

PAH Spectral Diversity in NGC 7027 and the Evolution of Aromatic Carriers

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ABSTRACT

Context. Polycyclic Aromatic Hydrocarbons (PAHs) constitute a significant fraction of the Universe’s carbon budget, playing a key role in the cosmic carbon cycle and dominating the mid-infrared spectra of astrophysical environments in which they reside. Although PAHs are known to form in the circumstellar envelopes of post-AGB stars, their formation and evolution are still not well-understood.

Aims. We aim to understand how pristine complex hydrocarbons and PAHs in circumstellar environments transition to the PAHs observed in the ISM.

Methods. The mid-infrared PAH spectra (5–18 μm) of the planetary nebula, NGC 7027, are investigated using spectral cubes from JWST MIRI-MRS.

Results. We report the first detection of spatially-resolved variations of the PAH spectral profiles across class $\mathcal{A}$, $\mathcal{AB}$, and $\mathcal{B}$ in all major PAH bands (6.2, 7.7, 8.6, and 11.2 μm) within a single source, NGC 7027. These variations are linked to morphological structures within NGC 7027. Clear correlations are revealed between the 6.2, 7.7, and 8.6 μm features, where the red components (6.26, 7.8, 8.65 μm) exhibit a strong correlation and the same is found for the blue components of the 6.2 and 7.7 μm (6.205 and 7.6 μm). The blue component of the 8.6 (8.56 μm) appears to be independent of the other components. We link this behaviour to differences in molecular structure of their PAH subpopulations. Decomposition of the 11.2 μm band confirms two previously identified components, with the broader 11.25 μm component attributed to emission from very small grains or PAH clusters rather than PAH emission.

Conclusions. We show that PAH profile classes generally vary with proximity to the central star’s UV radiation field, suggesting class $\mathcal{B}$ PAHs represent more processed species while class $\mathcal{A}$ PAHs remain relatively pristine, challenging current notions on the spectral evolution of PAHs.

Key words. circumstellar matter, ISM: molecules, techniques: spectroscopic, planetary nebulae: individual: NGC 7027

1. Introduction

The outflows of dying intermediate-mass stars (i.e., AGB stars) are the birth site for dust and carbon-related species, such as AHs (e.g., Frenklach & Feigelson 1989; Boersma et al. 2006; Galliano et al. 2008a; Tielens 2008). Carbon-rich AGB stars dictate the early chemistry in their circumstellar envelopes before the molecules and dust are later incorporated into the interstellar medium (ISM), providing the main source of carbon and other organic elements for the ISM (e.g., Cherchneff et al. 1992; Tielens 2005; Matsuura et al. 2009). Therefore, PAH emission from post-AGB stars and planetary nebulae (PNe) can be studied to unveil the PAH characteristics at the beginning stages of their lifecycle.

The characteristics of the PAH population are strongly influenced by the temperature, density, and radiation field of the environment in which they reside. It follows that the PAH emission bands reflect the conditions of their environment, and spectral variations arise in the form of relative intensity, peak emission position, and profile shape (e.g., Cohen et al. 1986; Smith et al. 2007; Galliano et al. 2008b).

Based on observed peak positions and profile shapes of the 3.3, 6.2, 7.7, and 11.2 μm aromatic infrared bands (AIBs), spectra can be categorized in different classes: $\mathcal{A}$ – $\mathcal{D}$ (Peeters et al. 2002b; van Diedenhoven et al. 2004; Matsuura et al. 2014; Sloan et al. 2014). These different AIB classes correlate with source type (i.e., H II regions, reflection nebulae, Herbig AeBe stars, planetary nebulae; Cohen et al. 1989; Bregman et al. 1989; Peeters et al. 2002b; van Diedenhoven et al. 2004) and the observed spectral differences are thought to reflect processing of the PAHs in the local environment by prevalent FUV photons, shocks, and/or gas phase chemistry (e.g., Peeters et al. 2002b; Boersma et al. 2008; Matsuura et al. 2014). Likely, there is an evolutionary relationship between these classes. Indeed, it has been suggested that recently formed PAHs are predominantly class $\mathcal{B}$ but processing in the harsh environment of the ISM converts them into class $\mathcal{A}$ PAHs (e.g., Peeters et al. 2002b; Boersma et al. 2008; Matsuura et al. 2014). A somewhat different scenario is envisioned by Joblin et al. (2008) in which PAHs formed in C-rich AGB outflows are rich in aliphatics and these species are converted into highly aromatic compounds in harsh radiation fields. There is observational evidence that this

conversion already occurs in the (proto)-planetary nebula phase (Goto et al. 2003, 2007).

Infrared studies with ISO-SWS have revealed that the planetary nebula, NGC 7027, has an AIB spectrum that is a mix of class $\mathcal{A}$ and $\mathcal{B}$ (Peeters et al. 2002b; van Diedenhoven et al. 2004). This source provides therefore a unique opportunity to assess the factors that drive the conversion from class $\mathcal{B}$ to class $\mathcal{A}$. However, the beam size of the SWS instrument was similar to the size of this source in the mid-IR and thus precluded a detailed study of the spatial distribution of the AIBs to trace this evolution in the outflow. The MIRI IFU (Wright et al. 2015; Wells et al. 2015) on board JWST (Gardner et al. 2006) with a pixel scale of 0.2" is well-suited to study the spatial-spectral distribution of the AIBs in this nebula.

In Section 2, we describe the AIB classification and in Section 3, we discuss the morphology of NGC 7027. Details about the observations, data reduction, and analysis are discussed in Section 4. We present the results in Section 5, followed by a discussion in Section 6. Finally, the conclusions of the study are laid out in Section 7.

2. AIB Classification

Class $\mathcal{A}$ profiles exhibit the bluest peak positions. For class $\mathcal{A}$ profiles, the 6.2 μm band has a peak position between 6.19 and 6.23 μm , the 7.6 μm feature is the dominant component of the 7.7 μm complex, and the 8.6 μm feature peaks between 8.58 and 8.62 μm (Peeters et al. 2002b). For the 11.2 μm band, a class $\mathcal{A}$ or $\mathcal{AB}$ profile peaks at 11.20-11.24 μm . The difference between the 11.2 μm $\mathcal{A}$ and $\mathcal{AB}$ classifications arise from the full width at half maximum (FWHM), where a class $\mathcal{A}$ profile has a narrower profile than that of class $\mathcal{AB}$ (van Diedenhoven et al. 2004). Class $\mathcal{B}$, on the other hand, demonstrates red-shifted peak positions. In this case, the 7.8 μm is the dominant component of the 7.7 μm complex and the 8.6 μm feature peaks at a wavelength longwards of 8.62 μm . Meanwhile, the 6.2 μm feature peaks between 6.24 and 6.28 μm , and the 11.2 μm is relatively broad with a peak at ~ 11.25 μm . In class $\mathcal{C}$ spectra, the 6.2 μm feature peaks at 6.29 μm and the 7-9 μm complex has a very broad band peaking around 8.2 μm (Peeters et al. 2017). Finally, class $\mathcal{D}$ has been assigned to PAH spectra with a broad feature peaking at 6.24 μm , a broad feature ranging from 7-9 μm peaking at 7.7 μm , and a peak position at ~ 11.4 μm of the 11.2 μm PAH band (Matsuura et al. 2014; Sloan et al. 2014). It is important to note that PAH spectra do not simply fall into a discrete class, but rather, seem to form a continuous distribution ranging from Class $\mathcal{A}$ to $\mathcal{D}$.

Observations demonstrate that each class has a connection to the astronomical object in which they are observed. Class $\mathcal{A}$ band profiles are attributed to interstellar material, typically being observed in reflection nebulae, the ISM, and H II regions. Class $\mathcal{B}$ and $\mathcal{C}$ are associated with circumstellar material, being most commonly detected in post-AGB stars, planetary nebulae, and isolated Herbig AeBe stars (e.g., Cohen et al. 1989; Bregman et al. 1989; Peeters et al. 2002b; Tielens 2008).

3. NGC 7027

NGC 7027 is a relatively nearby (~ 900 pc) carbon-rich planetary nebula (PN; Masson 1989; Zijlstra et al. 2008). At a young dynamical age of roughly 600 years, it is still at a relatively early stage of the PN phase of stellar evolution (Masson 1989). NGC 7027 is very bright; at its centre lies a very hot white dwarf

(WD) with an effective temperature of about 200 000 K and a luminosity of roughly 8000 $L_{\odot}$ (Latter et al. 2000; Zhang et al. 2005). The current core mass is estimated to be $\sim 0.65 M_{\odot}$ (Zijlstra et al. 2008), while the progenitor mass is estimated to have been 3-4 $M_{\odot}$ (Bernard Salas et al. 2001).

Numerous infrared and sub-mm observations have revealed that the material ejected during the AGB phase has formed a flattened ellipsoidal distribution (Fig. 2; Cox et al. 2002). This non-spherical distribution is likely due to the presence of a binary system at the centre of the nebula, as many studies of PNe suggest (e.g., Balick & Frank 2002; De Marco 2009; Moraga Baez et al. 2023). Strong, precessing jets have carved out bipolar cones that are being illuminated by the EUV and FUV photons from the hot central white dwarf (Latter et al. 2000; Cox et al. 2002). These conditions create an ionized nebula, which forms a dense, clumpy, and limb-brightened elliptical ring (Cox et al. 2002; Tielens 2005), an adjacent photodissociation region (PDR), and a surrounding molecular cloud, all expanding with a typical velocity of ~ 20 km s $^{-1}$ (Cox et al. 1997; Latter et al. 2000; Bublitz et al. 2023). A simplified schematic of NGC 7027 as viewed from the side is shown in Fig. 1.

