THE ASTROPHYSICAL JOURNAL, 507:281–286, 1998 November 1

NEAR-INFRARED SPECTROSCOPY OF THE PROTO–PLANETARY NEBULA CRL 618 AND THE ORIGIN OF THE HYDROCARBON DUST COMPONENT IN THE INTERSTELLAR MEDIUM

J. E. CHIAR AND Y. J. PENDLETON
NASA-Ames Research Center, MS 245-3, Moffett Field, CA 94035
T. R. GEBALLE
Joint Astronomy Centre, 660 North A'ohoku Place, Hilo, HI 96720
AND
A. G. G. M. TIELENS[1]
NASA-Ames Research Center, MS 245-3, Moffett Field, CA 94035
Received 1998 February 25; accepted 1998 June 8

ABSTRACT

A new 2.8–3.8 μm spectrum of the carbon-rich protoplanetary nebula CRL 618 confirms the previous detection of a circumstellar 3.4 μm absorption feature in this object (Lequeux & Jourdain de Muizon). The high resolution and high signal-to-noise ratio of our spectrum allow us to derive the detailed profile of this absorption feature, which is very similar to that observed in the spectrum of the Galactic center and also resembles the strong 3.4 μm emission feature in some post–asymptotic giant branch stars. A weak 3.3 μm unidentified infrared band, marginally detected in the CRL 618 spectrum of Lequeux & Jourdain de Muizon, is present in our spectrum. The existence of the 3.4 μm feature implies the presence of relatively short-chained, aliphatic hydrocarbon materials ($—CH_2—/—CH_3 \simeq 2–2.5$) in the circumstellar environment around CRL 618. It also implies that the carriers of the interstellar 3.4 μm feature are produced at least in part in circumstellar material, and it calls into question whether any are produced by the processing of interstellar ices in dense interstellar clouds, as has been previously proposed. Other features in the spectrum are recombination lines of hydrogen, rotational and vibration-rotation lines of molecular hydrogen, and a broad absorption probably due to a blend of HCN and C_2H_2 bands.

Subject headings: circumstellar matter — dust, extinction — ISM: individual (CRL 618) — ISM: molecules — line: profiles — stars: AGB and post-AGB

1. INTRODUCTION

CRL 618 (AFGL 618) is a bipolar protoplanetary nebula (PPN) that is rapidly evolving from the asymptotic giant branch (AGB) to the planetary nebula (PN) phase (Westbrook et al. 1975). The optically invisible central star is surrounded by a compact H II region about 0".25 in diameter; a bright infrared source, present at the position of the central star, lies between two visible reflection nebulosities (Westbrook et al. 1975). A very high velocity wind (200 km s^{-1}) is observed via lines of CO and H_2 (Gammie et al. 1989; Cernicharo et al. 1989; Burton & Geballe 1986). Lequeux & Jourdain de Muizon (1990) obtained a 3.1–3.8 μm spectrum of the object in a 5" aperture, which detected lines of atomic and molecular hydrogen and an absorption band near 3.4 μm. Their spectrum is the first evidence that circumstellar carbonaceous dust can carry a 3.4 μm absorption feature like that seen in the diffuse interstellar medium along several sightlines (Butchart et al. 1986; Adamson, Whittet, & Duley 1990; Sandford et al. 1991; Pendleton et al. 1994) and in other galaxies (Wright et al. 1996; Bridger, Wright, & Geballe 1993).

The 3.4 μm absorption feature is due to C—H stretching vibrations in saturated aliphatic hydrocarbons (Butchart et al. 1986; Adamson et al. 1990; Sandford et al. 1991; Pendleton et al. 1994). Several candidates have been suggested for the carrier of this feature (see Pendleton 1997 for a review). Among them are (1) meteoritic-like material (see, e.g., Pendleton 1997; Ehrenfreund et al. 1991); (2) organic residue produced either by ultraviolet (UV) photolysis (Greenberg et al. 1995; Allamandola, Sandford, & Valero 1988) or by ion bombardment of simple interstellar ices (see, e.g., Moore, Ferrante, & Nuth 1996; Strazzulla, Castornia, & Palumbo 1995); (3) hydrogenated amorphous carbon (HAC; see, e.g., Witt, Ryutov, & Furton 1996; Duley 1993; Ogmen & Duley 1988; Borghesi, Bussoletti, & Colangeli 1987); and (4) quenched carbonaceous composite (QCC; see, e.g., Sakata & Wada 1989). Organic residues and extract from the Murchison meteorite provide the closest matches to the interstellar feature. The presence of the 3.4 μm absorption feature in the spectrum of interstellar dust is often cited as evidence for the importance of dust formation in the ISM through UV processing of grain mantles in the interstellar medium (see, e.g., Greenberg 1989).

