IDENTIFICATION OF THREE NEW PROTOPLANETARY NEBULAE EXHIBITING THE UNIDENTIFIED FEATURE AT 21 µm

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ABSTRACT

Among its great findings, the Infrared Astronomical Satellite mission showed the existence of an unidentified mid-IR feature around 21 µm. Since its discovery, this feature has been detected in all C-rich protoplanetary nebulae (PPNe) of intermediate spectral type (F–G) and—weakly—in a few PNe and asymptotic giant branch (AGB) stars, but the nature of its carriers remains unknown. In this paper, we show the detection of this feature in the spectra of three new stars transiting from the AGB to the PN stage obtained with the Spitzer Space Telescope. Following a recent suggestion, we try to model the spectral energy distributions of our targets with amorphous carbon and FeO, which might be responsible for the unidentified feature. The fit thus obtained is not completely satisfactory, since the shape of the feature is not well matched. In an attempt to relate the unidentified feature to other dust features, we retrieved mid-IR spectra of all 21 µm sources currently known from Infrared Space Observatory and Spitzer online archives and noticed a correlation between the flux emitted in the 21 µm feature and that emitted at 7 and 11 µm (polycyclic aromatic hydrocarbon bands and hydrogenated amorphous carbon broad emission). Such a correlation may point to a common nature of the carriers.

Key words: circumstellar matter – infrared: stars – stars: AGB and post-AGB

Online-only material: color figures

1. INTRODUCTION

One of the major results of the Infrared Astronomical Satellite (IRAS) mission came from its Low Resolution Spectrometer (LRS) with the detection of a new broad feature around 21 µm (Kwok et al. 1989) in the spectra of stars that have gone through the asymptotic giant branch (AGB) phase. The existence of this feature was not recognized at once, because it is weak in the first object in which it was observed, IRAS 22272+5435, which was listed in the LRS Atlas as having a low-temperature continuum and silicate absorption (Volk et al. 1999). In the first paper about this feature, four sources are listed (namely IRAS 07134+1005, 23304+6147, 22272+5435, and 04296+3429); subsequent ground-based (United Kingdom InfraRed Telescope), airborne (Kuiper Airborne Observatory), and space-based (Infrared Space Observatory, ISO) observations confirmed those detections and also added new members to the group of 21 µm emitters. Observations with the ISO led to the conclusion that the feature actually peaks around 20.1 µm (Volk et al. 1999), although it is still today commonly referred to as the “21 µm feature.”

The feature has been detected almost exclusively in C-rich protoplanetary nebulae (PPNe), intermediate-mass stars (1–8 \(M_\odot\)) transiting from the AGB to the planetary nebula (PN) stage. During the AGB phase, stars lose most of their initial mass, with mass-loss rates ranging from \(10^{-7}\) up to \(10^{-3}\) \(M_\odot\) yr\(^{-1}\). The AGB stellar atmospheres are subject to periodic He flashes, which imply that enriched material produced by nucleosynthesis in the bottom layers is carried to the surface. If this dredge-up of the star is efficient enough, the chemistry of the cooled material in the circumstellar envelope (CSE) will be based on C rather than O, as normally expected. Depending on their \([\text{C}] / [\text{O}]\) ratio, we can then distinguish between O-rich and C-rich CSEs.

When the star has evolved past the tip of the AGB, the intense mass loss that characterizes the AGB has ceased, but the dust and gas in the CSE is typically so thick that the star cannot be detected at optical wavelengths. The expansion and subsequent dilution of the envelope leads to the optical detection of a post-AGB star, which typically has a double-peaked spectral energy distribution (SED), as the result of the radiation from the central source and its CSE.

The central star then evolves toward hotter temperatures, while its CSE continues to expand and dilute. If the central star does not evolve too slowly, a few thousand years after the AGB phase it is hot enough to ionize its CSE (\(T_e \sim 20–30 \times 10^3\) K), which can lead to the destruction of molecules and even dust grains. The point at which the ionization of the CSE occurs is in fact considered as the beginning of the PN phase.

All of the objects showing the 21 µm feature are C-rich and metal-poor with enhanced abundances of s-processed elements (Hrivnak et al. 2009), and typically with F–G spectral type. Besides the unidentified feature, their mid-IR spectra typically show a broad feature around 30 µm that is usually attributed to MgS (Molster et al. 2010) and has been found to consist of two features centered at 26 and 33 µm, though such a distinction is not observed in all sources (Hrivnak et al. 2009).

