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# ISO observations of IRAS 16594−4656: a new proto-planetary nebula with a strong 21 micron dust feature [1]

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## ABSTRACT

Based on ISO SWS+LWS observations, IRAS 16594−4656 is identified as a new member of the rare class of C-rich proto-planetary nebulae with the 21 $\mu$m dust feature in emission. In addition, the major PAHs emission bands at 3.3, 6.2, 7.7, 8.6 and 11.3 $\mu$m are detected, together with unusually strong features at 12.6 and 13.4 $\mu$m, very rarely observed, attributed to PAHs species with a high degree of hydrogenation.

The shapes and relative intensities of the various features found are consistent with a mixed population of transient decomposition products of large hydrogenated amorphous carbonaceous (HAC) grains, consisting of fullerenes with a different degree of hydrogenation, which we suggest to be the main carriers of the strong 21 $\mu$m feature, and a combination of small and large partially dehydrogenated cationic PAHs molecules excited by the visible radiation coming from the central star.

Additional features corresponding to crystalline silicates (mostly pyroxenes) are also tentatively detected, together with a possible very broad unidentified emission feature centered around 30 $\mu$m, previously reported to appear in combination with the 21 $\mu$m feature in other proto-planetary nebulae candidates.

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The combination of features corresponding to O-rich and C-rich dust grains found, if real, would suggest a recent change to a C-rich chemistry in the outer envelope of IRAS 16594−4656.

With the help of optical ground-based spectroscopy and recently obtained HST images we identify IRAS 16594−4656 as a new transition object between the AGB and the PN stage. The ground-based optical spectrum shows only the Balmer lines in emission and a faint, probably shocked excited, [O I] emission over a very red continuum where strong, probably circumstellar, DIBs at 5780 and 6281−6284 Å are clearly seen. HST WFPC2 continuum images reveal the presence of a bright central star surrounded by a bipolar reflection nebula with a multiple-axis morphology and a maximum size of $\sim 5'' \times 11''$.

*Subject headings:* stars: AGB and post-AGB - planetary nebulae: general - stars: individual: IRAS 16594−4656 - stars: infrared radiation

## 1. Introduction

In the last few years a small but increasing number of proto-planetary nebulae (PPNe, hereafter) candidates showing a strong 21 $\mu$m dust feature in emission have been identified (Kwok et al. 1989; Kwok et al. 1995; Justannont et al. 1996). The list comprises only a handful of objects so far and includes point-like F- and G-type stars, like IRAS 04296+3429, IRAS 05113+1347, IRAS 05341+0852, IRAS 07134+1005 (with the strongest 21 $\mu$m feature), IRAS 19500−1709, IRAS 20000+3239, IRAS 22223+4327, IRAS 22272+5435 and IRAS 23304+6147, still in the post-AGB phase. More recently, IRAS 02229+6208 has been added to this short list by Hrivnak et al. (1997) and a couple of additional potential candidates have also been suggested by Henning et al. (1996).

The origin of the 21 $\mu$m feature is still unknown. However, there are indications which suggest its association to a C-rich nature of the PPN. This is supported by the detection of molecular carbon ($C_2$ or $C_3$) absorption bands in the optical spectra of most of the G-type post-AGB stars above cited (Hrivnak 1995) as well as of CO emission in the millimeter wavelengths (Zuckerman et al. 1986; Woodsworth et al. 1990; Likkel et al. 1991; Omont et al. 1993) and other C-bearing molecules like HCN, CS and CN (Lindqvist et al. 1988; Omont et al. 1993) in their circumstellar envelopes.

Sometimes the 21 $\mu$m feature appears in association with a broad feature centered at 30 $\mu$m, extending from 24 to 45 $\mu$m, also observed in some C-rich AGB stars and in C-rich PNe, and with a strong 11−15 $\mu$m plateau. Unlike the 30 $\mu$m dust feature, this plateau has only been found in the 21 $\mu$m PPNe (Omont et al. 1995). Using the Kuiper Airborn Observatory (KAO), Omont et al. (1995) observed 5 of the sources showing the unidentified 21 $\mu$m emission feature and found

broad emission peaking around 30 $\mu$m in all cases, although its strength was not correlated with that of the 21 $\mu$m feature.

