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A 21 MICRON EMISSION FEATURE IN FOUR PROTO–PLANETARY NEBULAE

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ABSTRACT

We report the discovery of an unidentified emission feature at 21 μm in the LRS spectra of four *IRAS* sources. These objects all show large far-infrared excesses due to a circumstellar dust envelope surrounding a carbon-rich central star and are likely to be in the evolutionary phase between the asymptotic giant branch and planetary nebula stages. The strength of the feature and the carbon richness of the objects lead us to believe that this feature is due to the bending mode of a transient carbon-bearing molecule.

Subject headings: infrared: sources — nebulae: planetary — stars: circumstellar shells — stars: evolution

I. INTRODUCTION

The Low Resolution Spectrometer (LRS) was one of the survey instruments on the *IRAS* satellite. It was used to measure the spectra of bright point sources between 7.7 and 22.6 μm with a resolution varying from $\lambda/\Delta\lambda \sim 60$ in the short-wavelength side to ~ 20 in the long-wavelength side. Two overlapping wavelength bands were scanned simultaneously, one ranging from 7.7 to 13.4 μm and the other from 11.0 to 22.6 μm. It was in operation during the entire survey and produced 170,000 spectra linked to 50,000 sources (Atlas of Low Resolution *IRAS* Spectra 1986).

Among the 5425 sources in the publicly released Low Resolution Spectra Catalogue (LRSC) were over 2000 oxygen-rich asymptotic giant branch (AGB) stars which display the 9.7 μm silicate feature, ranging from strong emission to strong absorption (Volk and Kwok 1987). There are also over 400 carbon stars detected to have the 11.3 μm SiC feature (Little-Marenin 1986). In this *Letter*, we report the discovery of a new unidentified feature at 21 μm in a number of carbon-rich post-AGB objects.

II. GROUND-BASED IDENTIFICATION OF *IRAS* SOURCES

The *IRAS* sky survey has detected many low–color temperature (100–300 K) sources. Since 1985, we have been carrying out a program to identify these *IRAS* sources using ground-based infrared telescopes (Hrivnak, Kwok, and Boreiko 1985; Kwok, Hrivnak, and Boreiko 1987*a*, *b*). Many of these sources have no optical counterparts. However, a number of *IRAS* sources have been found to be coincident with relatively bright stars. The association of a strong far-infrared source with a bright visible star is surprising, for it suggests a large degree of transfer of stellar energy to a circumstellar dust shell which is optically thin. Such "double-peak" energy distributions have been suggested as a result of the termination of mass loss and the continued evolution of the star beyond the AGB. Two of the stars in this study are identified with relatively bright ($V < 10$) stars. IRAS 07134+1005 is associated with BD +10°1470 (HD 56126, SAO 96709, $V = 8.2$) and IRAS 22272+5435 is associated with BD +54°2787 (HDE 235858, SAO 34504, $V = 9.3$). The other two objects, IRAS 04296+3429 and 23304+6147, are associated with stars of $V = 13$–14. The spectral types of these stars range from early-F to mid-G, and all show characteristics of supergiants. The confirmation of the association and the optical spectra are discussed in more detail elsewhere (Hrivnak and Kwok 1989).

III. THE *IRAS* LOW-RESOLUTION SPECTRA

Among the cool *IRAS* sources which we found to be associated with bright stars, four were found to have very peculiar spectra in the LRS database. Figure 1 shows the LRS spectra of 04296+3429, 07134+1005, 22272+5435, and 23304+6147. A linear baseline has been subtracted from each band of the spectra. To correct for an error in the original LRS calibration, the spectra have been recalibrated using seven bright stars as flux standards (Volk and Cohen 1989). The two bands were then joined together by shifting one band relative to another until a good match was found. The resultant spectra were then convolved with the instrumental profile of the 12 μm band and normalized to the 12 μm in-band flux. In the case of IRAS 04296+3429, the spectrum was also smoothed over three channels using the "boxcar" method. Comparison with the background makes it clear that the small-scale variability in these spectra is due to noise variations, and that no narrow spectral features (e.g. emission lines) are present.

