Asymptotic Giant Branch Stars
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On the Origin of the 21 Micron Feature in Post-AGB Stars

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Abstract. The unidentified emission feature at 21 μm is now observed in 12 sources, all being objects in transition between the asymptotic giant branch and planetary nebulae phases. The relations between the 21 μm and other emission features, such as the PAH features and the broad 30 μm feature, and the possible origins of the 21 μm feature are discussed.

1. Introduction

Stars on the asymptotic giant branch (AGB) are classified as oxygen (M) or carbon (C) rich based on their photospheric abundances. Over 4 000 and 700 stars have been found to show the silicate and the SiC features, respectively, in the IRAS Low Resolution Spectrometer (LRS) database and these stars are generally associated with M and C stars, respectively (Kwok, Volk & Bidelman 1997). In addition to these features, strong emission features attributed to the PAH molecules are also found in planetary nebulae (PN). These molecules are believed to be synthesized in the AGB envelopes but are only excited by the UV radiation field during the PN stage. It therefore came as a surprise that proto-planetary nebulae (PPN), objects in transition between the AGB and PN phases, were found to show an entirely new, strong emission feature at 21 μm, a feature which is not seen in AGB stars or PN.

The unidentified emission feature at 21 μm was first discovered in the IRAS LRS spectra of four carbon-rich post-AGB stars (Kwok, Volk & Hrivnak 1989). Since the initial discovery, this feature has been detected by both airborne (Omont et al. 1995) and ground-based observations (Kwok, Hrivnak & Geballe 1995; Justtanont et al. 1996).

To date, twelve 21 μm sources have been identified. Their properties are summarized in Table 1. All these sources have relatively uniform properties. They are mostly carbon-rich F and G supergiants with strong infrared excesses.

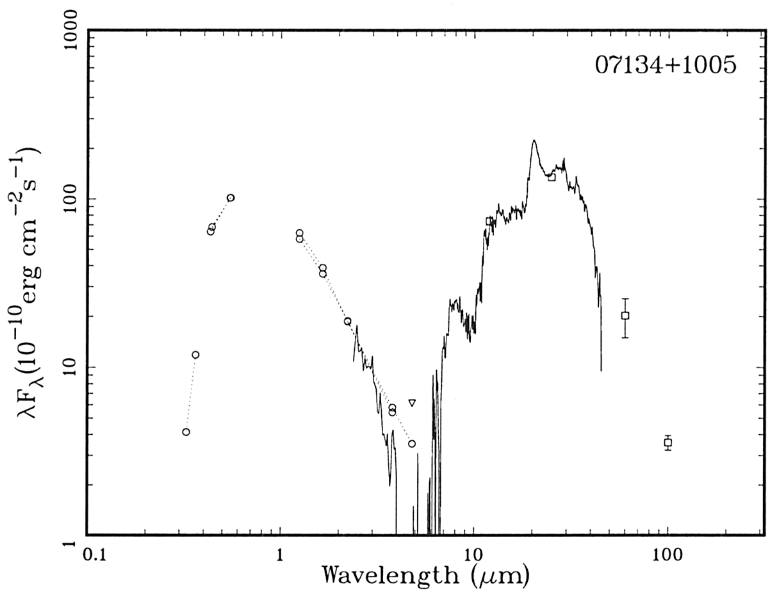

Figure 1. The spectral energy distribution of a typical 21 μm source. The high temperature component is the reddened photosphere and the low temperature component is the remnant dust envelope from the AGB phase.

Table 1. List of 21 μm sources and their common properties

Name	21 μm	30 μm	Sp. Ty.	Optical	PAH features	Mol. lines
02229+6208	medium	...	G8-K0 0-Ia	C_2, C_3	...	CO
04296+3429	strong	...	G0 Ia	C_2, C_3, CN	3.3, 3.4–3.5, 7.7,11.3	CO, HCN
05113+1347	medium	...	G8 Ia	C_2, C_3, CN	3.3, 11.3	CO
07134+1005	v. strong	medium	F5 I	C_2, CN	3.3, 6.9	CO, HCN
16594−4656	strong	...	...	...	...	CO
19500−1709	v. weak	...	F3 I	...	...	CO, HCN
20000+3239	weak	v. strong	G8 Ia	C_2, CN	7.7, 11.3	CO, HCN
AFGL 2688	weak	medium	F5 Iae	C_2, C_3, CN	3.3, 3.4–3.5	CO, HCN
22223+4327	medium	...	G0 Ia	C_2, C_3, CN	...	CO, HCN
22272+5435	strong	v. strong	G5 Ia	C_2, C_3, CN	3.3,3.4–3.5, 6.9, 7.7, 11.3	CO, HCN, CS
22574+6609	medium	...	...	...	7.7, 11.3	CO
23304+6147	v. strong	v. strong	G2 Ia	C_2, C_3, CN	7.7, 11.3	CO, HCN

