium model (Scalo 1973) appropriate to Y CVn ($N_C/N_O = 1.66$ [Gow 1977]) with $N_C/N_O = 1.5$, $\log P_g = 2$, and 2700 K (the choice of 2700 K will become apparent in the next section), the ratio of partial pressures of C_3 and SiC_2 is expected to be $P_{C_3}/P_{SiC_2} \sim 100$. If the C_3 5.2 μm band and SiC_2 5.7 μm band are of equal strength per molecule, then Scalo's model does not predict a strong SiC_2 band. However, the Merrill-Sanford electronic bands of SiC_2 are present in the visible spectrum of Y CVn, so some SiC_2 must be present. Electronic bands do tend to be much stronger than vibration-rotation bands, implying no contradiction, but the relative band strengths are not available. The inflection near 5.7 μm appears in both Spectrum II and Spectrum III, but there is also an inflection between 6.3 and 6.5 μm. Both inflections are near terrestrial water vapor bands, and may be due to imperfect atmospheric correction for H_2O. In either case, there is no clear indication of SiC_2 in Y CVn in any of our infrared spectra.

c) *Other Bands and Molecules*

At 7.5 μm in II and Spectrum III, there is a previously unobserved absorption band. In Table 2 we list the molecular species expected to be abundant in Y CVn on the basis of the Scalo (1973) and Tsuji (1964) models, and which have absorption bands between 4 and 8 μm. Consideration of temperature, relative abundance, and band center wavelength leaves only HCN, C_2H_2, and CS as real possibilities. Pierson, Fletcher, and Guntz (1956) show the 7.1 μm band of HCN and 7.5 μm band of C_2H_2 to be roughly equal in strength at room temperature. By combining the bands of both molecules, it appears that qualitative agreement is possible with Spectrum II. An overlapping of HCN *P*-branch and C_2H_2 *R*-branch, with the HCN absorption somewhat stronger, would reproduce the 7.45 μm minimum, while the HCN *R*-branch (7.0 μm) would be stronger than the C_2H_2 *P*-branch (7.8 μm). An additional contribution to the 7.45 μm minimum could come from a temperature-sensitive *Q*-branch of C_2H_2 (Bell and Nielsen 1950), which is centered at 1328.5 cm^{-1} (7.5 μm). The *Q*-branch becomes stronger as temperature increases. A contribution from CS is allowed in the 7.5 μm band, but cannot account for the band shape or the band center wavelength. It would be useful to test these conclusions at high resolution in the 7.5 μm band.

From Table 2, Tsuji's models show HCN to be about an order of magnitude more abundant than C_2H_2 at 2000 K, and the model is included for comparison. While trends in molecular abundances of Tsuji's model appear to be consistent with our data, none of them are exactly appropriate for Y CVn. In contrast, Scalo's models may be more consistent with our analysis. For $N_C/N_O = 1.5$, and $\log P_H = 2.0$, he finds $P_{HCN}/P_{C_2H_2} \approx 10$ at 2800 K, ≈ 1 at 2700 K, and $\approx \frac{1}{3}$ at 2600 K.

Since the bands at 7.5 and 3.1 μm involve both HCN and C_2H_2, their shapes should be sensitive to temperature changes on the order of 100 K at both high and medium resolution. Spectra I, II, and III Y CVn show band shape changes not attributable to noise, while the infrared continuum temperature changes on the order of 100 K. This change in the 3.1 μm band shape is displayed in Figure 4. Band variability at 3.1 μm also occurs in other carbon stars that we have observed more than once from the Kuiper Airborne Observatory or Learjet (Goebel *et al.* 1978*b*).

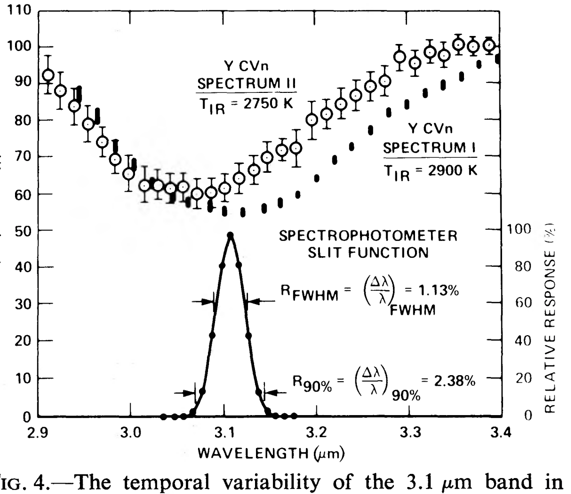

FIG. 4.—The temporal variability of the 3.1 μm band in Y CVn. Variation also occurs in other carbon stars as well, such as TX Psc and R Lep. 1 σ error bars deduced from multiple scans of the band are indicated vertically. The spectrophotometer slit function evaluated near 3.1 μm is also included.

