A&A 378, L41–L44 (2001)
DOI: 10.1051/0004-6361:20011264
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Astronomy & Astrophysics

Letter to the Editor

The discovery of the "21" μm and "30" μm emission features in Planetary Nebulae with Wolf-Rayet central stars*

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Received 25 July 2001 / Accepted 8 September 2001

Abstract. We report the discovery of the "21" μm and "30" μm features in the planetary nebulae around the hydrogen-deficient stars HD 826 and HD 158269. The carriers of these features are known to be produced in outflows around carbon-rich stars. This discovery demonstrates that the bulk of the dust in these nebulae has been produced during a carbon-rich phase before the atmospheres of these stars became hydrogen poor. This is the first time that the "21" μm feature has been detected in any planetary nebula. It shows that once formed its carrier can survive the formation of the nebula and the exposure to the UV radiation of the hot central star. This means that the carrier of "21" μm feature is not transient: the absence of the feature sets limits on the production of its carrier.

Key words. circumstellar matter – planetary nebulae: individual: NGC 40, NGC 6369 – stars: mass-loss – stars: evolution

1. Introduction

The precise evolutionary channel leading to the formation of Planetary Nebulae (PNe) with Wolf-Rayet ([WC]) central stars ([WC]-PNe) is not well established. While abundance studies of central stars of [WC]-PNe indicate that they are very H-poor, the nebulae show ample evidence for H-rich gas (e.g. Gorny & Stasinska 1995) and dust. Model calculations of AGB evolution show that the transition from H-rich to H-poor may be the result of a thermal pulse (TP) when the envelope mass has dropped below some threshold value, which may be as high as $\sim$0.01 $M_\odot$ (Herwig et al. 1999). It is not well understood whether this TP occurs when the star is still on the AGB or during the post-AGB evolution. For some stars, like V605 Aql, this transition has clearly occurred during the post-AGB phase. These systems harbour a small H-poor nebula within a large H-rich old nebula (e.g. Pollacco et al. 1992). The stellar C IV emission line in V605 Aql implies a [WC] spectral type (Guerrero & Manchado 1996). On the other hand, statistical analysis of the [WC]-PNe show that they are as a group not older than other PNe (Gorny 2001) and thus most of their central stars must have lost their H-rich envelope during or very soon after the AGB.

We are studying the infrared spectra of [WC]-PNe in order to reconstruct the mass loss history and chemical evolution of these objects. The dust content not only traces the conditions during the preceding phases; links them to precursor objects but also shows the type of materials fed into the ISM. The IR spectral appearance of C-rich evolved stars differs strongly from AGB, post-AGB to PNe objects. This is often interpreted as evidence for transient dust components.

In this letter we report on the discovery of the "21" μm and "30" μm dust features in two [WC]-PNe (NGC 40 ([WC 8]) and NGC 6369 ([WC 4])). These are ascribed to C-rich dust. The detection of the "21" μm feature is the first in a PN. We show that these detections imply that the TP which converted these stars to C-rich objects did not remove all H from the atmosphere of the star and was not responsible for the termination of the AGB. Furthermore, these observations may establish an evolutionary link between the [WC]-PNe and the "21" μm emitting post-AGB objects with cool central stars.

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* Based on observations obtained with ISO, an ESA project with instruments funded by ESA Member states (especially the PI countries: France, Germany, The Netherlands and the UK) with the participation of ISAS and NASA.

Article published by EDP Sciences and available at http://www.aanda.org or http://dx.doi.org/10.1051/0004-6361:20011264

Table 1. Source list. Observational details of the sources used in this study.