This work presents infrared spectra taken with the Short and Long Wavelength Spectrographs on board the Infrared Space Observatory (ISO) of IRAS 16594−4656 and identify this source as a new member of the rare class of objects showing the 21 $\mu$m dust feature in emission. Combining these data with ground-based low resolution spectroscopy and the available HST images we confirm it as a new transition object in the PPN phase.

In Section 2 we discuss the observations and the data reduction. Section 3 describes the various features observed in the infrared spectra and in the optical range. Finally, in Section 4, we discuss the possible carriers of the various features observed and the evolutionary stage of IRAS 16594−4656 in the context of post-AGB evolution and the formation of PNe. Conclusions are given in Section 5.

## 2. Observations

A full range 2.4 − 45 $\mu$m spectrum of IRAS 16594−4656 was obtained on 1997 February 16 using the SWS (de Graauw et al. 1996) on board ISO (Kessler et al. 1996) as part of the open time programme PGARCIA.PNE on spectroscopy of PPNe candidates. The spectrum was taken in the standard Astronomical Observing Template (AOT) SWS01 mode with speed 1. In addition, a full range 43 − 196.5 $\mu$m spectrum using the LWS (Clegg et al. 1996) was obtained on 1997 March 20 in the AOT LWS01 mode.

Absolute and relative flux calibrations (Swinyard et al. 1996) are based on observations of Uranus. The relative calibration accuracy in the continuum flux between the different detectors is estimated to be better than 30% (Saraceno et al. 1996; Schaeidt et al. 1996). The data, originally standard pipe-line processed, were reprocessed at the Max Planck Institute for Extraterrestrial Astronomy (Garching, Germany) in June 1997 using the latest version of the Interactive Analysis Software available to date. Each scan was corrected for detector dark current and small responsitivity drifts, by means of the on-board illuminators. All detector signals were inspected for spurious features (small jumps and glitches) which were removed. Correction for eventual low-frequency baseline fringes (Swinyard et al. 1996) was also applied.

The big flux jump observed in the SWS spectrum at around 29.5 $\mu$m, not removed in Figure 1, seems to be an artifact, since it exactly coincides with the change of aperture from band 3E to 4. Similar flux jumps have been observed in other slightly extended objects as a consequence of the change of aperture and/or small pointing errors (Waters et al. 1997). The good agreement found between our SWS spectrum and the overlapping region of the IRAS Low Resolution Spectrum (see Olnon et al. 1986) seems to exclude the possibility of a severe pointing error in the case of our observation. There was also a perfect match between the SWS and the LWS spectral regions.

Optical low resolution spectroscopy was carried out in 1990 February at the European Southern Observatory (La Silla, Chile) using a Boller & Chivens Spectrograph attached to the Cassegrain focus of the 1.52m ESO telescope and an RCA CCD as detector. The spectrum covers the range 3700 – 7100 Å with an effective spectral resolution of 4.8 Å. The exposure time was 1800 s. The spectrum was reduced using standard IRAF routines. The data reduction process includes bias and flat-field corrections, as well as wavelength calibration, sky subtraction and absolute flux calibration.

## 3. Results

### 3.1. The ISO spectrum

Figure 1 shows the combined ISO SWS+LWS spectrum of IRAS 16594−4656, where several prominent dust emission features are evident overimposed on a very cold dust continuum, together with the low excitation fine structure emission lines of [O I] 63.2 $\mu$m and [C II] 157.7 $\mu$m. Considering that IRAS 16594−4656 is seen at a low galactic latitude towards the inner Galaxy, it seems reasonable to attribute the presence of these lines in the ISO LWS spectrum to background emission from the general interstellar medium rather than to a Photo-Dissociation Region (PDR), since the ionizing flux coming from the central star is not enough yet to produce a significant ionization of the circumstellar shell.