TABLE 2

A. TSUJI'S MODEL[a] ($N_C/N_O = 5$, $\log P_g = 3.0$, $T_e = 2000$ K)

Molecule	Band Center[b] at 300 K (μm) or Band Head	Temperature Range of Maximum Partial Pressure ÷1000 K	$P_{\text{molec}}/P_{\text{HCN}}$
HCN	7.1, 4.8, 3.1	1.0–2.5	1.0
C_2H_2	7.5, 3.1	1.0–2.5	0.06
C_3	5.2 (3000 K)	2.1–3.2	4×10^{-5}
CH_4	7.7	< 1.2	4×10^{-5}
C_2H_4	6.9	< 1.2	6×10^{-7}
C_2N_2	3.9, 4.8	1.7–3.0	2×10^{-5}
C_6H_6	6.7	1.25	$< 10^{-16}$
	Si > S (Solar)		
CS	7.3	2.0–3.0	5×10^{-3}
SiS	6.6	< 2.0	2×10^{-3}
SiO	8.1	< 1.8	4×10^{-5}
SiC_2	5.7 (3000 K)	1.5–2.5	3×10^{-4}
H_2S	7.8	< 1.2	6×10^{-6}
	Si < S		
CS	7.3	< 3.5	3×10^{-2}
SiS	6.6	1.2–2.0	8×10^{-3}
SiO	8.1	> 1.8	3×10^{-5}
SiC_2	5.7 (3000 K)	1.8–2.8	2×10^{-4}
H_2S	7.8	< 1.2	6×10^{-6}

B. SCALO'S MODELS[c] ($N_C/N_O = 1.5$)

Molecule	$\log P_{\text{mol}} - \log P_{\text{H}}$	$P_{\text{mol}}/P_{\text{HCN}}$
	$\log P_g = 2.0$, $T_e = 2650$ K	
HCN	−6.6	1.0
C_2H_2	−6.6	1.0
C_3	−6.3	2.0
SiC_2	−8.0	0.04
CS	−4.8	63
SiS	−7.7	0.08
CO	−3.0	4000
CN	−4.5	130
C_2	−5.7	7.9
	$\log P_g = 0.0$, $T_e = 2300$ K	
HCN	−7.3	1.0
C_2H_2	−7.3	1.0
C_3	−6.3	10
SiC_2	−8.0	0.16
CS	−4.8	250
SiS	...	...
CO	−3.0	16,000
CN	−4.6	50
C_2	−5.9	25

[a] From Tsuji 1964, 1973.

[b] C_3 from Treffers and Gilra 1975, SiC from Treffers (private communication), polyatomics from Pierson *et al.* 1956, diatomics from Bailey (unpublished).

[c] From Scalo 1973.

The star Y CVn is not the most dramatic example. These band changes are also accompanied by temperature changes on the order of 100 K.

An interesting feature of Scalo's models is that, in principle, luminosity class can be determined from a knowledge of $P_{\rm HCN}/P_{\rm C_2H_2}$, $N_{\rm C}/N_{\rm O}$, and stellar temperature. In the case of Y CVn, if $P_{\rm HCN}/P_{\rm C_2H_2} = 1$, $N_{\rm C}/N_{\rm O} = 1.5$, and $T_e = 2650$ K, then $\log P_{\rm H} = 2$. If $T_e = 2300$ K, then $\log P_{\rm H} = 0$. All the other molecules listed in Table 2 from his models—CO, CN, C_2, C_3, SiS, *and* SiC_2—have the same ratios $P_{\rm mol}/P_{\rm H}$ in either case.