α(J2000)	δ(J2000)	TDT[a]	obs.mode[b]	obs.id
NGC 40; HD 826; IRAS 00102+7214				
00 13 01.10	+72 31 19.09	30003803	SWS01(3)	SWS_CAL
00 13 00.91	+72 31 19.99	44401917	SWS01(2)	MBARLOW
00 13 01.10	+72 31 19.09	81101203	SWS06	SWS_CAL
00 13 00.91	+72 31 19.99	47300616	LWS01	MBARLOW
NGC 6369; HD 158269; IRAS 17262−2343				
17 29 20.80	−23 45 32.00	45601901	SWS01(1)	SGORNY
17 29 20.80	−23 45 32.00	31100910	LWS01	CZHANG

[a] TDT number which uniquely identifies each ISO observation.
[b] SWS/LWS observing mode used (see de Graauw et al. 1996; Clegg et al. 1996). Numbers in brackets correspond to the scanning speed.

2. The observations

The data were obtained using the Short Wavelength Spectrometer (SWS) (de Graauw et al. 1996) on-board the Infrared Space Observatory (ISO) (Kessler et al. 1996). Details on the observations are given in Table 1.

The data were processed using SWS interactive analysis product; IA^3 (see de Graauw et al. 1996) using calibration files and procedures equivalent to pipeline version 9.5. NGC 40 has been observed multiple times and the data have been co-added after the pipeline reduction and bad data removal. Since the features we discuss here are fully resolved in all observing modes, we can safely combine the data obtained in all different modes maximising the S/N. Further data processing consisted of rebinning on a fixed resolution wavelength grid. The match between the individual sub-bands is excellent for both sources and there is no need to splice the sub-bands.

We compare the SWS spectra with the available IRAS photometry and the IRAS/LRS spectra. We find that the IRAS photometry lies well above the SWS observations. This indicates that the sources are more extended than the SWS apertures. Indeed the optical nebulae associated with NGC 40 and NGC 6369 are 60″ and 30″ while the largest SWS aperture measures $20 \times 33''$. Surprisingly the shape and slope of the SWS and IRAS/LRS spectra correspond very well. This indicates that the SWS spectrum is representative of the *bulk* of the dust in those nebula even if we do not see *all* dust emission.

Extended sources give rise to aperture jumps between the SWS sub-bands most notably around 29 μm because at those wavelengths the effective aperture changes from $14 \times 27''$ to $20 \times 33''$. We do not observe a flux jump in NGC 6369 and at most a jump of 20 percent in NGC 40. This means that there is not more dust located in the larger aperture. NGC 6369 has a ring-like structure in the optical. The SWS spectrum was taken from the east part of this ring and the largest aperture sees more of the relatively empty inner part of the ring.

