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THE NATURE OF DUST AROUND THE POST–ASYMPTOTIC GIANT BRANCH OBJECTS HD 161796 AND HD 179821

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ABSTRACT

Ground-based 7.4–24 μm spectra of two post–AGB objects, HD 161796 and HD 179821, show emission features at 10–12 μm and at 19 μm. These features also appear to be present in the *IRAS* LRS spectrum of another post–AGB object, Roberts 22. HD 161796 and HD 179821 also exhibit a very rapid increase in flux between 13 and 15.5 μm. In view of the O-rich photosphere of HD 161796 and the presence of OH maser emission around all three objects, we ascribe these features to various oxides. However, the observed spectral features are quite different from the canonical silicate features observed in most O-rich giants. The 10–12 and 19 μm bands may be due to olivines and the rapid rise in flux between 13 and 15.5 μm may be due to iron oxides. We argue that HD 161796 and the bipolar nebulae Roberts 22 and NGC 6302 have all undergone the third dredge-up, with most of the dredged-up carbon having been converted to nitrogen by envelope-burning. Carbon-rich grain material, produced during the interval between the end of the third dredge-up and the moment when envelope burning finally reduced the C/O ratio below unity again, could be responsible for the UIR bands now being excited in Roberts 22 and NGC 6302.

Subject headings: circumstellar matter — dust, extinction — infrared: stars — stars: supergiants

1. INTRODUCTION

It is known that low- and intermediate-mass stars evolve from red giants on the asymptotic giant branch (AGB) to become planetary nebulae. The objects in transition between these two phases are more difficult to find since the time it takes a star to pass through the transition phase (post–AGB) is comparatively short. Following the AFGL and *IRAS* surveys, a class of post–AGB objects, supergiants of intermediate spectral type, has been identified (Lamers et al. 1986; Parthasarathy & Pottasch 1986). Many of these objects are associated with optically bright stars, with an infrared excess due to detached dust shells; hence, the resulting energy distributions show double-peaked profiles (see, e.g., Kwok, Volk, & Hrivnak 1989; van der Veen, Habing, & Geballe 1989). They are believed to be low core mass stars ($\sim 0.6\ M_\odot$) in the pre–planetary nebula (PPN) phase, rapidly transiting from the AGB to the planetary nebula stage. Abundance analyses show some of them to be metal-poor (Bond 1991) and their low surface gravity reflects their small stellar mass and high luminosity. Here we report ground-based 7.4–24 μm spectra of two of these objects and compare them to those of other PPNs. The observations are detailed in § 2, and the results are discussed in § 3.

2. OBSERVATIONS

We observed HD 161796 (=IRAS 17436+5003) and HD 179821 (=AFGL 2343 = IRAS 19114+002) in 1991 May with the 3.8 m UKIRT, CGS3, a common-user 10 and 20 μm grating spectrometer built at University College London. CGS3 contains an array of 32 discrete As:Si photoconductive detectors, and three interchangeable permanently mounted gratings covering the 10 and 20 μm atmospheric windows. Two grating settings give a fully sampled 64-point spectrum of the chosen waveband. The two low-resolution gratings were used for the observations described here, covering 7.4–13.3 μm and 15.4–24.1 μm, respectively. All observations were made through a 5\".5 circular aperture and the spectral resolution, as determined from the FWHMs of ionic forbidden lines in planetary nebula spectra, was 0.18 μm for the 10 μm spectra and 0.27 μm for the 20 μm spectra.

The spectra were flux-calibrated using α Boo as a standard. We were not able to completely cancel the telluric ozone feature at 9.7 μm; hence, the residual structure in the spectrum of HD 161796 at 9.7 μm should be ignored. The flux levels of the 10 μm spectra were found to be in good agreement with those of the respective *IRAS* LRS spectra, but the flux level of the 20 μm spectrum of HD 161796 required a downward adjustment of 20% to agree with the LRS flux level, while the 20 μm spectrum of HD 179821 required an upward adjustment of 30%.

The CGS3 spectra are shown in Figure 1, with the error bars representing the 1 σ statistical uncertainties in the fluxes. The rather large error bars associated with the 20 μm spectra were due to poorer than average atmospheric conditions at the time the spectra were acquired.