As of this writing, 16 PPNe are known to exhibit the unidentified 21 µm feature (Hrivnak et al. 2009). Besides these sources, the feature has been detected weakly in three PNe (Hony et al. 2001; Volk 2003) and three AGB stars (Volk et al. 2000). It has not been observed in IRAS 01005+7910 (Cerrigone et al. 2009), a C-rich PPN with a hot central star (B0 I) that has already started to ionize its circumstellar shell (Cerrigone et al. 2011). Other hot post-AGB stars showing features of polycyclic aromatic hydrocarbons (PAHs) in their mid-IR spectra and therefore likely to be C-rich do not exhibit the feature either (Cerrigone et al. 2009). This leads to the
conclusion that the carrier must form during the AGB phase or very early afterward, and is probably easily destroyed as the radiation field of the central star hardens. Since its first detection, many different molecules have been considered as possible carriers of the 21 μm feature. The connection with the C-rich nature of the envelopes makes it obvious to take into account C-bearing molecules, for instance, TiC, doped-SiC, PAH, hydrogenated amorphous carbon (HAC), and fullerenes. Yet, non C-bearing molecules have been indicated as possible carriers as well, for example, SiS₂, FeO, Fe₂O₃, and Fe₃O₄ (Zhang et al. 2009). The main issues that arise with almost all of the proposed carriers are the presence of secondary features that are not detected in the astrophysical spectra, or the anomalous abundances necessary to account for the observed intensity of the feature. In this paper, we present observations obtained within a program aimed at characterizing the dust emission in objects transiting from the AGB to the PN stage with A–G spectral types, as a follow-up to our project presented in Cerrigone et al. (2009), which focused on sources with hot central stars (B spectral type). While the whole sample of transition targets will be presented in a separate paper along with data from other Spitzer programs (A. Hart et al. 2012, in preparation), here we will focus on three new sources that show the unidentified 21 μm feature. These are the only targets in our sample, where we find evidence for this feature.

2. OBSERVATIONS

The new observations presented in this paper were carried out with the Infrared Array Camera (IRAC; Fazio et al. 2004) and the InfraRed Spectrograph (IRS: Houck et al. 2004) on-board the Spitzer Space Telescope (Werner et al. 2004), within Program 50116 (PI: G. Fazio) in 2009 March and April. The IRS had four modules with different spectral resolutions. The short–low (SL) and long–low (LL) modules covered the 5.2–14.5 and 14.0–38.0 μm ranges, respectively, with spectral resolution R ~ 60–120. The short–high (SH) and long–high (LH) modules covered the 9.9–19.6 and 18.7–37.2 μm ranges with R ~ 600. Our spectral data were typically acquired in the low-resolution mode. Targets with IRS fluxes that would imply saturation with the IRS at longer wavelengths were observed in low resolution only between 5 and 14 μm (SL modules), while the 10–38 μm range was observed in high spectral resolution (SH and LH modules). In the latter case, a dedicated background observation was also performed for each target. For the three sources presented here, low-resolution observations were performed for IRAS 13245-5036 and 15482-5741, while low- and high-resolution data were collected for IRAS 14429-4539. IRAS 13245-5036 was not centered on the SL slit, therefore only LL data are available for this target.

Basic calibrated data were retrieved from the Spitzer Web archive. The observations of IRAS 13245-5036 were processed with the 18.7-0.0 pipeline by the Spitzer Science Center (SSC), while version 18.18.0 was applied to 14429-4539 and 15482-5741. The data were reduced following the standard recipe in the online IRS Cookbook: the background subtraction was performed from the off-target observations for low-resolution data (i.e., when one module is on the target, the other one is observing off-source) and from the dedicated background observation for the high-resolution data sets. The spectra were cleaned using IRSCLEAN, extracted and averaged together in

### Table 1: Photometry of Our Targets Obtained with IRAC

| Target      | 3.6 μm (mJy) | 4.5 μm (mJy) | 5.8 μm (mJy) | 8.0 μm (mJy) |
|-------------|--------------|--------------|--------------|--------------|
| 13245-5036  | 21.08        | 17.24        | 71.21        | 440.9        |
| 14429-4539  | 573.3        | 1132         | 3256         | . . .         |
| 15482-5741  | 40.41        | 32.37        | 47.39        | 209.3        |

Note. The absolute accuracy is about 5%.