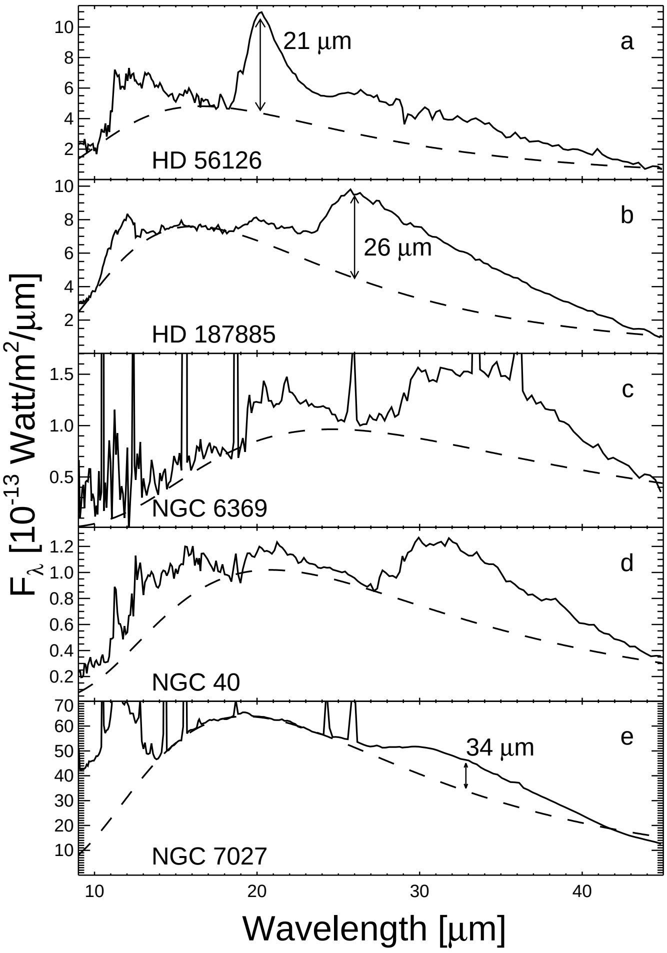

Fig. 1. Overview of the spectra of NGC 40 and NGC 6369. For comparison we also show the spectra of HD 56126, HD 187885 and NGC 7027. The dashed lines represent the continua we draw.

The LWS spectra are observed through a circular aperture of 1′. We do see a flux jump between the SWS and LWS spectra. The factors needed to bring the SWS and LWS spectra together at 45 μm are the same needed to bring the SWS and the IRAS/LRS spectra together, demonstrating that the LWS instrument does see the entire nebula.

3. Description of the spectra

We show the observed spectra of NGC 40 and NGC 6369 from 10 to 45 micron in Figs. 1c,d. Both mid-IR spectra are dominated by broad emission excesses from 20−25 and 26−45 μm. We also detect emission from polycyclic aromatic hydrocarbons (PAHs) (Allamandola et al. 1989) between 3.3−12.7 μm. NGC 40 also has a strong unidentified emission plateau from 10−19 μm. We concentrate on the two broad features around 20 and 30 μm. For comparison we also show the SWS spectra of the 21 μm objects

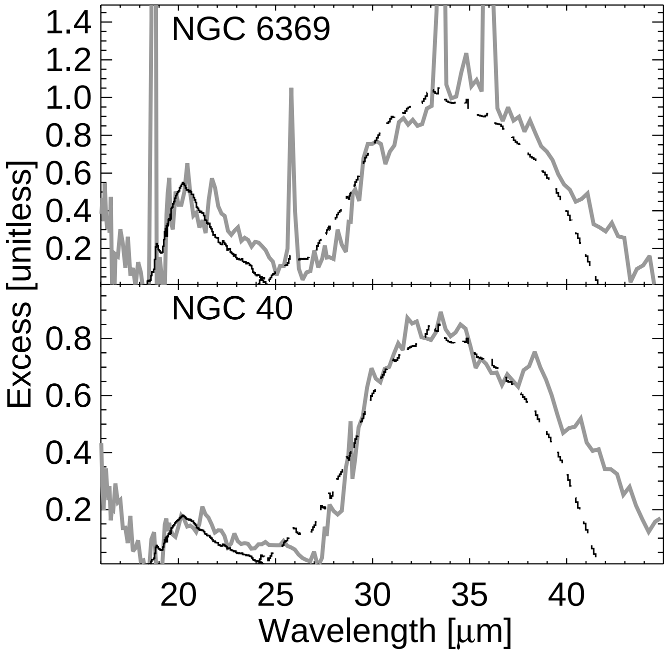

Fig. 2. A comparison of the observed emission features compared with the "21" μm (solid line) and the "30" μm (dashed line) features as derived from HD 56126 and NGC 7027 respectively.

HD 187885 and HD 56126 and the C-rich PN NGC 7027 (Figs. 1a,b,e, respectively).

A broad feature peaking near 21 μm is found to be an important component of the IR spectra of some C-rich proto-planetary nebulae (PPNe) (e.g. Kwok et al. 1989). This feature has up to now only been detected in a very uniform group of post-AGB sources; C-rich, within a narrow temperature range (Kwok et al. 1999), metal poor and s-process enhanced (Van Winckel & Reyniers 2000). These sources are generally termed the "21 μm objects".