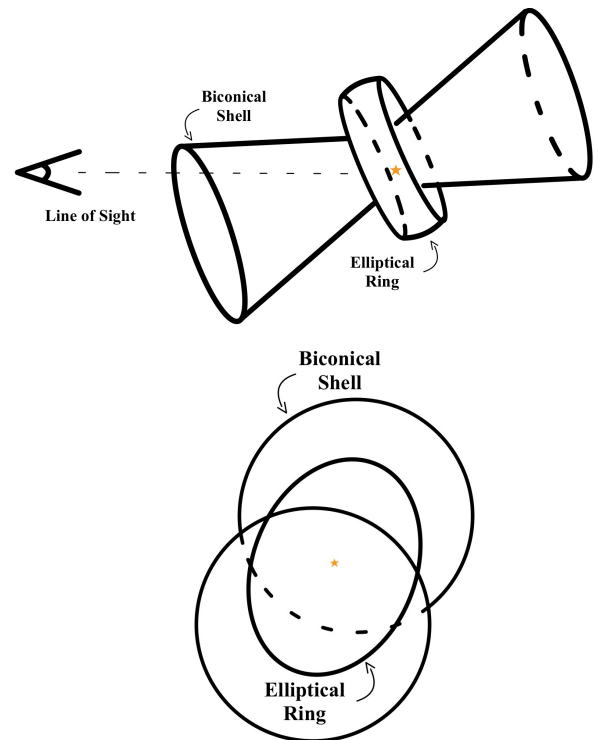


Fig. 1: Simplified schematic drawings of NGC 7027 as viewed from the side (top) and the front (bottom). The central star is shown in yellow. The H_2 emission lies primarily on the surface of the biconical shell, and is particularly bright along the rims, while the ionized gas and PAHs reside within the elliptical ring.

The H_2 morphology is remarkably different from the morphology of the ionized gas. The H_2 emission shows a four-lobed structure formed by a limb-brightened biconical shell (Fig. 2; Graham et al. 1993; Kastner et al. 1994). This hourglass-like shell is thought to be capped at both ends, producing the limb brightening observed in the outer rims of the bicone (Latter et al. 2000). The kinematics of the H_2 distribution reveal that the lower cone faces towards the line of sight and has an inclination angle of $i \sim 60^\circ$ and the upper cone faces away from the observer (Cox et al. 2002). There is enhanced H_2 emission in the equa-

torial waist due to limb brightening of the inner rims of the bi-conical shell (Latter et al. 2000; Cox et al. 2002). The asymmetry observed in the lobes is due to the presence of three bipolar outflows that, over time, have carved out holes in the H_2 distribution, the most pronounced being ‘Outflow 1’ at a position angle of -53° (Cox et al. 2002; Nakashima et al. 2010). Appendix A details the H_2 , ionized gas, and $6.2\ \mu\text{m}$ PAH emission as observed by JWST MIRI-MRS within the channel 1 field-of-view (CH1 FOV; Fig. A.1). The edges of the elliptical ring are pictured by the ionized gas and the $6.2\ \mu\text{m}$ PAH emission (which sits just outside the $H\ II$ region in the PDR), while the equatorial waist is delineated by the H_2 emission. The nebula seems to exhibit the typical layered PDR structure.

The CO emission, which traces the cold, dense material surrounding the PDR, sits further outside the H_2 emission and displays a roughly elliptical morphology with particularly bright edges in the NE and SW (Bublitz et al. 2023).

Narrow dust lanes are observed along the equatorial belt, and non-uniform dust filaments are observed surrounding the lobed and elliptical ring structures, most prominently around the north-east lobe (Kastner et al. 2020; Moraga Baez et al. 2023).

Outflow-driven shocks play an important role in the processing of ejected material and are thought to be a mechanism for very small grain and PAH formation in the PN via grain-grain collisions (Lau et al. 2016).

4. Observations, data reduction and analysis

We present JWST MIRI Medium Resolution Spectroscopy (MRS) Integral Field Unit (IFU, Wright et al. 2015; Wells et al. 2015; Wright et al. 2023; Argyriou et al. 2023) observations of NGC 7027 (program ID 01523, observation 1). A 3×3 mosaic was taken centred on the central star. The resulting spectral cubes cover a wavelength range of $4.9\text{--}27.9\ \mu\text{m}$ at a spectral resolution of $R \sim 1500\text{--}3500$ over a FOV of up to $9.8'' \times 8.5''$ depending on the channel (Fig. 2).

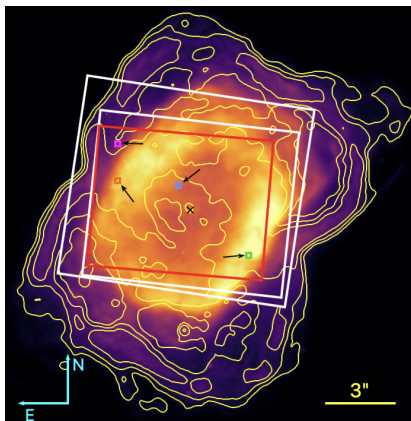


Fig. 2: HST/WFC3 NICMOS F212N image of NGC 7027 with JWST MIRI-MRS FOVs for channels 1 (red), 2, and 3 (white) overlaid. The black cross indicates the position of the central star. The yellow contours outline the H_2 gas morphology in the continuum-subtracted HST/NICMOS images from Latter et al. (2000). The small orange, pink, blue, and green boxes are the spaxels used to illustrate the AIB variability referred to hereinafter as the E ring, outer NE corner, inner region, and the SW ring, respectively. Credit: NASA/ESA, Latter et al. (2000).

We reduce the data using the JWST science calibration pipeline version 1.15.1 and the CRDS reference file context

1293. We used the default pipeline settings with the exception of performing a residual fringe correction in stage 2 of the pipeline and setting the output cube types to subchannels.

We use data from channels 1 to 3 ($4.9\text{--}18\ \mu\text{m}$). For comparative analysis, we use the pixel size of channel 3 ($0.2'' \times 0.2''$) and the FOV of the channel 1 mosaic ($7.5'' \times 6''$). We performed multiplicative stitching between subchannels to obtain the final spectra. We analyze individual spaxels and extract a spectrum across the channel 1 FOV, further referred to as the MIRI-MRS integrated spectrum (see Table B.1 for details).

We determine the dust continuum to extract the profiles of the 6.2 , $7.7\text{--}8.6$, and $11.2\ \mu\text{m}$ PAHs (see Appendix C for details) and classify their profiles based on the classification of Peeters et al. (2002a) and van Diedenhoven et al. (2004). To facilitate the discussion, we employ four spectra extracted in the apertures shown in Fig. 2 (see Table B.1), probing the NE corner - outside the elliptical ring (pink), the E side of the elliptical ring (orange), the central region (blue), and the SW portion of the elliptical ring (green).

5. Results

Overall, the PAH emission in the MIRI-MRS integrated spectrum (see Fig. D.1) of NGC 7027 resembles those reported in the literature (e.g., ISO-SWS; Peeters et al. 2002b; van Diedenhoven et al. 2004). However, due to the distinct extraction apertures ($7.5'' \times 6''$ for MIRI-MRS versus $14'' \times 20''$ for ISO-SWS), differences emerge upon close inspection of the spectral profiles (Fig. 3, Table E.1). The MIRI data reveals that the PAH emission varies systematically across the nebula.

5.1. Spatial Variation of the PAH Spectral Profiles

The spaxel spectra demonstrate wide PAH profile variation across NGC 7027 in each of the major features observed (Fig. 3). We investigate the profile class of the 6.2 , 7.7 , 8.6 , and $11.2\ \mu\text{m}$ PAH bands.

The spatial variations in PAH profile classes reveal a striking morphological pattern across NGC 7027. In the $6.2\ \mu\text{m}$ feature, the outer NE corner of the CH1 FOV (beyond the elliptical ring) is dominated by a strong class $\mathcal{A}$ profile, with a narrow profile peaking at $6.205\ \mu\text{m}$. Within the ring, however, this shifts to a clear class $\mathcal{B}$ profile, broader in shape and peaking at $6.24\ \mu\text{m}$. The central region presents an intermediate case: while the peak remains consistent with class $\mathcal{A}$, the band is noticeably broader than in the NE corner.

A similar progression is observed in the $7.7\ \mu\text{m}$ feature. In the NE corner, a class $\mathcal{A}$ profile is evident, where the $7.6\ \mu\text{m}$ component dominates over the $7.8\ \mu\text{m}$ band. In contrast, the ring exhibits a pure class $\mathcal{B}$ profile with a strong $7.8\ \mu\text{m}$ peak, while the inner region contains a mixture of intermediate class $\mathcal{AB}$ and class $\mathcal{B}$ profiles.