Beyond the CO first overtone minimum at 2.35 μm there is additional opacity. The likely possibilities are C_2 Ballik-Ramsay $\Delta V = -1$ (Ballik and Ramsay 1963), HCN $\nu_2 + \nu_3$ and $2\,\nu_2 + \nu_3$ Q-branches (Rank *et al.* 1960), C_2H ν_3 (Jacox 1975), and C_2H_2 $\nu_3 + \nu_4{}^1$, $\nu_1 + 2\,\nu_4{}^{2,0} + \nu_5{}^1$, $\nu_1 + \nu_4{}^1 + \nu_5{}^1$, and $\nu^1 + \nu_5{}^1$ combination bands (Bell and Nielsen 1950). Ridgway *et al.* (1976) have observed a line of the $\nu^1 + \nu_5{}^1$ C_2H_2 band in IRC +10216. Goebel *et al.* 1978*b* have identified the C_2H_2 bands in other carbon stars mainly of infrared temperature less than 2000 K. In Y CVn, $T_{\rm IR} \approx 2800$ K. For this higher temperature C_2 and perhaps HCN are the most likely candidates. Ab initio band shape calculations by D. Cooper (private communication) of C_2 at 2000 K and viewed by a 1% resolution slit function give good agreement with the two observed minima at 2.48 and 2.58 μm (see Fig. 5). High-resolution observations are needed from the Kuiper Airborne Observatory (KAO) to clarify the 2.5–2.9 μm region in Y CVn. Any unaccounted for lines may well come from C_2H, an abundant radical.

None of our spectra of Y CVn reveal significant CS at 3.9 μm or SiS at 6.6 μm. The CS molecule has been observed by Ridgway, Hall, and Carbon (1978) and Bregman, Goebel, and Strecker (1978) in other carbon stars, and may contribute to the 7.5 μm band observed here. The two molecules CS and SiS are among the most abundant of species; but their abundances are two orders of magnitude less than CO. Their lack of strong absorption bands is easily accounted for because they are diatomics; their fundamental and overtone bands should be considerably weaker than those due to CO. An instrumental spectral resolution of 2% further dilutes their strongest band heads. At high resolution, CS and SiS may be apparent in Y CVn at 7.3 and 6.6 μm. The relative strength of CS at 7.3 μm and SiS at 6.6 μm could provide a determination of the Si/S ratio based on Tsuji's models. Alternatively the CS and SiS measurements could choose whether Tsuji's models or Scalo's models in Table 2 are appropriate in carbon stars. Tsuji obtains a much lower partial pressure of CS than Scalo, even with a much greater $N_{\rm C}/N_{\rm O}$.

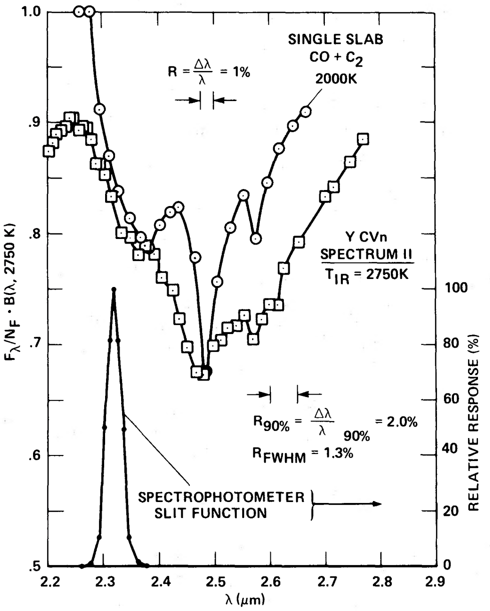

FIG. 5.—A comparison of the atmospheric opacity in the 2.5 μm region of Y CVn Spectrum II with a single slab opacity of 2000 K. CN opacity at 2.2 μm is not included in the computation, even though present in the star. The spectrophotometer slit function near 2.3 μm is also included.

d) *Dust Grains*

The well known particulate emission band of SiC at 11.5 μm is present in the spectrum of Y CVn. The band shape is similar to that observed in other carbon stars by Hackwell (1973), Treffers and Cohen (1974), and Forrest, Gillett, and Stein (1975). The usual interpretation is that SiC grains are injected into a circumstellar cloud by mass loss from the stellar photosphere (Gilra 1972; and Treffers and Cohen 1974). We have computed how the 11.5 μm band would appear if it were due to amorphous SiC based on the absorption coefficient given by Fagan (1973), and how it would appear if the band were due to the mixture of SiC crystalline forms measured by Dorschner, Friedemann, and Gürtler (1977). The crystalline material provides a reasonable fit to the 11.5 μm band in Y CVn, while the amorphous material does not (see Fig. 2). This confirms the conclusion of Treffers and Cohen (1974) that crystalline SiC is responsible for the 11.5 μm emission band.