The continuum spectrum beyond 60 $\mu$m has been corrected for the effect of the expected contamination from galactic cirrus emission as estimated by IRSKY at the galactic coordinates ($l_{II} = 340.4°$; $b_{II} = -3.3°$). The best fit for the resulting spectrum is obtained for a modified black-body emission at a temperature of 143 K, assuming an emissivity index of $\beta = 1$. Of course, adopting a unique temperature for the dust grains in the shell might be not realistic. However, it seems to be a good approximation, since it reproduces well the emission peak around 29 $\mu$m and the shape of the infrared continuum in the regions 2.4−18 $\mu$m and 45−197 $\mu$m, where no broad emission bands affecting the continuum are expected to be present. In addition, independent fits based on the emission observed in spectral regions corresponding to individual detectors yield always values in the range between 120 and 150 K, close to the value derived above. However, adopting a single black-body temperature of 143 K for the continuum observed from 2.4 to 197 $\mu$m would imply the presence of a significant excess of emission in the range 24−45 $\mu$m, similar in shape and intensity to the unidentified broad feature also observed in many other PPNe candidates. Such excess seems to be real, since it cannot be avoided by selecting a different emissitivity index or by the use of a simple combination of black-bodies at different temperatures in our fit.

Figure 1 also shows in detail several regions of interest in the ISO spectrum of IRAS 16594−4656, where most of the emission features discussed in the text are concentrated. In the upper left panel, the major emission bands at 3.3, 6.2, 7.7, 8.6 and 11.3 $\mu$m usually attributed

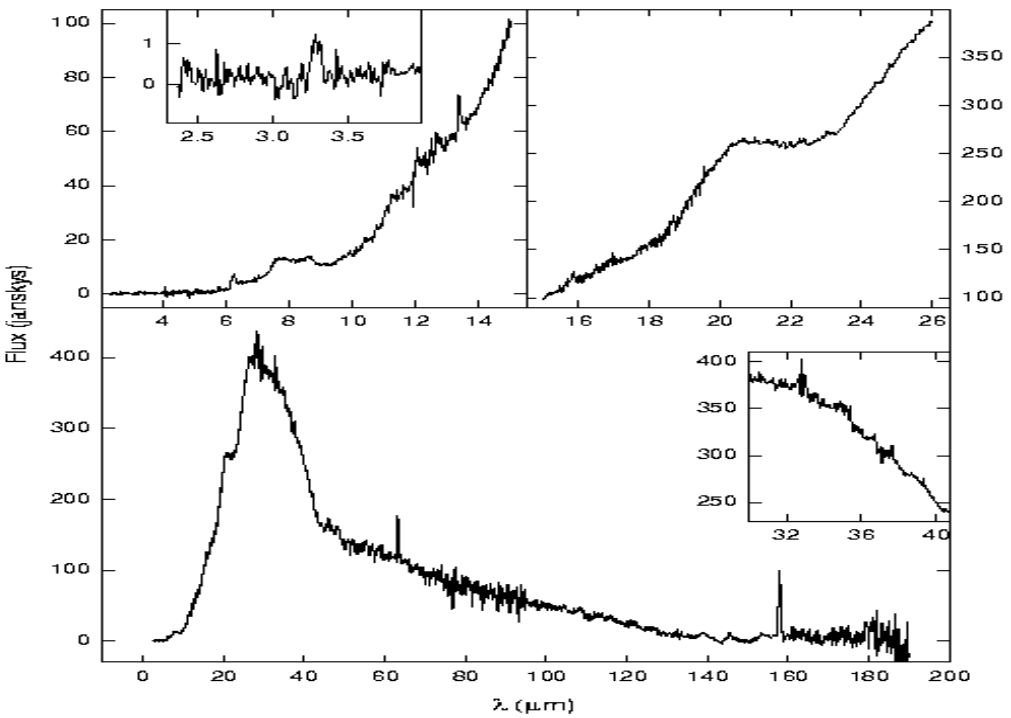


Fig. 1.— Combined ISO SWS+LWS spectrum of IRAS 16594−4656 between 2.4 and 197 $\mu$m. Some spectral regions discussed in the text are shown in detail.

to Polyciclic Aromatic Hydrocarbons (PAHs) can be identified, together with unusually strong emission bands at 12.6 and 13.4 $\mu$m. In the upper right panel the strong 21 $\mu$m feature, extending from 18.5 to 23 $\mu$m, is shown together with a weak emission feature centered at 23.5 $\mu$m. In the lower right panel of Figure 1, a plateau of emission is observed in the range 32−37 $\mu$m. Table 1 lists all the observed features indicating, for each of them, the peak wavelength, integrated flux in $10^{-14}$ W m$^{-2}$ with respect to the local continuum and the FWHM in $\mu$m.

