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A FAR-INFRARED EMISSION FEATURE IN CARBON-RICH STARS AND PLANETARY NEBULAE

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ABSTRACT

The 16–30 μm spectra of several carbon stars and the planetary nebulae IC 418 and NGC 6572 have been obtained using the NASA C-141 Kuiper Airborne Observatory. A newly observed emission feature appears in the spectrum of IRC +10216 and several other carbon stars at wavelengths greater than 24 μm. The feature is interpreted as resulting from a solid-state resonance in the dust grains which have condensed around these stars. A similar feature appears in the spectra of IC 418 and NGC 6572, implying that the same type of dust is present. Since the dust probably condensed from a carbon-rich gas, this indicates an evolutionary link between carbon stars and these planetary nebulae. No identification for the grain material has been found, but some clues are apparent which could aid in the identification.

Subject headings: infrared: spectra — nebulae: planetary — stars: carbon — stars: circumstellar shells

I. INTRODUCTION

The infrared spectra of many cool stars and planetary nebulae show excess flux which is attributed to emission from heated dust grains around the central star. The study of these spectra is interesting for several reasons. The process of grain formation and mass loss from stars is not well understood theoretically; therefore, information on the types and amounts of various grains which actually do form is needed. The planetary nebulae are thought to have evolved from cool stars; a study of the grain compositions can provide clues to possible evolutionary links. Finally, since the circumstellar envelopes are expanding, the dust grains will eventually populate the interstellar medium and later participate in the formation of new stars.

The thermal emission from grains occurs in the infrared. Different grains have emissivity features which are characteristic of the chemical and physical composition of the grain material. Therefore, the present study of the 16–30 μm spectra of carbon-rich stars and planetary nebulae was undertaken. We report here observations of a new feature in the 25–30 μm region found in carbon stars and two planetary nebulae (Forrest, Houck, and McCarthy 1980). Previous work on the spectra of oxygen-rich stars and the planetary nebulae NGC 7027 have been reported elsewhere (Forrest, McCarthy, and Houck 1979; McCarthy, Forrest, and Houck 1978; Forrest, McCarthy, and Houck 1980).

II. OBSERVING PLAN

The planetary nebulae and carbon-rich stars selected for this study are listed in Table 1 along with their 2 μm sky survey number (IRC, Neugebauer and Leighton 1979), their Air Force Geophysical Laboratory sky survey number (AFGL, Price and Walker 1976), the [19.8 μm]–[4.2 μm] color from the AFGL, the dates of our observations, and the best fit 16–23 μm temperature. Also included in Table 1 are the 19.8–4.2 μm color temperatures for these objects.

The carbon stars were selected to span a range of circumstellar shell optical thickness from very thin (Y CVn) to very thick (AFGL 3068) as judged by the color temperatures of the infrared continuum. Most of the infrared flux from Y CVn represents emission from the stellar photosphere; however, there is an emission feature around 11.5 μm usually attributed to silicon carbide (SiC) grains which have condensed in the circumstellar envelope (Goebel *et al.* 1980; Gilman 1969). The other objects show considerable excess emission in the infrared which comes from the circumstellar grains surrounding the star. The overall flux distribution is roughly like that of a blackbody, indicating that the grains have emissivity at all wavelengths. The characteristic grain temperatures are 300–1000 K. In addition, there is a small emission feature at 11.5 μm which, again, is probably due to SiC grains in the envelope (Treffers and Cohen 1974; Forrest, Gillett, and Stein 1975). For AFGL 3068, the 11.5 μm feature is seen in absorption, indicating a large optical depth in the shell (Jones *et al.* 1978).

