The Infrared Emission Features in the spectrum of WR 48a

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J.E. Chiar, E. Peeters, A.G.G.M. Tielens

Abstract We present the first detection of unidentified infrared (UIR) emission features at $\sim 6.4$ and $7.9 \, \mu m$ in the spectrum of the dusty WC8 Wolf-Rayet star WR 48a. Based on the H-deficient nature of WC-stars, we attribute the emission features to large carbonaceous molecules or amorphous carbon dust grains in the circumstellar environment of WR 48a. The $6.4 \, \mu m$ feature resembles the emission feature seen toward H-deficient PNe, while the $7.9 \, \mu m$ profile resembles that of some planetary nebulae with H-deficient WC10 central stars. These similarities point towards a similar origin of the dust in these H-deficient environments, and highlights the apparent sensitivity of the UIR bands to physical conditions. In the case of WR 48a and the [WC10]-PNe, shock processing may play a major role in dust formation.
5.1 Introduction

Infrared (IR) spectroscopy is a powerful tool for the study of the evolutionary link between interstellar and circumstellar polycyclic aromatic hydrocarbons (PAHs) and carbon dust. Dust and PAH composition is likely to reflect variations in chemical and physical conditions and history in different astrophysical environments. An inventory of PAH emission regions and their spectral characteristics has been carried out by Hon"y et al. (2001) and in Chapters 3 and 4. These authors find a correlation between the profiles of the PAH IR emission features and the astrophysical environment.

Despite their harsh environment - fast stellar winds and high stellar effective temperatures - some WC-type Wolf-Rayet stars are known to produce copious amounts of carbon dust in their winds. Wolf-Rayet stars represent one of the final stages of stellar evolution for massive stars. In general, they are thought to follow an evolutionary sequence divided into three phases WN - WC - WO, corresponding to the prevalence of different emission lines in their spectra (see van der Hucht 2001, for a review). Late-type WC stars are now known to be surrounded by heated circumstellar dust (Williams et al. 1987), although the process by which this dust forms and survives in the harsh WC-star environment is not well-understood (Cherchneff et al. 2000). The dust-producing WC stars have been divided into subtypes depending on the regularity of their dust formation. Of the five WC stars with the densest dust shells studied by van der Hucht et al. (1996), three (WR 104, WR 112, WR 118) are classified as persistent dust makers, one (WR 98a) is classified as having variable dust formation, and one (WR 48a) exhibits episodic dust formation (Williams 1999). In general, dust formation appears to be the effect of colliding winds in WC+OB binary systems (e.g., Williams 1997; van der Hucht 2001, and references therein).

The ISO/SWS spectra of a sample of WC stars have recently been analysed by Chiar & Tielens (2001). They identified an absorption feature at 6.2 $\mu$m with large (1 $\mu$m), circumstellar, amorphous carbon dust grains. In spite of the difficulty of condensing large grains in the harsh WC-star environment, subsequent studies (of WR 112 and WR 118) also suggest the presence of large grains in the dust shells of these stars (Marchenko et al. 2002; Yudin et al. 2001). Here, we present the IR spectrum of WR 48a which shows emission features at $\sim$ 6.4 and 7.9 $\mu$m similar to the well-known UIR bands seen throughout the cosmos.

5.2 Observations and data reduction

We present the 2.5–30 $\mu$m spectrum of WR 48a obtained with the Short-Wavelength Spectrometer (SWS) on the Infrared Space Observatory (ISO). Astronomical Observing Template (AOT) 01 speed 2 (TDT 07902703, $R \sim 270 – 700$) data are presented in the range 2.5–30 $\mu$m, excepting wavelengths 5.48–7.62, 7.98–8.88 $\mu$m where AOT 06 (TDT 60701201, $R \sim 900 – 2400$) data were available. All data presented here were reduced using the Interactive Analysis (IA$^3$) tool at the University of Groningen with pipeline version (OLP) 10.1 which uses the latest responsivity corrections. Standard data reduction techniques were used to correct for memory effects, subtract dark current, and calibrate for the responsivity of the detectors. The spectra from the individual detectors are flat-fielded (normalised), points lying $\sim 3\sigma$ above the norm are clipped, then the result is rebinned to a constant resolution appropriate for each band. This is done for each of the 12 bands. A final spectrum (Fig. 5.1) is created by shifting adjoining bands using a multiplicative factor within the known flux uncertainties for each band.
5.3 Analysis