### 3.2. Optical Data

Recent HST images obtained on 1997 March 23 through the broad F606W continuum filter with the Wide Field Planetary Camera 2 (WFPC2) under proposal 6565 (P.I.: Sun Kwok) reveal

Table 1: List of observed features in the ISO spectrum of IRAS 16594−4656.

| Wavelength $\lambda(\mu m)$ | Integrated flux ($10^{-14}$W m$^{-2}$) | FWHM ($\mu$m) | Identification |
|---|---|---|---|
| 3.29 | 1.42 | 0.06 | PAH |
| 6.23 | 5.31 | 0.15 | PAH |
| 7.73 | 24.7 | 0.74 | PAH |
| 8.60 | 8.65 | 0.50 | PAH |
| 11.31 | 7.40 | 0.57 | PAH |
| 12.58 | 5.47 | 0.31 | PAH |
| 13.37 | 1.89 | 0.08 | PAH |
| 20.34 | 100.1 | 2.26 | fullerenes |
| 23.50 | 0.40: | 0.30: | crystalline silicates |
| 32.57 | 0.41: | plateau | crystalline silicates |
| 32.97 | 1.40: | plateau | crystalline silicates |
| 33.59 | 0.42: | plateau | crystalline silicates |
| 35.16 | 0.47: | plateau | crystalline silicates |
| 35.29 | 0.40: | plateau | crystalline silicates |
| 35.61 | 0.15: | plateau | crystalline silicates |
| 40.50 | 0.10: | 0.10: | crystalline silicates |
| 42.07 | 0.18: | 0.18: | crystalline silicates? |
| 43.11 | 0.15: | 0.15: | crystalline silicates? |
| 44.16 | 0.25: | 0.25: | crystalline silicates? |
| 63.2 | 1.19 | 0.24 | [OI] |
| 157.7 | 0.51 | 0.09 | [CII] |

the presence of a bright central star surrounded by a multiple axis bipolar nebulosity with a complex morphology and a maximum size of $\sim 5'' \times 11''$. The lobes appear as pairs of elongated structures with at least four different bipolar axis at P.A. $\sim 34°$, $\sim 54°$, $\sim 84°$ and $\sim 124°$ suggesting that episodic mass loss may have produced a multiple shell ejection. A more detailed analysis of these images can be found in Hrivnak et al. (1998).

The optical spectrum of IRAS 16594−4656 (see Figure 2) shows only the Balmer emission lines of hydrogen overimposed on an extremely reddened continuum of undetermined spectral type, together with a faint extended [O I] emission at 6300 Å and strong Diffuse Interstellar Bands (DIBs) at 5780 and 6281−6284 Å of probable circumstellar origin. The H$\beta$ flux is found to be $\sim 1.13\ 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ and the H$\alpha$/H$\beta$ ratio is $\sim 28$. The blue end of the spectrum is not shown in this Figure because of the poor S/N ratio.

The emission lines observed are probably not due to photoionization, since radio continuum emission was not detected by van de Steene and Pottasch (1993). Taking into account the highly collimated structure revealed by the HST images, they are likely the result of shock excitation produced by a fast bipolar wind from the central source. The absence of spatial variations in the slightly extended 2-dimensional spectrum, indicate that the illuminated lobes emit probably as a consequence of dust scattering of the light coming from the central star. Similar reflection nebulae have been observed around other proto-typical bipolar PPNe, like M1−92 (Solf 1994).

## 4. Discussion

### 4.1. A C-rich star

Detected as a new H$\alpha$ emission star by Stephenson and Sanduleak (1977), IRAS 16594−4656 was first suggested to be a possible transition object between the AGB and the PN stage independently by Volk and Kwok (1989) and van der Veen et al. (1989), based on its IRAS colours, although it was wrongly classified as an O-rich PPN candidate at that moment because it appeared erroneously associated to the O-rich LRS class 74 in the IRAS LRS Catalogue (Olnon et al. 1986).

The first indication of a C-rich nature of IRAS 16594−4656 was the detection of broad CO molecular emission by Loup et al. (1990), corresponding to a circumstellar shell with an expansion velocity of $\sim 16$ km s$^{-1}$, in agreement with the non-detection of OH (te Lintel Hekkert et al. 1991; Silva et al. 1993), or SiO (Nyman et al. 1998) maser emission.