SMART⁴ (Higdon et al. 2004). The high spectral resolution data were extracted over the full slit, while the optimal extraction algorithm (Lebouteiller et al. 2010) was applied to the SL and LL observations.

The IRAC observations were performed in the high dynamic range mode with a small dither pattern, as very extended emission was not expected. In this observing mode, two sets of BCDs are created by default, corresponding to a long and a short exposure; in our case the exposures were, respectively, 12 s and 0.6 s long. All of the IRAC BCDs retrieved from the Spitzer archive were processed with the S18.18.0 pipeline. The BCDs were treated for artifact correction with the IDL code available from the SSC website and then multi-frame aperture photometry was performed with the MOsaicker and Point source EXtractor using a 10 pixel aperture and 12–20 pixel annulus, which is the standard for the IRAC calibration. As the IRAC absolute flux calibrators are known to be about 2%–3% and IRAC repeatability is at about the 1.5% level, we assume in the following that 5% is our photometric error. Since our targets are quite bright for IRAC, the photometry extraction was performed on short frames, to avoid any saturation effect, which was evident in IRAS 14429-4539 at 8.0 μm even in the short frames. The flux densities are listed in Table 1.

3. SPECTRA AND SED MODELING

Figure 1 shows the results of our spectral observations. For IRAS 13245-5036, only long-wavelength data are shown, because the short-wavelength slit (perpendicular to the long-wavelength one) was off the target. The 21 μm feature is evident in all of the three targets. IRAS 14429-4539 and 15482-5741 also clearly show the mid-IR features attributed to PAHs, although the balance among the features in the PAH bands seems to be very different in the two sources. In IRAS 14429-4539 these features closely resemble those detected in PNe and other C-rich stars, while usually this is not the case for the 21 μm sources, where the PAH features in the 10–17 μm range (due to CH out-of-plane bending modes) are often blended together in a plateau (see, for example, IRAS 22223+4327 in Figure 6) and are as strong or even stronger than the features in the 5–10 μm range (due to CC stretch and CH in-plane bending modes; Tielens 2008), as, for example, in IRAS 22574+6609. Figure 2 shows the normalized profiles of the 21 μm features in our targets and in IRAS 23304+6147, which can be considered as prototypical. As usually observed, the feature has a relatively regular spectral shape, with no hints for substructure. To estimate the relative contributions of the PAH features within the emission bands, we have fitted the spectra using the publicly available IDL tool PAHfit (Smith et al. 2007),

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⁴ SMART was developed by the IRS Team at Cornell University and is available through the Spitzer Science Center at Caltech.
specifically created to fit PAH features in low-resolution Spitzer spectra. The spectra were binned to a step size of 0.169 $\mu$m.

PAHfit performs a fit to the spectra assuming the continuum is given by a combination of gray bodies with set temperatures of 300, 200, 135, 90, 65, 50, 40, and 35 K and a stellar continuum given by a Planck curve at a temperature input by the user. The method of fitting gray bodies is based on the fact that at these wavelengths the underlying continuum is a combination of radiation from the central star and the dust surrounding it. The dust layer extends outward as far as it cannot be distinguished from the interstellar medium, therefore it is characterized by a continuum of temperatures, typically in the range of a few 100 K to 10–20 K. In our two cases, the software used gray bodies at 300, 200, and 135 K for IRAS 14429-4539 and at 300, 135, 90, and 35 K for 15482-5741. The fact that PAHfit returns different temperature combinations for the two sources should not be overinterpreted, as we are still fitting only a small spectral range. For the central stars, since all of our targets have been optically classified in Suárez et al. (2006), we adopt the temperatures approximately corresponding to their spectral classifications: 7000 K for 14429-4539 and 6500 K for 15482-5741. We list the output obtained from PAHfit in Tables 2 and 3 and the fits are shown in Figure 3. Besides PAH features, PAHfit also tries to fit several atomic lines, which we have included in our tables. These lines are blended with the PAH features: their presence is supposed to obtain a good fit. In IRAS 15482-5741, two atomic lines are particularly weak and marginal: no error estimates are given for these lines.