The infrared spectrum of WR 48a shows clear emission features at $\sim 6.4$ and $7.9 \ \mu m$, and silicate absorption features at 9.7 and $18 \ \mu m$. The latter two features are likely due to interstellar absorption (Roche & Aitken 1984; van der Hucht et al. 1985). In order to analyse the profiles of the emission features, the continuum had to be defined, most notably by correcting for silicate absorption. Chiar & Tielens (in preparation) analyse the 9.7 and $18 \ \mu m$ interstellar silicate absorption features toward several heavily extincted WR stars. They use the silicate spectrum of WR 98a along with the general interstellar extinction curve deduced by Martin & Whittet (1990) to construct a new interstellar extinction curve from 1–25 $\mu m$. This extinction curve is applied to the WR 48a spectrum to “correct” for silicate absorption in its spectrum, leaving behind emission features at $\sim 6.4$ and $7.9 \ \mu m$ (Fig. 5.1). We then fit and subtract a fourth order polynomial between 5.5–9 $\mu m$ (Fig. 5.2, top), to produce the emission spectrum shown in Fig. 5.2 (middle).

5.4 The UIR bands of WR 48a

The IR spectrum of WR 48a exhibits a weak, highly asymmetric emission band at $\sim 6.4 \ \mu m$, and a symmetric emission band at $7.9 \ \mu m$ (Fig. 5.2). These positions are close to the
characteristic wavelengths of UIR bands at 6.2 and 7.7 μm.

A systematic analysis of a large sample of sources representing a variety of astrophysical environments reveals the presence of large variations in profile and peak position of these two
UIR bands (Chapt. 3). These authors defined three classes for the observed 6.2 μm feature based on its peak position, i.e. sources with a 6.2 μm UIR band peaking at ∼6.22 μm, at 6.24–6.28 μm, and at ∼6.3 μm, belong to respectively class A, B and C. Similarly, three classes were defined for the 7.7 μm complex. Sources with a dominant 7.6, 7.8, and 8.2 μm component form class A′, B′, and C′, respectively. Sources with an 8.6 μm feature that peaks between 8.58–8.62 μm and beyond 8.62 μm, form classes A″ and B″, respectively. Sources with no 8.6 μm component form class C″. Astrophysically speaking, the 6–9 μm spectrum is also found to be sensitive to the type of object (Chapter 3), i.e. the local physical conditions where the carriers reside. HII regions, reflection nebulae, Herbig AeBe stars with associated HII regions, and extragalactic sources have class A, A′, and A″, 6.22, 7.6 and 8.6 μm features, respectively. Isolated Herbig AeBe stars, some post-AGBs, and most PNe belong to a second class of objects exhibiting features at 6.24–6.28, 7.8 and >8.62 μm (classes B, B′, and B″, respectively). Finally, two post AGB stars, that exhibit features at ∼6.3, 8.22, but none near 8.6 μm, form class C, C′, C″, respectively. An overview of the variations in the 6.2 and 7.7 μm UIR bands are shown in the bottom panel of Figure 5.2; the middle panel of this Figure compares the derived profiles for WR 48a.

The observed emission bands in WR 48a coincide with the wavelength range where UIR emission bands are observed. Following the classification of Chapter 3, the observed 6.4 μm feature belongs to class C. Nevertheless, the derived profile is unique; i.e. it is broader and more asymmetric compared to the class C profile (see Fig. 5.2). The 6.4 μm feature resembles that seen by Harrington et al. (1998) toward the hydrogen deficient PNe Abell 78 and IRAS 15154-5258. In contrast, the observed 7.9 μm complex belongs to class B′ and is similar to that of Hen 2-113, IRAS 07027-7934 and HD 100546 (see Fig. 5.3 and Fig. 15 in Chapter 3. Hen 2-113 and IRAS 07027-7934 are planetary nebulae with WC10 central stars.