The planetary nebula IC 418 was observed because of its unusual far-infrared spectrum reported by Moseley (1980). He found a steep fall in flux beyond 37 μm which was interpreted as due to either a narrow temperature distribution of graphite grains or a peculiar emissivity function of the grain material. Additional interest in IC 418 and NGC 6572 was generated by the discovery by Willner *et al.* (1979) that the nebulae had an

TABLE 1
OBJECTS INCLUDED IN THE OBSERVING PROGRAM

Name (1)	IRC (2)	AFGL (3)	[19.8 μm]–[4.2 μm][a] (4)	Dates Observed (5)	Best Fit Temperature (16–23 μm, K) (6)
			Planetary Nebulae		$\varepsilon_\lambda \approx 1/\lambda$
IC 418	...	...	-7.7[b] (310)	1980 March	125
NGC 6572......	...	...	-8.9[b] (275)	1978 May, 1980 July	121
			Carbon-Rich Stars		ε_λ = const.
Y CVn	+50219	1576	-0.6[c] (2250)	1978 May, 1979 July	2700
S Cep	+80048	2785	-1.8 (1000)	1979 July	475
V Cyg...........	+50338	2632	-1.7 (1025)	1978 May	450
CIT 5...........	+50096	489	-3.0 (675)	1980 July	450
IRC +40540 ...	+40540	3116	-4.3 (500)	1980 July	400
CW Leo	+10216	1381	-4.6[d] (475)	1980 March	300
AFGL 3068	...	3068	-7.6[e] (310)	1980 July	275

[a] In parentheses are the 19.8 μm–4.2 μm color temperatures in K.
[b] 4 μm from Willner *et al.* 1979; 20 μm from this paper.
[c] 20 μm from this paper.
[d] Becklin *et al.* 1969; Toombs *et al.* 1972.
[e] 4 μm from Jones *et al.* 1978.

emission feature near 11.5 μm similar to the one seen in carbon stars. They proposed that it might be due to SiC grains, suggesting condensation from a carbon-rich gas. The ionized gas in IC 418 appears to be carbon rich, based on the observations of Harrington *et al.* (1980); this provides another possible link to carbon stars.

The observations reported here were made using the 91 cm telescope of the Kuiper Airborne Observatory, flying above 12.5 km altitude to avoid atmospheric absorption. A grating spectrometer with a 10-element Si:Sb detector array built at Cornell University was used. The spectrometer has a resolution $\Delta\lambda \approx 0.16$ μm (FWHM) over the range from 16 to 30 μm with a beam size of 30″ on the sky. The instrument and calibration techniques are described in Forrest, McCarthy, and Houck (1980).

The 16–30 μm spectra are presented in Figures 1–2; the error of the flux calibration is estimated to be about $\pm 15\%$. For Figures 1 and 2*b*, the data have been averaged into bins of a 1 μm width to increase the signal-to-noise ratio. Data at the position of the 18.7 μm [S III] line has been suppressed for IC 418 and NGC 6572.

III. DISCUSSION

a) *The Nature of the Feature*

The most interesting aspect of these spectra is the new emission feature at $\lambda > 24$ μm, most clearly seen in IC 418 (Fig. 1), IRC +10216, and IRC +40540 (Fig. 2*a*). The feature appears as a sudden rise in emission between 23 and 26 μm with a leveling off in emission out to 30 μm, the longest wavelength observed here. The rise appears sharpest in the spectrum of IC 418 (23.5–25.5 μm). This peculiar spectral shape has not been observed previously in oxygen-rich stars (Forrest, McCarthy, and Houck 1979), galactic nebulae, or the planetary nebula NGC 7027 (McCarthy, Forrest, and Houck 1978; Forrest, McCarthy, and Houck 1980) and, therefore, indicates differences in the physical conditions between those objects and the objects in the present study.