As a further tool to analyze the properties of the envelopes in these stars, we performed radiative transfer modeling using the code DUSTY (Ivezić et al. 1999), which solves the equation of...
Table 2

Output Obtained from the IDL Tool PAHfit for IRAS 14429–4539

| Feature | Wavelength (μm) | Peak Intensity (Jy) | Flux (10⁻¹⁵ W m⁻²) |
|---------|----------------|---------------------|---------------------|
| PAH features | 5.3 | 5.27 | 0.24 ± 0.02 | 7.4 ± 0.5 |
|          | 6.2 | 6.22 | 3.84 ± 0.06 | 87 ± 1 |
|          | 6.7 | 6.69 | 0.515 ± 0.009 | 25.4 ± 0.4 |
|          | 7.4 | 7.42 | 0.71 ± 0.03 | 56 ± 2 |
|          | 7.8 | 7.85 | 8.16 ± 0.06 | 260 ± 2 |
|          | 8.3 | 8.33 | 1.40 ± 0.02 | 39.4 ± 0.5 |
|          | 8.6 | 8.61 | 4.32 ± 0.02 | 92 ± 2 |
|          | 10.7 | 10.68 | 1.48 ± 0.02 | 13.0 ± 0.2 |
|          | 11.3 | 11.33 | 8.31 ± 0.07 | 111 ± 1 |
|          | 12.0 | 11.99 | 3.75 ± 0.04 | 66.3 ± 0.6 |
|          | 12.6 | 12.62 | 3.75 ± 0.04 | 58.7 ± 0.6 |
|          | 13.5 | 13.48 | 1.67 ± 0.04 | 23.3 ± 0.6 |
|          | 14.2 | 14.19 | 0.86 ± 0.07 | 7.1 ± 0.6 |
|          | 17.4 | 17.37 | 0.3 ± 0.1 | 0.9 ± 0.4 |
| Atomic lines | H₂ S(5) | 6.90 | 1.09 ± 0.07 | 4.24 ± 0.27 |
|          | [Ar II] | 7.01 | 0.73 ± 0.04 | 2.77 ± 0.17 |
|          | H₂ S(4) | 8.10 | 3.66 ± 0.09 | 19.8 ± 0.5 |
|          | [Ar III] | 8.94 | 0.93 ± 0.02 | 4.06 ± 0.09 |
|          | [S IV] | 10.53 | 0.54 ± 0.03 | 1.71 ± 0.10 |
|          | H₂ S(2) | 12.30 | 0.39 ± 0.05 | 2.18 ± 0.12 |
|          | [Ne II] | 12.86 | 0.41 ± 0.06 | 0.88 ± 0.13 |
|          | H₂ S(1) | 17.08 | 0.90 ± 0.14 | 1.52 ± 0.24 |

Table 3

Output Obtained from the IDL Tool PAHfit for IRAS 15482–5741

| Feature | Wavelength (μm) | Peak Intensity (Jy) | Flux (10⁻¹⁵ W m⁻²) |
|---------|----------------|---------------------|---------------------|
| PAH features | 5.3 | 5.27 | 0.008 ± 0.002 | 0.25 ± 0.07 |
|          | 6.2 | 6.22 | 0.053 ± 0.002 | 1.21 ± 0.04 |
|          | 6.7 | 6.69 | 0.029 ± 0.001 | 1.42 ± 0.06 |
|          | 7.4 | 7.42 | 0.090 ± 0.002 | 7.2 ± 0.1 |
|          | 7.8 | 7.85 | 0.110 ± 0.002 | 3.51 ± 0.07 |
|          | 8.3 | 8.33 | 0.106 ± 0.002 | 3.00 ± 0.05 |
|          | 8.6 | 8.61 | 0.066 ± 0.001 | 1.40 ± 0.03 |
|          | 10.7 | 10.68 | 0.009 ± 0.004 | 0.08 ± 0.04 |
|          | 11.3 | 11.33 | 0.185 ± 0.005 | 2.46 ± 0.06 |
|          | 12.0 | 11.99 | 0.128 ± 0.004 | 2.27 ± 0.07 |
|          | 12.6 | 12.62 | 0.110 ± 0.006 | 1.72 ± 0.09 |
|          | 13.5 | 13.48 | 0.055 ± 0.004 | 0.77 ± 0.05 |
|          | 14.2 | 14.19 | 0.071 ± 0.007 | 0.59 ± 0.06 |
|          | 17.4 | 17.37 | 0.01 ± 0.01 | 0.045 ± 0.04 |
| Atomic lines | H₂ S(5) | 6.916 | 0.0648 ± n.a. | 0.22 ± n.a. |
|          | [Ar II] | 7.002 | 0.0336 ± n.a. | 0.11 ± n.a. |
|          | H₂ S(4) | 8.076 | 0.073 ± 0.003 | 0.39 ± 0.02 |
|          | [Ar III] | 8.994 | 0.060 ± 0.003 | 0.26 ± 0.01 |
|          | [S IV] | 12.264 | 0.06 ± 0.01 | 0.15 ± 0.02 |
|          | [Ne II] | 15.505 | 0.06 ± 0.02 | 0.12 ± 0.04 |
|          | H₂ S(1) | 17.085 | 0.011 ± 0.003 | 0.018 ± 0.005 |