**Figure 5.3** — UIR profile at 7.9 μm for WR 48a [thin line] compared to the scaled profile of Henize 2-113 [thick line], a planetary nebula with a WC10 central star.
([WC]-PNe) while HD 100546 is an isolated Herbig AeBe star. These sources show a class B “6.2” \( \mu m \) feature distinct from that of WR 48a. Thus, WR 48a belongs to two classes, B’ and C, derived from the “7.7” and “6.2” \( \mu m \) features respectively. Such mixed classes are present within the original sample as well (Chapter 3).

5.5 The Nature of the UIR Carrier in WR 48a

In Sect. 5.4, it is shown that the observed 6.4 and 7.9 \( \mu m \) emission features in WR 48a are similar to the so-called 6.2 and 7.7 \( \mu m \) UIR bands observed around some evolved stars and an isolated Herbig AeBe star. Nevertheless, WR 48a does not exhibit the 3.3, 8.6 and 11.2 \( \mu m \) UIR bands. These bands are attributed to the CH stretching and bending modes of PAHs and hence their non-appearance reflects the low H-content of the ejecta of WC stars (\(<10^{-2}\) by number relative to helium; Nugis & Niedzielski 1995; Torres 1988). As a consequence, PAHs cannot be present there and the condensation of soot in hydrogen poor environments must occur by pathways that bypass acetylene (C\(_2\)H\(_2\))-rich molecular intermediaries. Carbon soot (i.e., amorphous carbon) formation in these environments is expected to be initiated through the formation of carbon chains (C\(_2\), C\(_3\), C\(_4\), etc.) followed by the formation of aromatic ring structures (Cherchneff et al. 2000). The coalescence of large monocyclic rings may then form fullerene molecules (Rubin et al. 1991; von Helden et al. 1993; Kroto 1994). Amorphous carbon structures and grains can then form from carbon clusters of the fullerene family (Zhang et al. 1986).

The strongest bands for linear carbon chains with 3–20 C-atoms fall in the 4.4–5.0 \( \mu m \) range (Allamandola et al. 1999a) and, hence, these species cannot be responsible for the observed features in WR 48a. The vibrational characteristics of (non-aromatic) carbon ring molecules are unknown. Fullerenes have been studied in the laboratory. Specifically, the IR spectrum of C\(_{60}\) exhibits emission bands at 7.5, 8.6, 17.5 and 19.0 \( \mu m \) (Frum et al. 1991; Nemes et al. 1994). Two emission bands of C\(_{60}^+\) have been measured; they peak at 7.1 and 7.5 \( \mu m \) (Fulera et al. 1993). All of these peak positions clearly deviate from the positions of the observed emission bands in WR 48a. Coal and amorphous carbon show emission in the 6–9 \( \mu m \) region (Borghesi et al. 1987; Colangeli et al. 1995; Guillois et al. 1996). However, the presently available amorphous carbon and coal data either do not show emission features in the 7.4–11 \( \mu m \) region (Borghesi et al. 1987) or the profiles do not match the astronomical data (Colangeli et al. 1995; Guillois et al. 1996). More experimental data are needed on carbon rings and fullerene molecules as well as hydrogen-poor carbonaceous dust to settle this question.

It has proven to be very difficult to distinguish purely spectroscopically between molecular and grain carriers for the UIR bands. Essentially, the mid-IR spectrum reflects the bonding between nearest neighbour atoms and is little sensitive to the characteristics of the emitting species at large. From that point of view, it is unclear whether the carrier of the 6.4 and 7.9 \( \mu m \) feature in WR 48a is molecular or dust-like in nature. In general, the assignment of PAHs as the molecular carrier for the UIR bands is based mainly on two arguments (Tielens et al. 1999). First, the UIR bands are observed in reflection nebulae and the diffuse ISM where classical grains are too cool to emit at 3.3 \( \mu m \) (Sellgren 1984). Second, the observed high feature-to-continuum ratio is characteristic of a molecular carrier. For WR 48a, on the other hand, there is no unambiguous evidence for a molecular carrier. The dust continuum in the IR spectrum of WR 48a peaks at \( \sim 5-6 \) \( \mu m \), i.e. in the same wavelength region as
the emission bands, disqualifying the first argument. A dust-like carrier is insinuated by the low observed feature-to-continuum ratio in WR 48a ($\sim 0.1$). Thus, although molecules may contribute to the emission features, in this source, the emission may also be carried by dust grains.