The C_3 molecule is the principal vaporization product of graphite. The presence of C_3 in the photosphere and SiC in the circumstellar shell implies that both are capable of contributing to the violet opacity observed in Y CVn. Bregman and Bregman (1978) have shown that photospheric C_3 apparently dominates the violet opacity in this star. The presence of C_3 in the photosphere implies that graphite is a likely constituent of the circumstellar cloud. Graphite is not as easily identified as SiC due to a lack of distinct spectral features in the infrared. In principle, limits on the amount of graphite can be set by the depth of photospheric absorption features, principally the strong C_3 feature at 5.2 μm. The dust shell temperature is probably less than 1700 K, since SiC is expected to condense at 1700 K (Gilman 1969). This is a calculation beyond the scope of the present paper (Lucy 1976). But from the data of Figure 1, it appears there is little or no graphite in the circumstellar shell about Y CVn.

In spectrum III of Y CVn, there is an apparent emission feature at 22.5 μm (444 cm^{-1}). Although the signal-to-noise ratio (S/N) of the individual spectral points is only modest (about 12), still the feature appears 4 σ above the continuum level defined by the adjacent spectral elements. The 16–30 μm data were obtained at higher spectral resolution than is presented here. In the original data, the feature is apparent in several adjacent spectral elements. Spectrum III is a spectral average of 1 μm wide intervals between 18 and 25 μm, as discussed earlier, for the purpose of presenting a higher S/N ratio. Since these are the first observations of a spectral feature in this wavelength region in a carbon star, confirmation of the observations are necessary in Y CVn and other similar N type stars like RY Dra, X Cnc, or UU Aur. However, a brief discussion of the feature's nature and possible origin is warranted by the present data.

The 22.5 μm feature rises above the photospheric Rayleigh-Jeans continuum by about 40%, roughly the same amount as the 11.5 μm feature, which is attributable to crystalline SiC. The fractional half-width of the 22.5 μm band is no more than 4%, while that of the 11.5 μm band is 16%. The circumstance that these are the only two emission features in the infrared spectrum of Y CVn, naturally leads to their association with the circumstellar shell. Other carbon stars which have been observed in the 22.5 μm region do not show the feature. However, they are only a few in number, and their continua at these wavelengths are dominated by emission from thick circumstellar shells, presumably composed of graphite grains (Treffers and Cohen 1974). In contrast, Y CVn is dominated by photospheric continuum, and components other than graphite may be apparent. Treffers and Cohen (1974) do not see the feature in CIT 6 or IRC +10216, nor do Forrest, McCarthy, and Houck (1979) see it in V Cyg or CIT 6. The known optical properties of SiC or graphite have no outstanding features in this wavelength range.

None of the atomic or molecular species known or suspected to be abundant in Y CVn or its circumstellar shell provide a satisfactory identification. We suggest that the feature arises from a circumstellar condensate. In searching for a possible species, we have restricted ourselves to condensates of the most abundant heavy elements in a carbon star as adopted by QQT (1974): C, O, N, Fe, Si, S, and Mg. All of the O and N and most of the S should reside in some gaseous form—e.g., CO, N_2, CN, HCN, SiS, and H_2S. That leaves graphite, metallic iron, and possibly sulfur, along with the carbides, sulfides, and silicides, as the simplest possibilities.

The silicides are not well studied, but the few which have been measured by Nyquist and Kagel (1971) are featureless in this region. Further study is warranted. For example, Birkholz *et al.* (1968) have shown that β–$FeSi_2$ is a semiconductor, and has a lattice absorption at 22.5 μm. However, it has a stronger 27 μm band and can be ruled out.

Excepting SiC, the knowledge of carbide spectra is also very limited. Pure SiC shows no bands at these wavelengths of consequence (Tanzilli, Gebhardt, and Ulrich 1975). A weakly bound impurity species could produce a narrow absorption band in the acoustic phonon continuum (Sievers 1964) at wavelengths greater than the transverse optical phonon. Since these modes do not require conservation of lattice momentum during absorption, relatively high absorption cross sections may be possible.