3. DISCUSSION

HD 161796 and HD 179821 have been classified as F3 Ib and G5Ia, respectively (Fernie & Garrison 1984; Hrivnak, Kwok, & Volk 1989). Their overall energy distributions (Fig. 2; van der Veen et al. 1989; Humphreys & Ney 1974) show double-peaked profiles typical of post–AGB sources. The near-infrared and visible emission is due to direct stellar photospheric radiation, while the mid- and far-infrared emission probably originates in a detached dust shell ejected during the AGB phase. In contrast to many well-known PPNs, the atmosphere of HD 161796 has solar oxygen and carbon abundances, with nitrogen enhanced by 0.9 dex relative to solar while metals (i.e., Fe) are poor (Luck, Bond, & Lambert 1990). HD 161796 and HD 179821 both show OH maser emission

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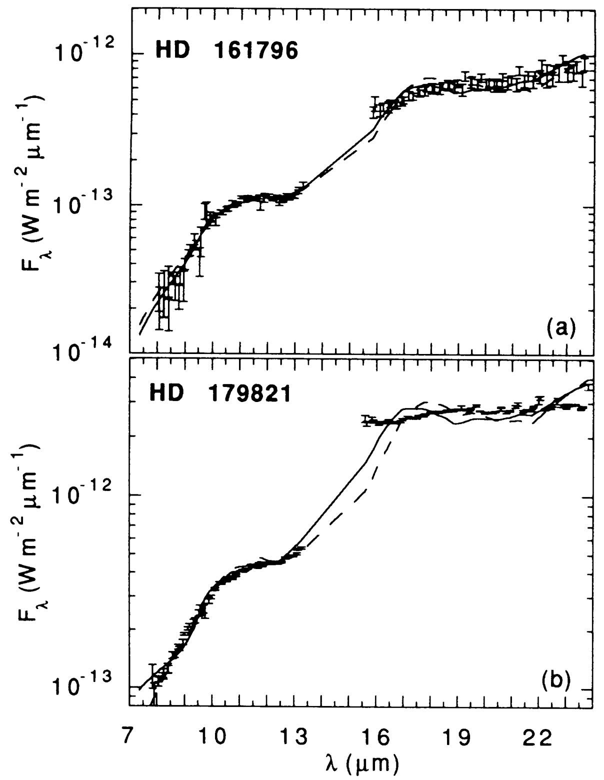

FIG. 1.—The 7–24 μm CGS3 spectra of HD 161796 and HD 179821, along with the best model fits (*dashed lines*) which use a combination of disordered olivine and a material with a smooth λ^{-1} emissivity (see text). The solid lines correspond to fits in which an additional magnetite grain component has been included. The error bars represent the 1 σ uncertainties in the fluxes.

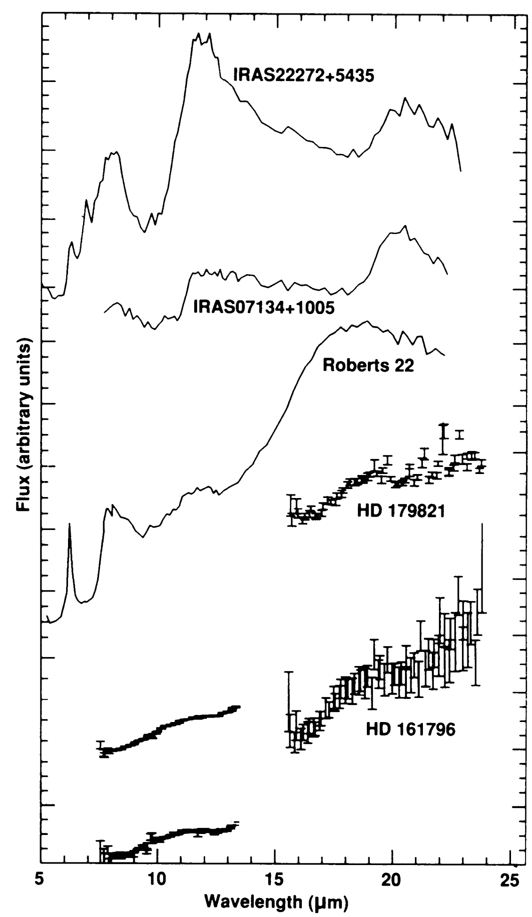

FIG. 3.—The CGS3 spectra of HD 161796 and HD 179821 are compared with the *IRAS* LRS spectra of three comparison sources. The spectrum of IRAS 22272+5435 between 5–8 μm is taken from Buss et al. (1990) and the 5–8 μm spectrum of Roberts 22 is from Cohen et al. (1989).

(Likkel et al. 1991), again indicative of an oxygen-rich circumstellar environment.