The $8.6\ \mu\text{m}$ feature follows the same spatial trend. A class $\mathcal{A}$ profile with a peak at $\sim 8.6\ \mu\text{m}$ is found in the NE corner, transitioning to a class $\mathcal{B}$ profile at $\sim 8.65\ \mu\text{m}$ within the ring, and reverting to class $\mathcal{A}$ profiles in the inner region.

Finally, the $11.2\ \mu\text{m}$ feature echoes this pattern. The NE corner again shows a class $\mathcal{A}$ profile at $11.2\ \mu\text{m}$, while the ring hosts class $\mathcal{B}$ profiles. The inner region, as with the $7.7\ \mu\text{m}$ band, displays a mixture of class $\mathcal{AB}$ and $\mathcal{B}$ profiles. Interestingly, scattered class $\mathcal{A}$ profiles are detected surrounding the H_2 emission (Fig. E.1). We explore the $11.2\ \mu\text{m}$ band in more detail and its relationship with the H_2 emission in the following section.

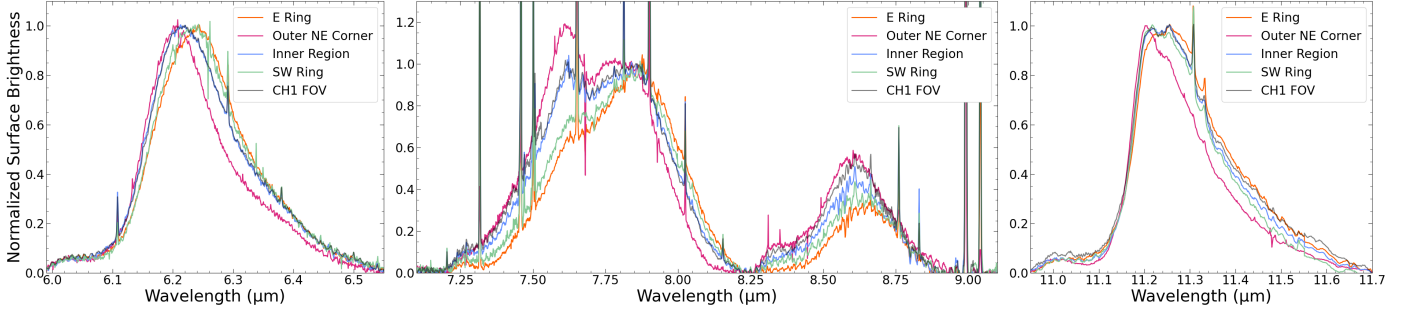


Fig. 3: Illustration of the 6.2, 7.9, and 11.2 μm profile variation across the nebula. The single spaxel spectra from Fig. 2 detailed in Table B.1 are utilized here.

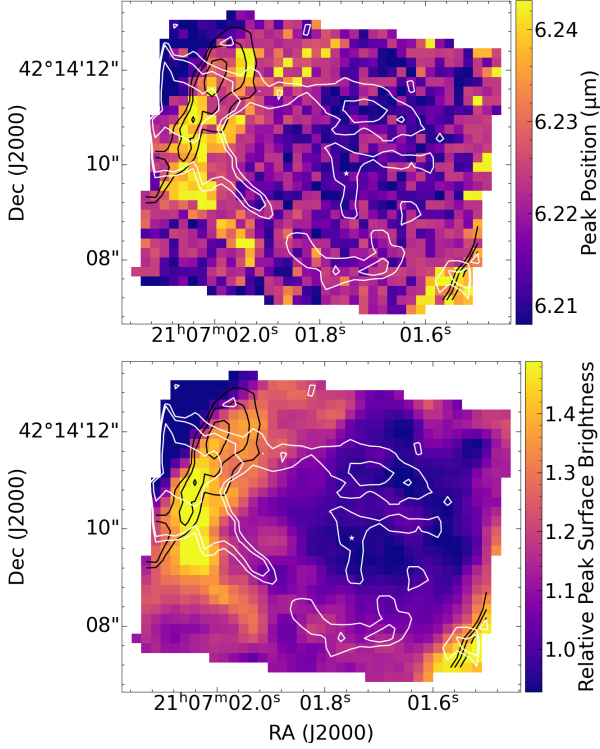


Fig. 4: Illustration of the profile variability with the peak position of the 6.2 μm PAH band (top) and the relative peak surface brightness of the 7.8 μm component with respect to the 7.6 μm component (bottom). Black and white contours represent the integrated 6.2 μm PAH surface brightness and the H_2 0-0 S(7) integrated surface brightness, respectively (Fig. A.1).

Summarizing, the spectral profiles of these four PAH bands (6.2, 7.7, 8.6, and 11.2 μm) display class $\mathcal{A}$, $\mathcal{AB}$, and $\mathcal{B}$ profiles which are linked to morphological structures within NGC 7027.

5.2. Disentangling the 11.2 μm Feature

The 11.2 μm feature is known to have at least two components, namely the 11.207 μm and 11.25 μm (Chown et al. 2024). Originally detected in the Orion Bar, the 11.207 μm is attributed to PAH emission while the broad 11.25 μm component is thought to be attributed to very small grains (VSGs) or PAH clusters (Chown et al. 2024; Pasquini et al. 2024; Khan et al. 2025). In the Orion Bar, the 11.25 μm VSG component is strongest in

the H_2 dissociation front and beyond. Following the method established by Khan et al. (2025), we isolated two components at 11.204 and 11.29 μm , referred to as the 11.207 and 11.25 μm components, respectively (see Appendix F for details).

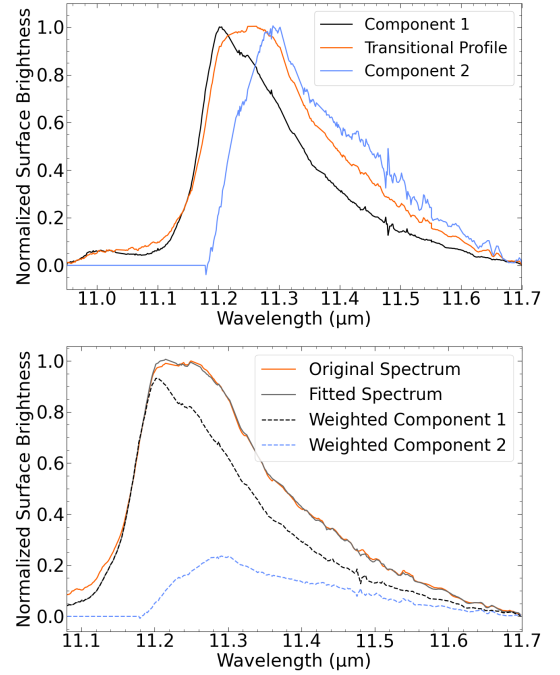


Fig. 5: Illustration of the 11.2 μm PAH band decomposition. Top: Normalized profiles of the first component, the narrowest profile, representing class $\mathcal{A}$, the broadest (transitional) profile representing class $\mathcal{B}$, and the second component used in the decomposition of the 11.2 μm feature. Bottom: Typical decomposition of the 11.2 μm band by components 1 and 2.

Spatial mapping (Fig. 6) reveals that the 11.207 μm component has a morphology akin to that of the 6.2 μm PAH feature, while the 11.25 μm component has a spatial distribution roughly resembling the H_2 morphology, similar to the Orion Bar observations, reinforcing that the 11.25 μm component is indeed distinct from the PAH emission.

5.3. Correlation Studies of the 6-9 μm Features

Motivated by the significant profile variation in the 6.2 and 8.6 μm features, we perform a similar decomposition as was done for the 11.2 μm band to investigate whether the variation arises from blending of two components. For the 6.2 μm feature,

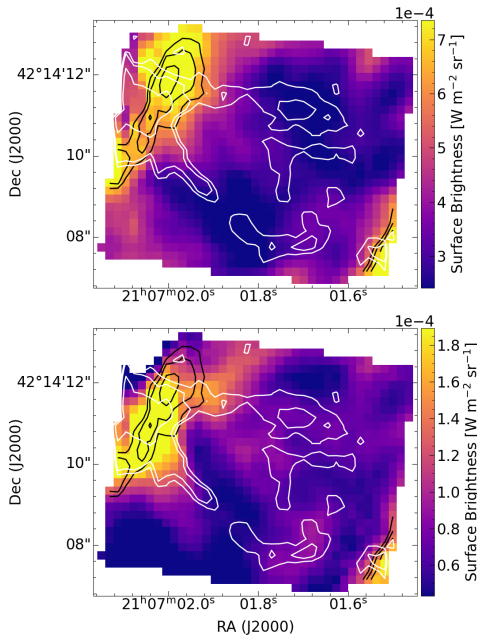


Fig. 6: Spatial maps of the integrated surface brightness of the 11.207 μm component (top) and of the 11.25 μm component (bottom). Contours are as in Fig. 4.

two components at 6.205 μm and 6.26 μm are successfully extracted and fit to reproduce all spectra (Fig. 7). The 6.205 μm component is the narrowest profile observed whilst the 6.26 μm component is extracted via subtraction of the 6.205 μm component from broadest profile observed. Fig. 8 shows two components successfully isolated from the 8.6 μm feature, at 8.56 and 8.65 μm . Here, the most red-shifted 8.6 μm profile is assigned as the first component and subtracted from the 8.6 μm profile exhibiting the most blue-shift to extract the second component. The weak 8.35 μm feature is extracted from the second component to isolate its emission. Details of the decompositions are found in Appendix F.