A very broad emission feature extending from 25−45 μm is abundantly detected in IR spectra of a variety of C-rich evolved objects ranging from intermediate mass loss AGB stars to PNe (Forrest et al. 1981). The feature is tentatively ascribed to MgS (e.g. Nuth et al. 1985; Goebel & Moseley 1985; Begemann et al. 1994). Hrivnak et al. (2000) show that the "30" μm feature in the 21 μm objects consists of a 26 and a 30 μm component. An extensive survey of the "30" μm feature in a wide range of C-rich evolved objects shows that its peak position can vary from 26 μm to 34 μm (Hony et al., in prep.), see Figs. 1b,e for an example of this shift. The two [WC]-PNe show a peak near 34 μm as do most regular C-rich PNe. In contrast in the 21 μm objects the "30" μm feature usually peaks at 26 μm as it does in most AGB stars.

To compare the features we observe in NGC 40 and NGC 6369 with other sources we extract the profiles of the excess emission. We construct a simple model continuum by fitting a modified blackbody ($F_\nu(\lambda) = B_\nu(\lambda,T)\times\lambda^{-p}$, where $B_\nu(\lambda,T)$ is the Planck function) to continuum points around 9−10, 16 and 45 μm. We keep the power (p) fixed at 0.5, a value which fits those sources well and also matches the slope of the LWS spectra when available. These continua are shown as dashed lines in Fig. 1. The excess emission in both sources is shown in Fig. 2.

For comparison we show the "30" μm feature of the C-rich PN NGC 7027 in Fig. 2. The "30" μm feature in the two [WC]-PNe compares well, both in peak position and in width, with the other PNe. The discrepancies at the longest wavelength may reflect the difficulties to draw a continuum for the spectrum of NGC 7027. The SWS and LWS spectra of NGC 7027 show a depression around 42 μm. This might be due to a residual instrumental effect.

For the comparison of the "21" μm feature in the [WC]-PNe with that in 21 μm objects, we have decomposed the emission from the latter objects in a 21 μm and a 26 μm component (see also Fig. 1). The thus derived "21" μm component rises steeply from 18.4 to 20.1 μm and slowly tapers off until 24.6 μm. See also Volk et al. (1999) who show the profile to be identical in all known 21 μm sources. We compare this profile to the excesses found in NGC 40 and NGC 6369 in Fig. 2. The profile compares well with the new observations, specifically the sharp rise and the long tail towards longer wavelengths. We also find an extra contribution near 21.5 μm not found in the 21 μm objects. This is the first time the "21" μm feature has been detected in an object other than a PPN with a low mass progenitor.

4. Discussion

The "21" μm feature is absent during the AGB phase, therefore its carrier is generally thought to have formed during a short period of enhanced mass loss which terminated the AGB phase. However this scenario does not explain why it is not detected in their successors, the PNe. This has led to the suggestion that the carrier is a transient, unstable constituent of the dust. These new detections demonstrate that the "21" μm carrier can survive into the PN phase, where it is exposed to UV radiation field of the hot central star; *it is a non-transient, stable dust component.* von Helden et al. (2000) identified TiC as the carrier of the "21" μm feature. The non-transient nature of the feature further strengthens its identification with the refractory TiC. This identification however implies extreme conditions during formation with high densities and consequently very high mass-loss rates: typically $>10^{-4}\ M_\odot$/yr.

The detection of these features in the spectra of [WC]-PNe has ramifications for our understanding of their evolution. The "30" μm feature is characteristic for the C-rich ejecta of AGB and post-AGB objects. The dominance of this band in the spectra of these [WC]-PNe implies that the bulk of the dust in these nebula was formed during a preceding C-rich phase. Clearly, the transition from O-rich to C-rich and the transition from H-rich to H-poor are decoupled for these objects. Thus, these nebulae have undergone normal AGB evolution from O-rich to C-rich well before the loss of the last 0.01 $M_{\odot}$ turned the central star into a [WC] star.