The 7.4–24 μm spectra of the two objects are very similar. They have very weak, broad 10–12 μm features. Their spectra rise sharply between 13 and 15.5 μm and peak around 25 μm (examination of the lower resolution *IRAS* LRS spectra extracted from the data base demonstrates that this sharp rise is real and not an artifact of our CGS3 calibration procedures). There is a distinct feature in the long-wavelength region peaking at about 19 μm. The emission features observed in these two objects are quite different from those observed in most O-rich giants. To some extent, this reflects the low emission temperature of the dust in these sources ($\simeq$150 K) as compared to O-rich giants ($\simeq$1000 K). However, the sharp rise in the emission between 13 and 15.5 μm as well as the emission feature peaking around 19 μm has not been observed before in any spectrum of an O-rich star.

Figure 3 compares these spectra with those of other well known PPNs. One characteristic of all the comparison objects (Roberts 22, IRAS 22272+5435, and IRAS 07134+1005) is the presence of the UIR features at 3.3, 6.2, and 7.7 μm, commonly ascribed to polycyclic aromatic hydrocarbons (PAHs; Allamandola, Tielens, & Barker 1989), which are absent in the spectra of HD 161796 and HD 179821. The *IRAS* LRS spec-

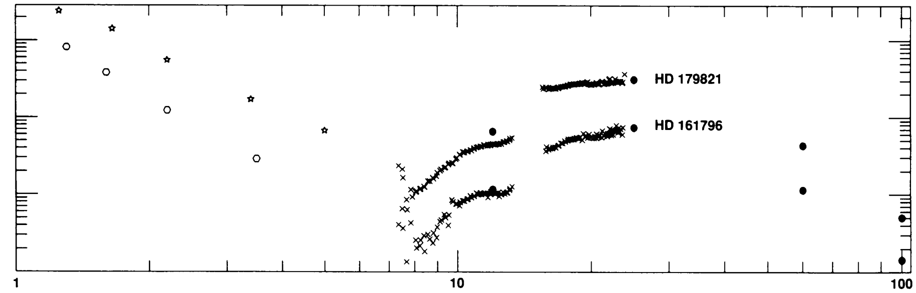

FIG. 2.—The 1–100 μm flux distributions of HD 161796 and HD 179821. The open circles are the near-infrared photometric data for HD 161796 from Humphreys & Ney (1974); the stars are the near-IR photometric data for HD 179821 from van der Veen et al. (1989); the solid dots are the color-corrected *IRAS* PSC fluxes and the crosses are the CGS3 data.

trum of Roberts 22 (=He 3-404) shows a 10–12.5 μm feature as well as a very broad band peaking between 17 and 22 μm. The former feature is similar to the 10–12 μm feature present in the spectra of HD 161796 and HD 179821, while the 19 μm feature present in their CGS3 spectra may correspond to the broad 17–22 μm feature seen in the LRS spectrum of Roberts 22. The other two PPNs also show broad-band emission features in their LRS 8–23 μm spectra (Fig. 3; Kwok et al. 1989; Buss et al. 1990), including the 21 μm band discovered by Kwok et al. However, the broad feature peaking at 12 μm in their spectra extends out to 17 μm and appears to differ from the 10–12 μm features present in the spectra of Roberts 22, HD 161796, and HD 179821. The photosphere of IRAS 22272+5435 is carbon-rich (Hrivnak & Kwok 1991) and the 12 μm feature in the spectra of it and IRAS 07134+1005 is thought to be due to PAH clusters or hydrogenated amorphous carbon (HAC) grains (Buss et al. 1990), with the 11.4 μm feature due to SiC also probably present. The fact that HD 161796 is O-rich (Luck et al. 1990) indicates that the 10–12 and 19 μm features observed in its spectrum are likely to be due to oxide carriers. The prominent 21 μm feature in the spectra of the two *IRAS*-named sources peaks significantly longward of the 19 μm features seen in the spectra of HD 161796 and HD 179821, consistent with the 21 μm band being due to a different (carbon-rich) carrier.