The spectrum from Lequeux & Jourdain de Muizon (1990) is of insufficient quality to permit a detailed comparison with the profiles observed in the diffuse ISM. In order to better characterize the 3.4 μm absorbing material around CRL 618, we have obtained a 2.8–3.8 μm spectrum of the core region of CRL 618 at higher resolution ($R \sim 1200$) and sensitivity than the previously published spectrum. In addition, we have obtained a 2.8–3.5 μm spectrum of the visually obscured carbon star IRC +10216 for comparison with CRL 618. The observations and data reduction are described in § 2, the spectral features are described in § 3, and the origin and evolution of the 3.4 μm absorption feature is discussed more thoroughly in § 4.

2. OBSERVATIONS AND DATA REDUCTION

Spectra of CRL 618 between 2.86 and 3.78 μm and of IRC +10216 between 2.85 and 3.50 μm were obtained on

---

[1] Present address: Kapteyn Astronomical Institute, P.O. Box 800, 9700 AV, Groningen, NL.

UT 1995 December 13 and 14 with the facility infrared spectrometer CGS4 at the United Kingdom Infrared Telescope (UKIRT) on Mauna Kea. The spectrometer employed a 256 × 256 InSb array, a 75 line mm^{-1} grating used in first order, and a 1ʺ.22 wide slit oriented east-west on the sky. The resolving power produced by this configuration is 380 × λ (μm). The spectra shown here cover 3ʺ.66 × 1ʺ.22 (east-west by north-south) regions centered on the continuum peaks of both objects and were flux-calibrated using spectra of HR 8873 (F7 V, $L = 4.39$ mag assumed) for CRL 618 and HR 3759 (F6 V, $L = 3.52$ mag) for IRC +10216. Flux calibration is accurate to ±20% for CRL 618 but is highly uncertain for IRC +10216 because the dome shutter was 90% closed during its observation to prevent saturation of the detector array by this bright source. Wavelength calibration was obtained from an argon lamp and is accurate to better than 0.001 μm.

A CGS4 spectrum of CRL 618 between 2.03 and 2.45 μm measured on UT 1993 January 19 with CGS4 was used to obtain the Brγ flux. At that time the instrument contained a 62 × 58 pixel array with a pixel subtending a 3ʺ.1 square on the sky. The continuum peak was centered in the slit, which was oriented east-west, and the spectrum of the brightest row was extracted from the array. Flux calibration, again accurate to ±20%, was obtained from a similarly extracted spectrum of HR 2233 (F6 V, $K = 4.3$ mag assumed), and wavelength calibration was derived from the spectrum of an argon lamp.

Second- and third-degree continuum fits were carried out on the CRL 618 flux-calibrated 3 μm spectrum in order to determine if the profiles of features at 3.0 μm (absorption), 3.3 μm (emission), and 3.4 μm (absorption) are affected by choice of continuum fit. There is little difference between the optical depth spectra calculated using either the second- or third-degree continuum. As the third-degree continuum appears to provide a better fit to the entire spectrum (Fig. 1), it is used to produce the optical depth spectra that follow. A blackbody, with $T = 525$ K, was used to produce the optical depth spectrum of IRC +10216 (Fig. 3).

3. RESULTS

Figure 1 shows the flux-calibrated spectrum of CRL 618. It contains broad absorption features at ~3.0 and 3.4 μm, a number of atomic hydrogen recombination lines from the Pfund series, and rotation-vibration as well as pure rotational lines of H_2. Tables 1 and 2 list these emission lines. A weak emission feature is apparent at 3.3 μm with the Pfδ H I line superposed on it.

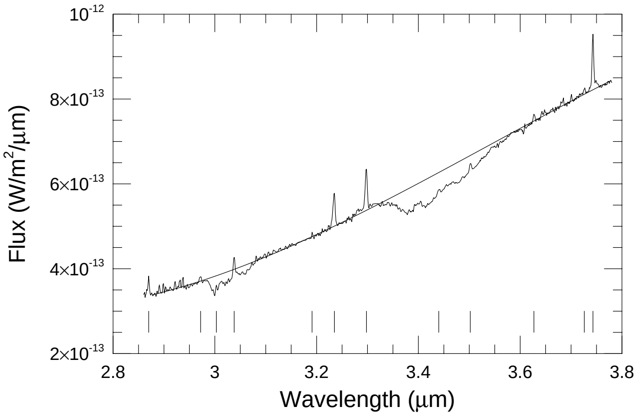

FIG. 1.—UKIRT spectrum of CRL 618 shown with third-order continuum fit. Vertical lines denote positions of atomic and molecular hydrogen lines listed in Tables 1 and 2. Uncertainties in the data can be estimated from local point-to-point variations in the spectrum.