As the 7.6 and 7.8 μm components in the 7.7 μm feature trace class $\mathcal{A}$ versus class $\mathcal{B}$ PAH populations, a decomposition was performed to examine the spatial distribution of each component independently. To do so, we fit the 7–9 μm complex using four Gaussian components representing the 7.6, 7.8, 8.2, and 8.6 μm features, consistent with the approach of Peeters et al. (2017) and Stock & Peeters (2017), but adopting a broader 8.2 μm component. The data are well-modelled with these Gaussian components and the integrated surface brightnesses of each component are measured (see Appendix F for details).

Analysis of component correlations provides further insight into the PAH interrelationships. Correlation plots between the 6.2, 7.7, and 8.6 μm components reveal that the blue components of the 6.2 and 7.7 μm bands (6.205 and G7.6 μm) are strongly correlated but neither are closely correlated with the blue or red component of the 8.6 μm band (Fig. 9). The three red components of the 6.2, 7.7, and 8.6 μm features (6.26, G7.8, and 8.65 μm) show tight correlations with each other, but none demonstrate correlations with the 6.205 and G7.6 μm components. The 8.56 μm component demonstrates an anti-correlation with the red components of the 6.2 and 7.7 μm components and is, therefore, separate from all other components. We refer the reader to Fig. G.1 for the correlation coefficients between all 6–9 μm components.

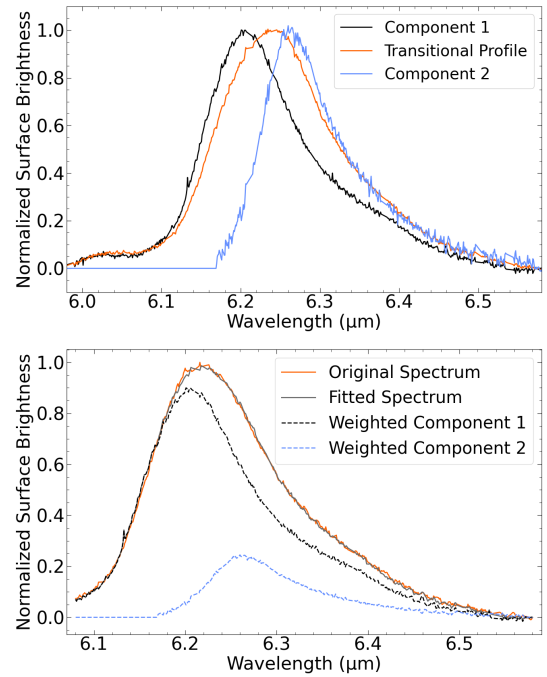


Fig. 7: Illustration of the decomposition of the 6.2 μm PAH band. Top: Normalized profiles of the first component, the narrowest profile representing class $\mathcal{A}$, the broadest (transitional) profile representing class $\mathcal{B}$, and the derived second component used in the decomposition. Bottom: Typical decomposition of the 6.2 μm PAH band with components 1 and 2.

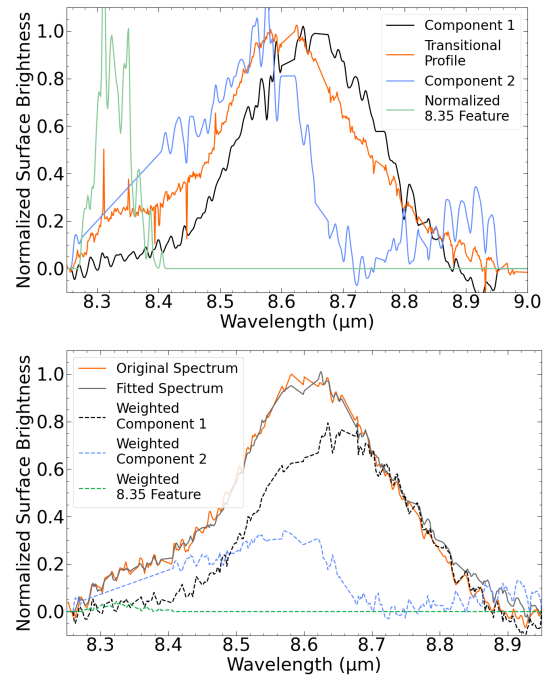


Fig. 8: Illustration of the decomposition of the 8.6 μm PAH band. Top: Normalized profiles of the red-shifted profile representing class $\mathcal{B}$ (the first component), the blue-shifted profile representing class $\mathcal{A}$ (the transitional profile), the derived second component used in the decomposition, and the extracted 8.35 μm feature. Bottom: Typical decomposition of the 8.6 μm PAH band with components 1 and 2, and the 8.35 μm feature.

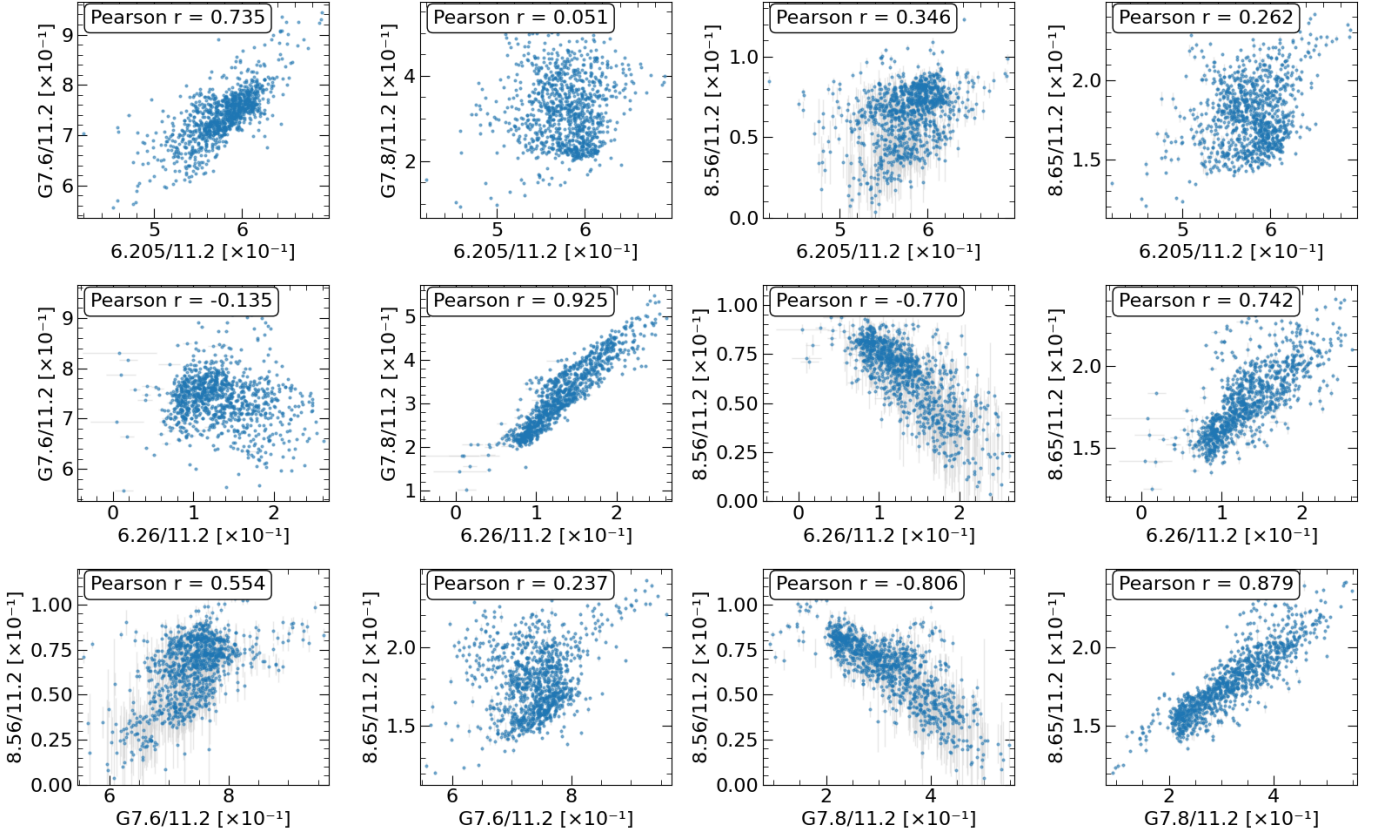


Fig. 9: Correlations between the 6.205, 6.26, G7.6, G7.8, 8.56, and 8.65 μm integrated component surface brightnesses normalized over the total 11.2 μm integrated surface brightness. Correlation coefficients are shown at the top and error bars are shown in light grey.

Examining component ratios (Fig. G.2) further highlights the uniqueness of the 11.25 μm component. The fractional contribution of the red component to the 6.2 (6.26/6.2), 7.7 (G7.8/7.7), 8.6 (8.65/8.6) ratios correlate strongly with each other, yet none correlate with the fractional contribution of the VSG component to the 11.2 (11.25/11.2), reinforcing the conclusion that the 11.25 μm emission arises from a carrier distinct from the carriers of the blue or red components of the 6.2, 7.7, and 8.6 μm PAH bands.

