PAHs Near and Far: Ground and Airborne 3-5 micron observations of PAHs in Planetary Nebulae and Star Forming Regions in the Era of JWST

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Polycyclic Aromatic Hydrocarbons (PAHs) exhibit bright, broad emission features throughout the infrared with main features at 3.3, 6.2, 7.7, 8.6, 11.3 and 12.7 μm. These bands arise from the UV excitation of PAHs and relaxation through the vibration, bending and/or stretching of the C–H and C–C bonds. This emission has been observed in multiple astronomical phenomena, including planetary nebulae, where they are believed to be formed, and star-forming regions, which has led to their use as a marker for estimating star formation rates in distant galaxies. Many of these bands are accessible from ground-based observatories, including 3.3 micron PAH feature and its associated aliphatic features at 3.4-3.6 microns. We used ground-based (Lick/FLITECAM and Keck/NIRSPEC) observations of the ~3-5 micron spectra of young planetary nebulae and nearby star-forming regions, to investigate the spatial distribution and spectral variation of PAH emission, and stratospheric (SOFIA/FLITECAM) observations to constrain the theoretical contribution of the 4.4-4.8 micron deuterated-PAH features and the weak 5.25 PAH emission feature. Studying young PNs and nearby star-forming regions with ground-based telescopes gives a unique opportunity for fully understanding PAH emission, processing and variation that can be used in interpreting the extra-galactic PAH spectra JWST will study.

Four PNs were observed on SOFIA with FLITCAM: NGC 7027, IC 5117, PNG 093.9-00.1 and BD +30 3638. All four had known PAH features, but emission in the weak 5.25 μm PAH band, had not been previously measured in IC 5117.. Each object was observed from ~2.8 to 5.41 μm, except for the 4.2–4.4 μm region, which is opaque.

The 3-5 μm emission in PNG 093.9-00.1 is markedly different from the other objects, with a central emission wavelength slightly blue-shifted from the more evolved PNs. Additionally the shape of the PAH emission in PNG 093.9-00.1 is more asymmetric. PNG 093.9-00.1 also shows no emission lines, while NGC 7027, BD +30 and IC 5117 show several atomic and forbidden emission lines. PNG 093.9-00.1 shows aliphatic emission structure similar to that found in NGC 7027. The other two PNs show a slight plateau at ~ 3.4 μm, which may be evidence of aliphatic emission, but do not show additional structures expected at 3.46, 3.52 and 2.56 μm. Deuterated PAHs (expected at 4.5 and 4.7 μm), are not detected. The equivalent width of the 3.3 μm and 5.25 μm PAH features and 3.4-3.6 μm aliphatic feature were determined. The aliphatic 3.4 to 3.6 μm features are especially prominent in NGC 7027 and PNG 093.9-00.1, with EW aliphatic to (3.3 μm) aromatic ratios of 0.495 and 0.470 respectively. (See Table 1).

Table 1. PAH AND ALIPHATIC RESULTS

Object Name	3.3μm Peak (μm)	3.3μm FWHM (μm)	3.3μm Class	3.3μm EW (μm)	Aliphatic EW (μm)	Ratio 3.4/PAH	3.3μm Flux (10^{-15}W/m^2)
NGC 7027	3.292±0.004	0.042±0.001	A	0.361±0.005	0.179±0.003	0.495	1153.1±0.6
BD +30 3639	3.292±0.002	0.042±0.002	A	0.204±0.005	0.049±0.003	0.240	88.3±0.07
IC 5117	3.292±0.004	0.041±0.002	A	0.096±0.007	0.027±0.005	0.281	11.9±0.06
PNG 093.9−00.1	3.290±0.002	0.044±0.003	A	0.302±0.002	0.142±0.002	0.470	39.3±0.02

NOTE— Flux has been corrected for slit loss assuming the angular size in Table 2 and a 2 arcsecond FLITECAM slit. Extraction width (arcsec): 7027: 6.97 (3-3.35μm), 6.78 (3.35-4.1μm); BD: 8.2 (3-3.35μm), 8.4 (3.35-4.1μm); IC: 4.3 (3-3.35μm), 3.7 (3.35-4.1μm); PNG: 6.1 (3-3.35μm), 5.8 (3.35-4.1μm). Cohen et al. reported 3.3 μm fluxes for of 62.8(10^{-15}W/m^2) for BD+30 3639 and 8.59(10^{-15}W/m^2) for IC 5117

The 5.25 μm feature was first detected by Allamandola et al. (1989a) in KAO observations, and has been studied in a small number of objects, including HII regions and PNs. Our observations show 5.25 μm emission in all four planetary nebulae in our sample. While this feature has been observed in three of the nebulae, this is the first measurement of 5.25 μm PAH emission in IC 5117. The 5.25 μm feature was measured by smoothing with a 5 pixel Gaussian, then fitting with MPFIT (Markwardt 2009). The central wavelength, equivalent width and flux of the feature in each object is listed in Table 2.