3.1. *Extinction Estimate*

The extinction toward CRL 618 can be estimated by comparing the free-free emission to the infrared atomic hydrogen recombination lines. For the compact H II region surrounding CRL 618, we assume an electron temperature, $T_e = 10^4$ K, and parameters given by Osterbrock (1974). We adopt a thermal flux of 2 Jy at 200 GHz (Martín-Pintado et al. 1988) to estimate the intensity of the hydrogen recombination lines. Expected line intensities for the infrared hydrogen recombination lines are then estimated using ratios given by Hummer & Storey (1987); Table 2 lists the results. Visual extinction is estimated assuming the average interstellar extinction law deduced by Martin & Whittet (1990). Our extinction estimates (Table 2) are within the range of values (60–100 mag) given by Lequeux & Jourdain de Muizon (1990); however, the visual extinction estimates increase with wavelength, thus our line of sight most likely intersects the scattering lobes and the true visual extinction through the dense torus to the central star is actually greater than 100 mag.

At the distance of CRL 618 (1.3 kpc; Loup et al. 1993), an interstellar visual extinction of only ~2 mag is expected based on the 1.8 mag kpc^{-1} estimate (see, e.g., Whittet 1992). The A_V estimates (Table 2) are wavelength-dependent as expected in a bipolar scattering nebula, and since the scattering lobes are apparent in the visible they have little visual extinction (Latter et al. 1992). Thus, we conclude that most of the extinction is consistent with *circumstellar* rather than *interstellar* dust.

3.2. *3.4 μm Absorption Feature*

The 3.4 μm absorption feature, with its relatively sharp leading edge, maximum absorption of $\tau \simeq 0.1$ near 3.40 μm, and shoulder at 3.48 μm strongly resembles the feature seen in the diffuse interstellar medium toward the Galactic center (Fig. 2). Using the observed relation between the optical depth, $\tau_{3.4}$, and A_V for interstellar dust in the local solar neighborhood (Pendleton et al. 1994), the estimated

TABLE 1

ATOMIC AND MOLECULAR HYDROGEN EMISSION-LINE FLUXES FOR CRL 618

WAVELENGTH				
Observed (μm)	Rest (μm)	IDENTIFICATION		FLUX[a] (10^{-16} W m^{-2})
2.870......	2.873	H I	11–5	1.3 ± 0.2
2.972......	2.974	H_2	2–1 O(3)	0.6 ± 0.2
3.003......	3.004	H_2	1–0 O(4)	0.4 ± 0.2
3.038......	3.039	H I	10–5	2.7 ± 0.3
3.191......	3.190	H_2	2–1 O(4)	0.3 ± 0.2
3.235......	3.235	H_2	1–0 O(5)	4.2 ± 0.4
3.298......	3.297	H I	9–5	4.2 ± 0.4
3.440......	3.438	H_2	2–1 O(5)	0.6 ± 0.2
3.502......	3.501	H_2	1–0 O(6)	0.7 ± 0.2
3.627......	3.625	H_2	0–0 S(15)	0.8 ± 0.2
3.726......	3.724	H_2	0–0 S(14)	0.4 ± 0.2
3.743......	3.741	H I	8–5	5.1 ± 0.5

[a] In 1ʺ.22 × 3ʺ.66 (north-south × east-west) aperture centered on continuum source.

TABLE 2

VISUAL EXTINCTION ESTIMATES FOR CRL 618 BASED ON MEASUREMENTS OF ATOMIC HYDROGEN RECOMBINATION LINES

LINE	WAVELENGTH (μm)	LINE FLUX Calculated (W m^{-2})	LINE FLUX Observed (W m^{-2})	EXTINCTION OF LINE (mag)	DERIVED A_V (mag)
Brγ......	2.166	3.3×10^{-14}	1.9×10^{-16}	5.6	59
Pfζ......	2.873	4.7×10^{-15}	1.3×10^{-16}	3.9	69
Pfϵ......	3.039	6.3×10^{-15}	2.5×10^{-16}	3.5	69
Pfδ......	3.297	8.7×10^{-15}	4.5×10^{-16}	3.2	74
Pfγ......	3.741	1.3×10^{-14}	5.3×10^{-16}	3.4	98

interstellar extinction $A_V \sim 2$ mag (§ 3.1) would give rise to an optical depth $\tau_{3.4} \sim 0.01$, which is much less than what is observed. Therefore, it is highly probable that the absorption is circumstellar.

The observed profile of the 3.4 μm feature in CRL 618 contains absorption maxima at 3.38, 3.42, and 3.48 μm (Fig. 2). Weak emission lines of H_2 may be present near the two short-wavelength maxima, but in view of the strengths of the clearly identified (and stronger) H_2 lines (see Table 1), molecular hydrogen cannot be the cause of this substructure. The profile of the 3.4 μm absorption feature toward GC IRS 6E (Pendleton et al. 1994), which probes the diffuse ISM, is remarkably similar to that of CRL 618 (Fig. 2). The band seen toward the Galactic center, however, has a less-pronounced structure at 3.4 μm. Substructure near 3.38, 3.41, and 3.49 μm in the diffuse ISM has been identified with methylene (—CH_2—) and methyl (—CH_3) groups (Sandford et al. 1991; Pendleton et al. 1994). Following these studies, we attribute the 3.4 μm feature in CRL 618 to an aliphatic hydrocarbon dust component; the relative strengths of the 3.38 μm (—CH_3) and 3.41 μm (—CH_2—) substructure imply a —CH_2—/—CH_3 ratio of 2–2.5 (Sandford et al. 1991).