The presence of strong PAHs features in the SWS spectrum of IRAS 16594−4656 now confirms this classification.

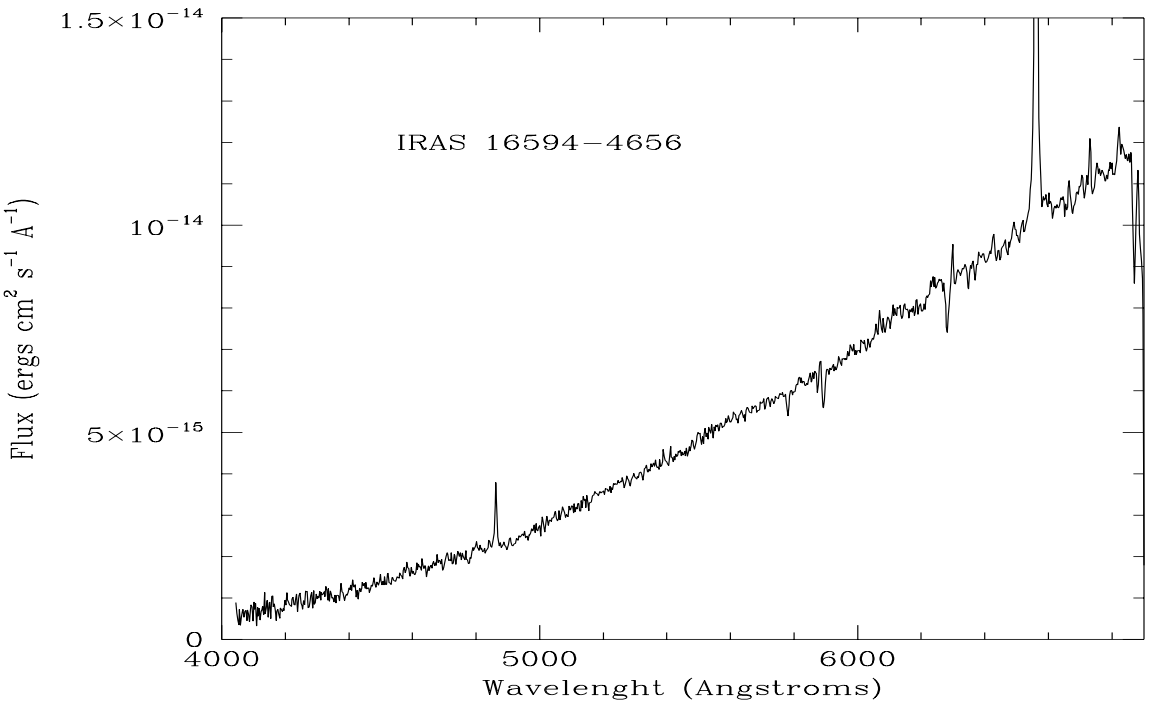


Fig. 2.— Low resolution optical spectrum of IRAS 16594−4656 between 3700 and 7100 Å taken at the 1.52m ESO telescope (La Silla, Chile).

### 4.2. The PAHs emission features

PAH molecules in the circumstellar envelope of stars produce strong features at 3.3, 6.2, 7.7, 8.6 and 11.3 $\mu$m (Buss et al. 1990; Geballe et al. 1992; Buss et al. 1993) which are usually observed in good agreement with laboratory predictions.

All of them are detected in IRAS 16594−4656. According to the laboratory measurements, the 3.3 and 8.6 $\mu$m bands are due to in-plane stretching modes of C-H bonds in PAHs, while the 6.2 and 7.7 $\mu$m bands correspond to stretching modes of C-C bonds. The 11-15 $\mu$m region is dominated by ring-deformation vibrational modes of PAHs. The band at 11.3 $\mu$m is produced by an out-of-plane bending vibration mode of C-H, while bands at 11.9, 12.7 and 13.5 $\mu$m are the signatures expected for C-H out-of-plane bending vibration modes for duo, trio and quatro hydrogen atoms, respectively (Allamandola et al. 1989; Justannont et al. 1996; Pauzat et al. 1997).

The shape and strength of the various infrared features depend on the excitation temperature and size distribution of the dust grains and this has been used to explore in detail the properties

of the grains in the circumstellar shell of IRAS 16594−4656.