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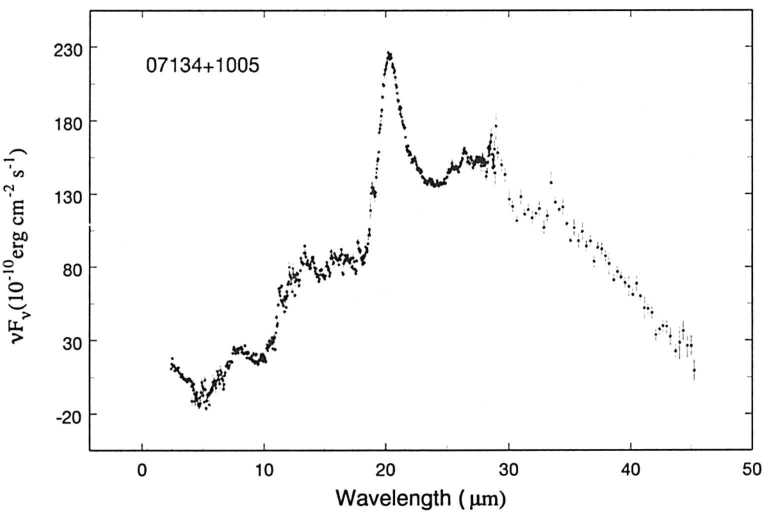

Figure 2. ISO SWS01 spectrum of IRAS 07134+1005.

2. The post-AGB nature of 21 μm sources

The post-AGB nature of the 21 μm sources is evident from (1) their intermediate spectral types (F-G); (2) the red IRAS colors (intermediate between the reddest AGB stars and PN); (3) the presence of C_2 and CN (Hrivnak 1995; Bakker et al. 1997) absorption bands consistent with large carbon enrichment through the 3rd dredge-up process; (4) excess of s-process elements (Van Winckel, this volume); and (5) their "double-peaked" spectral energy distributions, characteristic of dust shells detached from the stellar photospheres, implying the termination of mass loss sometime in the past (Fig. 1). These properties make the 21 μm sources the most unambiguous PPN objects.

3. ISO observations of 21 μm sources

Fig. 2 shows a typical infrared spectrum of a 21 μm source. Other than the strong, broad emission feature at 21 μm, the spectrum shows an almost flat continuum between 12 and 18 μm, and another broad feature between 11 and 13 μm. The sharp feature at 11.3 μm is likely to be associated with the C-H out-of-plane bend of PAH molecules. An unidentified, very broad emission feature at 30 μm is also often found in 21 μm sources.

The 21 μm features have almost exactly the same shape in each source after continuum subtraction. Fig. 3 shows the profiles of the 21 μm feature of 3 different sources at the higher resolution SWS06 mode of ISO ($\Delta\lambda/\lambda \sim 500$). The feature spans 19 to 23 μm with no obvious narrow substructures.

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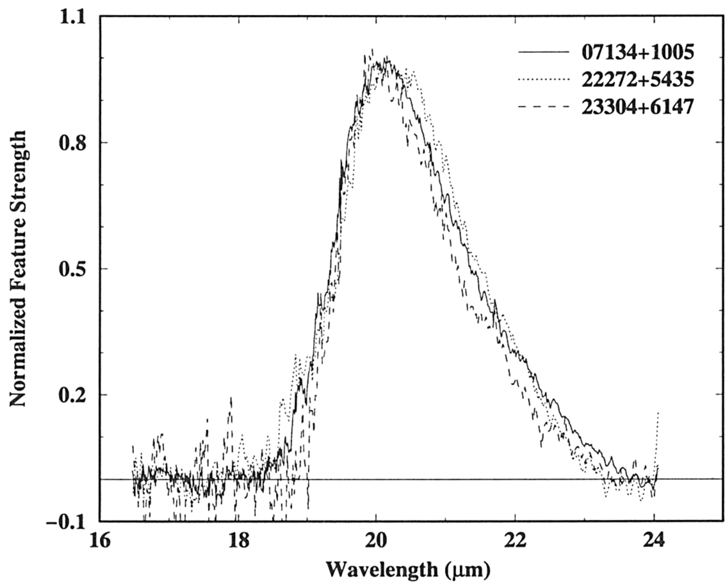

Figure 3. Overlay of the ISO SWS06 spectra of three 21 μm features.