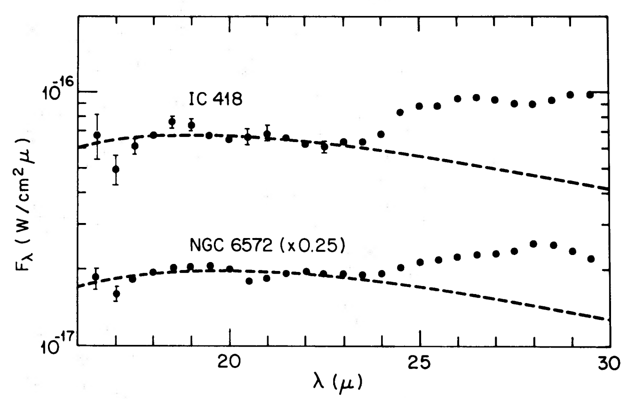

FIG. 1.—The 16–30 μm, $\Delta\lambda = 1.0$ μm spectra of IC 418 and NGC 6572, planetary nebulae with strong infrared continua due to dust emission. The dotted lines are the model fluxes described in the text. The new emission feature at $\lambda > 24$ μm is similar to that seen in the carbon stars in Fig. 2*a* and indicates that the same grain constituent is present in these objects. One sigma error bars are shown here and in Figs. 2*a* and 2*b* if the error exceeds 5% of the signal.

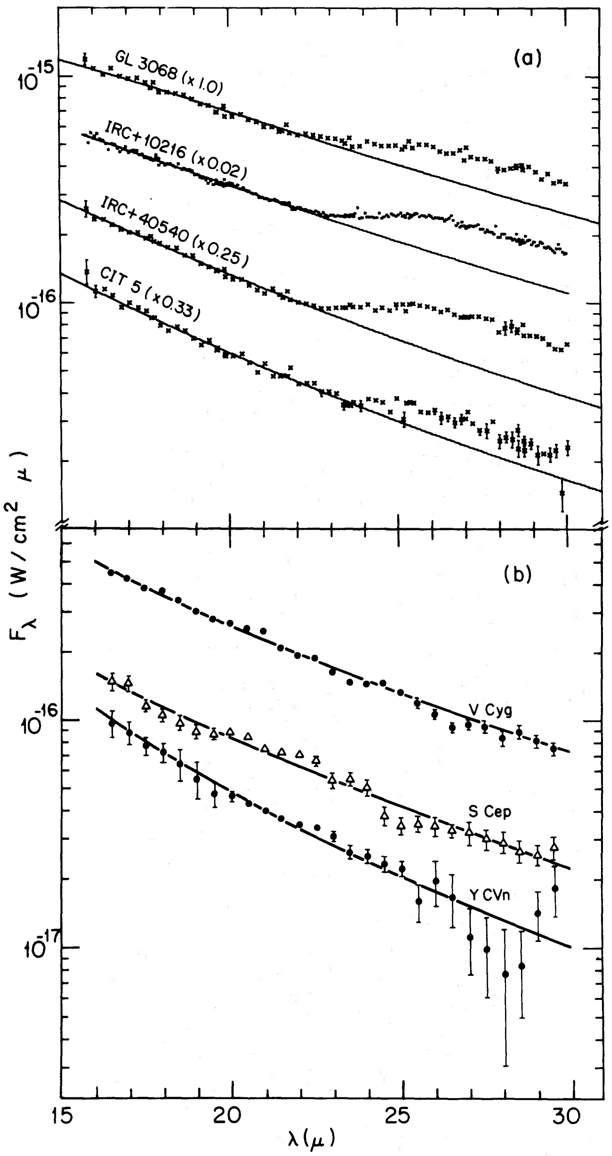

FIG. $2a$.—The 16–30 μm, $\Delta\lambda=0.16$ μm spectra of four carbon stars from Table 1. These stars are associated with very thick and extended clouds of gas and dust which result from the mass loss of the central star. The solid lines represent the models described in the text. The new emission feature at $\lambda>24$ μm seen here is most probably due to a solid-state resonance in the grains surrounding the stars. Evidently this grain constituent has condensed from the carbon-rich gas flowing from these stars. The "line" seen at 29.8 μm in IRC +10216 and CIT 5 is probably due to terrestrial H_2O. $2b$.—The 16–30 μm, $\Delta\lambda=1.0$ μm spectra of the three final carbon stars from Table 1. The shells around these stars are not as thick as those shown in Fig. $2a$. The solid lines represent the models described in the text. There is no evidence for the emission feature at $\lambda>24$ μm. This suggests that, in order to form, the new grain material requires the cooler, denser conditions found around the stars shown in Fig. $2a$.