Figure 3. Fits to the PAH features obtained with the IDL tool PAHfit. Single gray bodies are shown in red and their total as a thick gray line. PAH features are shown in blue and atomic lines in purple. The sum of all components is shown as a green line.

(A color version of this figure is available in the online journal.)

radiation transfer in a spherical shell of dust grains surrounding a central star. For the grain sizes, we adopted a standard Mathis–Rumpl–Nordsieck (Mathis et al. 1977) distribution of radii varying as \( a^{-3.5} \) with \( a_{\text{min}} = 0.005 \) μm and \( a_{\text{max}} = 0.25 \) μm, \( a \) being the radius of each grain (assumed spherical). A radial density distribution going as \( r^{-2} \) was implemented in all models and Planck curves were used to model the radiation from the central stars. The choice of a density distribution varying as \( r^{-2} \) is based on the expectation of a constant mass-loss rate. From the equation of mass continuity, we have that

\[
\rho(r) = \frac{M}{4\pi r^2 V_\infty},
\]

where \( V_\infty \) is the wind terminal velocity. As a consequence, if the mass-loss process is steady, the CSE will be characterized by \( \rho(r) \sim r^{-2} \). Toward the end of the AGB, the star is supposed to undergo a short (a few \( 10^3 \) yr) period of enhanced mass loss called the superwind phase, therefore departures from an \( r^{-2} \) distribution may be found in these stars. Once a satisfactory fit to the data was achieved, we reddened the modeled SED according to Cardelli et al. (1989), taking \( A_V \) as a free parameter. We also summed to the DUSTY model, an empirical fit to the 30 μm MgS feature obtained with an asymmetrical Gaussian. This was done to better reproduce the emission under the 21 μm feature, which we tried to model as due to FeO, as recently suggested by Zhang et al. (2009). DUSTY handles mixtures of chemical species as simulating a single-type grain constructed from an average. For both amorphous carbon and FeO, we used the default sets of optical constants that come with DUSTY. The details of the modeling are summarized in Table 4 and the models are shown in Figure 4.
The observational points used in modeling are from our IRAC photometry and the GSC2.2 (Lasker et al. 2008), NOMAD (Zacharias et al. 2005), DENIS (Epchtein et al. 1997), 2MASS (Skrutskie et al. 2006), AKARI (Murakami et al. 2007), and IRAS (Neugebauer et al. 1984) catalogs.

As often observed in post-AGB stars, we found that while the far-IR observational points can be fitted well, the model typically underestimates the radiation at near- and mid-IR wavelengths. This implies that a larger amount of hot dust is present in the CSE than what can be found in a smooth spherical shell. To account for such an emission component, we have tried different density distributions ($r^{-3}$ and $r^{-1}$), but found that a satisfactory fit can be obtained by running the code twice with $\rho(r) \sim r^{-2}$. In the first run we try to reproduce the data at wavelengths below about 10 $\mu$m, then in the second run we use as a central source the SED obtained as the output of the first run, which contains the central star and the hot dust. Such a density picture resembles a circumstellar environment where the mass-loss process is not constant with time, but subject to episodic enhancements. The presence of a hot-dust component can also be interpreted as an indication for a circumstellar (or circumbinary) disk (De Ruyter et al. 2006).