In all four sources there is a prominent feature at 21 μm with an almost flat "continuum" between 12 and 18 μm. The 21 μm feature has never been observed before, and the flat "continuum" is also unusual among sources in the LRS catalogue. The depression at 10 μm could be an absorption feature, but the continuum level is uncertain since the LRS does not extend below 7.7 μm. Extrapolation of the 1–5 μm measurement of the photospheric continuum to 10 μm seems to suggest that there is an emission feature at ~ 8 μm. This is the case for all four objects. If the lowest point near 10 μm indeed represents the true continuum, then the flat part of the spectrum

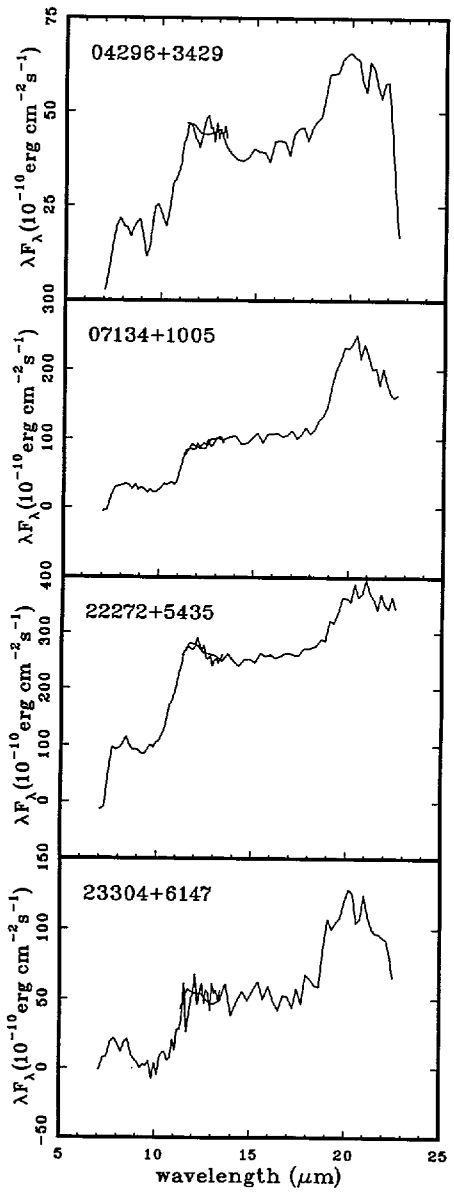

FIG. 1.—LRS spectra of 04296+3429, 07134+1005, 22272+5435, and 23304+6147. In each case, a linear baseline has been removed. The second band has also been shifted to ensure matching with the first band in the overlapping wavelength regions. The spectrum of 04296+3429 has been smoothed over three channels.

between 13 and 18 μm could be the result of a very broad emission feature. We note that the planetary nebula IC 418 also has a similar broad feature from 10.5 to 13 μm; however, in that source the continuum from 13 to 18 μm is steeper and the 21 μm feature is absent.

One could question whether this feature might have its origin in source contamination or instrumental effects. Since the LRS was a slitless spectrometer, searches were made within 20′ radius of each source for other *IRAS* point sources of comparative brightness at 12 or 25 μm which might cause contamination. For IRAS 04296+3429 there is a source 2′43″ away which is 20% as bright at 12 μm and 10% as bright at 25 μm and which may slightly be affecting the spectrum. On the sky-flux plates, IRAS 04296+3429 is about 40′ south and 5′ east of a very bright source, the LkHα 101 complex, but the scan direction is oriented so that there should be no hysteresis problem in the LRS detectors for 04296+3429. The source closest to IRAS 23304+6147 is 23300+6149 (IRC +60412, DS Cas), a carbon star. It is approximately as bright as 23304+6147 at 12 μm and 6% as bright at 25 μm, so it is not bright enough to be causing the 21 μm rise. For the other two sources, there is nothing bright nearby. Therefore, source contamination can be ruled out as the cause of the 21 μm feature. We also compared the individual LRS scans of each object to see if there are variations due to the different scan directions in the various observations. The 21 μm feature displays consistent shape in all individual LRS scans for each of the sources, and this appears to rule out instrumental effects.

Possibly by coincidence, all four sources are located in the outer galaxy within 10° of the plane (see Table 1). Assuming a typical scale height of 250 pc for late-type stars, their Galactic locations imply an average distance of ~1.5 kpc. We note that the Galactic distribution of N-type carbon stars is concentrated in the Galactic plane and the outer Galaxy (Stephenson 1965).