For IC 418, it is unlikely that the observed spectral shape could be due to an absorption feature at 23 μm because there is no visible or infrared indication of an optically thick dust cloud. The nebula is bright in the visible with only about 0.6 mag of visible extinction and much less extinction at 1 μm (Pipher and Terzian 1969). The dust emitting in the infrared is undoubtedly heated by radiation emanating from the visible planetary nebula. Thus, any optically thick dust clouds would require peculiar optical properties (extinction larger at 23 μm than at visible wavelengths) or special geometries (heated dust obscured but optical nebula visible). Neither of these possibilities is very plausible. Further, the data of Moseley (1980) show no excess far-infrared (~ 100 μm) emission as one would expect from a cloud optically thick at 23 μm. Therefore, it is concluded that an emission feature at $\lambda>24$ μm is responsible for the spectral shape observed in IC 418 and, by analogy, in the other objects observed here.

The emission feature is much too sharp to be explained by a superposition of two or more blackbody distributions. A blackbody peaking in the 25 μm region has a characteristic width of ~ 25 μm (cf. curves in Fig. 1), whereas the step is only 2–3 μm wide. Therefore, the feature must be due to a change in the emissivity of the circumstellar material. It is possible that it could be due to gaseous emission, but this is considered unlikely for several reasons. First, the similarity of the shape of the feature in IC 418, IRC +10216, and IRC +40540 would not be expected for gaseous emission; the temperatures and densities in these objects are quite different. More specifically, the smooth and broad character of the feature implies it cannot be due to a vibration-rotation or pure-rotation band of a simple molecule. From the lack of structure in the spectra of IRC +10216 and IRC +40540 (Fig. $2a$), any molecular lines would have to be spaced closer than about 0.1 μm to escape detection. Therefore, there must be at least 60 individual lines between 24 and 30 μm, corresponding to $J\geq 60$. If thermally excited pure rotation produced the band, then the rotational temperature $T_{\rm rot}=(J/2)(h\nu/k)\approx 10^4$ K, which seems much too high for the carbon stars (central star ~ 2000 K, dust shell $\lesssim 500$ K). If it were a vibration-rotation band with $(k/m)^{1/2}$ (where k is the vibration "spring constant" and m the reduced mass) small enough to resonate at 30 μm, the centrifugal force (proportional to J^2/mr^3) would tend to tear the molecule apart unless the reduced mass were very large (>200 amu). Further, for a rotational temperature ≤ 500 K, the product $mr^2 \geq (h^2J^2)/2kT \gtrsim 160$ amu (Å)^2. This again implies a very complex molecule. In addition, it would be difficult to heat individual molecules in the circumstellar envelope enough to give the observed emission. For IRC +10216, at least 2% of the total luminosity comes from this feature, and for IC 418, the feature represents at least 10% of the total luminosity.

A quite plausible explanation for the emission feature is a solid-state resonance in dust grains which are being heated by absorbed radiation. The enhanced emissivity of the grains at $\lambda > 24$ μm could be due to a resonance in a chemical bond or bonds, broadened by their presence in a solid, or to a collective excitation of the crystal lattice. Examples of the former are the 10 μm and 18 μm silicate features and the 3.1 μm ice feature. An example of the latter is the 11.5 μm SiC feature.