Concerning size, most of the major features above cited correspond to PAHs of very small size (a few atoms). However, the plateau emission observed around 7-8 $\mu$m is probably due to larger (300-400 C atoms) PAH molecules (Molster et al. 1996) which indicates that a mixed population of small and large grains coexist.

A high proportion of ionized grains increases the strength of the C-C bonds features with respect to the C-H bonds (Pauzat et al. 1997). Thus, stronger bands are expected at 6.2 and 7.7 $\mu$m when PAHs are ionized, while the band at 11.3 $\mu$m decreases in strength. This is exactly what it is observed in the case of IRAS 16594−4656, where the strength of the 11.3 $\mu$m is remarkably small compared to the strong features at 6.2 and 7.7 $\mu$m.

In addition, the peak positions of the various PAHs features are also sensitive to ionization (Langhoff 1996). In IRAS 16594−4656, ionization is shifting the bands at 12.7 and 13.5 $\mu$m towards shorter wavelengths. In a similar way, a red wing in the 6.2 $\mu$m band and blue wings in the 7.7 and 11.3 $\mu$m bands are seen, signatures previously detected in the laboratory when PAH molecules are ionized (Langhoff 1996). This would be consistent with the detection of DIBs in the optical spectrum of IRAS 16594−4656, since it has been suggested that small cationic PAHs are the main carriers of these DIBs (Salama et al. 1996). DIBs have also been detected in other C-rich objects showing strong PAH features such as the companion star of CS776, AC Her or IRAS 21282+5050 (Cohen and Jones, 1987; Le Bertre, 1990; Le Bertre and Lequeux, 1993), supporting this connection.

Different families of DIBs have been proposed to form under different ionization conditions (Krelowski et al. 1998). The familiy of narrow DIBS with the strongest features at 5797 and 6379 Å probably originate in the interstellar medium while the broad features at 4430, 5780 and 6280 Å would form in circumstellar shells. This is precisely the family of DIBs observed in IRAS 16594−4656 (although, unfortunately, the S/N ratio of our spectrum is too low in the blue to detect the feature at 4430 Å) and it is the same family which has been detected in the C-rich objects listed above. Against a circumstellar origin of the DIBs, it has been claimed that, in many cases, the strength of the DIBs features correlate with the strength of the interstellar NaI D feature (although this feature can also have a circumstellar origin and the analysis is not always simple), but this correlation only applies to the family of DIBs of interstellar origin.

Supporting our circumstellar interpretation of the DIBs observed in IRAS 16594−4656, the 5797 Å feature is not detected in our spectrum. In addition, it does not seem reasonable to interpret the extremely red slope of the continuum observed in the optical in terms of interstellar extinction, since IRAS 16594−4656 is not located in a galactic region of a very strong interstellar reddening and, moreover, we know that IRAS 16594−4656 is surrounded by a thick circumstellar shell (as derived from the far infrared emission). Taking this into account, the dust in the shell must be the main responsible for the extinction observed, and thus, it is reasonable to assume a circumstellar origin for any feature observed in the optical spectrum of this star.

The shape of the PAH bands is also very sensitive to the H-substitution pattern. The 12.7 $\mu$m band, for instance, is expected to be strong only if grains are highly hydrogenated. The 12.7/11.3 ratio decreases with dehydrogenation independently of ionization (Schutte et al. 1993) and one of the most significant characteristics of the ISO spectrum of IRAS 16594−4656 is the strong feature found around 12.7 $\mu$m, compared to the weak emission found at this wavelength in the post-AGB star HR 4049, the PPN IRAS 21282+5050 and the young PN NGC 7027 (Beintema et al. 1996). Even more remarkable, IRAS 16594−4656 shows also a strong feature at 13.5 $\mu$m. As already mentioned, this is the expected signature of four adjacent hydrogens on the aromatic ring of a PAH and implies a very high degree of hydrogenation. So far, only traces of it had been detected in the transition object IRAS 21282+5050 and in the young planetary nebula NGC 7027, being completely absent from HR 4049 (Beintema et al. 1996). It might be possible that these two features are just part of the famous broad plateau, also attributed to PAHs, previously reported to be present in the range 11−15 $\mu$m in a few other transition objects like IRAS 21282+5050 (Justannont et al. 1996) or IRAS 22272+5435 (Buss et al. 1993). The plateau effect may be the result of a blend of various out-of-plane deformation modes, possibly connected to large PAH clusters with different degrees of hydrogenation.