The processes that convert gaseous acetylene to solid dust grains in carbon-rich red giant outflows are similar to those occurring in terrestrial soot-producing environments such as hydrocarbon combustion and pyrolysis (Frenklach & Feigelson 1989, 1997). Thus, one might expect soot-like carbon material to be present in the C-rich outflow from an evolved star. The structure of terrestrial soot consists of aromatic hydrocarbon moieties (i.e., PAHs) bonded by weak van der Waals interactions and aliphatic hydrocarbon bridges. Amorphous carbon materials such as HAC and QCC have a three-dimensional carbonaceous structure consisting of connected aromatic and aliphatic units, and they exhibit a 3.4 μm absorption profile similar to the interstellar profile (Duley 1994; Colangeli et al. 1995; Sakata & Wada 1989). However, the available HAC and QCC spectra do not match the detailed structure of the CRL 618 spectrum. Apparently, the physical structure of the circumstellar carbonaceous dust differs somewhat from that of these laboratory products, presumably reflecting the difference in formation and evolutionary history.

A much closer match to the CRL 618 (and diffuse ISM) feature is provided by meteoritic organic matter (Ehrenfreund et al. 1991; Pendleton et al. 1994). The meteoritic organic component has a kerogen structure, i.e., an assemblage of aromatic and aliphatic compounds. While there is a structural resemblance between meteoritic kerogen and HAC, the two are spectroscopically distinct, possibly because of the presence of oxygen. Recall that HAC does not provide a good fit to the interstellar (Pendleton 1997) or circumstellar 3.4 μm feature. Figure 2 shows a comparison between the spectrum of CRL 618 and that of the sublimate from the acid-insoluble component from the Murchison meteorite (de Vries et al. 1993); the striking similarity between the meteoritic and circumstellar (and interstellar) features suggests the structure and chemical composition are alike in these environments.

3.3. *3.3 μm Unidentified Emission Feature*

Lequeux & Jourdain de Muizon (1990) tentatively detected a weak emission feature at 3.3 μm. As shown in Figure 1, the level of emission near 3.3 μm is significantly higher than the adjacent continuum. The feature in CRL 618, which underlies the sharp Pfδ atomic hydrogen line,

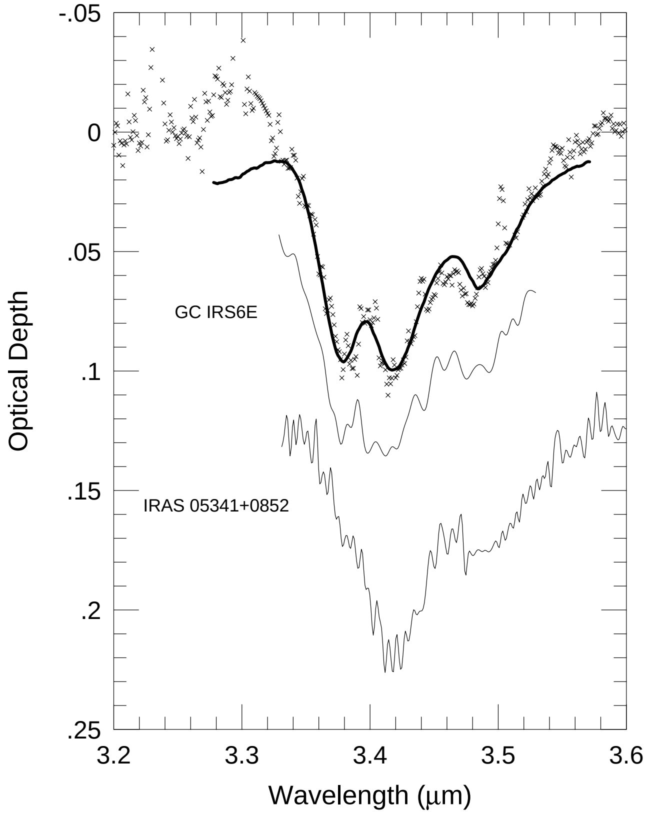

FIG. 2.—Optical depth plots in the region of the 3.4 μm feature: CRL 618 (*crosses*), Murchison meteorite extract (*heavy solid line;* de Vries et al. 1993), GC IRS6E (*middle solid line;* Pendleton et al. 1994), and the planetary nebula IRAS 05341+0852 (*lower solid line;* Joblin et al. 1996). The 3.4 μm emission feature in IRAS 05341+0852 has been inverted for comparison. All three spectra have been normalized to the depth of the CRL 618 spectrum at 3.492 μm.