Sulfur and the sulfides have been studied more than the carbides and silicides. Neither FeS (Kammori, Sato, and Kurosawa 1968) nor MgS (Povarennykh *et al.* 1971) possesses bands at the right places. Neither SiS or SiS_2 has been reported in the indexed literature. Sulfur crystals show a band at 21.6 μm and 11.8 μm (MacNeill 1963). But sulfur is not expected to be stable toward formation of S_2, FeS_2, or MgS in the circumstellar environment around a carbon star (J. Stevens, private communication). Solid FeS_2 is a material which needs further consideration. Verble and Wallis (1969) and Schlegel and Wachter (1976) have shown that FeS_2 has optical phonon modes between 22.5 and 25 μm. Schlegel and Wachter find no other bands between 1.2 and 22.5 μm. Before FeS_2 can be accepted or rejected, a calculation similar to that of Gilra (1972) for SiC or experiments similar to those of Dorschner, Friedemann, and Gürtler (1977) must be performed.

More complex condensates such as cyanides and thiocyanates are spectroscopically interesting. Whether one would expect such condensates is not known at the present time. For example, iron thiocyanate, $Fe(SCN)_2$, has a fairly strong and narrow band near 21.5 μm according to Nyquist and Kagel (1971). With the exception of a much stronger band near 4.7 μm, the 21.5 μm band is the strongest feature in the spectrum of $Fe(SCN)_2$. The 4.7 μm band might be obscured by the stronger photospheric background at the shorter wavelengths.

Unfortunately, we are left without a positive identification of the 22.5 μm emission feature. Further observations in the 20–25 μm region are planned in order to confirm the 22.5 μm feature.

One final point concerns the relation of the SiC emission in the infrared to the well known violet opacity. Although Y CVn is a SR*b* variable, the magnitude of variability is small, about $0.5m_v$. Many of the bands have nearly constant strength, such as the C_3 absorption and SiC emission bands in particular. With these factors in mind, we can compare the amounts of power absorbed, P_A(violet), by the violet bands as measured by Bregman and Bregman (1978) with the power emitted P_E(SiC) in the SiC emission band of Spectrum III. The ratio is $P_A(\text{violet})/P_E(\text{SiC}) = 7.8$. This ratio is too large to be accounted for by the variability of Y CVn. Thus the reradiation by circumstellar SiC is inadequate to account for the violet opacity in Y CVn. This result supports the conclusion of Bregman and Bregman that the violet opacity in early N type carbon stars is primarily due to photospheric C_3.

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Note added in manuscript.—On 1979 July 11, additional observations of Y CVn from the KAO between 20 and 25 μm were made which do not confirm the possible emission feature at 22.5 μm discussed in the text. These new data resulted in approximately a factor of 2 increase in the signal-to-noise ratio over that displayed in Figure 1. Within the errors, the shape of the spectrum is Rayleigh-Jeans and the flux level is the same as that seen in 1978 May. We must conclude that either the 22.5 μm feature is variable in time, or it is not real. The latter possibility seems most likely.—W. J. F.

