PAH and H$_2$ emission in the Ring Nebula

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Abstract.

This paper presents the Spitzer IRS (Infra Red Spectrograph) detection of mid-infrared polycyclic aromatic hydrocarbon (PAH) emission features and H$_2$ associated with dense knots in the ring of the “oxygen-rich” (C/O $\sim$ 0.6–0.8) planetary nebula (PN) NGC 6720 (Ring Nebula). We explored a further three oxygen-rich extended PNe with similar dataset available. These turned out to be non-detection of PAHs, although two of these do contain H$_2$ emission knots. The presence of PAHs is discussed in the context of a bottom-up formation mechanism, in which first small hydrocarbons, and later PAHs, are formed in warm dense knots inside the ionised regions of PNe.

1. Introduction

Polycyclic aromatic hydrocarbons (PAHs) are expected to be formed and processed in the circumstellar envelopes of evolved stars such as asymptotic giant branch (AGB) stars and (proto)-planetary nebulae (PNe). The processes related to PAH formation in oxygen-rich or carbon-rich environments are not known precisely, and both top-down or bottom-up formation scenarios have been proposed. Generally, silicate dust formation is related to oxygen-rich winds, while carbonaceous dust formation occurs primarily in carbon-rich winds. However, in several cases both oxygen-rich and carbon-rich dust features are seen in infrared spectra of PNe [1, 2]. For currently carbon-rich PNe the presence of dual-dust chemistry within the system can be explained by turning from oxygen-rich to carbon-rich along the evolution. Silicate dust was formed earlier when the star was oxygen-rich, and eventually the star became carbon-rich, enabling to form carbon-rich dust [3]. For PAHs observed in oxygen-rich Galactic Bulge PNe [1, 4, 5] this scenario is less satisfactory, and it is has been proposed that PAHs in these objects are formed in-situ in an UV-irradiated dense torus [3, 6]. In this scenario, CO is dissociated by UV photons, producing free carbon which through chemical production of hydrocarbons leads to the formation of PAHs. We explore this scenario by revisiting mid-infrared spectral imagery of several oxygen-rich, extended PNe.

2. Spitzer IRS maps

We reinvestigate 4 oxygen-rich (C/O $<$ 1) PNe (Table 1) for which IRS-SH Map observations are available from the Spitzer Science Archive. The IRS-SH footprints are shown on Legacy...
Table 1. PNe observed with *Spitzer* in *IRS-SH Map* mode.

| Target Name | Size (") | C/O  | PAHs? | H2?  | C/O references: | PAH references: | H2 references: |
|-------------|----------|------|-------|------|-----------------|-----------------|----------------|
| NGC 2346    | >55 x 55 | 0.35 | no    | yes  | [9, 10, 11]     |                  |                |
| NGC 2392    | 44 x 44  | 0.41 | no    | yes  | [9, 11, 8] (this work) |                |                |
| NGC 6720    | 68 x 98  | 0.62, 0.82 | yes  | yes  | [12, 13, 14, 15] |                |                |
| NGC 7009    | 24 x 32  | 0.32 | no    | no   |                 |                  |                |

Angular sizes are determined from HST images.

Archive HST images in Figure 1. The spectral cubes cover the range from 10–19.6 µm, with a spectral resolving power of ∼600 [7]. For NGC 6720 a low-resolution IRS-SL spectrum was also retrieved from the archive. PAH emission was detected in NGC 6720 [8], but *not in any of the other three* PNe (c.f. Figure 2). In the next sections we focus on the 11.3 µm PAH and H2 emission detected in the main dust ring of NGC 6720.

Figure 1. *Spitzer IRS-SH* footprints are shown on top of HST/WFPC2 Hα images of the 4 selected PNe (c.f. Table 1).