Our attempt to reproduce the 21 $\mu$m feature with FeO following Zhang et al. (2009) is not satisfactory. In particular, the spectral shape is not well reproduced and large abundances...
Table 5
Summary of the Archive Observations Available for All of the Known 21 μm Sources Besides the New Detections Reported in This Work

| Target         | Data Sets   | Range (μm) |
|----------------|-------------|------------|
| Z02220+6208    | SWS         | 2–45       |
| 04296+3429     | SL, SH, LH  | 5–37       |
| 05113+1347     | SH, LH      | 10–37      |
| 05341+0852     | SWS, SH, LH | 2–45       |
| 06530−0213     | SH, LH      | 10–37      |
| 07134+1005     | SWS         | 2–45       |
| 07430+1115     | SH, LH      | 10–37      |
| 16594-4656     | SWS         | 2–45       |
| 19477+2401     | SWS         | 2–45       |
| 19500−1709     | SWS         | 2–45       |
| 20000+3239     | SWS         | 2–45       |
| AFGL 2688      | SWS         | 2–45       |
| 22223+4327     | SL, SH, LH  | 5–37       |
| 22272+5435     | SWS         | 2–45       |
| 22574+6609     | SWS, SH, LH | 2–45       |
| 23304+6147     | SWS, SH, LH | 2–45       |

Notes. Targets not included in our analysis are in *italics*.

* Short wavelength spectrometer (ISO).
* Short–low IRS.
* Short–high IRS.
* Long–high IRS.

(~10% in mass) of FeO are necessary. Software allowing for a continuous range of ellipsoidal grain shapes has been found to account better for spectral shapes of dust features in general (Kemper et al. 2002). It is possible that a similar approach may improve the match between the model and the observational data also in our targets. Currently, this is not possible with DUSTY.

4. A LINK BETWEEN THE 21 μm FEATURE AND HYDROCARBON EMISSION?

It is known that the 21 μm feature is often—but not always—observed along with mid-IR PAH bands (Volk et al. 1999). Another source of mid-IR emission in the form of a very broad feature resembling an underlying continuum is given by HAC, whose molecular chains are considered as the precursors of PAHs. Given this qualitative observational link between these features, we have searched for a quantitative correlation.

We have retrieved from the ISO and Spitzer archives all of the available IR spectra approximately covering the 5–40 μm range for the so far known 21 μm PPNe. Table 5 lists the data found in the archives and used in the following analysis. Data for IRAS 05113+1347, 06530-0213, and 07430+1115 were not used because they do not cover the whole range from 5 μm, while the data set for IRAS 19477+2401 was not used because of its low quality (Hrivnak et al. 2000). When Spitzer data were available, we carried out our analysis on these, after combining them with the ISO data below 5 μm. Post-BCD data were retrieved from the Spitzer archive, while the highly processed data by Frieswijk et al. (2007) were retrieved from the ISO Web archive. Clear outliers in the ISO data were manually flagged out in SMART, then a standard σ-clip run was performed and the whole procedure (manual flagging and σ clipping) was repeated a second time, before averaging the data together. For all of the spectra the same spectral step of 0.169 μm was set in SMART. The spectra thus obtained are shown in Figures 5 and 6.

To enhance the dust features, we fitted the underlying continuum as a linear combination of four gray bodies with emissivity index β = 2. In doing so, we used the IDL routine MPFIT-FUN (Markwardt 2009), which fits a user-defined function to the data. Although four gray bodies were always included in the fitting procedure, in most cases the best-fitting combination had a gray body multiplied by such a low factor that made it negligible, thus obtaining a best-fit curve with three gray bodies only. The same behavior was observed in trials with more than four gray-body components: only three or four of them were significant. As mentioned previously, the infrared continuum in post-AGB stars is due to a combination of stellar radiation and thermal emission from dust, with the latter typically much stronger than the former. To avoid physically unreasonable solutions in the fit procedure, we have therefore limited the range of values investigated by the fitting routine to 0 < T < 15,000 K, which takes into account temperature values appropriate for both the dust (dust grains sublimate around 1000–2000 K) and the central star. The temperatures thus obtained are listed in Table 6.

Figure 5. Infrared spectra of the 21 μm sources known. A gray-body continuum is shown as a gray solid line and the single gray bodies as dashed gray lines in the right-side plots. On the left side, a closeup of the 3–24 μm range after continuum subtraction is shown. Gray-body temperatures are listed in Table 6.
Figure 6. Same as in Figure 5.