REFERENCES

Ballik, E. A., and Ramsay, D. A. 1963, *Ap. J.*, **137**, 61.
Bell, E. E., and Nielsen, H. H. 1950, *J. Chem. Phys.*, **18**, 1382.
Bikholz, V., Finkenrath, H., Naegele, J., and Uhle, N. 1968, *Phys. Stat. Sol.*, **30**, K81.
Bregman, J. D., and Bregman, J. N. 1978, *Ap. J. (Letters)*, **222**, L41.
Bregman, J. D., Goebel, J. H., and Strecker, D. W. 1978, *Ap. J. (Letters)*, **223**, L45.
Carbon, D. 1974, *Ap. J.*, **187**, 135.
Dorschner, J., Friedemann, C., and Gürtler, J. 1977, *Astr. Nach.*, **298**, 279.
Fagan, E. A. 1973, in *Proceedings of the Third International Conference on* SiC, ed. R. C. Marshall, J. W. Faust, Jr., and C. E. Ryan (Columbia: University of South Carolina Press), p. 542.
Forrest, W. J., Gillett, F. C., and Stein, W. A. 1975, *Ap. J.*, **195**, 423.
Forrest, W. J., McCarthy, J. F., and Houck, J. R. 1979, in preparation.
Gilman, R. C. 1969, *Ap. J. (Letters)*, **155**, L185.
Gilra, D. P. 1972, in *The Scientific Results from the Orbiting Astronomical Observatory* (*OAO 2*), ed. A. D. Code (NASA SP-310), p. 310.
Goebel, J. H., Bregman, J. D., Strecker, D. W., Witterborn, F. C., and Erickson, E. F. 1978*a*, *Ap. J. (Letters)*, **222**, L129.
Goebel, J. H., Strecker, D. W., Bregman, J. D., Witteborn, F. C., and Erickson, E. F. 1978*b*, *Bull. AAS*, **10**, 406.
Goorvitch, D., and Goebel, J. H. 1980, in preparation (G^2).
Gow, C. E. 1977, *Pub. A.S.P.*, **89**, 510.
Hackwell, J. A. 1973, *Astr. Ap.*, **21**, 239.
Jacox, M. E. 1975, *Chem. Phys.*, **7**, 424.
Johnson, H. R., Beebe, R. F., and Sneden, C. 1975, *Ap. J. Suppl.*, **29**, 123.
Johnson, H. R., Marenin, I. R., and Price, S. D. 1972, *J. Quant. Spectrosc. Rad. Transf.*, **12**, 189.
Jones, T., and Merrill, K. M. 1976, *Ap. J.*, **209**, 509.
Kammori, O., Sato, K., and Kurosawa, R. 1968, *Bunseki Kagadu*, **17**, 1270.
Lucy, L. B. 1976, *Ap. J.*, **205**, 482.
MacNeill, C. 1963, *J. Opt. Soc. Am.*, **53**, 398.
Nyquist, R. A., and Kagel, R. O. 1971, *Infrared Spectra of Inorganic Compounds* (New York: Academic Press), p. 87.
Pierson, R. H., Fletcher, A. N., and Guntz, E. St. C. 1956, *Analy. Chem.*, **28**, 1218.
Povarennykh, A. A., Sidorenko, G. A., Solntseva, L. S., and Solnstev, B. P. 1971, *Mineal. Sb. L'vov*, **25**, 306.
Puetter, R. C., Russell, R. W., Sellgren, K., and Soifer, B. T. 1977, *Pub. A.S.P.*, **89**, 320.
Puetter, R. C., Russell, R. W., Soifer, B. T., and Willner, S. P. 1979, *Ap. J.*, in press.
Querci, F. 1969, Thèse de doctorate de specialité, Faculté des Sciences, Université de Toulouse.
Querci, F., and Querci, M. 1974, in *Highlights of Astronomy*, Volume **3**, ed. G. Contopoulos (Dordrecht: Reidel), p. 341 (Q^2).
Querci, F., Querci, M., and Tsuji, T. 1974, *Astr. Ap.*, **31**, 265 (QQT).
Rank, D. H., Skorinko, G., Eastman, D. P., and Wiggins, T. A. 1960, *J. Opt. Soc. Am.*, **50**, 421.
Ridgway, S. T., Hall, D. N. B., and Carbon, D. F. 1978, *Bull. AAS*, **9**, 636.
Ridgway, S. T., Hall, D. N. B., Kleinmann, S. G., Weinberger, D. A., and Wojslaw, R. S. 1976, *Nature*, **264**, 345.
Scalo, J. M. 1973, *Ap. J.*, **184**, 809.
Schlegel, A., and Wachter, P. 1976, *J. Phys. C*, **9**, 3363.
Sievers, A. J. 1964, *Phys. Rev. Letters*, **13**, 310.
Strecker, D. W., Erickson, E. F., and Witteborn, F. C. 1979, *Ap. J. Suppl.*, in press.
Tanzilli, R. A., Gebhardt, J. J., and Ulrich, D. R. 1975, unclassified portion of a confidential report: Development of Infrared Materials, A. F. Project 7360 by General Electric Co., Philadephia, Pa. (Re-entry and environmental Systems Division).
Treffers, R. R., and Cohen, M. 1974, *Ap. J.*, **188**, 545.
Treffers, R. R., and Gilra, D. P. 1975, *Ap. J.*, **202**, 839.
Tsuji, T. 1964, *Ann. Tokyo Astr. Obs.*, **9**, 1.
———. 1973, *Astr. Ap.*, **23**, 411.
Verble, J. L., and Wallis, R. F. 1969, *Phys. Rev.*, **182**, 783.
Wing, R. F., and Spinrad, H. 1970, *Ap. J.*, **159**, 973.

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