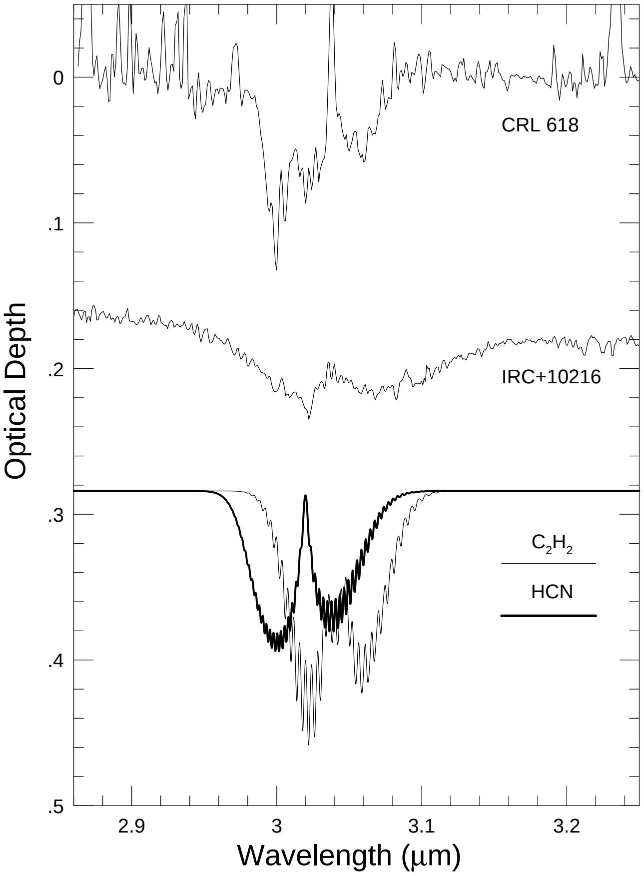

FIG. 3.—*Top:* Spectrum in the 3 μm region of CRL 618 compared with spectrum for the carbon star IRC +10216 (*middle;* normalized to the optical depth of the CRL 618 spectrum at 3.06 μm). *Bottom:* Calculated HCN and C_2H_2 spectra at $R = 1200$, $T = 200$ K, and $\Delta v = 10$ km s^{-1} are shown for comparison (model spectra courtesy of I. Yamamura 1997, private communication). The spectrum of IRC +10216 and the model data are offset for clarity.

appears to have the same peak position and width as the standard unidentified infrared (UIR) 3.3 μm feature seen in planetary nebulae (see, e.g., Nagata et al. 1988), and therefore we identify it as the aromatic C-H stretch vibration. We confirm the existence of this feature in CRL 618 at a strength of $3.1 \pm 0.3 \times 10^{-13}$ ergs cm^{-2} s^{-1}. UIR bands are not generally observed in AGB stars but are found in some post-AGB stars and in many dusty planetary nebulae. Some post-AGB objects, particularly of late spectral type, show weak 3.3 μm UIR emission features, which are often dwarfed by much stronger emission features due to aliphatic groups (at ∼3.4 μm; Geballe & van der Veen 1990; Geballe et al. 1992). If in post-AGB stars these features are emitted by the same carriers in the same locations as the UIR band carriers, these species must contain a large portion of aliphatic groups attached to the aromatic C-backbone. In CRL 618, the two features are not produced in the same location, since one is in emission and one is in absorption. The profile of the 3.4 μm UIR emission feature in the post-AGB object IRAS 05341+0852 (Joblin et al. 1996) differs somewhat from the 3.4 μm absorption feature in CRL 618 (Fig. 2). It is possible that, because of the difference in temperature (Joblin et al. 1995), the feature has a different profile in absorption than in emission, and/or that in CRL 618 superposition of weak 3.4–3.5 μm emission on the absorption partly influences the shape of the feature.

3.4. *Emission Lines*

The detected lines of atomic hydrogen include transitions from the Pfund ($n - 5$) series (Tables 1 and 2). Thronson (1981) and Latter et al. (1992) have demonstrated that the hydrogen recombination lines arise in a compact H II region that is visually obscured from our view but is not shielded from ionizing radiation from the central star. On the other hand, the relative intensities of the lines of H_2, which arise from the $v = 0$, 1, and 2 levels and from rotational levels as high as $J = 17$, imply that much of the emitting H_2 is excited by collisions, a conclusion reached by previous observers of H_2 lines at shorter wavelengths (see, e.g., Thronson 1981). However, Latter et al. (1992) concluded that a small fraction of the H_2 line emission is excited by ultraviolet photons in a photodissociation region separating the ionized gas from the surrounding molecular gas. The thermally excited H_2 must be largely shielded from the UV radiation from the central star.