b) *Interpretation of the Spectra*

As an aid in interpreting the observed emission feature, model continua have been fitted to the data from 16 to 23 μm and plotted in Figures 1 and 2. The temperatures of the best fitting models are given in Table 1. For the carbon stars, the model was a blackbody emission, i.e., emissivity ε_λ = constant. This form was chosen because the energy distribution of carbon stars approximates a blackbody over the wavelength range from 4 μm to beyond 40 μm (see Forrest, Gillett, and Stein 1975; Jones *et al.* 1978; Campbell *et al.* 1976). As discussed earlier, the continuum for Y CVn is primarily from the stellar photosphere but, for the other stars, represents almost entirely emission from the circumstellar envelope. For the planetary nebulae, it was found that the 16–23 μm continua could be fitted equally well by a blackbody or a $\varepsilon_\lambda \approx 1/\lambda$ model (for IC 418, a silicate emissivity model also gave a good fit). The $\varepsilon_\lambda \approx 1/\lambda$ model was chosen because it also fit the 70 μm data of Moseley (1980) which the other models did not.

i) *The Carbon Stars*

There is no evidence for the new dust-emission feature in V Cyg, S Cep, and Y CVn, whereas a feature does appear in the other carbon stars (Figs. 2*a* and 2*b*). Thus, even though some dust has formed in these stars ("SiC" in all three, "blackbody" emitters in V Cyg and S Cep), and mass loss is occurring, little or none of the new type of dust discovered here has formed. As the chemical composition of the shells should be similar (all are carbon rich), the most likely cause for this is the thickness of the shells. The thicker shells which do display the emissivity feature have lower temperatures and higher densities; evidently these conditions are necessary for the new dust to form. This suggests that the grain material may be relatively fragile and requires low temperatures for condensation.

The spectra of Figure 2*a* show systematic shape changes which are believed to be due to optical depth effects. The star CIT 5, with the thinnest shell, shows the sharpest step near 24.5 μm, while AFGL 3068, with the thickest shell, shows the most gradual transition to excess emission. Furthermore, there are differences in the relative amount of excess emission above the extrapolated 16–23 μm continuum. Taking IRC +10216 as an example, one finds that $\tau(24\ \mu\text{m}) \approx 1$, given the observed 24 μm flux, the 16–23 μm color temperature, and the approximate diameter of 2″ (McCarthy, Howell, and Low 1980; Toombs *et al.* 1972). Therefore, the presence of optical depth effects is plausible, and it is necessary to consider radiation-transfer effects in order to determine accurately the amount of dust and the intrinsic dust emissivity from the observed spectra.

ii) *The Planetary Nebulae*

The spectra of the planetary nebula IC 418 (Fig. 1*a*) also show an emission feature at $\lambda > 24$ μm similar in character to that seen in the carbon stars. This implies that the same type of dust also occurs in this planetary nebula. The rise in emission at 24.5 μm is somewhat more rapid than that in IRC +10216 and IRC +40540 but similar to that in CIT 5. This is consistent with the shell in IC 418 being optically thin.

In the far-infrared, IC 418 has an unusually large flux at 37 μm compared to the flux observed at longer wavelengths (Moseley 1980). This could be due to the emission feature found here extending beyond 30 μm. Moseley observed a flux of about 1.2×10^{-15} W cm^{-2} in his 28–52 μm bandpass, which is about a factor of 2 more than would be given by the 125 K continuum proposed here (see Fig. 1, Table 1). The feature found here emits about 6×10^{-17} W cm^{-2} μm^{-1} at 30 μm. Therefore, to explain the excess flux, the feature would have to keep emitting at that level out to about 38 μm. This suggests that the emission feature extends well beyond the longest wavelength observed here (30 μm).

The spectrum of the planetary nebula NGC 6572 (Fig. 1) also shows an emission feature at $\lambda > 24$ μm. The detailed spectral shape is different than in IC 418 in that the emission increases gradually out to ~28 μm. However, on the basis of the wavelength at which the feature occurs, it is likely that it represents emission from a similar type of material as is found in IC 418 and the thicker shell carbon stars. Because NGC 6572 is visible and there is no excess far-infrared emission (Moseley 1980), it is unlikely that the spectral shape is being affected by large optical depth near 24 μm. Therefore, the difference between NGC 6572 and IC 418 indicates a difference in the chemical and/or physical composition of the grain material.