IV. ENERGY DISTRIBUTION

Ground-based optical and near-infrared (*JHKLM*) photometry for these four sources has been obtained. Data for 07134+1005 have been given by Hrivnak, Kwok, and Volk (1989), and that for the other three sources will be reported elsewhere. *IRAS* data for all four objects are listed in Table 1, having first been color corrected. The energy distributions for IRAS 04926+3429, 22272+5435, and 23304+6147, using combined *IRAS* and ground-based data, are shown in Figure 2; that of 07134+1005 is shown by Hrivnak, Kwok, and Volk (1989).

In all four objects, the energy distributions show a double-peak behavior, with comparable amounts of energy in the photospheric and circumstellar components of each source. Radiative transfer calculations suggest that this can be produced by a dust shell detached from the photosphere, as the result of mass loss having terminated sometime in the past (Hrivnak, Kwok, and Volk 1988, 1989).

Because of the brightness of the central stars, the circumstellar shells around these four objects must be optically thin in the infrared. Thus, the *IRAS* colors should give a rough estimate of the maximum dust shell temperature. All four sources have very similar *IRAS* colors and are distributed below the blackbody line on the [12]–[25] versus [25]–[60] color-color diagram (cf. Volk and Kwok 1989, Fig. 3). This similarity in color suggests that the substance responsible for the 21 μm feature forms only under very restricted physical conditions. In this regard it is interesting that of these four sources, the two with the weaker 21 μm feature also have slightly bluer 12/25 colors than the other two.

Model fittings to the energy distribution have also been made. Details of the fitting procedure can be found in Volk and Kwok (1989) and are based upon a dust radiative transfer code. The envelope density distribution is assumed to have the form $n \propto r^{-\alpha}$. Central temperatures are based on the G5 I spectral types (Hrivnak and Kwok 1989). The opacity of SiC grains is used in the models, which, of course, will not produce a fit with the detailed features of the spectra. The model curves are intended to fit the general energy distributions only. The model fits are plotted in Figure 2 and the model parameters are listed

TABLE 1

IRAS OBSERVATIONS

OBJECT	l	b	COLOR-CORRECTED FLUX DENSITY (Jy) 12 μm	25 μm	60 μm	100 μm	VARIATION (%)
04296+3429.........	166.2	−9.1	15.4	42.3	12.8	9.2	11
07134+1005.........	206.7	10.0	29.6	112.8	40.4	12.1	...
22272+5435.........	103.3	−2.5	89.4	277.6	79.3	38.1	3
23304+6147.........	113.9	0.6	13.7	57.6	22.6	<30.9	9

TABLE 2

MODEL PARAMETERS

Object	T_* (K)	L_*/D^2 ($L_\odot$ kpc^{-2})	R_{in}/D (10^{15} cm kpc^{-1})	τ(11.3 μm)	α	A_v (mag)
04296+3429	5000	556	1.8	0.180	2.5	6.2
07134+1005[a].........	6600	1725	3.2	0.100	2.0	0.7
22272+5435	5000	3852	4.9	0.109	2.5	1.3
23304+6147	5000	627	2.2	0.221	2.25	4.7

[a] From Hrivnak, Kwok, and Volk 1989.

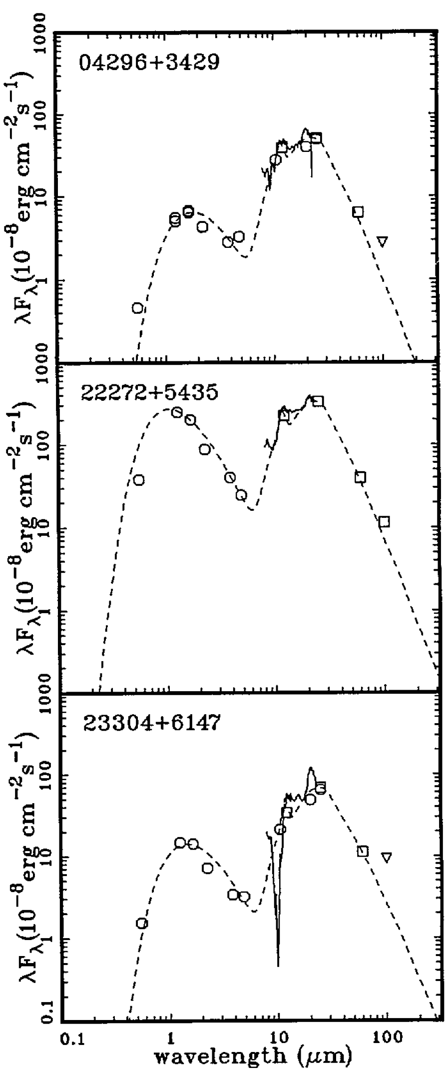

FIG. 2.—Energy distributions for 04296+3429, 22272+5435, and 23304+6147. The circles are ground-based observations, and the squares are color-corrected *IRAS* fluxes. The LRS spectra have been convolved with the 12 μm instrumental profile and normalized to the 12 μm point. The LRS spectra of 04296+3429 and 23304+6147 have been smoothed over three channels. The model curves are shown as dashed lines.