### 4.3. The 21 $\mu$m feature

Concerning the dust feature at 21 $\mu$m, it has recently been proposed to be produced also by PAH-related molecules. Beintema et al. (1996) suggest that the strong 21 $\mu$m feature, as well as a much weaker feature at 17 $\mu$m, not detected in our spectrum, could be related to in-plane deformation modes of the aromatic rings of PAHs, the 21 $\mu$m feature being the drumhead mode, where adjacent rings bend out-of-plane. More exotic carriers were proposed in the past, like $SiS_2$ grains, mantles of SMg covering amorphous carbon cores, HCN or iron oxides (see Kwok et al. 1995; Omont et al. 1995; Henning et al. 1996, and references therein), all them now discarded.

However, against the identification of PAH-related molecules as carriers of the 21 $\mu$m band, IRAS 07430+1115 has been found to show a very strong PAH emission at 3.3 and 11.3 $\mu$m but not the 21 $\mu$m feature (Hrivnak and Kwok, 1998) This is striking, since a correlation between $C_2$ absorption, 3.3 $\mu$m emission and the 21 $\mu$m had previously been reported by Kwok et al. (1995).

A good alternative are the fulleranes, the 3-dimensional analogues of PAHs. Webster (1995) found that a mixed population of fullerenes with a different degree of hydrogenation could produce a broad band over the whole 19-23 $\mu$m region. A very recent paper by Scott et al. (1997) shows that radiation-induced decomposition of large hydrogenated amorphous carbon (HAC) grains occur in stages first releasing small partially dehydrogenated PAH molecules and then short-living large PAH clusters and fullerene molecules.

This would be consistent with the apparent fragility of the carrier of the 21 $\mu$m band and would favour its identification as a short-lived decomposition product of HACs (as well as the

PAHs, but these are able to survive a longer time in the UV field produced by the central star). This would also explain why it is possible to detect sources with PAH features but without the 21 $\mu$m emission band, while all the 21 $\mu$m emitters do show PAHs features.

### 4.4. Other features

Additional weak emission features appear as tentatively detected in the ISO SWS spectrum of IRAS 16594−4656 betwen 32.5 and 35.6 $\mu$m. Similar features are observed in O-rich dust shells and are atrributed to crystalline silicates (Waters et al. 1996), the most promising candidates for the carriers being olivine and pyroxenes, with various mixtures of Fe and Mg. Crystalline pyroxenes show a peak at 40.5 $\mu$m together with weaker peaks at 23 and 33 $\mu$m (Koike et al. 1993; Jäger et al. 1994) which also appear in our spectrum, thus making them good candidates for being the dominant carriers of the features observed. Similar O-rich features have also recently been detected in the circumstellar envelopes of C-rich PNe with [WC] central stars (Waters et al. 1997) suggesting a recent change to a C-rich chemistry.

The detection of the broad 30 $\mu$m feature in IRAS 16594−4656 is more doubtful. The object with the strongest 30 $\mu$m feature known, IRAS 22272+5435, was studied in detail by Szczerba et al. (1997). In this study Szczerba et al. suggest that the 30 $\mu$m feature can be attributed to grains of pure magnesium sulfides – MgS – grains (Goebel and Moseley 1985) at a high enough temperature and with a broad distribution of shapes inside the shell. Apparently, the carrier of the 30 $\mu$m band condenses only at a low temperature and need a large mass-loss rate for its formation.

Finally, the unusual 3.4 $\mu$m feature is not detected in IRAS 16594−4656. The 3.4 $\mu$m emission is usually attributed to alkane C-H strectching modes in large PAH grains (Leger et al. 1989). This is an asymmetric C-H stretch in methyl groups attached to PAHs (methylated PAHs; see Joblin et al. 1996) and it might also be a short-lived transient decomposition product of HACs. Interestingly, all 3.4 $\mu$m strong sources are 21 $\mu$m strong sources, while the opposite is not true (Geballe et al. 1992), as it is in the case of IRAS 16594−4656.