3.5. *3.0 μm Absorption Feature*

The 3.0 μm feature in CRL 618 does not resemble the circumstellar or photospheric HCN and C_2H_2 absorption in carbon stars such as IRC +10216 (Fig. 3; see Ridgway, Carbon, & Hall 1978 for an analysis of these bands in IRC +10216). Figure 3 shows a comparison of the 3.0 μm feature in CRL 618 with models of absorption-line spectra for HCN and C_2H_2 (I. Yamamura 1997, private communication). Based on this comparison, we conclude that neither HCN or C_2H_2 on their own match the structure in the spectrum of CRL 618, and that the feature is most likely due to a combination of bands from cold 100–200 K HCN and C_2H_2 in the stellar outflow. The depth of the P and R branches depend on the velocity width of the individual rotation-vibration lines; thus, we infer $\Delta v = 10$–20 km s^{-1}, which places the HCN and C_2H_2 in the cool AGB wind surrounding this young planetary nebula.

4. ORIGIN AND EVOLUTION OF THE 3.4 μm FEATURE

These observations unambiguously demonstrate that the carrier of the interstellar 3.4 μm absorption feature exists in material ejected from some carbon-rich evolved stars. Previously, it has been suggested that the interstellar feature arises in organic residues produced by UV photolysis of dirty ices that originally formed in dark clouds (see, e.g., Sandford et al. 1991). However, it would be difficult to explain the prior presence of simple ices around a carbon-rich object like CRL 618; the dust has no oxygen available to form H_2O ices and temperatures are too warm for other common mantle constituents (e.g, solid CO) to form. Additional evidence against production of the 3.4 μm carrier by UV photolysis of ices is the recent discovery by Adamson et al. (1998) that the 3.4 μm feature along the line of sight toward the Galactic center is not polarized. Their finding strongly suggests that the 3.4 μm band is being produced by very small (unaligned) grains rather than organic mantles on silicate cores. Our observations suggest that carbon stars or their descendants are the source of the carrier of the 3.4 μm feature.

We now consider production of the carrier of the 3.4 μm feature in carbon-rich stellar outflows in general and the protoplanetary nebula CRL 618 in particular. In general, the infrared spectra of PNe are dominated by the standard UIR emission features, whereas the spectra of transition objects (post-AGB stars and protoplanetary nebula) show a variety of IR emission features, only some of which resemble those of PNe (Buss et al. 1993; Geballe 1997). It has been proposed frequently that the UIR features in PNe are emitted by a variety of polycyclic aromatic hydrocarbons (PAHs). An evolutionary sequence for circumstellar PAHs and carbonaceous dust has been suggested (Buss et al. 1993) in which processing of dust takes place in the transition stage. Carbon dust in the AGB phase has an amorphous structure as evidenced by the wavelength dependence of the dust emissivity required to fit the observed far-IR spectra of dusty carbon stars (Martin & Rogers 1987; Bagnulo, Doyle, & Griffin 1995). As demonstrated by the observed IR spectra, strengthening of the PAH emission features relative to the total dust emission is accompanied by an overall loss of H and a conversion of aliphatic to aromatic hydrocarbon structure. Both effects may reflect the increased strength of the far-ultraviolet (FUV) radiation field in the transition phase from AGB to PN; FUV photons are more efficient than visual photons in exciting the PAHs, and they can also drive the photochemical loss of —CH_3 and sidegroups from the PAHs (Joblin et al. 1996). CRL 618 seems to be at an intermediate stage in this transition. Probably because of its large circumstellar extinction, only a small part of the circumstellar dust/PAHs has been processed and hence the aliphatic spectral characteristics are more prominent than the aromatic ones in its infrared absorption spectrum. Shock implantation of H in C-rich dust will also give rise to aliphatic structure and a 3.4 μm absorption feature (see, e.g., Tielens et al. 1994). In that case, the 3.4 μm band may signify the processing of the AGB outflow material by the fast shock during the post-AGB phase (see below). The spectral difference between CRL 618 and the transition objects (3.4 μm absorption vs. emission) may also result from the extreme edge-on nature of the torus, and with a more titled geometry the CRL 618 spectrum might show 3.3 and 3.4 μm emission features.

The 3.4 μm absorption feature has not been detected in cool carbon stars, which are thought to be the progenitors of objects such as CRL 618. The 2 μm extinction toward the prototypical cool carbon star IRC +10216 is estimated to be $\sim$6 mag (Martin & Rogers 1987; Ridgway & Keady 1988), probably comparable to that for the core of CRL 618. Thus, one might expect the 3.4 μm hydrocarbon feature to be detectable toward carbon stars. This suggests that the simple scenario outlined above—condensation of amorphous carbon dust with a large aliphatic component in the AGB phase that is processed to aromatic dust during the PPN and PN phase—may need some adjustment. Perhaps the appearance of the 3.4 μm absorption feature during the transition from AGB to the PN phase reflects grain processing in shocks caused by fast ($\simeq$200 km s^{-1}) stellar winds (Frank, Balick, & Riley 1990) and the previously ejected, low-velocity ($\simeq$20 km s^{-1}) AGB wind.