This seems to be a very general characteristic for [WC]-PNe. The mid-IR spectra of all of these objects are dominated by the well known emission features due to PAHs (Cohen et al. 1989; 1999). The strong 3.3, 8.6, and 11.3 μm bands in these spectra attests to the presence (and importance) of H during the formation of the PAHs. In contrast, population I WC stars show mid IR spectra characterised by strong continua with very weak absorption features at 6.2 and 7.7 without any sign of the 3.3 and 11.2 μm feature (Chiar & Tielens 2001). We conclude that the [WC]-PNe went through a H-rich, C-rich phase during which the PAHs condensed.

The "'21" μm feature has been detected in C-rich post-AGB objects, however not in their precursors, the carbon stars. Hence, the the "21" μm carrier have must formed at the end of the AGB, during a burst of mass loss, which lasted short compared to the post-AGB phase, i.e., $\lesssim$1000 years. If we assume that the "21" μm carrier in the [WC]-PNe nebulae condensed similarly to all other known 21 μm emitting sources, this means this mass loss burst occurred *prior* to the TP which turned the star H-poor. Between leaving the AGB and this TP these objects may have appeared similar to the 21 μm objects. Likewise if a cool 21 μm object were to suffer a TP – turning it H-poor – it would become a PN similar to these PNe. We conclude that NGC 40 and NGC 6369 could represent successors to some of the cool 21 μm objects and that the *last* TP followed the mass loss burst. The low dynamical ages of the nebulae of NGC 40 and NGC 6369 ($\sim$5000 and $\sim$1500 yr) and the much longer timescale for TPs ($\gtrsim 10^4$ yr) shows that the production of the "21" μm carrier is not triggered by a TP.

It is tempting to further explore the evolutionary link between the "21" μm emitting PPNe and the [WC]-PNe, given the fact that these PPNe are the only objects known to exhibit the feature apart from the two PNe we present here. Van Winckel & Reyniers (2000) show that the 21 μm objects as a group are metal poor albeit with large intrinsic range ([Fe/H] = -0.3 to -1.0). Abundance determinations of NGC 40 and NGC 6369 (Perinotto 1991) show that [Ne/H] is -0.8 and -0.5. Assuming that the Ne abundance in those PNe is representative for the total metallicity (e.g. Pottasch 1984, chapter III.E), this means they fall in the range also observed for the 21 μm objects.

It is important to note that there cannot be a one-to-one correspondence between the 21 μm objects and the [WC]-PNe. Many [WC]-PNe show *no* signature of a long lasting C-rich mass-loss phase. Rather these nebulae are typified by a mixed chemistry with warm ejecta from both an O-rich and a C-rich phase (Waters et al. 1998). This is interpreted as evidence for a short ($\sim$1000 yr) transition phase during which the star first became C-rich and shortly after H-poor (Waters et al. 1998; Cohen et al. 1999), because the O-rich ejecta predate the C-rich material while still being close to the star. The "21" μm feature is not present in the mid-IR spectra of these mixed chemistry sources, excluding them as successors to the 21 μm objects. Likewise not every 21 μm object may evolve to become H-poor. Whether a star becomes H-poor is determined by the remaining envelope mass at the time of the last TP. Thus, the question arises where the PNe with the H-rich central stars and the "21" μm feature are. Due to observer bias few such PNe have been observed with SWS, however those which have been studied show no "21" μm feature. We now know that the feature is not transient. *Thus the absence of the feature implies non-production of its carrier.* Hence, those objects have not gone through a phase in which they produced the "21" μm carrier. We conclude that the chemical evolution, as determined by the H content of the atmosphere of the central star, and the mass-loss history; specifically the mass loss burst as traced by the "21" μm feature, are decoupled.

Acknowledgements. LBFMW and SH acknowledge financial support from an NWO *Pionier* grant.

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