Since IC 418 and NGC 6572 have a spectral feature at $\lambda > 24$ μm similar to that seen in carbon stars, it is concluded that at least one component of the grains condensed in a carbon-rich gas, which is strong evidence of an evolutionary link between carbon stars and some planetary nebulae. These two planetary nebulae also display an 11.5 μm feature similar to the SiC feature of carbon stars (Willner *et al.* 1979), which supports the evolutionary connection. However, not all planetary nebulae show these two features. For example, the continuum of NGC 7027 is smooth between 16 and 40 μm; BD +30°3639 is similar. This may be evidence for multiple evolutionary paths to the planetary nebula stage, but other processes may alter the dust composition and spectrum during evolution.

c) *Possibilities for the Grain Material*

Besides agreeing with the observed spectra, any possible grain material must be cosmically abundant and condense in a carbon-rich atmosphere. There is also a suggestion that the material has a lower condensation temperature than SiC or the "blackbody" grains. So far, no positive identification has been found for this new type of grain material.

Carbonates have features in the 24 μm region (see McCarthy, Forrest, and Houck 1978). However, the 11.3 μm and 7 μm features of carbonates are not seen in these objects (Willner *et al.* 1979; Treffers and Cohen 1974), so carbonates are not likely. The sulfides, such as FeS_2, have optical activity in the region beyond 20 μm (J. Goebel, private communication) and have a relatively low melting point. However, taking FeS_2 as an example, the infrared activity is due to optical phonons which would result in fairly sharp peaks in emissivity at 23.3 μm, 25.5 μm, 29.2 μm, 34.5 μm, and 36.1 μm (Schegel and Wachter 1976). Since this type of structure is not seen, one would have to consider whether effects such as particle shapes, mixtures of different sulfides, or amorphous composition could give the smooth spectrum seen.

There are two plausible candidate materials for which we have been unable to find infrared data in the 16–30 μm region. The first is Fe_3C (iron carbide), which Gilman (1969) and Lewis and Ney (1979) thought might form in a carbon-rich atmosphere. The second is carbyne, which in polymeric form is the organic residue of some carbonaceous chondrite meteorites (Whittaker *et al.* 1980; Hayatsu *et al.* 1980; Webster 1980). Carbynes consist of long chains of carbon atoms alternately connected by single and triple bonds. Radio emission lines from the related long-chain cyanopolyyne molecules up to HC_7N have been seen in IRC +10216 (Winnewisser and Walmsley 1978). As the resonant frequency of the C—C≡C bending mode is near 33 μm (Herzberg 1945), the solid carbynes may have a broadened feature in the 30 μm region. Other structures based on long chains of carbon atoms may also have features in the 30 μm region; for instance, poly(acetylene) has an infrared feature at 22.4 μm identified with the C—C=C bending mode (Shirakawa and Ikeda 1971). The stretching frequency of the C—C bond is near 11 μm, and it is possible this could contribute to the 11.5 μm resonance which is usually identified as SiC. Infrared measurements of these materials should be made.

IV. CONCLUSIONS

As a result of the present study of the 16–30 μm spectra, we conclude:

1. The new emission feature beginning at $\lambda = 24$ μm and extending beyond 30 μm and appearing in carbon stars and the planetary nebulae NGC 6572 and IC 418 is interpreted as resulting from a solid-state resonance in the grains in these objects.
2. This implies that at least one component of the grain material in these planetary nebulae is characteristic of condensation from a carbon-rich gas and indicates an evolutionary link between carbon stars and some planetary nebulae.
3. The new type of dust appears to form preferentially in dense, thick, and cool circumstellar shells of carbon stars. This property is distinct from that of SiC (11.5 μm) which seems to condense much more readily and may indicate the condensate is relatively fragile.
4. Further work is required to identify the grain material. Plausible candidates are the carbynes or other long-chain carbon polymers; infrared spectra of these materials should be measured. Spectra beyond 30 μm of the objects with the emission feature would aid in the identification.

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