in Table 2. An additional amount of interstellar extinction (A_v) is needed to fit the observed photospheric continuum.

Comparison of the model energy distributions with the observations would give the source luminosities if the distances were known. Lacking this information, we have scaled the parameters for a distance of 1 kpc and indicated the scaling of the model values with distance in Table 2 and below. The low derived luminosities (the expected luminosities of post–AGB objects should be at least 5000 $L_\odot$) imply that the sources are actually 1.5–4 kpc distant. The current inner radii R_{in} can be found from the model fittings. Using these with the expansion velocities from molecular line observations, the estimated times t_0 since the termination of mass loss (in units of yr kpc^{-1}) are 35, 151, and 44 for 04296+3429, 22272+5435, and 23304+6147, respectively. When extrapolated back to the tip of the AGB, all these sources had very high optical depths in the circumstellar envelope and were probably similar to infrared carbon stars such as IRC +10216 and AFGL 3068. The inferred mass loss rates (in units of $M_\odot$ yr^{-1} kpc^{-1}) are 4.4×10^{-5}, 6.5×10^{-5}, and 2.8×10^{-5} for 0429+3429, 22272+5435, and 23304+6147, respectively. The steep density gradients in the circumstellar envelopes suggest that these high rates were attained only briefly near the tip of the AGB.

V. ORIGIN OF THE 21 MICRON FEATURE

The broadness of the 21 μm feature suggests that it is not due to an atomic transition but is likely to be the result of a molecular band on a solid surface. The strength of the feature implies that it must originate from abundant atomic species. The extreme carbon richness of the objects (Hrivnak and Kwok 1989) points to carbon, and one might naturally think also of hydrogen, as the most likely constituents. The rarity of the feature suggests that it arises from a transient molecule. We have made a search of the ground-state vibration transitions of transient molecules, and found that a number of molecules have vibrational modes in this region (Jacox 1984; Nakamoto 1969). For example, the linear molecule HNC has bending modes at 18, 19, and 21 μm. If HNC is responsible for the 21 μm feature, then other stretching modes (N–H at 2.8 μm, N–C at 4.9 μm) are also expected. The molecule HNC has been observed in the gas phase both in interstellar clouds (Goldsmith *et al.* 1986) and in circumstellar envelopes (Olofsson *et al.* 1982). In the envelope of IRC +10216, the abundance ratio of HCN to HNC is ~ 300. The tie between the 21 μm feature and HNC is strengthened by the fact that HCN is strong in the circumstellar envelopes of the three sources observed (Omont 1989); however, there is no sign of the bending mode of HCN at 14 μm in the LRS spectra.

Among molecules, $[CNO]^-$ has a bending mode at 21 μm and stretching modes at 4.8 and 9.0 μm, and NCO has a bending mode at 20.5 μm and stretching modes at 7.8 and 5.2 μm. While further observations are needed before a firm identification is made, it is interesting to note the emission feature at 7.8 μm may correspond to the N–C band of NCO.

VI. CONCLUSION

Recent observations have established that stars in the transition phase between the AGB and planetary nebulae stages have certain characteristics. They display large far-infrared excesses originating from dust envelopes completely detached from the central stars which, in some cases, are clearly visible. The expansion of the envelopes can be measured through radio molecular line emissions. In this *Letter*, we report the detection of a strong infrared feature at 21 μm in four carbon-rich objects which are in this transitional phase of evolution. This feature has not been seen in any other sources. This new infrared feature probably originates from a bending mode of a transient molecule which is created after the AGB but is destroyed before the star becomes a planetary nebula, as it has not been detected in objects in either of these evolutionary phases. The identification of the origin of this feature will have significant implications for our understanding of the chemical evolution of stars in the late stages of their evolution.

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