The discovery of spectroscopic similarity between diffuse interstellar and circumstellar organics prompts a reassessment of the origin of organic matter in the ISM. Additional laboratory studies will be very important to determine which of these processes—C-dust condensation and UV processing or shock processing—is most important for the formation of the circumstellar 3.4 μm carrier. Our observations have shown that UV photolysis of ices is not the only route toward a 3.4 μm carrier. Further observations may determine whether the interstellar 3.4 μm carrier predominantly results from FUV photolysis of ices, stardust injection, or shock processing of carbon dust. Our results and the absence of the 3.4 μm aliphatic hydrocarbon feature in dense molecular clouds (Allamandola et al. 1993; Brooke, Sellgren, & Smith 1996; Chiar, Adamson, & Whittet 1996) challenge current ideas about the rapid cycling (10^7 yr; McKee 1989) of material between the diffuse ISM and dense clouds, since such cycling should result in the presence of the aliphatic hydrocarbons in both environments.

Our results raise the question of how much, if any, of the 3.4 μm absorption seen in the diffuse ISM is actually manufactured in the dense ISM as previously thought. The observed 3.4 μm interstellar band requires 3%–4% of elemental C (Pendleton et al. 1994). In addition to CRL 618, two groups of evolved objects, the cool post-AGB objects mentioned earlier and certain novae (the so-called class B and D UIR sources; Geballe 1997), show emission features that are nearly identical in spectral profile to the 3.4 μm absorption feature. Thus in addition to CRL 618–type objects, material from these object types may contribute to the interstellar feature. It remains to be determined whether this has produced sufficient material on a Galactic scale to account for the strength of the interstellar 3.4 μm feature.

We thank the referee, Greg Sloan, for his careful reading and helpful comments that improved the manuscript. The United Kingdom Infrared Telescope is operated by the Joint Astronomy Centre on behalf of the UK Particle Physics and Astronomy Research Council. J. E. C. holds a National Research Council–ARC Research Associateship. We thank P. Gerakines for help with the continuum fitting for IRC +10216. We are grateful to F. Helmich and I. Yamamura for providing model spectra of C_2H_2 and HCN.

REFERENCES

Adamson, A. J., Whittet, D. C. B., Chrysostomou, A., Hough, J. H., Aitken, D. K., Wright, G. S., & Roche, P. F. 1998, ApJ, submitted

Adamson, A. J., Whittet, D. C. B., & Duley, W. W. 1990, MNRAS, 243, 400

Allamandola, L. J., Sandford, S. A., Tielens, A. G. G. M., & Herbst, T. M. 1993, Science, 260, 64

Allamandola, L. J., Sandford, S. A., & Valero, G. 1988, Icarus, 76, 225

Bagnulo, S., Doyle, J. G., & Griffin, I. P. 1995, A&A, 301, 501

Borghesi, A., Bussoletti, E., & Colangeli, L. 1987, ApJ, 314, 422

Bridger, A., Wright, G., & Geballe, T. 1994, in Infrared Astronomy with Arrays: the Next Generation, ed. I. S. McLean (Dordrecht: Kluwer), 537

Brooke, T. Y., Sellgren, K., & Smith, R. G. 1996, ApJ, 459, 209

Burton, W. B., & Geballe, T. R. 1986, MNRAS, 223, 13P

Buss, R. H., Jr., Tielens, A. G. G. M., Cohen, M., Werner, M. W., Bregman J. D., & Witteborn, F. C. 1993, ApJ, 415, 250

Butchart, I., McFadzean, A. D., Whittet, D. C. B., Geballe, T. R., & Greenberg, J. M. 1986, A&A, 154, 5L

Cernicharo, J., Guelin, M., Martín-Pintado, J., Penalver, J., & Mauersberger, R. 1989, A&A, 22, L1

Chiar, J. E., Adamson, A. J., & Whittet, D. C. B. 1996, ApJ, 472, 665

Colangeli, L., Mennella, V., Palumbo, P., Rotundi, A., & Bussoletti, E. 1995, A&AS, 113, 561

de Vries, M. S., Reihs, K., Wendt, H. R., Golden, W. G., Hunziker, H. E., Fleming, R., Peterson, E., & Chang, S. 1993, Geochim. Cosmochim. Acta, 57, 933

Duley, W. W. 1993, in Dust and Chemistry in Astronomy, ed. T. J. Millar & D. A. Williams (Bristol: IOP), 71