Table 6 and the fitting curves are shown in Figures 5 and 6. We find that in all sources the emission is dominated by gray bodies reproducing dust emission (because of their temperatures) and stellar contributions are negligible. The continuum obtained as a combination of gray bodies is typically unable to properly isolate the feature at 21 μm, because of the substantial contributions from the features in the 26–33 μm range, which are often blended together.

Emission in the 5.5–18 μm range is present in all of the targets, as shown in the left-side closeups in Figures 5 and 6. After converting the spectra into W m⁻² μm⁻¹, we integrated the continuum-subtracted spectra to estimate the flux in the 5.5–18 μm and 18.5–23.5 μm ranges (the exact edges of the ranges were adapted to the emission in each source, turning out in differences of about 0.3 μm). To assess the emission in the 21 μm feature, a straight baseline was fitted to its red and blue edges and then subtracted before performing the integration, as shown in two examples in Figure 7. The emission in the 5–18 μm range is mostly due to PAHs but contributions from HACs are possible, while the 18.5–23.5 μm range is obviously dominated by the 21 μm feature.

In Figure 8, we plot the flux estimated in the 5.5–18 μm bands, indicated as the sum of the PAH 7 and 11 μm bands, versus that in the 21 μm feature. As can be seen in the plot, a correlation between the fluxes in the two wavelength ranges is evident; we can calculate a linear correlation coefficient of 0.79 ± 0.07. An explanation for the correlation may be that the abundances of the hydrocarbons and of the carrier of the 21 μm feature are linked together, possibly because of a common formation process and therefore the correlation would just reflect the different amounts of hydrocarbons and 21 μm carriers produced in the CSEs.

The colors of the dots in Figure 8 are proportional to the temperatures of the central stars, as derived from their spectral classifications, and range from red (coldest) to blue (hottest). No clear correlation is observed between the intensity of the features and the stellar temperature.

In principle, if the observed correlation were due only to a common excitation process for the molecules involved and then essentially to the hardening of the radiation field, we would expect to find a correlation with the temperature of the central star. There may be several reasons for this lack of correlation. For example, extinction effects can play a role. Also, one of the explanations for the existence of the 21 μm feature implies radiation-induced decomposition of large HAC grains into smaller PAHs (Scott et al. 1997). In this scenario, the carrier of the 21 μm feature would be a short-lived decomposition product. The efficiency of the processing of large grains would depend on both T eff and the location of the dust layer. A massive star will be hot enough to cause processing earlier than a low-mass star, with its dust still close to the central star. A low-mass star will reach the same temperature at a later age, with its dust farther away and will therefore need an even larger temperature to attain comparable processing.

5. SUMMARY

One of the main results of the IRAS mission was its discovery of the existence of a broad mid-IR feature around 20 μm. The feature has been detected almost exclusively in the CSEs of C-rich PPNe, with a few weak detections in their precursors (AGB stars) and successors (PNe). The nature of the feature is still unclear today, but it must be linked to the C-rich nature of...
the sources: its carriers are likely to be produced toward the very end of the AGB and are easily destroyed by UV radiation.

In this paper, we report about the detection of three new C-rich PPNe that exhibit this unidentified feature through observations performed with the IRS instrument onboard Spitzer. Besides the 21 μm feature, our targets also show mid-IR bands from PAHs and a broad feature around 30 μm commonly attributed to MgS. As the dispersion of the dust formed during the AGB creates a very extended shell around the central star, it can be expected that evidence for such large dust regions can be found in infrared images, but our IRAC observations do not point to any extended emission.

By a combination of catalog data and our new observations, we reconstruct the SEDs of our targets and model them with the code DUSTY. With a $r^{-2}$ density distribution, a good match of the observational points is possible, if the model assumes a circumstellar environment where the mass-loss process has not been constant with time. The use of FeO as a carrier of the 21 μm feature does not accurately reproduce the spectral shape of the feature.

We have retrieved the infrared spectra of the other 21 μm sources available in the ISO and Spitzer archives. A gray-body continuum has been subtracted from the spectra to enhance the features. After continuum subtraction, we have calculated the flux in the features from 5 to 18 μm, due to hydrocarbons, and that in the 21 μm feature, finding a clear correlation between them. We have not found any correlation with stellar temperatures. The correlation found between the 5–18 and 21 μm fluxes can point to a common origin of the carriers of the features.

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