### 4.5. The evolutionary stage of IRAS 16594−4656

The optical morphology shown by the HST images, the characteristics observed in the optical low resolution spectrum and the infrared properties of the dust in the circumstellar envelope derived from ISO data are all consistent with the identification of IRAS 16594−4656 as a new C-rich PPNe in the short transition phase between the end of the AGB and the PN stage.

The excitation of the 21 $\mu$m feature seems to be connected with the rapid changes experienced by objects in this transition phase since this feature is only observed during the short post-AGB phase of evolution (Kwok et al. 1989) and not in well known C-rich AGB stars like IRC 10216 or

in evolved C-rich PNe like NGC 7027 or IC 418.

The differences observed from source to source in the shape of the PAH features can be due to the evolution of the circumstellar dust as a result of grain-grain collisions and the shattering of large grains into smaller pieces.

Dust grains may be subject to rapidly changing radiation fields in the circumstellar envelopes of evolving PPNe. The low temperature of the exciting stars where the 21 $\mu$m bump has been observed suggest that the ionized PAH species detected are excited by visible radiation; not by UV radiation, which would first dehydrogenate and then destroy these molecules. This would explain why only PPNe with F-G type central stars show these features and not those with earlier type central stars, and why all they still show a very high degree of hydrogenation.

High velocity streaming of grains through gas may result in energetic grain-grain collisions (Jura and Kroto, 1990), which would also produce the fragmentation of large grains into smaller pieces. High velocity outflows are usually associated to bipolar structures. Interestingly, most of the objects in the short list of sources showing the 21 $\mu$m feature turned out to be bipolar (Meixner et al. 1997) and IRAS 16594−4656 displays also a significant bipolar morphology. This coincidence clearly deserves further study.

## 5. Conclusions

Based on the analysis of the ISO SWS+LWS spectrum combined with ground-based optical spectroscopy and recently available HST images, we identify IRAS 16594−4656 as a new member of the rare class of PPNe showing the 21$\mu$m dust feature.

The detection of CO emission at millimeter wavelengths and strong PAHs features in the SWS spectrum suggest a C-rich nature of the envelope, confirming the connection of the 21 $\mu$m feature with C-rich objects in the transition from the AGB to the PN stage.

Most of the dust features observed in IRAS 16594−4656 are interpreted as the result of radiation-induced decomposition of large HAC grains, which produce short-lived transient species like fullerenes and highly hydrogenated PAH clusters, only observed during the first stages of the short transition phase which precedes the formation of a new PN.

Fullerenes with various degrees of hydrogenation are suggested to be the main carriers of the 21 $\mu$m feature, while highly hydrogenated PAH clusters would be the carriers of the remarkably strong unsual bands observed at 12.6 and 13.4 $\mu$m.

The rest of features found in IRAS 16594−4656 can be explained by a combination of small and large PAH molecules, most of them ionized. Small, partially dehydrogenated grains would be responsible for the features observed at 3.3, 6.2, 7.7 and 8.6 $\mu$m while PAH clusters would account for the plateau emission observed at 7−8 $\mu$m and the features at 11.3, 12.6 and 13.4 $\mu$m.

As the central star evolves towards higher effective temperatures, the 21 $\mu$m feature is expected to disappear. In parallel, PAHs become ionized (increasing 6.2+7.7+8.6/11.3 ratio) and dehydrogenated (decreasing 12.7/11.3 ratio) by the increasingly harder UV radiation field until dust grains are completely destroyed.

The detection of circumstellar DIBs in the optical spectrum of IRAS 16594−4656 and similar transition objects supports the connection of these features with cationic PAHs as possible carriers. The apparent connection of bipolar morphologies with the presence of the 21 $\mu$m feature deserves further investigation.

The tentative detection of crystalline silicates, if real, suggests a recent change to a C-rich chemistry in IRAS 16594−4656. The possible, but more doubtful, presence of a broad 30 $\mu$m dust feature still needs to be confirmed, but it seems that the still unknown carrier of this feature is not related with transient decomposition products of large HAC grains.

The data here presented demonstrate that infrared dust features can be used to trace rapidly evolving objects in the short transition phase between the AGB and the PN stage and are a useful tool to study the physical properties and the chemical evolution of the dust grains in these circumstellar envelopes. However, the extension of this analysis to other transition objects also observed with ISO is needed in order to test the evolutionary scenario here suggested.

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