We thus find four distinct PAH subpopulations: the red 6–9 μm components (6.26, 7.8, 8.65 μm); the blue 6.205 and 7.6 μm components; the blue 8.56 μm component; and the 11.207 μm neutral PAH component. Additionally, the VSG/PAH cluster population is represented by the 11.25 μm component.

6. Discussion

6.1. Spectral friends

The correlation observed between the 6.2 and 7.7 μm blue components (6.205 μm and 7.6 μm) and the red components (6.26 μm , 7.8 μm , and 8.65 μm) of the 6.2, 7.7, and 8.6 μm PAH bands (Sec. 5) suggests that these components originate from two distinct PAH subpopulations, with a separate third subpopulation represented by the blue 8.56 μm component of the 8.6 μm feature. Understanding the underlying origin of these spectral relationships is crucial.

Ricca et al. (2021) reported that the 6.2 μm feature peaks at bluer wavelengths in elongated PAHs and at redder wavelengths in circular PAHs. Expanding on this result, Fig. 10 illustrates the 6.2 and 7.7 μm peak positions for a set of PAH molecules, offer-

ing insight into potential carriers of these emission components. We use the NASA Ames PAH Infrared Spectroscopic Database¹ version 4.0 (PAHdb; Bauschlicher et al. 2010; Boersma et al. 2014; Bauschlicher et al. 2018; Mattioda et al. 2020, Ricca et al. under review) to relate the peak positions of the 6.2 and 7.7 μm bands to their corresponding molecular structures for a collection of seven PAH species. Only cationic PAHs were selected because the 6.2 and 7.7 μm bands are dominated by PAH cations (Hudgins & Allamandola 1999). We further constrained the subset of species by limiting ourselves to PAHs with long straight edges containing adjacent C-H solo bonds (also denoted as zigzag edges) because the 11.2 μm feature, attributed to the solo C-H out-of-plane bending mode, dominates the 10–15 μm C-H out-of-plane bending modes features, indicating that compact species dominate the PAH family (Hony et al. 2001; Ricca et al. 2018, 2021).

We find that the PAHdb calculations of the 6.2 and 7.7 μm peak positions of these species span the full wavelength range covered by the 6.2 and 7.7 μm components in NGC 7027 and that the precise positions of these features are unique for specific PAH molecules. If these findings are confirmed by quantum chemistry studies on a larger set of astrophysically relevant species, the peak positions of the components contributing to the 6.2 and 7.7 μm features could prove to be a useful diagnostic of PAH molecules in space. Based on this small sample, species with a similar structure to $\text{C}_{62}\text{H}_{20}^+$ and $\text{C}_{78}\text{H}_{22}^+$ appear to be good candidates for the 6.205 and 7.6 μm components and molecules analogous to $\text{C}_{66}\text{H}_{20}^+$ are potential carriers of the 6.26 and 7.8 μm components. We do not exclude, however, the possi-

¹ <https://www.astrochemistry.org/pahdb>

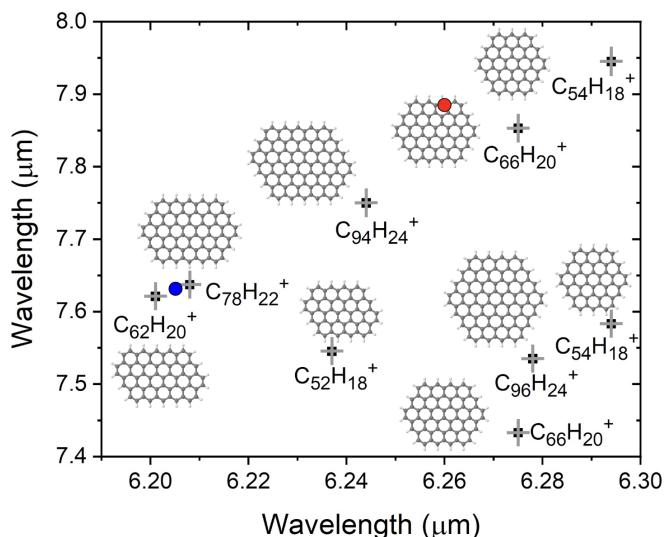


Fig. 10: The 6.2 and 7.7 μm peak positions of 7 cationic PAH species (data taken from Ricca et al. 2021). Uncertainties for the theoretical band positions, calculated in Mackie et al. (2016, 2018) and Lemmens et al. (2019), are shown by the grey error bars (for details see Appendix I). The blue and red circles represent the observed peak positions of the blue and red components of the 6.2 and 7.7 μm bands in NGC 7027, respectively.

bility that each subpopulation originates not from a single PAH species but is instead made up of a group of PAH species sharing similar spectral characteristics whose modes blend together into a single component. We do realize that the photochemical behaviour of these putative species will have to be very similar as well to preserve the good correlations observed while the PAH population is being processed by the strong radiation field.

Previous studies link these PAH components to structural characteristics. For instance, Peeters et al. (2017) attributed the G7.6 μm component to compact, cationic, small PAHs and the G7.8 μm component to neutral, very large PAHs or PAH clusters. However, our results here are inconsistent with these findings. We instead see the G7.8/G7.6 μm ratio map (Fig. H.2) closely resembles the 6.2/11.207 ratio map (Fig. H.1), a known tracer of the ionic to neutral PAH ratio. This suggests instead that the conditions that favor the G7.8 μm component also favor charged PAHs, while the conditions that favor neutral PAHs also favor the G7.6 μm component. However, the C-C stretching modes are very weak in neutral PAHs (Hudgins & Allamandola 1999) and such species are not expected to contribute major features to the 6–9 μm range (Oomens et al. 2003; Bauschlicher et al. 2008). It is likely that these variations have no connection with PAH charge but instead with both PAH size and structure (Bauschlicher et al. 2008, 2009). It has been suggested that a red peak position of the 7.7 μm band is indicative of PAHs with ~ 96 –130 C (Langhoff 1996; Bauschlicher et al. 2008; Joblin et al. 2008; Bauschlicher et al. 2009), albeit a few smaller sized PAHs also show a red 7.7 μm band (see e.g., Fig. 10). We do not see such a trend in the small subset of PAHs included in Fig. 10 due to its limited sample and size range.

Density Functional Theory (DFT) studies imply that the intrinsic strength of the 8.6 μm in-plane C-H bending mode is a strong function of the PAH size and molecular structure (Bauschlicher et al. 2008, 2009; Ricca et al. 2012). Comparison of these quantum chemistry studies with observations imply that the 8.6 μm band is carried by a subset of compact PAHs with

sizes in the range ~ 96 –150 C atoms. Irregular or smaller compact PAHs do not show a very distinct 8.6 μm band while very large compact PAHs (> 150 C atoms) show an 8.6 μm band that is much too strong compared to the C-C modes.

Given the 6.205 and 7.6 μm components have no clear 8.6 μm counterpart, this serves as an indication that these blue components originate from medium-sized, asymmetric PAHs, consistent with Ricca et al. (2021). However, medium-sized asymmetric PAHs may be carriers of the weak 8.35 μm feature since these PAHs have intrinsically weak C-H in-plane bending modes. Unfortunately, as the 8.35 μm feature is a weak band perched on the side of the much stronger 8.6 μm feature, it is difficult to ascertain a strong link between the 8.35 μm feature and the 6.205 and 7.6 μm components. The subpopulation traced by the red components (6.26, 7.8, and 8.65 μm) is likely composed of compact PAHs within the ~ 96 –150 C-atom size range, which is set by the 8.65 μm band. We note that the PAHs shown in Fig. 10 exhibit C-H in-plane bending emission shortwards of 8.5 μm . The anti-correlation observed between the 8.56 μm component and the red components of the 6.2 and 7.7 μm features indicate that the same conditions that favour the 6.205 and 7.6 μm , hamper the 8.56 μm . The lack of correlation with any other component suggests that perhaps the 8.56 μm component stems from PAHs that are very large (> 150 C atoms). In very large PAHs, the positive charge per carbon is very small and they behave more like neutrals, which have insignificant 6.2 and 7.7 μm emission (Ricca et al. 2012).

Since the 3.3/11.2 PAH band ratio is a known diagnostic of PAH size (e.g., Allamandola et al. 1989; Pech et al. 2002; Ricca et al. 2012), future observations of NGC 7027 including the 3.3 μm feature would prove useful in linking the PAH size across the nebula to the variations found in this analysis of the 6.2, 7.7, and 8.6 μm features.

6.2. PAH clusters & VSGs - Identity crisis of class $\mathcal{B}_{11.2}$

The 6.2, 7.7, and 8.6 μm PAH bands exhibit class $\mathcal{A}$, $\mathcal{AB}$, and $\mathcal{B}$ profiles across the nebula. However, the variation in the 11.2 μm band is dominated by the contribution from the newly identified 11.25 μm component, extracted here for the first time in a PN. As was demonstrated in Sec. 5, this component behaves distinct from the PAH emission. Our results are consistent with the assignment of the 11.25 μm emission to PAH clusters and/or very small grains (VSGs) put forward by Chown et al. (2024), Pasquini et al. (2024), and Khan et al. (2025). Consequently, it is difficult to interpret the variation in the 11.2 μm feature as a shift in PAH spectral class since the 11.25 μm component overshadows any subtle profile variations towards class $\mathcal{B}$. In fact, this component calls into question the existence of the 11.2 μm class $\mathcal{B}$ profile defined in van Dienenhoven et al. (2004), as it is tarnished by the VSG contribution. The unique behaviour of the class $\mathcal{B}_{11.2}$ was already noted in van Dienenhoven et al. (2004), where it was observed that class $\mathcal{B}_{11.2}$ differs from class $\mathcal{B}_{6-9}$. The recent discovery of the 11.25 μm component perhaps provides an explanation for the anomalous behaviour of the $\mathcal{B}_{11.2}$.