Duley, W. W. 1994, ApJ, 430, L133

Ehrenfreund, P., Robert, F., d'Hendecourt, L., & Behar, F. 1991, A&A, 252, 712

Frank, A., Balick, B., & Riley, J. 1990, AJ, 100, 1903

Frenklach, M., & Feigelson, E. D. 1989, ApJ, 341, 372

———. 1997, in ASP Conf. 122, From Stardust to Planetesimals, ed. Y. J. Pendleton & A. G. G. M. Tielens (San Francisco: ASP), 107

Gammie, C. F., Knapp, G. R., Phillips, T. G., & Falgarone, E. 1989, ApJ, 345, L87

Geballe, T. R. 1997, in ASP Conf. 122, From Stardust to Planetesimals, ed. Y. J. Pendleton & A. G. G. M. Tielens (San Francisco: ASP), 119

Geballe, T. R., Tielens, A. G. G. B., Kwok, S., & Hrivnak, B. J. 1992, ApJ, 387, L89

Geballe, T. R. & van der Veen, W. E. C. J. 1990, A&A, 235, L9

Greenberg, J. M. 1989, in Interstellar Dust, ed. L. J. Allamandola & A. G. G. M. Tielens (Dordrecht: Reidel), 345

Greenberg, J. M., Li, A., Mendoza-Gomez, C. X., Schutte, W. A., Gerakines, P. A., & De Groot, M. 1995, ApJ, 455, L177

Hummer, D. G., & Storey, P. J. 1987, MNRAS, 224, 801

Joblin, C., Boissel, P. L., Léger, A., d'Hendecourt, L. B., & Défourneau, D. 1995, A&A, 299, 835

Joblin, C., Tielens, A. G. G. M., Allamandola, L. J., & Geballe, T. R. 1996, ApJ, 458, 610

Latter, W. B., Maloney, P. R., Kelly, D. M., Black, J. H., Rieke, G. H., Rieke, M. J. 1992, ApJ, 389, 347

Lequeux, J., & Jourdain De Muizon, M. 1990, A&A, 240, L19

Loup, C., Forveille, T., Omont, A., & Paul, J. F. 1993, A&AS, 99, 291

Martin, P. G., & Rogers, C. 1987, ApJ, 322, 374

Martin, P. G., & Whittet, D. C. B. 1990, MNRAS, 357, 113

Martín-Pintado, J., Bujarabal, V., Bachiller, R., Gómez-González, J., & Planesas, J. 1988, A&A, 197, L15

McKee, C. F. 1989, ApJ, 345, 782

Moore, M. H., Ferrante, R. F., & Nuth, J. A., III, 1996, Planet Space Sci., 44, 927

Nagata, T., Tokunaga, A. T., Sellgren, K., Smith, R., Onaka, T., Nakada, Y., Sakata, A. 1988, ApJ, 326, 157

Ogmen, M., & Duley, W. W. 1988, ApJ, 334, L117

Osterbrock, D. E. 1974, Astrophysics of Gaseous Nebulae (San Francisco: Freeman)

Pendleton, Y. J. 1997, Origins of Life and Evolution of the Biosphere, 27, 53

Pendleton, Y. J., Sandford, S. A., Allamandola, L. J., Tielens, A. G. G. M., & Sellgren, K. 1994, ApJ, 437, 683

Ridgway, S. T., Carbon, D. F., & Hall, D. N. B. 1978, ApJ, 225, 138

Ridgway, S. T., & Keady, J. J. 1988, ApJ, 326, 843

Sakata, A., & Wada, S. 1989, in IAU Symp 135, Interstellar Dust, ed. L. J. Allamandola & A. G. G. M. Tielens (Dordrecht: Reidel), 191

Sandford, S. A., Allamandola, L. J., Tielens, A. G. G. M., Sellgren, K., Tapia, M., & Pendleton, Y. J. 1991, ApJ, 371, 607

Strazzulla, G., Castornia, A. C., Palumbo, M. E. 1995, Planet Space Sci., 43, 1247

Thronson, H. A. 1981, ApJ, 248, 984

Tielens, A. G. G. M., McKee, C. F., Seab, C. G., Hollenbach, D. J. 1994, ApJ, 431, 321

Westbrook, W. E., Becklin, E. E., Merrill, K. M., Neugebauer, G., Schmidt, M., Willner, S. P., & Wynn-Williams, C. G. 1975, ApJ, 202, 407

Whittet, D. C. B. 1992, Dust in the Galactic Environment (Bristol: IOP)

Witt, A. N., Ryutov, D., & Furton, D. G. 1996, in From Stardust to Planetesimals: Contributed Papers, NASA CP-3343, ed. M. E. Kress, Y. J. Pendleton, & A. G. G. M. Tielens (Moffett Field: NASA), 105

Wright, G., Geballe, T., Bridger, A., & Pendleton, Y. J. 1996, in New Extragalactic Perspectives in the New South Africa: Proc. of the International Conf. on Cold Dust and Galaxy Morphology, ed. D. L. Block & J. M. Greenberg (Dordrecht: Kluwer), 143