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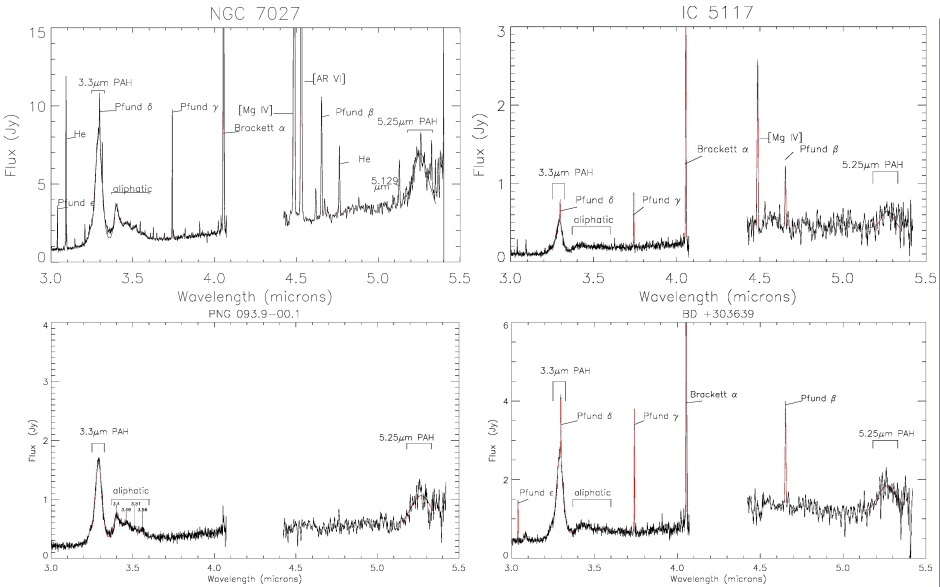
Table 2. 5.25 MICRON RESULTS

Object Name	Extraction Width(arcsec)	5.25μm Peak (μm)	5.25μm FWHM (μm)	5.25μm EW (μm)	5.25μm Flux (10^{-15}W/m^2)
NGC 7027	5.92	5.257±0.002	0.09±0.006	0.64±0.009	136.3±0.4
BD+30 3639	20.1	5.265±0.01	0.12±0.05	0.06±0.01	23.6±2.7
IC 5117	10.0	5.269±0.02	0.09±0.05	0.05±0.03	3.6±0.9
PNG 093.9−00.1	5.4	5.267±0.01	0.15±0.03	0.16±0.01	23.8±0.5

NOTE—Flux has been corrected for slit loss assuming the angular size in Table 1 and a 2 arcsecond FLITECAM slit.



Above: 3-5.5 μm SOFIA/FLITECAM spectra of four planetary nebulae, clockwise from top left: NGC 7027, IC 5117, BD +303639, and PNG 093.9-00.1. All four PNs exhibit PAH emission at 3.3 μm and the associated 3.4 μm aliphatic emission. The emission at 5.25 μm is measured here in IC 5117 for the first time. Differences in emission may be due to the age, the temperature of the central star, or the individual morphology of the nebula, or, most likely, a combination of characteristics. Studying spatial variations within these PNs with a Multi-Object Spectrograph could uncover additional emission variations due to nebular conditions. JWST's NIRSPEC instrument will allow such measurements in a variety of objects, including galactic shocks, SFRs, etc

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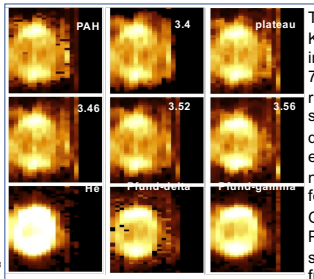
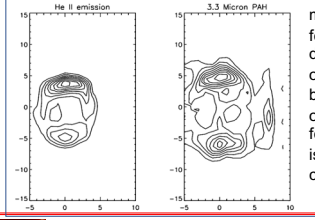
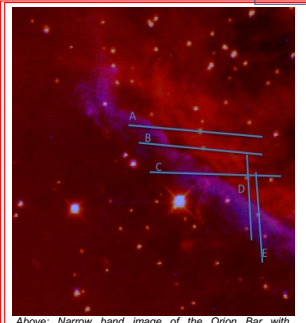


Top: : Narrow band images of NGC 7027 extracted from Keck/NIRSPEC data cube

Below: Contour images of NGC 7027 for atomic Helium emission and hydrocarbon PAH emission, illustrating the differences in emission distribution



The NIRSPEC instrument on the Keck telescope was used to investigate spatial variation within 7027 by creating a spatially resolved data cube with two spatial and one spectral dimensions, yielding spectra at each point over the extent of the nebula—over 600 total. Atomic features were fitted with Gaussians, while the underlying PAH plateau was modeled by a series of line segments. Total flux from each hydrocarbon feature was calculated. Narrow band images of NGC 7027 centered on each feature are seen above left. Atomic features exhibit a ring-like morphology, while hydrocarbon features exhibit bipolar distribution (center left). The point of max flux in the hydrocarbon bands is further from the central object than that of the atomic features. Hydrocarbon emission is diffuse and located within the classical 'ring' of NGC 7027



Above: Narrow band image of the Orion Bar with hydrogen emission in red, and 3.3 μm PAH emission in blue. 5 NIRSPEC slit pointings are overlaid and marked

Using Keck/NIRSPEC we obtained 5 slit pointings across and along the Orion Bar. The figure to the left shows a two-color narrow band image of emission in the bar, with red representing hydrogen emission and blue representing 3.3 μm PAH emission. Narrow band images are ground-based FLITECAM observations.

The figure to the right shows three spectra from slit pointing E. In this orientation, the strongest UV source is towards the upper right corner of the image. The 3.4 μm feature is more prominent (compared to the 3.3 μm feature strength) in the ionized region of the bar, which has also been observed in other regions (Sloan et al.)