3. PAH emission in NGC 6720

The 10–13.5 µm mid-infrared spectra for two PNe, NGC 2346 and NGC 6720 are shown in Figure 2. The 11.3 µm PAH emission feature is clearly detected at the position of the main ring of NGC 6720 [8]. Note the presence of numerous strong forbidden emission lines, highlighting the necessity of sufficiently high spectral resolution observations. Although we searched for PAH bands at 6.2 and 7.7 µm in the Spitzer IRS-SL spectra, there was no evidence for these bands. They are however of insufficient quality to set constraining upper limits. A similarly peculiar PAH spectrum, with a relatively strong 11.3 µm band, but weak 6.2 and 7.7 µm bands, is observed for the Horsehead H II region [16]. The integrated line intensity of the 11.3 µm PAH band (normalised to the total integrated infrared emission) is consistent with that expected from the C/O ratio of 0.6 [9]. The 11.3 µm PAH emission band profile in NGC 6720 is compared with other environments, such as NGC7027, Horsehead H II region, and M2-9 (Figure 3). The 11.3 µm PAH band in NGC 6720 reveals a pronounced red wing, similar to that of the Horsehead.

4. H2 knots in NGC 6270

Many PNe show evidence for 2.12 µm H2 emission from *photo-dissociation regions* (PDRs) associated with dense knots in their ionised regions [12]. Examples include NGC 2346 [15],
NGC 7293[17], and NGC 6720[13]. The Spitzer IRS SL and SH spectra (overlapping in the north-east part of the ring) provide line intensities for S(1) to S(4) H$_2$ rotationally excited lines. From the H$_2$ rotational diagram we obtain a molecular hydrogen density, N(H$_2$) = 10$^{18}$ cm$^{-2}$ and excitation temperature T$_{H_2}$ = 620 K (Figure 4).

From the increase of the H$_2$ intensity with radial distance (occurring at the PDR interface due to attenuation of UV photons) we derive a mean density n$_H$ $>$ 10$^4$ cm$^{-3}$ [8] (which corresponds also roughly to the pressure equilibrium at the ionisation front). From both the total integrated infrared dust emission and geometrical dilution we derive an effective radiation field at the location of the ring corresponding to G$_0$ $\sim$ 200–400 [8].

5. Bottom-up formation of PAHs: photochemistry of small hydrocarbons
In the bottom-up PAH formation scenario, CO is dissociated which produces abundant free atomic carbon which can then – under the right conditions – form small hydrocarbons[6, 3]. In the case of the NGC6720, N(C) $>$ 10 $\times$ N(CO) [18, 19]. C, CO and H$_2$ have a clumpy distribution with the presence of relatively dense knots (n$_H$ $>$ 10$^4$ cm$^{-3}$) exposed to a moderate radiation field of G$_0$ $\sim$ 200.

Carbon chemistry reactions with moderate activation energies (such as C$_2$ + H$_2$ $\rightarrow$ C$_2$H + H, C$_2$H + H$_2$ $\rightarrow$ C$_2$H$_2$ + H, and C$^+$ + H$_2$ $\rightarrow$ CH$^+$ + H) proceed slowly in the cold ISM, but can become rapid enough to control C-bearing species at relatively high temperature and density

Figure 2. Spitzer IRS-SH spectra for NGC 2346 (centre) and NGC 6720 (rim and centre).

Figure 3. 11.3 $\mu$m PAH features in Spitzer IRS-SH spectra of NGC 6270, NGC 7027, M2-9, and Horsehead H II region.

Figure 4. H$_2$ rotational diagram for a north-east region of the ring. N(H$_2$) = 10$^{18}$ cm$^{-2}$ and T$_{H_2}$ = 620 K.
prevailing in PDRs of (P)PN, such as we find for the knots in NGC 6720. How much these reactions compete with the oxygen chemistry needs to be evaluated.

6. Conclusions/Summary
A peculiar PAH emission spectrum is detected in the main ring of the planetary nebula NGC 6720. The PAH emission appears co-spatial with the clumpy H$_2$ distribution. This detection is unexpected from previous studies as well as the lack of PAH emission in the other oxygen-rich extended PNe investigated here. We propose that an efficient in-situ production of small hydrocarbons in the dense knots of NGC 6720 leads to the bottom-up production of PAHs. The specific conditions and mechanisms of forming PAHs from small hydrocarbons in dense knots, and why this leads to the peculiar observed PAH spectrum, needs to be investigated. In future work we will focus on mapping individual knots in millimetre molecular lines, tracing, for example, the photo-chemistry, in NGC 6720. With JWST we can map the distribution of H$_2$ and PAHs/eVSG in extended PNe (NIRCam) and study the PAH spectrum of individual knots and their micro-PDRs (MIRI).

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