4. Relationship with the 30 μm feature

The detection of a 30 μm emission feature in four 21 μm sources (07134+1005, 20000+3239, 22272+5435 and 23304+6147; Omont et al. 1995) suggests that these two features may share a common origin. However, the 30 μm feature has been seen in AGB stars (e.g. IRC +10216) and PN (e.g. IC 418) as well as in PPN (Cox 1993), while the 21 μm feature thus far appears to be restricted to PPN.

5. Relationship with the PAH molecule

There is strong evidence that the 21 μm feature is related to the PAH molecules. The 3.4-3.5 μm emission is particularly strong in 21 μm sources (Geballe et al. 1992). However, the 3.4-3.5 μm feature is absent in the strongest 21 μm emission source (IRAS 07134+1005; Kwok et al. 1990), so the correlation is not perfect.

The 3.4-3.5 μm feature has been suggested to be due to the hot bands of the fundamental 3.3 μm (CH stretch) feature (Barker et al. 1987), although this cannot be the case in PPN because the 3.4-3.5 μm feature is almost as strong as the 3.3 μm feature. More possibly, the 3.4-3.5 μm feature is due to aliphatic sidegroups (-CH_2, -CH_3) attached to the PAH molecules (Jourdain de Muizon et al. 1989).

The 6.9 μm feature is not seen in PN but is strong in 21 μm sources. It is therefore possible that the 3.3-3.4, 6.9, and 21 μm sources are related. However, IRAS 07134+1005 has a strong 6.9 μm feature but not the 3.4 μm feature.

6. Origin of the 21 μm feature

Many candidates have been proposed as possible carriers of the 21 μm feature, including:

- amides: urea or thiourea (Sourisseau et al. 1992)
- hydrogenated amorphous carbon (HAC; Buss et al. 1990)
- hydrogenated fullerenes ($C_{60}H_m$, m = 1, 2, ...60, or fulleranes; Webster 1995)
- maghemite (Fe_2O_3) or magnetite (Fe_3O_4; Cox 1990)
- solid SiS_2 (Nuth et al. 1985; Goebel 1993; Begemann et al. 1996)

In view of the fact that the 21 μm feature is seen exclusively in carbon-rich objects, it seems unlikely that it is due to inorganic materials such as SiS_2 or Fe_2O_3. The correlation of the 21 μm feature with the PAH features suggests that its carrier is a large carbon-based molecule. Most PAH molecules have ring deformation vibration modes around 20 μm, and mid-infrared laboratory emission spectroscopy of simple PAH molecules such as naphthalene, pyrene, and chrysene shows broad emission features in that region (P. Bernath, private communication).

Considering that fullerenes (C_{60}) are the 3-D analogues of the 2-D PAH molecules, their existence in carbon-rich objects is not unexpected. Emission spectra of gas-phase C_{60} show strong features at 7.1, 8.6, 17.5, and 19 μm (Frum et al. 1991), whereas the lowest vibrational mode of $C_{60}H_{60}$ is calculated to be at 23 μm (Webster 1995). For the other unsaturated hydrides ($C_{60}H_m$, m = 1 to 59), the perfect symmetry of the molecule is broken and the mode is no longer a narrow feature but bands peaking at wavelengths from 19 to 23 μm as m changes from 0 to 60. Webster (1995) suggests that the observed broad 21 μm feature is the result of a mixed population of fulleranes.

7. Evolutionary scenario

As a star evolves from the AGB to PN, its circumstellar environment (density, temperature, and radiation background) undergoes drastic changes. The dominant infrared emission features will likely change as the conditions for molecular formation, destruction, and excitation change. Acetylene (C_2H_2), widely considered to be the first building block of PAH molecules, has recently been detected in the atmospheres of carbon stars (Yamamura et al., this volume). Thus it is possible that PAH molecules are synthesized in AGB stars, but that the molecules are not excited because of the low temperatures of the central stars. HAC grains, made up of aromatic rings of various sizes bonded peripherally to polymeric or hydrocarbon species (Duley & Willams 1986), can also be made during the late AGB phase. Extreme carbon stars on the AGB have featureless dust continua (Volk et al. 1992) and these could be due to HAC grains. During the transition from the AGB to PN, these grains may be gradually shattered into smaller PAH molecules, possibly by high-velocity outflows now observed in

PPN. Then as the UV radiation background increases as the central star evolves to higher temperatures, the strengths of the PAH features increase. If 21 μm features are due to HAC grains, then the destruction of HAC grains will also imply the disappearance of the 21 μm feature beyond the PPN phase.

If the 21 μm feature is related to fulleranes and the disappearence of the 21 μm feature is the result of the loss of H atoms, then fullerenes should be detected in PN if they can be excited by UV photons or collisions. The infrared features of C_{60} have been searched in R CrB and IRC +10216 without success (Clayton et al. 1995), but a more extensive search in PN may be fruitful.

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