5.6 Conclusions

We have detected emission features at $\sim 6.4$ and 7.9 $\mu$m in the spectrum of the late-type WC star WR 48a. The central wavelengths of these features fall within the range of the well-known UIR emission features. Since late-type WC Wolf-Rayet stars lack hydrogen in their stellar winds, polycyclic aromatic hydrocarbon molecules cannot be responsible for the emission features. Instead, we attribute the emission to large “pure” carbon molecules or amorphous carbon dust.

The 6.4 $\mu$m emission feature in the WR 48a spectrum closely resembles that observed toward the H-deficient PNe Abell 78 and IRAS 15154-5258. For these objects, the 6.4 $\mu$m feature is attributed to small transiently heated H-free carbonaceous grains (Harrington et al. 1998) due to the non-detection of the corresponding C-H modes (at 8.6 and 11.2 $\mu$m) of aromatic compounds. Only one of the H-deficient PNe (IRAS 15154-5258) shows a hint of a broad emission feature near 8 $\mu$m. On the other hand, Hen 2-113 and IRAS 07027-7934, planetary nebulae with hydrogen deficient WC10 central stars, show an emission feature at 7.9 $\mu$m that resembles the one seen in WR 48a (Fig. 5.3). However, the “6.2” $\mu$m feature toward these [WC10]-PNe falls shortward of that toward WR 48a, at 6.27 $\mu$m. In addition, the Herbig AeBe star, HD 100546, also shows a feature at 7.9 $\mu$m like the one seen in the WR 48a spectrum, but like the [WC10]-PNe, the “6.2” $\mu$m feature also falls shortward of that toward WR 48a, at 6.25 $\mu$m.

Physical conditions certainly have an effect on the profiles of the UIR bands. The C-rich H-deficient conditions in the objects discussed above (with the exception of HD 100546) have the effect of shifting the “6.2” and “7.7” $\mu$m features toward longer wavelengths. An additional requirement may be associated with shock induced dust condensation or modification of the PAHs. However, these are not the only conditions which promote such spectral shifts. In particular, HD 100546 has a similarly shifted “7.7” $\mu$m peak position and profile as WR 48a. Nevertheless, the similarity of the “7.7” $\mu$m UIR band in WR 48a, a Population I WR star, and in the two Population II [WC10]-PNe is intriguing. This might indicate that the dust formation in these environments is alike. For WR 48a, dust is formed in the interaction region of the winds of the O-star and the WR star (e.g., Usov 1991). In the [WC10]-PNe systems, interaction between the fast wind from the WC nucleus with the cooler slowly moving ejecta of the AGB phase produces the necessary shock conditions. However, unlike WR 48a, Hen 2-113 and IRAS 07027-7934 show emission due to C-H stretching and bending modes at 3.3 and 11.2 $\mu$m (Cohen et al. 1989; Hony et al. 2001), indicative of a region of hydrogen-rich PAHs and dust. Perhaps, the strong shocks caused by the [WC10] wind modify the H-containing nebular PAHs and dust formed during an earlier evolutionary phase.

Five WC stars with dense dust shells were studied by van der Hucht et al. (1996): WR 48a, WR 98a, WR 104, WR 112, WR 118. The spectrum of WR 48a is the only one that shows evidence for emission features at the known UIR wavelengths, although Chiar & Tielens (2001) attribute an absorption feature at 6.2 $\mu$m in these objects to circumstellar amorphous carbon dust. Large grains ($\sim 1$ $\mu$m) were inferred based on the 6.2 $\mu$m profile’s integrated
absorption, the intrinsic strength of amorphous carbon and the small circumstellar visual extinction. Perhaps WR 48a provides a snapshot of the general dust condensation process in WC stars, frozen out due to the transient nature of the dust formation process in this object; a stage which is obfuscated in other dusty WC stars due to rapid dust growth. In this sense, a search for molecular intermediaries in the dust formation process (e.g. $C_n$ chains) in this source may prove to be fruitful.