6.3. PAH evolution

The spatial distribution of PAH spectral classes observed within the nebula (Sec. 5) has the potential to provide valuable insights into the evolutionary processing mechanisms acting upon PAHs. Class $\mathcal{B}$ profiles appear predominantly in the elliptical ring, while class $\mathcal{A}$ profiles appear in the region external to

the ring. We propose that the primary mechanism responsible for processing these PAHs is the star's intense UV radiation (e.g., Cox et al. 2002; Moraga Baez et al. 2023). Consequently, these results suggest that the class $\mathcal{B}$ PAHs are the material processed by UV radiation, while the class $\mathcal{A}$ PAHs are unrefined and shielded from such energetic interactions. This is a slightly different scenario than originally suggested by Peeters et al. (2002b) in which PAHs are injected by PNe into the ISM as class $\mathcal{B}$ and the conversion to class $\mathcal{A}$ occurs in the ISM, driven by the harsh radiation field. We emphasize, though, that the 5 – 15 μm spectra analyzed here are very consistent with predominantly aromatic materials (cf., Fig. 10). Near-infrared observations may provide insight into whether the photochemically-driven loss of small PAHs in NGC 7027 is accompanied by a loss of aliphatic material as seen in some post-AGB objects Goto et al. (2003, 2007).

We reconcile our results with earlier studies where class $\mathcal{A}$ is observed in the ISM and class $\mathcal{B}$ PAHs in PNe and protoplanetary disks as follows. In PNe, most of a star's initial mass is expelled during the AGB phase. The majority of this ejected material will never be processed by the star's harsh UV radiation or shocks, preserving its original, pristine state as it migrates into the ISM. PAHs in the ISM will, therefore, retain their original class $\mathcal{A}$ spectral profiles, consistent with PAH observations in the ISM. Conversely, despite the cooler temperatures in protoplanetary disk environments, the class $\mathcal{B}$ profiles observed could be linked to the strong radiation fields incident on these disks, effectively processing the PAH population.

Theoretical studies show that shocks can also process the circumstellar and interstellar PAH family (Micelotta et al. 2010). The circumstellar environment of NGC 7027 is heavily processed by the jet(s) emanating from the star(s) (Lau et al. 2016; Bublitz et al. 2023). However, the regions most heavily processed fall outside of the FOV of these observations. Future observational studies could be instrumental in testing these models and elucidating the effects of shocks on the PAH family in space.

7. Conclusions

We present, for the first time, high-resolution spectral data of the mid-IR PAH emission in NGC 7027 from JWST MIRI-MRS spectral cubes. Our findings are as follows:

1. We report the first observation of PAH spectral profile changes over different classes (here $\mathcal{A}$, $\mathcal{AB}$, and $\mathcal{B}$) in each of the major features observed (6.2, 7.7, 8.6, and 11.2 μm) within a single extended target.
2. We decompose the 6.2 μm feature into two new components at 6.05 and 6.26 μm , the 7.7 μm feature into two Gaussian components: G7.6 and G7.8 μm , and the 8.6 μm feature into two components at 8.56 and 8.65 μm . Correlation plots reveal that the 6.05 and G7.6 μm components are strongly correlated and the red components of the three features (6.26, G7.8, and 8.65 μm) exhibit a tight correlation, while no correlation is observed between the red and blue components of the features. The 8.56 μm component is not observed to have a strong relationship with any of the other components. We, therefore, hypothesize that these components represent three distinct PAH subpopulations, with the blue 6.2 and 7.7 μm components belonging to medium-sized asymmetric PAHs (like e.g. $\text{C}_{62}\text{H}_{20}^+$), the red 6.2, 7.7, and 8.6 μm components to large (96–150 C atoms), compact symmetric PAHs and the 8.56 μm component to very large PAHs (≥ 150 C atoms).

3. A successful decomposition is performed of the 11.2 μm band into its two formerly reported components: 11.207 and 11.25 μm (Pasquini et al. 2024; Khan et al. 2025). We confirm that these components behave similarly in NGC 7027 as in previous studies of the Orion Bar, in which the 11.207 μm component represents the neutral PAH emission and the 11.25 μm component represents unique emission potentially from VSGs or PAH clusters, thus, casting doubt on the existence of the class $\mathcal{B}$ 11.2 μm profile as described by van Diedenoven et al. (2004). The 11.2 μm band shows no clear counterpart to the red/blue components observed in the 6.2, 7.7, and 8.6 μm bands, nor is any link found between these components and the 11.25 μm component.
4. Class $\mathcal{B}$ profiles are observed in the elliptical ring closer to the harsh UV radiation whereas class $\mathcal{A}$ profiles are detected further outside the ring. The profile variations across NGC 7027, therefore, indicate that class $\mathcal{A}$ PAH profiles presumably originate from less refined PAHs and that the class $\mathcal{B}$ PAH emission arises from more processed PAH species. This implies that the majority of PAHs present in PNe enter the ISM as class $\mathcal{A}$, shifting the perception of the evolution of PAH profile classes throughout the PAH lifecycle.

Future spectroscopic work needs to be done to investigate the origin of the different PAH feature components and profile classes. Additional high-resolution spectral data from NGC 7027 and other PNe would help in disentangling the nature of PAHs in the early phases of their evolution.

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Appendix A: NGC 7027 Morphology

The morphological structures in the MIRI MRS CH1 FOV of NGC 7027 are demonstrated by the integrated surface brightness maps of the H I recombination line Pfund α ($n=6-5$), 6.2 μm PAH feature, and the H₂ 0-0 S(7) emission line, shown in Fig. A.1. The Pfund α emission traces the H II region which has the form of an elliptical shell. The 6.2 μm PAH emission sits just outside of the Pfund α emission and traces the atomic PDR, and morphologically resembles the ionized gas. Finally, the H₂ emission outlines the surface of the molecular PDR.

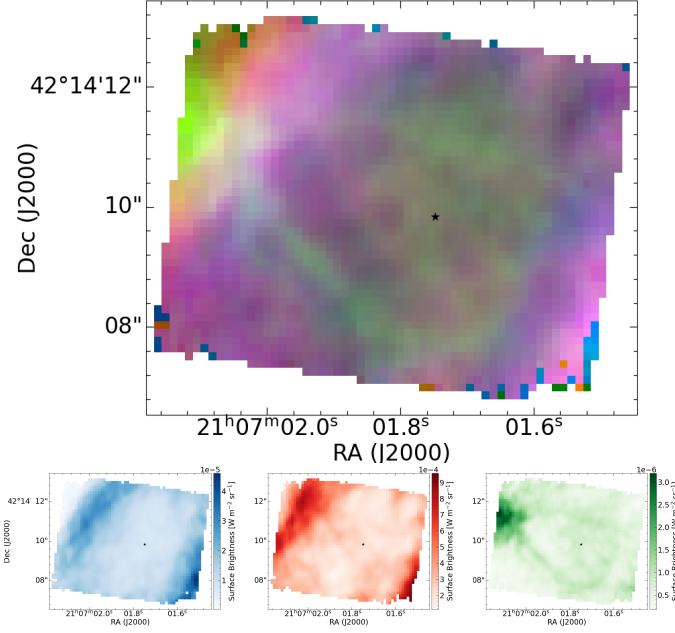


Fig. A.1: Three-colour image of the 6.2 μm PAH feature (red), H₂ 0-0 S(7) emission line (green), and the Pfund α ($n=6-5$) emission line (blue) integrated surface brightness RGB maps in the NGC 7027 MIRI CH1 FOV (top). The individual integrated surface brightness images are shown in the bottom panels.

Appendix B: Extraction Apertures

We utilize five extraction apertures in this study for the MIRI-MRS spectral cube and reference the ISO-SWS data. The information about the position and size each of these is given in Table B.1. The MIRI-MRS data have a position angle of 74.67° .

Table B.1: Information about the NGC 7027 extraction apertures utilized. Right ascension and declination (J2000) are given in [21:07:ss.ss] and [+42:14:ss.ss] respectively.

Aperture	RA (ss.ss)	Dec (ss.ss)	Size ("×")
ISO-SWS FOV ¹	01.70	09.10	14×20
MIRI-MRS CH1 FOV	01.802	10.01	7.5×6.0
Outer NE Corner Pixel	02.044	12.56	0.2×0.2
E Ring Pixel	02.044	10.96	0.2×0.2
Inner Region Pixel	01.810	10.76	0.2×0.2
SW Ring Pixel	01.540	07.76	0.2×0.2

¹ Target Dedicated Time (TDT) number is 55800537.