Disordered olivine, (Mg, Fe)$_2$SiO$_4$, shows a broad band peaking at 10–11 μm, with another peak at 18–19 μm (Kratschmer & Huffman 1979; Koike & Tsuchiyama 1992), so olivine is a possible candidate for identification with the features seen in the spectra of HD 161796 and HD 179821. We have fitted our observed spectra using a χ^2 minimization routine based on the one described for the 10 μm region by Aitken et al. (1979), Aitken & Roche (1982), and Whitmore (1986). The program has been extended by R. J. Sylvester to include extra grain materials and to enable the fitting of 20 μm spectra simultaneously with 10 μm spectra. First of all, we fitted just the 10 μm spectra of HD 161796 and HD 179821, using a combination of two components: (*a*) a featureless continuum having a λ^{-1} emissivity; and (*b*) material with the grain properties measured for radiation-disordered olivine by Kratschmer & Huffman (1979). Good fits were obtained to the 10 μm spectra of both stars, as shown by the low values obtained for χ^2/N_f (Table 1). The relatively low temperature of the olivine component (~90 K; Table 1) shifts the peak of the feature to longer wavelengths than normally encountered. The entries under "fraction" in Table 1 represent the fraction of the flux at 10.0 μm contributed by each component.

Although excellent fits to the 10 μm spectra were obtained using just olivine and continuum components, a simultaneous fit to the 10 and 20 μm spectra using just these two components produced a much worse fit (Figs. 1*a* and 1*b*, *dashed lines*; see also Table 1). In particular, the rapid increase in flux between 13 and 15.5 μm could not be matched. Cox (1990) has discussed the potential importance of iron oxides for the interpretation of midinfrared astronomical spectra. As shown in his Figure 3, the infrared absorption spectra of Fe$_3$O$_4$ (magnetite) and Fe$_2$O$_3$ (maghemite) both show low-level featureless absorption in the 10 μm region, along with a rapid rise in absorption between 13 and 16 μm. We therefore carried out a three-component fit to our observed spectra, adding a magnetite component to the olivine and blackbody × emissivity components. The optical constants for magnetite (from Lien 1990) were kindly provided by P. Cox. As shown in Figures 1*a* and 1*b* (*solid line*) and Table 1, improved fits are obtained by the addition of a magnetite component. The 10 μm region is largely unaffected by the addition of a magnetite component. However, even with the addition of magnetite, the fits to the 20 μm region could clearly do with further improvement. Fe$_3$O$_4$ possesses prominent emissivity peaks at 17 and 25 μm and these do not appear to be present in the observed spectra of HD 161796 and HD 179821. On the other hand, compared to the Fe$_3$O$_4$ spectrum, the spectrum of γ-Fe$_2$O$_3$ reproduced by Cox (1990) shows a sharper rise between 13 and 16 μm and a much flatter plateau longward of 16 μm. We would therefore expect γ-Fe$_2$O$_3$ to provide an improved fit, but suitable optical constants are unfortunately unavailable to us. The observed peak at 18–19 μm is not properly matched by the radiation-disordered silicate of Kratschmer & Huffman (1979). Koike & Tsuchiyama (1992) have found that the 18 μm peak of amorphous olivine shifts to longer wavelengths upon heating or hydration, so it would be valuable to have optical constants for such material.

Aluminum oxide is an expected high-temperature condensate in O-rich outflows (cf. Tielens 1990). Aluminum oxides show a prominent band around 12 μm, and they may contribute to the observed 10–12 μm feature in these two HD stars. Thermodynamic considerations suggest that iron can condense in the metallic form or become incorporated into silicates, depending on the physical conditions. It is conceivable that kinetics considerations favor nucleation and growth of iron oxides instead. Alternatively, metallic iron may simply "rust" in the H$_2$O-rich outflow from these objects. In all probability, the 12 μm feature in the spectra of HD 161796, HD 179821, and Roberts 22 have the same carrier. Likewise, we expect the 19 μm feature to be due to the same material in all three sources.

The olivine grain component is found to have a temperature of ~90 K around both stars (Table 1). We find, from a detailed spherical transfer model for silicate grains around a 6000 $L_\odot$ F star, that for a standard MRN grain size distribution (Mathis, Rumpl & Nordsieck 1977), such a grain temperature corresponds to a typical distance of 2.4 × 10^{16} cm from the star. The

TABLE 1

χ^2 FITTING PARAMETERS FOR HD 161796 AND HD 179821

Source	BB × Emissivity		Olivine		Magnetite			
	Fraction	T(K)	Fraction	T(K)	Fraction	T(K)	χ^2/N_f	Comments
HD 161796	0.73	157	0.27	88	...	...	1.57	10 μm fit only
	0.83	159	0.17	84	...	...	3.30	10 and 20 μm fit
	0.72	161	0.27	93	0.01	70	2.37	10 and 20 μm fit
HD 179821	0.88	157	0.12	91	...	...	0.91	10 μm fit only
	0.79	158	0.21	86	...	...	20.98	10 and 20 μm fit
	0.48	225	0.34	95	0.18	95	12.05	10 and 20 μm fit

measured CO expansion velocities are 14 and 33 km s^{-1} for HD 161796 and HD 179821, respectively (Likkel et al. 1991). The corresponding ages since shell ejection would therefore be 540 yr for HD 161796 and 230 yr for HD 179821. Such ages are broadly consistent with the transition times expected for H-shell burning nuclei with masses between 0.60 and 0.64 $M_\odot$ (see Fig. 2 of Schoenberner 1990).

