THE RICH SPECTRUM OF CIRCUMSTELLAR PAHs IN IRAS 16594-4656: A NEW PROTO-PLANETARY NEBULA WITH A STRONG 21 MICRON DUST FEATURE *

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ABSTRACT

Based on ISO SWS+LWS observations, we identify IRAS 16594-4656 as a new member of the rare class of C-rich proto-planetary nebulae with the 21 microns dust feature in emission. In addition, the major PAHs emission bands at 3.3, 6.2, 7.7, 8.6 and 11.3 microns are detected, together with unusually strong features at 12.6 and 13.4 microns, 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 microns 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 detected. 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.

Key words: stars: AGB and post-AGB; planetary nebulae: general; stars: individual; IRAS 16594−4656; stars: infrared radiation.

1. OBSERVATIONS

A full range 2.4 − 45 μm spectrum of IRAS 16594−4656 was obtained on 1997 February 16 using 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 μm spectrum using 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.

2. DISCUSSION

2.1. 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 μm (Buss et al. 1990; Geballe et al. 1992; Buss et al. 1993) which are usually observed in good agreement with laboratory predictions. All them are detected in IRAS 16594−4656. According to the laboratory measurements, the 3.3 and 8.6 μm bands are due to in-plane stretching modes of C-H bonds in PAHs, while the 6.2 and 7.7 μm bands correspond to stretching modes of C-C bonds. The 11-15 μm region is dominated by ring-deformation vibrational modes of PAHs. The band at 11.3 μm is produced by an out-of-plane bending vibration mode of C-H, while bands at 11.9, 12.7 and 13.5 μm are the signatures expected for C-H out-of-plane bending vibration modes for duo, trio and quatro hydrogen atoms,

*ISO is an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) and with the participation of ISAS and NASA.

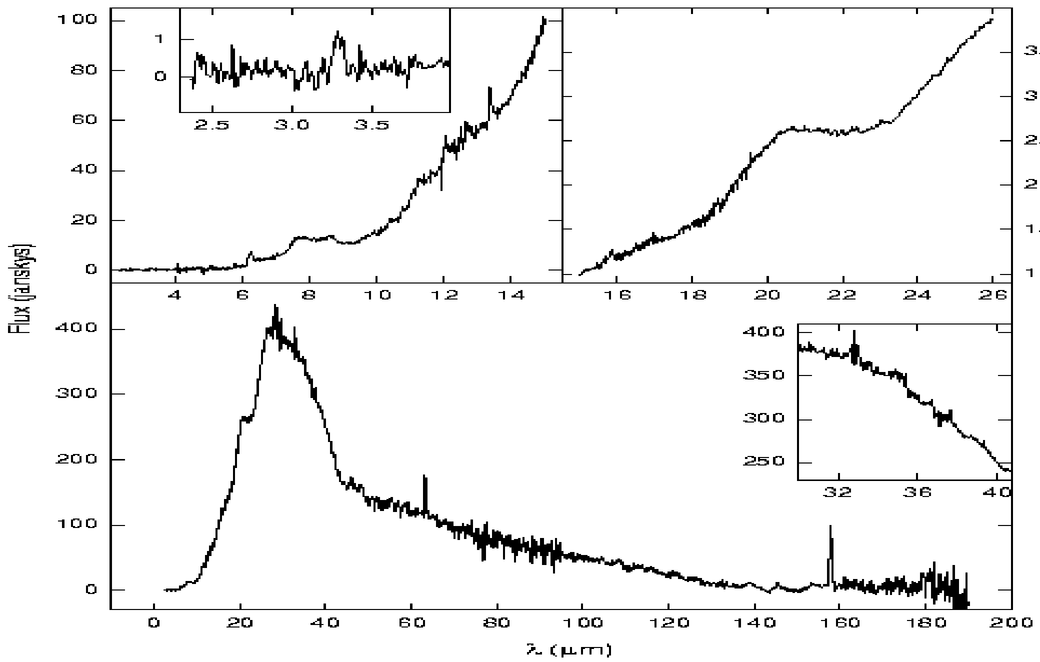

Figure 1. Combined ISO SWS+LWS spectrum of IRAS 16594−4656 between 2.4 and 197 μm. Some spectral regions discussed in the text are shown in detail.

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

Wavelength $\lambda(\mu m)$	Flux $(10^{-14} W\ m^{-2})$	FWHM (μm)	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:	silicates
32.57	0.41:	plateau	silicates
32.97	1.40:	plateau	silicates
33.59	0.42:	plateau	silicates
35.16	0.47:	plateau	silicates
35.29	0.40:	plateau	silicates
35.61	0.15:	plateau	silicates
40.50	0.10:	0.10:	silicates
42.07	0.18:	0.18:	silicates?
43.11	0.15:	0.15:	silicates?
44.16	0.25:	0.25:	silicates?
63.2	1.19	0.24	[OI]
157.7	0.51	0.09	[CII]

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 μm 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 μm when PAHs are ionized, while the band at 11.3 μm decreases in strength. In IRAS 16594−4656 the strength of the 11.3 μm is remarkably small compared to the strong features at 6.2 and 7.7 μm. 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 μm towards shorter wavelengths. In a similar way, a red wing in the 6.2 μm band and blue wings in the 7.7 and 11.3 μm bands are seen, signatures previously detected in the laboratory when PAH molecules are ionized (Langhoff 1996).

The shape of the PAH bands is also very sensitive to the H-substitution pattern. The 12.7 μm 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 μm, 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 μm. 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 μm 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.

2.2. The 21 μm feature

Beintema et al. (1996) suggest that the strong 21 μm feature, as well as a much weaker feature at 17 μm, not detected in our spectrum, could be related to in-plane deformation modes of the aromatic rings of PAHs, the 21 μm 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 μm band, IRAS 07430+1115 has been found to show a very strong PAH emission at 3.3 and 11.3 μm but not the 21 μm feature (Hrivnak and Kwok, 1998) This is striking, since a correlation between C_2 absorption, 3.3 μm emission and the 21 μm 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 μm 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 μm 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 μm emission band, while all the 21 μm emitters do show PAHs features.

2.3. 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 μm. 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 μm together with weaker peaks at 23 and 33 μm (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.

Finally, the unusual 3.4 μm feature is not detected in IRAS 16594−4656. The 3.4 μm 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 μm strong sources are 21 μm strong sources, while the opposite is not true (Geballe et al. 1992), as it is in the case of IRAS 16594−4656.

2.4. 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 μm 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).

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 μm 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 μm 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.

ACKNOWLEDGEMENTS

This work has partially been funded through grant PB94−1274 from the Spanish Dirección General de Investigación Científica y Técnica (DGICYT) and grant PB97−1435−CO2−02 from the Dirección General de Enseñanza Superior e Investigación Científica (DGESIC).

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