Appendix C: Continuum determination

In order to isolate the PAH emission, the rising dust continuum emission and the emission from other contributors must be removed from the spectra. To trace out the continuum emission, we place anchor points at wavelengths solely probing the dust continuum emission and on either side of each PAH band. We estimate the continuum emission for the MIRI-MRS spectral cube in two ways: one version has anchor points at 8.225 and 8.25 μm and another without anchor points around 8.2 μm (Fig. C.1). In addition, we fit both spectra with a plateau (PL) continuum, which is simply a linear fit between any two specified points and a spline curve (global spline, GS) elsewhere. The PL continuum is used to fit linearly underneath the main PAH features to avoid unusual effects from the spline curve which artificially augment or diminish the strength of the PAH emission. We thus use these PL continua for all plots and analysis. Following the original classification of Peeters et al. (2002a), we use the PL continuum with anchor points at $\sim 8.2 \mu\text{m}$ for the profile classification of the 7.7 and 8.6 μm PAH bands. For all other analyses, the PL continuum without the anchor points at $\sim 8.2 \mu\text{m}$ is used.

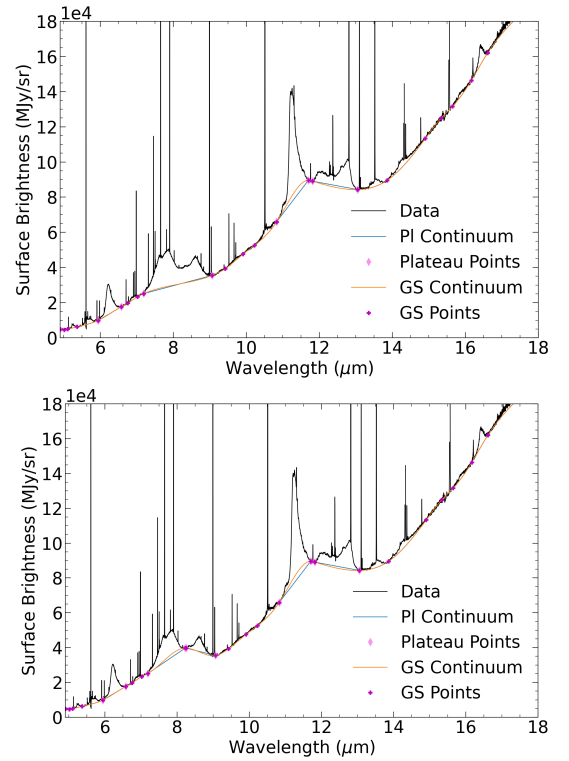


Fig. C.1: Illustration of the global spline (GS, orange) and plateau (PL, green) continuum without (top) and with (bottom) an anchor point near 8.2 μm for the MIRI-MRS integrated spectrum of NGC 7027.

Appendix D: PAH Profile Classes of the MIRI-MRS Integrated Spectrum of NGC 7027

Fig. D.1 shows the MIRI-MRS integrated spectrum of NGC 7027 along with archetypal spectra for PAH profile classes $\mathcal{A}$ and $\mathcal{B}$ for each of the 6.2, 7.7, 8.6, and 11.2 μm features. The MIRI integrated spectrum shows a mix of PAH profile classes. The 6.2 and 8.6 μm PAH profiles exhibit a class $\mathcal{A}$ profile whereas the 7.7 and 11.2 μm features show a class $\mathcal{AB}$ profile.

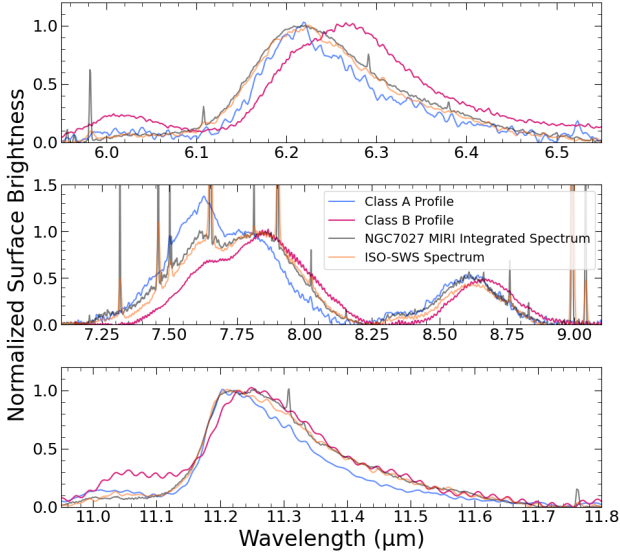


Fig. D.1: The MIRI-MRS integrated spectrum of NGC 7027 along with the PAH profile class $\mathcal{A}$ (blue) and $\mathcal{B}$ (red) for the 6.2, 7-9, and 11.2 μm features (exemplified by IRAS 23133+6050 and HD 44179 respectively; taken from Peeters et al. 2002a; van Diedenhoven et al. 2004).

Table E.1: Overview of the PAH spectral classes in NGC 7027.

Class	Position (μm)	FWHM (μm)	Region
6.2 μm PAH			
$\mathcal{A}$	6.19-6.23	~ 0.14	ISO-SWS ^b , Outer NE Corner
$\mathcal{AB}$	6.19-6.23	~ 0.165	MIRI-MRS ^a , Inner Region
$\mathcal{B}$	> 6.24	~ 0.165	E Ring, SW Ring
7.7 μm PAH			
$\mathcal{A}$	~ 7.6	–	Outer NE Corner
$\mathcal{AB}$	~ 7.6 and ~ 7.8	–	MIRI-MRS ^a , Inner Region
$\mathcal{B}$	~ 7.8	–	ISO-SWS ^b , E Ring, SW Ring
8.6 μm PAH			
$\mathcal{A}$	8.58-8.62	–	MIRI-MRS ^a , Outer NE Corner, Inner Region
$\mathcal{B}$	> 8.62	–	ISO-SWS ^b , E Ring, SW Ring
11.2 μm PAH			
$\mathcal{A}$	11.20-11.24	~ 0.17	Outer NE Corner
$\mathcal{AB}$	11.20-11.24	~ 0.21	ISO-SWS ^b , SW Ring
$\mathcal{B}$	~ 11.25	~ 0.20	MIRI-MRS ^a , E Ring, Inner Region

Notes. ^(a) MIRI-MRS spectrum integrated over channel 1 FOV (see Fig. 2). ^(b) FOV of $14'' \times 20''$.

Appendix E: Profile Variability Across NGC 7027

Table E.1 demonstrates the rich variety of the PAH spectral characteristics of the ISO-SWS, MIRI-MRS, and spaxel apertures of NGC 7027 (Fig. 2; Table B.1). The outer NE corner is consistently characterized by class $\mathcal{A}$ profiles, while the E and SW ring are consistently characterized by class $\mathcal{B}$ profiles, with the

exception of the 11.2 μm spectrum in SW ring, which is class $\mathcal{AB}$. The spectra of ISO-SWS, MIRI-MRS, and the inner region, exhibit variation in spectral classes across the distinct PAH bands.

The 6.2 and 11.2 μm profile FWHMs across the nebula are measured. Fig. E.1 displays the changes in the profile widths across NGC 7027. Interestingly, the FWHM map of the 11.2 μm feature roughly follows the H_2 contours.

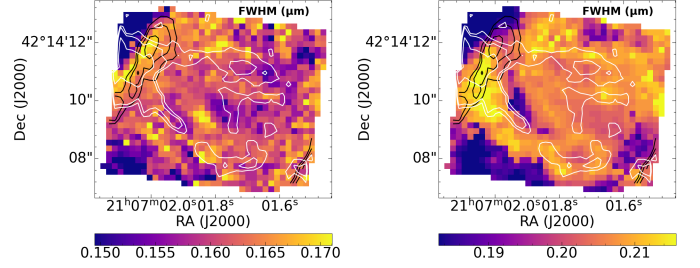


Fig. E.1: Profile width variability of the 6.2 (left) and 11.2 μm (right) features. Contours are as in Fig. 4.

Appendix F: Feature Decompositions

Motivated by the decomposition performed on the 11.2 μm band by Khan et al. (2025), the 6.2 μm band is decomposed using the same method. We use the narrowest profile in the MIRI-MRS cube at 6.205 μm as the first component, and subtract this (scaled) component from the broadest profile in our mosaic to reveal component 2 which has a peak position of 6.26 μm (Fig. 7). Subsequently, we fit the 6.2 μm profile at each spaxel with a linear combination of these two components. This decomposition accurately models the 6.2 μm profiles observed in the mosaic (Fig. 7). The integrated surface brightnesses of each component are measured and used for analysis.

To reveal the contribution from each of the main PAH features within the 7-9 μm complex across the nebula, we fit the 7-9 μm complex using four Gaussian profiles to model the emission from the 7.6, 7.8, 8.2, and 8.6 μm features following the method used in Peeters et al. (2017) and Stock & Peeters (2017). We follow the methodology employed by Stock & Peeters (2017) to determine the peak position and FWHM of these Gaussians. The fitting routine tends towards a broad G8.2 component, rather than a narrow G8.2 (as done by Peeters et al. (2017) and Stock & Peeters (2017)). Subsequently, we fix the peak position (FWHM) to 7.636 (0.354), 7.889 (0.215), 8.042 (0.853), and 8.625 (0.305) μm , while we allow the amplitude to vary for each spectrum. We obtain very good fits to the spectra using a broad G8.2 component as shown in Fig. F.1, where the 8.2 μm component seems to represent both the 8.2 μm feature employed by these authors and the underlying 7-9 μm plateau upon which these four PAH bands sit.