Roberts 22, whose 10–25 μm spectrum is similar to those of HD 161796 and HD 179821 (Fig. 3), is a bipolar nebula with an A2 Ie central star and OH maser emission (Allen, Hyland, & Caswell 1980). The dust around it appears to be concentrated in a circumstellar disk; mass ejection at the tip of the AGB may have occurred preferentially in the equatorial plane. The high-excitation bipolar planetary nebula NGC 6302 resembles Roberts 22 in that its infrared spectrum simultaneously exhibits the signatures of carbon-rich material (the 8.6 and 11.3 μm UIR bands; Roche & Aitken 1986) and oxygen-rich material (an 18 μm silicate emission feature is prominent in a CGS3 spectrum which we have acquired; in addition, Payne, Phillips, & Terzian (1988) suggest that an OH maser is associated with the nebula). The nebula itself is O-rich (Aller et al. 1981). Lester & Dinerstein (1984) found the 10 μm emission from NGC 6302 to be concentrated in a disklike configuration. Bipolar type I planetary nebulae such as NGC 6302 are believed to originate from stars at the high-mass end of the PN progenitor star mass distribution (Zuckerman & Gatley 1988). The nitrogen abundance is significantly enhanced in NGC 6302 (Aller et al. 1981), but the total C + N + O abundance significantly exceeds solar, once the highest ionization stages of C, N, and O are allowed for. Since the CN and CNO cycles operating before the first and second dredge-ups cannot increase the total C + N + O abundance, this indicates that the third dredge-up (of material from the He-burning region) must have occurred, followed by the conversion of much of the dredged-up carbon to nitrogen by envelope burning (via the CN cycle at the bottom of the hydrogen envelope; cf. Renzini & Voli 1981). There would have been a phase, immediately after the third dredge-up had occurred, when the envelope was C-rich, until envelope burning by the CN cycle once again reduced the C/O ratio below unity (Brett 1991). Oxygen-rich grains would have been produced before the third dredge-up and after the envelope burning, with carbon-rich grains produced immediately after the third dredge-up. With the subsequent evolution of the central star to higher temperatures, the conditions in the ejected nebulosity became favorable for the excitation of the UIR bands, which would be seen superposed on the emission by the oxygen-rich grains. A similar scenario seems applicable to Roberts 22.

Luck et al. (1990) found nitrogen to be enhanced by 0.9 dex relative to solar in the spectrum of HD 161796, but at the same time found carbon and oxygen to have solar abundances. This indicates that in these low-mass ($\simeq 1\ M_\odot$) stars the dredge-up of carbon has been followed by envelope burning as well (Luck et al. 1990). It is somewhat surprising that these two post–AGB stars have undergone envelope burning, since their initial main-sequence masses, and current core masses, are presumably smaller than those of Roberts 22 and NGC 6302. Since the C-rich UIR bands can be excited by stars as cool as 5000 K (Buss et al. 1990; Hrivnak & Kwok 1991), their absence in the spectra of HD 161796 and HD 179821 may imply the absence of a C-rich phase during the evolution of these stars, which would require the envelope burning to have operated extremely quickly. Alternatively, a transient C-rich photospheric phase may have occurred sufficiently long ago that the C-rich ejecta are now far enough from the cool central star that the UIR bands are inefficiently excited. As the stars become hotter and emit more energetic photons, extended UIR emission may then become apparent. While other post–AGB supergiants of intermediate spectral type do manage to exhibit UIR band emission now (e.g., the Cygnus egg, IRAS 22272+5435, HR 4049), their photospheres are C-rich, so that C-rich material undoubtedly exists close to the stars, making it more easy to excite significant UIR band emission. The differences in stellar evolution between various types of post–AGB stars are presently not well understood. Further IR spectroscopic studies of post–AGB supergiants may be very useful to unravel these questions, where we emphasize that circumstellar dust may provide a memory of previous stellar evolution phases.

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