Given the variation in the 8.6 μm profiles, we perform a similar decomposition on this feature as done for the 6.2 μm band to reveal the potential underlying components. Here, we use the most red-shifted profile in the MIRI-MRS cube at 8.65 μm as the first component, and subtract this (scaled) component from the profile exhibiting the largest blue-shift to uncover component 2 with a peak position of 8.56 μm (Fig. 8). We extract the 8.35 μm feature which sits on top of the 8.56 μm component by subtracting a linear continuum underneath it. Subsequently,

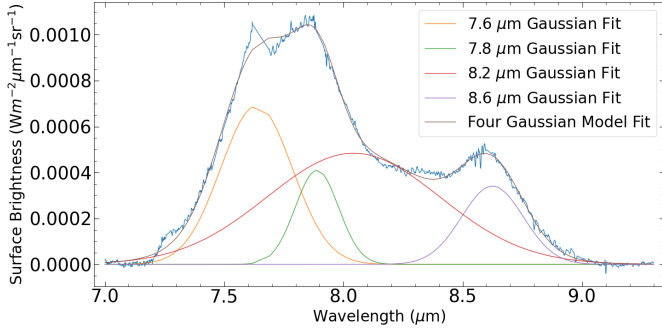


Fig. F.1: Four-Gaussian decomposition of the 7-9 μm complex employing a broad G8.2 profile for an example spectrum. Components are G7.6, G7.8, G8.2, and G8.6 μm .

we fit the 8.6 μm profile at each spaxel with a linear combination of these two components and the 8.35 μm feature. The observed 8.6 μm profiles are well-modelled and the integrated surface brightnesses of each component are utilized for analysis.

Following the method in Khan et al. (2025), we consider the narrowest 11.2 profile in our mosaic as the primary component, which peaks at 11.204 μm , whereas in the OB the 11.207 μm component peaks at 11.20 μm . Second, we consider the broadest 11.2 profile in the spectral cube and subtract the scaled component 1 to obtain component 2, namely the 11.25 μm component, which peaks at 11.29 μm in NGC 7027 and in the OB (Khan et al. 2025). It is important to note that the primary component found here in NGC 7027 is broader than that of the OB, likely due to residual contamination from the secondary component, even in the narrowest profile. We attribute the slight differences in peak position to the decomposition method. Since the widest profile in NGC 7027 is broader than the widest profile in the OB, the 11.25 μm component here is also slightly broader than in the OB.

Using a linear combination of these two weighted components, we successfully decompose the 11.2 μm profile of each spaxel in the mosaic (see Fig. 5) and subsequently integrate the components to measure their integrated surface brightness spatially.

Appendix G: Feature Correlations

The heat-map highlighting the Pearson correlation coefficients between the 6-9 μm components is shown in Fig. G.1. All features are normalized over the 11.207 μm PAH component to remove any correlative behaviour that is simply due to the contribution of the total PAH emission since we aim to uncover the underlying relationships between PAH components.

Figure G.2 shows no significant correlation between 11.25 and the red components of the 6.2, 7.7, and 8.6 μm features. On the other hand, the 6.26, G7.8, and 8.65 μm components demonstrate tight correlations with each other. Therefore, these plots serve as another indication that the 11.25 μm component exhibits unique behaviour from the PAHs, while the 6.26, 7.8, and 8.65 μm components belong to the same PAH subpopulation.

Appendix H: PAH Band Ratio Maps

The ratio of the integrated surface brightness of PAH bands are calculated to reveal the relative strength of the features spatially. In particular, we calculate the 6.2/11.207 PAH band ratio since this ratio is a known tracer of PAH charge. We use the

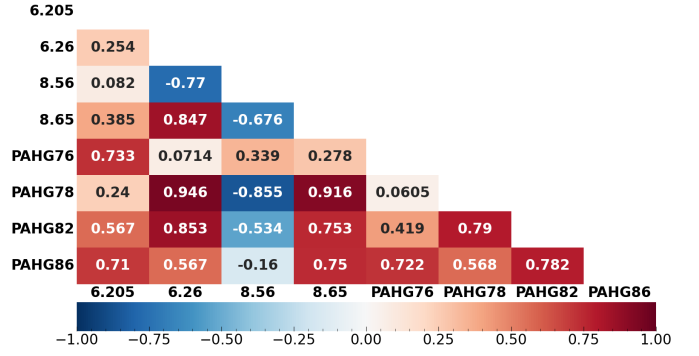


Fig. G.1: Heat-map demonstrating the strength of correlations between the 6-9 μm components when normalized to the 11.207 μm PAH component, where the intersection between two components displays their correlation coefficient. Redder boxes indicate a strong correlation, bluer boxes indicate a strong anti-correlation, and light boxes are present when there is little-to-no correlation.

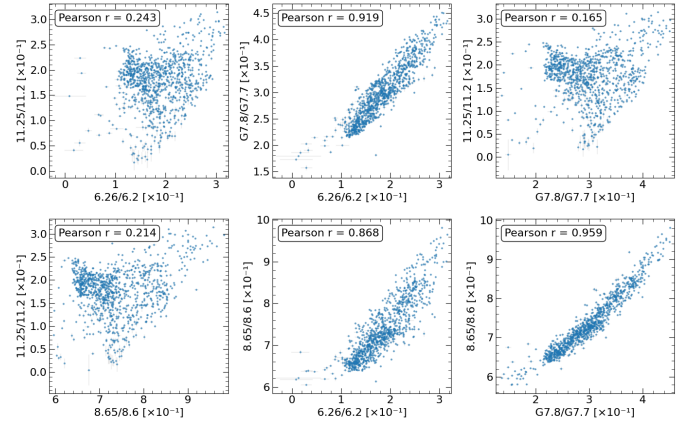


Fig. G.2: Correlation plots between the 6.26, 7.8, 8.65, and 11.25 μm components normalized over their feature totals. The Pearson correlation coefficient is shown in the top left corner of the plots. Error bars are shown in light grey.

11.207 μm component since it contains only the PAH contribution to the 11.2 μm , without significant contamination from the 11.25 μm VSG/cluster component. The map reveals that, in general, the ionic PAHs dominate in the ring more than anywhere else. The ratio map of the G7.8/G7.6 PAH components is calculated and reveals a roughly co-spatial relationship with the 6.2/11.207 map.

Appendix I: Theoretical 6.2 and 7.7 μm Band Positions

For a set of small PAHs, the mid-infrared (5-18 μm) region has been studied in a cold molecular beam and modeled using anharmonic theory (Lemmens et al. 2019). Comparison between the FELIX free-electron laser experimental spectra and second-order vibrational perturbation theory calculations shows agreement in peak positions within $\sim 0.5\%$, on average. Given that the FELIX bandwidth is $\sim 1\%$ of the photon energy, the theoretical values may in some cases be more accurate than the experimental determinations.

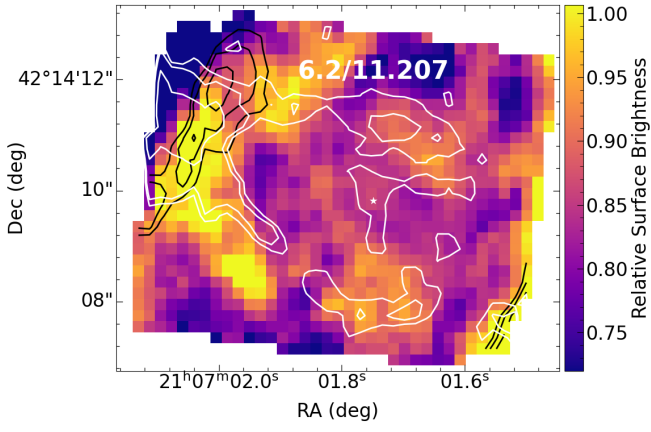


Fig. H.1: Spatial map of the 6.2 μm feature over the 11.207 μm component ratio. Contours are as in Fig. 4.

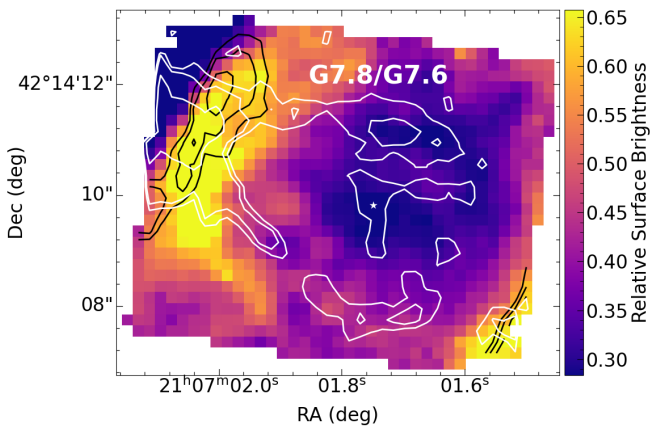


Fig. H.2: Spatial map of the G7.8 μm component over the G7.6 μm component ratio. Contours are as in Fig. 4.